Close and Distant Electric Fields due to Lightning Attaching to the Gaisberg Tower

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Abstract: We examine current and electric field waveforms produced by lightning strikes initiated from the Gaisberg Tower located in Salzburg, Austria. Current was measured at the top of the tower and electric field measured simultaneously at close (170 m from the tower), and far (79 or 109 km from the tower) distances. In this preliminary study, we establish the criteria for characterizing current and electric field pulses that occur during the initial stage of upward lightning flashes (including those at the initiation of the initial stage) based on the characteristics of the measurement system used to record the current and electric field waveforms and the occurrence context of the pulses in the flash. Of the seven negative upward flashes analyzed in this study, two flashes had bipolar IS background current, which were first negative, followed by brief (duration < 2 ms) positive current, and then negative again. The initial stage background current was negative in the other five flashes. Overall, 71% of the pulses occurring during the initial stage were positive bipolar, 2% were positive unipolar, and 27% were negative unipolar. No negative bipolar pulses were found. The total duration of unipolar pulses ranged from 4.9 to 702 μs and that of bipolar pulses ranged from 4.1 to 197 μs.

Keywords : Upward lightning, Gaisberg Tower, current, two-station electric field

1. INTRODUCTION

Upward lightning from tall objects on ground can be an important aspect of winter lightning (e.g., in Japan). Majority of lightning attaching to wind turbines along the west coast of Japan during the winter season of this type [Ishii et al., 2015]. As a result it has attracted a lot of interest in recent years [e.g., Saito et al., 2011; Ishii et al., 2012; Smorgonskiy et al., 2016], including a CIGRE Working Group (C4.36) assembled to examine the characteristics of upward (and other winter-type) lightning discharges. Upward lightning involves an upward leader initiated from the top of a tall structure which bridges the gap between the tower-top and the overhead cloud charge region. An initial continuous current (ICC) flows along this channel typically for tens to several hundred milliseconds. There often exist current pulses, referred to as ICC pulses, superimposed on the slowly-varying ICC. The upward leader and the initial continuous current compose the initial stage (IS) of upward lightning. The initial stage is sometimes followed by one or more downward-leader-return-stroke sequences, the latter being similar to subsequent return strokes in downward lightning.

Zhou et al. [2012a,b] examine the characteristics of upward lightning discharges from the Gaisberg Tower, which is a 100 m high radio tower on Gaisberg, a 1287 m tall (above mean sea level) mountain near the City of Salzburg in Austria. In this paper, we present initial results of our study to examine in detail the characteristics of ICC pulses and corresponding electric field changes measured at near and far distances from the Gaisberg Tower.

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2. INSTRUMENTATION AND DATA

A current measuring shunt is located at the base of a 1.5-m high air terminal on top of the Gaisberg Tower. The shunt has an impedance of 0.25 mΩ and a bandwidth from DC to 3.2 MHz. Two separate fiber optic links (Nicolet ISOBE 3000, with bandwidth from DC to 15 MHz) with vertical scale limits of ±2 kA and ±40 kA are used to transmit signals from the shunt to the 8-bit (12-bit after May 16, 2012) digital acquisition system located at a nearby housing facility. The current sampling rate was 20 MHz, and the total record length is 800 ms with a 15 ms pre-trigger time. The trigger threshold of the system was set at ±200 A. Prior to analysis, the current waveforms are filtered using a second order Butterworth low pass filter with a –3 dB at 250 kHz to remove high frequency noise and resampled at 5 MHz.

Two electric field measurement systems, one at a distance of 170 m, and the other at a distance of 79 km (during 2006-2007) or 109 km (2008 onwards) from the tower were used to measure the electric field changes associated with lightning strikes to the Gaisberg Tower. Each electric field measurement system consisted of a flat plate antenna with an active integrator and amplifier. For the measurement system at 170 m, the electrical signal from the integrator output was sent to a 12-bit digital acquisition system via a fiber optic link (ISOBE 5000, from DC to 25 MHz). For the measurement system at 109 km, a fiber optic link was used up to July, 2013 after which a double shielded coaxial cable was used to transmit the data from the integrator to the digital acquisition system. The field measurement systems had a frequency bandwidth from 300 Hz (which translates to a decay time constant of 0.5 ms) to 1 MHz. The sampling rate was 5 MHz (sampling interval of 200 ns), and the total record length of electric field waveforms is 5 s with a 2 s pre-trigger time. Both current and electric field records are GPS time stamped.

