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Origin of lightning electric field signatures showing two return-stroke waveforms separated in time by a millisecond or less

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Abstract. Based on simultaneous single-station electric field and multiple-station TV records of 76 negative cloud-to-ground flashes in Florida, we have examined the relation between (1) the electric field waveforms characteristic of return strokes but separated by the relatively short time interval of typically some tens to some hundreds of microseconds (the extreme values were 15 μs and 3.3 ms) and (2) the number of TV-observed channel terminations on ground. Double field waveforms (15 total) were observed in about 20 % of all flashes analyzed. Nine of the 15 double field waveforms were associated with lightning channels having double terminations on ground. The remaining six double field waveforms were associated with channels showing single ground attachments. The latter observation suggests that double field waveforms can be due to two return strokes, each initiated by its own leader process, occurring in the same channel within a millisecond or less of each other. Such short interstroke intervals imply that the minimum time for the lightning channel to decay to the point that a new leader-return stroke sequence can occur is significantly shorter than previously thought.

Introduction

Guo and Krider [1982], studying the optical and electric field signatures of lightning return strokes at the NASA Kennedy Space Center (KSC), Florida, observed that 5 (2%) of 246 first-stroke electric field records exhibited two fast-rising waveforms separated by 46 to 110 μs. Each of the fast-rising waveforms was characteristic of a ground return stroke. The second waveform had an initial peak comparable in magnitude to that of the first waveform, as illustrated in their Figure 6. These pairs of field waveforms were accompanied by two abrupt components in the simultaneously recorded all-sky light signal. *Guo and Krider* [1982] postulated that their field and light observations were due to two return strokes being initiated by two branches of the same stepped leader, that is, due to a single stroke creating two terminations on the ground. *Schonland et al.* [1935, Figure 6] show streak-camera images of two leader branches apparently originating from a single trunk hidden inside the cloud and producing two return strokes separated in time by 73 μs. We have observed, in various studies of the electric fields produced by ground flashes, the double field waveforms which we, following *Guo and Krider* [1982], had assumed to be associated with double-ground leaders. An example of one of those waveforms, from a study collaborative with M. Brook of New Mexico Institute of Mining and Technology, is given in Figure 1. The waveform was recorded by *Brook* [1992] in 1991 at the NASA Kennedy Space Center (KSC) using a 12-bit, 2-MHz digitizer. The digitizer was fed from a flat-plate antenna via an integrator and a low-pass antialiasing filter. The overall bandwidth of this electric field measuring system was 0.1 Hz to about 1 MHz [*Brook*, 1992].

To examine further *Guo and Krider*'s [1982] hypothesis regarding the relation between the double field waveforms and double-channel ground terminations, we have studied (1) 13 events that exhibited double-ground terminations as determined by TV records, 9 of which showed double field waveforms, and (2) 6 events that showed double field waveforms but exhibited single attachments to ground as determined by TV records. In this paper we present the results of this analysis and discuss some new inferences based on our observations.

Data and Results

The data analyzed here were derived from simultaneous single-station wideband electric field and multiple-station TV records of 76 negative flashes studied previously by *Rakov and Uman* [1990a, b, c], *Rakov et al.* [1990, 1992a, 1994], and *Thottappillil et al.* [1990, 1992]. The TV records enabled us to identify, characterize, and locate (in conjunction with thunder ranging and visual observations) the lightning channels associated with individual strokes. The flashes occurred at distances of 2 to 20 km during three convective thunderstorms in July 1979 near Tampa, Florida. A description of the measuring system and data processing techniques can be found in the work of *Beasley*

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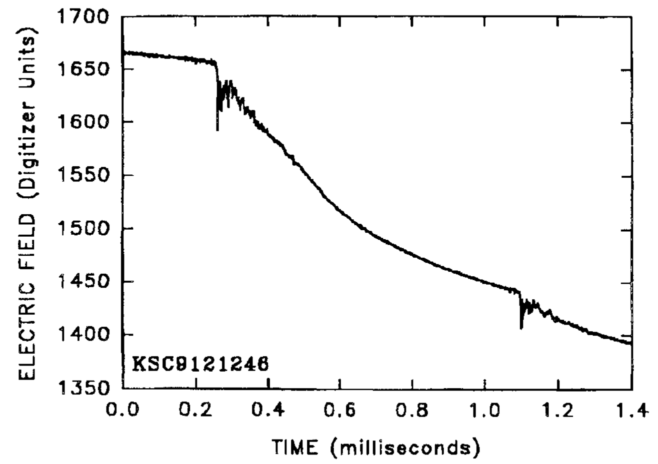

Figure 1. An example of an electric field signature showing two waveforms characteristic of return strokes. The record was obtained by M. Brook in 1991 at the Kennedy Space Center. The two waveforms are separated by about 850 μs and are associated with second stroke of a negative ground flash. Note that the slow field change following the initial peak of the second waveform has a higher slope than prior to the peak, indicative of the fact that appreciable charge transfer is associated with the second event as well as with the first event. Here and in the following figures, positive (atmospheric electricity sign convention) electric field change deflects downward.

et al. [1982], *Master et al.* [1984], and *Rakov and Uman* [1990a].

