Burst of intra-cloud discharges during initial continuous current in a rocket-triggered lightning flash

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Abstract: The measurement with one pair of low-frequency (30-300 kHz) magnetic induction coils with high sensitivity reveals a long sequence of small intra-cloud discharges accompanying the initial continuous current in a rocket-triggered lightning flash on August 3, 2013. The time-scale of these small discharges is about 2-4 μs and the inter-pulse interval is typically 20 to 45 μs. These discharges, which are not readily detectable in the very high-frequency (VHF) range in this case, most likely occurred as the stepping process of a positive leader as it progressed into a negative cloud charge region in the lower part of thunderstorm. The varying magnitude of these magnetic pulses is largely caused by the variation in the direction of positive leader propagation as resolved by a short-baseline VHF lightning imaging system.

1. Introduction

As a novel and maneuverable approach to create electrical discharges of considerable spatial scales at favorable locations, the triggered lightning experiment has been conducted for decades as an effective tool to facilitate the study of physical processes involved in cloud-to-ground (CG) lightning strokes [*Fieux et al.*, 1978; *Wang et al.*, 1999]. The majority of triggered lightning is of negative polarity by transferring negative charge from cloud to ground. Recently, the resemblance between rocket-triggered lightning and upward lightning from tall objects, which is of more practical concern, brought more research interests to artificially triggered lightning [*Miki et al.*, 2005; *Warner et al.*, 2012], and the study of rocket-triggered lightning might shed light on the understanding of physical mechanism of object-initiated lightning strokes.

The initial continuous current (ICC) is typically observed in rocket-triggered lightning flashes [*Wang et al.*, 1999; *Qie et al.*, 2011], as well as object-initiated lightning strokes [*Miki et al.*, 2005; *Flache et al.*, 2008]. The analysis of *Wang et al.* [1999] with respect to 37 triggered lightning events in the United States indicates that the average magnitude of ICC ranges between 30 A and 300 A, with a mean duration of 279 ms and average charge transfer of 27 C. During the early stage of ICC, there is usually an upward positive leader that ascends at a mean velocity ranging widely from ~1.0×10^4 m/s to ~1.0×10^5 m/s, and the positive leader might accelerate with increasing height [*Edens et al.*, 2012; *Jiang et al.*, 2013]. During the mature stage of ICC, the upward positive leader typically ascends into the in-cloud charge region and the relevant lightning processes are difficult to characterize. Therefore, the in-cloud process associated with this characteristic process remains mysterious, and it is the subject of the work presented here.

In this paper, we report the measurement of low-frequency magnetic fields from a long sequence of small intra-cloud discharges during the initial continuing current in a rocket-triggered lightning flash on August 3, 2013. The temporal and spatial features of these discharges are investigated with concurrent measurements of several instruments, including high-speed camera, short-baseline lightning imaging system, low-frequency magnetic coils, and slow and fast electric field sensors. It is suggested that the observed burst of magnetic radiation are linked to the electrical breakdown, or stepping process, when the positive leader encounters with negatively charged cloud particles in the lower part of thunderclouds.

2. Measurements and observations

Most measurements were acquired at the main observation site (37.8282°N, 118.1150°E) located at 970 m range to the northeast of the rocket launch site (37.8197°N, 118.1123°E) in north of Shandong Province, China. One Phantom V711 high-speed camera was operated at 20,000 fps (50 μs image interval) to record the high-speed images of triggered lightning; there was also a short-baseline very high-frequency (VHF) lightning location system that is capable of resolving the high time-resolution evolution of lightning channels in the 2-dimensional (2D) space [*Sun et al.*, 2013]. Recently, *Yoshida et al.* [2013] and *Edens et al.* [2012] have reported the observation of in-cloud processes during triggered lightning with VHF techniques in Florida and central New Mexico, respectively. The additional contemporary data for our event include broadband *E*-field change measurements with a slow antenna and a fast antenna that were both deployed at the main observation site and at distance of 70 m from the rocket launch site, and low-frequency (30-300 kHz) magnetic fields measured with a pair of magnetic induction coils, which are oriented in north-south and east-west direction, respectively. The sampling rate of both electric and magnetic fields is 5 MHz. The measurement of channel base current was obtained through a shunt and a Pearson coil, for which the combined dynamic range of current measurement (with sampling rate of 10 MHz) is 10 A to 40 kA. In this writing, we use the physics sign convention: if the positive charge is raised from ground to cloud, it will induce a negative deflection in the surface electric field, and the associated (upward) current is positive.

