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Characterization of vertical electric fields 500 m and 30 m from triggered lightning

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Abstract. Vertical electric field waveforms of leader-return stroke sequences measured 500 m and 30 m from rocket-triggered lightning are presented. The 500-m data were recorded during the summer of 1986, the 30-m data during the summer of 1991, both at the NASA Kennedy Space Center, Florida. The 40 leader-return stroke field waveforms at 500 m and the 8 waveforms at 30 m all appear as asymmetrical V-shaped pulses, the bottom of the V being associated with the transition from the leader to the return stroke. Only two waveforms at 30 m were suitable for quantitative analysis. The widths of the V at half of peak value for these are 1.8 and 5.0 µs, while for the 500-m data they are 1 to 2 orders of magnitude greater, with a median value of 100 µs. Applying a widely used and simple leader model to the measured leader electric fields at 500 m, we infer, for the bottom kilometer or so of the leader channel, leader speeds between $2\mathrm{x}10^6$ and $2\mathrm{x}10^7$ m/s and leader charges per unit length of $0.02\mathrm{x}10^{-3}$ to $0.08\mathrm{x}10^{-3}$ C/m. From the two measured leader electric field changes at 30 m we infer, using the same leader model, for the bottom 100 meters or so of the leader channel, speeds of $3\mathrm{x}10^7$ and $1\mathrm{x}10^7$ m/s (the corresponding measured waveform half widths are 1.8 µs and 5.0 µs) and charges per unit length of $0.14\mathrm{x}10^{-3}$ and $0.02\mathrm{x}10^{-3}$ C/m (the corresponding measured leader field changes are 81 kV/m and 12 kV/m). The corresponding measured return stroke peak currents for the above two cases are 40 kA and 7 kA, respectively. A positive correlation is observed between the magnitude of the leader field change at 500 m and the ensuing return stroke current peak.

1. Introduction

Return stroke electric fields from lightning have been well characterized at distances from about one to a few hundred kilometers [e.g., *Fisher and Uman*, 1972; *Lin et al.*, 1979; *Weidman and Krider*, 1982; *Cooray and Lundquist*, 1985; *Willett et al.*, 1989; *Rakov and Uman*, 1990a, b], and leader electric fields have been well characterized at distances from about 1 to 50 km [e.g., *Beasley et al.*, 1982; *Thomson et al.*, 1985; *Rakov and Uman*, 1990c]. Measurements of leader or return stroke fields at distances less than a kilometer for either natural or triggered (artificially initiated) lightning are few and limited (e.g., *Leteinturier et al.* [1990] for return stroke field derivatives from triggered lightning at 50 m; *Beasley et al.* [1982] for two leader fields from natural lightning at about 300 m and 500 m; and *Rakov and Uman* [1990c] for five leader fields from triggered lightning at 500 m). In this paper we present and discuss measurements of the electric field at ground level from leaders and return strokes of triggered lightning at 500 m and at 30 m. In order to estimate the leader speed and charge per unit length from the measured fields at 500 m and 30 m, we employ a simple leader model in which the leader channel is assumed to be uniformly charged and to extend vertically downward at a constant speed [e.g., *Schonland et al.*, 1938; *Uman*, 1987, Appendix A].

2. Experiment

Vertical electric fields at ground level from rocket-triggered lightning [*Uman*, 1987, chapter 12; *Willett*, 1992] were measured at the NASA Kennedy Space Center at distances of 500 m and 30 m during the summers of 1986 and 1991, respectively. During the 1986 experiment the rockets were launched from a land-based triggering facility on the western edge of Mosquito Lagoon, a body of shallow salt water. Lightning generally attached to a rod about 20 m above ground level. A sketch of the experiment site, depicting the relative positions of the electric field sensor, the triggering facility, and the shoreline of Mosquito Lagoon, is shown in Figure 1a. The field measurements were made about 500 m west of the triggering site with the propagation path being completely over land of approximate conductivity $1.6\mathrm{x}10^{-2}$ S/m [*Georgiadis et al.*, 1992]. The sensor used was the spheri-

