Rise Times of Impulsive High-Current Processes in Cloud-to-Ground Lightning

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***Abstract*—Measurements are presented of electric-field derivative (dE/dt) waveforms that were radiated by first and subsequent return strokes, stepped, and dart-stepped-leader steps just before return strokes and "characteristic pulses" in normal (negative) cloud-to-ground lightning under conditions of minimal distortion due to ground-wave propagation. The main dE/dt peaks produced by the fast-rising portions of all of these processes are found to have similar durations [mean full-width at half-maximum (FWHM) ranging from 79 $\pm$ 20 ns for subsequent strokes to 54 $\pm$ 17 ns for stepped-leader steps], although widely differing absolute magnitudes (spanning nearly a factor of four). Field-change (E) signatures of first strokes are examined in greater detail after eliminating the 39% of events with multiple dE/dt peaks during their fast-rising portions. The "slow fronts" beginning these waveforms had durations of 3.7 $\pm$ 1.2 μs and amplitudes 50% $\pm$ 10% of peak E. The latter ratio was uncorrelated with either peak E or peak dE/dt. The range-normalized peak magnitudes of the remaining fast-rising portions of these field changes were well correlated with those of the corresponding dE/dt signatures, whereas the values of FWHM of dE/dt were uncorrelated with peak dE/dt and only poorly correlated with peak E.**

***Index Terms*—Lightning, terrestrial atmosphere.**

I. Introduction

THE temporal structure and peak amplitude of wide-band electric radiation-field (E) and field-derivative (dE/dt) waveforms have been well described in the recent literature for normal (negative) first return strokes in natural cloud-to-ground (C/G) lightning [14], [26], [28], [29], [35] and for negative subsequent strokes in rocket-triggered lightning [5], [15], [17], [24], [32]. The characteristics of waveforms produced by subsequent return strokes [1], [13], [26], [29], leader steps just before the onset of return strokes [1], [11], [13], [26], [29], and pulses within the preliminary-breakdown process [1], [3], [13], [27], [29] in natural C/G flashes are less well known. The most important reason for this deficiency has been the difficulty of obtaining wide-band recordings of events smaller than or subsequent to the first return stroke, without at the same time introducing serious biases due to the digitizer deadtime and/or the finite trigger threshold that was used to record these waveforms ("trigger bias").

Here we will discuss selected characteristics of numerous absolutely calibrated wide-band recordings of natural first and subsequent return strokes, the leader steps that occurred in the few tens of microseconds before the onset of these strokes, and the "characteristic pulses" in the preliminary breakdown process [3], that are available from an experiment in which selective attenuation of the higher frequencies due to ground-wave propagation was minimal. We focus on the relation between rise time and amplitude of the initial fast field variations that are prominent features in the signatures of all of the lightning events mentioned above—a relation that does not appear to be compromised by trigger bias. In the process we note and correct for two important, but poorly recognized, characteristics of the field changes in natural first strokes that complicate this relationship—multiple dE/dt peaks during the onset and extremely narrow E peaks. Looking at the entire class of fast transitions in waveforms radiated by C/G flashes, we present evidence that suggests the rise times of all impulsive, high-current processes in lightning tend to be constant and relatively independent of the magnitude of either the current or the current derivative.

II. Experiment

During 1985, E and dE/dt signatures from offshore lightning were recorded near the NASA Kennedy Space Center (KSC), FL, at a site that was located as close as possible to the Atlantic Ocean so as to minimize the effects of propagation [14], [35]. The locations of the strike points of C/G flashes were obtained from a network of three gated wide-band magnetic direction finders (DFs) operated by the USAF Eastern Space and Missile Center and KSC. The principles of operation of the DFs and the lightning locating system have been described by [10] and [12] and the estimated location accuracy is about 1 km [19]. A map showing the locations of the DF sites and the experiment is given by [34].

The dE/dt signatures were digitized at a sampling frequency of 100 MHz with a bandwidth of better than 30 MHz and an amplitude resolution of 8 b. The E signals were sampled at 10 MHz with about 3-MHz bandwidth and 10-b resolution. The whole system was absolutely calibrated and was triggered on the output of an RF receiver tuned to 5 MHz with a bandwidth of 0.9 MHz. This method has previously been shown to minimize trigger bias [14], [35]. In particular, the Appendix of the latter reference presents detailed evidence that the mean width of the dE/dt peaks is not biased by our triggering technique.

Fast- and slow-E waveforms were used to determine the type of lightning process that produced each dE/dt signature. (Definitions of "fast-E" and "slow-E" recordings have been given by [9].) Although there was a 100-ms deadtime between different events yielding fast-E and dE/dt recordings in a given flash, up to seven such waveform pairs could be recorded within the

