Experimental Study of Lightning-Induced Currents in a Buried Loop Conductor and a Grounded Vertical Conductor

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***Abstract*—Currents induced in: 1) a 100 m×30 m buried rectangular loop conductor (counterpoise) and 2) a grounded vertical conductor of 7-m height by natural and rocket-triggered lightning at distances ranging from 60 to 300 m were recorded in 2005 at the International Center for Lightning Research and Testing (ICLRT). The peak values of 12 triggered lightning channel-base currents and the peak values of the induced currents in the counterpoise are strongly correlated. The first few microseconds of the current induced in the vertical conductor by triggered lightning return strokes 100 m away resemble electric field time-derivative waveforms simultaneously measured at the ICLRT. During a close natural lightning flash, five pre-first-return-stroke current pulses with peak currents up to 140 A were measured in the vertical conductor. These are apparently associated with multiple attempts of an upward-moving unconnected leader occurring in response to the charge lowered by downward-propagating leader steps.**

***Index Terms*—Antenna measurements, current measurements, electromagnetic coupling, grounding electrodes, lightning protection.**

I. Introduction

LIGHTNING can induce currents in grounded metallic wire systems that can be large enough to cause damage to electronic devices connected to the systems. Experimental data are presented here on the interaction of nearby lightning with two such systems: 1) a 100 m×30 m buried loop conductor (counterpoise) protecting the lighting system of a test runway [1] and 2) a 7-m-long vertical grounded conductor. The extended nature of counterpoises makes such grounding systems susceptible to induced effects of electromagnetic fields generated by nearby lightning return strokes. Studies of lightning-induced currents in horizontal grounding electrodes have been conducted previously by Tsumura *et al.* [2], Yamaguchi *et al.* [3], and Tanabe [4], and in buried cables by Petrache *et al.* [5] and Paolone *et al.* [6]. Significant currents in a vertically extended metallic conductor in response to nearby lightning can occur in two different ways: 1) via coupling of the lightning electromagnetic fields resulting in induced conduction current confined to the metallic conductor and its ground connection and 2) via coupling of the lightning electromagnetic fields resulting in a breakdown process such as corona or an upward-moving leader at the top of the conductor with conduction current flowing from the conductor into the ionized air above as well as in the conductor. Measured currents in a vertical conductor apparently produced by both mechanisms are presented here. Currents in a 3.4-m-long vertical conductor induced by lightning-like currents from a surge generator have been measured and presented along with model-predicted results by Kumar *et al.* [7].

Natural negative cloud-to-ground lightning (e.g., [8]) is the most common lightning discharge between cloud and ground and is initiated by a stepped leader that moves negative charge downward with an average speed of the order of 10^5 m/s [9]–[11]. The interstep time interval for leader steps ranges from 5–100 μs [9], [10], [12]. Krider *et al.* [13] measured the interstep time intervals of 130 leader steps occurring within 200 μs of return stroke initiation and found an average interstep interval of 25 μs. When the negative stepped leader approaches ground, the electric field between the leader tip and ground increases until it exceeds a critical value for the initiation of an upward-moving positive leader, or leaders, from the ground (often from tall and sharp objects on the ground) that propagates toward the tip of the downward-moving leader. The characteristics of the upward-moving leader that signifies the beginning of the attachment process in cloud-to-ground lightning are poorly documented. Most published data on upward-moving leaders are average velocities and lengths extracted from time-resolved optical records. Yokoyama *et al.* [11], using the Automatic Lightning Progressing Feature Observation System (ALPS) optical imaging system, measured average propagation speeds of upward-connecting leaders from an 80-m tower between 0.8×10^5 and 2.7×10^5 m/s for three events and total leader lengths between 25 and 125 m for five events. Stepping of both the downward- and upward-moving leaders was observed. Orville and Idone [14], using streak-camera photographs, infer lengths of 20 and 30 m for two upward-connecting leaders initiated from ground. Krider and Ladd [15] photographed two unconnected upward leaders of 8- and 10-m length originating within 15-m horizontal distance from the eventual lightning channel termination point. Note that statistics on upward leader length have a very small sample size and are likely biased toward larger values since short upward-moving leaders are difficult to detect in optical records due to the low luminosity of positive leaders

