Reconstructing initial continuous current in rocket-triggered lightning with close magnetic measurement

Gaopeng Lu, Yanfeng Fan, Hongbo Zhang, Rubin Jiang, Mingyuan Liu, and Xiushu Qie
Key Laboratory of Middle Atmosphere and Global Environment Observation, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, 100029, China

gaopenglu@gmail.com

Steven A. Cummer
Electrical and Computer Engineering Department, Duke University, Durham, North Carolina 27606, United States

cummer@ee.duke.edu

Abstract— We present a new method that remotely measures the initial continuous current in classical rocket-and-wire triggered lightning using a compact dB/dt sensor deployed at 78 m distance from the channel base. The current waveform retrieved from the numerical integration of close magnetic signals perfectly shows the general feature and all the slow variations (such as M-components) embedded in the channel-base current measured with a shunt. This method was applied to several rocket-triggered lightning flashes in 2014, including one flash containing a long continuous current similar to that occurring in natural lightning. In comparison with the shunt measurement, the new method has the advantage of significantly reduced noise (with the lower detection threshold as small as a few mA). Our method could be applied to remotely probe the initial continuous current in upward lightning from high objects and altitude-triggered lightning, as well as continuing current in natural cloud-to-ground lightning strokes at a sufficiently close range.

Keywords—initial continuous current; long continuing current; rocket-and-wire triggered lightning; low-frequency magnetic sensor; remote sensing.

I. INTRODUCTION

The initial continuous current (ICC) is a characteristic process of the classical rocket-and-wire triggered lightning where a grounded metallic wire is released from an ascending rocket [Fieux et al., 1975; Hubert et al., 1984; Fisher et al., 1993; Lalande et al., 1998]. When the upward leader initiated from the wire undergoes a sustained development, the triggering wire becomes a conduit where electrical charge is continuously transported from the in-cloud reservoir to ground. With typical amplitude of 20-300 A and a relatively long duration (typically longer than 100 ms), the ICC usually accounts for the major charge transfer in rocket-triggered lightning [Hubert et al., 1984; Wang et al., 1999]. It has been observed that the initial continuous current is also present in both altitude-triggered lightning (where the lower portion of metallic wire is replaced with a nylon wire so that the ascending wire is not grounded) [Zheng et al., 2013] and upward lightning from tall objects [Miki et al., 2005; Diendorfer et al., 2009; Zhou et al., 2011]. The ICC in rocket-triggered lightning can be directly measured by applying a shunt (or a current transformer, such as Pearson coil) at the channel base [e.g., Qie et al., 2011], which makes it possible to precisely quantify the charge transfer in rocket-triggered lightning. However, one major problem is that the channel-base current spans a wide dynamic range so that the conventional measurement is usually set with a bias toward the return strokes typically with peak current in excess of 10 kA, and thus weak current pulses during the initial stage of triggered lightning and small variations superimposed on the initial continuous current usually cannot be precisely measured. Figure 1 shows an example of channel-base current (combining the measurements of 5-mΩ shunt and Pearson coil with different measurement ranges) for a rocket-triggered lightning flash during the SHandong Artificial Triggered Lightning Experiment in 2013 [Lu et al., 2014]. We can see that initial current pulses within 1 ms after the onset of a sustained upward positive leader might contain some pulses that are difficult to be resolved in the channel base current, primarily due to a relatively noise level (about 8 A) of the current measurement.

![Figure 1. Channel-base current measured for a rocket-triggered lightning flash on August 2, 2013 during the SHandong Artificial Triggered Lightning Experiment.](image-url)

Moreover, for altitude-triggered lightning where the triggering wire is not grounded and thus the lightning charge transfer usually does not follow the lightning rod, or upward lightning from high objects with a complicated grounding structure, the measurement of channel-base current demands substantially more efforts. Therefore, the new technique is desired to...
improve the capability to quantitatively measure the initial continuous current in situations where the lightning current flows through an unexpected strike point.