The near field measurement system was installed on a 4 m high metal platform at a distance of 170 m from the Gaisberg Tower. The near field measurement is affected by its location on top of

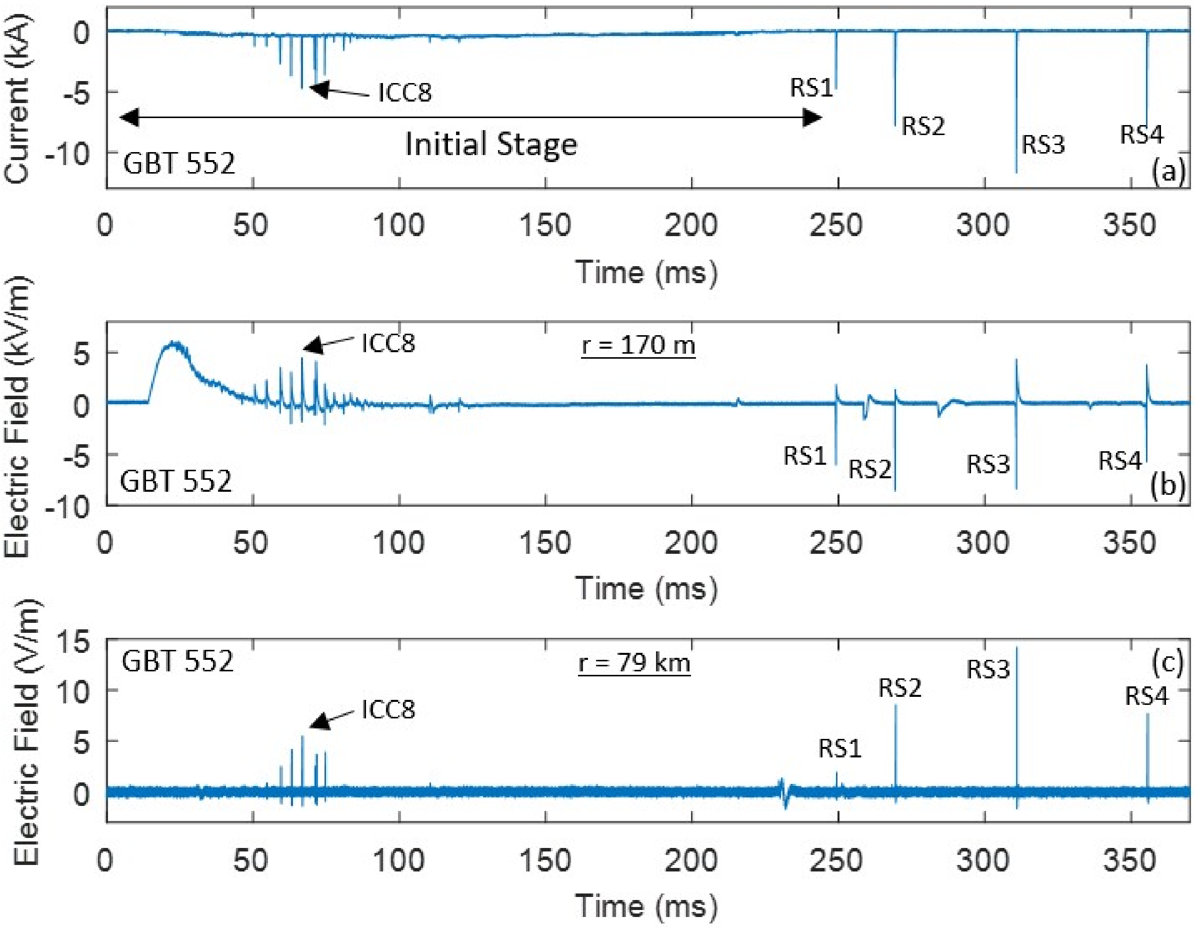

Fig. 1. (a) Current, (b) electric field at 170 m, and (c) electric field at 79 km for the upward negative flash GBT #552, shown on a 400-ms timescale. The initial stage was followed by four downward leader-return stroke sequences. An expanded version of one of the ICC pulses (ICC8) occurring during the initial stage of this flash is shown in Figure 2.

