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Bursts of Magnetic Pulses from Upward Positive Leader during the Initial Continuous Current of Rocket-Triggered Lightning

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Abstract**—**In this paper, we examined the bursts of magnetic pulses from upward positive leader during the initial continuous current of rocket-triggered lightning to reveal more details regarding the stepwise feature of positive leader during the initial stage of classical rocket-and-wire triggered lightning with broadband magnetic fields recorded at 78 m and 970 m distance from the channel base, respectively. The elongation of positive leader channel shortly after its inception generates a series of impulsive current pulses whose propagation along the triggering wire radiates the magnetic pulses recorded at two different distances. These current pulses are likely attenuated seriously as the positive leader becomes sufficiently long, while the subsequent elongation of positive leader seems to be achieved by the successive extension through the retrograding progression of negative breakdown similar to the negative recoil leaders.

Keywords—initial current pulses; rocket-triggered lightning; low-frequency magnetic sensor.

I INTRODUCTION

The initial stage of classical rocket-and-wire triggered lightning is defined as the interval that begins with the inception of a sustained positive leader from the triggering wire and ends at the termination of initial continuous current [*Miki et al.*, 2005; *Biagi et al.*, 2011]. The stepwise propagation of positive leader during the initial stage of triggered lightning has been noted in many studies. In our previous work, the sensitive low-frequency (LF) magnetic sensor that is originally designed to remotely probe distant lightning discharges [e.g., *Lu et al.*, 2013] has been applied to detect weak current pulses during the initial stage of rocket-triggered lightning [*Jiang et al.*, 2013]. With data acquired during the SHandong Artificially Triggered Lightning Experiment (SHATLE) in summer of 2013, we reported the observation of a burst of magnetic pulses recorded at 970 m distance from the channel base of a rocket-triggered lightning flash, which is attributed to the stepwise propagation of positive leader during the initial continuous current [*Lu et al.*, 2014].

To further explore whether this observation is common to rocket-triggered lightning, during the SHATLE campaign in 2014, we deployed two broadband magnetic sensors at distances of 78 m (on the roof of control room) and 970 m (at the main observation building), respectively, from the lightning triggering site. The observations of these impulsive pulses provide unambiguous evidence that the positive leaders propagates at a stepwise manner at least during some period early in rocket-triggered lightning. Also, the measurements at two different distances reveal some new features for the radiation mechanism of electromagnetic pulses during the upward progression of positive leader, as well as the stepwise propagation of positive leader during the initial stage of rocket-triggered lightning.

II Data and measurement

The measurement in 2014 was set up as sketched in Figure 1a. The low-frequency (LF) magnetic field was measured at the main observation site and the control room that are located at 970 m and 78 m distance, respectively, from the rocket launcher. The similar burst of magnetic pulses during the ICC stage is observed for all the nine rocket-triggered lightning flashes in 2014. In this paper, we focus the analysis on triggered lightning at 04:17:18 UTC on August 18, 2014. We examine this event because the channel-base current is relatively simple by containing one relatively short initial continuous current (with duration of approximately 100 ms). The total charge transferred by the ICC to ground is estimated to be only -5 C.

As shown in Figure 1b, the upward positive leader is initiated when the rocket reached an altitude (above the ground level, AGL) of 245 m. The field of view for the high-speed camera operated at 970 m distance from the channel base was not sufficiently large to capture the entire positive leader channel.

