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Time derivative of the electric field 10, 14, and 30 m from triggered lightning strokes

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Abstract. We have directly measured the time derivative of the electric field of triggered lightning strokes at distances of 10, 14, and 30 m. The data were taken in 1998 at the International Center for Lightning Research and Testing at Camp Blanding, Florida. We compare our results with those of similar triggered lightning measurements made previously at the Kennedy Space Center at distances of 50 m and 5 km and in France at 50 m. We also compare our electric field derivative waveforms with previous measurements at the Kennedy Space Center of natural lightning strokes over the Atlantic Ocean at distances of the order of tens of kilometers and with overland natural lightning data obtained at 0.7 to 14 km in Germany. Our return stroke electric field derivative peak values normalized (assuming the inverse distance dependence valid for radiation fields) to 100 km are similar to all previous measurements for both natural and triggered lightning at distances from 50 m to about 50 km, all being several tens of volts per meter per microsecond, with the exception of the German overland peak derivative values which are an order of magnitude lower. Our 10- to 30-m field derivative zero-to-peak risetimes are typically 50 to 100 ns (minimum of 30 ns and maximum of 180 ns), and widths at half-peak value are typically 100 to 200 ns. There is essentially no difference between our electric field derivative waveshapes measured simultaneously at 10 m and at 30 m, with the closer waveform being about a factor of 2 greater in amplitude. Fourier analysis of our electric field derivative waveforms indicates that the primary frequency content of the waveforms is below about 20 MHz. Our close return stroke field derivative waveforms differ from those of Leteinturier et al. (1990) recorded 50 m from triggered lightning at the Kennedy Space Center in 1985 in that their derivative waveforms typically decrease rapidly after the peak and exhibit zero crossings and in that their waveforms tend to have multiple peaks, while our derivative waveforms are generally single peaked and decay more gradually to zero after the peak, with no zero crossings. We argue that the differences between their waveforms and ours are related to the relatively large rocket-launching structure used at the Kennedy Space Center in 1985.

1. Introduction and Literature Review

An accurate knowledge of the time derivative of the electric field intensity produced by very close lightning strokes is important for several reasons: (1) the field derivative contains information on the physics of the attachment process and the initial stages of the return stroke process; (2) measured field derivatives have been used with a simple return stroke model, the so-called transmission line model [e.g., *Uman and McLain*, 1969, 1970a, b; *Rakov and Uman*, 1998], to infer channel base current derivatives or return stroke speeds for both natural and triggered lightning return strokes [*Leteinturier et al.*, 1990; *Willett et al.*, 1989, 1998; *Krider et al.*, 1996]; and (3) the field derivative is an important parameter in calculating the effects of the potentially deleterious coupling of lightning fields to various systems [e.g., *Uman*, 1988].

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1.1. Natural Lightning at Distances of Tens of Kilometers, Florida

Krider et al. [1996] reported on 1984 measurements of the time derivative of the vertical electric field of 63 negative first return strokes with a system "designed to provide a time resolution of about 10 ns." The strokes occurred in one thunderstorm over the Atlantic Ocean about 35 km east of the measuring site which was located on the easternmost tip of Cape Canaveral, Florida. *Krider et al.* [1996] found a mean peak electric field derivative of about 40 V m^{-1} μs^{-1} normalized to 100 km (using the inverse distance dependence valid for radiation fields propagating over perfectly conducting ground), with a derivative pulse width of about 100 ns at half maximum and about 200 ns at zero level. Employing the methodology of *Zeddam et al.* [1990] for evaluating propagation effects, *Krider et al.* [1996] estimated that the peak field derivative would have been reduced by about 20% and the derivative pulse width increased by about 30% in propagating over a calm sea surface, and they calculated mean peak and mean width values corrected for propagation of 46 V m^{-1} μs^{-1} and 75 ns, respectively. They did not correct for potential propagation effects caused by a rough ocean surface [*Ming and Cooray*, 1994], since any waves that might have been present were of unknown height; nor did they correct for propagation effects over the few tens of meters of beach from the shoreline to the antenna location [*Cooray and Ming*, 1994], which they argue are small. These additional corrections would potentially further increase the estimated peak derivative value and decrease the estimated derivative pulse half-peak width. In an earlier analysis of the same 1984 data set, *Leteinturier et al.* [1985] and *Leteinturier and Hamelin* [1990] found a normalized mean peak derivative for six subsequent strokes preceded by dart leaders (subsequent strokes were not considered by *Krider et al.* [1996]) of 41 V m^{-1} μs^{-1}, for seven subsequent strokes preceded by dart-stepped leaders of 52 V m^{-1} μs^{-1}, and for 62 first strokes of 45 V m^{-1} μs^{-1}, all values uncorrected for propagation effects. Stroke mean derivative pulse widths at half-peak value were 81, 99, and 97 ns, respectively, again uncorrected for propagation effects.

In a similar but earlier experiment in 1978, *Weidman and Krider* [1980] made electric field derivative measurements with 10-ns resolution from natural lightning over Tampa Bay and the Gulf of Mexico on the west coast of Florida using a measuring station 10 m from the salt water. For 97 strokes, mostly first strokes, they found a mean of 29 V m^{-1} μs^{-1} with a standard deviation of 12 V m^{-1} μs^{-1} normalized to 100 km, uncorrected for propagation.

Willett et al. [1990, 1998] reported on 1985 measurements of the electric field derivative for negative lightning strokes in thunderstorms over the Atlantic Ocean near Cape Canaveral similar to the 1984 measurements reported by *Krider et al.* [1996]. The antenna was 45 m from the Atlantic Ocean on Playalinda Beach, a narrow barrier island 5 km or so east of the Florida mainland. For 131 first strokes in the range 6 to 40 km, *Willett et al.* [1998] found a mean peak derivative of 42 V m^{-1} μs^{-1} normalized to 100 km and a mean derivative pulse width at half of peak value of 64 ns, both values corrected for propagation effects by using the same approach as *Krider et al.* [1996], described above. The 15% smaller mean derivative pulse width than that found by *Krider et al.* [1996] was attributed by *Willett et al.* [1998] to the use of a "more modern digitizer" and the fact that the waveforms "were analyzed with more precision." *Willett et al*'s. [1998] system had a stated bandwidth of 30 MHz, a sampling interval of 10 ns, and 8-bit amplitude resolution.

Le Vine et al. [1989] reported that the mean peak field derivative normalized to 100 km for 16 subsequent strokes in natural negative lightning strikes at about 35 km over the Atlantic Ocean in 1987 was 48 V m^{-1} μs^{-1}, with the mean width at half-peak value being 78 ns, both values uncorrected for propagation effects. *Le Vine et al.* [1989] also showed that natural subsequent stroke field derivative waveforms were very similar to the field derivative waveforms of triggered strokes at 5.16 km, as will be discussed further below.

The characteristics of electric field derivative waveforms from the studies discussed above (and from other studies) are summarized in Table 1.

1.2. Triggered Lightning at 5.16 km, Florida

Willett et al. [1989] and *Le Vine et al.* [1989] both reported on the same 1987 measurements of electric field derivatives at a distance of 5.16 km from negative triggered lightning strokes. The discharges were triggered (artificially initiated) at the Kennedy Space Center, Florida by using the rocket-and-wire technique [e.g., *Uman et al.*, 1997; *Rakov et al.*, 1998]. Triggered stroke field derivative waveshapes, as noted above, were shown by *Le Vine et al.* [1989] to be very similar to those of natural subsequent strokes. Additionally, subsequent strokes in natural lightning exhibit peak values of field derivative and 10-90% risetimes of the so-called "fast field transition" in the electric field waveform similar to those of natural first strokes, although there are significant differences in the overall first and subsequent stroke electric field waveforms [*Leteinturier et al.*, 1985; *Weidman and Krider*, 1978, 1980, 1984; *Weidman*, 1982; *Le Vine et al.*, 1989; *Leteinturier and Hamelin*, 1990]. The field measuring station for the 5.16-km triggered lightning data was on Playalinda Beach (see section 1.1). Field propagation was across the salt water of Mosquito Lagoon, with the antenna located about 200 m from the shoreline. The terrain between the shoreline and the antenna was mostly marsh. The mean derivative peak measured for 28 triggered negative strokes, when normalized to 100 km, was 52 V m^{-1} μs^{-1}, and the mean derivative pulse width at half-peak value was 61 ns, both values uncorrected for propagation effects, perhaps small, and both values being similar to those obtained by *Leteinturier et al.* [1985], *Le Vine et al.* [1989], *Krider et al.* [1996], and *Willett et al.* [1998] for natural lightning first and subsequent strokes from thunderstorms over the Atlantic Ocean at distances of the order of tens of kilometers, as listed in Table 1.

1.3. Triggered Lightning at 50 m, Florida and France

Leteinturier et al. [1990] and *Weidman et al.* [1986] describe electric field derivative measurements made 50 m from negative triggered lightning strokes in Florida in 1985 and in France in 1986. Their system risetime was stated to be less than 4.5 ns. *Leteinturier et al.* [1990] found peak derivative values generally in the 100 to 200 kV m^{-1} μs^{-1} range, with a mean of 129 kV m^{-1} μs^{-1} for 31 strokes in Florida and a mean of about 100 kV m^{-1} μs^{-1} for 9 strokes in France. Note that for the measurements in both Florida and France the 50-m field propagation path was entirely over land and no correction was made for any potential effects of propagation. Derivative pulse widths at half-peak value for the five waveforms presented by *Leteinturier et al.* [1990] from the Kennedy Space Center (Florida) and St. Privat d'Allier (France) experiments and the three more waveforms from the same Kennedy Space Center experiment published by *Weidman et al.* [1986] appear to be near 100 ns, larger than those for the more distant measurements described in sections 1.1 and 1.2 after those measurements are corrected for the effects of propagation. If the 50-m peak derivative values of *Leteinturier et al.* [1990] are normalized to 100 km by assuming the inverse distance relationship valid for radiation fields, the means obtained, 65 V m^{-1} μs^{-1} in Florida and 50 V m^{-1} μs^{-1} in France, are comparable to the 100-km normalized 5.16-km triggered lightning values of *Willett et al.* [1989] and *Le Vine et al.* [1989], 52 V m^{-1} μs^{-1} (uncorrected for potential propagation effects), and to the tens of kilometers natural first and subsequent stroke values (corrected for propagation) for lightning over the Atlantic Ocean, all found in Table 1.