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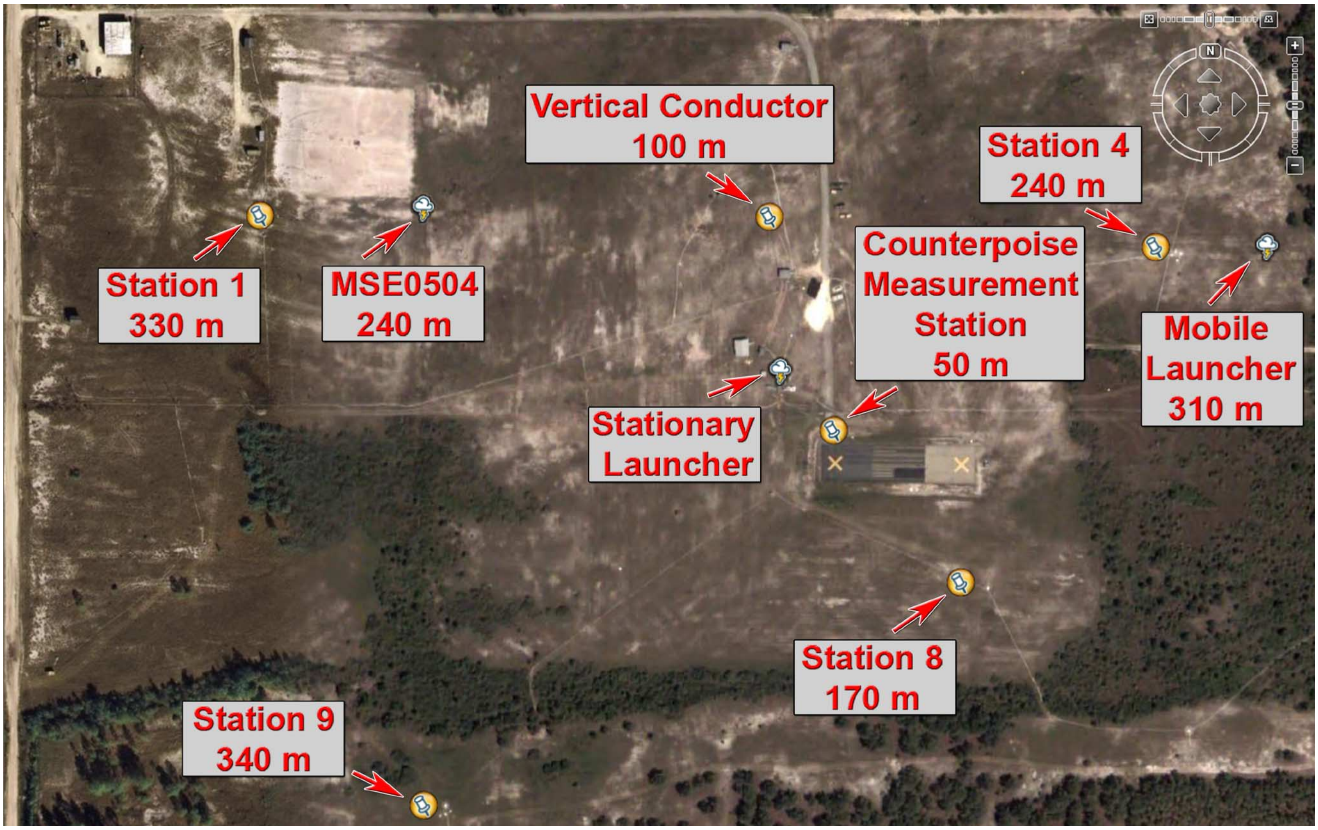

Fig. 1. Satellite image of the ICLRT. Objects relevant to the induced current experiment and their distances from the stationary launcher are indicated. Also shown is the location of natural flash MSE0504. Copyright Goole Earth.