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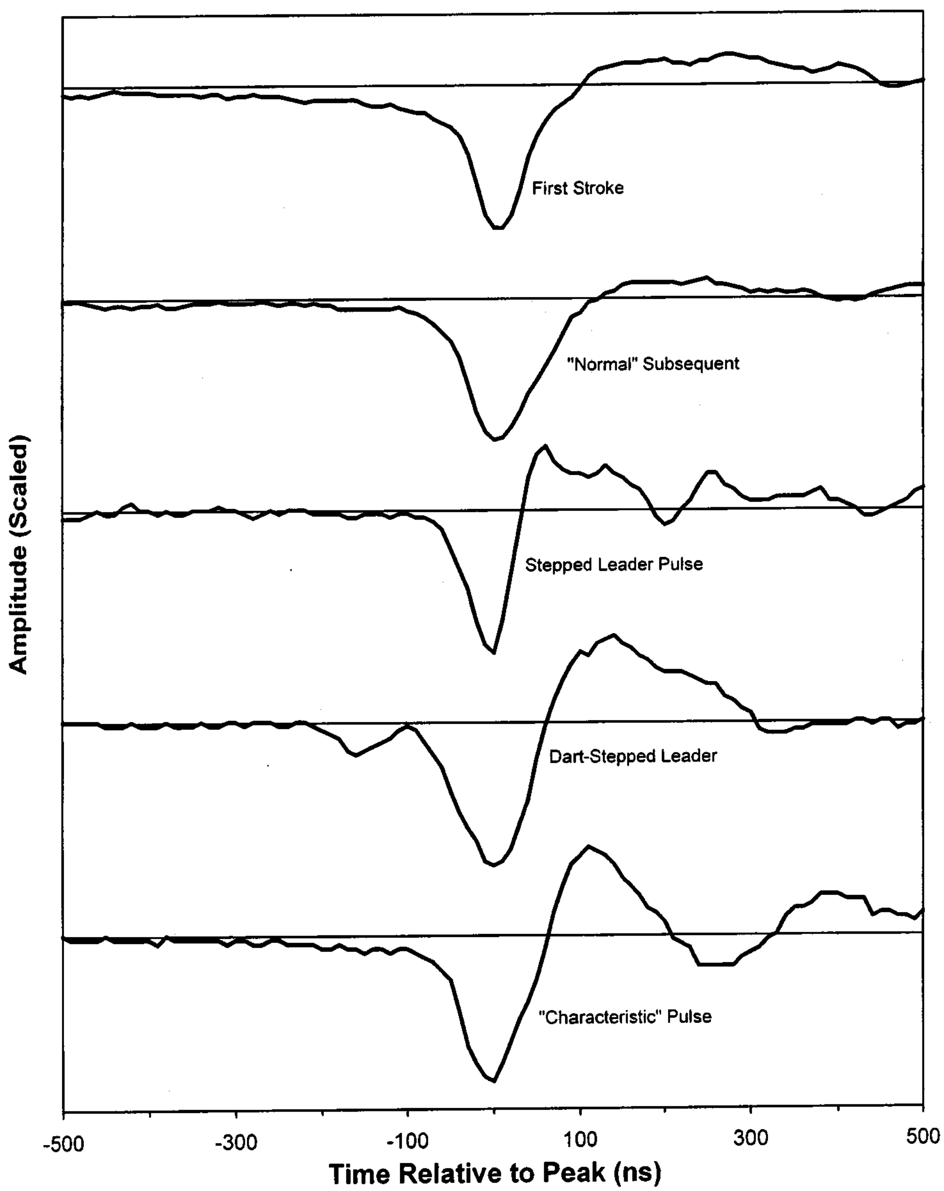

Fig. 1. Examples of observed dE/dt signatures from first and subsequent return strokes, stepped and dart-stepped leader steps, and characteristic pulses. Only 1 μs of time is shown in each case. The amplitudes of the negative-going peaks are all scaled the same. We use the "physics" sign convention, where normal (negative) return strokes produce downward-directed or negative electric-field changes.

duration of each 1.075 s slow-E recording. Examples of various waveforms measured in 1985 and the associated energy spectra have been given in [34]. A block diagram of the digital recording system can be found in [33]. Further details of the data-acquisition system and plots of all waveforms used in this study, have been given by [2] and by [8].

All of the C/G flashes recorded in this experiment effectively lowered negative charge toward ground, hence, they produced downward-directed (negative) electric-field changes, following the normal physics convention. The primary parameters used in this study are the range-normalized peak amplitude $(dE/dt)_p$ and the full-width at half-maximum (FWHM) of the largest negative-going dE/dt pulse that is associated with the (negative) fast-rising portion of each E-field signature. (FWHM is measured here using a linear interpolation between the 100 Megasamples per second of dE/dt data.) Examples of typical dE/dt signatures from first and subsequent return strokes, individual stepped and dart-stepped leader pulses and characteristic pulses are given in Fig. 1. For first return strokes we also consider both the entire (negative-going) fast-field change (E_p) and just the fast-rising portion of this field change (E_f), as illustrated in Fig. 2.

FWHM of dE/dt is preferred over other conventional measures of rise time (e.g., the 10–90% rise time of E) for this study because the former measure emphasizes the fast-rising portion of the field change. FWHM is often poorly correlated with the 10–90% rise time of E, especially in first return strokes, where the slow front generally constitutes a major fraction of the field change. Even rocket-triggered (subsequent) return strokes display a poor correlation between these two parameters, however,