Depasse [1992, 1994] reported on electric field and electric field derivative measurements made with a sampling interval of 10 ns in France in 1990 and 1991 at 50 m from negative triggered lightning. For 14 strokes, the peak electric field derivative was in the range 4.6 to 143.6 kV m^{-1} μs^{-1}, the mean derivative peak normalized to 100 km was 41 V m^{-1} μs^{-1}, similar to the data discussed above, and the normalized median was 24 V m^{-1} μs^{-1}.

Table 1. Characteristics of Electric Field Derivative Waveforms Normalized to 100 km for Negative Return Strokes From Various Studies

Source	Location and Year	Sample Size and Stroke Type	Bandwidth or Equivalent	Mean Peak *dE/dt* V m^{-1} μs^{-1}	Standard Deviation of Peak *dE/dt*, V m^{-1} μs^{-1}	Mean HPW, ns	Standard Deviation of HPW, ns	Propagation Path Including Distance
Krider et al. [1996]	Florida, 1984	63 natural first	10-ns resolution	46 [a]	13	75 [a]	15	tens of kilometers, salt water
Weidman and Krider [1980]	Florida, 1978	97 natural first (primarily)	10-ns resolution	29	12	-	-	tens of kilometers, salt water
Leteinturier et al. [1985], *Leteinturier and Hamelin* [1990]	Florida, 1984	62 natural first	10-ns resolution	45	13	81	11	tens of kilometers, salt water
Leteinturier et al. [1985], *Leteinturier and Hamelin* [1990]	Florida, 1984	6 natural subsequent preceded by dart leaders	10-ns resolution	41	18	97	18	tens of kilometers, salt water
Leteinturier and Hamelin [1990]	Florida, 1984	7 natural subsequent preceded by dart-stepped leaders	10-ns resolution	52	12	99	17	tens of kilometers, salt water
Willett et al. [1998]	Florida, 1985	131 natural first	30 MHz 10-ns sampling	42 [a]	13	64 [a]	22	tens of kilometers, salt water
Le Vine et al. [1989]	Florida, 1987	16 natural subsequent	30 MHz 10 ns sampling	48	18	78	21	about 35 km, salt water
Willett et al. [1989], *Le Vine et al.* [1989]	Florida, 1987	28 triggered	10-ns resolution	52	15	61	22	5.16 km, salt water
Leteinturier et al. [1990]	Florida, 1985	31 triggered	4.5-ns risetime 5-ns sampling	65	29	near 100 (4 examples)	-	50 m, land
Leteinturier et al. [1990]	France, 1986	9 triggered	4.5-ns risetime 5-ns sampling	50	32	near 100 (1 example)	-	50 m, land

Table 1. (continued)

Source	Location and Year	Sample Size and Stroke Type	Bandwidth or Equivalent	Mean Peak *dE/dt* V m^{-1} µs^{-1}	Standard Deviation of Peak *dE/dt*, V m^{-1} µs^{-1}	Mean HPW, ns	Standard Deviation of HPW, ns	Propagation Path Including Distance
Heidler and Hopf [1998]	Germany, 1988-1993	148 natural first	40-MHz 10-ns sampling	5.4	3.4	620	300	0.7 to 19 km, land
Heidler and Hopf [1998]	Germany, 1988-1993	302 natural subsequent	40-MHz 10-ns sampling	4.4	2.2	620	250	0.7 to 19 km, land
Baker et al. [1987]	New Mexico, 1986	1 triggered	10-ns sampling	41	-	-	-	60 m, land
Depasse [1992, 1994]	France 1990-1991	14 triggered	10-ns sampling	41 median: 24	8.8	870 (10%-10%)	860	50 m, land
Present work	Florida (Camp Blanding), 1998	7 at 10 m 4 at 14 m 7 at 30 m triggered	see Table 2[b]	21 27 43	3.7 11 12	160 240, 140[c] 110	140 170, 80[c] 40	10 to 30 m, land

Normalizing *dE/dt* at close range to 100 km using the inverse proportionality characteristic of radiation fields may be invalid, since the close fields may not be pure radiation, and is done here solely for purposes of comparison. HPW, half-peak width.

[a] data corrected for propagation effects using theory (see discussion in text).

[b] four waveforms at 10 m and three waveforms at 30 m were saturated.

[c] excluding a half-peak width of 510 ns.

1.4. Natural Lightning at 0.7 to 14 km, Germany

Heidler and Hopf [1998] measured electric field derivative peaks and derivative pulse widths for natural negative lightning near Munich, Germany, at ranges from 700 m to 14 km. Their results from three separate study periods in which different instruments were used differ markedly from the data described in sections 1.1 to 1.3. For two of the three periods, *Heidler and Hopf* [1998] find mean derivative peaks normalized to 100 km of 3.0 and 5.4 V m^{-1} μs^{-1} for negative first strokes and 3.0 and 4.4 V m^{-1} μs^{-1} for negative subsequent strokes, with mean derivative pulse widths of 630 ns and 620 ns for first strokes and 520 ns and 620 ns for subsequents, as listed in Table 1. They argue, on the basis of model calculations, that the order-of-magnitude difference between their observations and those in Florida cannot be solely due to effects associated with the electric field propagation over land in southern Germany and therefore must be attributed in part to differences in the source. *Heidler and Hopf* [1998] suggest that the fact that the lightning struck salt water in the Florida studies whereas in Germany it struck the land may well be in part responsible for the difference between the field derivative data obtained in Florida and in Germany. In section 5 we argue against this hypothesis on the basis of our close measurements of triggered lightning strikes to ground. Interestingly, *Heidler and Hopf* [1998] found that the mean electric field derivative peak for positive strokes was appreciably higher than that for negative strokes, in contrast with the finding of *Cooray et al.* [1998], who reported that the derivative peak for positive strokes was a factor of 1.5 to 2 lower than its counterpart for negative strokes.

1.5. Comments

Results from the previous studies discussed in sections 1.1-1.4, some additional data not discussed in the text, and some of our 1998 results are summarized in Table 1. In section 4 we give a detailed characterization and examples of (1) measured electric field derivative waveforms and computed electric field waveforms at 10, 14, and 30 m and (2) simultaneously measured current waveforms and computed current derivative waveforms corresponding to the field and field derivative data. In section 5 we compare our data with the data of others and attempt to explain the observed differences. We additionally discuss, from our and other data, whether the electric field derivative at very close range is primarily radiation field or primarily electrostatic field or whether neither of these field components is clearly dominant. We also discuss the applicability of the transmission line model to deriving return stroke speeds from measured electric field derivative and current derivative data.

2. Theory

The vertical electric field intensity at ground level, $z = 0$, at range D produced by the vertical current-carrying channel above the perfectly conducting plane shown in Figure 1, as first

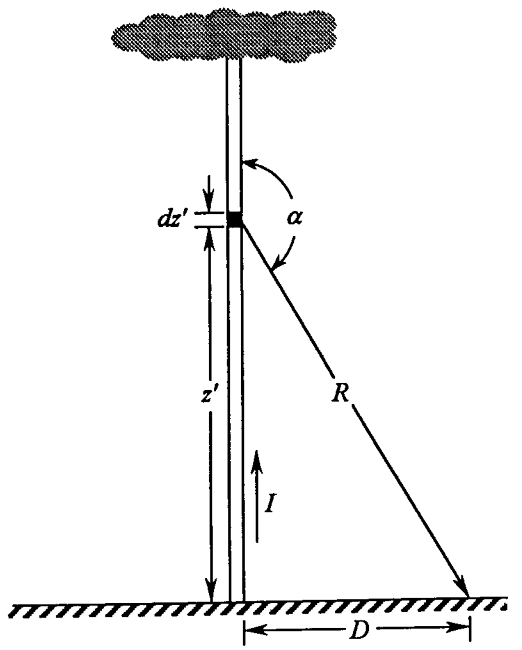

Figure 1. Straight vertical lightning channel above a flat perfectly conducting surface. Parameters used in equation (1) are shown.

derived in the time domain by *Uman et al.* [1975] and *Master et al.* [1981], is

$$E(D,t) = \frac{1}{2\pi\epsilon_0}\int_0^{H(t)}\left(-\frac{\sin^2 \alpha}{c^2 R}\frac{\partial I(z',t-R/c)}{\partial t} + \frac{(2-3\sin^2\alpha)}{cR^2}I(z',t-R/c) + \frac{(2-3\sin^2\alpha)}{R^3}\int_{t_b(z')}^{t} I(z',\tau-R/c)d\tau\right)dz', \quad (1)$$

where ϵ_0 is the permittivity of free space, c is the speed of light, $I(z',t)$ is the channel current, the lower integral limit $t_b(z')$ is the time at which the current is "seen" by the observer to begin at the channel section at height z' and the upper integral limit $H(t)$ is the "radiating" length of the channel [see *Thottappillil et al.*, 1997], and other geometrical parameters in (1) are defined in Figure 1. The first term in (1) is called the radiation field. In the frequency (f) domain for an angle α near 90°, the radiation field from an elemental current source is dominant for distances $D \gg (c/\omega) = (\lambda/2\pi)$, where $\lambda = c/f$ and $\omega = 2\pi f$ [e.g., *Kraus and Fleisch*, 1999]. Since the frequencies involved in measured field derivative pulses having widths of the order of 100 ns are certainly above a few hundred kilohertz, the time domain derivative field should be primarily radiation field beyond a few kilometers or so. The electric radiation field intensity is accompanied by a magnetic radiation field (flux density) with the same time domain waveshape and with an amplitude relation $E_{rad}/B_{rad} = c$ for propagation perpendicular to the direction of current flow. For a pure radiation field at a range such that all significant elemental sources have α near 90° and an assumed upward propagating current wave of the form $I(z',t) = I(0,t - z'/v)$ above a perfectly conducting ground plane, the so-called transmission line model, the vertical field derivative on the ground plane a distance D from the source is related to the current derivative at $z' = 0$ by [Uman et al., 1975]

$$\frac{dE(D,t)}{dt} = -\frac{v}{2\pi\epsilon_0 c^2 D}\frac{dI(0,t-D/c)}{dt}, \quad (2)$$

where v is the return stroke speed. Equation (2) has been used to estimate either v or peak dI/dt, given measured peak dE/dt and either measured peak dI/dt or v, respectively [*Leteinturier et al.*, 1990; *Willett et al.*, 1989, 1998; *Krider et al.*, 1996]. There is controversy regarding the validity of (2) because, first, the transmission line model may not be applicable and, if it is in general, it may still not be applicable as early as the time of peak dI/dt [e.g., *Rakov and Uman*, 1998]; second, even if the transmission line model is applicable, the conditions for the validity of (2) may not be met at close range; and third, many estimates of v based on measurements made at close range and the use of (2) are significantly greater than the speed of light, which is physically unreasonable. Additionally, *Depasse* [1994] found that the correlation coefficient between the electric field derivative at 50 m and the causative current derivative for eight events was 0.57 and was not statistically significant (the 95% confidence interval for the correlation coefficient contained zero), as it should be if (2) were valid, although *Leteinturier et al.* [1990] reported a strong correlation between current derivative and field derivative with correlation coefficients of 0.94 for their 1985 data and 0.95 for their 1986 data.