In this paper, we described an approach to remotely measure the initial continuous current through the measurement of low-frequency (LF) magnetic signals with a compact sensor deployed at 78 m distance from the channel base of rocket-triggered lightning. The numerical integral of magnetic signals is used to reconstruct the time-resolved waveform of channel-base current as measured by a shunt. One prominent advantage of our method, in addition to its easiness to implement, is that the background noise in the retrieved current waveform is considerably reduced so that the relatively slow variations (such as M-components with timescales typically longer than 200 μs) as weak as a few hundred mA can be readily discerned. It is also shown that this method will make it possible to remotely measure the continuing current in natural cloud-to-ground (CG) lightning for which the stroke location is usually unpredictable and thus the direct measurement of channel-base current is almost impossible.

II. MEASUREMENTS

During the SHandong Artificially Triggered Lightning Experiment (SHATLE) in summer of 2014, as sketched in Figure 2, two magnetic sensors were respectively deployed at distances of 78 m (on the roof of control room) and 970 m (at the main observation building) from the lightning triggering site. The channel-base current of rocket-triggered lightning was measured with both a 5-mΩ shunt (with bandwidth of 0-3.2 MHz) and a Pearson coil (with bandwidth of 0.9 Hz to 1.5 MHz), which have different measurement range of 8 A to 2 kA and 40 A to 30 kA, respectively. The two induction coils of magnetic sensor at 78 m range were oriented in azimuthal and vertical direction (relative to the lightning channel), respectively; the coils of sensor at the main observation site were oriented in north-south and east-west direction, respectively.

Due to the high sensitivity of our magnetic sensor [e.g., Lu et al., 2014], the measurement data acquired in summer of 2014 is subject to a saturation for fast magnetic pulses (with timescales of a few μs to 200 μs) with amplitude in excess of about 60 nT. In this paper, we mainly present the results for the analyses of two rocket-triggered lightning flashes on August 18 and August 23, respectively.

Figure 3 shows the ICC of the triggered lightning at 16:11:06 UTC on 23 August 2014. The snapshot image of this event is shown in the inset of Figure 2. As shown in Figure 3a, this is a relatively simple case of rocket-triggered lightning current by containing only the ICC that lasted about 120 ms, over which the total charge transfer accumulated to -5 C. About 20 ms after the initial current pulses driven by the stepping of a sustained upward positive leader that incepted when the rocket reached an altitude of 370 m (above the ground level, AGL), there was a distinct millisecond-scale variation typical to classical rocket-triggered lightning, which was linked to the disintegration of triggering wire and the following reestablishment of lightning current [Wang et al., 1999; Rakov et al., 2003].

Figure 3. (a) Time-resolved current waveform measured with a 0.5-mΩ shunt at the channel base for the rocket-triggered lightning at 16:11:06 UTC on August 23, 2014. (b) Time-resolved current waveform (absolute value in logarithmic scale) combined from the measurement with shunt and Pearson coil for the triggered lightning at 04:17:18 UTC on August 18, 2014. We can clearly see that the noise level of the channel-base current is approximately 8 A.

The channel-base current waveform measured for the triggered lightning at 04:17:18 UTC on August 18 was relatively complicated by comprising six subsequent strokes,
and the sixth stroke was followed by a long continuing current, similar to a rocket-triggered lightning flash examined by Zhou et al. [2013]. As the channel-base current for this event spans a broad range from ~10 A to 20 kA, we plot the time-resolved current waveform in logarithmic scale by combining the two measurements of channel-base current. It can be clearly seen that the noise level of the channel-base current using the shunt is about 8 A during the SHATLE measurement. The first long excursion of ~230 ms duration was the initial continuous current (ICC), which transferred a total of 18.4 C negative charge; after the ICC, there was the occurrence of a sequence of six subsequent strokes with peak current ranging between 2 kA and 18 kA. The last return stroke was followed by another long excursion of ~260 ms duration, which was caused by a long continuing current interrupted by several millisecond-scale variations called M-components [Rakov et al., 1995].

The triggered lightning at 04:17:18 UTC on August 18 will be examined as the main example in this paper; both initial continuous current and the long continuing current will be reconstructed from the close magnetic measurement.

The frequency response of magnetic sensors used in the observation, including the induction coil and amplifying circuit, is plotted in Figure 4. The 3-dB bandwidth of the magnetic sensor is 6-330 kHz; below 6 kHz, the sensor behaves roughly as a dB/dt sensor [Cummer et al., 2011]. Therefore, the relatively fast processes with time scales typically shorter than 1 ms in rocket-triggered lightning (such as return stroke, leader stepping, and K process) are mainly characterized by the B-sensor part; the relatively slow processes with time scales longer than 1 ms, such as continuing current (tens to hundreds of milliseconds) [Williams and Brook, 1963; Fisher et al., 1993; Miki et al., 2005], initial current and M-component (typically longer than 2 ms) [Qie et al., 2014], are primarily sensed by the dB/dt portion.