There were a total of 15 (out of 190) strokes of order 1 through 3 that appeared to attach to ground at two points. Strokes of order 4 and higher (156 total) never showed double grounds in the TV records. For 2 of the 15 double-ground strokes, the appropriate electric field record was not available. Pertinent features of the remaining 13 double-ground strokes are summarized in Table 1. Nine of the 13 double-ground strokes, events 1 through 9 in Table 1, showed two field waveforms characteristic of return strokes (examples are given in Figures 2 and 3) following a single field change characteristic of a negatively charged downward moving leader [*Rakov and Uman*, 1990c]. Two of these nine events, events 1 and 2 in Table 1, did not exhibit a pronounced quiet interval between the two portions of the overall field signature. The estimated separation times between the initial peaks of the first and second waveforms were 22 and 15 μs, and the inclusion of those two events in the double waveform group was to some extent an educated guess. The greatest separation time was 3.3 ms (event 6 in Table 1). Each of the other four double-ground strokes, events 10 through 13 in Table 1, showed a multiply peaked waveform (an example is given in Figure 4) with time separation between the first and the last major peaks being of the order of a few tens of microseconds. It is possible that these multiply peaked electric field signatures were composed of two (or more) waveforms, but we could not clearly identify these.

Further, and more important for the present analysis, six strokes that were single grounded (about 2 % of all single-ground strokes) exhibited two field waveforms characteristic of return strokes (examples are given in Figures 5 and 6), similar to the double-ground events 1 through 9. Pertinent features of those six single-ground strokes are summarized in Table 2.

The double field waveforms, associated with both single-ground events and double-ground events, were observed in about 20 % of all the flashes analyzed here.

It is worth noting that, in an extension of the observations of *Guo and Krider* [1982], we found double field waveforms to be associated not only with first strokes but also with subsequent strokes, although never with the 115 strokes of order 5 or higher. Additionally, both the fraction of flashes showing double field waveforms and the average time separation between those waveforms is larger in our study than in the study of *Guo and Krider* [1982], apparently because their analysis was limited by a relatively short oscilloscope sweep of 200 μs, whereas our data are based on continuous tape records and hence have no fixed upper time bound.

Analysis and Discussion

We first discuss double-ground events 1 through 9 presented in Table 1; that is, those double-ground events that showed separable double field waveforms. The height

Table 1. Characterization of Double-Ground Strokes

Event	Flash	Stroke Order	E_s/E_p	h/H	ΔT, μs
1	221003	1	1.05	<0.5	22
2	191416	1	0.87	0.5-1	15
3	220651	1	0.22	1	100
4	224251	1	0.33	0.5	165
5	220339	1	0.56	0.5	287
		Figure 2			
6	220623	1	0.65	0.5-1	3335
7	185725	1	0.40	>1	442
8	220525	1	0.51	>1	513
9	220832	3*	0.35	>1	596
		Figure 3			
10	223917	3†	-	<0.25	-
		Figure 4			
11	220319	2†	-	0.25	-
12	223917	1	-	>1	-
13	184422	1	-	>1	-

E_p and E_s are the initial peaks of the first and second waveforms, respectively, of the double field signature; h and H are the height above ground of the channel branching point and the total height of the visible part of the channel, respectively; h/H > 1 means that the branching point does not appear in TV image and is assumed to be hidden inside the cloud. ΔT is the time separation between the initial peaks of the first and second waveforms of the double field signature.

*A new path between the cloud base and the ground was created in addition to that followed by strokes 1 and 2.

†A new, double-ground path, different from that followed by the previous stroke(s) was created.

