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Characterization of Initial Current Pulses in Rocket-Triggered Lightning with Sensitive Magnetic Sensor

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***Abstract*—**We report the new measurement of initial current pulses in rocket-triggered lightning with a broadband magnetic sensor at 78 m distance. The high sensitivity of our sensor makes it possible to detect weak ripple deflections (as low as 0.4 A) that are not readily resolved in the conventional measurements of channel-base current during the SHandong Artificially Triggered Lightning Experiment (SHATLE). The discernible magnetic pulses within 1 ms after the inception of a sustained upward positive leader from the triggering wire can be classified into impulsive pulses and ripple pulses according to the discernibility of separation between individual pulses. The timescale (usually >20 μs) of ripple pulses is substantially longer than the leading impulsive pulses (with timescales typically <10 μs), and the amplitude is significantly reduced, whereas there is no considerable difference in the inter-pulse pulse. Along with our previous finding on the burst of magnetic pulses during the initial continuous current (ICC) in rocket-triggered lightning, the new measurements confirm that the step-wise propagation is a common feature for the upward positive leader in rocket-triggered lightning, while the stepping of positive leader prior to ICC is predominantly manifested by ripple pulses. The precedence of impulsive magnetic pulse measured at 78 m distance relative to the arrival of corresponding current pulse at the channel base indicates that the ionization wave launched by individual stepping of positive leader propagates downward along the existing lightning channel and triggering wire at a mean velocity of 1.23×10^8 m/s to 2.25×10^8 m/s.

Keywords*—*initial current pulses; impulsive and ripple pulses; rocket-triggered lightning; low-frequency magnetic sensor; positive leader stepping

I INTRODUCTION

In the classical rocket-and-wire triggered lightning, a rocket tailing a thin copper (or steel) wire is launched into the air at a velocity of ~100-200 m/s [Fieux et al., 1975; Hubert et al., 1984; Lalande et al., 1998]. As the triggering wire is connected to a grounded metallic rod, the ground potential is immediately brought to the altitude of ascending wire. When the potential gradient around the wire tip is sufficiently strong, attempted breakdown into ambient air will occur, causing transient current pulses; under favorable situations, the breakdown will lead to the inception of a sustained positive leader that extends in a stepwise manner [Yoshida et al., 2010], driving a sequence of current pulses (called precursor or initial current pulses) carrying negative charge that propagate from the leader tip downward to the channel base [Willett et al., 1999; Biagi et al., 2011]. The magnitude of initial current pulses measured at the channel base is usually below 100 A, and the associated charge transfer is typically on the order of 10 μC [Lalande et al., 1998; Jiang et al., 2013].

As a proxy for characterizing the leader inception and propagation, the initial current pulses are usually measured at the channel base with a shunt or current transformer (such as a Pearson coil) [Fisher et al., 1993; Qie et al., 2011; Biagi et al., 2012], and the associated electromagnetic radiation could also be measured at close range [Schoene et al., 2003; Wang et al., 2012]. However, because the current flowing through the channel base during the lifetime of triggered lightning spans a wide range from a few A to several tens of kA [Fisher et al., 1993; Thottappillil et al., 1995; Wang et al., 1999], the dynamic range of measuring system is often not sufficient to resolve weak current pulses below the detection level, and thus is not fully capable of characterizing initial current pulses and the associated positive leader stepping in rocket-triggered lightning. Therefore, additional measurements with higher sensitivity are desired to characterize the initial current pulses associated with leader inception and subsequent propagation in the rocket-triggered lightning.

During the SHATLE campaign in summer of 2014, a broadband magnetic sensor with two orthogonal induction coils was deployed at 78 m distance from the lightning rod (made of copper), and the similar sensor was adopted by Lu et al. [2014] to reveal the burst of magnetic pulses measurable at 970 m distance from the channel base during the initial continuous current of rocket-triggered lightning. The high sensitivity of our magnetic sensor makes it an auxiliary tool to characterize weak current pulses that could also be measured by conventional techniques with considerably more efforts, providing a convenient remote-sensing approach to characterize initial current pulses in rocket-triggered lightning. Also, the concurrent measurement of channel-base current and magnetic fields at close range likely provides a new method to estimate the downward propagating velocity of current pulses launched by individual positive leader stepping.