the platform, which itself is on top of the Gaisberg mountain. The field enhancement factors on top of the platform (with respect to nearby flat ground) and on top of the mountain (with respect to the bottom of the mountain) were, respectively, 7.8 and 2.8 [Zhou et al., 2011]. During 2005-2013 the far field measuring system was installed in Wels, Austria (79 km from the tower) on top of a building. No amplitude calibration is available for the far field measurement for data collected in this period. In our analysis we will not use the amplitude of pulses in flashes occurring during this period to draw any conclusions. Starting 2014, the far field measuring system has been located in Neudorf, Austria (109 km from the tower) on the roof of a building. A field enhancement factor of 2.5 was determined for the antenna location on the roof of the building with respect to flat ground by calibrating against a second flat plate antenna placed on flat ground near the building and comparing lightning radiation field data measured simultaneously by each system [Hanke, 2014].

In this paper we analyze current and electric field of seven negative upward flashes that occurred in 2007 and discuss the criteria used to examine the initial stage current and field characteristics along with some initial results.

3. METHODOLOGY AND INITIAL RESULTS

Figure 1 shows the current and electric fields measured at near and far distances for a negative upward flash at the Gaisberg Tower (GBT 552). The IS was followed by four return strokes. As discussed in Section 1, the IS current waveform in this flash is composed of faster (sub-microsecond, microsecond, and millisecond-scale) pulses superimposed on a slowly varying current lasting for many tens to hundreds of milliseconds. One of the ICC pulses in the IS is shown on a 420 µs timescale in Figure 2. As expected, the near (170 m from the tower) field waveform is dominated by electrostatic field component and the far field (at 79 km) is predominantly radiation. Due to the complexity of the current waveforms associated with the processes involved in upward leader formation and propagation, there are no clear criteria to analyze the characteristics of these pulses. Typically, pulses with relatively low peak currents (<1 kA) and short duration (microsecond-scale) are ignored. In this paper, we establish the criteria for characterizing these pulses in detail based on the characteristics of the measurement system used to record the current and electric field waveforms and the occurrence context of the pulses in the flash.

We define an ICC "pulse" as a fast variation in current relative to the slower (tens-to-hundreds-of-milliseconds-scale) "background" continuing current, so by definition, we only include in this category current variations with total durations of

