MULTIPLE PULSES IN THE ELECTRIC FIELD DERIVATIVE, dE/dt, DURING THE ONSET OF FIRST
RETURN STROKES IN CLOUD-TO-GROUND LIGHTNING

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ABSTRACT: Many (37\%) of the dE/dt waveforms radiated by the first return stroke in cloud-to-ground
lightning contain multiple peaks in the interval from 1\,\mu s before to 1\,\mu s after (–1\,\mu s to +1\,\mu s) the largest
(dominant) peak. 28\% contain one or more peaks in the interval from 4\,\mu s before to 1\,\mu s before the
dominant peak (-4\,\mu s to –1\,\mu s) and just the dominant peak in the interval from –1\,\mu s to +1\,\mu s. When the
integral of dE/dt is computed and compared with E, the integrated waveform, E_{int}, often has considerable
fine-structure that is not resolved by the 10 MHz digitizer. This structure includes fast pulses near the
beginning of the slow front, large peaks and shoulders within the slow front and during the fast transition,
and very narrow peaks in E_{int}. Our overall conclusion is that the electromagnetic environment near the
point(s) where lightning leaders attach to ground, and perhaps even the physics of the attachment
process, is more complicated than is commonly assumed in the lightning literature.

INTRODUCTION
Fast, time-resolved measurements of the electric field (E) waveforms and the time-derivatives
(dE/dt) that are radiated by natural first return strokes have been described previously by Weidman and
and others. Weidman and Krider (1978, 1980) have noted that the shape of the initial E field, when it is
recorded under conditions where there is minimal distortion due to the effects of ground-wave
propagation, typically begins with a slow, concave front that lasts for several microseconds. This front is
followed by a fast transition to peak (in tens to hundreds of nanoseconds), and after this transition, there
are a variety of subsidiary peaks and other features that are thought to be due to the effects of branches
and the complex geometry of the channel and/or traveling waves of current during the attachment
process (Weidman and Krider, 1978; Weidman et al., 1986; Willett et al., 1988; Leteinturier et al. 1990).
We have recently re-examined the detailed structure of 131 dE/dt and E signatures that were radiated by
natural first return strokes striking seawater at ranges of 5 to 50 km with the goal of quantifying the
detailed fine-structure of these fields on a time-scale of tens to hundreds of nanoseconds.

DATA DESCRIPTION
A block diagram of the digital data recording system is given in Willett et al. (1989, Fig. 1). E
waveforms were digitized using a 10-bit A/D converter operating at a sampling frequency of 10 MHz, and
dE/dt waveforms were digitized using an 8-bit A/D converter and a sampling frequency of 100 MHz. The
type of lightning process that triggered the recording system was determined from the shape and
structure of the E waveform and the time it occurred within the overall slow-E record. All CG flashes in
our dataset effectively lowered negative charge toward ground, and the initial E fields were negative or
downward transitions following the normal physics convention. The amplitudes of all waveforms given
below have been range-normalized to 100 km, assuming that the radiated field has an inverse distance
dependence on range.

RESULTS
The primary focus of this report will be on a 5\,\mu s interval that corresponds to the onset of the
stroke, i.e. the slow front and the initial peak in the E waveform. We start by examining the number and
timing of large peaks that appear in the dE/dt records, and then we consider the effects that these peaks
have on the shapes of the E signatures. To determine the fine-structure of E, each dE/dt record (100
MHz) has been numerically integrated (using the trapezoid rule) over a 15\,\mu s interval that includes the
peak E, and because the resulting wave shape was very sensitive to small offsets in dE/dt, we
systematically tried a number of offsets and then selected the one that provided the best fit to the digitized
E record (10 MHz). Our notation for the integrated dE/dt waveform is E_{int}. Figure 1a shows the initial
portion of a “classical” $E_{int}$ waveform that has a slow, concave front followed by a fast transition to peak and little additional structure [see Weidman and Krider (1978)] together with the corresponding $dE/dt$ signature. Events that have a single peak in $dE/dt$ tend to produce this shape and will be termed “Type A” strokes.

Figure 1. Examples of $dE/dt$ and $E_{int}$ (integrated $dE/dt$) waveforms produced by (a) a “classical” first return stroke and (b) a first stroke with multiple peaks in $dE/dt$ within ±1 µs of the dominant peak.

Figure 1b shows the $dE/dt$ and $E_{int}$ signatures from a stroke that produced multiple pulses in $dE/dt$ near the time of the peak $E$. Since multiple pulses were present in a significant fraction of our $dE/dt$ records, we will now discuss the characteristics of these waveforms in more detail. The dominant peak in $dE/dt$ is defined to be the largest, negative-going peak that occurs in a $dE/dt$ record during the fast transition in $E$. (Note in Figure 1 that the origin of the time-axis coincides with the time of the dominant peak.) A pulse in $dE/dt$, in addition to the dominant peak, has been included in this analysis if it has (1) a (negative) peak amplitude that is at least 10% of the dominant peak and (2) the amplitude of the (positive-going) return of that signal crosses a (negative) level that is 50% of its own (negative) peak. An example of such a pulse can be seen in the upper panel of Figure 1b at approximately –0.5 µs. A complex cluster of pulses will be termed a “burst”, and one such example can be seen in Figure 2a between 0 and –2 µs.