II Data and measurement

A. Setup of measurements

The installation of SHATLE has been introduced in detail before this paper[e.g., Qie et al., 2009], note that the two-axis magnetic sensors which consists of two orthogonal induction coils were installed on the roof of a control room located 78 m to the northwest of the rocket launching facility and the main observation building at 970 m range from the channel base respectively(see Figure 1a). Along with the signal preconditioning and amplifying circuit modified from the sensor that was most sensitive to 20-400 kHz lightning signals [Lu et al., 2014], the magnetic sensor used in this measurement had a broader 3-dB bandwidth of 6-340 kHz(see Figure 2a). The relatively high sensitivity of magnetic sensor (with scale factor of ~0.1 V/nT) makes it possible to detect weak current pulses below the detection level (~8 A) of conventional channel-base current measurement. Two high-speed cameras, Phantom V711 (25,000 fps) and M310 (3,200 fps) were also installed in the main observation building to acquire the image sequence of leader progression after the inception from triggering wire (made of steel), making it possible to determine the height of rocket upon the inception of a sustained upward positive leader (as listed in Table 1), as well as the height of leader stepping linked to relatively large initial current pulses [e.g., Lu et al., 2008; Biagi et al., 2011; Jiang et al., 2013]. Both channel-base current and magnetic signals were sampled at 10 MHz with 12-bit amplitude resolution using a Yokogawa DL750 digitizing oscilloscope. In this paper, the polarity of magnetic field driven by a negative current pulse propagating downward through the channel base is defined to be positive (in the cylindrical coordinate system centered at the channel base). Because of the limited range of input voltage for the digitizing oscilloscope, the magnetic measurement is saturated at about 60 nT.

Table 1.

Date	Time (UTC)	$H_{pl,inception}$ (m, AGL)	$H_{pl,full}$ (m)	Type of channel-base current	Video observation
August 13	04:10:32	260	>150	ICC only	M310
August 18	04:13:28	140	101	ICC only	M310, V711
	04:17:18	245	270	ICC-RSs with CC	M310, V711
August 23	16:11:06	360	>293	ICC only	M310, V711
	16:29:52	152	112	ICC only	M310, V711

B. Initial magnetic pulses of positive leader

The data examined here are obtained for five rocket-triggered lightning flashes on three days in August of 2014 (see Table 1). All of these triggered lightning flashes were of negative polarity (i.e., negative charge was transferred from cloud to ground during the flash) according to the concurrent electric field (E-field) change data on the ground.

Figure 1b show the measurement of initial current pulses in comparison with the magnetic fields recorded at 78 m distance from the channel base for the rocket-triggered lightning at 0417:18 UTC on August 18, 2014, for which the upward positive leader initiated when the rocket reached an altitude of 245 m, illustrating the context of initial current pulses examined in this paper. As shown in the figure, within a few milliseconds after the onset of initial positive leader (at time 0), the magnetic sensor at 78 m range recorded a sequence of magnetic pulses. In addition to the first magnetic pulses with prominent impulsive feature corresponding to the pulses that can be readily discerned in the current waveform within 0.5 ms after the onset of positive leader, the magnetic recording exhibits a longer sequence of periodic deflections with significantly reduced amplitude (ripple-like deflections shown in inset) for which the associated current pulses could not be identified in the channel-base current waveform, demonstrating the capability of our magnetic sensor to characterize weak current pulses associated with the positive leader progression.

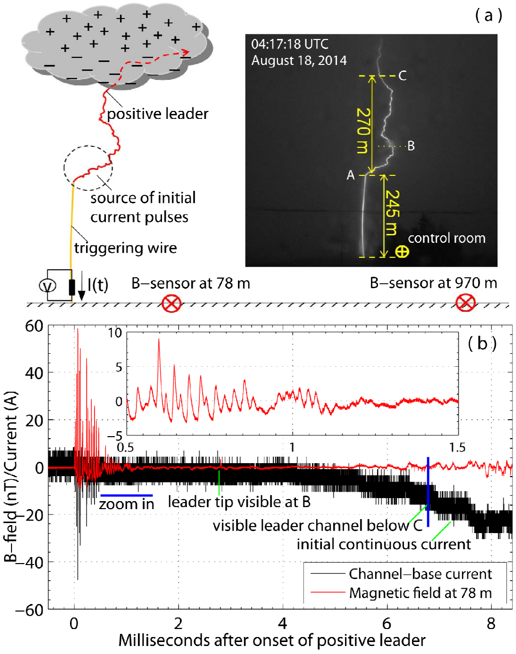

Figure 1. (a) Sketch of magnetic measurements during the SHantong Artificial Triggered Lightning Experiment in summer of 2014. (b) Magnetic fields (red line) measured at 78 m distance in comparison with the channel-base current (black line) measured with a 5-mΩ shunt during the initial stage (until the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

