# Close electric field signatures of dart leader/return stroke sequences in rocket-triggered lightning showing residual fields

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[1] Vertical electric field waveforms due to dart leader/return stroke sequences measured on the ground 15 and 30 m from the negative lightning channel are used to examine the so-called residual electric field, the difference between the leader electric field change, and the following return stroke electric field change. At these distances, no residual field is expected if the return stroke neutralizes essentially all the charge deposited by the leader within a few hundred meters above ground. There is a clear tendency for strokes having larger peak currents to be associated with larger residual electric fields. The ratio of residual electric fields at 15 and 30 m suggests that the residual field varies as $r^{-1.5}$, where r is the horizontal distance from the lightning channel. The residual electric field is found from modeling to be associated with an equivalent point charge of the order of hundreds of microcoulombs to a few millicoulombs at a height of 15 to 30 m deposited by the leader but presumably left unneutralized by the return stroke. This residual point charge decays exponentially on a timescale of the order of milliseconds to tens of milliseconds. While the nature of the residual charge is unknown, it could be associated with small branches formed near the descending leader tip just prior to or during the attachment process. In long laboratory spark experiments, such branches have apparently been observed to lose their connection with the main channel.

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## 1. Introduction

[2] Close triggered-lightning electric fields exhibit a characteristic asymmetric V-shaped waveform [e.g., *Rubinstein et al.*, 1995; *Crawford et al.*, 2001] with the bottom of the V corresponding to the transition from the dart leader stage to the return stroke stage. Dart leader/return stroke sequences (strokes) in triggered lightning are similar to subsequent strokes in natural lightning. At distances of the order of a few tens of meters or less, the magnitude of the return stroke field change $\Delta E_{RS}$ (the trailing edge of the V-shaped pulse) is expected to be equal to the corresponding leader field change magnitude $\Delta E_L$ (the leading edge of the V-shaped pulse), with the electric field returning to its prestroke value (flattening) within a few tens of microseconds of the beginning of the return stroke [e.g., *Thottappillil et al.*, 1997]. This view is consistent with the dart leader charge near ground being completely neutralized by the return stroke process on a tens-of-microseconds timescale. However, in many records, $\Delta E_{RS}$ is appreciably smaller than $\Delta E_L$, as illustrated in Figure 1a. We refer to this difference as the residual electric field, RE = $\Delta E_L - \Delta E_{RS}$. Note that when the return stroke electric field abruptly "flattens" at a level that is lower than the prestroke level, a return stroke current of the order of kiloamperes continues to flow to the ground (see Figure 1b). The residual electric field decreases (field returns to the prestroke level) on a timescale of the order of milliseconds to tens of milliseconds, suggesting that the return stroke leaves some unneutralized charge near ground and that this charge is neutralized by a slower process, other than the return stroke. Within the same flash, some strokes may exhibit an RE, while others do not, as illustrated in Figure 2. It is clear from Figure 2 that the RE is more pronounced at 15 m than at 30 m.

[3] In this paper, we examine the value of the RE 20 μs after the beginning of the return stroke (see Figure 1a), when the field might be expected to have returned to its background value, and its dependence on return stroke peak


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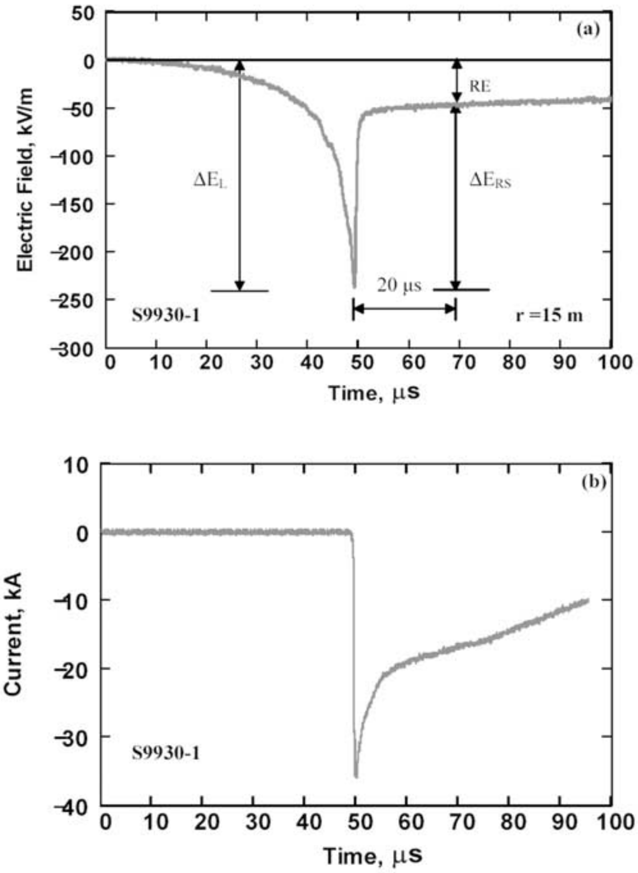


**Figure 1.** (a) Residual electric field (initial value), RE, measured 20 μs after the negative electric field peak and (b) the corresponding channel-base current waveform. Note that current in excess of 10 kA continues to flow to ground after the electric field abruptly flattens between 50 and 55 μs. The current waveform may be slightly clipped. See color version of this figure in the HTML.

current and on distance. At 20 μs the return stroke front is expected to be at a height of 2 km, if one assumes a typical return stroke speed of $10^8$ m/s [e.g., *Idone and Orville*, 1982; *Idone et al.*, 1984]. We use a point charge model to infer, from measured values of the RE at the two distances, the causative (residual) charge and its height above ground. We also examine the variation of the inferred residual charge and its height with time and the correlation of each of these two parameters with return stroke peak current.

## 2. Experiments and Data

[4] Data used in this paper were acquired at the International Center for Lightning Research and Testing (ICLRT) at Camp Blanding, Florida, in 1999, 2000, and 2001. The rocket-and-wire technique [e.g., *Rakov et al.*, 1998] was used to artificially initiate (trigger) lightning from natural thunderclouds. In this study, we use electric field measurements 15 and 30 m from the negative lightning channel and current measurements at the channel base. Recordings on both microsecond and millisecond timescales were obtained (although not for all strokes simultaneously), as described below. Most of the statistical results presented in this paper are based on the more numerous microsecond-scale measurements, while the millisecond-scale measurements are used for studying the time variation of the residual charge inferred from the time variation of the measured residual electric fields. Besides the electric field measurements at 15 and 30 m, we also obtained a limited number of millisecond-scale electric field records at 5 m. We used the 5-m data as redundant information to test the validity of the modeling results based on measurements obtained at 15 and 30 m.

