Characteristics and simulation of lightning current waveforms during one artificially triggered lightning

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ABSTRACT

In the summer of 2005, one negative lightning flash was artificially triggered in Shandong Province (117°48′ E, 37°42′ N), middle latitude region of eastern China. The flash included 10 return strokes, and the geometric mean value of the current peak was 11.9 kA (the average value was 12.6 kA) with a maximum of 21.0 kA and a minimum of 6.6 kA, similar to the subsequent return strokes in natural lightning. The geometric mean value of half peak width was 39 μs (the average value was 40 μs), which was much larger than the usual result. Based on the Diendorfer and Uman (DU) model, the return-stroke current waveforms and charge distribution along the lightning channel are discussed. The simulated current waveforms, being divided into breakdown and corona current components, are in agreement with the optical measurements when the two different discharge time constants are properly chosen.

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1. Introduction

The knowledge of lightning current parameters (such as peak value, time derivatives, half width and so on) is an important issue in the application regarding lightning protection and also in studies for the physical interpretation of lightning processes. Artificially triggered lightning provides an effective way to measure directly the discharge current at the base of the channel, and many new results have been achieved in the last decade (e.g. Laroche et al., 1991; Lalande et al., 1998; Rakov et al., 1998, 2005; Liu et al., 1994, 1998; Pinto et al., 2005; Saba et al., 2005; Qie et al., 2007, 2009—this issue).

In China, Liu et al. (1998) measured the discharge current of artificially triggered lightning during single-cell-storms in Pingliang, Gansu Province (106°69′E, 35°57′N), and found that the triggered lightning was characterized by only a continuous current stage with a peak current of several hundreds of amperes and a duration time of several hundreds of milliseconds. The lightning flash was triggered successfully only in a condition of negative surface electric field controlled by a larger-than-usual lower positive charge center at the base of plateau thunderstorms in Gansu Province. Until now there is not much information on the return-stroke current waveform with high time resolution in China.

Since the summer of 2005, an artificially triggered lightning experiment has been conducted in Binzhou, Shandong Province (117°48′ E, 37°42′ N), middle latitude region of eastern China. The lightning current was measured at the base of the discharge channel by two Rogowski coils with a bandwidth of 300 Hz–1 MHz, the current values up to 2 kA and 100 kA were measured by these two coils, respectively. A 1 Ω-shunt was used to measure current below 100 kA. The signals from the coils and the shunt were transmitted through optical fibre to an 8-channel oscilloscope in a control room which was 60 m away from the launching site. More detailed information about the experiment is given by Qie et al. (2007, 2009—this issue).

Five lightning flashes were successfully triggered in the summer of 2005, and they were named 0501, 0502, 0503, 0504, and 0505, respectively. The flash 0503 was successfully triggered in a positive surface electric field environment
controlled by negative charge overhead, and the corresponding surface electric field was about 4 kV m$^{-1}$. Yang et al. (2008) analyzed the initial stage in two triggered lightning flashes of 0503 and 0602. In this paper the characteristics of the discharge current of flash 0503 will be discussed in detail based on the experiment data and the DU return-stroke model simulation.

2. The characteristics of the return-stroke current waveform

The left panel in Fig. 1 shows a still picture of flash 0503 taken at 60 m from the lightning discharge channel. The picture shows that the discharge channel was blown from left to right because of the horizontal wind, just like that taken by a streak camera. The smooth bright channel on the left resulted from the explosion of the wire by the upward leader current, and the right 10 channels corresponded to 10 return strokes. The right panel in Fig. 1 was taken at a distance of 550 m from the discharge channel. The straight bright line in the figure was associated with the melting of the triggered wire, and the triggering height was estimated to be about 300 m; the upper luminous part was associated with the lightning channel in the air.