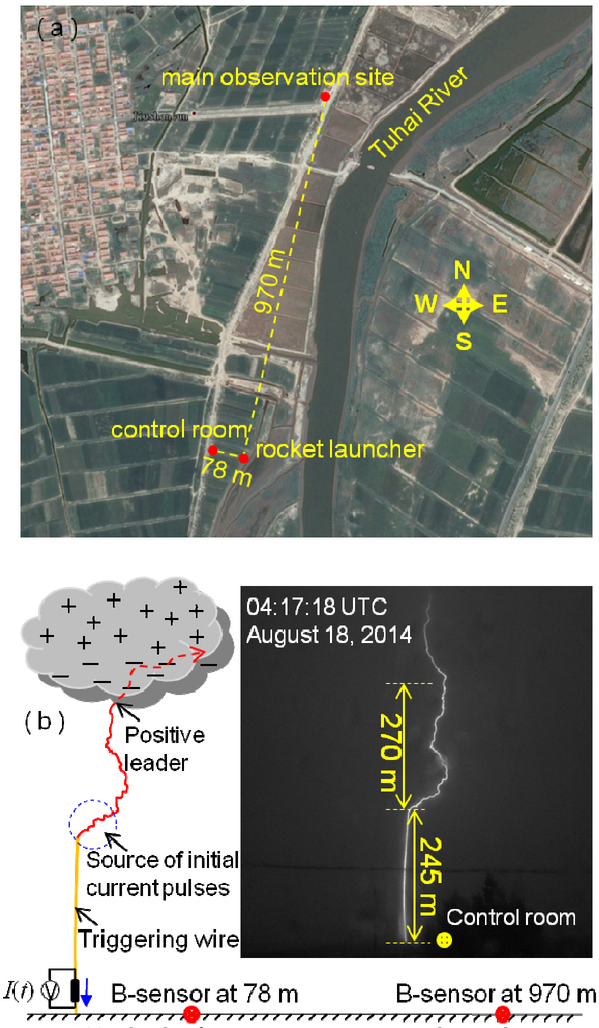

Figure 1. (a) Sketch of magnetic measurements during the SHantong Artificial Triggered Lightning Experiment in summer of 2014. (b) Magnetic fields (red line) measured at 78 m distance in comparison with the channel-base current (black line) measured with a 5-mΩ shunt during the initial stage (until the initial continuous current) of the triggered lightning at 04:17:18 UTC on August 18, 2014 (shown in inset of Figure 2a).

The 3-dB bandwidth of induction coil magnetic sensor with the amplifying circuit used in our measurements is 3-400 kHz; below 3 kHz, the sensor functions as a dB/dt sensor. At the main observation site, the data were recorded continuously at 1 MHz sampling rate; at the control room, the magnetic signals (and the channel-base current waveform) were recorded in trigger mode at 10 MHz sampling rate.

III Characterization of initial current pulses

The burst of magnetic pulses during the initial continuous current was observed for all the nine triggered lightning flashes in 2014, demonstrating that the serendipitous observation reported by *Lu et al.* [2014] is a common phenomenon for the rocket-triggered lightning of negative polarity (namely the initial upward leader is positive). Figure 2 shows the typical observation for the triggered lightning shown in the inset of Figure 1b.

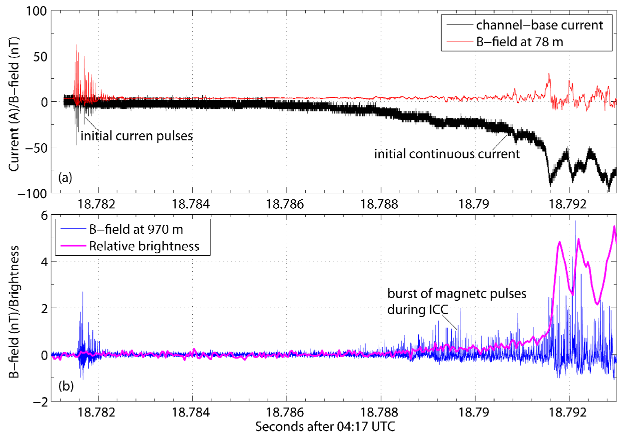

Figure 2. (a) Channel-base current and low-frequency magnetic fields at 78 m distance and (b) low-frequency magnetic fields at 970 m for the rocket-triggered lightning at 04:17:18 UTC on August 18, 2014.

For this rocket-triggered lightning flash, the leader channel was barely visible in the high-speed imagery when the channel-base current reached about 20 A. During the ICC, the negative charge is continuously transported to ground through the lightning channel. The examination of in-cloud activity during the ICC using the very high-frequency (VHF) mapping results indicates that there are not many VHF sources during the ICC, while the upward progression of positive leader prior to the ICC is active in VHF radiation [*Sun et al.*, 2014].

As shown by the magnetic signals recorded at 78 m distance from the channel base, the initial current pulses registered at the channel base were associated with a sequence of magnetic pulses. These initial magnetic pulses were also recorded at 970 m distance.

The burst of magnetic pulses became obvious about 6 ms after the inception of positive leader and lasted over 6 ms, and the largest pulse appeared to be twice as strong as the biggest initial magnetic pulse. Similar to the case examined by *Lu et al.* [2014], there is not significant difference between the inter-pulse interval during the initial magnetic pulses and the burst of magnetic pulses during the ICC stage.

As shown in Figure 2a, the resolution in the channel-base current measurement is relatively poor so that the detailed variation cannot be resolved clearly. Therefore, we choose to examine the temporal integral of current, namely the cumulative charge transfer through the channel base, during the upward progression of positive leader in comparison with the low-frequency magnetic field recorded at 970m distance. With this method, the noise in the current measurement will be significantly reduced as the temporal integral of noise always goes to zero.

