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Key Points:

- The waveform of magnetic pulses radiated by lightning discharges as measured at 2-m depth is modified due to the propagation through soil
- The modification of magnetic pulses caused by the propagation through soil depends on the timescale of the magnetic pulse
- Preliminary simulation of near-range magnetic field is carried out based on channel-base current with the transmission line model

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Underground Measurement of Magnetic Field Pulses During the Early Stage of Rocket-Triggered Lightning

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Abstract We examined the underground magnetic field near the lightning channel with low-frequency magnetic sensor based on SHandong Triggering Lightning Experiment (SHATLE). Two sensors were deployed, one at 1-m height above ground and another one at 2-m depth underground at a distance of 78 m from the lightning channel, and the magnetic pulses during the initial stage of triggered lightning were recorded. The experimental results show that the microsecond-scale magnetic pulses radiated by the upward lightning leader can be detected in the subsurface space and the magnetic signal is modified by the soil medium. Specifically, the amplitude at the depth of 2 m is attenuated typically more than 55%, and the attenuation decreases as the timescale of the magnetic pulse increases; meanwhile, the peak time of the underground magnetic pulse is delayed by about 0.6 μ s, and the half-peak width of the magnetic pulse is increased by 0.2–0.8 μ s (namely, by 20% to 32%). The results of Fourier analysis indicate that the component with relatively high frequency is subject to more attenuation than is the component with relatively low frequency. In addition, the simulation of magnetic field with the channel-base current by using the transmission line model is consistent with the measurement, indicating that the modification on the waveform characteristics of the lightning pulse measured underground could provide valuable information for retrieving the electromagnetic parameters of soil.

Plain Language Summary The broadband electromagnetic radiation of lightning discharges can penetrate the soil and affect the underground electronic facilities, and meanwhile, the detection of lightning signals below the ground surface can be used as a tool to explore the underground space. To investigate the influence of soil medium on the lightning radiation, the low-frequency magnetic sensors are deployed at 1-m height above the ground and 2-m depth underground to measure the magnetic field pulse at a distance of 78 m from the lightning channel artificially created in the rocket-triggered lightning experiment. After the magnetic field pulse propagates through the soil, the amplitude of the pulse waveform attenuates, the half-peak width increases, and the peak time delays. The variation in the waveform characteristics is quantified and analyzed. We discuss the reason for the variation of characteristics, which is related to the timescale of the pulse. In addition, relevant simulation was developed based on the transmission line model, and the result is consistent with the measured data. It is possible to invert formation electromagnetic parameters according to the variation of the waveform characteristics.

1. Introduction

Powerful current and associated electromagnetic pulse generated by the lightning discharge process could cause damages to grounding buildings, electronic equipment, signal transmission devices, and even biological lives (Ishii et al., 2005; Rakov et al., 1996; Wang et al., 1999). Moreover, mankind has been gradually extending the living space to the underground in recent years (Xie et al., 2017), and the issue whether the underground engineering equipment could be affected by lightning radiation is worth further investigation. For instance, the cable pipeline and field equipment are often laid underground to avoid the electromagnetic disturbance, but the malfunction of equipment still occurs in the event of lightning,

Figure 1. (a) Sketch of the relative position between the device and the two lightning rods (the tower triggered-lightning site is at a distance of 60 m and the classical triggered-lightning site is at 78 m). (b) Sketch of underground magnetic measurements during SHAndong Triggering Lightning Experiment (SHATLE) in summer of 2017. DAQ = data acquisition.

Figure 2. Frequency response of broadband magnetic sensors used for measuring the underground lightning magnetic field during SHAndong Triggering Lightning Experiment (SHATLE) in summer of 2017. The 3-dB bandwidth is 2–800 kHz, and the gain is set to be 0.005 V/nT for the initial upward leader and 0.0005 V/nT for the return stroke.

and this work has been studied by establishing numerical models (Sato et al., 2005; Yang et al., 2010; Zhang, 2013) and carrying out field experiments (Paolone et al., 2005; Petrache et al., 2005; Tesche et al., 1998; Zeddami & Degauque, 1987). Meanwhile, an effective algorithm has been proposed to estimate the underground lightning field and evaluate the influence of earth conductivity on the distribution of underground electromagnetic field (Delfino et al., 2007).