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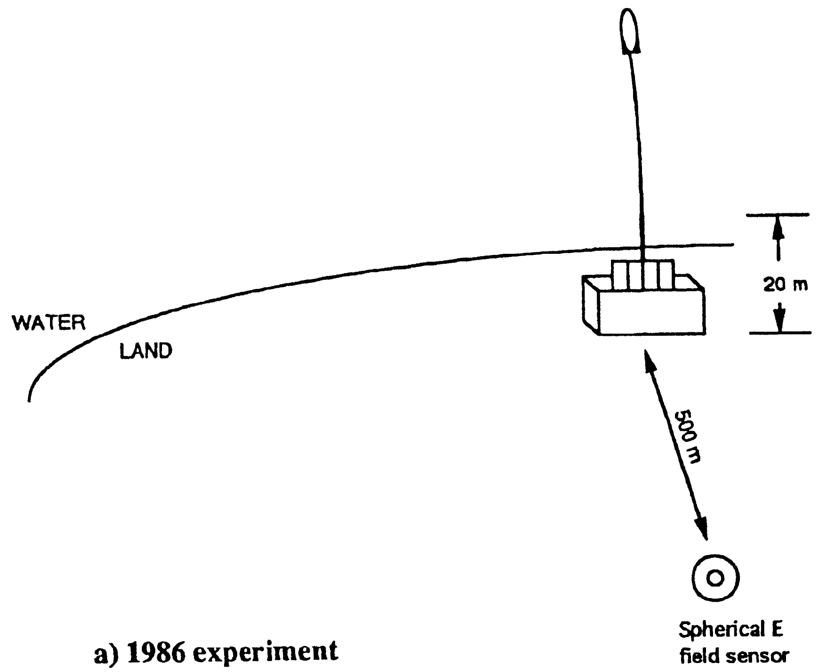
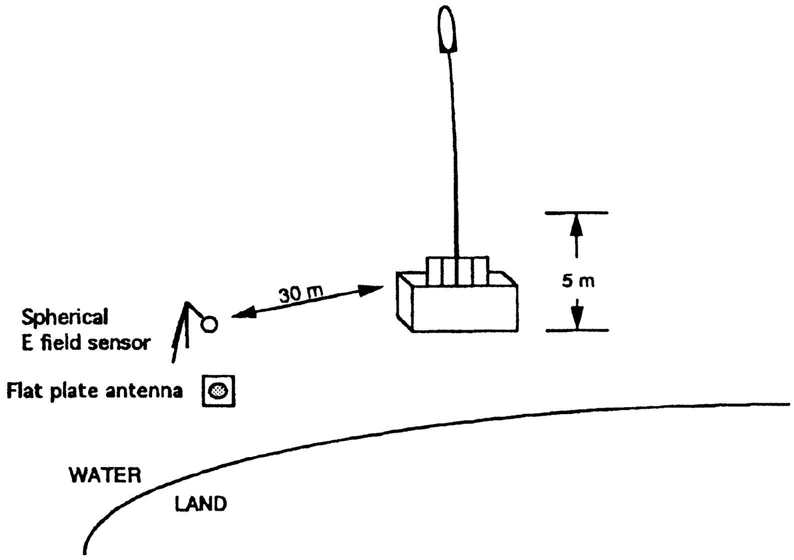


a) 1986 experiment



b) 1991 experiment

Figure 1. Experimental sites at the Kennedy Space Center, Florida. The triggering structure and sensor arrangement in (a) 1986 and (b) 1991.

cal antenna described by *Thomson et al.* [1988]. The vertical electric field signals were relayed via fiberoptic cables to a Honeywell 101 analog tape recorder and recorded in the FM mode. The bandwidth of the complete system was determined by the bandwidth of the Honeywell recorder, dc to 500 kHz. The analog records were later digitized at an effective rate of 5 M samples/s for analysis.

During the 1991 experiment the triggering rockets were launched over Mosquito Lagoon from a smaller structure, with lightning generally attaching to a rod about 5 m above water level (see Figure 1b). The electric field measurements were made 30 m from the triggering site using two different sensors: a flat plate antenna for measuring the time derivative of the electric field [*Uman*, 1987, Appendix C] and a spherical sensor of bandwidth 1 kHz to 150 MHz manufactured by Thomson CSF, France, for measuring the electric field directly. Signals from the sensors were relayed via fiberoptic cables and 20-MHz antialiasing filters, which determined the system upper bandwidth, to a Le Croy digitizing oscilloscope operating at 100 M samples/s. The field time derivative measurements made with the flat plate antenna all exhibited some degree of saturation and were used only to verify the general feature of the field waveforms obtained directly from the spherical sensor.

3. Analysis

500-m Data

Electric fields at 500 m were obtained for 8 flashes containing a total of 40 strokes. All strokes lowered negative charge to Earth. Examples of leader-return stroke waveforms at 500 m are found in Figures 2 and 3. The vertical electric field begins with a relatively slow negative field change (atmospheric electricity sign convention; *Uman* [1987], Appendix A) consistent with the lowering of negative charge by the leader. This slow change is followed by a fast positive field change due to the removal of leader charge by the return stroke. The arrows in Figures 2 and 3 mark the assumed transition from leader to the return stroke. The early portions of the leaders are not shown in the waveforms of Figure 3 but were available from the tape-recorded data, the total waveforms being used in the analysis. Note that for the fields at 500 m, we did not have simultaneous time-correlated current measurements to identify the exact onset time of the return stroke as we did for the 30 m data to be presented, so that our estimate of the return stroke onset is based on our experience with the 30-m data. The overall field waveforms appear as asymmetrical V-shaped pulses with a typical width at half peak of the order of 100 μs, this width being essentially determined by the duration of the leader field change since the return stroke field change takes only a few microseconds. Figure 2 illustrates how the half width of the V-shaped pulse, the leader field change ΔE_{L}, and the return stroke field change ΔE_{RS} have been determined from the waveforms. Table 1 gives characteristics of the leader-return stroke waveforms at 500 m. Columns 1 and 2 contain the flash identification and the order of the stroke (note that in triggered lightning there is no first stroke initiated by a stepped leader, as in natural lightning), respectively, column 3 the half width, column 4 the leader electric field change, column 5 the ratio $\Delta E_{\mathrm{L}}/\Delta E_{\mathrm{RS}}$, column 6 the return stroke peak current, and column 7 the interstroke interval preceding the stroke.

The return stroke peak currents in column 6 were directly measured at the triggering facility and have been obtained from the report published by *Barret et al.* [1986]. Their digitizers recorded only currents having peaks greater than or equal to their system trigger level, 6 kA, and therefore it is assumed that strokes identified in the field records but for which no peak current was given by *Barret et al.* [1986] had currents less than 6 kA. It is possible, however, that a stroke may not have been recorded by the triggered current measuring system for other reasons. *Barret et al.* [1986] also present overall current records for the duration of the flash. These overall records do not allow measurements of the current peaks, but can be used to correlate individual strokes in the field and current records.