(e.g., [16]), limits of the spatial and temporal resolution of optical measurement systems, and objects obstructing the view of the bottom of the lightning channel. Upward-moving leaders from ground may or may not connect with the downward-moving leader—the former are termed "upward-connecting leaders" and the latter are termed "unconnected upward leaders" [8].

The attachment process is concluded with the connection of the upward- and downward-moving leaders and the resulting initiation of an initially bidirectional return stroke current wave that neutralizes the charge deposited by both leaders. The stepped-leader/first-return-stroke sequence may be followed by one or more dart-leader/subsequent-return-stroke sequences that also contain an attachment process involving an upward-moving leader that has a propagation speed of the order of 10^7 m/s [17]. However, the length of the upward-connecting leader during the stepped-leader/first-return-stroke sequence is significantly longer (tens of meters to flat ground or small objects [10], [11], [14]) than the length of the upward-connecting leader during the dart-leader/subsequent-return-stroke sequence (a few meters to 20 m [14], [17], [18]). The larger electric potential of the downward-moving stepped leader that travels through virgin air causes a longer upward leader than the downward-moving dart leader that has a lower electric potential (the dart leader travels through a channel conditioned by the first return stroke and possibly by preceding subsequent return strokes and continuing currents).

The experiments discussed in this paper were performed at the International Center for Lightning Research and Testing (ICLRT), which is an outdoor facility occupying about 1 km^2 at the Camp Blanding Army National Guard Base, located in north-central Florida, approximately midway between Gainesville, home of the University of Florida, and Jacksonville. At the ICLRT, lightning is triggered (artificially initiated) from natural overhead thunderclouds for a variety of purposes using the rocket-and-wire technique (e.g., [19]). Rocket-triggered lightning is typically composed of an initial stage involving an initial continuous current of the order of 100 A with a duration of hundreds of milliseconds, which is initiated by an upward-propagating leader from the rocket tip, followed by one or more dart-leader/return-stroke sequences that are very similar, if not identical, to the dart-leader/return-stroke sequences in natural lightning. Rocket-triggered lightning does not contain natural lightning's downward-moving stepped leader (although downward leaders in triggered lightning sometimes exhibit stepping) and first return stroke. Natural lightning discharges are also studied at the ICLRT.

II. Experiment

Fig. 1 shows a Google Earth satellite image of the ICLRT-including the locations of the two rocket launchers used in the present experiment, the induced current measurement stations (the vertical conductor and the counterpoise), and the dE/dt antennas (stations 1, 4, 8, and 9).

Lightning was triggered from: 1) a mobile launcher, a power utility vehicle with a rocket launcher installed in its "bucket" and 2) a stationary launcher, an 11-m-tall wooden tower with a rocket launcher on the top. Currents of lightning strikes triggered from the stationary launcher were directed to a test object (test house) located northwest of the launcher via a metallic conductor, where they were injected into the test house's lightning protection system [20]. Triggered-lightning currents from the mobile launcher were directed into the ground in the vicinity of the launcher.

The dimensions of the rectangular closed-loop counterpoise, made of a stranded conductor with a diameter of 4 mm, was 100 m in the east-west direction and 30 m in the north-south direction. The counterpoise was buried at a depth of approximately 0.3 m. Additional details about the counterpoise can be found in [1].

The vertical conductor was a 7-m-long copper wire with a diameter of 5 mm and was grounded using three closely spaced ground rods of 3-m length. The measured low-frequency, low-current grounding resistance was about 700 Ω.