In this paper, the magnetic pulses recorded at 78 m distance from the channel base during the initial stage of rocket-triggered lightning are classified into two categories, namely impulsive pulses and ripple pulses, according to the discernibility of separation between adjacent pulses. For the impulsive pulses, due to a relatively short timescale (namely the duration of magnetic signal radiated by each current pulse) ranging from 4 μs to 10 μs, there is a distinct separation from the following pulse; for the ripple pulses, the temporal separation between two adjacent magnetic pulses is difficult to resolve (because two pulses are partially overlapped), and thus the pulse duration could not be easily determined although it is almost certainly longer than the inter-pulse interval (defined as difference between the peak time of adjacent pulses, typically around 20 μs). As shown in Figure 2d, the impulsive pulses could also be discerned in the magnetic field recorded at 970 m distance from the channel base, while the ripple pulses are hardly identified.

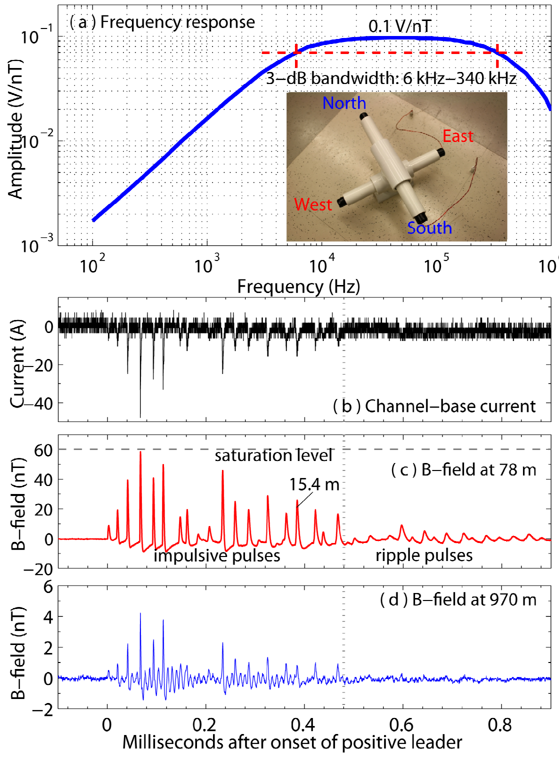

Figure 2. (a) Frequency response of the broadband magnetic sensor used in the triggered lightning experiment in 2014 at the SHATLE. (b) Initial current pulses measured at the channel base and corresponding magnetic pulses measured at 78 m distance (panel c) and 970 m distance (panel d), respectively, from the lightning rod for the triggered lightning at 04:17:18 UTC on August 18, 2014. For one magnetic pulse at about 0.38 ms after the inception of positive leader, the leader tip is determined to be 15.4 m above the inception altitude at 245 m (see Table 1).

III Characterization of initial current pulses

A. Variation in magnitude and time scale

In this section, we present the main results on the characterization of initial current pulses with broadband magnetic signals recorded at 78 m distance for five classical rocket-triggered lightning flashes during the summer of 2014. In general, the impulsive pulses dominate the signal strength with magnitude typically above 20 nT, whereas the ripple pulses measured at 78 m distance from the channel base are usually weaker than 20 nT. In addition to the distinct contrast in magnitude, there is a major difference in the duration of pulses in two categories. As shown in Figure 3, in the first period of 0.42 ms dominated by impulsive pulses, the timescale of magnetic pulses is as short as 8 μs and typically less than 10 μs, whereas for the subsequent 0.42 ms predominated by ripple pulses with reduced amplitude, the timescale of individual magnetic pulses can only be estimated to be longer than the inter-pulse interval (about 20 μs) due to the partial overlapping. Over the equally long time window, two panels contain almost the same number of pulses (approximately 20 pulses in each), indicating that there is no significant change in the occurrence rate of pulses. Therefore, the appearance as impulsive pulses or ripple pulses is primarily caused by the variation in the timescale of individual pulses.