[5] The general experimental setup and instrumentation are described by *Crawford et al.* [2001], *Rakov et al.* [2001], *Uman et al.* [2002], *Schoene et al.* [2003a, 2003b], and *Kodali et al.* [2005]. The rocket launcher was placed underground with the top of the launcher flush with ground in a 4 m × 4 m × 4 m pit. The pit and the launcher were located in the center of a 70 m × 70 m buried metallic grid designed to eliminate ground surface arcing and to minimize field propagation effects due to finite ground conductivity. The strike object was a vertical metallic rod protruding 1 or 2 m above ground in 1999 and a 2-m rod surrounded by and electrically connected to a 3 m diameter horizontal ring elevated to 1.5 m height in 2000 and 2001. Both "microsecond-scale" (sampling rate 25 MHz, record length 100 μs) and "millisecond-scale" (sampling rate 10 MHz, record length 52 ms) electric field records were obtained in 2000 and 2001 and only microsecond-scale electric field records in 1999. A summary of the number of strokes recorded at each distance and number of those showing measurable residual electric fields is given in Table 1. Decay time constants of the millisecond-scale measurement systems at 15 and 30 m were 163 and 84 ms, respectively, and those at 5 m were 887 ms for two strokes (in flashes S0012 and S0013) and as short as 3.5 ms for the remainder of strokes. A total of about 100 strokes were analyzed, although the sample size varied depending on the distance and the feature examined. Only seven strokes recorded at 5 m were suitable for the analyses presented in this paper, with only one being suitable for the analysis of time variation of the residual charge. The millisecond-scale measurements at 15 and 30 m were not significantly influenced by the finite system decay time constant (163 ms and 84 ms, respectively, versus the 24-ms time interval analyzed here).

[6] In measuring residual fields from microsecond-scale electric field records, there is often some uncertainty regarding the actual leader starting point. We assumed that the leader field change starts from zero field level, which implies that there is no electric field offset at the time of leader beginning. Thus residual electric field is measured from the zero field level to a point on the electric field waveform 20 μs after its negative peak, as shown in Figure 1a. Alternatively, the residual electric field can be measured with respect to the first data point, as done, for example, by *Schoene et al.* [2003a], assuming that the leader field changes at 15 and 30 m begin within 50 μs of the return stroke, which was the duration of the pretrigger part of the recorded waveform, and that any nonzero value for this data point is due to electric field offset. Leader electric field changes measured using these two alternative approaches differ in most cases by less than 15% (by 7 and 9% on average at 15 and 30 m,

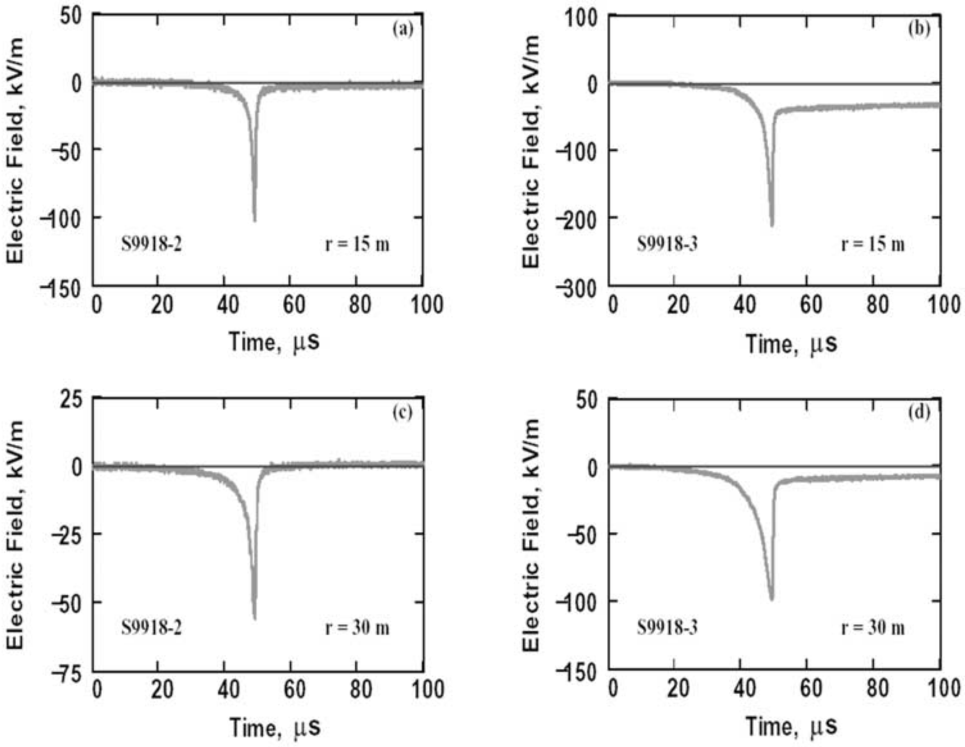


**Figure 2.** Vertical electric field waveforms for strokes 2 and 3 of flash S9918 at (a and b) 15 m and (c and d) 30 m. Note that the larger stroke 3 exhibits a pronounced residual electric field, which is larger, relative to the field peak, at 15 m (Figure 2b) than at 30 m (Figure 2d), while the smaller stroke 2 (Figures 2a and 2c) essentially does not show this feature. See color version of this figure in the HTML.

respectively). We additionally compared leader electric field changes measured from both microsecond-scale records and corresponding millisecond-scale records. The latter had a 1-ms pretrigger versus a 50-μs pretrigger for the microsecond-scale records and therefore were more suitable for determining the leader field change starting point. The mean values of the ratio of leader field changes from microsecond- and millisecond-scale records are 1.1 (ranging from 0.72 to 1.7; sample size 18) and 1.2 (ranging from 0.59 to 2.0; sample size 22) at 15 and 30 m, respectively. Peak currents were measured in the microsecond-scale records of channel-based current waveforms.

## 3. Analysis

[7] Histograms of the residual electric field at 15 and 30 m from the microsecond-scale records are shown in Figures 3a and 3b, respectively. The magnitude of the RE varied from a few percent to 25% of $\Delta E_L$. The histograms appear to be indicative of log normal distributions. The mean values are 20 kV/m at 15 m and 8 kV/m at 30 m.

**Table 1.** A Summary of the Number of Strokes Recorded at Each Distance and Number of Those Showing Measurable Residual Electric Fields

| Number of Strokes or Percentage | Microsecond-Scale Field Records | | | | Millisecond-Scale Field Records | | |
|---|---|---|---|---|---|---|---|
| | 1999 | 2000 | 2001 | 1999–2001 | 2000 | 2001 | 2000–2001 |
| *Distance of 5 m* | | | | | | | |
| Total strokes | - | - | - | - | 7 | 16 | 23 |
| Strokes with RE | - | - | - | - | 2 | 16 | 18 |
| Percent with RE | - | - | - | - | 29 | 100 | 78 |
| *Distance of 15 m* | | | | | | | |
| Total strokes | 51 | 42 | 13 | 106 | 19 | 6 | 25 |
| Strokes with RE | 45 | 38 | 13 | 96 | 13 | 6 | 19 |
| Percent with RE | 88 | 91 | 100 | 91 | 68 | 100 | 76 |
| *Distance of 30 m* | | | | | | | |
| Total strokes | 44 | 47 | 13 | 104 | 17 | 8 | 25 |
| Strokes with RE | 35 | 29 | 13 | 77 | 13 | 8 | 21 |
| Percent with RE | 80 | 62 | 100 | 74 | 77 | 100 | 84 |