Current viewing resistors (CVRs) manufactured by T&M Research Products, Inc., were used to measure both the lightning channel currents and the induced currents. The currents of the lightning triggered from the tower launcher were measured with two systems: 1) a 1.231-mΩ CVR sensed the current at the tower launcher and 2) a 1.286-mΩ CVR sensed the current on the test-house roof (both CVRs had a 12-MHz upper frequency response). The currents of the lightning triggered from the mobile launcher were measured at the launcher with a 2.460-mΩ CVR (48-MHz upper frequency response). Induced currents were sensed at the bottom of the vertical conductor and at the northwest corner of the counterpoise with a 1.033-mΩ CVR (8-MHz upper frequency response) and a 1.270-mΩ CVR (12-MHz upper frequency response), respectively. All signals were transmitted to the launch control trailer through Nicolet Isobe 3000 fiber optic links (15-MHz upper frequency response), where they were filtered with 5-MHz custom-made low-pass filters and sampled at either 100 MHz (lightning currents sensed at the stationary and mobile launchers), 20 MHz (lightning currents sensed on the test-house roof), or 50 MHz (induced currents) using 8-bit LeCroy digital oscilloscopes. The induced currents were each measured with two different attenuation settings—a current measurement with high attenuation that could measure currents up to a few thousand amperes and a current measurement with low attenuation that could measure currents up to a few hundred amperes.

III. Data Presentation and Discussion

Induced currents during seven rocket-triggered lightning flashes and one natural flash were measured in the counterpoise and vertical conductor. The seven triggered flashes contained a total of 12 return strokes. According to U.S. National Lightning Detection Network (NLDN) records, the natural flash MSE0504 consisted of four return strokes. Data for the first two of these four strokes, both in the same channel, were recorded in our experiment. The location (ground attachment point) of flash MSE0504 was determined from dE/dt measurements at stations 1, 4, 8, and 9 (Fig. 1) using the time-of-arrival location method.

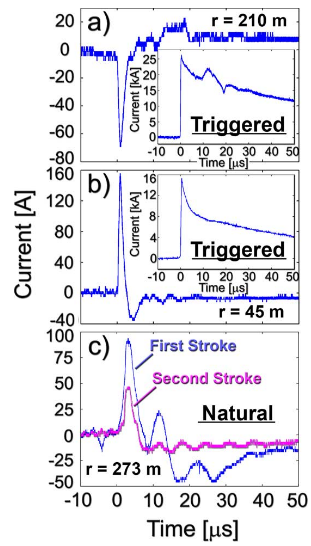

Fig. 2. Currents induced in the counterpoise. (a) Stroke 0503-2 triggered from the mobile launcher located 210 m northeast of the counterpoise. (b) Stroke 0517-2 triggered from the stationary launcher located 45 m northwest of the counterpoise. (c) Strokes 1 and 2 in natural flash MSE0504 striking 273 m northwest of the counterpoise. The insets in (a) and (b) show the measured channel-base currents of strokes 0503-2 and 0517-2, respectively. The return strokes begin at $t = 0$.

A. Currents Induced in the Counterpoise During Rocket-Triggered and Natural Lightning

Fig. 2 shows representative examples of currents in the counterpoise during the second return stroke in flash 0503 triggered from the mobile launcher, which was located 210 m from the nearest corner of the counterpoise [Fig. 2(a)], and the second return stroke in flash 0517 triggered from the stationary launcher, which was located 45 m from the nearest corner of the counterpoise [Fig. 2(b)]. Both return stroke currents are shown in the insets of Figs. 2(a) and (b). Fig. 2(c) shows currents in the counterpoise during the first and second return strokes of natural flash MSE0504, which terminated on ground 273 m northwest of the counterpoise. All counterpoise currents are characterized by an initial pulse with durations ranging from 2 to 8 μs followed by a polarity change. The currents cease to flow after some tens of microseconds. The counterpoise currents during rocket-triggered lightning initiated from the mobile launcher have negative peak values, and the counterpoise currents during rocket-triggered lightning initiated from the stationary launcher and during the natural lightning strokes have positive peak values. We believe that the initial current pulse in the counterpoise was produced by coupling of the lightning's electromagnetic field to the counterpoise.[1] The different polarities are likely related to the different

[1]We believe that the pulses are due to electromagnetic coupling and not due to lightning current injected into the counterpoise through the soil because high-frequency components of lightning current traversing soil are damped significantly (the soil acts as a low-pass filter). This has been shown with soon-to-be published data from a different rocket-triggered lightning experiment at the ICLRT.