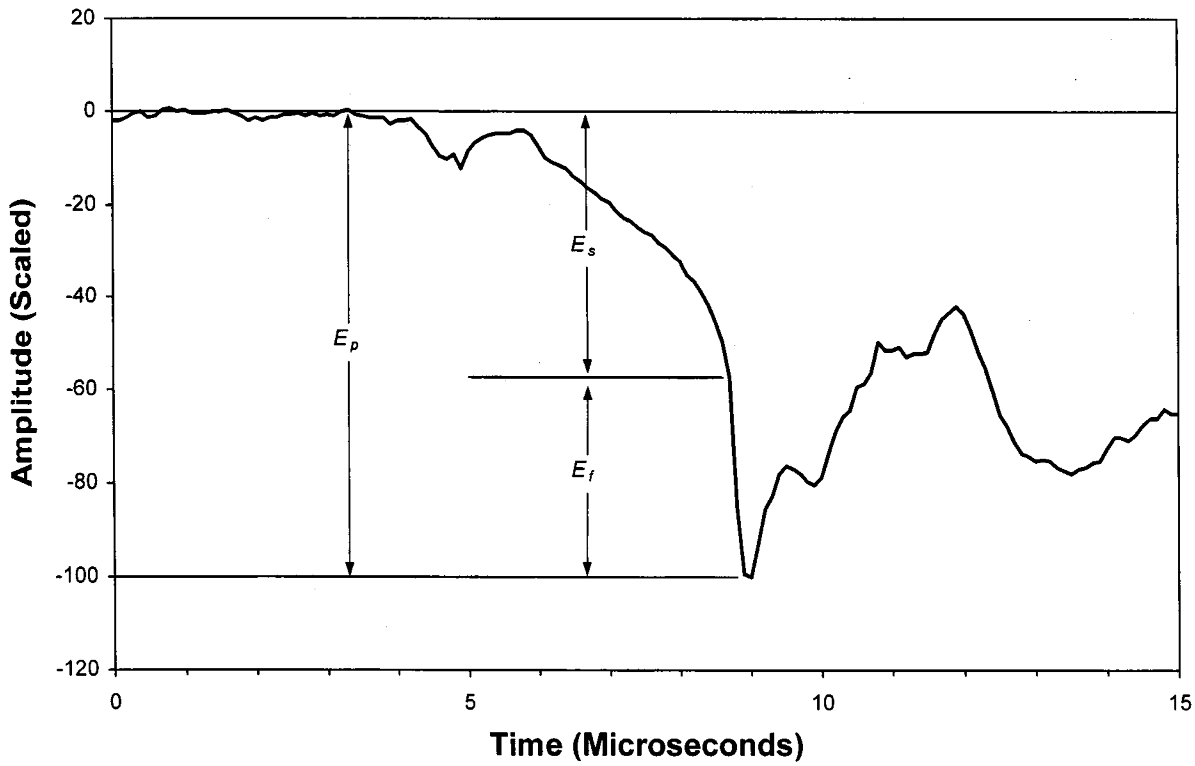

Fig. 2. Illustration of the definitions of the slow front E_s and the fast-rising portion E_f of the entire (negative-going) fast-field change E_p for a normal (negative) first return stroke. 15 μs of this fast-E waveform are shown. The peak amplitude is scaled to 100 units.

correlation coefficient only -0.089 for the 28 strokes reported by Willett *et al.* [32], where mean 10–90% rise time exceeds mean FWHM by a factor of six.

Essentially the same data set used in the present study has been previously analyzed in the frequency domain by Willett *et al.* [34], who also plotted maps of the lightning locations in the storms of interest (August 8, 10, and 14). Willett *et al.* [34] also pointed out, based on the similarity of the spectra, that the time-domain dE/dt waveforms of all fast-rising lightning processes might be similar, but this hypothesis has apparently not been explored further in the literature. Except for the first return strokes, which were discussed in detail by Willett *et al.* [35], the time-domain statistics of these data have only received a preliminary overview by Bailey *et al.* [1]. No obvious differences among the three storm days have been observed.

III. Results

A study of Fig. 1 suggests that on this highly resolved time scale, the measured dE/dt signatures of all the lightning processes discussed here are remarkably similar, at least with regard to the shape of the main negative-going peak. (Although it is conceivable that this similarity is due to all of the dE/dt waveforms' being degraded to the same width by propagation over the ocean surface and the narrow strip of beach between our antennas and the source [e.g., [4]], we think this unlikely. For rocket-triggered return strokes recorded during a very similar campaign but with a significantly longer overland path, we know that the FWHM of dE/dt was essentially the same as that directly measured for the current derivative [32]. Note that no corrections for propagation have been made herein. For a more complete discussion of propagation effects, see [14] and [34, app. C].) The primary differences among the waveforms in Fig. 1 lie in the magnitude and duration of the positive-going overshoot of dE/dt. This observation leads to the following hypothesis: the rise times of the fast-rising portions of E-field pulses that are radiated by all high-current lightning processes are similar independent of the magnitude of either the corresponding field change or its time derivative. In the following, we attempt to substantiate this hypothesis by examining both the dependence of FWHM on E_f for a subset of the natural first strokes that were previously studied by Willett *et al.* [35] and the dependence of FWHM on $(dE/dt)_p$ for a much larger set of events of all types from C/G flashes.

A. First Strokes

Before comparing FWHM with E_f for first strokes, we must address three complicating factors. First, Fig. 3 shows a first stroke with multiple dE/dt peaks during the initial fast-rising portion of its E signature. It turns out that 39% of the 125 first strokes for which we have usable E waveforms are of this type. This phenomenon has not previously been discussed in the literature, to our knowledge, although such waveforms can be found,