Figure 1a shows an image of lightning channel for the flash; the relative brightness for the selected image area (enclosed by the red square) is shown by the red line in Figure 1c, in comparison with time-resolved elevation angle of detectable VHF sources during the flash. This flash contained an initial continuous current (ICC) of ~120 ms and 16 subsequent CG strokes over a time interval of 0.9 s, all of which were of negative polarity with peak current ranging between -5.8 kA and -32.5 kA. Figures 1c and 1d only show the measurement for ICC and the first 12 strokes that were recorded on the high-speed camera.

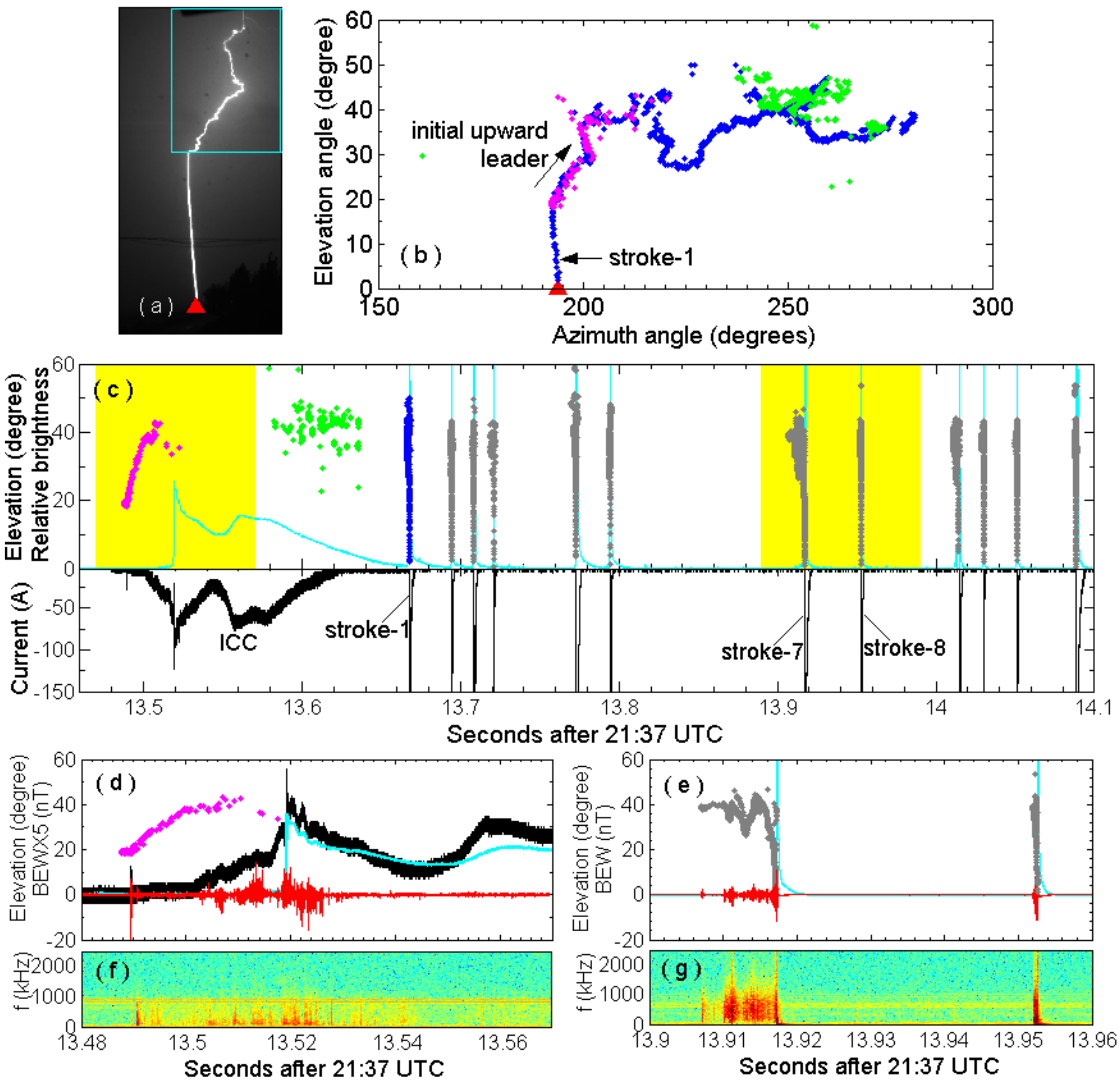

Figure 1. An overview of the multi-disciplinary measurements for the rocket-triggered lightning flash on August 3, 2013. (a) Camera view of lightning channel. (b) The 2D view of flash structure with VHF sources detected during the initial continuous current and the first stroke. (c) Comparison of time-resolved elevation of VHF sources, channel-base current waveform, and relative brightness for the square region in Figure 1a. The data are not shown for the last four strokes (between 14.1 s and 14.6 s) for which the high-speed image was not acquired due to the malfunction of high-speed camera. The relative brightness of high-speed images is intentionally clipped at 60, and the channel base current is clipped at -150 A. Panels (d, e) show the comparison of broadband LF magnetic field with flash development shown by the short baseline TOA technique. Note that the burst of intra-cloud discharges occurred during the enhancement of ICC, mainly around the current surge associated with the disintegration of the steel wire. Panels (f, g) show the spectrogram of magnetic field, demonstrating the broadband feature lightning signals.

The 2D view of VHF imaging result for ICC and the first stroke (Figure 1b) demonstrates an overall structure of the triggered lightning. The evolution of this flash is mainly confined below the elevation angle of 50° and within the azimuth range of 190°-280° (in this paper, the azimuth angle is defined as the clockwise angle relative to true north; for instance, the rocket launch site is located at the azimuth angle of 194° relative to the main observation site). Other strokes, with timescales ranging between 0.2 ms and 10 ms, developed similarly to the first stroke by initiating from roughly the same cloud region and propagating along the identical lightning channel. The initial continuous current was initiated by an upward positive leader that incepted when the rocket reached an altitude of about 330 m. For this flash, the upward extension of positive leader was hardly discernible in the high-speed imagery due to the intervention of heavy rain. However, the development of upward positive leader was resolved by the short-baseline system, as shown by pink dots in Figures 1b and 1c. According to the 2D imaging results, the positive leader likely ascended to a height of about 900 m above ground level over ~20 ms, yielding an estimated average 2D ascending velocity of about 2.8×10^4 m/s.