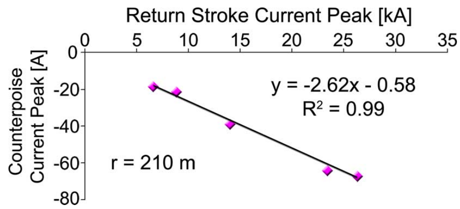

Fig. 3. Current peaks of lightning return strokes triggered from the mobile launcher located 210 m northeast of the counterpoise versus counterpoise current peaks.

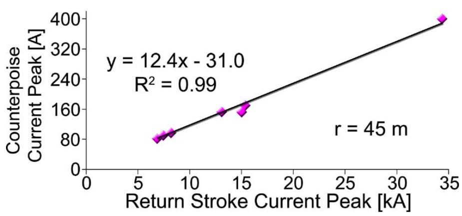

Fig. 4. Current peaks of lightning return strokes triggered from the stationary launcher located 45 m northwest the counterpoise versus counterpoise current peaks.

polarities of the lightning's horizontal electric field components at the counterpoise due to the different locations of the causative return stroke currents, that is, northeast of the counterpoise for return stroke currents from the mobile launcher and northwest of the counterpoise for return stroke currents from both the stationary launcher and the natural lightning (Fig. 1).

The peak values of the induced counterpoise currents versus the peak values of the causative rocket-triggered lightning return stroke currents are plotted in Figs. 3 and 4. The figures show that the peak values of the induced currents (*y*-axis) and the lightning return stroke current peak values (*x*-axis) are strongly linearly correlated ($R^2 = 0.99$, where R^2 is the determination coefficient) for both the mobile launcher experiment (Fig. 3) and the stationary launcher experiment (Fig. 4). The peak values of the induced currents and the peak values of the time derivative of the lightning return stroke currents are also correlated ($R^2 = 0.85$ for the mobile launcher experiment and $R^2 = 0.89$ for the stationary launcher experiment). No correlation has been found between the peak values of the induced currents and the 30–90% risetimes of the lightning return stroke currents. The ratio of the slopes in the regression equations ($12.4/2.62 = 4.7$) and the ratio of the inverse distances of the lightning strokes from the counterpoise ($210/45 = 4.7$) are equal, which suggests that the slopes (absolute values) have an inverse distance relationship.

The inverse distance relationship and the return stroke peak current–counterpoise peak current relationship allows us to estimate the return stroke peak current $I_{p,\mathrm{RS}}$, from the counterpoise peak current $I_{p,\mathrm{CP}}$, at any distance *r* and vice versa for triggered lightning strokes using the empirical equation

$$I_{p,\mathrm{RS}} = 1.81\, r\, |I_{p,\mathrm{CP}}|\,. \tag{1}$$

We now assume that (1) is valid for estimating the current peaks of the two natural lightning strokes in flash MSE0504, which could not be measured directly.[2] The distance *r* of flash MSE0504 to the northwest corner is 273 m, the counterpoise current peak $I_{p,\mathrm{CP}}$ during the first return stroke is 94 A, and $I_{p,\mathrm{CP}}$ during the second return stroke is −47 A. The calculated return stroke current peak values $I_{p,\mathrm{RS}}$ from (1) are 46 kA for the first return stroke and 23 kA for the second return stroke in flash MSE0504. For comparison, the peak currents of the two strokes reported by the U.S. NLDN from distant radiation field measurements are 65 kA for the first stroke and 34 kA for the second stroke. The discrepancy between our peak current estimations and the NLDN peak current estimations are likely due to one or more of the following: 1) inaccuracy of (1); 2) an inaccurate strike location for flash MSE0504 (which is unlikely); and/or 3) inaccuracy in the NLDN system in estimating peak currents. Note that (1) likely depends on the angle of the lightning strike location, relative to, say, the northerly direction at the center of the counterpoise. However, the stationary and mobile launcher locations and the strike location of flash MSE0504 have a similar magnitude of angle (Fig. 1). Also note that Jerauld *et al.* [21] found that the NLDN tended to underestimate peak currents by about 18% in 2002–2004. Since then, changes have been made in the NLDN algorithm.