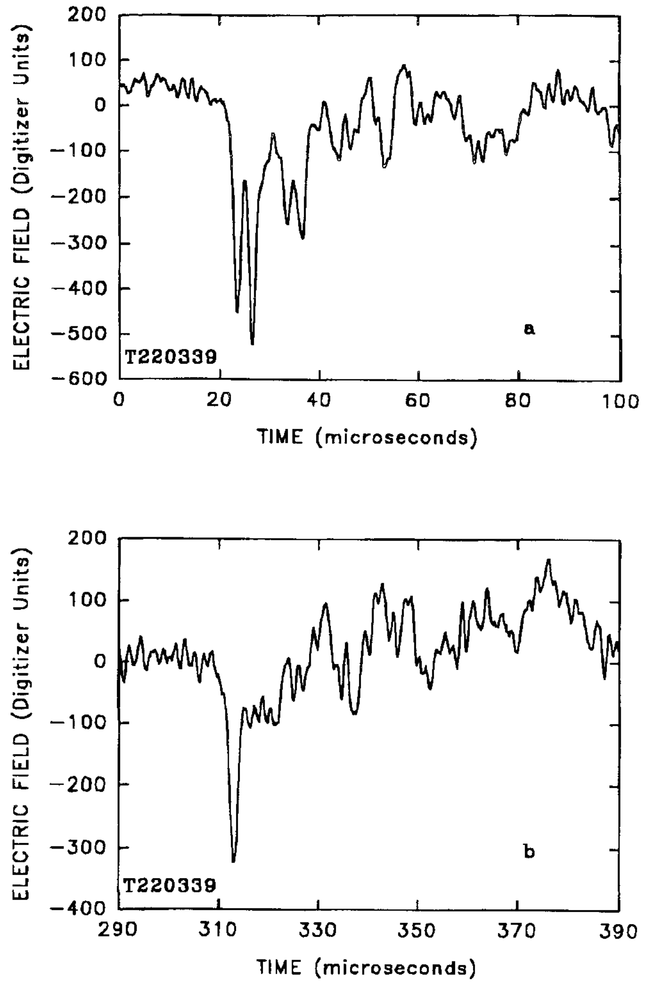

Figure 2. (a) Primary and (b) secondary waveforms of the electric field signature of a double-ground single-stroke negative ground flash (event 5 in Table 1) at about 20 km. The channel branching point was at the middle of the visible part of the channel. The separation between the waveforms is 287 μs. This record and those in the following figures were obtained by the University of Florida lightning research group in 1979 near Tampa, Florida.

of the cloud base in Florida is typically 1 km [*Idone and Orville*, 1982]. Even if we consider the inclination and large-scale tortuosity of the lightning path and the possibility of the lightning channel emerging from the front of the cloud rather than from the cloud base, the two-dimensional channel lengths in our TV images are unlikely to exceed 2 km. Some confirmation of this limit comes from the fact that the maximum channel length for leader and return-stroke speed measurements made in Florida has been 1.4 km [*Jordan et al.*, 1992; *Idone and Orville*, 1982]. Further, the minimum two-dimensional speed of the return stroke, measured over the lowest channel section (from some hundreds of meters to a few kilometers in length) in various geographical locations is about the same and is about 2x10^7 m/s [*Idone and Orville*, 1982; *Rakov et al.*, 1992b, Table 2]. Based on a maximum channel length of 2 km and a minimum return-stroke speed of 2x10^7 m/s, we can roughly estimate the maximum time for a return stroke to reach a given height h on a channel, whose total visible height is H. For the case of two downward leader branches competing for an earlier attachment to Earth, the time for the upward moving return stroke along the more successful branch to reach the channel branching point in the middle of the visible portion of the channel (h/H=0.5) and then to begin discharging the less successful branch should not exceed 50 μs, and the time for that return stroke to reach the branching point at the top of the visible portion of the channel (h/H=1) should not exceed 100 μs. Note that for the bottom part of the channel, particularly below the branching point, the return-stroke speed should be higher than that averaged over the entire visible channel and used to make the above propagation-time estimates. It is not clear whether the transfer of ground potential to the branching point by the upward moving return stroke usually terminates the development of the less successful branch, as intuitively would seem to be the case. Sometimes, apparently, it does not: *Schonland et al.* [1935] reported observing three cases of return strokes propagating from the branching point along the ungrounded branch and catching up to the stepped leader that was

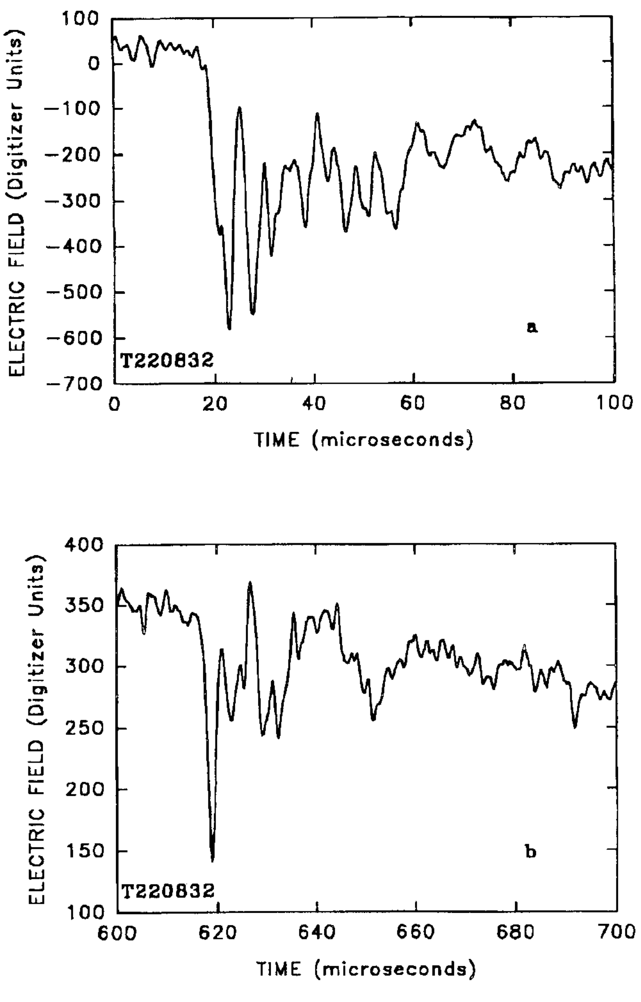

Figure 3. (a) Primary and (b) secondary waveforms of the electric field signature of a double-ground third stroke (event 9 in Table 1) of a four-stroke negative ground flash at about 8 km. The channel branching point was apparently hidden inside the cloud. The separation between the waveforms is 596 μs.