Flash 0503 struck the lightning rod, and the current waveforms of 10 return strokes have been well recorded. Fig. 2 shows the overall current waveform measured at the base of the channel. It contains initial-stage discharge (IS) and 10 return strokes (marked as R1–R10 in the figure), and the overall discharge time of flash 0503 was about 1120 ms. The discharge time of IS was about 20 ms, the neutralized charge of IS was $-1.6 \text{ C}$, and the geometric mean value of current pulses produced by the upward positive leaders was 23 A, ranging from 16.9 to 41.0 A. The time interval between two strokes ranged from 18 to 210 ms with a mean interval of 87 ms. The geometric mean value of the return-stroke current peak was 11.9 kA (the average value was 12.6 kA) with a maximum of 21.0 kA and a minimum of 6.6 kA, similar to the subsequent return strokes in natural lightning, the result was in agreement with the results of triggered flashes by Rakov et al. (2005) and Pinto et al. (2005), and of natural flashes by Anderson and Eriksson (1980). The average value of neutralized charge for 10 return strokes was $-0.58 \text{ C}$, and the total neutralized charge by the flash was $-5.8 \text{ C}$. By analyzing the 10 return strokes of flash 0503, a relationship between the peak current $I_p$ (kA) and the neutralized charge $Q$ (C) can be derived:

$$I_p = 18.5Q^{0.65}.$$  

This relation is obviously biased with the results from Berger et al. (1975) ($I_p = 10.6Q^{0.7}$). Berger might consider part of the neutralized charge during the continuing current stage as a return-stroke process, so the neutralized charge value could be overestimated.

Fig. 3 shows the current waveforms of two return strokes of flash 0503 (2nd and 7th strokes). The left panels correspond to overall return-stroke waveforms, and the right panels to the time expanded waveforms. The current waveform average rise time from 30% to 90% peak in our case was about 0.8 $\mu$s, 2 times
higher than others (e.g. Rakov et al., 2005; Fisher et al., 1993). The possible reason is that we used a lower sample rate of 1 μs, and the rise-time value could be overestimated. The geometric mean value of half peak width was 39 μs (the average value was 40 μs), which was 4 times larger than the typical values by Rakov et al. (2005), and 30 times larger than that by Saba et al. (2005) for altitude triggered lightning. Saba et al. (2005) suggested that the higher peak current usually indicates a shorter duration of the strokes. Although the peak current in our case was similar to others, the duration was longer, thus the destructive power might be larger due to its long effect on the object.

3. The components of the current waveforms at the channel base

It is of general consensus that the dart leader current travels along a thin conducting channel, the central core having a diameter of not more than a few centimeters.
However, the charge brought down by the dart leader will not remain on this thin conducting channel, instead it will disperse outwards, owing to the high electric field, giving rise to the corona sheath with a diameter of about 2 m (Cooray, 1993; Maslowski and Rakov, 2006, 2007). At the tip of the leader, charges are predominantly deposited in the leader head because time is not sufficient for full radial expansion of the deposited charge. With increasing heights above the downward-moving tip, more and more charge may be deposited in the surrounding corona sheath and less charge in the leader core correspondingly. Therefore, it is reasonable to assume that the discharging process includes two components, a breakdown current from discharging the leader head and core, and a corona current from discharging the corona sheath (Cabrera and Cooray, 1992). The measured return-stroke current at the ground strike point in our experiment, as shown in Fig. 3, now is divided into two current components associated with the two physical processes above. Then each of the two components is calculated using the analytical expression suggested by Heliker (1985).

\[ i(0, t) = \frac{i_0}{\mu} \left( \frac{t}{\tau_1} \right)^2 e^{-t/\tau_2} \]  

where \( i_0 \) is the amplitude, \( \mu \) the amplitude correction factor, \( \tau_1 \) the current rise-time constant, and \( \tau_2 \) the current decay time constant. Eq. (1) is preferable to the commonly used double-exponential function (Uman and Mclain, 1969).