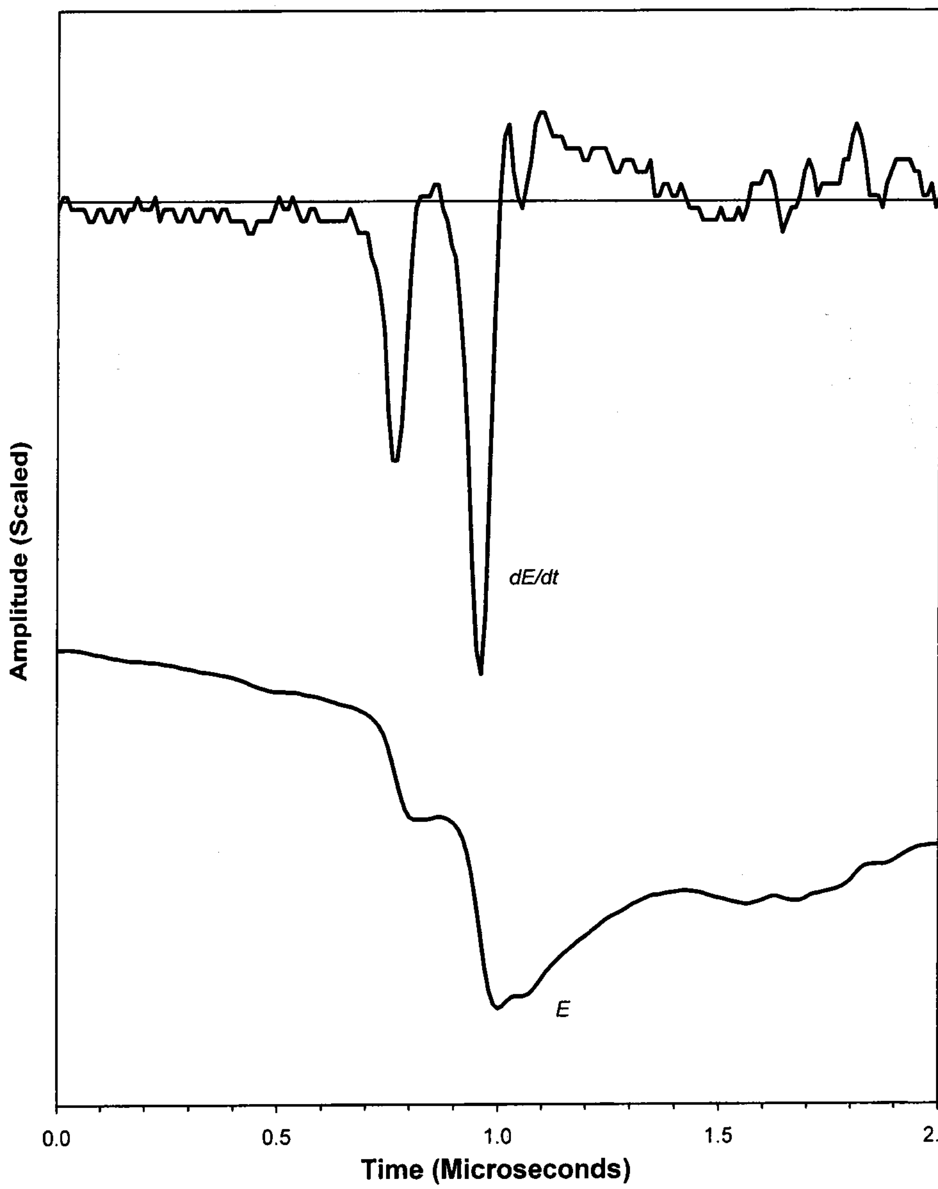

Fig. 3. Example of a first return stroke with multiple dE/dt peaks during the fast-rising portion of its E signature. E (obtained by numerical integration of the dE/dt record) and dE/dt are shown on identical time scales of 2 μs. The amplitude scales are arbitrary.

for example, in [33] and [34]. Since it clearly makes little sense to compare the field change E_f corresponding to the integral of multiple dE/dt peaks with $(dE/dt)_p$ measured on only the largest peak, these events were excluded from the present analysis. Multiple dE/dt peaks during the onset of return strokes and other lightning processes will be discussed in a future publication.

The second complicating factor is illustrated by Fig. 4, which shows a first stroke with an extremely sharp E peak. Such peaks were discussed previously by Willett *et al.* [31], but have been generally assumed to be confined primarily to rocket-triggered subsequent strokes. Among our 76 remaining first-stroke waveforms, however, we found six cases in which the magnitudes of E_p and E_f were significantly underestimated if we used the (bandwidth-limited) E record alone. (This phenomenon will also be treated more completely in a future publication.) Corrections to the values of peak E were made by integrating the dE/dt records for these cases, as illustrated in the figure.

Finally, Fig. 2 shows the "slow front" in a natural first stroke, a feature first quantified by Weidman and Krider [26]. To determine E_f for our set of first return strokes, it was necessary to identify the "break point" between the slow front and the fast-rising portion of each field change. This was done by eye on the E record and, if necessary, on the integrated dE/dt waveform. We found that the slow fronts in our 76 first strokes had an average duration of 3.7 ± 1.2 μs and an average amplitude of 50% $\pm$ 10% relative to E_p. These results compare well with the previous statistics of Weidman and Krider [26], but are substantially larger than those