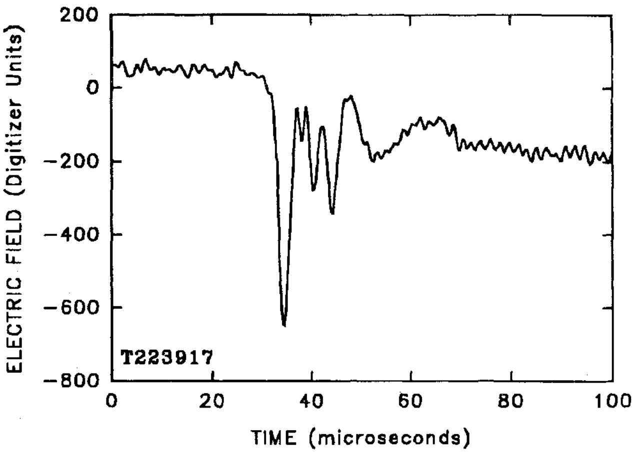

Figure 4. Electric field signature of a double-ground third stroke (event 10 in Table 1) of an eight-stroke negative ground flash at about 7 km. The channel branching point was at the lowest quarter of the visible part of the channel (two TV images).

continuing to progress toward ground. In two cases the branch was terminated, while in one case (an unusually slow return stroke along a horizontal branch apparently near 10 km in length), the branch extended an additional 1.9 km at stepped-leader speed, 1.3x10^5 m/s, and exhibited a luminosity recoil at its termination point, perhaps a pocket of space charge in the air. It is worth noting that *Schonland et al.* [1935] also observed stepped-leader branches which stopped propagating before the leader main trunk contacted ground and others which stopped propagating at about the time the leader trunk touched ground. If we assume that a return stroke catching up to the stepped-leader branch tip terminates further extension of the branch and that the return-stroke speeds along the main trunk and along the branches are similar [*Schonland and Collens*, 1934], the maximum time to discharge the less successful branch should be about the same as the time for the return stroke to travel up to the branching point. If the ungrounded branch is completely discharged by the return stroke before that branch has contacted ground, no second return stroke can be initiated and therefore the electric field signature would appear as a single, not a double, waveform. Thus to inhibit a double ground, even a very slow return stroke requires times not exceeding 100 and 200 μs for h/H=0.5 and h/H=1, respectively, twice the times to reach the branching point. Of course, a return stroke can travel at a speed more than an order of magnitude higher than the minimum value of 2x10^7 m/s, resulting in propagation times more than an order of magnitude less than the above estimated maximum values.

Double Ground Attachment

For events 1 through 3 in Table 1 the observed time separations between the two waveforms, 15 to 100 μs, are smaller than the maximum estimated times for the propagation of the return stroke from the first leader ground to the channel branching point (h/H of <0.5 to 1) and down the other branch to ground. Hence each of the corresponding double field waveforms can reasonably be associated with a double-ground leader, in confirmation of the hypothesis of *Guo and Krider* [1982].

For events 4 and 5 in Table 1 the observed values of ΔT are 165 and 287 μs, respectively, apparently greater than the time of about 100 μs required for even a very slow return stroke to discharge the less successful channel branch (h/H=0.5). For event 6 the time required to discharge the less successful branch (h/H<1) cannot exceed 200 μs, more than an order of magnitude smaller than the observed time separation of about 3.3 ms between the two waveforms. Thus the double field waveforms exhibited by events 4 through 6 are unlikely to be due to return strokes initiated by two branches of the same leader, in contradiction to the hypothesis of *Guo and Krider* [1982]. The 3.3-ms separation between the waveforms of event 6 is longer than the minimum interstroke interval of 3 ms in 76 flashes comprising our database. In our previous analyses of the same data [e.g., *Rakov and Uman*, 1990b] we observed a number of situations in which two strokes separated in time by less than 17 ms were unresolved in the TV records, that is, appeared on the same 17-ms field. We could distinguish between such strokes if the electric field records showed waveforms characteristic of two separate leader-return stroke sequences. As to event 6 (included in this study because of its double-ground termination), it was treated in the previous analyses as a stroke initiated by a double-grounded leader followed in 3.3 ms by some in-cloud process, not as two strokes separated by 3.3 ms, because there was no pronounced leader-type field change preceding the second return-stroke-type waveform. It is likely that this second waveform is indeed due to a return stroke initiated by its own leader with the electric field change of this leader appearing unpronounced, presumably because of overlap with the more prominent field changes of the in-cloud processes initiated by the preceding return stroke. In any case we exclude event 6 from further analysis and discussion, which will be concerned with double field signatures exhibiting separation times of a millisecond or less.