The LF magnetic fields recorded for the two time intervals marked yellow in Figure 1c are shown in Figures 1e and 1f, respectively, in comparison with VHF and channel-base current; the associated spectrogram demonstrates the characteristic broadband feature of lightning signals. The burst of magnetic pulses that became most distinct about 15 ms after the inception of positive leader is of our particular interest. Figure 1f shows the measurement for strokes 7 and 8 that were preceded by stepped leader (~10 ms) and dart leader (~0.6 ms), respectively; apparently, the occurrence of stepped leader is largely due to a relatively long inter-stroke interval (>100 ms) after the previous stroke. It is commonly observed that the spectrum of magnetic signals (Fig.1f, 1g) from ground strokes at close range contains components up to 2.5 MHz. Therefore, the burst of magnetic pulses in Figure 1e is most likely linked to intracloud events.

The channel-base current increased as the positive leader extended upward. The millisecond-scale current pulse at 13.52 s is associated with the disintegration of the steel wire (~30 ms after the onset of upward leader) caused by Joule heating and the subsequent reestablishment of current flow along the positive leader channel [*Wang et al.*, 1999; *Yoshida et al.*, 2010]. There is not much detectable VHF radiation after this current surge, whereas the LF magnetic radiation remained active for another 6 ms. Overall, there are a total of more than 800 magnetic pulses with magnitude twice the noise level over the 25-ms time interval. The ICC exhibited another enhancement shortly before 13.56 s, whereas there is no observation of active LF or VHF radiation. A burst of VHF sources (green dots) were detected late in ICC and thereafter, and the associated lightning activity is speculated to involve the progression of multiple lightning leaders; unfortunately, there is no recording of magnetic field associated with this burst of VHF radiation. Overall, the ICC process associated with the burst of magnetic pulses is not particularly intense with a total charge transfer of -4.9±0.1 C and average magnitude of ~40 A, which are among the weakest ICCs in rocket-triggered lightning according to *Wang et al.* [1999] and *Miki et al.* [2005]; in contrast, the overall charge transferred by the subsequent 16 strokes is -25±3 C. Also, the development of upward leader was much simpler than the case reported by *Edens et al.* [2012], who examined an extensive triggered lightning flash with five positive leader branches that propagated at velocities in the range of 1-3×10^4 m/s.