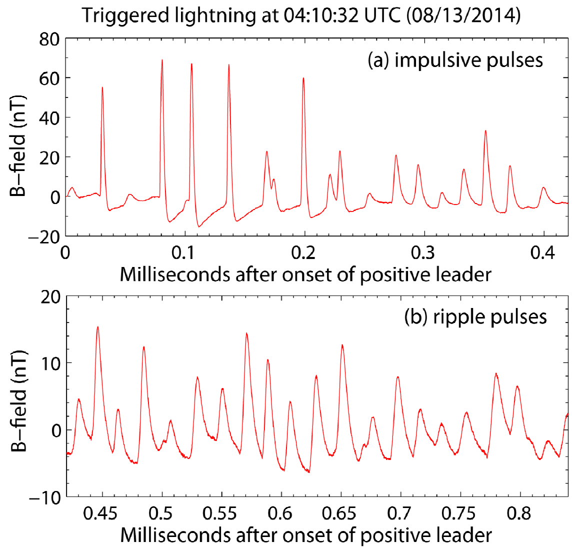

Figure 3. Comparison between magnetic pulses during the two consecutive 0.42 ms intervals dominated by impulsive pulses and ripple pulses, respectively, showing different timescales of magnetic pulses during these two intervals.

There is approximately a linear correlation between the magnitude of initial current pulse and corresponding magnetic pulse. Figure 4 shows the linear fitting results for four triggered lightning flashes with good measurements of both channel-base current and magnetic fields; for the triggered lightning on August 13, the current measurement used a reduced gain so that the initial current pulses were not well resolved. The coefficient of linear fitting varies between 1.52 nT/A and 1.79 nT/A for the four cases (each with 10-15 pulses suitable for the analysis), demonstrating the feasibility of using the magnetic sensor as a stand-alone instrument to remotely detect weak current pulses in rocket-triggered lightning with good accuracy. According to the linear coefficient between magnetic field and current derived above, the lowest current pulse reaching the channel base that could be comfortably resolved with magnetic measurement at 78 m distance is estimated to be 0.4 A, which is substantially lower than the noise level (~8 A) of conventional channel-base current measurement during SHATLE. For the rocket-triggered lightning examined in this paper, the minimum (first) current pulse associated with the initiation of a sustained positive leader was ~3.2 A, and the associated charge transfer was approximately 12 μC.

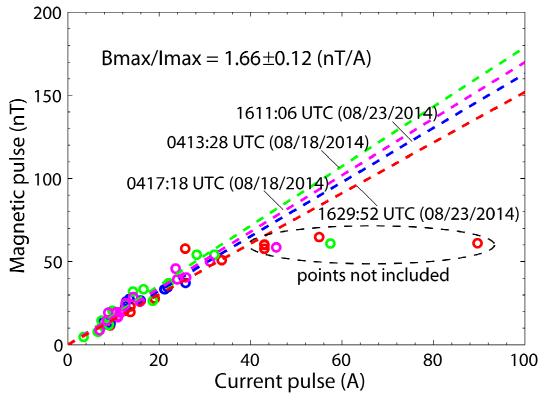

Figure 4. Relationship between initial current pulses (measured at the channel base) and associated magnetic fields measured at 78 m distance for four triggered lightning flashes. The seven measurements (corresponding to current pulses with magnitude greater than 40 A) subject to a saturation of magnetic field are not included in the analysis of a correlation between the magnitude of magnetic pulses and current pulses.

B. Statistics of inter-pulse intervals

By dividing the sequence of magnetic pulses associated with the initial current pulses into two intervals of impulsive pulses and ripple pulses, respectively, we examined the statistics of inter-pulse interval for pulses in two categories. According to the histogram in Figure 5, the intervals between adjacent magnetic pulses in each category is typically around 26 μs, consistent with previous measurements [Biagi et al., 2011; Wang et al., 2012; Jiang et al., 2013]. There is no significant difference between the typical inter-pulse interval for the impulsive pulses and ripple pulses. Nevertheless, our analysis suggests that the stepwise propagation is a common feature for the upward positive leader in rocket-triggered lightning within quite a few ms after its inception, but the magnitude of impulsivity might vary considerably during the progression of positive leader.

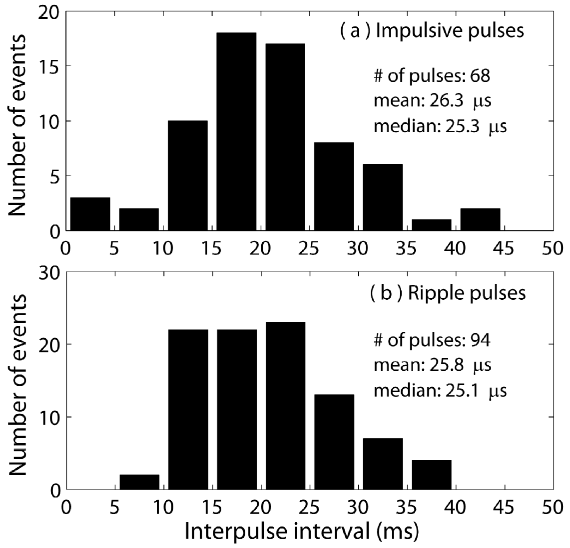

Figure 5. Statistics of inter-pulse intervals for (a) impulsive pulses and (b) ripple pulses during the initial stage of triggered lightning.