The third term in (1) is called the electrostatic field. In the frequency domain for angles α near 90° the electrostatic field from an elemental source becomes dominant for distances $D \ll \lambda/2\pi$ [e.g., *Kraus and Fleisch*, 1999]. The issue of dominant field components has practical significance beyond the estimation of dI/dt and v because radiation field penetration through apertures in metallic surfaces and coupling to systems such as internal wiring in aircraft is different from electrostatic field penetration and coupling. While, as was previously noted, the radiation electric field has a coupled magnetic field of the same waveshape, the electrostatic field does not have a coupled magnetic field. Rather, for $D \ll \lambda/2\pi$ the lightning current produces a magnetic field that is dominated by its induction component which has a different waveshape from the electrostatic field [*Uman et al.*, 1975; *Rakov et al.*, 1998].

3. Experiment

Electric field derivatives for triggered lightning strokes were measured in north central Florida at the International Center for Lightning Research and Testing at Camp Blanding [e.g., *Uman et al.*, 1997; *Rakov et al.*, 1998] during 1998 by using flat plate antennas terminated in 50-ohm resistors followed by fiber-optic links and digitizers. The antennas were very similar to the antennas used by *Leteinturier et al.* [1990] in 1985 and 1986 and *Depasse* [1992, 1994] in 1990-1991 except that ours and Depasse's were installed on the ground, whereas Leteinturier et al.'s were mounted on top of metal structures of about 3-m height. Our antenna system, in response to an input square wave with a zero-to-peak risetime of about 4 ns, produces an output derivative of the square wave, an "impulse," whose zero-to-peak risetime is 3.8 ns. Since the maximum slope of the input square wave probably occurs in the 1- to 3-ns range of the 4-ns square wave risetime, the derivative measurement system output risetime to an ideal step function input should be 3 ns or less. In different experiments our derivative signals were (1)

Table 2. Electric Field Derivative Characteristics at 10, 14, and 30 m (Camp Blanding, 1998)

Flash	Stroke Order	Bandwidth, MHz	Sampling Rate, MHz	$\lvert dE/dt_{L} \rvert$, kV m^{-1} µs^{-1}	dE/dt_{RS}, kV m^{-1} µs^{-1}	T_{RS}, ns	T_{HPW}, ns	RS Peak Current, kA	RS Peak dI/dt, kA µs^{-1}	RS Speed, m s^{-1}	Observed Surface Arcing	Remarks
						10-m Distance						
S9806	1	20	50	98.3	186	30	30	15.6	48	1.9×10^{8}	yes	two peaks
S9806	2	20	50	33.4	218	60	130	11.5	70	1.6×10^{8}	no	
S9814	1	10	25	80.7	142	30	490	23.8	96	7.4×10^{7}	yes	two peaks
S9818	1	10	25	155	>270	>30	<110	8.4	64		yes	clipped dE/dt_{RS}
S9818	2	10	25	67.3	236	70	130	10.5	55	2.2×10^{8}	no	
S9818	3	10	25	101	>269	>60	<140	18.9	132		no	clipped dE/dt_{RS}
S9819	1	10	25	101	260	70	130	13.0	77	1.7×10^{8}	yes	
S9819	2	10	25	47.1	>272	>70	<130	14.9	101		no	clipped dE/dt_{RS}
S9819	3	10	25	119	>272	>30	<130	22.3	131		yes	two peaks, first clipped
S9819	4	10	25	28.3	234	80	110	7.0	52	2.3×10^{8}	yes	
S9819	5	10	25	56.9	187	70	90	7.3	55	1.7×10^{8}	no	
Mean				80.7	209	60	160	13.9	80.1	1.7×10^{8}		
GM				71.6	205	50	120	12.8	75.2	1.6×10^{8}		for 7 RS, 11 leaders
SD				36.9	37.1	20	140	5.5	29.3	4.6×10^{7}		

Table 2. (continued)

Flash	Stroke Order	Bandwidth, MHz	Sampling Rate, MHz	$\lvert dE/dt_L \rvert$, kV m^{-1} µs^{-1}	dE/dt_{RS}, kV m^{-1} µs^{-1}	T_{RS}, ns	T_{HPW}, ns	RS Peak Current, kA	RS Peak dI/dt, kA µs^{-1}	RS Speed, m s^{-1}	Observed Surface Arcing	Remarks
					14-m Distance							
S9827	1	100	200	118	299	180	250	16.1	45	4.7×10^8	yes	
S9827	2			NR	NR	NR	NR	16.9			no	
S9828	1	100	200	61.5	84.2	60	510	12.8	NR		no	
S9829	1	100	200	63.6	206	40	60	12.8	62	2.3×10^8	NR	
S9829	2			NR	NR	NR	NR	33.2			NR	
S9829	3			NR	NR	NR	NR	10.4			NR	
S9829	4			NR	NR	NR	NR	10.4			NR	
S9831	1	100	200	34.9	173	120	120	9.9	53	2.3×10^8	no	
S9831	2			NR	NR	NR	NR	5.9			no	
S9831	3			NR	NR	NR	NR	10.5			no	
Mean				69.6	191	100	240	13.9	53.3	3.1×10^8		for 4 RS, 4 leaders
GM				63.4	173	80	170	12.6	52.9	2.9×10^8		
SD				30.4	76.8	50	170	7.1	6.9	1.1×10^8		
					30-m Distance							
S9814	1	20	50	21.3	121	170	110	23.8	96	1.9×10^8	yes	two peaks
S9818	1	20	50	29.7	180	80	80	8.4	64	4.2×10^8	yes	
S9818	2	20	50	10.8	121	60	80	10.5	55	3.3×10^8	no	
S9818	3	20	50	21.2	>171	>140	<110	18.9	132		no	clipped dE/dt_{RS}

Table 2. (continued)

Flash	Stroke Order	Bandwidth, MHz	Sampling Rate, MHz	$\lvert dE/dt_L \rvert$, kV m^{-1} µs^{-1}	dE/dt_{RS}, kV m^{-1} µs^{-1}	T_{RS}, ns	T_{HPW}, ns	RS Peak Current, kA	RS Peak dI/dt, kA µs^{-1}	RS Speed, m s^{-1}	Observed Surface Arcing	Remarks
S9819	1	20	50	17.1	143	60	130	13.0	77	2.8×10^8	yes	
S9819	2	20	50	13.9	>169	>140	<110	14.9	101		no	clipped dE/dt_{RS}
S9819	3	20	50	26.3	>168	>70	<120	22.3	131		yes	clipped dE/dt_{RS}
S9819	4	20	50	4.6	109	120	100	7.0	52	3.1×10^8	yes	
S9819	5	20	50	10.4	107	60	60	7.3	55	2.9×10^8	no	
S9822	1	100	200	73.2	226	50	180	30.4	152	2.2×10^8	yes	
S9822	2			NR	NR	NR	NR	11.4			no	
S9822	3			NR	NR	NR	NR	14.1			no	
S9822	4			NR	NR	NR	NR	22.7			no	
S9822	5			NR	NR	NR	NR	<5			no	
Mean				22.9	144	90	110	14.0	91.5	2.9×10^8		
GM				17.8	139	80	100	12.7	85.0	2.8×10^8		for 7 RS, 10 leaders
SD				18.3	41.0	40	40	6.0	34.9	7.0×10^7		

The leader peak derivative value, dE/dt_L, is always negative (its absolute value is given). RS, return stroke; T_{RS}, zero-to-peak risetime of the RS derivative waveform; T_{HPW}, width at half of peak value of the RS derivative waveform; GM, geometric mean; SD, standard deviation; NR, not readable or no record. Other quantities are well known. Clipped waveforms were not used in computing mean, GM, and SD values. RS speed was estimated using equation (2). dI/dt was obtained by numerical differentiation of current waveforms.

digitized at a sampling interval of 5 ns with no antialiasing filter, (2) digitized at 20 ns following a 20-MHz antialiasing filter, and (3) digitized at 40 ns following a 10-MHz antialiasing filter. In all experiments except 3 we used Nanofast fiber-optic links with a 3-dB bandwidth of 270 MHz. For 3 we used a Meret fiber-optic link with a 3-dB bandwidth of about 10 MHz. The digitizing oscilloscopes used were manufactured by LeCroy and by Nicolet. Sampling rates and bandwidths for the recorded data are listed in Table 2. Since without an antialiasing filter the system bandwidth was near or above 100 MHz, the data sampled at 5 ns (200 MHz) were potentially subject to some aliasing, but as we shall see in the next section, the derivative waveforms do not contain frequencies much above 20 MHz, so that from a practical point of view there were no observable effects of aliasing. In 1998, lightning was triggered from a 5-m-tall ground-based launcher topped with a 5-m vertical rod for a total launch structure height of 10 m for part of the experiment (flashes S9806-S9819) and a 5-m launcher height plus 1-m vertical rod for a total height of 6 m for the other part (flashes S9822-S9831). The 10-m structure was grounded by three interconnected 8-foot (about 2.5 m) vertical ground rods with a total measured low-current, low-frequency grounding resistance of 350 ohms, and the 6-m structure was grounded by one 60-foot (about 18.5 m) ground rod plus three 8-foot (about 2.5 m) ground rods with a total low-current, low-frequency grounding resistance of 58 ohms. The return stroke current in the triggered flashes was measured at the launcher with a noninductive shunt having a 45-ns risetime, and the current waveform was sampled at a 40-ns interval (25-MHz sampling rate). The upper frequency response for the current measurement was about 8 MHz. Additional information on the various measuring systems used at Camp Blanding is given by *Uman et al.* [1997] and *Rakov et al.* [1995, 1998].