Even though there are differences between our and the NLDN estimated peak currents, the ratio, both of our first and second return stroke peak current estimates (46 and 23 kA) and of the NLDN first and second return stroke peak current estimates (65 and 34 kA), are very similar, about 2. Thus, the ratios of the peak currents are likely correct confirming that return stroke peak currents and counterpoise peak currents are indeed linearly related for a given type of event at a given distance.

B. Currents Induced in the Vertical Conductor During Rocket-Triggered Lightning

Fig. 5 shows representative examples of currents that were measured in the vertical conductor during lightning triggered from the stationary launcher located 100 m south of the vertical conductor (Fig. 1). The vertical conductor current shown in Fig. 5 was measured during stroke 0517-2—a 15–kA stroke, whose current is depicted in the inset of Fig. 2(b). Additionally, Fig. 5 shows d*E*/d*t* waveforms measured at stations 8, 4, 1, and 9 that were located at distances ranging from 170 to 340 m from the stationary launcher (Fig. 1).

It is clear from Fig. 5 that the d*E*/d*t* waveshapes measured at all stations are very similar for the time period from about 0.3 μs prior to return stroke initiation to about 0.4 μs after the return stroke initiation. The waveshape similarity probably indicates that the electric field during this time is dominated by the radiation field component, which has the same waveshape at any

[2]Generally, first return stroke currents and rocket-triggered lightning currents have different waveshapes. However, applying (1), which was obtained for rocket-triggered lightning currents, to first return stroke currents appears to be reasonable since (a) the strong correlation between induced current peaks and lightning return stroke current peaks and (b) the lack of correlation between induced current peaks and risetimes of lightning return stroke currents both indicate that (1) does not depend significantly on the waveshape of the lightning current.

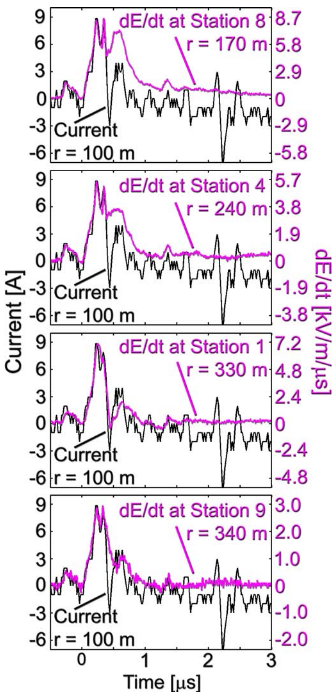

Fig. 5. Current induced in the vertical conductor during stroke 0517-2 triggered from the stationary launcher and dE/dt measured at stations 8, 4, 1, and 9. The polarity of the current is reversed for illustrative purposes. The distances of the vertical conductor and dE/dt measurement stations from the stationary launcher are given. The return stroke begins at $t = 0$.