Electric field changes from 8 of the 40 strokes were saturated (at the bottom of the V) and hence the leader field change values for these are shown in Table 1 with a "greater than" symbol preceding them, and the half widths of the V with a "less than" symbol preceding them. The leader-to-return stroke field change ratio for these 8 strokes could not be determined. The ratio of the leader to return stroke field change is always negative and ranges from -1.3 to -0.4. The median values of the half width, leader field change, leader-to-return stroke field ratio, return stroke peak current, and interstroke interval are 100 μs, 1250 V/m, -0.8, 8 kA, and 32 ms, respectively. The medians are given instead of the arithmetic or geometric means because of the significant number of values (see Table 1) being either lower or upper limits.

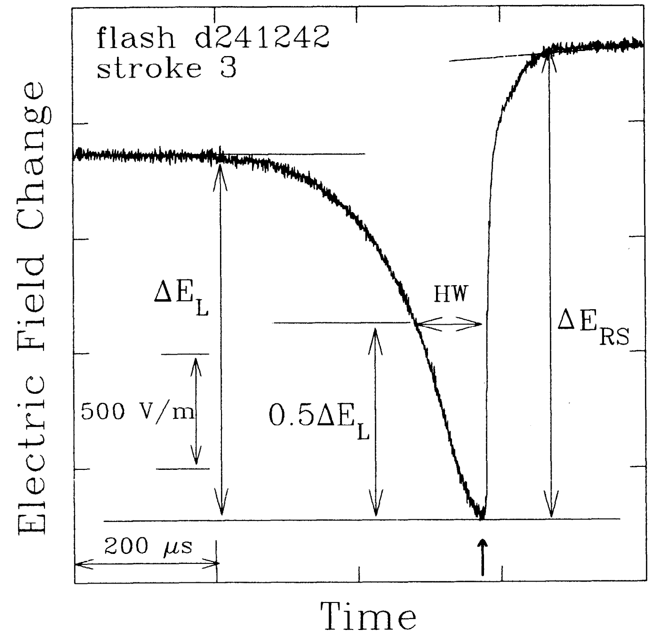


Figure 2. Example of the measurement of half width (HW), leader field change (ΔE_{L}), and return stroke field change (ΔE_{RS}) for flash d241f242, stroke 3, at 500 m, recorded on August 29, 1986.

30-m Data

Electric fields at 30 m were obtained for 5 flashes containing 8 strokes. Fields of two strokes (see Figure 4) were recorded without saturation by the Thomson CSF sensor and were suitable for quantitative analysis. All fields at 30 m, like the fields at 500 m, are asymmetrically V-shaped, with the initial negative transition being associated with the leader and the following positive transition with the return stroke, whose initiation is marked in Figure 4 with arrows, as it was in Figures 2 and 3. For the fields at 30 m the transition from the leader to the return stroke was identified by the start of the simultaneously measured and time-correlated channel-base current provided by the French research group from Centre d'Etude Nucleaires de Grenoble (CENG) (see Acknowledgments). The width of the V at half peak of the leader field change for the two waveforms discussed above is only a few microseconds, 1.8 μs and 5.0 μs, significantly smaller than for the fields at 500 m. The return stroke waveforms become relatively flat about 10 to 20 μs after the start of the return stroke field change.

Some characteristics of the two waveforms recorded by the Thomson CSF sensor are given in Table 2. As in Table 1 we give the flash identification, the stroke order within the triggered flash, half width of the V, maximum leader field change, the leader-to-return stroke field change ratio, and the return stroke peak current.