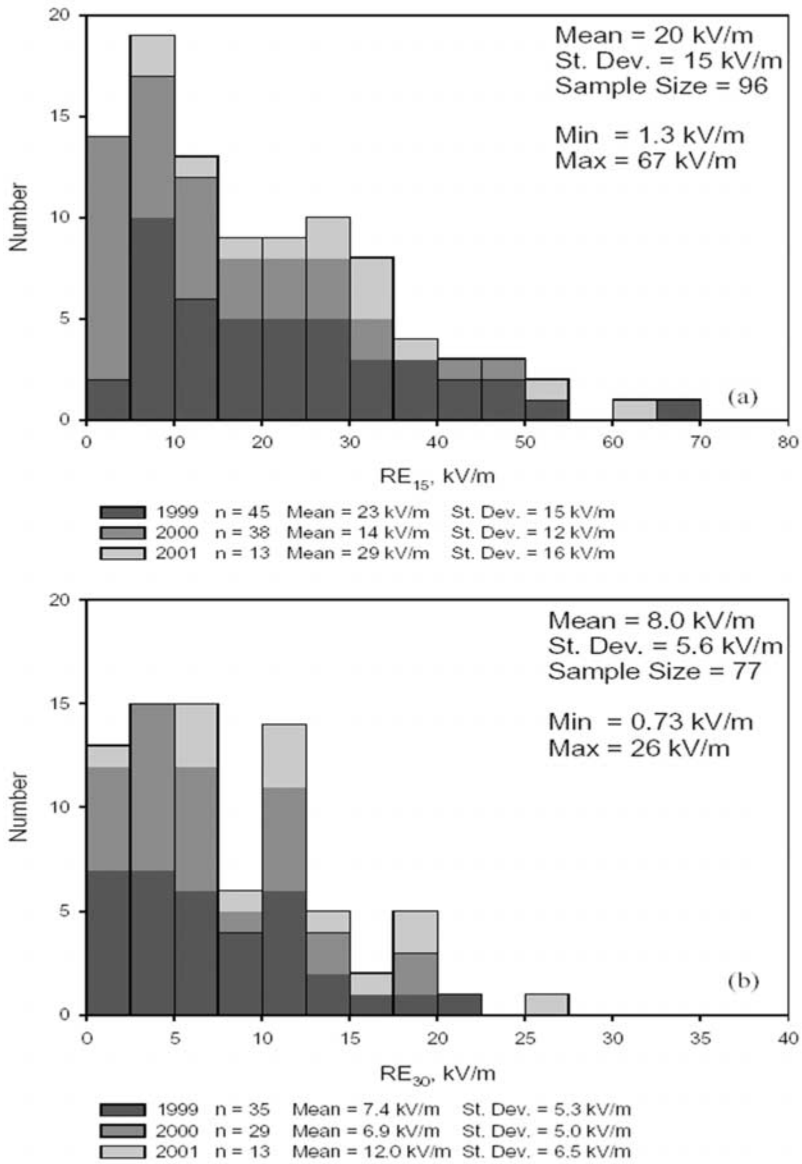


**Figure 3.** Residual electric field from microsecond-scale field records at (a) 15 and (b) 30 m. See color version of this figure in the HTML.

Histograms of the ratio of residual electric fields at 15 and 30 m from millisecond- and microsecond-scale records are shown in Figures 4a and 4b, respectively. The mean values, 2.9 from millisecond-scale records and 2.8 from microsecond-scale records, are very similar and close to 3, which is in contrast with the ratio of $\Delta E_L$ at 15 m and 30 m that is close to 2 [*Crawford et al.*, 2001]. For $\Delta E_L$ a ratio close to 2 (an inverse distance dependence) is consistent with a more or less uniform distribution of charge along the channel within a few hundred meters above ground [*Rubinstein et al.*, 1995; *Crawford et al.*, 2001]. For the RE a ratio close to 3 (an $r^{-1.5}$ distance dependence, assuming that RE varies as $r^{-k}$ where k = const) suggests a more or less concentrated residual charge elevated above ground, as opposed to charge more or less uniformly distributed along the channel. We will show, from modeling, in section 4 that the residual charge can often be approximated by a point charge at a height of 15 to 30 m, whose magnitude decreases exponentially with time. Scatterplots of the residual electric field at 15 and 30 m versus peak current are presented in Figure 5. There is a clear tendency for the larger strokes (strokes having larger peak currents) to be associated with the larger residual electric fields.

## 4. Modeling

[8] We modeled the postulated residual charge by an equivalent point charge located above the ground and used our measurements of RE at 15 and 30 m to estimate the magnitude and height of this equivalent charge 20 μs after the beginning of the return stroke and, when data were available, as a function of time (up to 24 ms). Overall results can be summarized as follows. The initial values (at 20 μs) of equivalent point charge magnitude are found to be typically 0.5 to 2.0 mC, and the heights are 15 to 30 m.

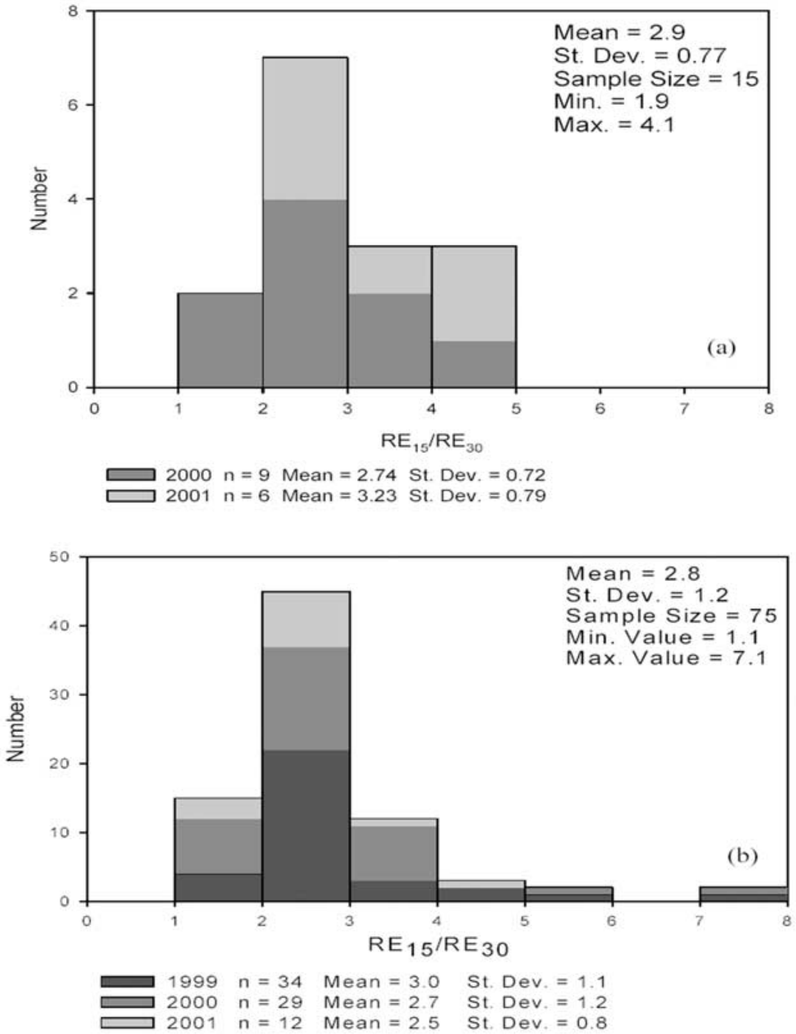


**Figure 4.** (a) Ratio of residual electric fields at 15 and 30 m for 2000 and 2001 from millisecond-scale records and (b) ratio of residual electric fields at 15 and 30 m for 1999, 2000, and 2001 from microsecond-scale records. See color version of this figure in the HTML.