On the other hand, the electromagnetic wave radiated by lightning has been utilized to detect the stratigraphic information of the underground near surface in the field of geospace science (Topp et al., 1980). In addition, the soil moisture content, electrical parameters, and even the formation structure could be determined based on the electromagnetic induction method, such as ground-penetrating radar (Calamita et al., 2015; Jafarov et al., 2018; Liu & Qian, 2015). Apparently, lightning flashes occur at all times in the Earth's space, and it would be a great thing if lightning can be exploited as a natural radiation source because of its extraordinary high power to make exploration. A novel tomographic surveying technology has been proposed by Yeh et al. (2008) to use the powerful excitation of lightning electromagnetic wave as a source of detection, and therefore, it is suggested that the corresponding signal sensor network should be established to provide the long-term monitoring of the large-scale features of surface and underground conformation. There are also great potential possibilities for utilizing lightning, as a strong excitation source, to detect the shallow structures of the ground. All in all, it is valuable to characterize the underground electromagnetic signals of lightning discharges.

The technique of rocket-and-wire-triggered lightning makes it possible to create a lightning discharge under a controllable situation, which provides the favorable conditions for studying the characteristic parameters of lightning process (Fieux et al., 1975; Qie et al., 2010, 2011; Wang et al., 1999). Over the years, the experimental results have provided a possibility for the scholars to study the physical effects and mechanism of lightning process (e.g., Fan et al., 2017; Lu et al., 2016; Zhang et al., 2017). In this work, we apply the triggered lightning experiment during SHAndong Triggering Lightning Experiment (SHATLE) in summer of 2017 to measure the underground magnetic field near the lightning channel and investigate the signal modification caused by the soil. The relevant numerical simulation is also carried out to reveal the characteristics of underground signal propagation. The characteristics of magnetic pulses from the initial upward leader measured on the surface (at 1-m height) and underground (at 2-m depth) at a distance of 78 m are compared, and the relationship between the current pulse and associated magnetic field is discussed. Our efforts provide a preliminary understanding for the further study of the underground magnetic field distribution due to lightning, which is important for revealing the electromagnetic parameters of soil layer by analyzing the variation of characteristic parameters of the lightning pulse when it propagates through the ground.

This paper is organized as follows. In section 2, we describe the experiment and the data examined in this paper. In section 3, the analysis of data is carried out and three main parameters are defined to characterize the difference between the magnetic pulses from the precursor and the initial upward lightning leader as measured at the 1-m height and the 2-m

Table 1*Three Rocket-Triggered Lightning Flashes Recorded by Underground Device During SHATLE in Summer of 2017*

Serial number	Time (UTC)	Magnetic field (m)	Type	Number of return strokes
Tr_201702	30 July, 1831:48	60	Negative flash (hit the tower)	3
Tr_201703	30 July, 1841:49	60	Negative flash (hit the tower)	4
Tr_201705	5 August, 0839:57	78	Negative flash (hit the lightning rod)	2

Note. SHATLE = SHAndong Triggering Lightning Experiment.

Figure 3. (a) High-speed video images captured at 970-m distance showing the initial upward leader and the lightning channel during initial continuous current (ICC) and two subsequent return strokes (RS1 and RS2) for the triggered lightning at 0839:57 UTC on 5 August 2017. The height of the rocket upon the inception of a sustained upward negative leader is estimated to be about 200 m. (b) Waveform of current measured at the channel base shows the current pulses from the precursors and initial upward leader followed by ICC and two subsequent return strokes (causing saturation in the measurement of channel-base current and other measurements). (c) The E -field change recorded at 60-m distance and (d) the low-frequency magnetic field recorded at 78-m distance show the electromagnetic pulses from the precursor and initial upward leader. The circled number marks the sequence of pulses examined in the analysis.

Figure 4. (a) Lightning current pulses associated with the initial upward leader during the triggered lightning at 0839:57 UTC measured at the channel base and the corresponding magnetic pulses measured at the 1-m height above ground and 2-m depth underground, respectively, at a distance of 78 m. (b) The corresponding E -field change measured at 60-m distance and (c) low-frequency magnetic field measured at 970-m distance. The circled number marks the sequence of pulses examined in the analysis.

are ensconced at 1-m height and 2-m underground, at a distance of 78 m from the rocket launching site. The direction of both coils in each sensor is aligned to measure the azimuthal magnetic field radiated by the vertical lightning channel at the site of lightning rod. During the SHATLE campaign in summer of 2017, the measurement of the underground magnetic field was obtained for three rocket-triggered lightning flashes, and the detail information of these events is shown in Table 1. However, the channel-base current is only

measured for classical rocket-triggered lightning Tr_201705 (Figure 3a), which is further examined in this paper.