4. Data

All return strokes observed lowered negative charge to Earth. A summary of the statistical characteristics of our electric field derivative measurements at distances of 10, 14, and 30 m is given in Table 1. A detailed characterization is found in Table 2. Definitions of the measured parameters in Tables 1 and 2 are found in Figure 2. Note that both the electric field and its derivative initially have a negative (atmospheric electricity sign convention) excursion that is due to the dart leader's transferring negative charge downward along its channel toward Earth. The positive peak in the derivative following the initial negative (leader) part of the electric field derivative waveform is related to the effective transfer of leader charge to Earth by the return stroke after the leader attaches to Earth. Note also from Figure 2 that we assume that the return stroke begins at the time the field derivative waveform crosses zero, that is, when the electric field intensity waveform begins to increase after the minimum point of the V-shaped leader-return stroke electric field waveforms shown in Figure 3. Figure 3 shows examples of measured electric field derivatives and the corresponding numerically calculated (by integration) electric field intensities at distances of 10, 14, and 30 m. The source currents are also shown. Our return stroke derivatives typically have a zero-to-peak risetime of 50 to 100 ns (minimum of 30 ns and maximum of 180 ns), a single dominant peak, a width at half-peak value of 100 to 200 ns, and a gradual decay to zero after the peak in a few hundred nanoseconds, as is evident in Table 2 and Figure 3. For some events we obtained electric field derivative data at the same distance with two different systems having 10- and 20-MHz upper frequency responses and 25- and 50-MHz sampling rates, respectively. We could not visually discern a significant difference between the two measured data sets. Nevertheless,

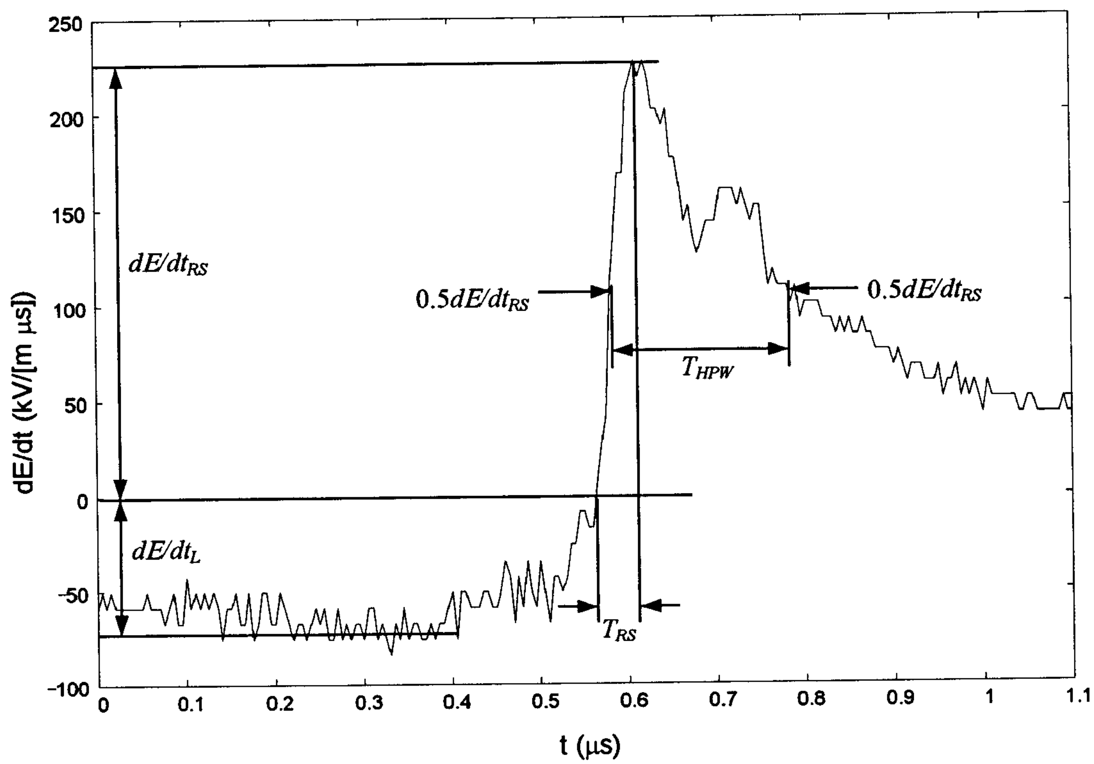

Figure 2. Example of electric field derivative waveform on which the measured parameters given in Table 2 are defined. The waveform is recorded at a distance of 30 m for stroke 9822-1 at Camp Blanding, Florida.

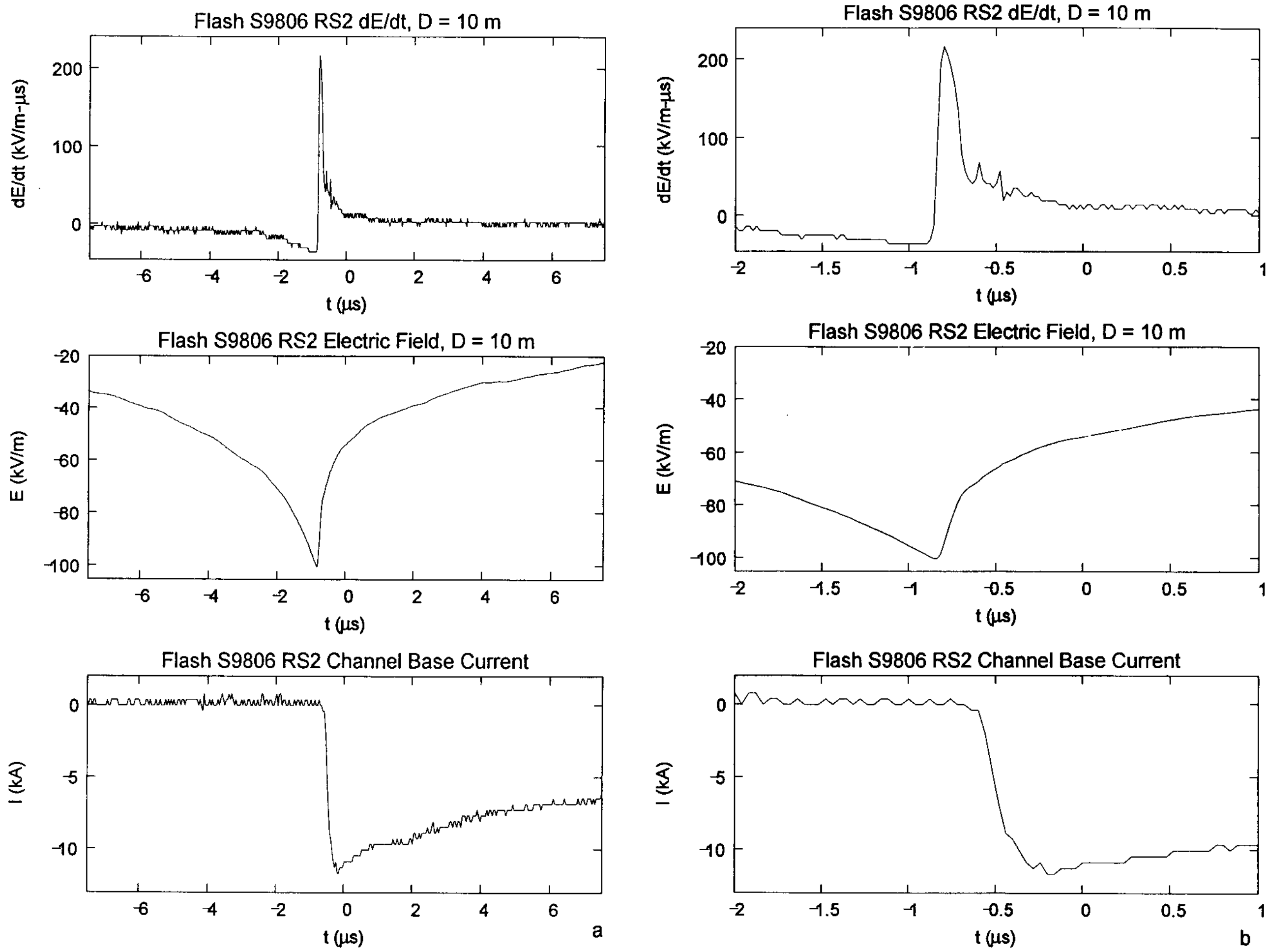

Figure 3. Directly measured time derivatives of the electric field intensity dE/dt, shown on 15-μs and 3-μs time scales, for (a, b) stroke 9806-2 at 10 m, (c, d) stroke 9829-1 at 14 m, and (e, f) stroke 9818-2 at 30 m along with the electric field intensity E obtained by integration of the derivative signals and the measured return stroke current I. No attempt was made to accurately align the E and I waveforms.

we use only the 20-MHz data when both 20-MHz and 10-MHz data are available because numerical low-pass filtering of representative samples of our 20-MHz data to simulate 10-MHz data indicated some degradation of the peak derivative values. The degradation was from a few percent for waveforms of 100 ns or greater half-peak widths to 30% for the smallest half-peak width of 30 ns (stroke 9806-1). Note from Table 2 that some derivative waveforms at 10 m were recorded only with a 10-MHz bandwidth system, and since in those cases the measured half-peak widths were near or greater than 100 ns, no significant degradation of the peaks is expected to have occurred. In Fourier-analyzing our 100-MHz data, we found that the amplitude of the frequency spectrum of the derivative waveforms above about 20 MHz was 2 orders of magnitude below the peak amplitude. Thus most of the significant frequency content of the field derivative signal is below 20 MHz or so.