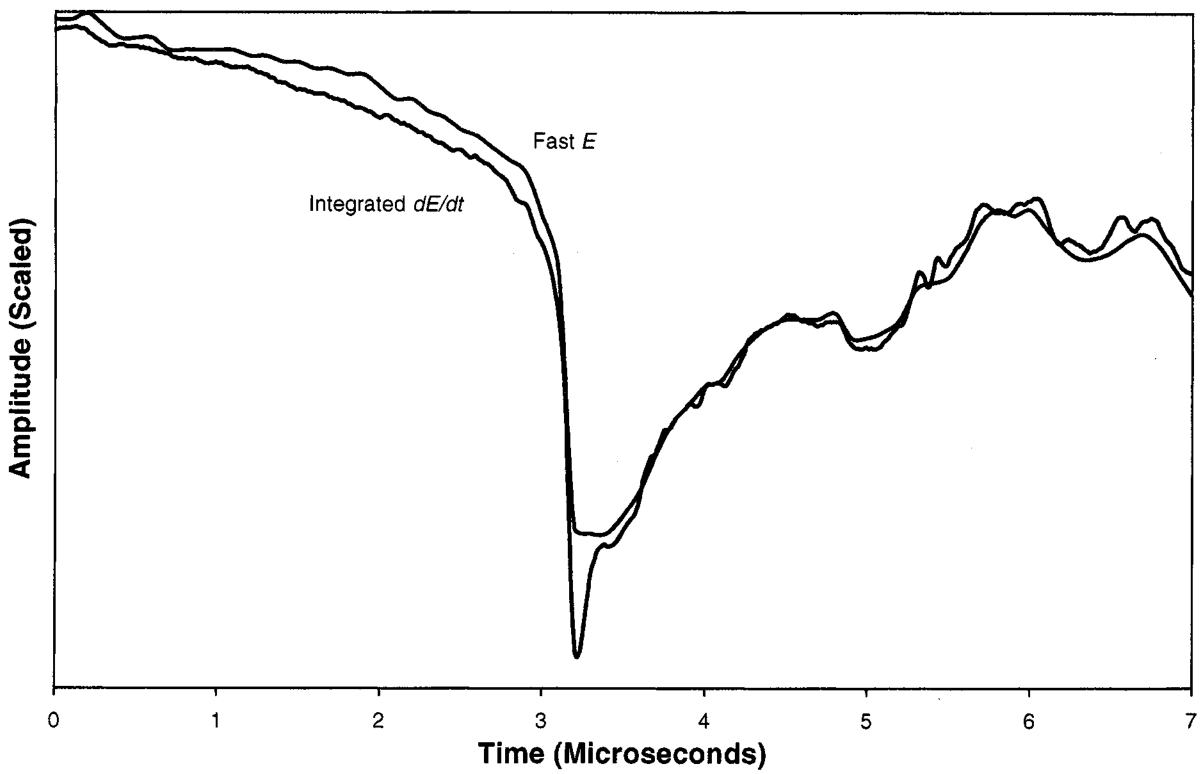

Fig. 4. Example of a first stroke with an extremely sharp E peak. The direct (10 MHz) E record is compared with the integral of the dE/dt (100 MHz) record to show the strong effect of instrumentation bandwidth in such cases; 7 μs of time are shown. The amplitude scale is arbitrary.

of Master *et al.* [20]. E_p itself averaged -7.9 ± 3.6 V/m range normalized to 100 km in reasonable agreement with the value of -8.6 ± 4.4 V/m reported by Willett *et al.* [35] for the complete set of 125 first strokes. (Here and elsewhere in this paper, the error bars quoted on average values are the observed standard deviations.)

Fig. 5 shows $-E_f$ plotted against $-(dE/dt)_p$ for the first strokes that had single dE/dt peaks. There is an obvious correlation, the correlation coefficient of $+0.69$ being significantly different from zero at well above the 99% level. We found that the greatest improvement in this correlation (relative to the poor correlation between E_p and $(dE/dt)_p$ for all first strokes, not shown) was obtained by eliminating the events with multiple dE/dt peaks, a small additional improvement resulting from removing the slow fronts. Looking at this another way, the relative amplitudes of the slow fronts were found to be uncorrelated with both E_f and $(dE/dt)_p$.

Fig. 5 indicates that the fast-rising portions of the E signatures radiated by first return strokes have an approximately constant rise time—83 ns, based on the slope of the regression line—that is independent of amplitude. This observation is confirmed by Fig. 6, based solely on the dE/dt data for the same set of 76 events. No correlation is found between FWHM and $(dE/dt)_p$. Further, the coefficient of variation (standard deviation divided by magnitude of mean) of FWHM is only 22% compared to 31% for $(dE/dt)_p$ and 40% for E_f. Finally, the average FWHM is 76 ± 16 ns in reasonable agreement with the rise time of E that was estimated from the regression line in Fig. 5.

B. All Events

The beauty of comparing FWHM and $(dE/dt)_p$ as in Fig. 6 is that, although range-normalization of dE/dt is required, the comparison can be done without concern about slow fronts, fast-rising field changes having multiple dE/dt peaks, or even the bandwidth limitations of the E recording system. More importantly, this comparison can be done not only for first return strokes, where trigger bias is not a significant problem, but also for other lightning processes, which may suffer significant amplitude bias in our dataset because of the preferential exclusion of small events. Thus, the constant-rise-time hypothesis suggested above can be further tested by comparing FWHM and $(dE/dt)_p$ for all located first and subsequent strokes, stepped- and dart-stepped leader pulses and characteristic pulses that initiated C/G flashes in our 1985 dataset.

This comparison is shown in Fig. 7 for a total of 381 separate events. There is a weak correlation of $+0.34$, significantly different from zero at well above the 99% level, but the coefficient of variation of FWHM, only 0.31, is less than half that of $(dE/dt)_p$, which is equal to 0.65 in our dataset. Thus, although there is some evidence for smaller FWHM in smaller events (discussed further below), there is a clear tendency for all high-current impulsive lightning processes to have the same rise time.

IV. Discussion

The statistics of individual lightning processes will not be discussed in detail here for several reasons. First, trigger bias has