2. Measurement and Data

The experiment was carried out during SHATLE in summer of 2017. As shown in Figure 1, we made synchronous observations for the triggered lightning, including the channel-base current, optical image of high-speed video camera (Phantom V1612), E -field change (ΔE) measurement at 60-m range, and low-frequency magnetic field measurement at the distances of 78 and 970 m. The channel-base current was measured with a 5-m Ω shunt (bandwidth of 0–3.2 MHz) at a sampling rate of 20 MHz. The E -field change was measured with a fast antenna (with bandwidth of 2 MHz and time constant of 0.1 ms), which is sampled at 5 MHz. The high-speed video camera was operated at 90,000 fps (with 6- μ s exposure time and spatial resolution of 256 pixels $\times$ 512 pixels). The magnetic fields at 1 m above ground and 2 m underground were measured with the magnetic sensor of induction coil type modified from that used in our previous measurements (Fan et al., 2018; Lu et al., 2014, 2016). The output of B -field sensor was recorded continuously with a data acquisition system at 10-MHz sampling rate. As shown in Figure 2, the gain of two coils for both sensors is set to be 0.005 V/nT (for precursor, initial leader pulse, and continuous current) and 0.0005 V/nT (for return stroke), and the bandwidth of both is 2–800 kHz.

In our analysis, the downward transmission of negative charge is negative according to convention of atmospheric electricity, and the negative direction of magnetic field is taken as counterclockwise. The magnetic sensors

Figure 5. Characteristic parameters of lightning electromagnetic pulse measured by the low-frequency magnetic field sensors at the 1-m height and 2-m depth. B_p denotes the peak value of pulse, and t_{50} denotes the half-peak width of pulse.

As shown in Figure 3b, the measurement of channel-base current shows the presence of precursor pulses during the ascending process of wired rocket, followed by initial upward leader pulses, initial continuous current, and two subsequent return strokes (RS1 and RS2; Biagi et al., 2012; Qie et al., 2011; Wang et al., 1999). Note that there is no any other disturbance before the initial stage according to the measurements of E -field change at 60-m distance (Figure 3c) and B -field at 78-m distance (Figure 3d), indicating that there are no discharges in clouds. However, they correspond to the channel-base current very well during the initial stage, and the E -field change confirm that the measured base current does not contain a large displacement current. The current pulse is unipolar during the initial stage of Tr_201705, which is similar to the measurement of Jiang et al. (2013). The radiation from the precursor current pulses is readily observed in the measurements of ΔE and B -field, both having relatively high signal-to-noise ratio to detect weak current pulses with magnitude as low as a few hundred milliamperes (Lu et al., 2016). The magnetic

Table 2
Characteristic Parameters of Magnetic Field Pulses From Precursor and Initial Upward Leader for Triggered Lightning Tr_201705

Characteristic	Precursor pulse	Initial upward leader pulse
Attenuation (%)	61.7	59.7
Delay time of the peak (μs)	0.58	0.72
t_{50} (1-m height; μs)	1.35	1.83
t_{50} (2-m depth; μs)	1.90	2.59
Time difference (μs)	0.55	0.76

pulses of the precursor measured at close distance are typically unipolar, and the sequence of magnetic pulses following the inception of a sustained upward positive leader contains 11 impulsive pulses and a longer sequence of ripple pulses lasting longer than 600 μs .

3. Analysis and Results

In this section, we mainly examine the measurements associated with the initial upward leader and its precursor pulse. As shown in Figure 4a, the B -fields measured at the 1-m height above ground and the 2-m depth underground are significantly different for the precursor and initial leader

pulses of triggered lightning Tr_201705. It can be seen that the B -field pulses measured underground during the initial phase suffers obvious amplitude attenuation compared with the surface measurement, and there is also difference in the half-peak width and peak-time lag of the pulse waveform. Some of these relatively large B -field pulses can also be detected at 970-m distance with bipolar pattern (see Figure 4c). As shown in Figure 4b, the characteristics of ΔE waveform recorded at 60 m are generally consistent with those in Fan et al. (2018) in that the height of rocket upon the inception of a sustained upward leader is between 160 and 290 m (above the ground level).