C. *Propagation velocity of initial current pulses*

As sketched in Figure 6a, upon the occurrence of a positive stepping, the magnetic pulse propagates at the speed of light (c) to the sensor; meanwhile, the launched current pulse propagates at a different speed to the channel base. For the triggered lightning examined in this paper, it is commonly observed that the magnetic pulse of positive stepping was received before the associated current pulse reaching the channel base, indicating that the current pulse propagates at a speed (v) smaller than *c*. Biagi et al. [2012] attributed the current propagation speed being less than the speed of light to the increased capacitance per unit length. As the current pulse propagates along both the existing leader channel (less than 10 m for impulsive pulses) and the triggering wire (usually longer than 100 m), we can only estimate the mean velocity for the downward propagation of current pulse before reaching the ground. Figure 6b shows an example (for the triggered lightning shown in Figure 1) where the arrival of magnetic pulse precedes the current pulse by 0.6 µs (with 0.1 µs uncertainty due to the sampling interval) as determined by identifying the first data point at least two times of the average noise level in each measurement. All the systematic delays (e.g., the transmission delay in the current and magnetic signal from sensors to the digital oscilloscope) have been taken into account when calculating this time different.

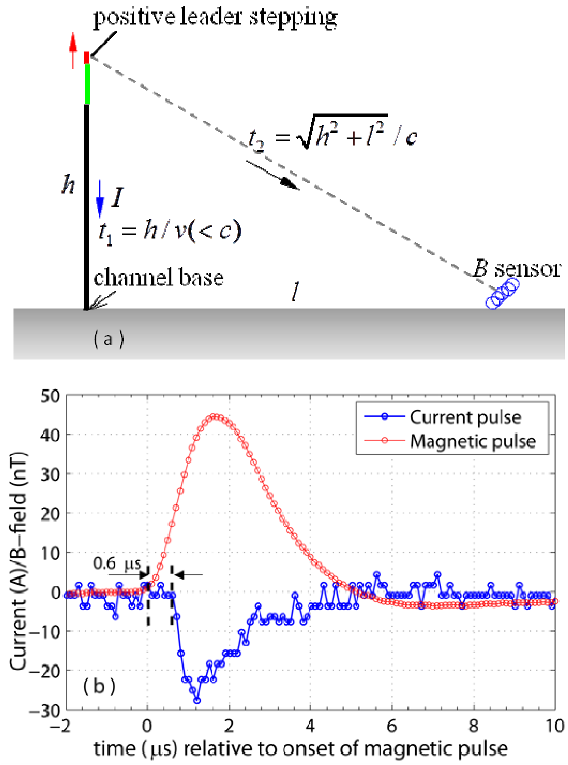

Figure 6. (a) Schematic diagram for the propagation of initial current pulses to the channel base and the propagation of corresponding magnetic signal to the sensor. The current pulse is driven by the positive leader stepping (red segment, at an altitude of *h* above the ground level), and propagates downward along the existing leader channel (green segment) and the triggering wire (black segment). (b) The difference between the time of arrival for the initial current pulse and corresponding magnetic pulse measured at 78 m range is determined with the first data point at least two times of the average noise level in each measurement (with the signal transmission delay from the sensor to the oscilloscope is taken into account for both measurements).

By presuming that the lightning channel is vertical to ground, this time difference is calculated as follows,

$$\Delta t = t_1 - t_2 = h / v - \sqrt{h^2 + l^2} / c \quad (1)$$

where h is the height of leader tip (as listed in Table 1), and l is the distance from the channel base to the magnetic sensor.

For the magnetic pulses associated with relatively intense current pulses (e.g., >40 A), the determination of arrival time is not affected by the saturated waveform. However, due to the limited resolution (~3 A) in the current measurement, it is difficult to comfortably indentify the onset of current pulse. We only selected a small number of pulses for which the time difference can be constrained with relatively small uncertainty (⩽0.1 µs). Given the rocket altitude upon the occurrence of initial current pulses, we estimated the velocity of current pulses propagating downward the wire for different triggered lightning according to equation (1).