Although the evolution of positive leader was not resolved by the short-baseline system during most of the duration of the burst of magnetic pulses, we may constrain its progression along the lightning path traveled by the dart leader prior to the first stroke, as shown by the blue dots in Figure 1b. This dart leader had a short duration of 1.5 ms, strongly suggesting that it has followed an existing lightning path that, for the particular case here, should have been created by the initial positive leader. Hence, we can anticipate that the unresolved positive leader progression contained some tortuosity associated with the extension into a negative cloud region in the lower part of thunderclouds.

3. Analysis and discussions

Magnetic field measurements at close range have been involved in triggered lightning experiments [*Uman et al.*, 2002; *Schoene et al.*, 2003; *Yang et al.*, 2010]. The measurement of triggered lightning reported here, however, was probably the first attempt to use magnetic sensors that are literally designed for remotely probing lightning discharges at the range of a few thousand kilometers [e.g., *Cummer et al.*, 2011; *Lu et al.*, 2013]. Consequently, our magnetic measurement, with background noise level of 0.05 nT, is very sensitive to weak microsecond-scale discharges within a few km, which might explain the detection of burst of magnetic pulses reported here. It should be noted that the electrical field change recorded at 70 m distance from the rocket launch site did not record noticeable variation associated with these magnetic pulses, most likely due to a relatively small gain.

These magnetic pulses, with timescale of 2-4 μs, exhibited a highly organized manner that persisted about 20 ms with more than 300 events of varying magnitude. Figures 3a and 3b show a 3-ms data sample for the two coils of magnetic sensor, demonstrating a remarkable periodic occurrence of small discharges; the inset figures show the detailed waveform over the selected 200-μs time interval. For comparison, the current pulses and associated magnetic pulses (both normalized by the peak intensity) associated with the initiation of upward positive leader are plotted in Figure 2d. Note that the polarity of magnetic pulses shown in Figures 2a and 2c is opposite to that associated with the onset of the upward positive leader. The inception of upward positive leader involved a sequence of more than eight unipolar pulses in the channel-base current [e.g., *Jiang et al.*, 2013], with magnitude ranging between <10 A and 28 A; each current pulse at the channel base corresponds with a magnetic pulse of ~3 μs timescale, but not with discernible deflection in the *E*-field measurement at 70 m distance. The ratio of magnetic field versus current varies for different pulses, which is not surprising as the magnetic sensor recorded the signal from the stepping of positive leader which, according to the mechanism of leader progression [e.g., *Petersen and Beasley*, 2013, Fig.10], will cause a current surge traveling from the tip of positive leader downward to the channel base. This current surge will experience some attenuation due to the intrinsic impedance of leader channel that also varies during the leader progression. Also, in addition to the magnitude of current pulse caused by the stepping of positive leader, the intensity of magnetic pulse also depends on the geometric length and the exact orientation of stepping. With the estimated velocity (2.8×10^4 m/s) for positive leader and the average inter-pulse interval of ~20 μs, the spatial scale of each positive leader stepping is estimated to be about 0.6 m.

Figures 2b and 2d show the histogram of inter-pulse intervals for magnetic pulses in two directions over the time interval from 13.502 s to 13.528 s, with magnitude at least five times the noise level. The inter-pulse interval peaks between 20 and 45 μs for magnetic pulses in both directions, which is similar to the value (~20 μs) of initial positive leaders in triggered lightning [e.g., *Jiang et al.*, 2013]. Previous observations indicate that the inter-stepping interval of positive leaders in natural +CG strokes is also about 20 μs [*Cooray and Lundquist*; 1982]. Most recently, *Kong et al.* [2009] reported the observation of a sequence of 26 pulses with average separation of 17 μs in a downward positive leader.

