A COMPARISON OF CHANNEL-BASE CURRENTS AND OPTICAL SIGNALS FOR ROCKET-TRIGGERED LIGHTNING STROKES

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ABSTRACT: A comparative analysis has been performed for the channel-base current and light waveforms of rocket-triggered lightning strokes. It has been found that the current and light signals have a remarkable linear relationship in their rising portions. However, just after the peaks, the linearity disappears, and the light signals usually decrease faster than the currents in the next several microseconds. Later this trend is reversed and in some cases, even when the currents keep decreasing, the light signals show another rising trend. The findings support the idea of evaluating the variation of return stroke current along the lightning stroke channel using light signals if that evaluation is limited to the rising portions of those signals.

INTRODUCTION

Knowledge of the current distribution along the return-stroke channel is very important for return-stroke modeling (e.g., Thottappillil et al., 1997; Rakov and Uman, 1998). An indirect measurement through optical observation, as suggested by Jordan and Uman (1983), seems to be the only practical way to evaluate the current distribution. In order to perform such an evaluation, the relationship between the current and the light signals should be known. There are several publications addressing this relation (e.g., Flowers, 1943; Idone et al., 1985; Cavin et al., 1987; Gomes and Cooray, 1998). Generally, as the discharge current increases, the emitted light signal also increases (Flowers, 1943). Idone et al. (1985) found a strong correlation between lightning peak current and peak luminosity for the return strokes within each of two New Mexico rocket-triggered flashes. However, Idone et al. found an apparent disparity between the rise times of the two signals. The light signal appeared to rise slower than the current. However, one should note that the light signals used in their study were emitted from a channel segment 50 m above the ground, which could be very different from the channel base signals, as shown by Wang et al. (1999a). Cavin et al. (1987) presented the relation for laboratory discharges with peak currents of 50 kA and 100 kA and a rise time of several hundred microseconds. A hysteresis-type relation between the current and light was given in their Figure 11. The light signal follows the current only at the very initial portion of the rising stage. Gomes and Cooray (1998) investigated the correlation for various laboratory spark discharges. They found a linear relationship not only between the current amplitude and the light amplitude but also between the current rise time and light rise time. Since some of these studies are for laboratory sparks, as opposed to lightning; and some of them lack sufficiently convincing data, the relation between lightning return stroke current and light is in need of further research. In this paper, we study the correlation using the channel-base currents and optical signals generated very close to the current measurement point in rocket-triggered lightning strokes. We believe that our results provide new insights into the relation between lightning return stroke current and light waveforms.

INSTRUMENTATION AND DATA

All data for the study were taken during the rocket-triggered lightning experiment in summer 1997 at the International Center for Lightning Research and Testing at Camp Blanding, Florida. Information on the Camp Blanding lightning research and testing facility is found in papers by Uman et al. (1997) and Rakov et al. (1998). For the lightning current measurements, a coaxial current viewing resistor (shunt) was used. Its output was transmitted through a fiber optic link and recorded using both a digitizing oscilloscope for relatively high (mostly return-stroke) current and a tape recorder for relatively low continuing current. Tape-recorded data were subsequently digitized. Sampling intervals of 40 ns and 2 μs were used for the relatively high current and the relatively low continuing current records, respectively. For the optical measurements a digital optical imaging system ALPS (Automatic Lightning Progressing Feature Observation System) that was specifically designed for recording the luminous progression of lightning discharges was used. The version of ALPS used in this study consists of a conventional camera lens, a photodiode array module, large dynamic range amplifiers, a main channel digitizer, and a personal computer system, and has been described in detail by Wang et al. (1999a). The photodiode array module consisted of 256 (16×16) pin photodiodes, and each of the diodes operates at wavelengths from 400 to 1000 nm with a response time of less than 3 ns. The ALPS can operate at a time resolution (inter-frame interval) from 100 ns to 50 μs with either internal or external trigger and can record up to 16,000 frames for each event with up to 16,000 frames of pre-trigger. The inter-frame interval used in the present study was 100 ns, and thus the resulting total recording time per event was 1.6 ms. The ALPS was installed 250 m from the rocket launcher and viewed an effective area of 50×50 m² in a vertical plane just above the tip of a grounded metallic rod mounted on the rocket launcher, yielding a spatial resolution of about 3.6 m. ALPS data can be used to analyze the progression of the lightning leaders and return strokes. Some results obtained using ALPS at Camp Blanding have been previously published by Wang
et al. (1999a,b). For the present study, the light signals from only the lowest channel section having a length less than 3.6 m were used for comparison with the corresponding current waveforms. This is the first measurement of the light signal generated very close to the current measurement point.