One selected B -field pulse is shown in Figure 5 to describe the characteristic parameters used to examine the influence of soil on the underground magnetic pulse. During the initial stage of triggered lightning Tr_201705, for a reliable analysis, a total of 35 relatively large B -field pulses with magnitude >25.0 nT in the measurement at the 1-m height (including 24 precursor pulses and 11 initial leader pulses) are extracted for further analysis, and the peak strength, peak time, and half-peak width of individual pulses are calculated. The attenuation of B -field pulses measured at the 2-m depth relative to that measured at the 1-m height is investigated, and the results are shown in Table 2.

3.1. Attenuation and Widening of Impulsive Magnetic Pulse

The electromagnetic signal radiating from the lightning channel attenuates when it propagates through the subsurface soil, and the characteristic attenuation in the peak of time-resolved B -field waveform is examined with the following formula:

$$\eta = \frac{B_{s,\max} - B_{u,\max}}{B_{s,\max}} \times 100\% \quad (1)$$

where η is the amplitude attenuation ratio (%), $B_{s,\max}$ is the peak value of the surface measurement pulse (nT), and $B_{u,\max}$ is the peak value of the 2-m depth underground pulse (nT). As shown in Table 2 and Figure 6, the attenuation ratio of electromagnetic pulse caused by the propagation through soil is between 56.8% and 65.7%, and the attenuation of precursor pulses is greater than that of the initial upward leader pulse.

Figure 6. Peak intensity of magnetic pulse measured at the 1-m height and 2-m depth and corresponding peak value attenuation ratio caused by the propagation through the soil layer.

The statistical results on the half-peak width of lightning pulses during the early stage of triggered lightning are shown in Figure 7. The half-peak width of pulses measured at the 1-m height ranges from 1.0 to 2.5 μs (the average for the precursor and initial upward leader is 1.35 and 1.83 μs , respectively), and the half-peak width of the 2-m-depth underground pulse is 1.2–3.7 μs (the average for the precursor and initial upward leader is 1.90 and 2.59 μs , respectively). The half-peak width of pulses (for measurements at both the 1-m height and the 2-m depth) increases with time, indicating that the component of pulses with relatively low frequency increases with time; however, in comparison with the pulses measured at the 1-m height, the half-peak width of pulses measured at the 2-m depth is increased by 0.2–0.8 μs (namely, by 20% to 32%). The widening of magnetic pulse indicates that the proportion of the low-frequency part of the pulse signal increases. Subsequently, the peak time of magnetic pulses measured at 2-m depth is delayed behind the surface measurement by

Figure 7. Variation in the half-peak width of magnetic pulse measured at the 1-m height and 2-m depth with the serial number of pulses (which increases with time).

propagating leader and propagate downward along the leader channel (Fan et al., 2018). We compared the magnetic fields (measured at the 1-m height and the 2-m depth) of ripple pulses and impulsive pulses at a distance of 78 m; apparently, the attenuation of impulsive pulses due to the propagation through soil is more significant than that of the ripple pulses. Therefore, considering the timescale of individual pulses, it is obvious that the attenuation of lightning-induced electromagnetic wave propagating through the soil medium is more significant for the lightning pulses with smaller timescale, and this will be quantitatively elaborated in the following discussion.

Figure 8. Channel-base current (black line) and corresponding magnetic field (red line for that recorded at the 2-m depth and blue line for that recorded at the 1-m height) measured at 78-m distance for (a) impulsive pulses and (b) ripple pulses during the initial stage of triggered lightning Tr_201705. Note that there is an offset in the current wave and magnetic field during the phase of ripple pulses. The current offset reflects the presence of initial continuous current, which also causes an excursion in the magnetic field measured at 78-m distance.

about 0.6 μs , and the delay of initial upward leader pulses is more obvious than that of the precursor pulses (as shown in Table 2).