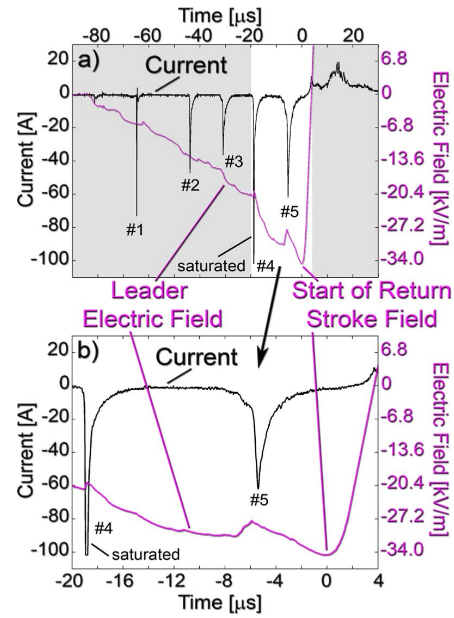

Fig. 6. Natural flash MSE0504, pre-first-return-stroke current pulses measured in the vertical conductor located 210 m east of the strike point and electric field measured at station 1 located 100 m west of the strike point displayed on (a) 120-μs and (b) 24-μs time scales. The polarity of the measured current is reversed for illustrative purposes. The first return stroke begins at $t = 0$. Note that pulse # 4 is saturated at 100 A. An unsaturated current record with high attenuation setting shows that pulse #4 has a peak value of 140 A.

distance [22]. For times after 0.4 μs, the closer dE/dt waveforms at 170 and 240 m show a hump that is likely associated with the electrostatic and intermediate electric field components as defined by Uman *et al*. [23].

Fig. 5 further illustrates that, for times before 0.4 μs, the current induced in the vertical conductor resembles the dE/dt waveshapes. The similarity of the current in the vertical conductor and the dE/dt waveforms suggests that the vertical conductor acts as a dE/dt antenna. The hump present in the dE/dt waveforms measured at 170 and 240 m is also expected to be present in the dE/dt field at the vertical conductor 100 m from the lightning, if the hump is indeed attributable to the electrostatic and induction field components. However, the vertical conductor current does not exhibit a hump, which is possibly due to a limited low-frequency response of the vertical conductor dE/dt "antenna." Note that the vertical conductor current in Fig. 5 shows some oscillations at 2 μs, which are not present in any of the dE/dt records. We speculate that the oscillations may indicate electrical breakdown of the soil around the vertical wire grounding [24].

We estimated the dE/dt peak value at the vertical conductor to be roughly 15 kV/(m·μs) using the peak value of the dE/dt measured at station 8 and using the 1/r distance relationship of pure radiation field (induction and static field components are also present to some degree at the time of dE/dt peak value at station 8, which will introduce some inaccuracy in the dE/dt estimation). We can use the calculated dE/dt peak value at the vertical conductor to obtain a proportionality coefficient between measured vertical conductor current peak and dE/dt peak. This conversion factor is 1.6 kV/(m·μs·A).

C. Currents Induced in the Vertical Conductor During Natural Lightning

Currents before and during the first return stroke of natural flash MSE0504 were measured in the vertical conductor located 210 m east of the strike point (Fig. 1). Five sharp current pulses were measured in the vertical conductor prior to the first return stroke of flash MSE0504 (Fig. 6). The time intervals between pulses range from 12 to 21 μs. The peak values of pulses #1, #2, #3, #4, and #5 are 73, 47, 36, 140, and 62 A, respectively. The polarity of the pulses is positive and indicates an upward-directed transfer of positive charge (the polarity of the current in Fig. 6 was reversed for illustrative purposes). Fig. 6(a) shows all five current pulses on a 120-μs time scale, and Fig. 6(b) shows pulses #4 and #5 on a 24-μs time scale. Additionally, the electric field at station 1 (station 1 is located 100 m west of the strike point, see Fig. 1) is displayed in Fig. 6. The electric field was obtained by integrating the dE/dt waveform measured at station 1.

Apparently, the five pre-return-stroke current pulses are associated with steps of the downward-moving stepped leader (see Section I). The time intervals between the current pulses range from 12 to 21 μs, which is close to the average interstep time interval of downward-moving-leader steps of 25 μs found by Krider *et al*. [13]. This suggests that the electric field variations due to leader steps induced the current pulses in the vertical conductor. Fig. 6(b) shows that the last two current pulses coincide with pronounced changes in the electric field at station 1, which are due to leader steps [25], [26].