Fig. 4 shows the two comparisons of the simulated and measured return-stroke current waveforms, the left panel corresponds to the 2nd stroke, and the right panel to the 7th stroke; the dashed line is the simulated value, and the solid line is the measured value. By varying the discharging parameters, the best fit between the simulated and measured current waveforms for \( i_0, \mu, \tau_1 \) and \( \tau_2 \) are found and described in Table 1. The \( i_{BD} \) is the breakdown current from discharging the leader core, \( i_c \) is the corona current from discharging the corona sheath, and \( i(0, t) \) is total current \( (i(0, t) = i_c + i_{BD}) \). However, due to the lower sample rate of current waveforms in our experiment, the fitted discharging parameters \( \tau_{BD} \) and \( \tau_c \) are possibly overestimated.

### Table 1

<table>
<thead>
<tr>
<th>Parameters</th>
<th>( i_{BD} )</th>
<th>( i_c )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometric mean</td>
<td>11.9</td>
<td>6.9</td>
</tr>
<tr>
<td>Range</td>
<td>7.6–16.3</td>
<td>4.5–10</td>
</tr>
<tr>
<td>Geometric mean</td>
<td>0.6</td>
<td>0.6</td>
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<tr>
<td>Range</td>
<td>0.5–0.96</td>
<td>–</td>
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<tr>
<td>( \tau_{BD} ) (( \mu s ))</td>
<td>1.1</td>
<td>6.9</td>
</tr>
<tr>
<td>Range</td>
<td>0.9–1.2</td>
<td>4.5</td>
</tr>
<tr>
<td>( \tau_c ) (( \mu s ))</td>
<td>3.6</td>
<td>50</td>
</tr>
<tr>
<td>Range</td>
<td>3.5–3.3</td>
<td>40–55</td>
</tr>
</tbody>
</table>

**4. Simulation of lightning current waveforms along the channel**

Based on the DU return-stroke model, for a specified current at the ground strike point \( i(0, t) \) and a discharge time constant \( \tau_0 \) along the lightning channel, the current \( i(z, t) \) at a height of \( z \) is determined by Diendorfer and Uman (1990).

\[ i(z, t) = i(0, t_m) - i(0, z/v') e^{-t/\tau_0} \]  

where, \( t_m = t + z/c \), \( v' = v/(1 + v/c) \), \( t_c = t - z/v \), \( v' \) is the return-stroke speed, \( c \) is the light speed, and \( z \) is the height at time \( t \).

The current distribution \( i(z, t) \) along the channel can be depicted with Eqs. (1) and (2), respectively, by superimposing the currents corresponding to the breakdown current \( i_{BD} \) and the corona current \( i_c \) characterized by \( \tau_{BD} \) and \( \tau_c \).

Fig. 5 shows the simulated current waveforms at different heights in the channel ranging from 0 m to 5 km (0, 200 m, 500 m, 1 km, 2 km, 3 km, 4 km, and 5 km), corresponding to curves 1 to 8. The polarity of the plotted current waveform in Fig. 5 is inverted for comparison with the optical pulses characteristics along with the lightning channel (Wang et al., 2005). In Fig. 5a, \( i_{BD} \) and \( i_c \) are assumed to have the same time constant \( \tau_{BD} = \tau_c = 0.9 \mu s \), and found that the characteristics of the simulated current waveforms along the channel are not similar to the variation of light pulse waveforms observed by Wang et al. (2005). In Fig. 5b, due to the separation of corona and core discharging processes, \( \tau_{BD} \) and \( \tau_c \) are assumed to be 1.7 and 15 \( \mu s \) respectively, an increase of the current waveform rise time with channel height is found along with a similar decrease of the current peak, which is in agreement with the optical measurement.

![Fig. 5](image-url)
results (Wang et al., 2005), thus providing a partial justification for using the two different discharge constants. However, compared with the simulated current waveform given by Baba et al. (2004), their result attenuates more in the upper region of the return-stroke channel than that in Fig. 5b. The possible reason is that the fitted discharging parameters of current waveforms could be overestimated due to the low sample rate of 1 μs in our experiment.