3.2. Modification of Different Initial Upward Leader Pulses

As shown in Figure 8a, in the first 300- μs time interval dominated by impulsive pulses, the half-peak width of impulsive magnetic pulses is as short as 2 μs and typically less than 3 μs ; for the subsequent time interval of about 600 μs dominated by ripple pulses (Figure 8b) with reduced amplitude and longer timescale (typically more than 5 μs), the half-peak width can only be roughly estimated because of the partial overlapping of each other. The statistical analysis on the recurrence rate and interpulse interval of impulsive pulses and ripple pulses indicate that they involve the similar formation mechanism (Lu et al., 2016). However, the ripple pulses with smaller amplitude following the impulsive pulses are produced due to the low-pass filtering effect of the prolonging leader with high impedance when the current pulses initiate at the tip of upward-

propagating leader and propagate downward along the leader channel (Fan et al., 2018). It is generally believed that the attenuation of electromagnetic waves propagating in the lossy medium such as soil could be caused by a variety of factors, such as dielectric conductivity, dielectric relaxation properties, and electromagnetic relaxation properties (Vuran & Akyildiz, 2010). The attenuation of the time-resolved lightning pulse is a comprehensive effect of electromagnetic wave propagating through soil. The high-frequency part of electromagnetic wave is absorbed and is unable to reach the underground detector when the signal propagates through the soil due to its dispersion effect on electromagnetic wave. The reduction of the high-frequency part of the pulse causes an increase in the proportion of low-frequency components and also the increase in the width of waveform and peak-time delay in the time domain. According to the electromagnetic theory, the propagation velocity of electromagnetic waves in soil media is less than $c \sim 3 \times 10^8$ m/s (namely, the propagation velocity of electromagnetic wave in free space). The fact that the electromagnetic pulse radiated by lightning discharges propagates through the soil with different frequencies corresponding to different phase velocities may also interpret the delay of peak time.

4. Discussions

The close-range magnetic field is closely related to the discharging intensity (characterized by peak current, magnitude of charge of each pulse, etc.). Also, the time-resolved magnetic field waveform at a point in space is the superposition of radiation from various segments of lightning channel and also depends on the spatial and temporal scales of discharge process. The modification of magnetic field pulse propagating through soil varies for the components of different frequencies, and the analysis in the frequency domain might provide more information for this modification.

Figure 9. Relationship between the peak of magnetic field pulse and corresponding current pulses (Tr_201705): (a) for the 1-m height and (b) for the 2-m depth. Note that there is some similarity in the trend of relationship between the magnetic pulse magnitude and current peak for both the measurements at the 1-m height and the 2-m depth, especially for the initial upward leader pulse (the coefficient of linear fitting was estimated to be 1.91 nT/A at the 1-m height but with smaller coefficient [0.81 nT/A] at the 2-m depth).

4.1. Relationship Between Current, Charge Transfer, and Magnetic Pulse

As shown in Figure 9, the magnitude of magnetic field pulse is positively correlated with the corresponding current pulse for the measurements at the 1-m height and the 2-m depth. There is a good linear relationship between the current pulses and associated magnetic pulses for the initial upward leader (by ignoring the two abnormal point values, the offset of the two points is due to the high peak current but with small duration; e.g., Fan et al., 2018; Lu et al., 2016). For the precursory discharges, there is no clear linear relationship between the current pulse and the magnetic field pulse. Note that there is a similarity in the trend of the relationship between the magnetic pulse magnitude and the current pulse for both the measurements at the 1-m height and the 2-m depth. Preliminarily, it can be indicated that the modification of soil to the magnetic field seems to be certain when the condition of the signal source and channel medium is unaltered and fixed.

As shown in Figure 10a, the magnitude of electric charge transferred via current pulses measured at the channel base varies widely for different pulses. The strongest current pulse for the precursor reached the maximum magnitude of 79.0 A with associated charge transfer approximately 51.6 μC , and the maximum magnitude of charge transfer is 55.9 μC , corresponding to 35.3 A. The charge transfer by individual current pulses during the initial upward leader varies from 33.2 (24.7 A) to 102 μC (40.7 A). Figure 10b shows the relationship between the intensity of the current pulse and the attenuation ratio of the associated magnetic pulse due to the propagation through soil, showing a relatively weak linear correlation. Moreover, considering the relationship between current intensity, charge magnitude, and attenuation ratio, that pulse with little timescale will attenuate dramatically can be concluded.