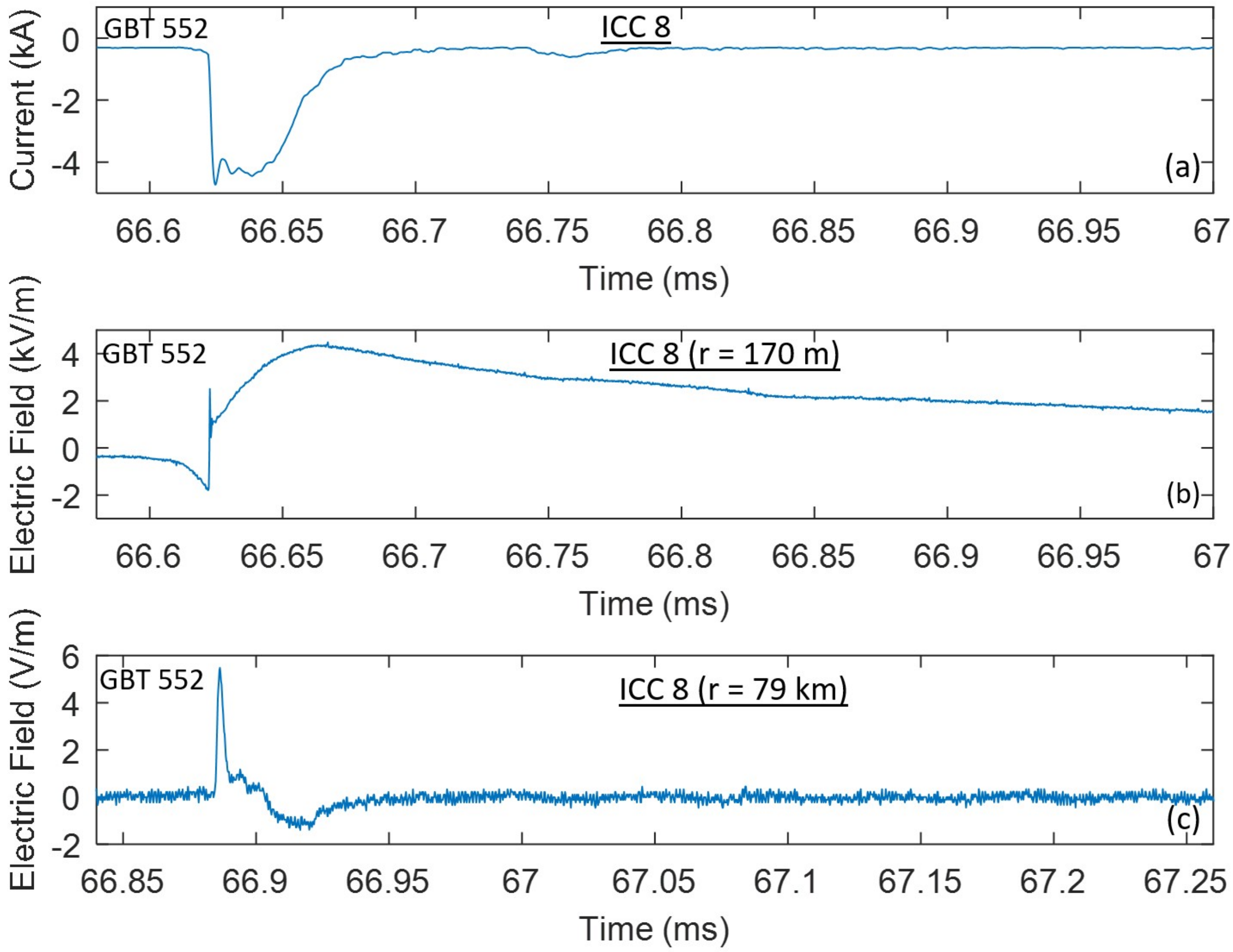

Fig. 2. (a) Current, (b) electric field at 170 m, and (c) electric field at 79 km for ICC8 in upward negative flash GBT #552, shown on a 420-µs timescale. See Figure 1 for more details.

less than 1 ms. The –3 dB upper limit of frequency bandwidth of the current and electric field measurement systems of 250 kHz and 1 MHz, respectively, translate to full cycle time domain signals of 4 µs and 1 µs. So, we exclude current and field pulses having total duration of less than 4 µs and 1 µs, respectively, as characteristics of shorter duration pulses will likely be affected by the bandwidth limitations. This also means that current pulses having risetimes as low as 4 x 0.33 = 1.32 µs and electric field pulses, pulses with risetimes of 1 x 0.33 = 0.33 µs can be measured without significant distortion. Finally, all waveforms are sampled at 5 MHz (sampling interval of 200 ns). Based on these factors we establish a lower measurement limit for the current risetime of 1.5 µs and field risetime of 600 ns (at least 3 sample points). Pulses having shorter risetimes were excluded. Also, current and field pulses with peak-to-peak amplitudes less than twice that of the average noise level were excluded. For each flash, the current waveform was used as a reference and the electric field waveform corresponding to each current pulse was examined as long as all the criteria described above were satisfied. For low-amplitude ICC pulses (peak current < 2 kA), the digitizer channel with a vertical scale limit of ±2 kA was used. For pulses with higher peak currents, the digitizer channel with a vertical scale limit of ±40 kA was used.