In Table 2 we give return stroke peak derivative values for only the first peak in the overall derivative waveform if there is more than one peak. The presence of multiple peaks is noted in the table. Our arithmetic mean peak derivative value for seven return strokes at 30 m is 144 kV m^{-1} μs^{-1}, for four strokes at 14 m is 190 kV m^{-1} μs^{-1}, and for seven strokes at 10 m is 209 kV m^{-1} μs^{-1}. The geometric mean values are not much different from the arithmetic means. Note from Table 2 that seven waveforms, four at 10 m and three at 30 m, were clipped (saturated) and that the clipping level was about 270 kV m^{-1} μs^{-1} at 10 m and about 170 kV m^{-1} μs^{-1} at 30 m. The clipped waveforms are not included in the statistical analyses. Thus the means for the return strokes given in Table 2 for 10 m and 30 m are necessarily underestimates. Further, ground surface arcing or other phenomena occurring in concert with ground arcing apparently affected some waveforms, complicating their structure and perhaps changing their amplitudes. Arcing that was identified in 16-mm framing camera or video records is noted in Table 2. The field derivative waveforms at 10 and 30 m shown in Figure 4 are produced by event 9814-1 which exhibited ground arcing. The waveforms have two peaks 300 ns apart at both 10 and 30 m, followed in only the 10-m waveform by an additional peak 6 μs later. The plotted waveforms are normalized to the amplitude of the second peak. The amplitudes of the first peaks at 10 and 30 m were not much different (Table 2), although the 10-m peak could have been degraded by the 10-MHz bandwidth, whereas for the peaks 300 ns later (data not listed in Table 2) the 10-m peak was about a factor of 2 greater, as is characteristic of the single-peaked waveforms. For the four examples of derivative waveforms measured simultaneously at 10 and 30 m for which there was no

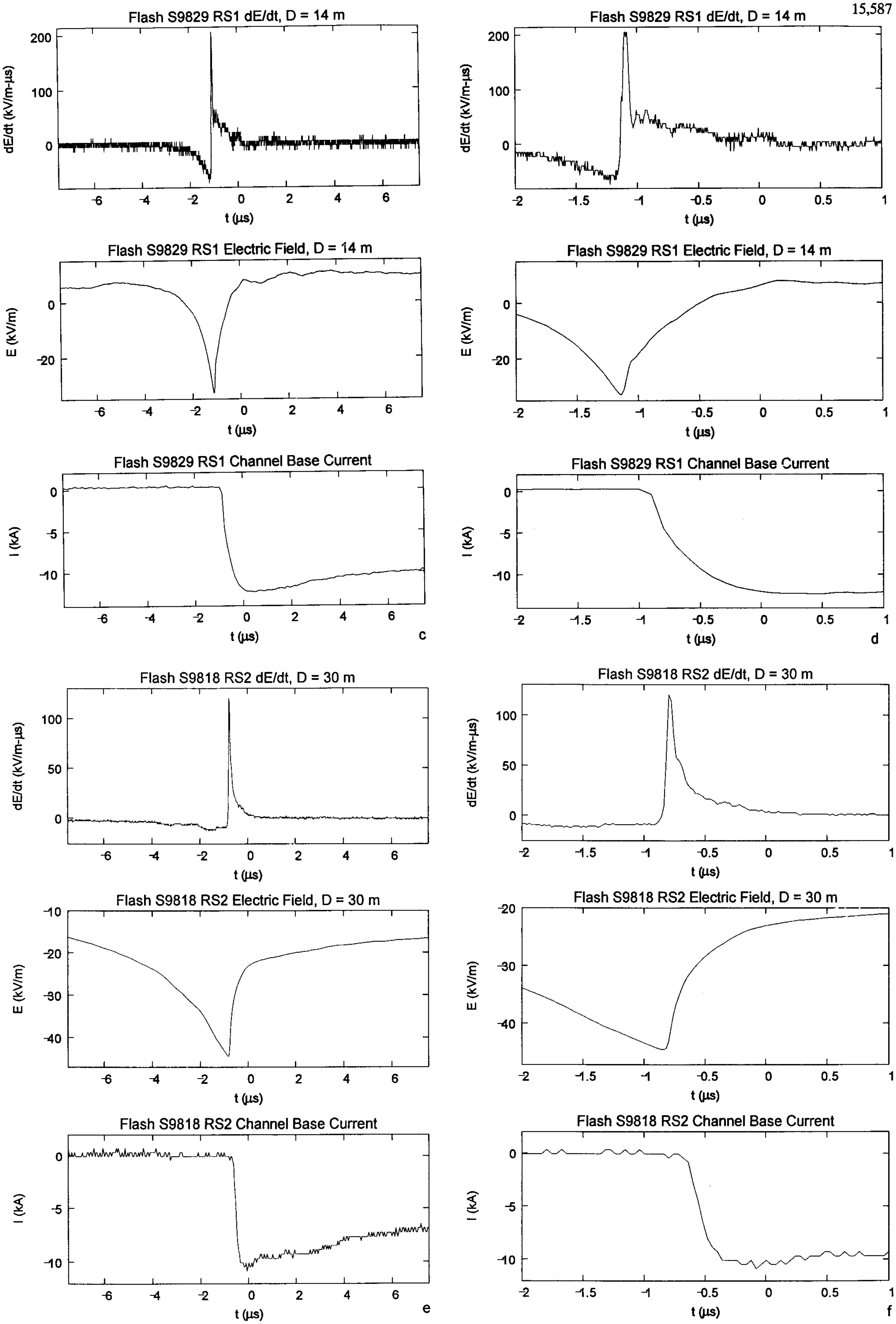

Figure 3. (continued)

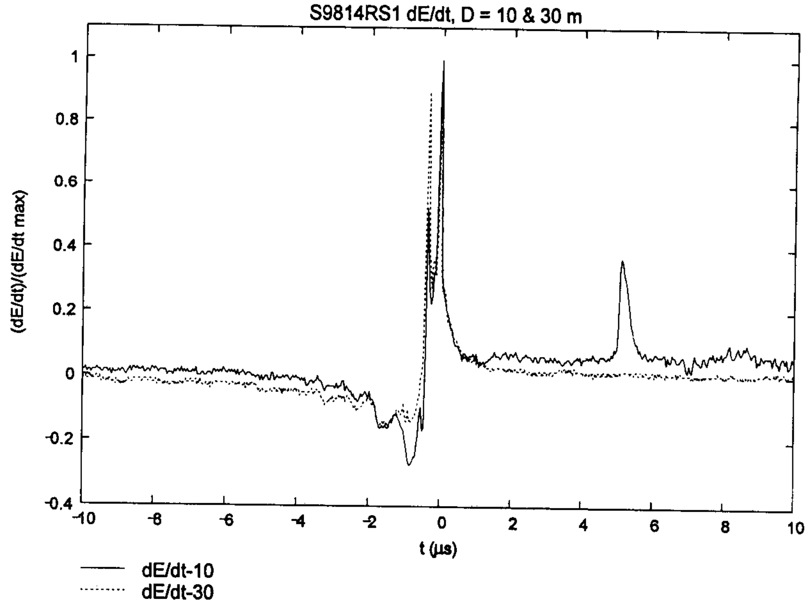

Figure 4. Overlay of the 10-m and 30-m electric field derivative waveforms for stroke 9814-1. Note that the 10-m waveform has the larger leader field change and an additional peak 6 μs after the primary return stroke double peak. Data are normalized to the second of the two peaks. Values for the first peaks are found in Table 2.

saturation or apparent influence of ground arcing (events 9818-2, 9819-1, 9819-4, and 9819-5), there is essentially no difference in the return stroke portion of the waveshapes at 10 and 30 m, and the 10-m amplitudes are about twice the 30-m amplitudes (see Table 2). The fact that individual return stroke field derivative waveshapes do not vary much between 10 m and 30 m is illustrated in both Figure 4 and Figure 5. Our derivative peak values vary from a minimum of 84 kV m^{-1} μs^{-1} (at a distance of 14 m) to a maximum of 299 kV m^{-1} μs^{-1} (also at a distance of 14 m) excluding the saturated waveforms at 10 m and 30 m We did not observe such small derivative values as those reported by *Rubinstein et al.* [1992], 8 kV m^{-1} μs^{-1} at 30 m, and *Depasse* [1994], 4.6 kV m^{-1} μs^{-1} at 50 m. Our derivative peaks normalized to 100 km (assuming the field derivative is inversely proportional to distance, as it would be for a radiation field propagating over a perfectly conducting earth) are 43 V m^{-1} μs^{-1}, 27 V m^{-1} μs^{-1}, and 21 V m^{-1} μs^{-1} for the 30-m, 14-m, and 10-m data, respectively. The mean zero-to-peak risetime is 90 ns at 30 m, 100 ns at 14 m, and 60 ns at 10 m. The mean derivative pulse width at half-peak value is 110 ns at 30 m, 240 ns at 14 m (or 140 ns if the one unusually large value, 510 ns, is excluded), and 160 ns at 10 m. Our 30-m mean peak

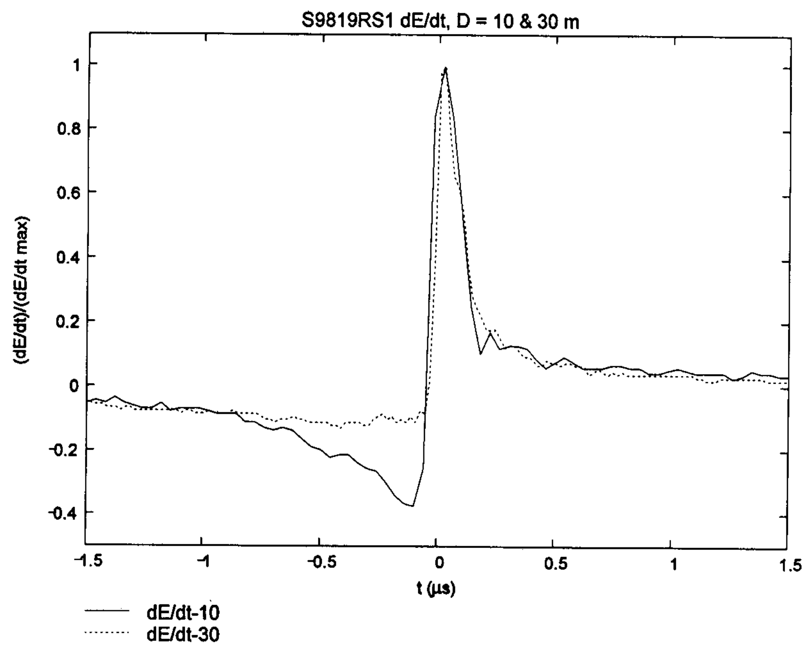

Figure 5. Overlay of the 10-m and 30-m electric field derivative waveforms for stroke 9819-1 normalized to the peak values. Values for the peaks are found in Table 2.