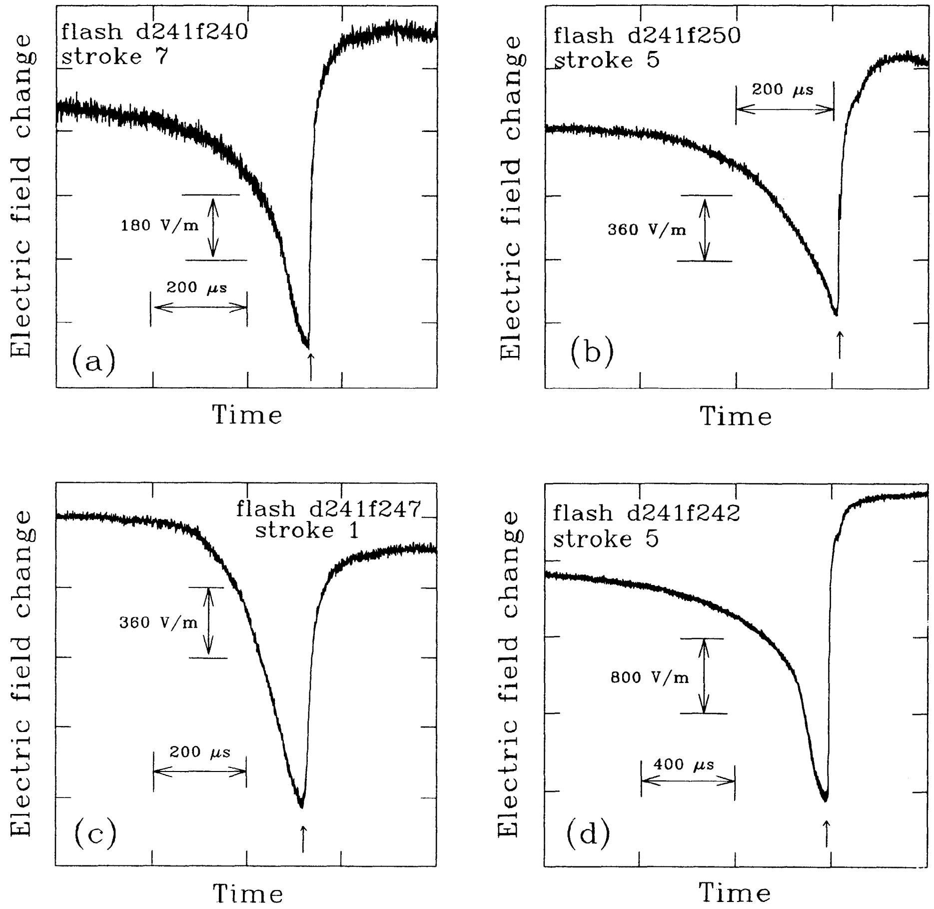


Figure 3. Vertical electric fields for five leader-return stroke sequences measured at 500 m on August 29, 1986. Arrows mark the assumed start of the return stroke. Start of the leader field changes is not shown in the Figure. (a) Flash d241f240, stroke 7; (b) flash d241f250, stroke 5; (c) flash d241f247, stroke 1, and (d) flash d241f242, stroke 5.

4. Discussion

Although the vertical electric fields measured at both 500 m and 30 m from triggered lightning exhibit asymmetrical V-shaped signatures, the width of the V is appreciably less for the fields at 30 m (some microseconds) than for the fields at 500 m (a few tens to a few hundreds of microseconds). The difference in the width of the field waveforms at 500 m and 30 m can be explained using a simple leader model [e.g., *Schonland et al.*, 1938; *Uman*, 1987, Appendix A] in which the leader is assumed to emerge from the center of a volume of charge in the cloud and to propagate vertically toward the ground. The charging of the leader as its length is extended results in a decrease of charge in the source volume. It is assumed that the charge volume involved in the leader processes is spherically symmetrical or its dimensions are small compared to the distance to the field measuring point and that the new charge is deposited only at the tip of the leader. A comprehensive theoretical study of lightning leader models can be found in work by *Thomson* [1985], who discusses errors involved in this simple and most widely used model.

Consider first the leader field variation for the more general case of a non-uniformly charged leader having a vertical channel above a perfectly conducting ground. The magnitude of the vertical component of the field change at ground a horizontal distance r from the strike point due to an elemental section of the channel Δz at height z containing a line charge density $\rho_L(z)$ can be written, including the effect of charge depletion in the cloud, as follows

$$\Delta E_z = \frac{\rho_L(z)\Delta z}{2\pi\varepsilon_0} f(z) \tag{1}$$

where

$$f(z) = \frac{z}{\left(z^2 + r^2\right)^{3/2}} - \frac{H}{\left(H^2 + r^2\right)^{3/2}}$$

and H is the height of the cloud charge center [*Thomson*, 1985; *Uman*, 1987].

In Figure 5 we plot $f(z)$ versus z for r = 500 m and 30 m. Note that $f(z)$ is purely a function of geometry. If a uniform charge model is assumed, the relative contribution of each channel section of equal length to the total field is given by the value of $f(z)$. It can be shown that $f(z)$ has a maximum value at a height $z = r/\sqrt{2}$. For the uniform charge case the fields at 500 m are essentially determined by the channel section below a height of the order of 1000 m (Figure 5a). In fact, about 90% of the leader field change at 500 m for a uniform leader is due

Table 1. Characterization of Measured Vertical Electric Fields due to Leader Return Stroke Sequences 500 m From Triggered Lightning, NASA Kennedy Space Center, 1986

Flash	Stroke Order*	Half Width of the V, μs	ΔE_L, V/m	$\frac{\Delta E_L}{\Delta E_{RS}}$	I_n Peak, kA†	Previous Interstroke Interval, ms
d232f001	1	<60	>2240	-	41	-
	2	46	1220	-0.8	<6‡	40
	3	<82	>2210	-	36	46
	4	<56	>2160	-	55	68
	5	<130	>2240	-	25	64
	6	100	1400	-0.9	<6‡	62
	7	<172	>2160	-	38	90
d240f001	1	75	1380	-1.0	12	-
	2	140	1250	-0.9	16	82
	3	2100	600	-0.8	<6‡	126
d240f002	1	65	1300	-1.0	-	-
	2	170	1060	-0.8	-	102
d241f240	1	-	-	-	<6‡	-
	2	290	1580	-0.5	15	37
	3	108	690	-1.0	<6‡	8
	4	42	960	-0.8	6	11
	5	40	1030	-0.9	8	13
	6	72	910	-0.9	7	17
	7	76	690	-0.8	6	16
	8	<60	>2330	-	32	77
d241f242	1	60	770	-1.3	<6‡	-
	2	50	1840	-0.8	13	42
	3	100	1680	-0.8	11	53
	4	270	1430	-1.3	<6‡	14
	5	125	2080	-0.7	19	145
d241f245	1	<30	>2270	-	39	-
	2	330	870	-0.4	13	31
	3	40	1450	-0.8	10	11
d241f247	1	108	1440	-1.1	<6‡	-
	2	116	1300	-0.9	<6‡	13
	3	<40	>2310	-	26	32
	4	200	1010	-0.8	8	30
d241f250	1	330	760	-0.8	<6‡	-
	2	500	660	-0.9	<6‡	14
	3	300	640	-0.7	<6‡	21
	4	180	680	-0.9	<6‡	5
	5	120	1040	-0.7	10	32
	6	160	810	-0.8	7	18
	7	100	1110	-0.8	11	26
	8	250	740	-0.8	6	27