In theory, based on the polarity of the IS background current and the initial polarity of unipolar and bipolar ICC pulses, these pulses can be divided into the following eight types: (1) Positive bipolar pulse overlaid on positive IS background current, (2) Positive bipolar pulse overlaid on negative IS background current, (3) Negative bipolar pulse overlaid on positive IS background current, (4) Negative bipolar pulse overlaid on negative IS background current, (5) Positive unipolar pulse (with no measureable opposite polarity overshoot) overlaid on positive IS background current, (6) Positive unipolar pulse overlaid on negative IS background current, (7) Negative unipolar pulse overlaid on positive IS background current, (8) Negative unipolar pulse overlaid on negative IS background current. Of the seven flashes analyzed in this study, two flashes had bipolar IS background current, which were first negative, followed by brief (duration < 2 ms) positive current, and then negative again. In the other five flashes the IS background current was negative. 2.8% (5) of the pulses were of type 1, 68.2% (122) were of type 2, 2.2% (4) were of type 6, and 26.8% (48) were of type 8. No pulses of types 3, 4, 5, and 7 were found. Overall, 71% of the pulses were positive bipolar, 2% were positive unipolar, and 27% were negative unipolar. No negative bipolar pulses were found. Figure 2 shows an example of a negative unipolar ICC pulse overlaid on

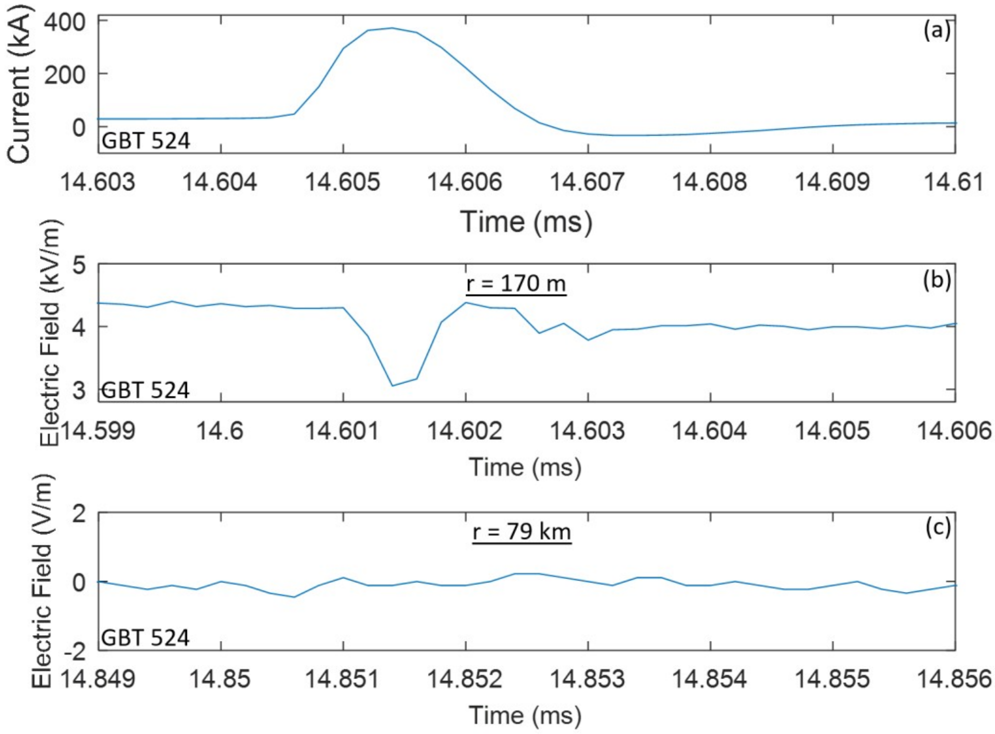

Fig. 3. (a) Current, (b) electric field at 170 m, and (c) electric field at 79 km for a positive bipolar ICC pulse overlaid on positive IS background current in upward negative flash GBT #524, shown on a 7-µs timescale. The signal-to-noise ratio of the corresponding radiation field signature at 79 km was not sufficient for it to be measured as seen from (c).