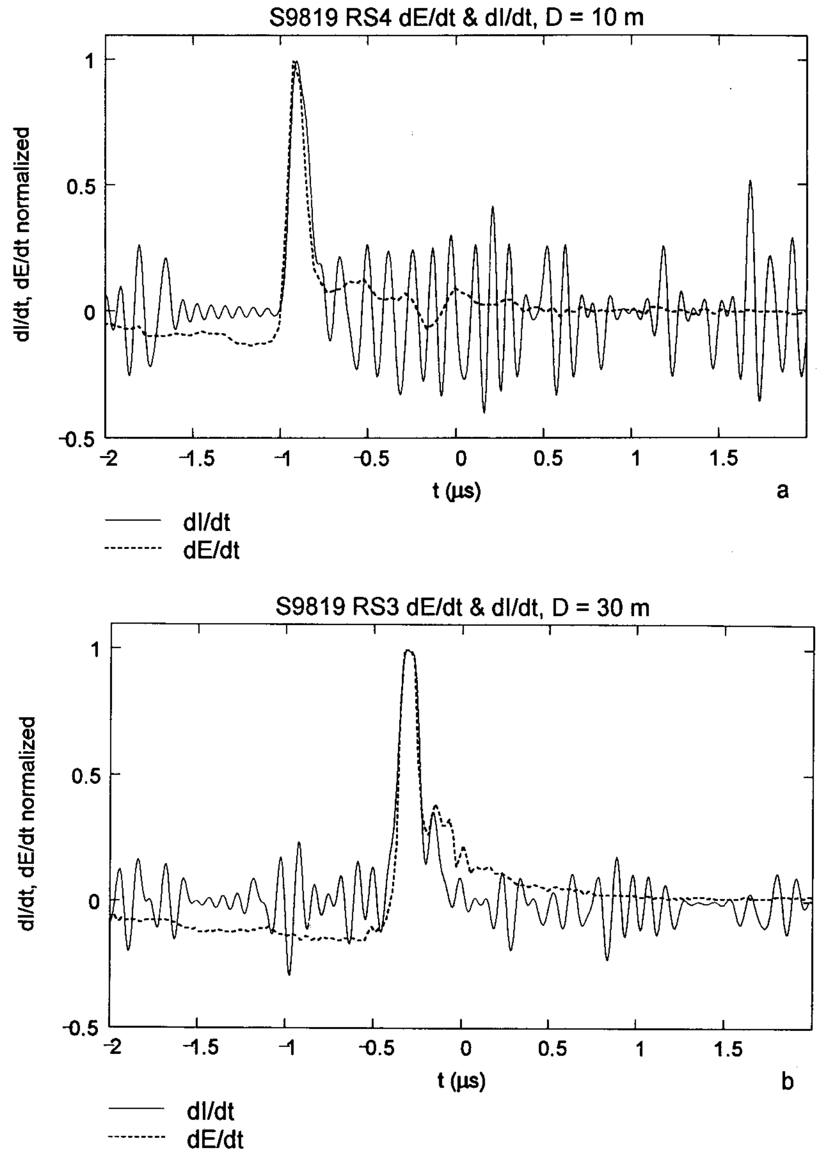

Figure 6. Overlays of current derivative and the electric field derivative waveforms for (a) stroke 9819-4, dE/dt at 10 m and (b) stroke 9819-3, dE/dt at 30 m.

derivative value normalized to 100 km, 43 V m^{-1} μs^{-1}, is less than *Leteinturier et al.*'s [1990] normalized Florida 50-m value, 65 V m^{-1} μs^{-1}, but similar to *Krider et al.*'s [1996] and *Willett et al.*'s [1989, 1998] normalized distant first stroke values. Our 10- and 14-m normalized peak derivative values are almost a factor of 2 smaller than our 30-m data, possibly because of the biases from signal saturation and/or small data samples. Our typical half-peak widths, 100 to 200 ns, appear to be not much different from those for the 50-m waveforms shown by *Leteinturier et al.* [1990] even though our ranges are smaller, 10 to 30 m, but we have observed individual widths both considerably smaller, 30 ns (although this waveform appears to be associated with ground arcing) and 60 ns, and considerably larger, 510 ns (Table 2).

Figure 6 shows two examples of current derivative waveforms overlaid on electric field derivative waveforms. The current derivatives were computed numerically from the directly measured currents via a zero-insertion interpolation technique [*Stearns and David*, 1988]. Despite both the noisy nature of the computed derivatives and the fact that there could have been some degradation in the current derivative waveforms due to the 8-MHz bandwidth of the current-measuring system, we nevertheless find current and return stroke field derivatives to be similar in waveshape, at least to the time of half-peak value on the tail. Table 2 contains the peak current derivative data and the return stroke speeds calculated from equation (2). For 17 strokes we find a mean speed of 2.5 x 10^8 m s^{-1} with a standard deviation of 1 x 10^8 m s^{-1}. The correlation coefficient for peak current derivative and peak field derivative for the 17 strokes is 0.53 and is significant.

5. Discussion

5.1. Comparison With Kennedy Space Center and St. Privat d'Allier (France) Data

In this section we will compare both electric field derivative measurements and electric field measurements from lightning

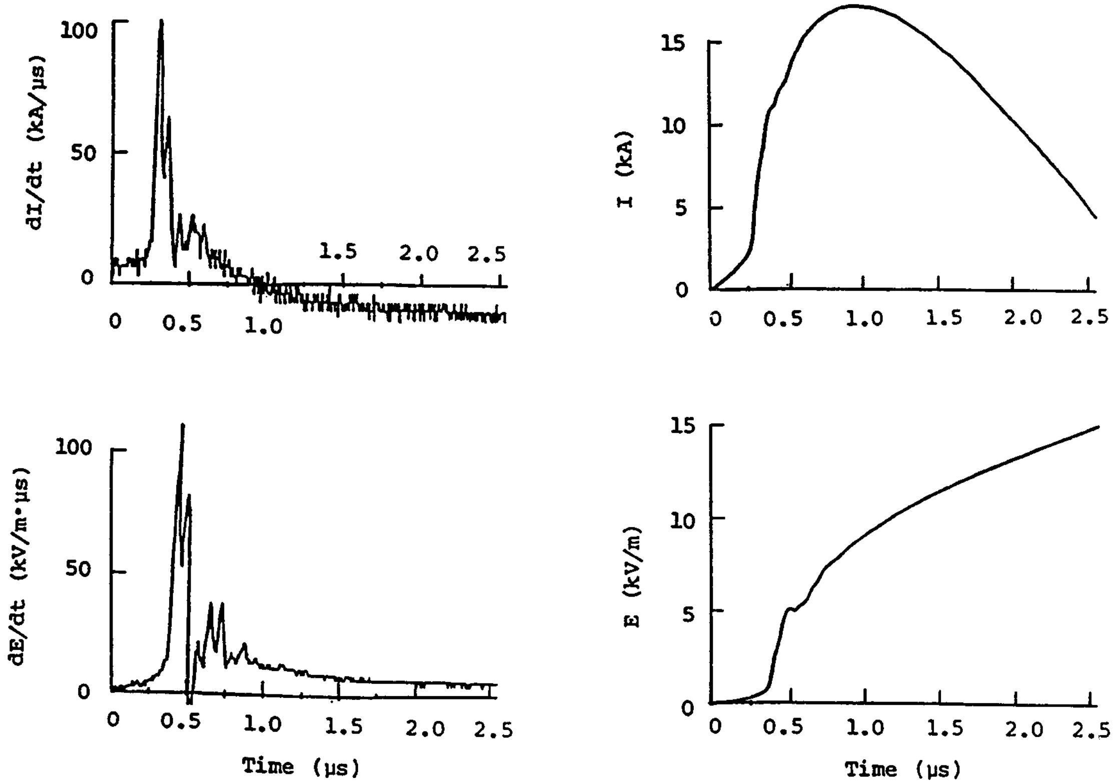

Figure 7. Example of measured *dI/dt* and *dE/dt* at 50 m for a return stroke triggered during the 1985 experiment at Kennedy Space Center, Florida, event 8504d (July 17, 1909:51.234 UT). Numerical integrations of both derivative signals are shown at right. Adapted from *Leteinturier et al.* [1990].

triggered at different sites and present evidence to show that the differences between our waveforms and the 1985 waveforms from the Kennedy Space Center of *Leteinturier et al.* [1990] are due to the effects of the relatively large launch structure at the Kennedy Space Center.