The current recording instruments and ALPS were triggered simultaneously when the channel-base current exceeded the preset threshold level. For precise comparison, the current and light signals are aligned using their peak derivatives.

Four triggered lightning strokes, listed in Table 1, are suitable for the present study. These four strokes occurred in four different triggered flashes. All the flashes are typical of negative rocket-triggered lightning discharges that are characterized by an initial stage followed by dart leader/return stroke sequences (Wang et al., 1999c). The strokes analyzed here are all the first strokes following the initial stage. Their return stroke peak currents and current 10-to-90% rise times are also included in Table 1.


table 1. return stroke data summary

<table>
<thead>
<tr>
<th>No.</th>
<th>Date and Time (UTC)</th>
<th>Peak current (kA)</th>
<th>10-to-90% current rise time (µs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>19-Jun-97, 21:49:43</td>
<td>5.3</td>
<td>3.9</td>
</tr>
<tr>
<td>2</td>
<td>24-Jun-97, 19:30:09</td>
<td>12</td>
<td>0.6</td>
</tr>
<tr>
<td>3</td>
<td>26-Jun-97, 20:26:02</td>
<td>21</td>
<td>0.2</td>
</tr>
<tr>
<td>4</td>
<td>26-Jun-97, 20:37:07</td>
<td>12</td>
<td>0.9</td>
</tr>
</tbody>
</table>

ANALYSIS AND RESULTS

Figure 1 shows the channel-base current and the channel-base light waveforms of the return stroke triggered at 20:37:07, 6/26/1997. Figure 2 presents the scatter plot of the current and the light signal in flash presented in Figure 1. From these two figures, the relation between the current and the light signal can be divided into four stages. In stage 1 (from \( t = 0 \) to \( t = 1.3 \mu s \)), both the current and light signals increase sharply and they exhibit a strong linear relationship. The time-expanded waveforms for the initial 2.7 µs are shown in Figure 3. In this figure, both the current and light signals are in arbitrary

Figure 1. The channel-base current and light waveforms of the return stroke in flash triggered at 16:37:07, 6/26/1997 at Camp Blanding, Florida.

Figure 3. Comparison between the current and light waveforms shown in Figure 1 for the initial 2.7 µs.

Figure 2. The scatter plot of the current and light signals shown in Figure 1. Four stages are labeled: (1) 0 – 1.3 µs, (2) 1.3 – 7 µs, (3) 7 – 55 µs, (4) > 55 µs.

Figure 4. The scatter plot of the current and light signals for only the rising portion shown in Figure 3. Data points in this figure correspond to stage 1 of Fig. 2.
units so that their peaks are the same. As evident in Figure 3, prior to the peaks, the light signal follows the current very closely. The corresponding linear regression line is shown in Figure 4, and the correlation coefficient is greater than 0.99. In stage 2 (from \( t = 1.3 \mu s \) to \( t = 7 \mu s \)), both the current and light signals decrease, but the decrease in current is much slower than the decrease in the light signal. In stage 3 (from \( t = 7 \mu s \) to \( t = 55 \mu s \)), the light signal remains at a more or less constant level, but the current exhibits a continuing decrease. In stage 4 (after \( t = 55 \mu s \)), both the current and the light signal show a relatively slow decay.