4.2. Analysis in the Frequency Domain

Fourier analysis is applied to precursor pulses and initial upward leader pulses with the same window size (Figure 11), and the cumulative

amplitude of the signal frequency is also calculated based on Fourier analysis (dashed line in the figure). The results show that the frequency of the precursor pulse and the initial upward leader pulse are both below 2 MHz, and the signal over 2 MHz cannot be distinguished from noise. We divide the signal band into three sections: 2.5–50 kHz (relative low-frequency component), 50 kHz to 2 MHz (relative high-frequency component), and over 2 MHz. It is found that the low-frequency component occupied a small proportion compared with the high-frequency component for the precursor signal and the initial upward leader signal measured at the 1-m height, but the proportion of low frequency increased dramatically to the signals measured at the 2-m depth, so the half-peak width is also exhibited increasing on the time domain waveform. The attenuation effect of soil on the low-frequency component is weaker than on the high-frequency parts, and the low-frequency components occupied higher proportions in the initial upward leader pulse signal than did those in the precursor pulse signal measured at the 1-m height; the initial upward leader pulse makes its half-peak width wider than that of the precursor pulse. Therefore, for the single pulse, the attenuation ratio of the magnetic field for the upward positive leader is less than that for the precursor (as shown in Table 3), which is consistent with the results shown in Figure 6. It also confirms that the statistics of pulse intensity parameters can represent the characteristics of signal attenuation. Meanwhile, we consider the fact that the effect of the time delay of the initial pulse is more obvious than that of the precursor pulse due to the magnetic pulse of the initial upward leader consisting of more low-frequency components and the signal traveling slower in the soil than the precursor pulse when in conjunction with the result described in Figure 8.

Figure 10. (a) Relationship between the peak current and the corresponding electric charge transferred to ground. (b) Relationship between the attenuation ratio and the peak of corresponding current pulse. Note the relationship between the magnitude of electric charge transferred via current pulse and the current peak is not proportionate accurately, indicating that the timescale of the pulse is variable. Specifically, large magnitude of electric charge with larger current peak corresponds to smaller timescale, and large magnitude of electric charge with smaller current peak corresponds to larger timescale. Considering the relationship between attenuation and current peak (b), the conclusion that the pulse with smaller (larger) timescale attenuate more apparent (unapparent) can be drawn.

5. Simulation with the Transmission Line Model

To further understand the modification of soil on the close-range magnetic field radiated by initial current pulses during the upward lightning leader, we use the channel-base current to simulate the near-range magnetic pulses of the initial upward leader propagating through the soil with the method of moments based on the transmission line model (Baba & Rakov, 2003; Uman & McLain, 1969). The geometry relevant to this issue is shown in Figure 12. In the simulation, it is assumed that the current pulse propagates downward along the straight and vertical wire (lightning) channel; the current varying with height and time could be denoted by $i(z', t - R(z')/c)$ (from an observation position at retarded time $t - R(z')/c$ when the channel is divided into elemental section dz at height of z' and each of them can be considered as an electric dipole; Delfino et al., 2009; Uman & McLain, 1969). Based on the channel-base current waveform, the distribution of current in a channel at every moment can be determined when we assume the propagating speed of the current pulse to be constant. The height of the lightning channel (H) can be obtained from the optical observation. The vector potential for the induction field at the observation point can be given by equation (2):

$$\mathbf{A}(z', r, t) = \frac{\mu_0}{4\pi} \int_0^H \frac{i(z', t - R(z')/c)}{R(z')} \hat{\mathbf{z}} dz \quad (2)$$

where t is the time at the observation point, H is the height (length) of the lightning channel, $R(z')$ is the distance between the source point and the observation one, and $\hat{\mathbf{z}}$ denotes the direction of $\mathbf{A}$. Then, the magnetic field at a point in space can be derived by equation (3) uniquely along with Lorentz condition (Uman & McLain, 1969; Uman et al., 1975):

$$\mathbf{B} = \nabla \times \mathbf{A} \quad (3)$$

When considering the boundary of the ground as a conductor by adding the image channel part and radiation parts of the field involved, the magnetic field in space can be given by equation (4):

$$\mathbf{B} = \frac{\mu_0}{4\pi} \hat{\Phi} \left(\int_0^H \left(\frac{\sin \theta}{R(z')^2} i(z', t - R(z')/c) + \frac{\sin \theta}{R(z')} \frac{\partial i(z', t - R(z')/c)}{\partial t} \right) dz + \int_{-H}^0 \left(\frac{\sin \theta_m}{R_m(z')^2} i(z', t - R_m(z')/c) + \frac{\sin \theta_m}{c R_m(z')} \frac{\partial i(z', t - R_m(z')/c)}{\partial t} \right) dz \right) \quad (4)$$

where $\sin \theta = l/R(z')$, $\sin \theta_m = 1/R_m(z')$, and $\hat{\Phi}$ denotes the direction of $\mathbf{B}$; the first term in the integral part on the right of equation (4) is the induction field, and the second term is the radiation field. In this case, $R(z') = \sqrt{(l-1)^2 + z'^2}$ and $R_m(z') = \sqrt{(l+1)^2 + z'^2}$, and we replaced $\frac{\partial i(z', t - R(z')/c)}{\partial t}$ by $\frac{\Delta i(z', t - R(z')/c)}{\Delta t}$ when we compute the radiation.