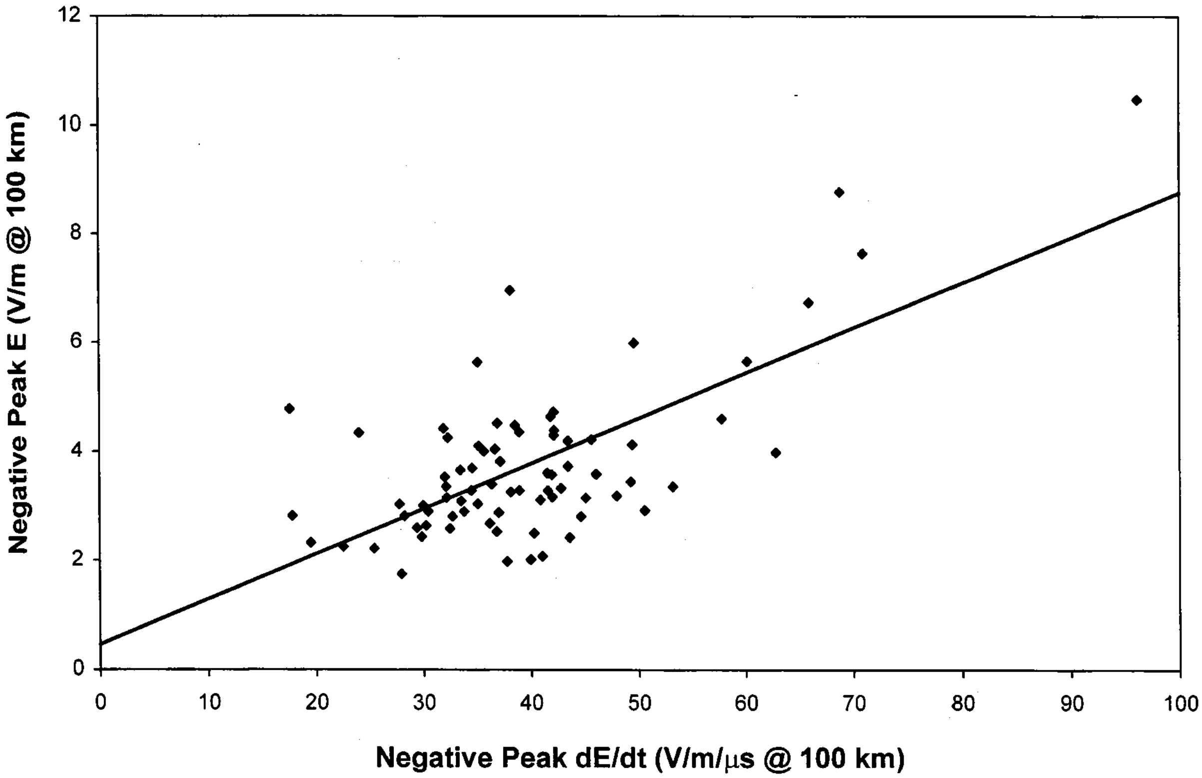

Fig. 5. The negative of E_f plotted against the negative of $(dE/dt)_p$ for our set of 76 first strokes with single dE/dt peaks, uncorrected for propagation. The regression line is also shown.

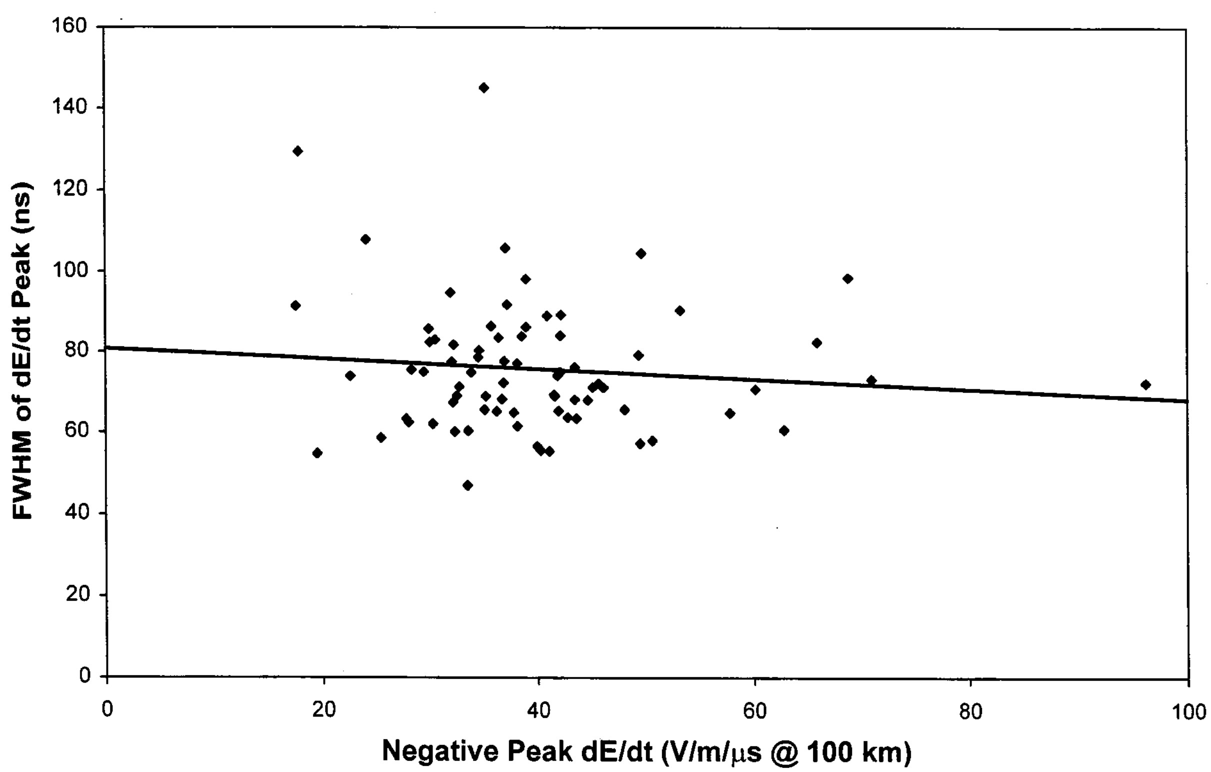

Fig. 6. The FWHM plotted against the negative of $(dE/dt)_p$ for our set of 76 first strokes with single dE/dt peaks, uncorrected for propagation. The regression line is also shown.