For the four cases of triggered lightning on August 18 and 23 with good channel-base current measurement (Table

1), the rocket height upon the occurrence of initial current pulses varies between 140 m and 360 m, and the estimated velocity of current pulses propagating from the leader tip downward to the channel base ranges from 1.23×10^8 m/s to 2.25×10^8 m/s (or 0.41c to 0.75c, where c~3.0×10^8 m/s is the speed of light in the air). The estimated velocity varies 5-8% (due to the 0.1-μs variance when determining the difference between the time of arrival for current pulse and magnetic pulse) around a mean value for individual pulses during the same upward positive leader. Apparently, the downward propagating speed of current pulses is much faster than the two-dimensional (2D) speed of upward positive leader (typically ranging from 1.0×10^4 m/s to 2.0×10^5 m/s) as inferred from the high-speed video imaging [Lu et al., 2008; Biagi et al., 2009, 2011; Jiang et al., 2013] and very-high frequency (VHF) lightning mapping observations [Dong et al., 2001; Yoshida et al., 2010; Hill et al., 2012; Sun et al., 2014].

Our results are appreciably smaller than that (decreasing from 0.93c to 0.76c as the wire-top height increases from 80 m to 340 m, for the copper triggering wire) derived by Biagi et al. [2012] based upon the oscillatory waveform of precursor current pulses measured at the channel base. The apparent difference could be explained as that our method estimates the average velocity over the entire propagation path from the tip of positive leader to the channel base, whereas Biagi et al. [2012] derived the instantaneous speed at the lowest segment of the triggering wire. Further efforts are desired to investigate the variation in the velocity of downward propagating current pulse launched by individual positive stepping when it approaches the ground.

IV Summary and discussions

In this paper, we examined the initial current pulses in rocket-triggered lightning with the broadband (with 3-dB bandwidth of 6 kHz to 340 kHz) magnetic field measured at 78 m distance from the channel base. With a relatively high sensitivity, our magnetic sensor is able to detect signals from transient current pulses with magnitude as weak as 0.4 A launched by the individual stepping of positive leader, and thus provides a convenient approach of remote sensing to characterize the propagation of positive leader during the initial stage of classical rocket-triggered lightning.

For the rocket-triggered lightning examined in this work, the initial current pulses usually appear first as 10-15 impulsive pulses (with timescales typically <10 μs) within about 0.4 ms after the inception of an upward positive leader, and then as ripple pulses with substantially reduced amplitude (typically <20 nT) and longer timescales (>20 μs). The observation of impulsive pulses and ripple pulses, along with our previous report on the burst of magnetic pulses during the initial continuous current [Lu et al., 2014], suggests that the stepwise propagation is a common feature of positive leader early in the rocket-triggered lightning. On a statistical basis, there is no major difference between the inter-pulse intervals for pulses in these two categories, which both have typical inter-pulse intervals of about 25 μs. However, the variation in the magnitude and timescale of current pulses does demonstrate an impact of the elongation of positive leader channel, presumably due to the increasing channel resistance [Biagi et al., 2009].

Using the linear correlation between impulsive magnetic pulses and corresponding current pulses, we inferred that the minimum current pulse associated with the inception of a sustained positive leader was about 3.2 A (roughly half of the resolution of shunt measurement), which could not be readily resolved with the shunt measurement of channel-base current during SHATLE.

It is generally observed that the impulsive magnetic pulse radiated by the positive leader stepping arrived at the magnetic sensor 0.40 to 0.70 μs before the associated current pulse reached the channel base. Using this delay that can be reliably determined for relatively large current pulses, the downward propagating velocity of current pulses launched by the stepping of positive leader is estimated to be 0.41c to 0.75c (or 1.23×10^8 m/s to 2.25×10^8 m/s). Our results show a trend that the velocity of downward propagation is larger when the positive leader initiates at a higher altitude, which is desired to be further examined through concurrent measurement with higher sampling rates and better resolution of channel-base current.

In summary, the measurement with a sensitive magnetic sensor close to the channel base (at 78 m distance in this paper) proves to be an effective and convenient approach (as a remote sensing technique) to characterize the initial current pulses of rocket-triggered lightning, which is very useful to obtain more insights on the inception and sustained growth of positive leader. The method described in this paper to examine the stepping of positive leader in artificially triggered lightning could also be applied to study the upward lightning leader from tall buildings [Miki et al., 2005; Zhou et al., 2011; Gao et al., 2014], especially for the spontaneous initiation without invoking triggering lightning strokes [e.g., Jiang et al., 2014].

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