The triggering installation in 1985 at the Kennedy Space Center was a 15.5-m-high metallic structure mounted centrally on a metal meshwork of 4.5-m height and 15 m x 15 m base, whereas ours at Camp Blanding was smaller, a 5-m-high set of eight launch tubes which for part of the experiment had a 5-m rod on top and for part a 1-m rod (see section 3). The launch site for the data of *Leteinturier et al.* [1990] in France in 1986 was similar to ours at Camp Blanding. Another difference between the different launch sites was the grounding resistance. The low-current, low-frequency grounding resistance of the 1985 launch structure at the Kennedy Space Center was reported to be 0.12 ohm and in France in 1986 was about 10 ohms, while the grounding resistance in our Camp Blanding, Florida, study was larger: 350 ohms for part of the experiment (flashes S9806 to S9819) and 58 ohms for the other part (flashes S9822 to S9831).

Typical field and field derivative waveforms from *Leteinturier et al.* [1990] and *Weidman et al.* [1986] for triggered lightning at 50 m from the 1985 Kennedy Space Center studies and from *Krider et al.* [1996] for natural lightning over the Atlantic Ocean at 30 to 50 km are shown in Figures 7 and 8, respectively. *Leteinturier et al.* [1990] apparently assume that the return stroke begins at the bottom of the negative excursion of the electric field derivative associated with the leader, whereas we, as noted in the previous section, assume that the return stroke is initiated when the electric field derivative is zero. From extrapolating the data on leader peak field derivative and return stroke peak field derivative in Table 2 and Figure 3, we infer that there is probably not more than a 10% or so difference on average in the results at 50 m using the two different definitions, but there is a more significant difference in using the different definitions at closer ranges: at 30 m the leader derivative peak is on average about 15% of the return stroke derivative peak, and at 10 and 14 m it is between 35 and 40%. For event 9828-1 at 14 m, the leader field derivative is more than 70% of the return stroke field derivative. *Rakov et al.* [1998] were apparently the first to note that leader and return stroke field derivatives can be comparable at very close range.

The field derivative waveforms from the 1985 Kennedy Space Center experiment often have a prominent double peak followed by a rapid downward excursion and zero crossing, as illustrated in Figure 7, whereas our field derivative waveforms generally have a single peak and a more gradual decay to zero with no zero crossing, as illustrated in Figure 3. The Kennedy Space Center current derivative waveforms of *Leteinturier et al.* [1990] and *Weidman et al.* [1986] also exhibit double peaks similar to their field derivative waveforms (Figure 7). The one 1986 French field derivative example shown by *Leteinturier et al.* [1990], from a launcher of similar size to ours, does not exhibit a zero crossing like their Kennedy Space Center data but rather remains positive after the peak, similar to our data in Figure 3. *Depasse* [1992] in his Ph.D. dissertation presents eight electric field derivative waveforms (one of which is reproduced by *Depasse* [1994]) obtained in 1990 and 1991 in France, three for events triggered from a ground-based launcher and five for events triggered from a launcher placed on a 15-m-

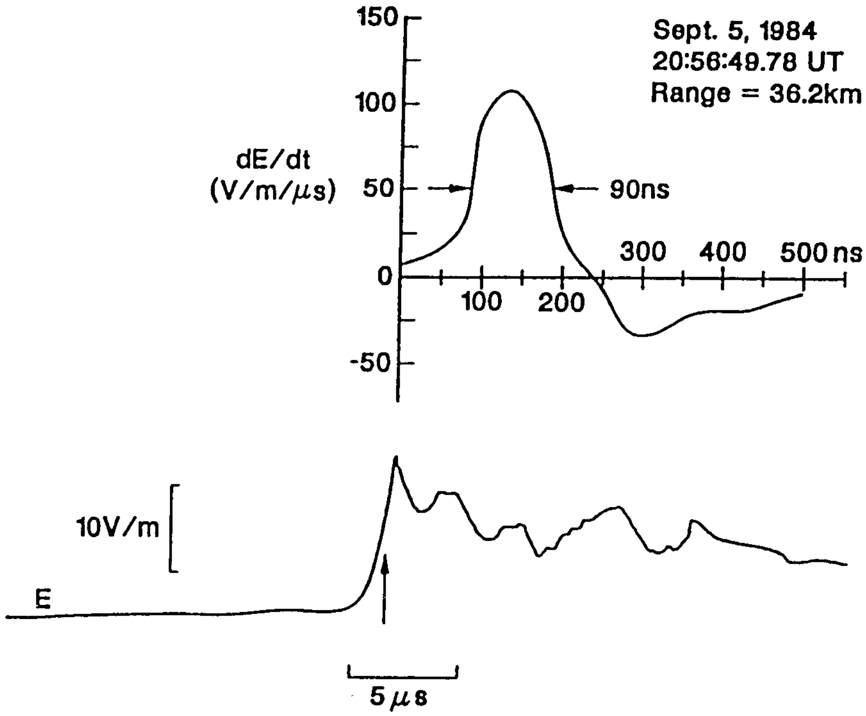

Figure 8. Examples of (top) the time derivative of the electric field intensity *dE/dt* and (bottom) the electric field intensity *E* produced by a first return stroke at a distance of 36 km over the Atlantic Ocean. The propagation path was almost entirely over salt water. The vertical arrow under the *E* record shows the time of the *dE/dt* trigger. Adapted from *Krider et al.* [1996].

high tower. None of the three ground-based launcher derivative waveforms exhibits the zero crossing, while two out of five tower launcher waveforms do, one does not, and the remaining two show a pronounced dip that results in a shoulder in the electric field waveform. From the evidence above, it appears that the electric field derivative waveform for lightning triggered from large launch structures differs from that of small structures in that the waveforms from large structures can exhibit zero crossings.

Further evidence of the differences in the radiated fields between large and small launch structures is seen in the electric field waveforms. Our observed electric field intensity waveforms at 10, 14, and 30 m (and those of *Rubinstein et al.* [1992, 1995] at 30 m and of *Rakov et al.* [1998] at 30, 50, and 110 m, all obtained using small launchers) do not exhibit the initial peak within the first few hundred nanoseconds superimposed on the rising portion of the electric field waveforms, as is seen in the 1985 Kennedy Space Center data (Figure 7). These Kennedy Space Center electric field waveforms were computed from the field derivative data that exhibited a zero crossing, a change in the sign of the derivative, leading to the initial electric field peak. A similar initial electric field peak is seen in the one example of a direct field measurement at 50 m in France given by *Depasse* [1994] for a flash triggered from a launch structure similar in height to the 1985 Kennedy Space Center launch structure. *Leteinturier et al.* [1990] state that their 1986 French electric fields obtained by integrating derivative waveforms for lightning triggered from a launch structure similar in size to ours showed "no clear peaks." Thus both the initial peaks on the electric field waveforms and the electric field derivative zero crossings would appear to be related to the presence of relatively large launch structures.

While none of our close electric field waveforms exhibit submicrosecond peaks, some of our close field waveforms (e.g., Figures 3b and 3d) do exhibit a slope change near the time at which the Kennedy Space Center waveforms show such a peak. Note also in Figure 7 that *Leteinturier et al.*'s [1990] currents, obtained by numerical integration of their measured current derivatives, have a pronounced discontinuity in slope at the same time their electric fields have the initial peak, similar data being shown by *Weidman et al.* [1986], while some of our current waveforms show a similar but more subtle slope discontinuity at the time of the electric field slope change (e.g., Figures 3b and 3d). Triggered lightning current waveforms having a similar slope discontinuity are also shown and discussed by *Leteinturier et al.* [1991] from the 1987 and 1988 Kennedy Space Center triggered lightning studies and shown in Figure 7 of *Willett et al.* [1988] from the 1986 triggered lightning experiments in France. Clearly, the salient features of the electric field waveforms are determined by the behavior of the return stroke current. The fact that the current waveform measured at the channel base often exhibits an initial rise to peak composed of a higher rate of change portion followed by a lower rate of change portion (a convex front) is indicative of important physics that is presently not understood. Perhaps the current slope discontinuity is due to return stroke current reflections within the upward connecting leader/grounded launch structure system, as discussed by *Leteinturier et al.* [1990] in attempting to explain the initial peaks in their electric field waveforms. Alternatively, the current slope discontinuity may be due to the physics of the return-stroke process in the channel, such as the superposition of individual current components from the channel core and from the surrounding corona envelope occurring on different time scales. In either of these two cases, the simple transmission line model would not reproduce well the physical processes involved.

Leteinturier et al. [1990] attribute the initial peak in their electric field records from the Kennedy Space Center to the fact that the return stroke starts at the top of the launch structure and propagates both upward and downward, with the downward current wave producing the field peak when it reflects off ground. They suggest that the multiple peaks in their derivative waveforms are associated with reflections over 10-m distances, 10 m being roughly the distance between the top of the Kennedy Space Center launch structure and the current-measuring devices which were themselves about 10 m above the ground. An additional hypothesis on the origin of the multiple peaks in the field derivative waveforms of *Leteinturier et al.* [1990] and *Weidman et al.* [1986] (note that their derivative waveforms did not always exhibit multiple peaks) can be constructed from the observation in our experiments that multiple derivative peaks sometimes occur in situations when there is ground surface arcing. In describing the 1985 Kennedy Space Center launch structure, *Hamelin et al.* [1986] state "the ground plane was probably not very efficient; one could observe arcs between meshes of the metallic mesh cage during a flash, revealing bad equipotentiality." Additionally, *Rakov et al.* [1998] have shown that ground arcing is associated with the larger return stroke currents which in turn are more likely to be associated with dart-stepped leaders preceding the return stroke. The leader portion of the double-peak waveform presented in Figure 4, which was associated with surface arcing, shows evidence of stepping. Dart-stepped leaders can be branched. A return stroke that encounters a branched leader channel might well produce both a structured electric field due to the channel branching and ground arcing due to the relatively large current injected into the Earth. In this hypothesis, our few structured derivative waveforms and the double-peak field derivative waveforms in the Kennedy Space Center data would be attributed to channel branching effects, although we do not have any optical confirmation of this. If this be true, one would not be able to use a return stroke model with a straight vertical channel, as was done by *Leteinturier et al.* [1990] to derive return stroke properties such as upward propagation speed.