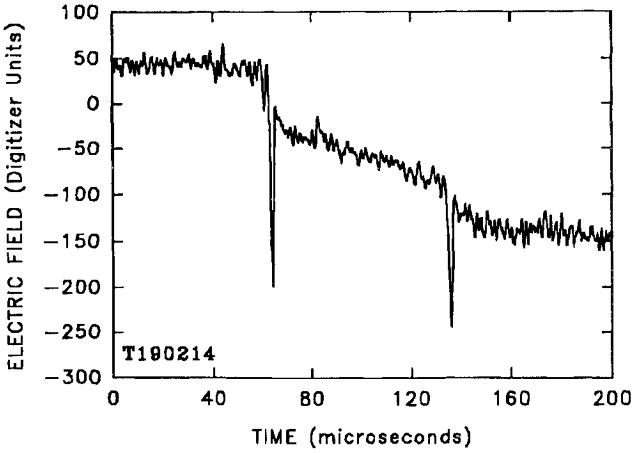

Figure 5. Primary and secondary waveforms of the electric field signature of a single-ground second stroke (event 1 in Table 2) of a three-stroke negative ground flash at about 5 km. There were two TV images showing a single path to ground. The separation between the waveforms is 72 μs.

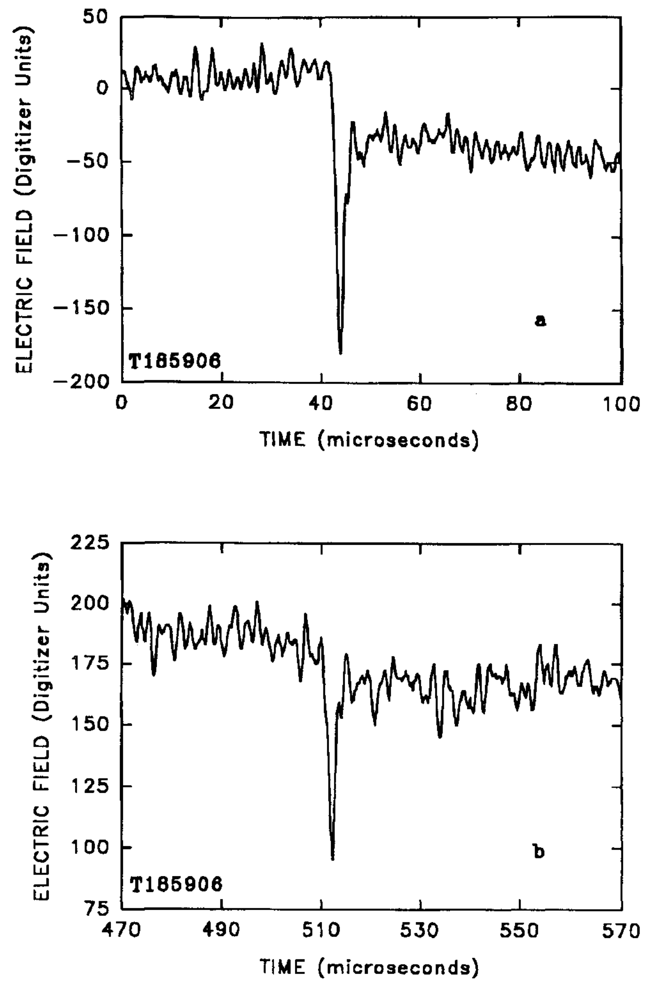

Figure 6. (a) Primary and (b) secondary waveforms of the electric field signature of a single-ground third stroke (event 4 in Table 2) of a four-stroke negative ground flash at about 6 km. The separation between the waveforms is 469 μs.

For events 7 through 9 in Table 1, for which the channel branching point is presumably hidden inside the cloud (h/H > 1), we cannot make any estimates of the time for the return stroke to reach the branching point and discharge the less successful branch since, even if we assume the channel branching point to be located at the height of the cloud charge source, we do not know the return-stroke speed in the upper, in-cloud sections of the lightning channel, except that it is likely to be significantly lower than that in the channel sections below the cloud base [*Idone and Orville*, 1982]. Thus these events cannot be used to verify or to refute *Guo and Krider*'s [1982] hypothesis.

Double-ground events 10 through 13 in Table 1 did not show unambiguous double field waveforms in their electric field records, as discussed earlier, only exhibiting multiple field peaks separated by less than 15 μs. The time interval between the first and the last major peaks varied from 18 to 28 μs, comparable with the separations between the two waveforms of events 1 and 2. Perhaps one of the subsidiary peaks is the initial peak of the return stroke associated with the second ground strike point documented in the TV records. Interestingly, the time separations between the major peaks are similar for events 10 and 11, which have the branching point in the lowest quarter of the channel, and for events 12 and 13, which presumably have the branching point hidden inside the cloud. *Weidman and Krider* [1978] found similar multiple field peaks to be characteristic of virtually all first return strokes and attributed those peaks to the effects of ungrounded branches, while *Cooray and Lundquist* [1985] apparently associated the most pronounced dips between field peaks with the major channel branches. Summarizing, for events 10 through 13 in Table 1 we find no relation between the multiple-peak field structure and the observed double termination on ground.