In equation (4), the boundary conditions are satisfied by adding the image channel when we assume the ground to be perfectly conductive, and the close-range magnetic field is simulated according to the relevant parameters. As a matter of fact, the ground is not so perfect when we determine the magnetic field in underground space, and the ground should be regarded as a medium rather than a perfect conductor, especially for a low-frequency signal. Therefore, the signal measured at point Q (at 2-m depth) could be from the source point and propagate through the air and soil, and there is reflection and transmission at the interface

Figure 11. Spectral analysis on the magnetic signals (a) for precursors and (b) for initial upward leader pulses during the early stage of the rocket-triggered lightning Tr_201705. The data of dashed line is calculated by accumulating the amplitude of spectral analysis result; thus, we can calculate the attenuation proportion in different frequency spectrum. Red denotes the 2-m-depth signal, and blue denotes the 1-m height).

through the soil, and a certain frequency (20, 100, and 500 kHz) is selected to represent the all-band signal, and relevant parameters (including propagating speed, transmission factor, and reflection factor) were determined. Based on that, the corresponding underground magnetic field was simulated, and the results are shown in Figure 13. The simulation curve (Figures 13a–13c) could not fit with the measurement perfectly, but when the result of each frequency is superposed according to the magnitude ratio derived from the frequency analysis of measurement, there is a good agreement between the experiments and the

(marked by N in Figure 12). The transmission factor (T) and reflection factor (R) of electromagnetic waves are considered to be the same as those at normal incidence by equations (5a) and (5b) (Dos Santos Cavalcante et al., 1982).

$$R = \frac{\eta_g - \eta_0}{\eta_g + \eta_0} \quad (5a)$$

$$T = \frac{2\eta_g}{\eta_g + \eta_0} \quad (5b)$$

where η is the wave impedance for air, $\eta_0 = \sqrt{\frac{\mu_0}{\epsilon_0}}$, and for the ground, $\eta_g = \sqrt{\frac{\mu_0}{\epsilon_r \epsilon_0 + \frac{\sigma}{j\omega}}}$. The propagation speed of electromagnetic wave in the ground medium (v_g) can be calculated by equation (6):

$$v_g = \frac{1}{\sqrt{\frac{\mu_0 \mu_r \epsilon_r \epsilon_0}{2} \left[\sqrt{1 + \left(\frac{\sigma}{\epsilon_r \epsilon_0 \omega} \right)^2} + 1 \right]}} \quad (6)$$

As an example, Figure 13 shows the simulation result and the measurement with respect to a single pulse. The vertical length of the lightning channel (H) is 200 m, and the channel is divided into 2,000 elements for the calculation. The propagating speed of the current pulse along with the channel is assumed to be 180 m/ μ s referring to Lu et al. (2016). When we calculate the underground magnetic field, it is assumed that the relative dielectric constant in soil ϵ_r is 9.0, the relative permeability of soil μ_r is 1.0, and the soil conductivity σ is 0.02 S/m (e.g., Cooray, 2001; Zhang et al., 2015).

To obtain the time-resolved waveform of the underground magnetic field, the velocity of electromagnetic wave in the soil medium and the transmission and reflection factors should be given first, and these parameters are relevant to the frequency of the signal. For the simulation of the underground magnetic field, it is assumed that the broadband signal possesses the same parameter of a specific-frequency signal when propagating

Table 3

Energy Proportion of Different Frequency Bands and Associated Attenuation Ratio of Magnetic Pulse During the Initial Process of Triggered Lightning (Tr_201705)

Type	Frequency band	Energy proportion (1-m height; %)	Energy proportion (2-m depth; %)	Ratio of energy attenuation ratio (%)
Precursor pulse	2.5 to 50 kHz	22.76	48.10	14.29
	50 kHz to 2 MHz	77.06	51.20	85.71
	>2 MHz	0.16	0.70	0.00
Initial upward leader pulse	2.5–50 kHz	26.63	44.27	20.80
	50 kHz to 2 MHz	73.35	55.64	79.20
	>2 MHz	0.02	0.09	0.00