Figure 4. Frequency response of the low-frequency magnetic field sensor as measured in the laboratory, showing that the magnetic sensor works approximately as a B sensor between 6 kHz and 340 kHz, and as a dB/dt sensor below 6 kHz.

III. DATA AND METHOD

Figure 5 shows the measurement of channel-base current (Fig.5a) and magnetic fields recorded at 78 m (Fig.5b) and 970 m (Fig.5c), respectively, for the initial continuous current of rocket-triggered lightning on August 18, 2014. The height of rocket upon the inception of initial upward positive leader was about 245 m for this case, and the vertical scale of lightning channel visible in the high-speed video observation is at least 600 m. The initial current variation (ICV) is rather complicated for this case. In Figure 5a, the enhancement of current at 18.99 s (about 200 ms after the inception of positive leader) was an M-component with a relatively long timescale (~10 ms).

As shown in Figure 5b, the magnetic signals of initial current pulses are particularly clear in the measurement recorded at 78 m distance. These magnetic pulses were examined in details by Lu et al. [2016], which is associated with a burst of microsecond-scale deflections shown in the magnetic signals recorded at 78 m distance.

For the magnetic signals recorded at 970 m range, as shown in Figure 5c, the general pattern is significantly different. At a range from the channel base that is comparable to the vertical scale of lightning channel, other fast pulses are mostly linked to in-cloud processes. For example, the ICV was associated with a burst of magnetic pulses (over ~10 ms) that could be attributed to the stepping of positive leader when it enters the negative cloud region in the thundercloud [Lu et al., 2014]. For the rocket-triggered lightning during the SHATLE campaign, the triggering wire usually has been unreeled over 150 m long upon the occurrence of initial current pulses [Sun et al., 2014; Lu et al., 2015]. Before the ICC becomes discernible typically a few milliseconds later, the positive
leader still extends upward at a velocity ranging widely from 2×10^4 m/s to 1.8×10^4 m/s [e.g., Jiang et al., 2013]. Therefore, for a vertical current flow with relatively slow variations (e.g., longer than 1 ms), the magnetic field measured at 78 m distance from the channel base is related to the current through Biot-Savart law. Our earlier work that calculates the electromagnetic field radiated by lightning current based on the transmission-line model show that for current pulses with timescales longer than 1 ms, we have the following relationship,

\[
B_l(t) = \int_{t'=0}^{t} \frac{dB_l}{dt'} dt' = \alpha h(t)I(t),
\]

where \(h(t)\) is the height of lightning channel at time \(t\), and \(\alpha\) is the coefficient to be determined. In general, the magnetic field measured by the sensor also contains the background noise, \(B_n\), for which there is \(\int_{t'=0}^{t} \frac{dB_n}{dt'} dt' \approx 0\). Consequently, equation (1) can be rewritten as

\[
I(t) = \frac{1}{\alpha \cdot h(t)} \int_{t'=0}^{t} \frac{dB}{dt'} dt',
\]

where \(B=B_l+B_n\) is the magnetic signal recorded at 78 m distance. According to equation (2), we can numerically integrate the magnetic signal at 78 m distance to retrieve the current waveform flowing along the lightning path, for lightning current pulses with timescale longer than about 1 ms. For current pulses with relatively short time scales, such as 10 μs for the initial current pulses associated with the stepping of a sustained positive leader [Jiang et al., 2012], there is an approximate linear correlation between channel-base current and magnetic field [Lu et al., 2016].

We also applied the method described above to the magnetic fields measured at 970 m distance. One possible reason is that at a distance comparable to the vertical scale of lightning channel, the magnetic signal received by the sensor. Nevertheless, further experimental studies are desired to determine the range within which the method proposed in this paper is applicable to reconstruct the channel-base current waveform. As mentioned earlier in this section, the magnetic field measured at 970 m distance from the channel distance is dominated by the radiation from the in-cloud processes. For the magnetic field measured at 970 m distance, the signal contains more signals caused by fast discharges, such as K processes.