*Note that in the triggered lightning analyzed here, as opposed to natural lightning, there is no first stroke initiated by a stepped leader. Thus all listed strokes, including number 1, are "subsequent" ones in the sense that they followed a channel previously created by the initial processes of triggered lightning [e.g., *Fisher et al.*, 1993]. This note applies to Table 2 as well.

†Return stroke current peak values from *Barret et al.* [1986]

‡These return strokes presumably had peaks below the trigger threshold of 6 kA.

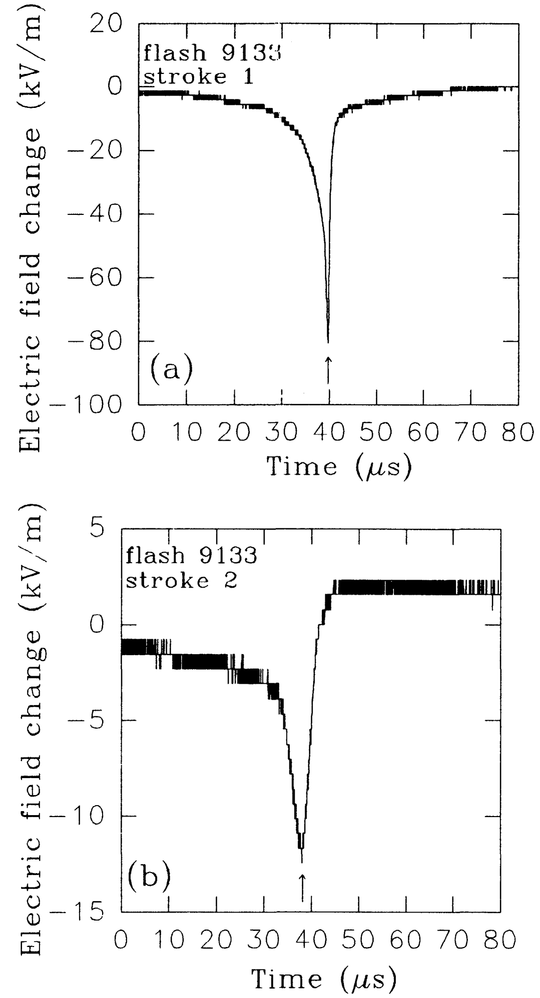


Figure 4. Vertical electric fields for two leader-return stroke sequences measured at 30 m in 1991. Arrows mark the start of the return stroke. (a) Flash 9133, stroke 1 on August 25; (b) flash 9133, stroke 2 on August 25.

to the charge below 2500 m, 70% below 1200 m, 15% below 280 m, and 2% below 100 m. The field at 30 m is essentially determined by the channel section below a height of the order of 100 m (Figure 5b). In fact, about 90% of the leader field change at 30 m for a uniform leader is due to charge below 280 m, 70% below 100 m, and 5% below 10 m. One can therefore obtain an estimate of the effective average channel charge in an appropriate height range by using the uniform charge model and the measured fields close to the channel.

The overall leader field change at any time t is given by

$$E_Z(t) = \lim_{\Delta z \to 0} \sum_{z=H_B(t)}^{H} \Delta E_Z = \int_{z=H_B(t)}^{H} dE_Z \tag{2}$$

where $H_B(t) = H - vt$ is the height of the bottom of the leader at time t, v is the leader speed assumed to be constant, and ΔE_Z is taken from (1). For a uniformly charged leader, (2) can be integrated to yield [*Uman*, 1987, Appendix A]

$$E_z(t) = \frac{\rho_L}{2\pi\varepsilon_0 r}\left[\frac{1}{(1+H_B^2(t)/r^2)^{1/2}} - \frac{1}{(1+H^2/r^2)^{1/2}} - \frac{(H-H_B(t))H}{r^2(1+H^2/r^2)^{3/2}}\right] \tag{3}$$

Figure 6a shows the leader electric field per unit charge density calculated at 500 m for a leader reaching ground and having four different values of the speed v: $2\text{x}10^6$ m/s, $5\text{x}10^6$ m/s, $1\text{x}10^7$ m/s, and $2\text{x}10^7$ m/s. The half widths of the calculated waveforms in Figure 6a, measured from the half peak of the leader field change to the end of the leader field change, corresponding to the above speeds are 371 μs, 149 μs, 74 μs, and 37 μs, respectively. These half width values approximately represent the range of values of the half widths of the experimental waveforms (measured as shown in Figure 2) given in Table 1, excluding the one unusually large half width of 2.1 ms. The model-predicted half widths at 500 m are inversely proportional to the assumed leader speed. The speeds that allow the reproduction of the half widths of the V seen in the present measurements (which can be viewed as leader speed estimates), $2\text{x}10^6$ to $2\text{x}10^7$ m/s, are in reasonable agreement with the leader speeds measured photographically for triggered lightning at the Kennedy Space Center in 1987 and 1989, about $6\text{x}10^6$ to $2.5\text{x}10^7$ m/s [*Jordan et al.*, 1992]. Note again that our estimates of leader speed are for the bottom kilometer or so of the leader since the field change is due to the charge below that height.