5.2. Comparison With German Overland Data

We are unable to add any support to the view of *Heidler and Hopf* [1998] that their relatively small derivative peaks and relatively large derivative half-peak widths (section 1.4, Table 1) are in part due to the fact that the flashes they observed in Germany terminated on land as opposed to the strikes to water in the studies of *Le Vine et al.* [1989], *Krider et al.* [1996], and *Willett et al.* [1998]. Our close electric field derivative data for triggered lightning strikes to land at Camp Blanding are consistent in peak value (normalized to 100 km assuming that the peak is primarily determined by the radiation field component) within a factor of 2 or 3 with the distant natural lightning data for which the lightning struck the Atlantic Ocean (section 1.1, Table 1). The half-peak widths of our close derivative fields are significantly smaller than those of *Heidler and Hopf* [1998], although our mean half-peak widths are a factor of 2 or so larger that those of the more distant measurements of *Le Vine et al.* [1989], *Krider et al.* [1996], and *Willett et al.* [1998].

5.3. Proportion of Radiation Field in Total Field

For distances of 50 m and less, the mean width of the return stroke electric field derivative waveform is a factor of 2 or so greater than that for the derivative measurements obtained at tens of kilometers for natural lightning (Figure 8), after correction is made for propagation effects, and similarly wider than that for the triggered lightning data at 5.16 km with no correction for propagation. The distant waveforms must be primarily radiation field. Thus the fact that the close waveforms are wider than the distant ones could potentially be interpreted as evidence that at least the latter part (after 50 to 100 ns) of the close derivative waveform contains induction and electrostatic field components in addition to radiation. Since radiation field and electrostatic field waveshapes are in general different theoretically (see (1)), if both field components were present, one might expect to see discernible changes in slope or other transitions in the overall electric field waveform after the time of derivative peak when the radiation field would be expected to have its largest value. As was noted earlier, the electric field waveforms of some of our strokes do show pronounced slope changes after the derivative pulse peak, examples being found in Figures 3b and 3d. An argument can be made that our derivative waveforms, at least to the time of half-peak value on the tail, are primarily radiation field because, first, they do not appreciably change shape from 10 m to 30 m, whereas if all three field components were present, one might expect some appreciable change in waveshape since each component has, in general, a different distance dependence, although because of the geometrical factors in front of the terms in (1) and the unknown vertical distribution of elemental sources, it is certainly possible that all three field components could vary similarly as a function of distance for very close distances, and, second, individual current derivatives and electric field derivatives appear to be similar in waveshape (Figure 6), as predicted by (2), although the current derivative waveforms are "contaminated" by a relatively large noise resulting from our numerical differentiation of the measured current waveforms. *Leteinturier et al.* [1990] previously argued that the close field derivatives were primarily radiation field because their current derivative and field derivative waveshapes were similar and because the peak values of the two derivatives were strongly correlated (correlation coefficient of 0.94 in 1985 and 0.95 in 1986), as predicted by the transmission line model for radiation fields for the situation when return stroke speeds do not vary much from stroke to stroke. In our data, while the current derivative and field derivative waveshapes appear to be similar, there is no clear relationship between the individual current derivative and field derivative peak values, the correlation coefficient for 17 strokes being 0.53, similar to the correlation coefficient of 0.57 for 8 strokes found by *Depasse* [1994].

A further argument for the close derivative waveform being primarily radiation can be made from the data of *Weidman et al.* [1986] and *Hamelin et al.* [1986]. *Weidman et al.* [1986] in their Figure 7 and *Hamelin et al.* [1986] in their Figures 9 and 14 give electric field derivative waveforms simultaneously measured for two return strokes at 50 m and 5 km. For the stroke where there appears to be only slight saturation of the 5-km derivative, the waveforms are similar, with two peaks and a zero crossing at about 200 ns, implying that the 50-m waveform contains a significant radiation field component since the 5-km waveform must be primarily radiation field. For this stroke the ratio of the field derivative peaks at the two distances is less than about 150, with the 5-km peak being underestimated owing to saturation, and *Weidman et al.* [1986], presumably describing both their Figure 7 and six similar additional measurements not shown in the paper, state "the ratio between the *dE/dt* measurements 50 m and 5 km away from the discharge is very nearly as 100, which is the range ratio," the ratio that would be expected for a radiation field. On the other hand, *Leteinturier et al.* [1988] and *Leteinturier and Hamelin* [1990] report for all their data (they do not consider simultaneous measurements at 50 m and 5 km for individual events) that the ratio of the field derivative to the current derivative at 5 km (normalized to 100 km) from 1987 obtained by using a small launcher differs considerably from the same ratio at 50 m (similarly normalized) from 1985 obtained by using a large launcher, with the 1985 tower launcher field derivative to current derivative ratio being similar to that for the 1986 measurements in France, where a smaller launcher was used.

The proportion of electrostatic and induction field components relative to the radiation field component in general increases with decreasing distance, at least to the distance at which the geometry and the fact that the source is moving upward and away from the antenna affects the three field components differently from the case when all channel source points are roughly equidistant from the measurement point, as follows from (1). For an elemental current source radiating in free space at a frequency of about 3 MHz, consistent with a field derivative width at half-peak value of 150 ns, and an angle α near 90°, the radiation field and the electrostatic field are theoretically equal at about 20 m, $\lambda/2\pi$, where $\lambda = 100$ m. Thus to the extent that the return stroke can be approximated by such an elemental current source radiating near 3 MHz, it can be argued from basic electromagnetic theory that there is no dominant field component in the derivative pulse. On the other hand, if the dominant or primary frequency in the derivative peak considerably exceeds 3 MHz and/or the distance of the radiating source at the return stroke's primary radiation height considerably exceeds 20 m, the derivative peak value would be composed primarily of the radiation field component to the extent that the source is simple, as described above. To estimate the frequency content of the field derivative pulse, we numerically low-pass filtered our 20- and 100-MHz waveforms to simulate 10- and 5-MHz waveforms. For the narrowest half-peak width, 30 ns (event 9806-1), filtering from 20 MHz to 10 MHz reduced the peak by about 30% and to 5 MHz by about 60%. For typical half-peak widths near 100 ns, 10-MHz filtering of the 20-MHz data reduced the peak signal by a few percent and 5-MHz filtering by about 15%. Similar results were obtained in numerically filtering the 100-MHz data. Clearly, frequency components in the 5- to 10-MHz range contribute significantly to the field derivative peak, supporting the argument that there is considerable radiation field component in the peak.

5.4. Transmission Line Model

Leteinturier et al. [1990] used equation (2), valid only for radiation fields with the angle α in equation (1) near 90°, with simultaneously measured current derivatives and field derivatives at 50 m to calculate return stroke speeds, many of which they found to be near or higher than the speed of light, 3 x 10^8 m s^{-1}, with a mean value of about the speed of light. They discuss several reasons why the speed derived from equation (2) could be about twice that found from optical measurements [see also *Rakov and Uman*, 1998]. From theory, *Baum* [1990] has suggested that return strokes propagate at the speed of light near the very bottom of the return stroke channel and invoked the measurements of *Leteinturier et al.* [1990] to support his hypothesis. However, most optical speed measurements, averaged over hundreds of meters of the channel, are near 1 x 10^8 m s^{-1}. Further, *Wang et al.* [1999b] recently measured the return stroke speed profiles in the bottom 400 m of two triggered lightning return strokes using an optical imaging system with tens of meters spatial resolution and 100-ns time resolution and found the speed at the very bottom of the channel for these strokes to be about one-third and one-half the speed of light, but *Wang et al.* [1999a], in two different triggered lightning strokes, estimated speed values of two-thirds the speed of light and near the speed of light within some tens of meters of the ground. To support the validity of the computed speed values being near the speed of light, *Leteinturier et al.* [1990] used the transmission line model to calculate the ratio of total peak field derivative to the radiation field derivative assuming a current waveform similar to that they observed (a current derivative zero crossing of about 200 ns) and a return stroke speed of 2.5 x 10^8 m s^{-1}. They found the total peak derivative to be 1.1 times the radiation peak derivative, i.e., the derivative peak at 50 m to be essentially radiation field. However, they also calculated that for current derivative waveforms wider than about 200 ns at zero level and/or for speeds lower than 2.5 x 10^8 m s^{-1}, the ratio of total field derivative to radiation field derivative would increase. For example, for a 200-ns zero crossing and a speed of 1 x 10^8 m s^{-1}, the ratio was about 1.4 . *Cooray* [1989], using the transmission line model with a current waveform composed of four linear sections and a return stroke speed of 1 x 10^8 m s^{-1}, calculated that only 40% of the initial peak field was radiation at 50 m. For these last two examples, a larger peak field derivative than that for a pure radiation field due to the presence of electrostatic and induction field components will yield a proportionately larger transmission line speed via equation (2).

As was noted in the previous section, we have used our field derivatives and current derivatives (obtained by numerical differentiation of our current records) with equation (2) to compute the return stroke speeds given in Table 2. For 17 strokes our mean speed was 2.5 x 10^8 m s^{-1}, not too much different from the results of *Leteinturier et al.* [1990], who found a mean of about 3 x 10^8 m s^{-1} for 40 triggered strokes. However, our speeds could be overestimated if we are underestimating the peak current derivative because the upper frequency response of our current measurement system of about 8 MHz has degraded the peak derivative values (section 3). Note also that because of the noise generated in the numerical differentiation of our current waveforms (Figure 6) we introduce errors of the order of 10% in the peak current derivative values.

5.5. Future Research

To understand the characteristics of the electric field derivative, including the contribution from the radiation field component, modeling employing return stroke models other than the transmission line model that was used by *Leteinturier et al.* [1990] and by *Cooray* [1989] may be helpful. Other available models have been discussed, for example, by *Rakov and Uman* [1998]. To model properly, however, one needs to take account, at a minimum, of the effects of the presence of upward connecting discharges above the triggering structure [*Wang et al.* 1999a], of the effects of the triggering structure in supporting current waves, and of the effects of the Earth, waves. Simultaneous measurements of both electric field and magnetic field derivatives at close range may also help to clarify the issue. It is interesting to note that the electric and magnetic field derivatives 200 m from lightning strikes to the Peissenberg tower in southern Germany are very similar while their full widths at half value are significantly greater than the width of the corresponding current derivative [*Zundl*, 1994].

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