The magnitude of the residual charge decreases with time, while the height remains approximately constant, except for the cases when surges (M components) occurred after the return stroke and disturbed the quasi-electrostatic solution for the residual charge. It is worth noting that the equivalent point charge model is very sensitive to the presence of M components; even small surges, unpronounced in the 15- and 30-m electric field records, can disturb the time-varying point charge solutions.

[9] The equation for electric field RE due to a point charge $Q$ located at a height $H$ above ground and at a horizontal distance $r$ from the observation point is given by [e.g., *Rakov and Uman*, 2003, equation (3.2)]

$$RE = \frac{2QH}{4\pi\varepsilon_0 (H^2 + r^2)^{3/2}} \tag{1}$$

which is derived using the method of images to account for the presence of ground, assumed to be a perfect conductor. Equation (1) can be evaluated at two distances, r = 15 m and r = 30 m, and thus can be solved for the two unknowns, $Q$ and $H$. As noted earlier, residual electric fields measured at 5 m were used to test the validity of solution based on the RE measurements at 15 and 30 m.

[10] We first present our modeling results based on millisecond-scale records and then those based on microsecond-scale records. Figure 6 shows the millisecond-scale field records at 15 and 30 m for flash S0107, and Figure 7 shows the corresponding residual charge and height versus time obtained using the procedure described above. In order to minimize noise, a moving averaging technique was applied to the field waveforms with an averaging window of 100 μs, and then data points were selected with a 20 μs sampling interval. Different averaging windows were tested, including 5, 20, and 100 μs, and 100 μs was found to be optimal. As can be seen from Figure 7, the residual charge decays exponentially with time with a time constant of about 2 ms, while the height remains approximately constant at around 20–25 m. This analysis suggests that there exists an equivalent point charge at a height of around 20–25 m that is deposited by the leader but not neutralized by

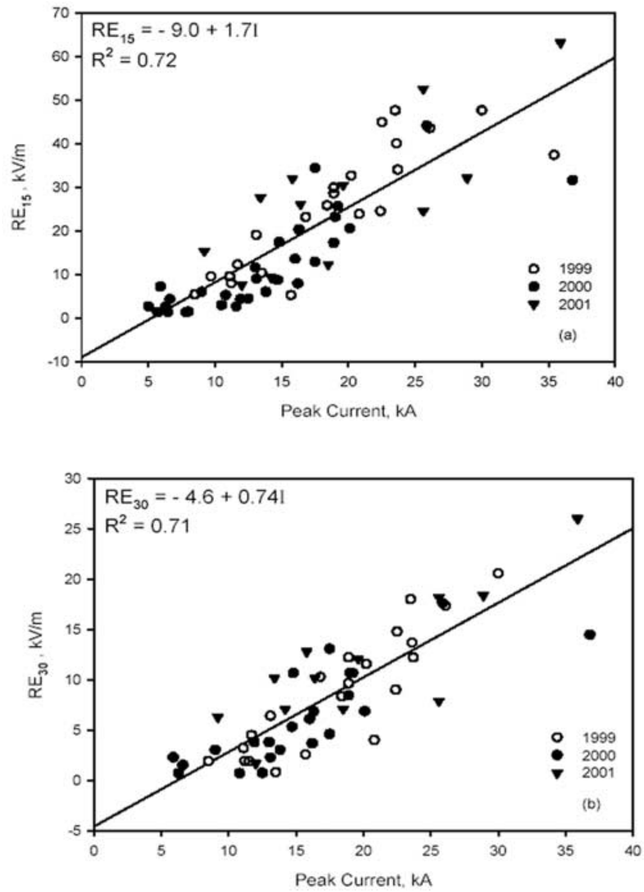


**Figure 5.** (a) Residual electric field, $RE_{15} = (\Delta E_{15} - \Delta E_{RS15})$, versus peak current, I, for 1999, 2000, and 2001 and (b) residual electric field, $RE_{30} = (\Delta E_{30} - \Delta E_{RS30})$, versus peak current, I, for 1999, 2000, and 2001.

the return stroke. The exponential decay of charge in Figure 7 can be approximated as

$$Q = 0.85 + 1.6\ \exp\left(-4.9 \times 10^{-4} t\right) \qquad (2)$$

where $t$ is in microseconds and $Q$ is in millicoulombs. The argument of the exponential function can be written as $(-t/\tau)$ where $\tau$ = 2041 μs (about 2 ms) is the exponential decay time constant. In general, $Q = Q_1 + Q_2\ \exp(-t/\tau)$, with the initial residual charge, $Q_0$ (defined as the residual charge at $t$ = 20 μs), being given by $Q_0 = Q_1 + Q_2\ \exp(-20/\tau)$.

[11] Results obtained from millisecond-scale electric field records at 15 and 30 m are summarized in Table 2. This table includes all six events for which millisecond-scale records at 15 and 30 m suitable for the charge/height analysis are available except for event S0013, for which the electrostatic point charge solution is disturbed by M components. The latter event is included in the analysis of the initial value of residual charge and its height, results of which are presented below.

[12] We now discuss the initial value (at 20 μs after the return stroke begins) of residual charge and its height inferred from microsecond-scale records. Figure 8a shows the histogram of inferred residual charge with a mean value of 1.3 mC. Figure 8b shows the histogram of inferred height, from which the initial residual charge is located at a mean height of 25 m. Figures 9a and 9b present scatterplots of residual charge versus peak current and height versus peak current, respectively. There is a linear correlation between the inferred residual charge and peak current with determination coefficient of 0.71. There exists no relationship between the height of inferred residual charge and peak current.

[13] Inferences regarding the magnitude and height of the residual charge based on measurements at two distances, 15 and 30 m, are model-dependent. In the following, we test the validity of the time-varying two-distance solutions using measurements at a third distance, 5 m, for which we have suitable data for one event, S0012-1 (see Figure 10). Inferred values of initial charge, time constant, $\tau$, and minimum, maximum, and average heights for flash S0012 for three different pairs of millisecond-scale records, 5 and 15 m, 15 and 30 m, and 5 and 30 m, are presented in Table 3. Note that $\tau$ is a parameter of the exponential fitting function, not that of the point charge model. As seen in Table 3, the values of initial charge, $\tau$, and height calculated from electric fields measured at three different pairs of distances are similar, supporting the validity of the point charge approximation of the residual charge. The largest variation is observed for $\tau$, from 1.6 to 3.6 ms.