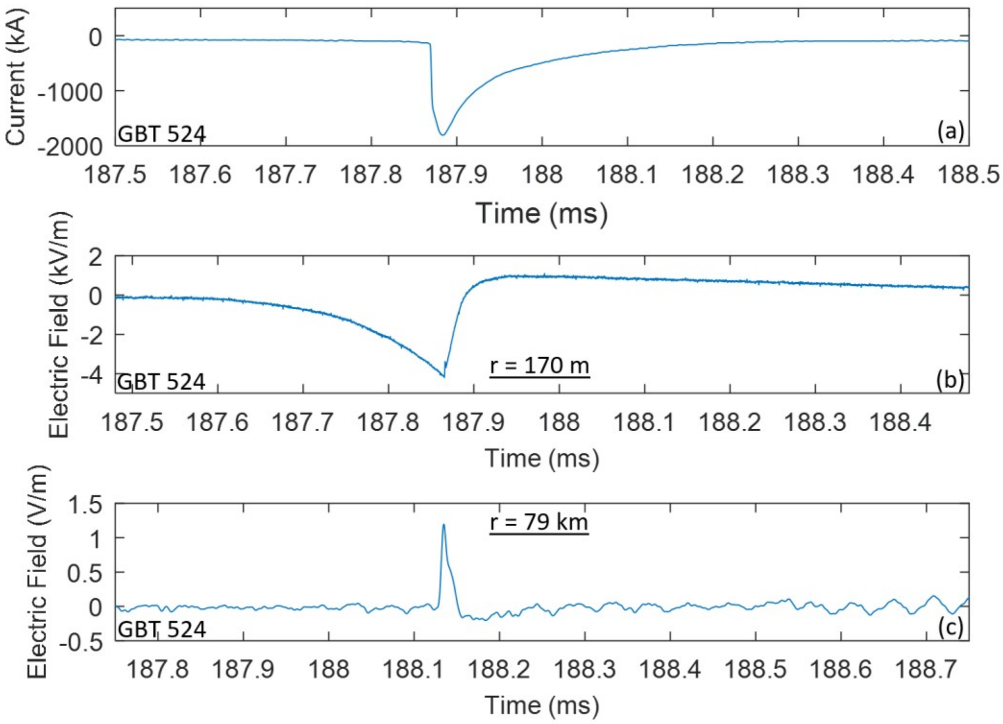

Fig. 4. (a) Current, (b) electric field at 170 m, and (c) electric field at 79 km for a negative unipolar ICC pulse overlaid on negative IS background current in upward negative flash GBT #524, shown on a 1.0-ms timescale.

a negative IS background current. Figure 3 shows an example of a positive bipolar ICC pulse overlaid on a positive IS background current.

The total duration of a unipolar ICC pulse was defined as the time interval between the initial deflection from the background current level to the point where the falling edge of the pulse reaches 10% of the peak value. The total duration of a bipolar ICC pulse was defined as the time interval between the initial deflection from the background current level to the point where the opposite polarity falls back to the background current level.