IV. RESULTS AND ANALYSIS

The method described above is applied to reconstruct the initial continuous current from the magnetic signals. In general, the current waveform can be retrieved with fairly high consistency, including the small millisecond-scale deflections (such as initial current variations and \(M\)-components). The same method has been applied to the initial continuous current measured for other rocket-triggered lightning measured for other rocket-triggered lightning in the summer campaign in 2014. For these events, the magnetic signals recorded at 78 m distance are subject to saturation at some part of the measurement (and therefore so far we have not made this method applicable for reconstructing the current waveform of return strokes). Therefore, we only reconstruct the current waveform for the unsaturated measurement, and the time-resolve current waveform can be generally reconstructed. In the future, the gain of magnetic sensor will be adjusted to be less affected by saturation. The analysis using the unsaturated measurement indicates that the calibration coefficient does not vary for different cases, implying that this technique is not sensitive to the geometry of lightning channel.

For the ICC in different triggered lightning, the value of proportional coefficient in equation (2) is almost identical, indicating that the coefficient is independent of the channel length. This is important for the practical application of this technique. We have also tried to reconstruct the saturated magnetic signal using the measurement of the vertical induction coil, but the result is not as good as that using the horizontal coil. Therefore, it is still desirable to install two coils with different (by a factor of ~1000) gains in the future measurement.

It should be noted that the treatment of continuing current in natural CG strokes could be complicated than that in the rocket-triggered lightning as investigated here. First of all, the stroke channel of natural lightning usually contains some tortuosity. Further numerical analyses are desired to explore the feasibility to use the dB/dt sensor as an effective tool to remotely detect the continuing current in natural CG strokes.

A. Retrieved current waveform

The channel-base current waveform reconstructed from the magnetic signal shown in Figure 5b using the method described in section 3 is plotted in Figure 6a, which is generally consistent with the measurement with shunt (Figure 5a). All the major features discerned in the shunt measurement are present in the retrieved current waveform. The good consistency between the retrieved current waveform and the measured current is largely caused by the fact that the ICC is mainly composed of charge transfer processes with timescales longer than 1 ms.
Figure 6. Comparison between direct measurement of channel-base current and initial continuous current reconstructed from the magnetic field data recorded at 78 km distance from the channel base.

Figure 6b compares the result of numerical integral with the shunt measurement with respect to the channel-base current measured around the time with abundant deflections in the current waveform. All the millisecond-scale variations (such as $M$-components) in the direct measurement could be distinctly resolved in the current waveform retrieved from the close magnetic field. The initial current pulses are not retrieved as these current pulses are of microsecond time scale.

To quantitatively demonstrate that the noise level in the channel-base current retrieved from the integral of close magnetic measurement is substantially reduced in comparison with the direct channel-base current measurement, we performed the Fourier transform of retrieved current waveform. Note that the numerical integral is also applied to the component above 6 kHz, and therefore we need to compensate by dividing the result of Fourier transform by the following equation

$$A(f) = \frac{1}{1 + j2\pi f / 6000} \quad (3)$$

As shown in Figure 7, the result of Fourier transform for the retrieved current waveform indicates that the reconstructed waveform is generally consistent with the measured one below about 6 kHz. The flat part of the component beginning approximately at 30 kHz is from the background noise. Therefore, from a technical perspective, the noise floor in the channel-based current retrieved from close magnetic field is only about 1/10 of that for the measurement with a shunt (namely the close magnetic field measurement can be used to detect the slow current variation as weak as a few hundred mA).

Figure 7. Fourier transform of channel-base current from the measurement with a shunt (blue line) and from the integral of close magnetic field (red line).

B. Long continuing current

The main advantage of our method to retrieve the time-resolved waveform of current pulses with relatively long time scale is that it is a remote sensing approach that does not anticipate the current flow to propagate through a desired location. Provided that the magnetic sensor is installed sufficiently close to the lightning channel, the current waveform could be reconstructed through the numerical integral of recorded magnetic signals.

In this section, we applied our method to the long continuing current (i.e., the second long excursion of ~270 ms in Figure 3b) that followed the sixth return stroke of triggered lightning at 04:17:19 UTC on August 18, 2014, demonstrating the possibility of using numerical integral of close magnetic signals to remotely detect long continuing current in natural CG strokes.