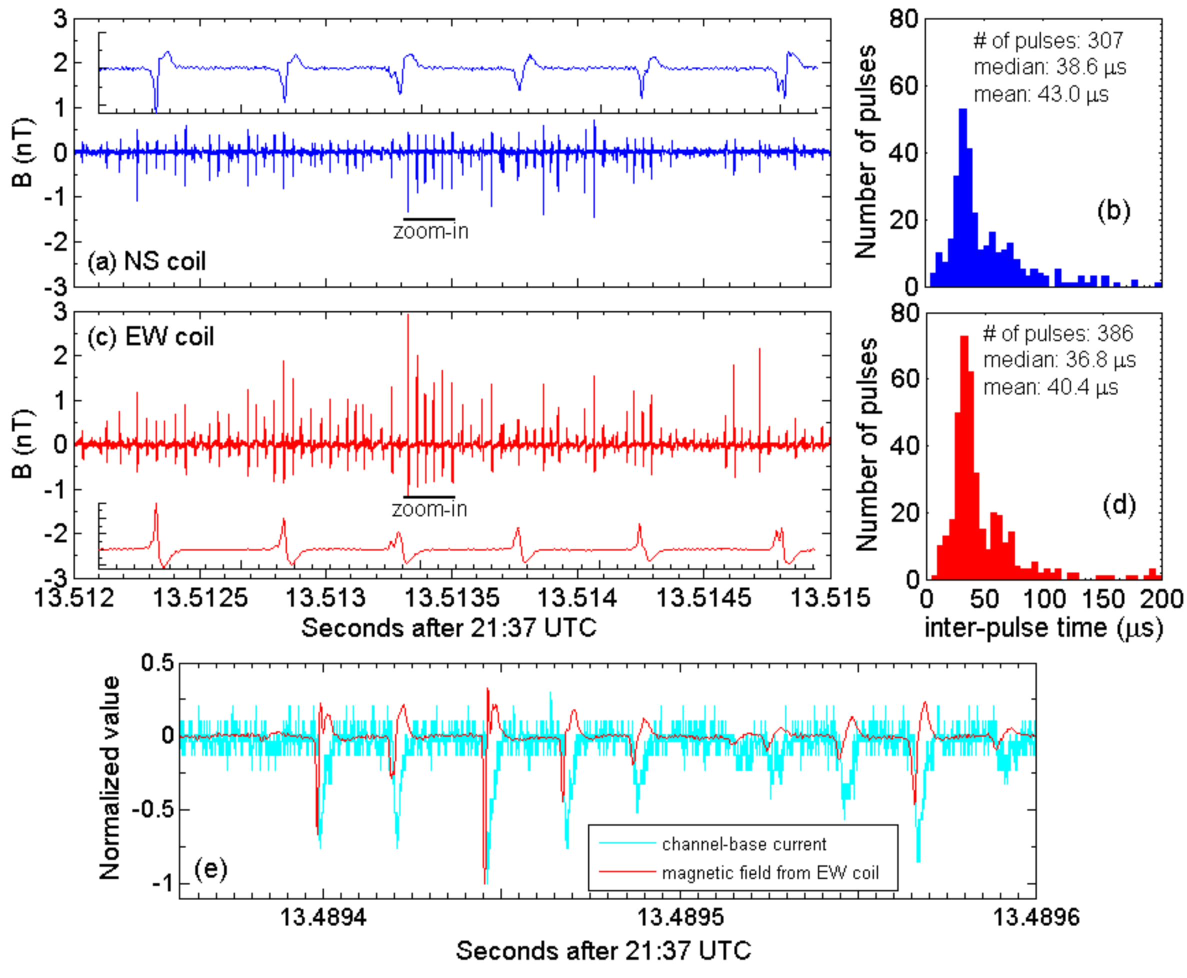

Figure 2. Panels (a)-(d): The LF magnetic field over 3 ms showing the periodic pattern of small in-cloud discharges. The statistics of more than 300 pulses (with magnitude five times the noise level) scattering over 25 ms indicates that the inter-pulse intervals are typically 20-45 μs. Panel (e) compares the channel-base current waveform and the magnetic field

recorded by the EW coil. The initial current pulses did not cause noticeable deflections in the electric field waveform recorded at 70 m range from the rocket launch site, which confirms that the electric field sensor at the main observation site did not record the signals corresponding to the burst of magnetic pulses because of a small gain.

The similarity in both the timescale and the inter-pulse interval strongly suggests that the burst of magnetic pulses might have occurred in association with the stepping of positive leader, rather than recoil negative leaders that sometimes retrograde along the positive leader in progression. The relatively larger inter-stepping interval for our flash might be associated with the relatively high altitude (>400 m) of positive leader progression. As the initial continuous current in our case was not particularly strong, we assume that the velocity of positive leader did not vary substantially from 2.8×10^4 m/s for the first 20 ms. With this assumption, the stepping of positive leader during the initial continuous current would have occurred on a spatial scale of about 1 m.