Single Ground Attachment

We now discuss the six events presented in Table 2, each of which appeared single grounded in one or two TV images (in most cases with no evidence of rain which could potentially obscure another channel) and to an observer but exhibited two distinct return-stroke-type waveforms in its electric field signature. We cannot rule out the possibility that additional channel terminations have escaped both TV imaging and observer view, but we think this possibility is remote. Note that except for event 1, each of the measured values of ΔT is of the order of some hundreds of microseconds and that if the double field waveforms were associated with a double-ground leader, those time separations would be indicative of a channel branching point hidden inside the cloud (h/H > 1) (see our discussion of events in Table 1). Thus any multiple channel terminations that might originate in the close proximity of ground and be obscured by trees cannot be responsible for the observed double field waveforms. Further, for the two first strokes in Table 2, both primary and secondary waveforms are multiply peaked (similar to the double waveform shown in Figure 6 of *Guo and Krider* [1982]), while for the four subsequent strokes, both primary and secondary waveforms are single peaked and relatively smooth. In the latter four cases, if one of the waveforms were associated with a new (undetected) path

Table 2. Characterization of Single-Ground Strokes Showing Two Waveforms Characteristic of Return Strokes in Their Electric Field Signatures

Event	Flash	Stroke Order	E_p, V/m	E_s/E_p	ΔT, μs
1	190214	2	1.4	0.68	72
		Figure 5			
2	221157	1	7.8	0.23	198
3	191107	4*	4.2	0.69	308
4	185906	3*	1.6	0.45	469
		Figure 6			
5	190004	3*	3.6	0.20	810
6	191631	1	4.8	0.41	1023

E_p, E_s, and ΔT are the same as in Table 1.

*The preceding subsequent stroke created a new path to ground.

from the cloud to ground, a multiply peaked waveform characteristic of a first stroke would be expected. In general, the secondary field waveform appears very much like the primary in shape and on average is about half the primary in magnitude. It is worth noting that all the subsequent strokes in Table 2 followed a stroke that created a new path to ground, a fact possibly suggesting relatively poor channel conditioning [*Rakov and Uman*, 1990b] and hence relatively early channel current cutoff.

Since the hypothesis of *Guo and Krider* [1982] apparently is not valid for events 4 and 5 from Table 1 and, more important, for all six events in Table 2, we hypothesize that the observed double field waveforms for those events are due to two sequential return strokes of the same flash, each being initiated by its own leader, rather than by the double branching of a single leader. We have additionally considered four alternate physical situations for producing the observed double field signatures and found all of them to be unlikely. This discussion is found in Appendix A.

In the following, which is concerned with the newly advanced hypothesis, we will use the term "primary" for the leader and return stroke in the first sequence and the term "secondary" for those in the second sequence. In the case of single-ground events, the scenario appears to be straightforward, while for the double-ground events inconsistent with *Guo and Krider*'s [1982] hypothesis some additional comments are appropriate. We briefly describe a suggested hypothetical mechanism as applied to the double-ground events 4 and 5 in Table 1: The primary leader develops two branches. Either both are grounded and produce inseparable return-stroke field waveforms (a situation similar to that for events 10 through 13 in Table 1) or the second branch terminates close to but above ground. The secondary leader either can complete the development of the second branch to ground or can involve both branches by initiating two return strokes inseparable in the electric field records.

For our hypothesis regarding two leader-return stroke sequences in the same channel within a millisecond or less to be true, two conditions must be present.

1. The primary return-stroke current at the channel base must cease after some tens to a few hundreds of microseconds. If the current were still to flow through the channel bottom after this time, any additional charge source available to the channel would presumably result in an M component rather than a leader-return stroke sequence, the former producing a channel-base current pulse having a risetime typically 2 to 3 orders of magnitude longer than that of a return-stroke current pulse [*Fisher et al.*, 1993].

2. The secondary leader must exhibit a relatively high speed so as to complete its trip from the cloud charge source to ground in some tens to a few hundreds of microseconds or that leader must be launched from a charged channel section significantly lower than the primary cloud charge source.

We now discuss the plausibility of these two conditions. In Appendix B we have summarized the presently existing data on the shortest times for return-stroke and leader processes. It follows from this summary that a return-stroke channel cutoff time of 150 μs or so can occur, though rarely, and that propagation times of the order of 100 to 200 μs are not unreasonable for the fastest leaders.

The minimum leader propagation times inferred in Appendix B are for leaders following an interstroke interval longer than a few milliseconds. No measurements exist for leaders following interstroke intervals of a millisecond or less, and we can only speculate on the behavior of such early leaders. Two such speculations follow.

1. *Jordan et al.* [1992], studying both natural and rocket-triggered lightning leaders, reported a decrease in maximum observed dart-leader speed for successive interstroke interval ranges of 2-30, 30-70, and 70-138 ms, with a maximum speed ever measured of 4.9×10^7 m/s being found in the first range. Perhaps for the submillisecond-aged channels the maximum dart-leader speed is even larger than this value.