The effective constant charge density required on the leader channel to produce the field amplitudes in column 4 of Table 1 can be obtained from the ratio of the field amplitudes in Table 1 to the maximum field change, shown in Figure 6a (31,000 kV/C), produced at 500 m by a model leader channel having unit line charge density (1 C/m). The charge density calculated is in the range

Table 2. Characterization of Measured Vertical Electric Field due to Leader Return Stroke Sequences 30 m From Triggered Lightning, NASA Kennedy Space Center, 1991

Flash	Stroke Order*	Half Width of the V, μs	ΔE_L, kV/m	$\frac{\Delta E_L}{\Delta E_{RS}}$	I_{RS} Peak, kA
9133	1	1.8	81	-1	40
	2	5.0	12	-0.8	7

*See note to Table 1.

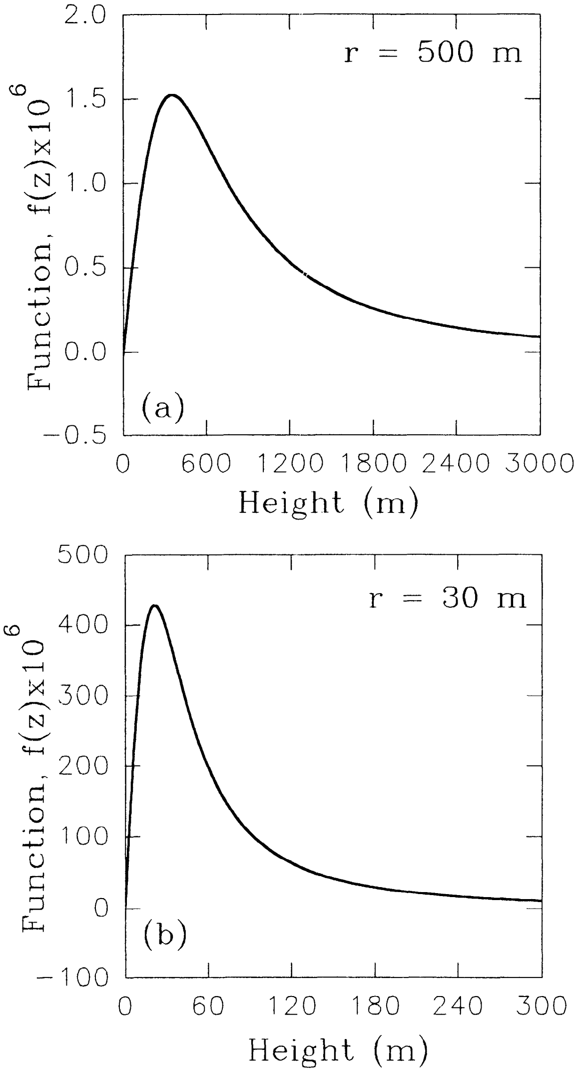


Figure 5. Function $f(z)$ versus z from (1) for two distances: (a) 500 m and (b) 30 m from the lightning channel.

$0.02\mathrm{x}10^{-3}$ to $0.08\mathrm{x}10^{-3}$ C/m and, as already discussed, characterizes a channel section of the order of 1000 m in length above ground (see Figure 5b). Note that the upper limit of $0.08\mathrm{x}10^{-3}$ C/m is an underestimate, since eight of the large field changes are saturated.

Figure 6b shows the calculated leader fields 30 m from the channel for a leader reaching ground and having a unit line charge density. The values of leader speed that we used, $1\mathrm{x}10^{7}$ m/s, $2\mathrm{x}10^{7}$ m/s, and $3\mathrm{x}10^{7}$ m/s to reproduce the range of half widths of our field waveforms are in the range reported by *Jordan et al.* [1992]. The half widths in Figure 6b corresponding to the above three speeds are 5.1 μs, 2.6 μs, and 1.7 μs, respectively. The speeds 3 x 10^{7} m/s and 1 x 10^{7} m/s producing half widths 1.7 μs and 5.1 μs, respectively, in Figure 6b can be viewed as estimates of the leader speeds corresponding to the observed half-width values 1.8 μs and 5.0 μs in Figures 4a and 4b. Like the half widths at 500 m, the model-predicted half widths at 30 m are inversely proportional to the assumed leader speeds. The effective constant charge density required on the leader channel to produce the maximum field changes shown in Figures 4a and 4b (see also Table 2) is obtained from the ratio of maximum field changes in Figures 4a and 4b (81 kV/m and 12 kV/m) to the maximum field change produced by a unit charge density shown in Figure 6b (585,000 kV/C). The charge density values are $0.14\mathrm{x}10^{-3}$ and $0.02\mathrm{x}10^{-3}$ C/m, respectively, and characterize a channel section of the order of 100 m above ground (see Figure 5a), as do the leader speeds given above.