Figure 5 presents the channel-base current and light waveforms of the three remaining return strokes listed in Table 1. Figure 6 gives the corresponding scatter plots. All the strokes show a linear relationship for the currents and light signals in their rising stages up to the peaks. After the peaks, the light signal of the 21:49:43, 19-Jun-97 event (No.1), which is the weakest one among the four events listed in Table 1, exhibits a slower decrease than the remaining three events. This difference is also seen in the scatter plots shown in Figure 6 (No.1). The reason for this slower light decrease is unknown.

![Figure 5] The channel-base current and light waveform of return strokes No. 1, No. 2, No. 3 listed in Table 1.

![Figure 6] The scatter plots for the channel-base current and light signals shown in Figure 5.

**DISCUSSION**

I done et al. (1985) examined the correlation between peak light intensity \((L_s)\) and peak current \((I_k)\) for 39 subsequent return strokes in two New Mexico triggered lightning flashes. Significant correlation was found for the following pairs of parameters: \(L_s \) vs. \( I_k \), \( \log L_s \) vs. \( \log I_k \), \( \log L_s \) vs. \( I_k \), \( \log I_k \) vs. \( I_k \). However, concerning the rise time, I done et al. found an apparent disparity between the two signals. The light signal appeared to rise slower than the current. One should note that the light signals used in their study were emitted from a channel segment 50 m above the ground. Light waveforms change considerably along the channel, so that their light and current waveforms characterized different parts of the channel. As an example, Figure 7 shows a comparison of the light signals from the channel base and from a channel segment 50 m high for stroke No. 3. The return stroke begins at \( t = 0 \), so the portion of the signal for \( t < 0 \) is due to the dart leader.
section 50 m high for event No. 3. As the return stroke wave propagated over the bottom 50 m, the rise time of the light signal increased by more than a factor of 3, and its peak decreased by nearly 40% (Wang et al., 1999a).

Strokes with different rise times are expected to show different attenuation characteristics. Our results indicate that the return stroke light signals follow closely their corresponding current waveforms during the rising stage, up to the peak. Gomes and Cooray (1998) published similar results for laboratory spark discharges. In their experiments, they studied various current rise times (up to 16 μs) and amplitudes (up to 3.5 kA). Covin et al. (1987) presented a hysteresis-type relation for the currents and light signals of the laboratory discharges. Although our results also show some kind of hysteresis behavior, they apparently differ from their results in two respects. First, the light signal in their experiments follows the current waveform only at the very initial stage as opposed to the whole rising stage in our study. Second, the hysteresis curves presented by them do not have any tendency for crossing between the rising and decaying stages. In our data, all the hysteresis curves show a tendency for crossing. This implies that the lightning light signal tends to last longer than its corresponding current. Note that the current rise times in their experiments are several hundred microseconds, much longer than those observed for lightning. This may be the primary reason for the disparities between their and our results.

One may ask (1) why the light signals follow the current waveforms so closely during the whole rising stage, and (2) why in some cases, even when the current keeps decreasing, the light signal shows another rising portion. The latter feature is observed in electric field waveforms as well. To answer these questions, additional information including the temperature and radius of the lightning channel as a function of time, is needed.

CONCLUSION
This paper has presented the results of a comparison of channel-base current waveform and light waveform for rocket-triggered lightning return strokes. It has been found that the current and light signals have a remarkable linear relationship during the entire rising stage, up to the peak value. The findings support the idea of evaluating the variation of return stroke current with channel height by using light signals if that evaluation is limited to the rising portion of the waveforms. After the peak, the light signal usually decreases faster than the current in the next several microseconds. Later this trend is reversed and in some cases, even when the current keeps decreasing, the light signal shows another rising trend.

REFERENCES

Flowers, J. W., The channel of the spark discharge, Phys. Rev. 64, Numbers 7 and 8, 225-234, 1943.