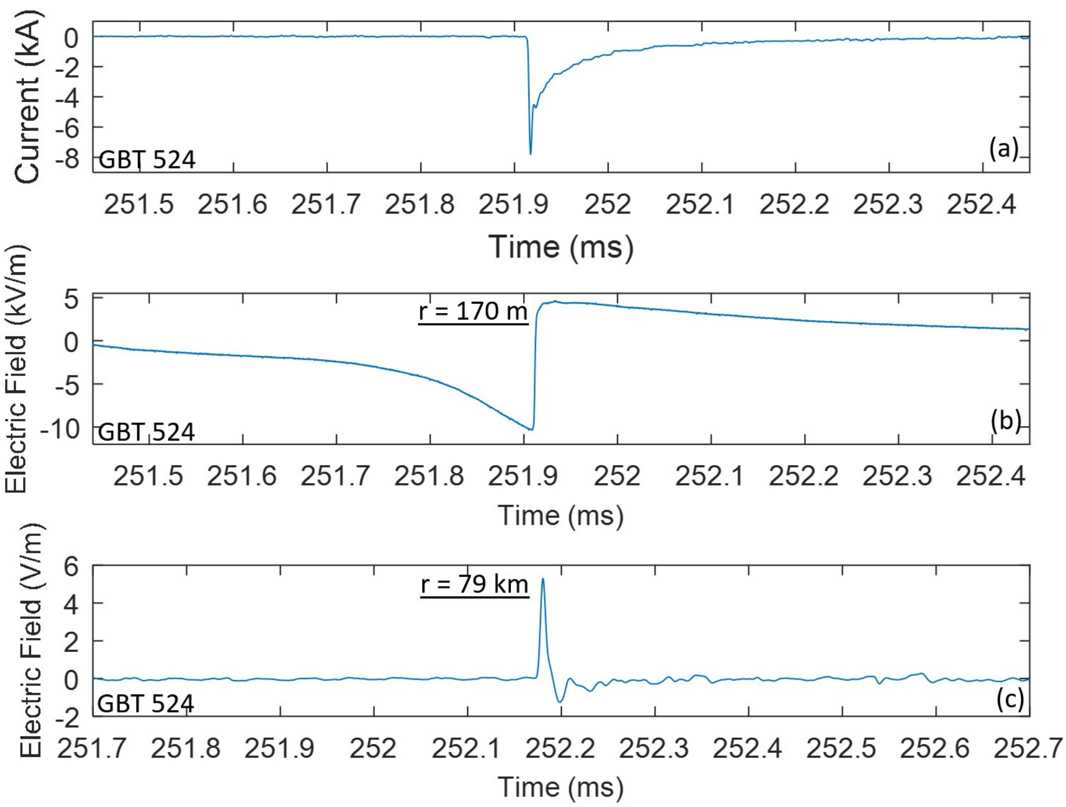

Fig. 5. (a) Current, (b) electric field at 170 m, and (c) electric field at 79 km for a negative return stroke in upward negative flash GBT #524, shown on a 1.0-ms timescale.

In the seven flashes analyzed in this study, the total duration of unipolar ICC pulses ranged from 4.9 to 702 µs with the median duration being 228 µs and that of bipolar ICC pulses ranged from 4.1 to 197 µs with the median duration being 6.1 µs. Additionally, low-amplitude bipolar pulses tend to occur more often toward the beginning of the initial stage, while high-amplitude unipolar pulses are more likely to occur at later times. From the above discussion we conclude that characteristics and occurrence context of unipolar and bipolar ICC pulses are quite different, at least on average, and they are likely associated with different processes occurring in different stages of the IS.

In some cases, the close electric field changes produced immediately before and after an ICC pulse resemble those associated with the leader-return-stroke sequence. Figure 4 shows an example of such an ICC pulse and, for comparison, Figure 5 shows a return stroke occurring later in the same flash. A time-window of 1 ms is shown in each case. This leads us to believe that, at least in some cases, processes associated with producing ICC pulses could be looked at as being similar to leader-RS processes, but occurring in the presence of a pre-existing continuing current.

4. SUMMARY

Due to the complexity of the current waveforms associated with the processes involved in upward leader formation and propagation, there are no clear criteria to analyze the characteristics of these pulses. Typically, pulses with relatively low peak currents (<1 kA) and short duration (microsecond-scale) are ignored. In this paper, we describe initial results as we examine in detail the characteristics of ICC pulses in upward discharges. We establish the criteria for characterizing these pulses based on the characteristics of the measurement system used to record the current and electric field waveforms and the occurrence context of the pulses in the flash. In theory, we can categorize ICC pulses into eight types based on the polarity of the IS background current and the initial polarity of each pulse. Of the seven flashes analyzed in this study, two flashes had bipolar IS background current, which were first negative, followed by brief (duration < 2 ms) positive current, and then negative again. In the other five flashes the IS background current was negative. 2.8% of the pulses were of type 1, 68.2% were of type 2, 2.2% were of type 6, and 26.8% were of type 8. No pulses of types 3, 4, 5, and 7 were found. Overall, 71% of the pulses were positive bipolar, 2% were positive unipolar, and 27% were negative unipolar. No negative bipolar pulses were found. The total duration of unipolar ICC pulses ranged from 4.9 to 702 µs with the median being 228 µs and that of bipolar ICC pulses ranged from 4.1 to 197 µs with the median being 6.1 µs.

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