2. In many cases the secondary return-stroke-type waveform appears to be superimposed on the R_c-type portion of the primary return-stroke waveform (see, for example, Figure 1), following the R_b portion whose duration is typically 100 μs [*Malan and Schonland*, 1951]. This behavior may imply that the R_c processes occur predominantly in the upper sections of the lightning channel and are not associated with charge transfer to ground, an inference similar to that of *Krehbiel et al.* [1979] based on their observation of the dependence of the R_c polarity on distance using multiple-station electric field measurements. Perhaps the R_c processes charge an upper channel section which is effectively disconnected from ground, as suggested by *Krehbiel* [1981] from multiple-station field measurements, and when a sufficiently high charge is accumulated, a secondary leader can be initiated from that section, rather than from the higher cloud charge source, toward ground along the remnants of the lower channel section. If this speculation be true, the leader propagation times would be shorter than estimated above, but an additional time would be required to make the upper channel section a charge source capable of initiating a downward leader. On the other hand, it is possible that some of the primary-leader charge left behind by a weak primary return stroke might contribute to the initiation of the secondary leader. In the latter case, the secondary and primary leaders should apparently not be viewed as totally separate processes. Perhaps relevant to the question of whether channel charge that the return stroke does not remove can launch a dart leader is the observation of *Schonland et al.* [1935], noted earlier, regarding the initiation of a stepped leader from the tip of a long ungrounded leader branch that had just been overrun by a return stroke.

Summarizing our discussion, we conclude that our hypothesis that two consecutive leader-return stroke sequences can develop in the same channel within a millisecond or less appears feasible, although further observations are needed before it can be positively proven.

Concluding Remarks

The new hypothesis has potentially important implications regarding the adequacy of the interstroke-interval distributions now in the literature. The minimum values of these interstroke intervals are given in Table 3, with the shortest documented interval being 1.9 ms. If the hypothesis be true, the distribution of interstroke intervals would have to be extended to the submillisecond range.

Table 3. Observed Minimum Values of Interstroke Time Interval

Reference	Geographical Location	Sample Size	Minimum Interval, ms	Comments
Schonland [1956]	South Africa	1482	<10	Electric fields and photography. Natural lightning.
Malan [1956]	South Africa	N/A	15*	Photography. Natural lightning.
Kitagawa and Brook [*Jordan* et al., 1992]	New Mexico	96	3.1	Photography and electric fields. Natural lightning.
Rakov and Uman [1990a]	Florida	270	3	Electric fields. Natural lightning.
Atlas of lightning currents [*Berger*, 1972]	Switzerland	115	2.9	Currents. Tower downward lightning.
Beierl [1992]	Germany	31	7	Currents. Tower lightning.
Idone et al. [1984]	New Mexico (1981)	32	1.9	Photography and currents. Triggered lightning.
Jordan et al. [1992]	Florida (1987 and 1989)	36	13	Photography and currents. Triggered lightning.
Fisher et al. [1993]	Florida (1990) Alabama (1991)	22 30	3 11	Currents. Triggered lightning.

*This value was postulated by *Malan* [1956] to be a limit below which the status of the lightning channel is such that no leader can develop along that channel.

Finally, we note that a secondary leader-return stroke sequence occurring within the first millisecond of the primary return stroke, when the current may well flow in the upper channel sections while the channel bottom is cut off at the ground, might differ (in addition to presumably having a higher leader speed and leaving aside our speculation on the initiation of the leader from a sufficiently charged upper channel section) in its salient properties from the "normal" leader-return stroke sequence following a normal interstroke interval when there is probably no current flow along the entire channel section below the cloud base. Perhaps the secondary leader-return stroke sequences are more closely related to M components than to normal leader-return stroke sequences and, if so, should better be called R components, a term implying a process similar to an M component but, as opposed to the latter, initiating a return stroke. Clearly, the processes occurring during the first millisecond following the return stroke are in need of further study.

Appendix A

Physical Situations, Other Than Two Consecutive Leader-Return Stroke Sequences in the Same Flash, Potentially Capable of Producing the Observed Double-Field Waveforms but Argued Here to be Unlikely to Do So

Random overlap of field signatures produced by two return strokes that belong to independent lightning discharges. The probability of two relatively close return strokes from two independent lightning flashes occurring within 1 ms or so is determined by the distributions of four parameters: the local ground flashing rate (typically 10 min^{-1} or less), the ground flash duration (typically some hundreds of milliseconds), the number of strokes per flash (typically 4 to 5), and the time interval between strokes (typically some tens of milliseconds). This probability, as can be inferred from the given typical values of the influencing parameters, should be very low. Here we only need argue that the probability of flash overlap taken alone is very small in our data (actual flash separations are larger than a few seconds in our continuous field records), with the probability of a submillisecond separation between strokes of the overlapping flashes therefore being negligible.