[14] Additionally, for testing the validity of the point charge approximation, we used millisecond-scale electric

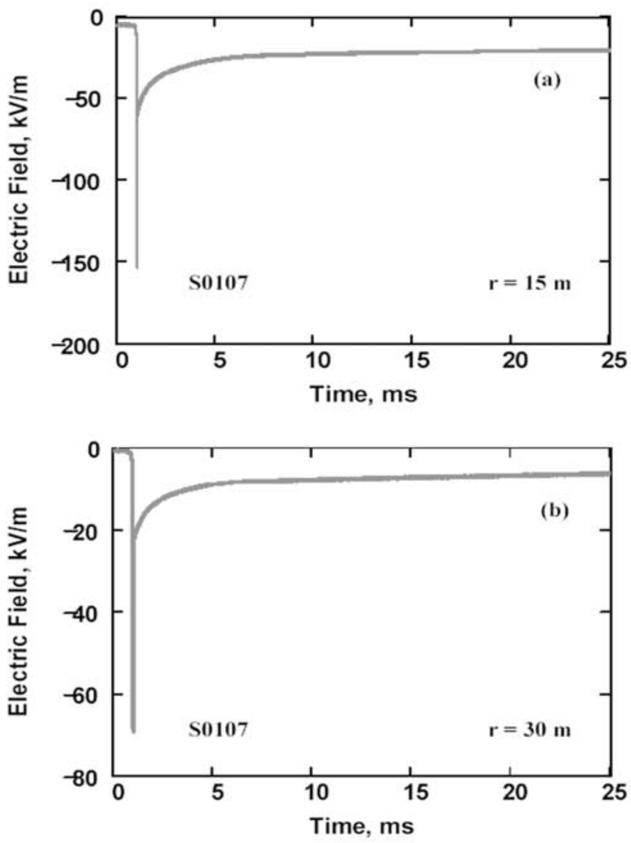


**Figure 6.** Millisecond-scale electric field records of S0107-1 at (a) 15 and (b) 30 m. See color version of this figure in the HTML.

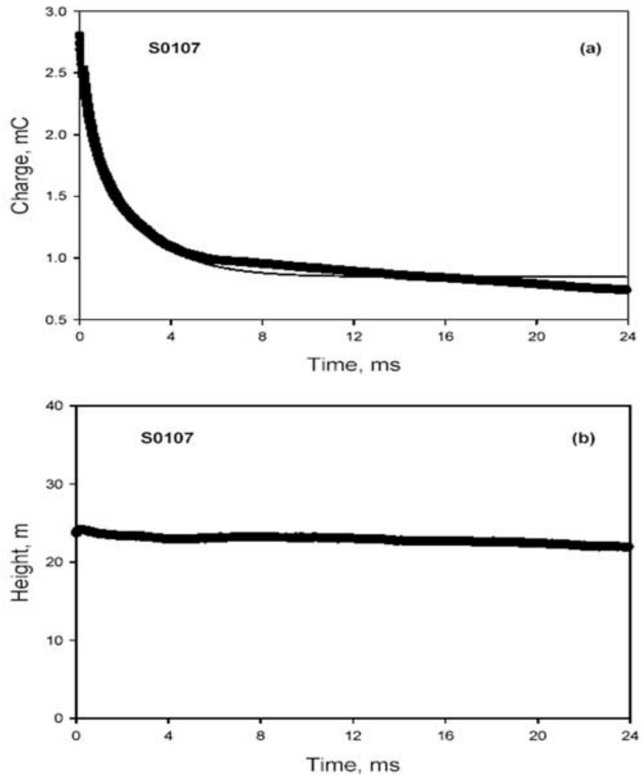


**Figure 7.** (a) Charge and (b) height versus time for S0107-1. Thick lines represent inferences from RE measured at 15 and 30 m, and thin line in Figure 7a represents approximation by equation $Q = 0.85 + 1.6 \exp(-4.9 \times 10^{-4} t)$, where $t$ is in microseconds and $Q$ in millicoulombs. The exponential approximation is characterized by the correlation coefficient of 0.98.

field measurements at three distances at 20 μs, allowing us to infer the initial value of the residual charge and its height above ground. (The time variation for these events (a total of six) either could not be obtained due to a fast (3.5 ms) decay time constant employed in the electric field measuring system at 5 m for events S0105, S0107, S0118, S0119, and S0123 or was influenced by pronounced M components, for event S0013.) Results for event S0012, which are found in Table 3, are also included in Table 4 for completeness, so that the total number of events in Table 4 is seven. As seen in Table 4, for the majority of events, there is a reasonably good agreement among the values of initial residual charge and its height estimated from the three different pairs of measured electric fields. The "worst case" height ratio in Table 4 ranges from 1.08 to 2.55 with a mean value of 1.53 for 15/30 and 5/15 m. If the largest value (2.55) is excluded, the mean percentage difference for the worst case is as small as 25%. It follows from the above that the point charge model is a reasonable approximation to the residual charge of the triggered-lightning events analyzed here.

## 5. Discussion

[15] We have examined the electric field signatures of negative dart leader/return stroke sequences in triggered lightning showing residual fields. Such an "abnormal" electric field behavior indicates that not all the leader charge is neutralized by the return stroke. This residual charge is comparable to the charge of an individual step of a dart-stepped leader in triggered lightning [*Rakov et al.*, 1998] or to the charge on the dart leader channel section of the order of 10 m in length [*Kodali et al.*, 2005]. The nature of the residual charge inferred from measurements within 30 m of the triggered-lightning channel is unknown. Our analysis indicates that this charge is concentrated, located close to (within a few tens of meters of) the ground, and is associated with the larger strokes. We speculate that the residual charge studied here might be associated with small branches at the descending leader tip formed just prior to or during the attachment process. Such branches have been observed in long laboratory spark experiments, as illustrated in Figure 11 adapted from *Shcherbakov et al.* [2002, 2003]. Note that the more luminous portion of the left branch above the junction region in Figure 11 appears to be disconnected from the main channel (this may be difficult to see in the reproduction, but is clearly seen in the original with color-coded light intensity). This phenomenon, if it occurs in lightning, might well explain how the branch charge can be left unneutralized by the return stroke. It is likely that the occurrence of such branches increases with increasing stroke intensity, which would be consistent with

**Table 2.** Residual Charge and Height, up to 24 ms, Inferred From Millisecond-Scale Electric Fields Measured at 15 and 30 m in 2000 and 2001

| Flash/Stroke ID | Peak Current, kA | Inferred Residual Charge, mC | | | Exponential Decay Time Constant τ, μs | Height, m | | |
|---|---|---|---|---|---|---|---|---|
| | | Initial | Final | Mean | | Maximum | Minimum | Mean |
| | | | | *2000* | | | | |
| S0012-1 | 20.8[a] | 1.6 | 0.28 | 0.42 | 3600 | 25 | 22 | 23 |
| S0025-1 | 15.1 | 0.71 | 0.35 | 0.41 | 1613 | 29 | 25 | 28 |
| S0029-1 | 6.3 | 0.25 | 0.05 | 0.40 | 323 | 42 | 25 | 28 |
| | | | | *2001* | | | | |
| S0107-1 | 41.1 | 2.8 | 0.74 | 0.98 | 2041 | 24 | 21 | 23 |
| S0118-1 | 19.8 | 0.96 | 0.10 | 0.22 | 3846 | 23 | 15 | 18 |
| S0119-1 | 24.7 | 1.1 | 0.22 | 0.31 | 2128 | 25 | 21 | 23 |

[a]Strike object current, while all other values in this column represent currents injected into the buried grounding grid. For two events, S0105-1 and S0123-1 (not presented in Table 2), the point charge model could not be used to estimate variations of residual charge and its height up to 24 ms because the electric field records did not exhibit RE at 30 m, after 60 and 420 μs, respectively. No millisecond-scale electric fields were obtained in 1999. The initial and final values of residual charge are determined at 20 μs and 24 ms after the beginning of the return stroke, respectively.