The measurement of magnetic pulses driven by the initial current pulses around the onset of upward positive leader also provides an excellent dataset for evaluating the direction finding capability of magnetic coils. On this basis, we can further infer the azimuth range of positive leader progression inside the cloud. Figure 3 shows the results of the direction finding with the magnetic pulses in the chosen time interval. In the calculation of azimuth angle, we only process magnetic pulses with magnitude five times the noise level, and further require that the peak time of magnetic pulses in two directions is consistent within 2 sampling intervals (i.e., 0.4 μs). The magnetic fields recorded by two coils since the onset of upward positive leader are shown in Figures 3a and 3b, respectively, where the red (for positive) and blue (for negative) sticks on the bottom indicate the polarity of magnetic pulses. With the five largest magnetic pulses within 10 ms after the inception of positive leader, the calculated azimuth angle of current sources (red line in Fig.3d) is in agreement (≤1°) with the imaging result of short-baseline system. In the calculation of azimuth angle, we presume that the source current is positive (i.e., positive leader propagating upward).

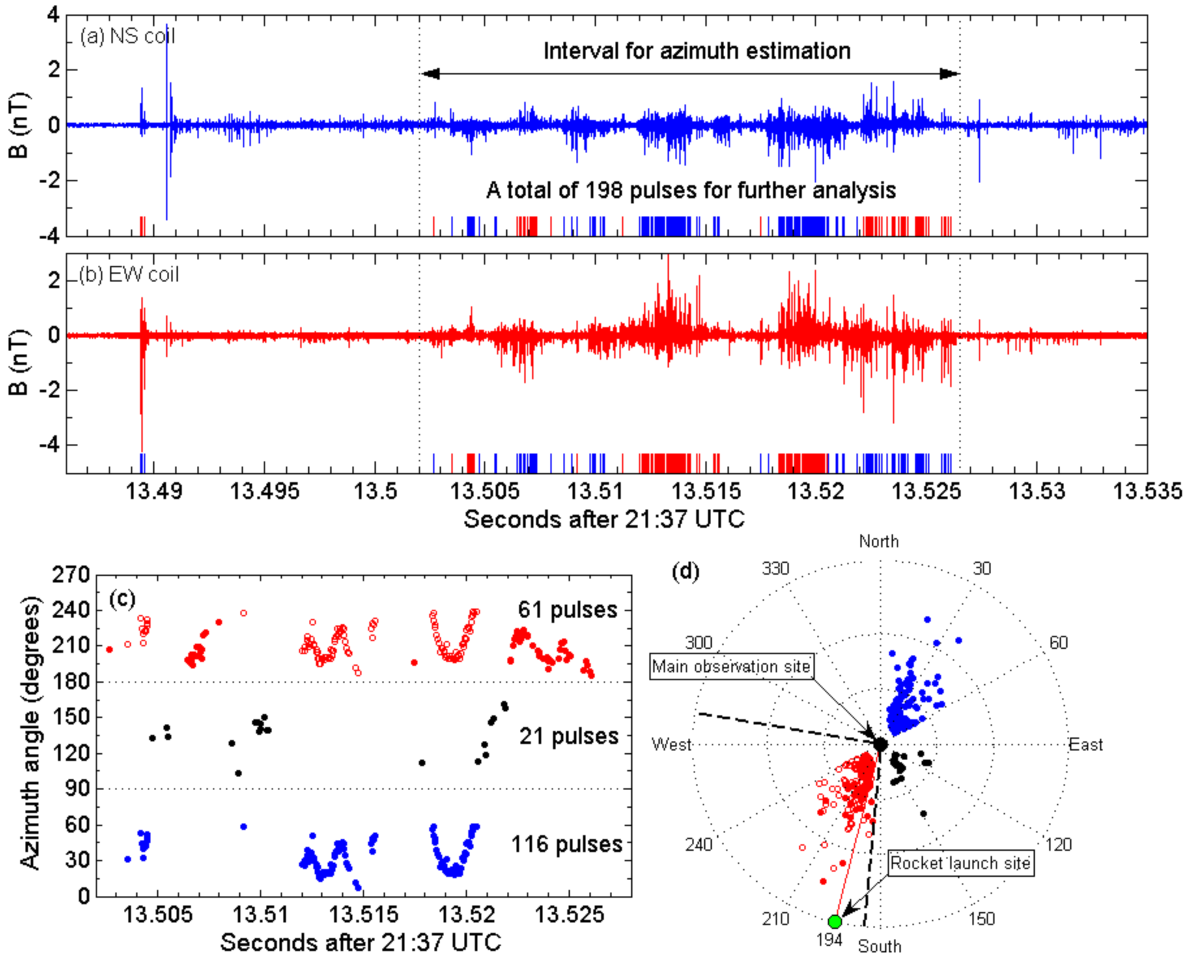

Figure 3. Panels (a, b): LF magnetic fields associated with the initial continuous current. The bars on the bottom of Figures 3a and 3b mark the polarity (red for positive, and blue for negative) of individual magnetic pulses. Panel (c): Variation in the direction of positive leader stepping during the initial continuous current. Note that the magnetic pulses between 13.50 s and 13.53 s appear to be related to a continuous progression of certain intracloud events. (d) An overview of azimuth angle of source discharges of magnetic pulses in the polar coordinate system.

Among the 198 paired magnetic pulses between 13.502 s and 13.527 s that are selected for the calculation of azimuth angle, only about one third (red dots in Fig.3c, 3d) are determined with azimuth angle in the range for the evolution of triggered lightning (defined by two thick dash lines in Fig.3d). More than half (blue dots in the figure) were actually in the azimuth range of 0-90°. However, if we presume that the source current of these pulses is negative (i.e., positive leader propagating downward), they could be also constrained in the azimuth range of triggered lightning. Indeed, as shown in Figure 1b, if the positive leader propagated along the same lightning path as traveled by the dart leader prior to the first stroke, the positive leader had propagated downward over a considerable portion of its duration. Therefore, the vast majority of intracloud discharges could be located in the azimuth range of triggered lightning as observed by the short-baseline VHF system. A pattern of continuous progression is obvious over several periods of the selected interval. There are also some pulses whose azimuth angle is inferred to be in the range of 90-180°; as shown in Figure 3c, most of these pulses occurred during the transition in the vertical orientation of positive leader, and thus they could be attributed to positive leader stepping in horizontal direction. In summary, the burst of magnetic pulses reported here reflects the successive stepping of positive leader when it progressed into the cloud region, where there might be a large number of negatively charged cloud particles.