Secondary waveform is due to a stroke triggered elsewhere by the primary stroke. If a lightning discharge to ground were triggered by the abrupt change of electric field inside the cloud due to the return-stroke process of another discharge, the triggered discharge would be initiated by a stepped leader which requires at least a few milliseconds [*Beasley et al.*, 1982] to create a path to ground and produce a return stroke. This time is 1 to 2 orders of magnitude greater than most of the observed time separations between the primary and the secondary waveforms in this study and all the separations reported by *Guo and Krider* [1982]. Additionally, as mentioned in the body of the paper, for subsequent single-channel strokes from Table 2 the secondary waveforms appear single peaked and relatively smooth, a fact suggesting that they are associated with a return stroke in the previously formed channel rather than in a newly created one.

Secondary waveform is an ionospheric or other reflection of the primary waveform. Since *Guo and Krider* [1982] observed their five secondary field waveforms to be invariably accompanied by optical radiation and since most of our secondary field waveforms appeared to contain appreciable slow, predominantly electrostatic field changes (similar to those evident in Figure 1) indicative of close charge transfer, we consider this possibility highly unlikely. It is worth noting that waveforms shown in Figures 2 through 6 were recorded on a direct channel of a tape recorder with a 3-dB bandwidth of 400 Hz to 1.5 MHz. Because of the insufficient lower frequency response, the slower, predominantly electrostatic field changes following the return-stroke initial peak are not faithfully reproduced in these figures. In the simultaneous records from an FM channel (6-dB bandwidth from near dc to 500 kHz) the slower field changes appear much more pronounced, similar to those evident in Figure 1 (recorded with a system having a bandwidth of about 0.1 Hz to 1 MHz). We show the direct-channel records here because those better reproduce the fine structure of the field waveforms.

Secondary waveform is associated with an M component. *Rakov et al.* [1992a] have analyzed the microsecond-scale electric field pulses associated with M components separated mostly by 3 to 40 ms from the preceding return stroke. The M field pulses tended to occur early in the overall M-component process and hence are likely to be associated with the initiation of the M component inside the cloud. Waveforms of the M field pulses were found to be highly variable and distinctly different from the waveforms characteristic of return strokes in ground flashes. The polarity of the M pulses was predominantly negative, that is, opposite to that of a return-stroke field pulse in a lightning discharge lowering negative charge to ground. Unless the electric field pulses associated with M components occurring within the first few milliseconds of the return stroke are different in both their waveshape and polarity from those analyzed by *Rakov et al.* [1992a], the likelihood that the secondary return-stroke-type waveform is due to an M component is remote.

Appendix B

Summary of Available Data on the Extremely Short Return Stroke and Leader Processes

Return strokes. *McCann* [1944], using a photographic surge-current recorder with a sensitivity of about 0.2 A, found that a few (apparently 2 of 30) lightning-stroke currents analyzed had a duration of 600 µs or shorter. *Hubert* [1984, Figure 7b] reported a current waveform having a 8.2-kA peak and a roughly 150-µs duration for the first return stroke in an anomalous (not following the wire) rocket-triggered lightning flash, which apparently did terminate on the triggering facility. Two negative subsequent-stroke currents, 75 f and 84 g, out of a total of 115 measured in Switzerland and included in the atlas of lightning currents offered by *Berger* [1972], were apparently shorter than 150 and 100 µs, respectively, while all the first-stroke currents were longer than 150 µs. *Evans and Walker* [1963], taking high-speed cinematic records (exposure time of 2 µs and spacing between frames of 77 µs) of the lowest 10 m or so of the lightning channels terminating on a tower, have analyzed the duration of the luminosity of individual strokes in three lightning flashes. In one flash they observed several short-lived strokes whose luminosity apparently lasted for 200 µs within a probable estimated error of about 50 µs, while all strokes occurring in the other two flashes were luminous for time intervals ranging from 500 µs to 2.3 ms. No information on stroke order was available.

Leaders. *Rakov and Uman* [1990a], analyzing electric field waveforms of 154 leaders that initiated return strokes along the channel formed by a preceding stroke of the same flash, found a geometric mean leader duration of 1.8 ms with 10 (about 6%) values in the range of 200 to 500 µs. The maximum two-dimensional dart-leader speed for natural lightning, measured over the channel section below the cloud base, was 2.4×10^7 m/s [*Jordan et al.*, 1992]. For rocket-triggered lightning, 11 (about 30%) of 36 dart leaders analyzed by *Jordan et al.* [1992] had a speed of 2.0×10^7 m/s or higher with the maximum measured value being 4.9×10^7 m/s. Thus the ranges of dart-leader speed and return-stroke speed overlap; that is, the faster dart leaders can propagate at speeds comparable with those of the slower return strokes. Assuming the total length of the lightning channel to be in the range of 5 to 9 km and extrapolating the maximum leader speeds measured over the visible portion of the channel to the entire channel, we can estimate the durations of the fastest observed dart leaders in natural lightning and in triggered lightning to be approximately in the ranges of 210 to 380 µs and 100 to 180 µs, respectively.

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