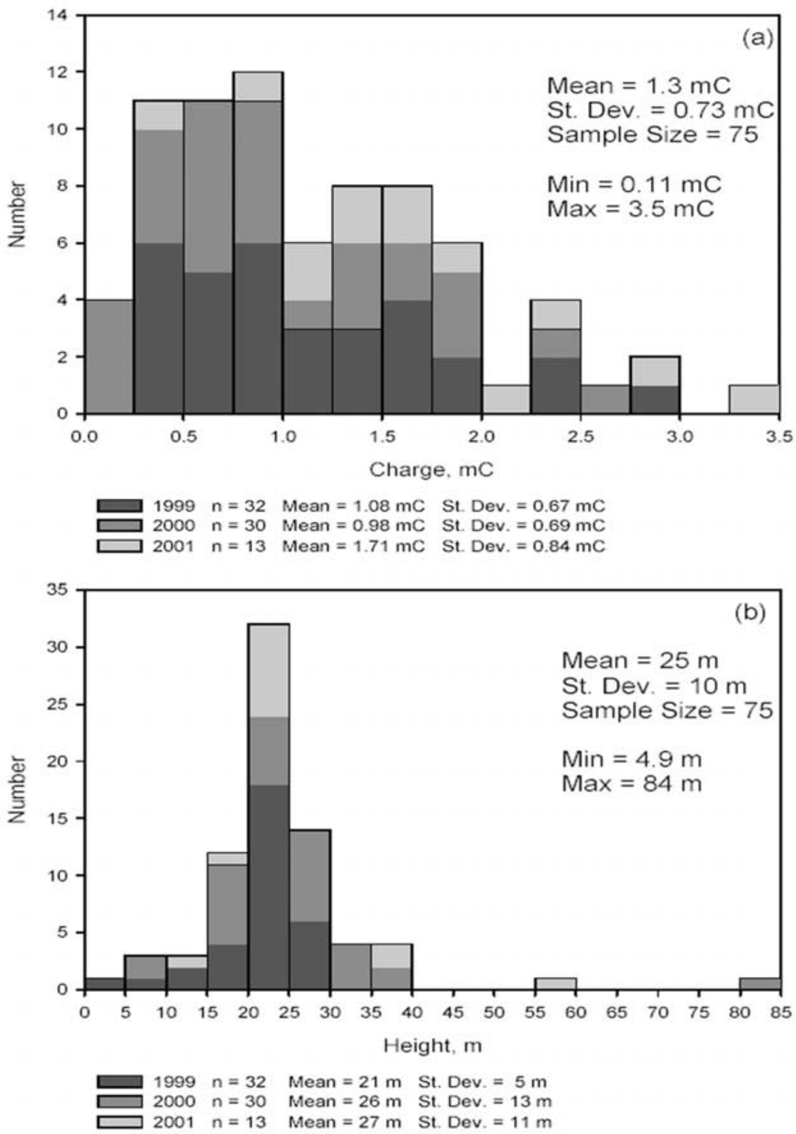


**Figure 8.** (a) Histogram of residual charge, 20 μs after the beginning of return stroke, from microsecond-scale electric field records obtained in 1999, 2000, and 2001. (b) Histogram of height, 20 μs after the beginning of the return stroke, from microsecond-scale electric field records obtained in 1999, 2000, and 2001. See color version of this figure in the HTML.

our observed trend for larger strokes to exhibit more pronounced residual electric fields. It should be noted that the branches described above have never been observed in dart leaders. Further, the formation of such branches should be related to the height of the junction between the descending leader and an upward connecting leader and therefore should be different for strike objects of different height and also for first and subsequent strokes.

[16] We now discuss strokes exhibiting an electric field deficit ($\Delta E_{RS} < \Delta E_L$) in natural negative lightning at distances of the order of kilometers (typically, $\Delta E_{RS} > \Delta E_L$ at these distances) and compare them with strokes showing residual electric fields when observed within 30 m of the lightning channel. In all these natural lightning strokes, the net leader electric field change is negative (atmospheric electricity sign convention), so that the electric field after the stroke has lowered negative charge to ground is more negative than the prestroke electric field. The residual electric field observed within 30 m can be viewed as a special case of electric field deficit, in which $\Delta E_{RS}$ is expected to be equal to $\Delta E_L$. Strokes with an electric field deficit are also referred to as strokes with a net negative electric field change. *Rakov et al.* [1990] examined 218 first and subsequent strokes in 70 flashes in Florida and found that 18 (8%) of them exhibited an electric field deficit. All 18 strokes were subsequent strokes, with 89% occurring after the fourth stroke. Natural lightning strokes with $\Delta E_{RS} < \Delta E_L$ studied by *Rakov et al.* [1990] were relatively small (the geometric mean peak current was inferred to be less than 3 kA), whereas in our study of very close triggered-lightning larger strokes were more likely to exhibit residual fields (see Figures 5a and 5b). (It is worth noting that the electric field deficit at distances of the order of kilometers was apparently observed in association with

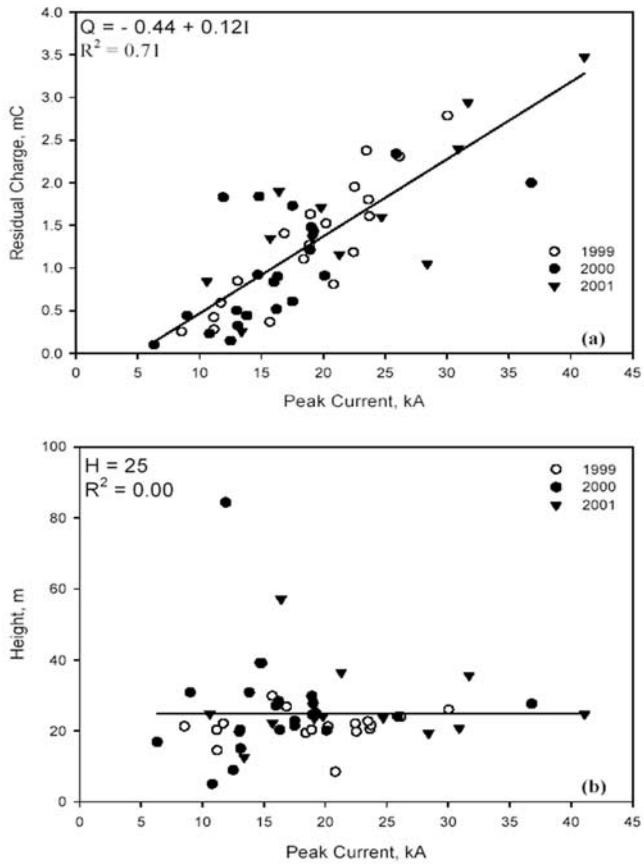


**Figure 9.** Scatterplots of (a) initial residual charge versus current and (b) its height versus current from microsecond-scale electric field records obtained in 1999, 2000, and 2001.

larger strokes [e.g., *Krehbiel et al.*, 1979; *Shao et al.*, 1995] as well, but it is not clear how often this occurs.) Also, in relatively distant observations of natural lightning, the strokes with $\Delta E_{RS} < \Delta E_L$ were the minority, less than 10%, while in the present study, more than three quarters of strokes exhibited this feature (see Table 1).