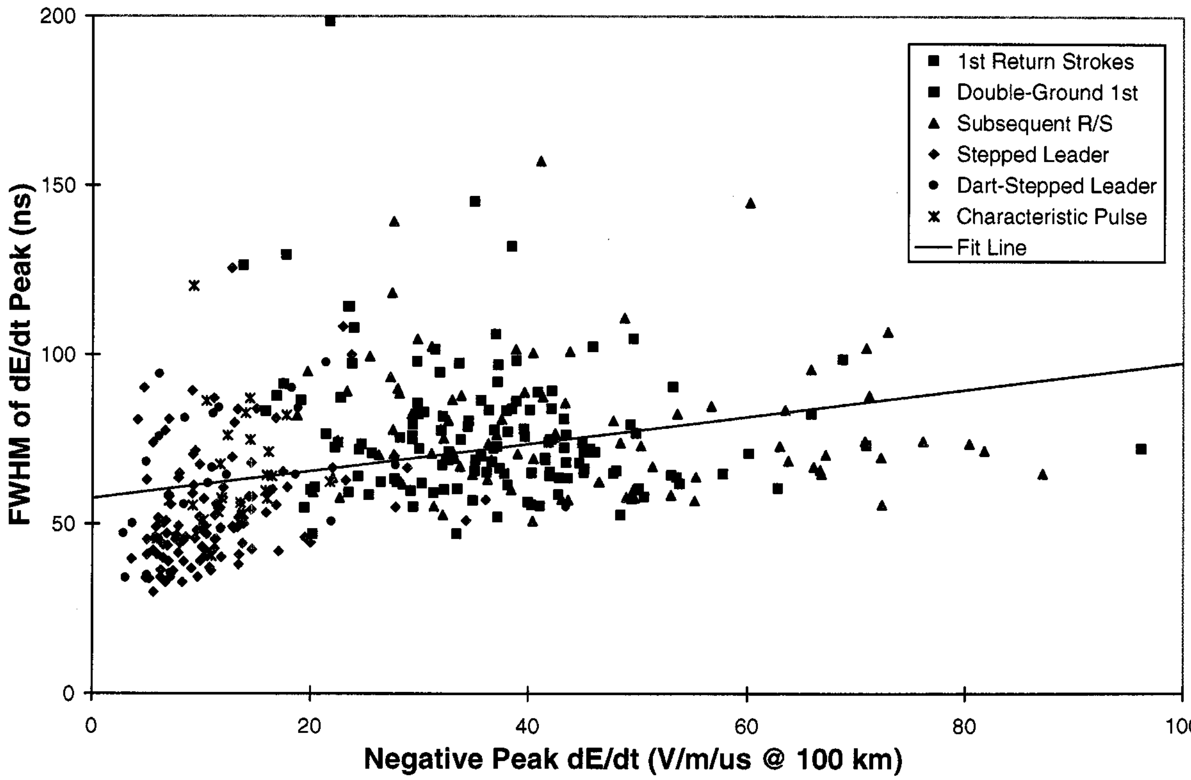

Fig. 7. The FWHM plotted against the negative of $(dE/dt)_p$ for 381 events from located C/G flashes, including first and subsequent strokes, stepped and dart-stepped leader steps, and characteristic pulses, uncorrected for propagation. The regression line is also shown.

probably produced a significant over estimate of the mean amplitudes of all processes except first strokes (as discussed previously) and stepped-leader pulses (because nearly every recorded first stroke provided a leader step). Second, we plan to reanalyze our data on stepped and dart-stepped leader pulses, using all the pulses in each return-stroke record and considering any dependence on the time interval between steps and/or the time before the corresponding return stroke (e.g., [11]). Third, we will try to estimate the trigger bias in our set of subsequent return strokes by considering the dead time of the data system relative to the order of the stroke in the flash [21], [22], as indicated by our slow-field recordings. Finally, we must account for any slow fronts that may be present in subsequent return strokes and leader steps and for the presence of multiple peaks in dE/dt, before the E statistics will be meaningful in the present context. These issues will be considered further in future publications.

Nevertheless, we expect that neither our finite (RF) trigger threshold nor the order of, nor time delay between, events in a flash will influence significantly the average FWHM for any of the lightning processes in our data set. Therefore, the statistics of FWHM for these individual processes are given in Table I. Note that all of the mean values are comparable. Although the difference between the largest mean (for subsequent return strokes) and the smallest mean (for stepped-leader pulses) is statistically significant at well above the 99% level by Student's t-test, this difference is only 38% of their common mean, which is rather small compared to a 128% relative difference between the corresponding means of $(dE/dt)_p$ (not shown).

Part of the difference in the mean FWHM between return strokes and other events in Table I (hence, part of the nonzero correlation found in Fig. 7) could be due to the effects of propagation over the ocean. Willett *et al.* [35] have estimated that the observed FWHM of the average first stroke in this dataset was increased by about 22% and that the magnitude of the observed $(dE/dt)_p$ was decreased by about 11% from the respective values at the source (assumed to be at the surface) by selective attenuation of the higher frequencies during propagation over 22 km of seawater. This attenuation should have been less severe for elevated sources (such as leader steps and especially characteristic pulses) and these processes do indeed show smaller averages of FWHM than do return strokes. Although difficult to quantify, this argument does support our hypothesis that rise time tends to be independent of amplitude.

Part of the correlation seen in Fig. 7 is apparently real, however. A correlation of $+0.31$, statistically significant at well above the 99% level, is observed between FWHM and $-(dE/dt)_p$ for the stepped-leader pulses alone. Nevertheless, the coefficient of variation of $(dE/dt)_p$ is still substantially larger than that of FWHM for these events.