As mentioned earlier, the height of the triggering structure was about 20 m in the 1986 experiment and about 5 m in the 1991 experiment. Presumably the leader terminates at those heights (neglecting any upward streamers), not at ground level, as assumed in the model. However, the triggering structure height has a very small effect on the calculated leader fields at 500 m and 30 m, since the integral of $f(z)$ (see Figure 5 and equation (2)) from ground to the triggering structure height is a very small fraction of the integral of $f(z)$ over the entire leader channel. In fact, if the leader is allowed to terminate at the height of the triggering structure, the calculated maximum field change will be about 1% less than the value in Figure 6a for 500 m and about 3% less than the value in Figure 6b for 30 m. The corresponding increase in waveform half widths will be about 3% for 500 m and about 10% for 30m.

Interestingly, for very close field measurements where $H^2 >> r^2$, and for either $H_B(t)=0$ (leader touching the ground) or $H^2_B(t) << r^2$ and $H_B(t) << H$ (leader close to the ground), (3) for the vertical electric field change at a perfectly-conducting ground due to a uniformly charged leader becomes approximately

$$E_z(H_B(t)=0) \approx \frac{\rho_L}{2\pi\epsilon_0 r} \tag{4}$$

That is, very close to the channel the vertical electrostatic field at ground falls off as $1/r$, as opposed to $1/r^3$ far from the channel ($H^2 << r^2$). Interestingly, (4) is exactly the same expression as the horizontal field from an infinitely long, uniform line charge. When compared to Figures 6a and 6b, in which (2) is plotted, the error involved in using (4) for calculating total leader field change is about 15% for the case of 500 m, and about 1% for the case of 30 m.

We now briefly discuss our estimates of line charge density for the leader channel. *Krehbiel et al.* [1979, Table 1] found that the total charge involved in subsequent strokes varies from 1.0 C to 11 C, with a mean around 5 C. Assuming a mean path length of 8 km, the charge per unit length is in the range $0.1\mathrm{x}10^{-3}$ to $1.4\mathrm{x}10^{-3}$ C/m, which is an order of magnitude larger than the charge estimates in the present study (although a number of our leader field changes were saturated and hence in those cases lower limits to the charge per unit length were obtained). On the other hand, net stroke charges may not be representative of the leader channel charges since the former may contain contributions from short duration continuing currents following the return stroke phase.

In the model the assumption that the charge per unit length of the leader, once deposited by the leader tip, does not vary with time allows a decoupling of the leader speed and leader charge density so that the half width is