[17] At distances from the lightning of the order of kilometers, field contributions from different channel sections are such that the entire lightning channel, including its in-cloud part, is "observable" with instruments located on ground. (In contrast, at distances less than 30 m from the lightning channel, the electric field is dominated by contributions from channel sections located within a few hundred meters above ground [e.g., *Rubinstein et al.*, 1995]. Therefore, owing to the limited dynamic range of the instrumentation set to record close fields, any lightning processes occurring above a few hundred meters height are undetectable at distances less than 30 m.) As a result, the residual electric field at larger distances can be due to either (1) the unneutralized negative leader charge remaining along the channel (for example, due to the failure of the return stroke to drain the negative charge from the periphery of the channel corona sheath) or (2) neutralization "in situ" of positive in-cloud charge (e.g., induced in the cloud by the preceding stroke) during the course of the negative leader, so that not all the leader charge is available for neutralization by the return stroke. (If not all the positive in-cloud charge is neutralized by the leader, it will cause additional negative charge to be induced in the upper part of the channel.) These two interpretations were considered by *Jacobson and Krider* [1976] and *Rakov et al.* [1990]. In natural lightning the residual charge on the bottom portion of the channel (within 1–2 km of ground) was inferred to play a role in preventing the following leader from terminating at the same point on ground [*Shao et al.*, 1995]. (It is worth noting that residual charges within a few tens of meters above ground are unlikely to be detected at distances of the order of kilometers. Indeed, for many strokes analyzed here, the residual field was observed at 15 m but was undetectable at 30 m, this fact being the primary reason why most of the sample sizes for 30 m in Table 1 are smaller than for 15 m.) Both interpretations for relatively distant observations find some confirmation in the fact that strokes showing negative net field changes commonly have very small initial (predominately radiation) electric field peaks. Either (1) these strokes might be small because some leader charge was spent to neutralize positive charge in situ in the cloud and the return stroke operated only on a portion of the leader charge, or (2) small return stroke currents might be easier to cut off (assuming that the current at the time of cutoff, of the order of hundreds of microseconds after the beginning of the return stroke, is positively correlated

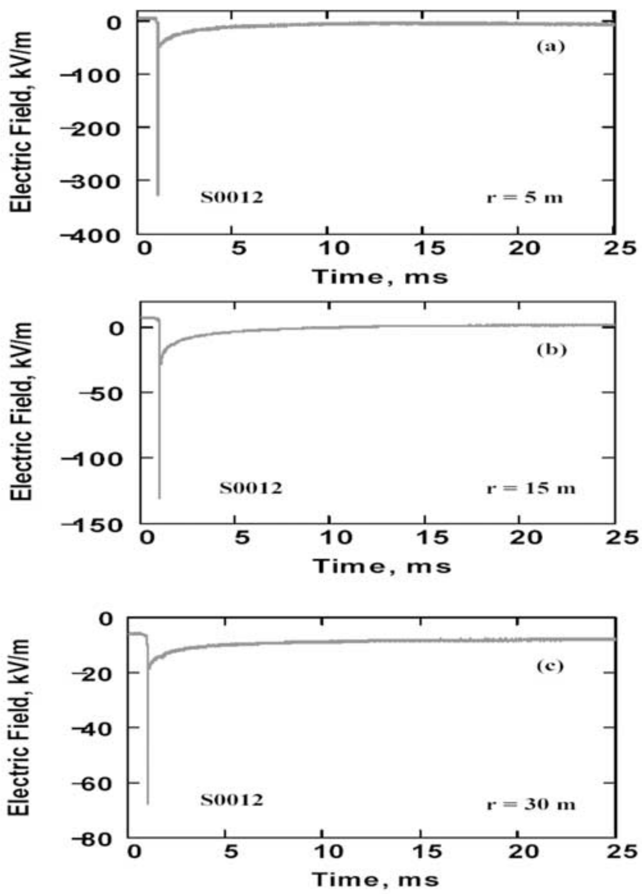


**Figure 10.** Millisecond-scale electric field records at (a) 5, (b) 15, and (c) 30 m for S0012-1. See color version of this figure in the HTML.

**Table 3.** Characterization of the Residual Charge for Flash S0012 From Three Different Pairs of Electric Field Records

| Parameter | Observation Distances | | |
|---|---|---|---|
| | 5 and 15 m | 15 and 30 m | 5 and 30 m |
| Initial charge, mC | 1.5 | 1.6 | 1.8 |
| $\tau$, ms | 1.6 | 3.6 | 3.5 |
| Height averaged over 24 ms, m | 23 | 23 | 23 |
| Minimum height, m | 17 | 22 | 19 |
| Maximum height, m | 29 | 25 | 25 |

with the peak current) prematurely near the ground, so that the leader charge deposited along the channel has to be neutralized by a slower process other than the return stroke.

[18] The latter explanation might be interpreted to imply that the abrupt electric field flattening at a lower than prestroke level is indicative of the cutoff of the return stroke current. However, this is not necessarily the case, as evidenced by electric field and current records shown in Figures 1a and 1b, respectively, in which a current of the order of kiloamperes continues to flow to the ground after the abrupt electric field flattening has occurred. Clearly, return stroke current can flow without removing charge deposited by the leader near the channel termination on ground.

## 6. Summary

[19] In many triggered-lightning electric field waveforms measured within a few tens of meters of the lightning channel, the magnitude of the return stroke electric field change is smaller than the magnitude of the leader electric field change. This feature implies that not all the leader charge is neutralized by the return stroke. There is a clear tendency for larger strokes to be associated with larger residual electric fields. Comparison of residual electric fields observed at different distances suggests that in many cases they can be viewed as being due to an equivalent point charge of the order of hundreds of microcoulombs to a few millicoulombs located at a height of 15 to 30 m above ground that decays exponentially on a timescale of the order of milliseconds to tens of milliseconds. The residual charge may be associated with small branches formed near the descending leader tip that lost their connection with the main channel.