A. Previous Literature

The best previous measurements of dE/dt from first return strokes in natural lightning were by reported by Krider *et al.* [14], who estimated a mean FWHM of 75 ± 15 ns for 61 events (after correction for propagation over 35 km of sea water),

TABLE I
MEAN STANDARD DEVIATION COEFFICIENT OF VARIATION AND NUMBER OF EVENTS FOR FWHM OF THE MAIN NEGATIVE-GOING dE/dt PEAK IN VARIOUS C/G LIGHTNING PROCESSES, UNCORRECTED FOR PROPAGATION

Event Type	Mean (ns)	Std. (ns)	CoV (%)	# Events
First Strokes	77	20	26	133
Subsequent Strokes	79	20	25	85
Stepped Leader Pulses	54	17	31	114
Dart-Stepped Leaders	64	19	30	24
Characteristic Pulses	65	17	26	25
All Events	69	22	31	381

giving a coefficient of variation of 20% in reasonable agreement with the present (uncorrected) results (see also [35]). Statistics reported by Weidman [29] and by Weidman and Krider [30]for first strokes are also in good agreement with these values.

There have been wide-band observations of the radiation-field component of dE/dt from subsequent return strokes in rocket-triggered lightning that we can assume to be relatively free of propagation effects. Willett *et al.* [32] reported a mean FWHM of 61 ± 22 ns on a set of 28 triggered strokes, giving a coefficient of variation of 36%. The corresponding coefficient of variation for $(dE/dt)_p$ was only 30%—smaller than that of FWHM in contrast to the present results. Nevertheless, there was a good correlation (+0.69) between E_p and $(dE/dt)_p$ for these measurements, in which slow fronts are presumed to have been relatively small. The rise times in these triggered strokes were appreciably faster than in the present data for natural subsequent strokes, although propagation effects on the triggered events were probably less because they were generally closer to the antennas.

Direct measurements of current derivative (dI/dt) in triggered lightning are also relevant. Leteinturier *et al.* [16] and Depasse [5] give excellent summaries of these data, covering several experiments. Considering all 73 of their events (some of which were identical with those studied in dE/dt by Willett *et al.* [32]), Leteinturier *et al.* [16] found the mean full width at half maximum of dI/dt to be 91 ± 61 ns, but for 56 single-dE/dt-peak events they reported 74 ± 56 ns. These two means bracket the value given in Table I for FWHM of dE/dt in natural subsequent strokes, but their coefficients of variation are much larger, apparently because of the combination of data from experiments over different surfaces. Leteinturier *et al.* [15] have reported a linear relationship between $(dI/dt)_p$ and peak current (I_p) in their data, whereas Depasse [5] reported a power-law relationship with an exponent close to one, both suggesting that rise time might be independent of amplitude, as argued here.

Fisher *et al.* [6] have reported a relatively strong positive correlation between 10–90% or 30–90% averaged dI/dt and I_p and essentially no correlation between I_p and 10–90% rise time for rocket-triggered return strokes in Florida and Alabama. These results led those authors to conclude that "the rise time is a parameter that is determined by the breakdown physics and is not related to the magnitude of the breakdown, at least in the peak current range studied (4 to 38 kA)." Although their data are not directly comparable to the present results, primarily because the significantly lower bandwidths of their instrumentation were inadequate to resolve the narrow dI/dt signatures that are inferred here and that have been measured directly in previous rocket-triggering experiments, our data extend their conclusion to faster rise times and to other lightning processes than rocket-triggered return strokes.

We should mention that there is some evidence that the fast-rising portions of the fields radiated by natural return strokes striking land may be different from those that strike the ocean. Heidler and Hopf [7] have reported measurements with mean $(dE/dt)_p$ magnitude about ten times smaller, and with mean FWHM about ten times larger, than those discussed above. They argue that these differences cannot be due primarily to propagation over the short distances to their measurement site. On the other hand, such large differences are not evident in a comparison of dI/dt measurements of rocket-triggered return strokes between mountainous terrain in France and brackish water in Florida [15], [5].

The first measurements of events other than return strokes in natural C/G flashes that were not seriously contaminated by propagation effects or bandwidth limitations were made by Weidman [29] and reported by Weidman and Krider [30]. Their measurements for stepped leader pulses and for what are believed to have been characteristic pulses are in good agreement with those in Table I. In fact, Weidman [29] found the same ranking of mean FWHM as ours among the three kinds of lighting processes that he recorded with a completely over-water path. Krider *et al.* [13] have also given similar results and Bailey *et al.* [1] have previously reported results from preliminary analyses of the present data set.

B. Implications

While there is no unique relationship between the observed radiation-field waveforms and the currents flowing in the lightning channels that produced them, under many conditions there is a close correspondence, as indicated for example, by the well-known “transmission-line model” (e.g., [18], [23]). Therefore, it is tempting to extend the hypothesis of similar rise times in all fast-rising field-change signatures, as argued above, to the onset of all fast rising channel currents. If we accept this extended hypothesis, we are forced to look for a physical mechanism that will limit the rise times of high-current pulses in lightning over a broad range of amplitudes. Such a mechanism is not apparent but might be related to the rate at which free electrons can be created at the front of a high-current discharge propagating in a previously ionized and heated channel. Further speculation about such mechanisms is beyond the scope of this paper.

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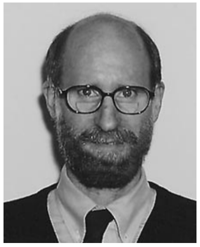

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