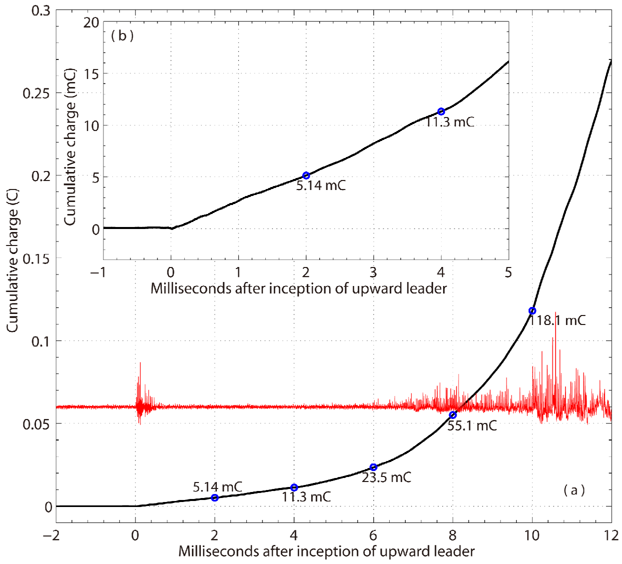

Figure 3. (a) Cumulative charge transferred during the upward propagation of positive leader after the inception in comparison with the low-frequency magnetic field recorded at 970 m distance. (b) Cumulative charge transfer within 5 ms after the leader inception.

B. Positive leader during initial current pulses

Within 0.8 ms after the inception of upward positive leader, as shown in Figure 3a, a series of magnetic pulses were recorded in association with the initial current pulses registered at the channel base. After 0.8 ms, although there is no visible magnetic pulse recorded at 970 m distance, the cumulative charge transfer continues to increase steadily. As shown in the inset Figure 3b, within about 4 ms after the leader inception, the charge transfer increases almost linearly, which indicates that although there is no associated magnetic pulses recorded at both 78 m and 970 m distance, the positive leader continues to propagate upward without significant difference from the initial development. However, the radiation mechanism for the magnetic field changes.

The simulation with a transmission line model has been shown to reproduce the magnetic pulses recorded at 78 m distance [*Fan et al.*, 2016]. In this model, it is presumed that the magnetic pulses recorded at both 78 m and 970 m distance are driven by the propagation of a current pulse along the triggering wire; the current pulse is launched by the stepwise extension of positive leader. As the positive leaders becomes longer, the resistance of lightning channel becomes lager and therefore the propagation of current pulse is subject to a serious attenuation At some stage during the upward propagation of positive leader, the current pulse reaching the upper end of triggering wire is no longer of impulsive form, and therefore the magnetic pulse is no longer measurable. Based on the correlation between the initial current pulses and corresponding magnetic pulses, it is estimated that the magnetic sensor deployed at 78 m distance from the triggered lightning rod could measure impulse current pulse as small as 0.5 A. Hence, the magnetic sensor could be used as an stand-alone device to register weak lightning discharge events during artificially triggered lightning.

C. Positive leader during the initial continuous current

Based on the discussions above, the resistance of leader channel has been very high at about 6 ms after the inception of leader [*Bazelyan and Raizer*, 1998] so that the current pulse associated with the stepping of positive leader cannot reach the triggering wire. Therefore, the burst of magnetic pulses recorded between 6 ms and 12 ms needs a different explanation. In this paper, we found that a dipole model is sufficient to explain the occurrence of these magnetic pulses.

A detailed examination of leader extension during the ICC indicates that the two-dimensional (2D) length of leader extension between two adjacent pulses is about 1.5 meters [e.g., *Biagi et al.*, 2011; *Hill et al.*, 2012]. Therefore, the dipole model is reasonable as the physical dimension of the current pulse is much smaller than the distance (about 1 kilometer) between the radiating source and the magnetic sensor. These pulses are actually also visible in the magnetic signals recorded at 78 m distance, although at this distance the magnetic signals driven by the current flow associated with individual positive leader stepping dominate.

Therefore, the radiation mechanism of magnetic pulses recorded at the initial stage and during the ICC of triggered lightning seems to be fundamentally different. The propagation of positive leader at the initial stage appears to be very quite at the low-frequency band, while it becomes an active radiator during the ICC stage.

IV Summary and discussions

During the summer of 2014, the low-frequency magnetic fields recorded at 78 m and 970 m distance in the SHATLE experiment indicates that the burst of magnetic pulses during the initial continuous current as reported by *Lu et al*. [2014] is common in rocket-triggered lightning at SHATLE. In this paper, we examined in details the observation for one typical event to reveal some features on the stepwise propagation of positive leader during the initial stage of rocket-triggered lightning.

The magnetic pulses corresponding to the initial current pulses are driven by the propagation of current pulses launched by the stepping of positive leader, which itself does not seem to be a strong source of LF radiation. As the positive leader propagates upward, the channel resistance becomes larger and the current pulse is subject to a serious attenuation so that the current pulse reaching the upper end of triggering wire is no longer an impulsive input.

The burst of magnetic pulses produced during the initial continuous current is most likely attributed to the fast negative breakdown occurring in a retrograding manner along the positive leader, and therefore the associated magnetic pulses could be simulated as a dipole radiation, which is clearly different from the radiation manner of upward positive leader shortly after the inception from the tip of triggering wire.

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