**Table 4.** Initial Residual Charge, $Q_0$, and Height, $H_0$, From Three Different Pairs of Electric Field Records

| Parameter | Observation Distances | | |
|---|---|---|---|
| | 5 and 15 m | 15 and 30 m | 5 and 30 m |
| | *Flash/Stroke ID S0012-1* | | |
| $Q_0$, mC | 1.5 | 1.6 | 1.8 |
| $H_0$, m | 21 | 24 | 22 |
| | *Flash/Stroke ID S0013-1* | | |
| $Q_0$, mC | 0.15 | 0.20 | 0.21 |
| $H_0$, m | 13 | 20 | 16 |
| | *Flash/Stroke ID S0105-1* | | |
| $Q_0$, mC | 0.74 | 0.79 | 0.81 |
| $H_0$, m | 13 | 14 | 13 |
| | *Flash/Stroke ID S0107-1* | | |
| $Q_0$, mC | 2.3 | 2.8 | 3.0 |
| $H_0$, m | 18 | 24 | 21 |
| | *Flash/Stroke ID S0118-1* | | |
| $Q_0$, mC | 0.73 | 0.96 | 1.1 |
| $H_0$, m | 14 | 23 | 17 |
| | *Flash/Stroke ID S0119-1* | | |
| $Q_0$, mC | 0.80 | 1.1 | 1.4 |
| $H_0$, m | 9.4 | 24 | 14 |
| | *Flash/Stroke ID S0123-1* | | |
| $Q_0$, mC | 0.85 | 1.0 | 1.1 |
| $H_0$, m | 12 | 17 | 14 |

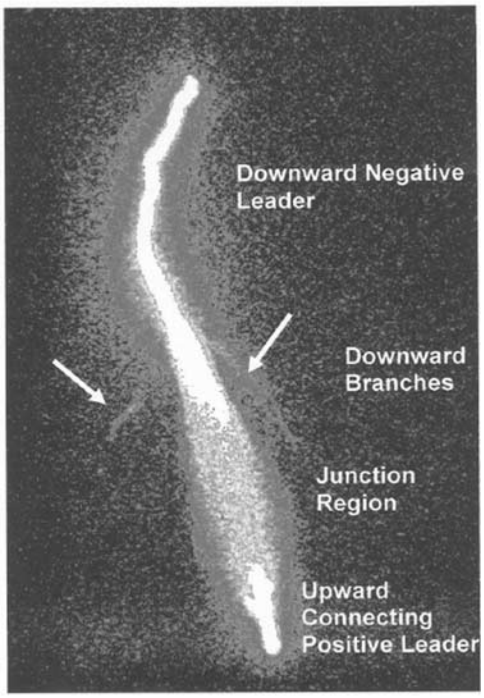


**Figure 11.** A 5.5 m spark between negative high-voltage electrode (at the top) and 0.5-m rod on the grounded plane (at the bottom) at the time of the upward connecting positive leader meeting the downward negative leader. Light intensity is color coded, with the highest intensity shown in white. Note two small downward branches (indicated by white arrows) just above the junction region. The image was obtained using image converter camera K008 with frame duration (exposure time) 0.2 μs at the high-voltage facility in Istra, Russia. Adapted from *Shcherbakov et al.* [2002, 2003]. See color version of this figure in the HTML.

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## References

Crawford, D. E., V. A. Rakov, M. A. Uman, G. H. Schnetzer, K. J. Rambo, M. V. Stapleton, and R. J. Fisher (2001), The close lightning electromagnetic environment: Dart-leader electric field change versus distance, *J. Geophys. Res.*, *106*, 14,909–14,917.
Idone, V. P., and R. E. Orville (1982), Lightning return stroke velocities in the Thunderstorm Research International Program (TRIP), *J. Geophys. Res.*, *87*, 4903–4915.
Idone, V. P., R. E. Orville, P. Hubert, L. Barret, and A. Eybert-Berard (1984), Correlated observations of three triggered lightning flashes, *J. Geophys. Res.*, *89*, 1385–1394.
Jacobson, E. A., and E. P. Krider (1976), Electrostatic field changes produced by Florida lightning, *J. Atmos. Sci.*, *33*, 103–117.

Kodali, V., V. A. Rakov, M. A. Uman, K. J. Rambo, G. H. Schnetzer, and J. Schoene (2005), Triggered-lightning properties inferred from measured currents and very close electric fields, *J. Atmos. Res.*, in press.

Krehbiel, P. R., M. Brook, and R. McCrory (1979), An analysis of the charge structure of lightning discharges to the ground, *J. Geophys. Res.*, *84*, 2432–2456.

Rakov, V. A., and M. A. Uman (2003), *Lightning: Physics and Effects*, Cambridge Univ. Press, New York.

Rakov, V. A., M. A. Uman, D. M. Jordan, and C. A. Priore III (1990), Ratio of leader to return stroke field change for first and subsequent lightning strokes, *J. Geophys. Res.*, *95*, 16,579–16,587.

Rakov, V. A., et al. (1998), New insights into lightning processes gained from triggered-lightning experiments in Florida and Alabama, *J. Geophys. Res.*, *103*, 14,117–14,130.

Rakov, V. A., D. E. Crawford, K. J. Rambo, G. H. Schnetzer, M. A. Uman, and R. Thottappillil (2001), M-component mode of charge transfer to ground in lightning discharges, *J. Geophys. Res.*, *106*, 22,817–22,831.

Rubinstein, M., F. Rachidi, M. A. Uman, R. Thottappillil, V. A. Rakov, and C. A. Nucci (1995), Characterization of vertical electric fields 500 m and 30 m from triggered lightning, *J. Geophys. Res.*, *100*, 8863–8872.

Schoene, J., M. A. Uman, V. A. Rakov, V. Kodali, K. J. Rambo, and G. H. Schnetzer (2003a), Statistical characteristics of the electric and magnetic fields and their time derivatives 15 m and 30 m from triggered lightning, *J. Geophys. Res.*, *108*(D6), 4192, doi:10.1029/2002JD002698.

Schoene, J., M. A. Uman, V. A. Rakov, K. J. Rambo, J. Jerauld, and G. H. Schnetzer (2003b), Test of the transmission line model and the traveling current source model with triggered lightning return strokes at very close range, *J. Geophys. Res.*, *108*(D23), 4737, doi:10.1029/2003JD003683.

Shao, X. M., P. R. Krehbiel, R. J. Thomas, and W. Rison (1995), Radio interferometric observations of cloud-to-ground lightning phenomena in Florida, *J. Geophys. Res.*, *100*, 2749–2783.

Shcherbakov, Y. V., V. B. Lebedev, V. A. Rakov, G. G. Feldman, D. I. Sukharevskij, B. N. Gorin, V. S. Syssoev, M. A. Karpov, and A. V. Senik (2002), High-speed optical studies of long spark (Istra, Russia) and triggered lightning (Camp Blanding, Florida): Initial results, in *Proceedings of the International Congress on High Speed Photography and Photonics*, vol. 4948, pp. 837–845, Int. Soc. Opt. Eng., Bellingham, Wash.

Shcherbakov, Y. V., V. S. Syssoev, V. B. Lebedev, B. N. Gorin, and V. A. Rakov (2003), High-Speed Optical studies of long spark (Istra, Russia) and triggered lightning (Camp Blanding, Florida): Novel devices and initial results, in *Proceedings of the International Conference on Lightning and Static Electricity*, *Pap. I03-9 PMY*, pp. 1–8, Soc. of Auto. Eng., Warrendale, Pa.

Thottappillil, R., V. A. Rakov, and M. A. Uman (1997), Distribution of charge along the lightning channel: Relation to remote electric and magnetic fields and to return-stroke models, *J. Geophys. Res.*, *102*, 6987–7006.

Uman, M. A., J. Schoene, V. A. Rakov, K. J. Rambo, and G. H. Schnetzer (2002), Correlated time derivatives of current, electric field intensity, and magnetic flux density for triggered lightning at 15 m, *J. Geophys. Res.*, *107*(D13), 4160, doi:10.1029/2000JD000249.

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