Again, we are primarily interested in the large pulses in $dE/dt$ that occur in the interval from 4 µs before to 1 µs after the dominant peak, i.e. –4 µs to +1 µs. We assume that all pulses prior to –4 µs (the typical duration of the slow front) are produced by the final steps of the stepped-leader process rather than by the onset of the stroke itself. Of course, some of the pulses after –4 µs could be due to leader steps. Leader pulses, like the pulses at approximately –5.5 µs in Figure 1b and near –5 µs in Figure 2b, will be the subject of another paper at this conference (Baffou et al., 2003).

Within our sample of 131 first stroke waveforms, each having a dominant peak in $dE/dt$, 49 (37%) had one or more additional peaks within ±1 µs of the dominant peak. These events will be termed “Type B” strokes. Of the remaining 82 events, 37 (or 28% of the total) had one or more large peaks in $dE/dt$ in the interval from –4 µs to –1 µs of the dominant peak. These will be designated “Type C” strokes. Thus, 86 out of the 131 events in our data set – an astonishing 66% of the total – produced multiple peaks in $dE/dt$ within the 5 µs interval that corresponded to the onset of the stroke. The 49 Type B events, i.e. strokes that had large subsidiary peaks in $dE/dt$ within 1 µs of (and in addition to) the dominant peak, produced a total of 136 subsidiary peaks; thus there were an average of (136 + 49)/49 = 3.8 peaks in $dE/dt$ per Type B event. The associated $E_{int}$ waveforms contain either an inflection point or, if the (negative) $dE/dt$ pulse is followed by a positive going zero crossing, a small peak that is within or near the fast transition. We term these structures “$\gamma$-peaks” or “$\gamma$-shoulders,” and an example is given in Figure 1b.
Figure 2. Examples of (a) a Type C event that produced a convex change in $E_{\text{int}}$ during the slow front and (b) a leader step impulse near $-5 \mu s$ and a narrow peak in the return stroke.

Figure 2b shows an example of an $E_{\text{int}}$ waveform that had a very narrow peak and that was under-sampled by the E digitizer operating at 10 MHz. Since narrow peaks were a common feature in our data set and since the values of peak E are often used to estimate the peak current in return strokes (Rakov and Uman, 1998), we have compared the peak values of $E_{\text{int}}$ with the peaks of the E waveforms that were obtained with the 10 MHz digitizer. The median peak $E_{\text{int}}$ and peak E were $-7.8$ V/m and $-7.2$ V/m, respectively, and the corresponding means and standard deviations were $-8.9 \pm 4.4$ V/m and $-8.6 \pm 4.4$ V/m, respectively. 13 of the 131 strokes in our data set had a peak $E_{\text{int}}$ that exceeded peak E by more than 15%.

We have also examined the $dE/dt$ waveforms that were radiated by return strokes that came after the first stroke in multiple-stroke flashes (and that had E waveforms similar to the subsequent strokes described by Weidman and Krider [1978]) to see whether these waveforms also contained multiple peaks in $dE/dt$ near the time of the peak E, and Table 1 summarizes our results. (Note: Type C waveforms have been omitted from Table 1 because the fronts in subsequent stroke fields tend to be short or poorly defined.) It should be noted that a significant fraction of the subsequent strokes in natural lightning do produce multiple peaks in $dE/dt$ within 1 $\mu s$ of the peak E, and that subsequent strokes preceded by dart-stepped leaders have a larger fraction with multiple peaks in this interval than first strokes (66% vs. 37%). Uman et al. (2000) have also reported that subsequent strokes in rocket-triggered lightning sometimes produce multiple peaks in $dE/dt$ during the onset of E (see their Figure 4). The fine structure of $dE/dt$ and E waveforms radiated by subsequent return strokes in natural lightning will be the subject of a future paper.

DISCUSSION

At this point it should be noted that, if there are large, submicrosecond variations in $dE/dt$ and E during the onset of first and subsequent strokes, then there must also be similar variations in the source current, I, at or very close to the point(s) where the leader attaches to the surface. Large values of $dl/dt$ will be produced by the onset or termination of any large current that flows in response to the breakdown of large potential differences. Possible causes include multiple pulses of current in a single channel, such as might occur if there are discrete steps within the development of an upward or downward leader, reflections of current during the attachment process, or the development of multiple channels, such as forks, loops, or branches near the ground, or some combination of the above. In any case, our results clearly show that the electromagnetic fields that are produced just before and during the onset of the first return stroke, and perhaps even the physics of the attachment process, are more complicated than is commonly assumed in the lightning literature, [see, for example, Rakov and Uman (1998)].
Table 1. Summary of the peaks in dE/dt during the onset of first and subsequent return strokes.

<table>
<thead>
<tr>
<th>Type of Return Stroke</th>
<th>Total Number of Events</th>
<th>Number with multiple peaks in dE/dt within –1 to +1 µµµµs (Type B)</th>
<th>Number with multiple peaks in dE/dt within –4 to -1 µµµµs (Type C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>First Return Strokes</td>
<td>131</td>
<td>49 (37.4 %)</td>
<td>37 (28 %)</td>
</tr>
<tr>
<td>Subsequent Stroke with Normal or Chaotic Leader</td>
<td>54</td>
<td>17 (31.5 %)</td>
<td></td>
</tr>
<tr>
<td>Subsequent with Dart-Steped Leader</td>
<td>32</td>
<td>21 (65.6 %)</td>
<td></td>
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REFERENCES