Figure 12. Geometrical model for calculating the underground magnetic field radiated by the nearby lightning channel. The permeability and dielectric constant of the air space are $\mu_0 \sim 8.85 \times 10^{-12}$ (F/m) and $\epsilon_0 \sim 4 \times \pi \times 10^{-7}$ (H/m; assumed to be free space), respectively; the relative permeability and dielectric constant of the soil are μ_r and ϵ_r ; and conductivity is σ . LF = low frequency.

Figure 13. Simulation of magnetic field (1-m height and 2-m depth) using the channel-base current pulse during the initial upward leader phase with the transmission line model. The current pulse used in the simulation starts at 57.58145 s with maximum amplitude of 28.7 A, and the peak of the magnetic field pulse measured at the 1-m height and at the 2-m depth is 61.8 and 27.1 nT, respectively. Certain single-frequency electromagnetic wave is selected to represent the all-band signal as propagating through the soil, and relevant parameters (including propagating speed, transmission factor, and reflection factor) were determined. Based on that, the corresponding underground magnetic field was simulated: (a) 20, (b) 100, (c) 800 kHz; (d) further, these three results are superposed with corresponding coefficients (0.44, 0.36, and 0.20) that are estimated roughly according to the magnitude ratio of each frequency part from the former frequency analysis results.

simulations (Figure 13d). Noting that there are idealized assumptions in the calculation process, the simulation results at the 1-m height are slightly larger due to adding the image channel for boundary condition by considering the ground as a perfect conductor arbitrarily, but for the underground magnetic field, the result is not perfect because of the simplified calculation on the broadband signal by assembling signals with specific frequency, and the choice of ratio corresponding to each frequency is somewhat crude. Nevertheless, the method described above is sufficient to reveal that the main modification characteristics caused by soil for the electromagnetic signal proved to be broadband, and the modification for the signal depends on the different frequency component that is also the dispersion effect of soil medium, namely. Moreover, the deformation of the underground time-resolved pulse is formed somehow by superposition of change on the different frequency part. We also apply this method to simulate the underground magnetic signals from the precursory current pulses and obtain good agreement with measurements.

6. Conclusions

In order to experimentally investigate the influence of soil on the underground electromagnetic pulse for close lightning discharges, during SHATLE in summer of 2017, we measured the low-frequency magnetic fields at the 1-m height above ground and the 2-m depth underground during the initial stage of rocket-triggered lightning. Our analysis was primarily focused on the precursor and initial upward leader pulses, and the main findings are summarized as follows:

The amplitude of magnetic field radiated by the current pulse during the lightning discharge can be attenuated by the soil medium. Specifically, the attenuation ratio of the peak is typically more than 55% at 2-m depth. The attenuation of the pulse in the process of the initial upward leader, especially for ripple pulses with relatively long timescale, is usually less than that of the precursor pulses (e.g., Lu et al., 2016). Meanwhile, the half-peak width of pulse is increased, and there was a time lag in the peak time of each pulse signal when it propagates through the surface soil layer. Generally speaking, the signal pulse with a longer timescale was subjected to weak attenuation, and the attenuation of high-frequency signals is more apparent than that of low-frequency signals.

There is a good linear relationship between current and near-range magnetic field for the initial upward leader pulse, but it is poor for precursory discharges, indicating that the strength of magnetic field is determined not only by current intensity but also by its duration. Further, there is a similarity in the trend of the relationship between the magnetic pulse magnitude and current pulse for both the measurements at the 1-m height and the 2-m depth. Preliminarily, it can be indicated that the modification of soil to the magnetic field seems to be certain when the condition of the signal source and channel medium is unaltered and fixed.

The simulation results for the 1-m height and the 2-m depth based on the transmission line model are consistent with the measurement, which indicates that our simulation method is effective in revealing the modification of soil on the near-range magnetic field. Also, the modification depends on the frequency, and the deformation of the underground time-resolved pulse is formed somehow by superposition of modification on the different-frequency part. In addition, the characteristics of lightning signal propagation according to the electromagnetic theory are revealed, and the present work provides useful information and guidance for the future investigation of lightning effects in underground space.

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