The broadband magnetic signals recorded at 78 m and 970 m distance are plotted in Figures 8b and 8c, respectively. As shown in the corresponding channel-base current, there are several $M$-components superimposed on the continuing current, leading to current surges with magnitude up to 500 A. The magnetic signal recorded at 78 m was saturated at the moments corresponding to the return stroke (with peak current of -19 kA) and the largest $M$-component.
Figure 8. Channel-base current (panel a) and magnetic fields (panels b and c for 78 and 970 m distance, respectively) measured for the continuing current in the triggered lightning at 0417:18 UTC on August 18, 2014.

Due to the saturation of magnetic pulse driven by the relatively strong $M$-component (with current peaking at 1.4 kA) at about 19.237 s, we processed the magnetic signals measured at 78 m distance in two separated time intervals divided by the $M$-component that caused the saturation. The current waveform retrieved from the numerical integration of close magnetic signals is shown in Figure 9.

Figure 9. Comparison between direct measurement of channel-base current and initial continuous current reconstructed from the magnetic field data recorded at 78 m distance from the channel base.

The $M$-component superimposed on the long continuing current can be well retrieved. One interesting observation related to $M$-component is plotted in Figure 10. The $M$-component is attributed to the interception of recoil leader with existing lightning channel. The LF magnetic signal recorded at 78 m distance is very interesting in that it indicates that the physical process leading to $M$-component as well as the direction measurement of current enhancement at the channel base due to the $M$-component (see Figure 11).

Figure 10. (a) Low-frequency magnetic signals recorded respectively at 78 m and 970 m distance from the channel base for an $M$-component during the rocket-triggered lightning flash at 04:17:19 UTC on August 18, 2014. (b) Current pulse for the $M$-component as measured by the 5-mΩ shunt and the waveform retrieved from the numerical integral of LF magnetic signal measured at 78 m distance.

DISCUSSIONS AND SUMMARY

In this paper, we describe a method based on the close magnetic field with low-frequency magnetic sensor to reconstruct the channel base current for the rocket-triggered lightning located at 78 m distance from the sensor. This method takes the advantage of two facts. First of all, the numerical integration of random noise goes to zero. Secondly, the continuing current usually contains charge transfer with time scales longer than 1 ms, for which at lightning magnitude field at 78 m distance is dominated by the induction component, which is approximately proportional to the current along the lightning channel. The method described in this paper could also be applied to the altitude-triggered lightning, where the lowest portion of triggering wire is nylon and therefore the direct measurement of initial continuous current is not available. The measurement of altitude-triggered lightning has rarely been reported except for a few cases where the downward leader happens to strike the lightning rod [e.g., Saba et al., 2005; Zheng et al., 2013]. Although the actual stroke location is always displaced from the rod, the stroke distance usually still satisfies that presumption that the induction component dominates the magnetic field. The rocket-triggered lightning is similar to the upward lightning initiated from tall buildings, where the initial continuous current is also commonly observed [Flache et al.,
2008; Zhou et al., 2011]. Although the situation is often complicated due to the geometry of structure, our method is probably suitable to remotely measure the initial continuous current of upward lightning from tall buildings. As one step toward developing a remote sensing method that is capable of measuring continuing current in natural CG strokes with relatively high resolution and dynamic range, we deployed a method to retrieve the time-resolution waveform of channel-base current with significantly reduced noise. In addition to providing an alternative means to remotely measure the channel-base current in rocket-and-wire triggered lightning, the method presented in this work makes it possible to record the current waveform.

Magnetic field measurements have been applied to measure the current of return strokes [Yang et al., 2008, 2010]. Therefore, it is desirable to develop a comprehensive procedure that remotely measures the channel-base current in both rocket-triggered lightning and upward lightning from tall buildings.

ACKNOWLEDGMENT

This work is supported by National Key Basic Research and Development Program (973) (2014CB441405), “The Hundred Talents Program” of Chinese Academy of Sciences (2013068), and National Natural Science Foundation of China (41305005). The data used for the analyses in this paper and the technical details of magnetic sensor are available upon request from Gaopeng Lu (gaopenglu@gmail.com).

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