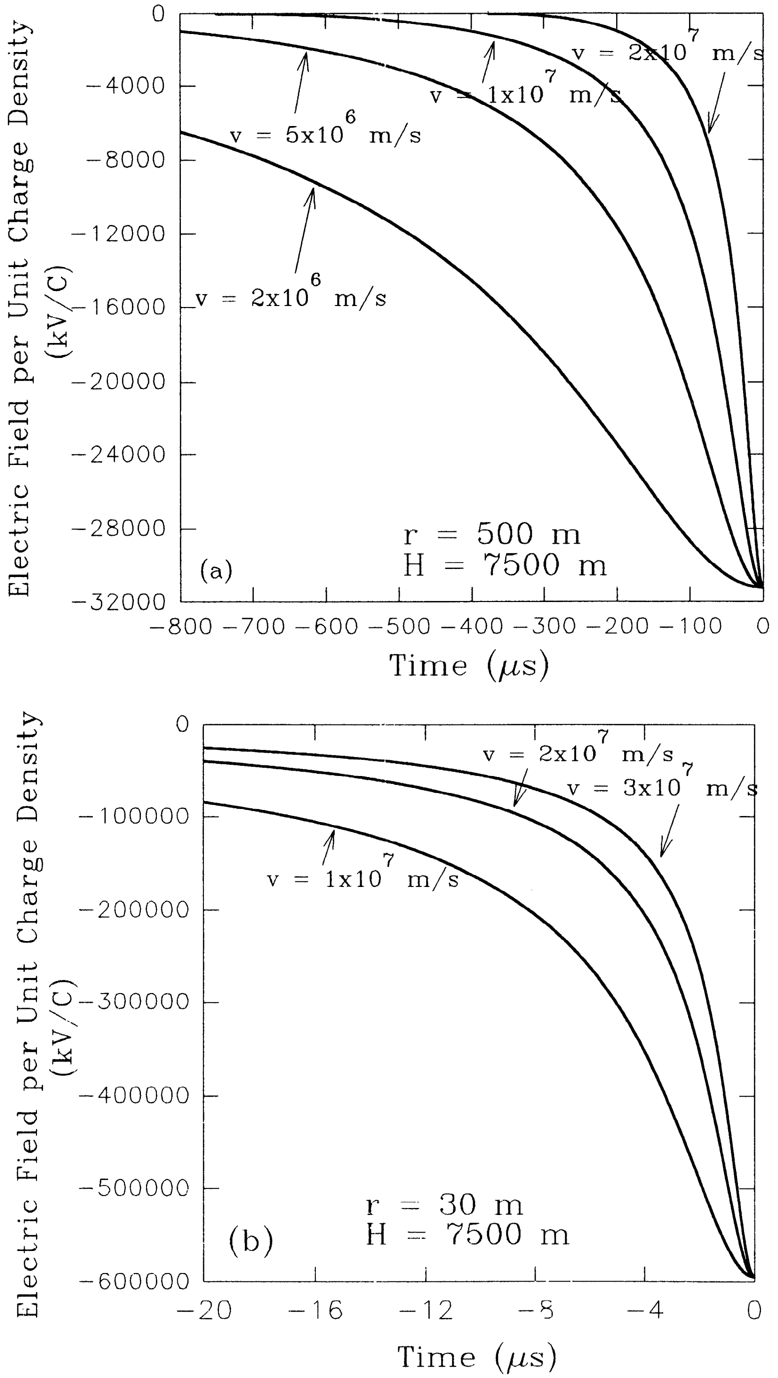


Figure 6. Leader electric field calculations using a uniformly charged vertical line model with constant speed. The height of the charge source is chosen as $H = 7.5$ km, although the close fields are relatively insensitive to the value of H. At $t = 0$, $H_B = 0$ rather than $H_B = H$, as in (3). (a) Calculation at 500 m. The leader speeds are 2 x 10^6 m/s, 5 x 10^6 m/s, 1x10^7 m/s, and 2x10^7 m/s. (b) Calculation at 30 m. The leader speeds are 1x10^7 m/s, 2x10^7 m/s, and 3x10^7 m/s.

independent of the maximum leader field change. Figure 7 shows a scatter plot of the maximum leader field change and the half width for the experimental waveforms. There is no apparent correlation between the two. However, one might expect, on physical grounds, that the leaders with the larger charge per unit length would travel faster and hence produce the smaller half widths. Further, *Jordan et al.* [1992] observed that strokes with larger return stroke current peaks had faster leaders, consistent with the above physical view. On the other hand, we found a linear correlation (correlation coefficient equals 0.8) between the maximum leader field change and the succeeding return stroke current peak (Figure 8), implying that the return stroke current peak is proportional to the equivalent charge per unit length deposited by the preceding leader within the bottom kilometer or so. Note that for the two strokes at 30 m, the ratios of the model-predicted line charge density to the corresponding mea-

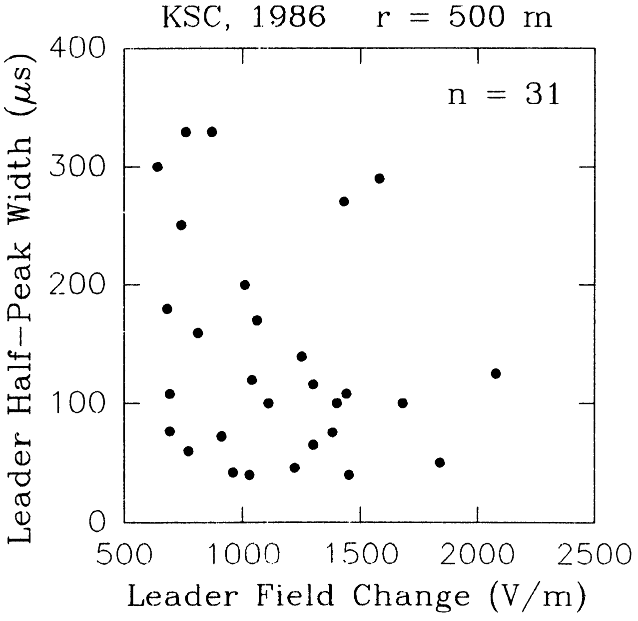


Figure 7. Scatter plot of the half width versus maximum field change of the leader.

sured peak current are similar (the difference is of the order of 20%), implying a linear relationship between these two parameters.

It is important to note that all leader speeds and leader charges inferred here from the electric field waveforms are model dependent [*Thomson*, 1985]. We used the simplest leader model available, since we did not have any information to justify the use of a more sophisticated model.

Finally, to the extent that leader-return stroke fields from artificially initiated lightning can be considered similar to those from natural lightning [e.g, *Le Vine et al.*, 1989; *Jordan et al.*, 1992; *Fisher et al.*, 1993], the observed fast change of the leader field at 30 m can have important implications in the interaction of close lightning with electric power and communication systems. For example, in the calculation of voltages induced by nearby lightning on overhead lines, it is generally assumed that the electromagnetic field changes associated with the leader phase produce much lower induced voltages than those caused by the field changes associated with the return stroke [e.g., *Master and Uman*, 1984; *Diendorfer*, 1990; *Nucci et al.*, 1993]. The results presented in this paper render this assumption questionable.

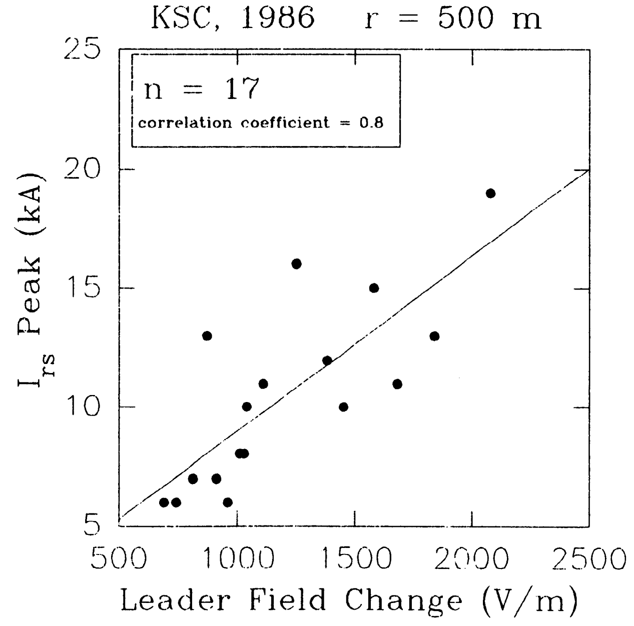


Figure 8. Scatter plot of return stroke peak current versus maximum leader field change.

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