5. Numerical simulation of the charge distribution along the channel

According to the continuity equation, the charge per unit length \( \rho(z,t) \) and the current \( i(z,t) \) in a return-stroke channel are given by

\[
\rho(z,t) = -\frac{i}{c} \frac{\partial i(z,t)}{\partial z} \, dt + \frac{i(z,t)}{\nu}.
\]

(3)

Combining Eqs. (2) and (3), we obtain the total charge density for the DU model, as described by Thottappillil et al. (1997)

\[
\rho(z,t) = -\frac{i(0,t+z/c)}{c} e^{-(t-z/c)/\tau_{bd}} \frac{\partial}{\partial z} \left[ \frac{i(0,z/\nu^*)}{\nu} + \tau_d \frac{di(0,z/\nu^*)}{dt} \right]
\]

\[
+ \frac{1}{\nu} \left[ \frac{i(0,z/\nu^*)}{\nu} + \tau_d \frac{di(0,z/\nu^*)}{dt} \right].
\]

(4)

The first three terms of Eq. (4) are the transferred charge density components, and the last two terms are deposited charge density components. The deposited charge on the return-stroke channel will neutralize the charges of the dart leader. At the return-stroke front, \( \rho(z,t) = 0 \), similar to the transmission line type models, but in contrast to the Bruce and Golde (BG) model and the traveling current source (TCS) model.

The transferred and deposited charge density distribution along the lightning channel below 5 km is plotted in Fig. 6a, corresponding to the current distribution from Fig. 5b. In Fig. 6a the charge density deposited along the channel during the return-stroke process neutralizes the leader charge, and decreases along the channel. In Fig. 6b the transferred charge density decreases with time, after a sufficient long time the current in the channel ceases to flow and the first three terms of Eq. (4), representing the transferred charge, become zero.

6. Results and discussion

In the summer of 2005 one negative lightning flash was successfully triggered in a positive surface electric field environment in Shandong Province (117°48′ E, 37°42′ N). This flash included 10 return strokes, the time interval between two strokes ranged from 18 to 210 ms with a mean interval of 87 ms, and the geometric mean value of the current peak was 11.9 kA with a maximum of 21.0 kA and a minimum of 6.6 kA, similar to the subsequent return strokes in natural lightning. The geometric mean value of half peak width was 39 μs (the average value was 40 μs), which was much larger than the usual value in other places, indicating that the destructivity might be larger due to its long time effect on the object. The return-stroke current peak \( I_p (\text{KA}) \) and neutralized charge \( Q(C) \) has a relationship of \( I_p = 18.5Q^{0.65} \). This relation is obviously biased with the results from Berger et al. (1975) \( I_p = 10.6Q^{0.7} \) who might consider part of the neutralized charge during the continuing current stage as a return stroke, so the neutralized charge value was overestimated.

The leader channel is usually considered to consist of a channel core surrounded by a radially formed corona sheath, so the return-stroke current measured at ground level can be divided into two components named a breakdown current and a corona current. Based on the DU model, the spatial and temporal variation of the current waveforms along the channel is predicted, and it is found that the simulated current waveforms are in good agreement with the optical measurement result if the discharge time constants are properly chosen (\( \tau_{bd} = 1.7 \mu s \) and \( \tau_c = 15 \mu s \)). However, due to the lower sample rate of current waveforms in our experiment, the fitted discharge parameters \( \tau_{bd} \) and \( \tau_c \) are possibly overestimated. It is found that some other return-stroke current models, such as TL, BG, MTLE, and MTLL, cannot predict the simulated current waveform in agreement with the optical measurement results along the channel. For example, the MTLE and MTLL models can predict the attenuation of the peak current along the lightning channel, but cannot simulate the increase of current waveform rise time along the lightning channel; the TL and BG model does not...
predict attenuation along the lightning channel. Therefore, compared with some other return-stroke models, the DU model is more physically reasonable and preferable in simulating the current along the lightning channel.

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