The pre-return-stroke current pulses evident in Fig. 6 are likely associated with an attempted upward positive leader (although no optical records are available) emerging from the tip of the vertical conductor. The absence of significant current between current pulses indicates that the leader failed to form a self-propagating channel. In principle, the current pulses measured in the vertical conductor could be produced by coupling of the lightning electromagnetic fields resulting in induced conduction current confined to the metallic conductor and ground connection. We will argue next that the latter is not the case.

The factor that converts currents measured in the vertical conductor to dE/dt in Section III-B is 1.6 kV/(m·μs·A). If the current pulses were indeed due to a coupling mechanism similar to the one discussed in Section III-B, the vertical conductor antenna would measure dE/dt peak values ranging from 58–224 kV/(m·μs). However, the largest pre-return-stroke dE/dt peak value measured at stations 1 located 100 m from the strike point of flash MSE0504 (Fig. 1) was considerably smaller [13 kV/(m·μs)]. On the other hand, the current peak induced by the first return stroke, occurring at 3.9 μs in Fig. 6, yields a dE/dt value of 18 kV/(m·μs), derived using the triggered lightning conversion factor, which is consistent with the dE/dt measurements made at stations 4, 8, and 9 (the station 1 measurement was saturated).

Corona discharge is caused by the electrical breakdown of air near sharp conducting objects that results in the emission of streamers from these objects and needs to be examined as a possible source of the impulsive currents in Fig. 6. Moore *et al.* [27] measured current in a sharp, conically tipped Franklin rod mounted on a 6-m-high mast during nearby lightning. The current contained pre-return-stroke pulses that Moore *et al.* attributed to corona current flow at the tip of the Franklin rod. The pulses measured by Moore *et al.* and the pulses measured in the vertical conductor show a remarkable resemblance in terms of waveshape and interpulse time interval. However, the peak values of the pulses measured by Moore *et al.* are about four orders of magnitudes lower than the vertical conductor pulses seen in Fig. 6. The fact that the peak values of the vertical conductor pulses are considerably larger than the peak values of the pulses in Moore *et al.* and other studies of corona discharges (e.g., [28]) suggests that the current pulses measured in the vertical conductor are not attributable to corona discharge.

The current in the vertical wire during the return stroke is characterized by a smaller hump followed by a larger hump 12 μs later. The initial smaller hump is apparently caused by the electric field produced by the return stroke current and charge in its primary channel to ground. We speculate that the larger hump is produced by the electric field produced by the current and charge in the leader branch that caused the pre-return-stroke current pulses in the wire. The current and charge in the leader channel branch caused a larger current in the wire than the current and charge in the primary return stroke channel because the leader branch was likely closer to the wire than the main return stroke channel.

IV. Summary and Conclusion

1) The counterpoise currents induced by return strokes are characterized by an initial pulse a few microseconds wide followed by an opposite polarity overshoot of smaller magnitude, tens of microseconds wide.
2) The peak values of lightning return stroke currents and the peak values of currents induced in the buried counterpoise at distances of both 45 and 210 m from the lightning strike point are strongly correlated. The largest current induced in the counterpoise from rocket-triggered lightning at a distance of 210 m was 70 A. The return stroke peak current associated with this event was 26 kA. The largest current induced in the buried counterpoise from rocket-triggered lightning at a distance of 45 m was 160 A. The return stroke peak current associated with this event was 15 kA.
3) The grounded vertical conductor acts as a dE/dt antenna for the first half a microsecond or so after return stroke initiation.
4) The largest current induced in the grounded vertical conductor associated with natural lightning striking ground about 210 m away was 140 A. The observed multiple current pulses were likely associated with multiple attempts of an upward-moving unconnected leader generated in response to a nearby downward-propagating stepped leader. The identification and characterization of the upward-moving unconnected leader have many implications for the lightning protection of equipment vulnerable to sparks and large induced current pulses (e.g., the lightning protection of fuel tanks).

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