For the triggered lightning flash examined in this paper, the successive stepping of positive leader, which became active more than 10 ms after the initiation of positive leader, did not cause discernable deflections in the channel-base current. *Jiang et al.* [2013] reported the observation of sub-millisecond fluctuations in the channel-base current 2-5 ms after the positive leader inception, and therefore these current surges are not substantially different from those around the onset of positive leader. The duration of these pulses is 20-40 μs, which is fairly close to the inter-pulse interval for our case. Consequently, the stepping of positive leader might occasionally result in observable variations in the channel base current when it is not very long after the inception of upward positive leader.

4. Conclusion

We report the observation of a long sequence of >800 magnetic pulses over about 25 ms during the initial continuous current in a rocket-triggered lightning flash with a relatively simple spatial structure. With typical timescales of 2-4 μs and inter-pulse time interval of 20-45 μs, this burst of magnetic pulses is attributed to the successive stepping of a single positive leader that progressed into the negative charge region in the lower part of thunderclouds. It is possible that the highly organized pattern of these magnetic pulses, although with intermittent inversions in the polarity caused by varying pointing direction of positive leader, is largely related to the simplicity of positive leader development in this case.

The case examined here is a relatively weak event compared to triggered lightning examined in previous studies [e.g., *Miki et al.*, 2005; *Yoshida et al.*, 2010]. Therefore, it merits further effort to conduct the same measurement for ICC of varying magnitude in triggered lightning. Also, the initial continuous current is commonly observed in triggered lightning from tall objects [*Miki et al.*, 2005; *Flache et al.*, 2008; *Zhou et al.*, 2011]. Hence, it is of particular interest to implement contemporary magnetic field measurements to see whether the ICC process in object-initiated lightning could also be associated with the similar burst of intra-cloud discharges as reported for our particular event. Nevertheless, more dedicated measurements are desired to characterize the intra-cloud lightning discharges that are possibly linked to the initial continuous current in both rocket-triggered and object-initiated lightning flashes, and similar measurements could also be conducted for triggered lightning experiments at other places. Moreover, it is also necessary to look into the ambient condition for the transition in the radiation pattern of positive leader, which might explain why the positive leader is usually less readily detected by the VHF techniques in comparison with the negative counterpart.

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