Electrical Development in Lightning before Initial Breakdown Pulses

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ABSTRACT: This study focuses on the initial development of lightning flashes occurring before the first initial breakdown (IB) pulse in the flashes, as determined by electric field change (E-change) measurements. The initial E-change (IEC) was measured in 18 negative cloud-to-ground (CG) flashes and 18 typical intracloud (IC) flashes in the vicinity of the NASA Kennedy Space Center in Florida, USA, in the summers of 2010 and 2011. For the CG flashes the IEC values averaged 0.5 V/m with a median of 1.5 V/m and a range of 0.1 – 6.5 V/m (not distance-normalized). For IC flashes the IEC values averaged -6.1 V/m with a median of -3.9 V/m and a range of -0.7 to -23.4 V/m (not distance-normalized). These small E-changes were observable because the horizontal distances between sensor and the IEC events were short: 0.2 – 6.9 km for CG flashes and 0.5 – 6.2 km for IC flashes. In all cases the sensors were within the reversal distance of the IEC events. For CG flashes the IEC increased linearly with time up to the first IB pulse; the IEC durations for CG flashes averaged 0.18 ms with a median of 0.16 ms and a range of 0.08 – 0.33 ms. For IC flashes the IEC decreased linearly with time with an average duration of 1.53 ms, a median of 0.92 ms, and a range of 0.09 – 5.7 ms. For both types of flashes the IEC and the first half-cycle of the following IB pulse had opposite polarities. However, for both types of flashes the IEC and the electrostatic change of the following IB pulse had the same polarity.

INTRODUCTION

The physical processes that occur during lightning initiation are still unknown. Remote detection of electromagnetic radiation from a developing lightning flash has been one of the only ways of investigating lightning initiation. It has been found that the beginning of both cloud-to-ground (CG) and intracloud (IC) lightning flashes is characterized in electric field change (E-change) data by a series of bipolar pulses [e.g., Clarence and Malan, 1957; Kitagawa and Brook, 1960; Weidman and Krider, 1979] that have been given various names and are called initial breakdown pulses or IB pulses herein. The IB pulses typically occur during the first 2-10 ms of CG flashes and the first 5-20 ms for IC flashes [e.g., Clarence and Malan; Bils et al., 1988]. Recent measurements indicate that the beginning of essentially all lightning flashes includes IB pulses [e.g., Marshall et al., 2014, and references therein].

This study reports on a relatively small, relatively slow E-change that occurs before the first IB pulse in both CG and IC flashes. We hypothesize that this initial E-change (called IEC herein) is due to the first charge motions of the developing lightning flash.

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DATA SOURCES

The two main data sources were an array of electric field change sensors and a VHF lightning mapping system. The data were collected at the NASA Kennedy Space Center (KSC) in Florida, USA, during July and August of 2010 and 2011. We use the physics definition of electric field polarity: the direction of the electric field at a particular location is the same as the direction of the electric force on a positive test charge placed at that location.

Electric field change sensors

Our E-change sensors used flat plate antennas to detect electric field changes. They were calibrated, had a bandwidth of either 0.16 Hz – 2.6 MHz or 0.016 Hz – 2.6 MHz, with the lower frequency due to an RC decay time of either 1 s or 10 s. The E-change data were digitized with a 12-bit A/D converter at 10 MSamples/s; typically 500 ms of data were captured whenever a floating trigger level was exceeded (though shorter capture times were occasionally used). Some E-change data were recorded 10 MSamples/s; in other cases the 10 MS/s data were averaged and recorded at 5 or 1 MS/s. The least significant bit for most sensors was between 0.15 and 0.30 V/m. In 2010 we deployed 5 E-change sensors over a region of about 30 x 40 km [see map in Stolzenburg et al., 2012]. In 2011 we had a 10-sensor array covering an area of about 70 x 100 km [see map in Karunarathne et al., 2013].

As mentioned above, the IEC events had small amplitudes. For this reason, all of the IEC events presented herein were located less than 7 km horizontally of the E-change sensor that detected the IEC. Having an array of sensors increased the possibility of having an E-change sensor close enough to detect the initial E-change of a flash.

Lightning event locations from LDAR2

During 2010 and 2011 Kennedy Space Center operated a VHF lightning locating system that we call LDAR2 herein (for 2nd generation Lightning Detection And Ranging system). The LDAR2 system was made up of nine VHF sensors distributed across an area that spanned about 50 km x 70 km centered on KSC. LDAR2 provided (x, y, z) locations of short impulsive VHF lightning events if at least four sensors detected the event [e.g., Thomas et al., 2004]. Altitude, z, was measured relative to mean sea level, and the (x, y) horizontal locations were measured relative to an origin at KSC. According to Thomas et al. [2004], LDAR2 is a commercial version of the Lightning Mapping Array or LMA [Rison et al., 1999]. The horizontal location errors of LDAR2 were 100-200 m for the flashes studied herein, which were located near the center of the LDAR2 array [Murphy et al., 2008], and vertical location errors were estimated as 240-480 m [e.g., Thomas et al., 2004]. In about 40% of the IEC measurements, an LDAR2 event was coincident with the beginning of the IEC. LDAR2 events were sometimes coincident with changes in the linear slope of the IEC. Examples of these coincidences are shown below.

DATA

Initial E-changes of CG flashes

An example of the IEC in a CG flash is shown in Figure 1, which plots E-change and LDAR2 events versus time. The E-change data (scale on left axis) are shown for two sensors, K02 and K14, while the altitude (scale on right axis) of LDAR2 events are plotted versus their arrival time at the K02 sensor. The horizontal position of the first LDAR2 event in Figure 1 was 3.2 km and 16.3 km, respectively, from the K02 and K14 sensors; the first LDAR2 event altitude was 6.2 km, as shown. Since the IEC occurred close to the K02 sensor, it is visible in the K02 data.

Figure 1a gives an overview of the first 50 ms of the flash and includes the first return stroke. Since the K02 sensor was within the reversal distance of the first LDAR2 event, the E-change leading to the first return stroke was positive, while there was a negative E-change at the more distant K14 sensor (located beyond the reversal distance).

Figure 1b shows the first 1.5 ms of the flash including the IEC (described in the next paragraph) and the first several IB pulses. Note that there is a net positive E-change (net positive offset) for almost every IB pulse detected with the K02 sensor but no net offset for IB pulses detected with the more distant K14 sensor. This difference suggests that the positive IB pulse offsets in the K02 data were due primarily to the electrostatic contributions to the E-change, which vary as $1/R^3$, where R is the slant range from the sensor to the IB pulses. Eack [2004] found similar electrostatic offsets in narrow bipolar pulses recorded be sensors close to the events.

Figure 1c shows 0.5 ms of data, including the IEC and the first IB pulse. During the first 0.2 ms of Figure 1c, there was no E-change at both sensors, and this zero E-change state extended back to the beginning of the triggered data 14 ms earlier (not shown). Thus, after at least 14 ms of zero E-change, the IEC began abruptly at the same time as the first LDAR2 event of the flash; we mark this time as the flash initiation. The E-change rose rapidly for about 0.01 ms, then for the next 0.14 ms the slope of the E-change maintained a slower steady rate, until a small negative pulse was seen in the E-change data (marked with "begin E slope change"). After that negative pulse, the slope of the IEC increased for the last 0.03 ms. The IEC ended with the first IB pulse. The overall E-change of the IEC was 4.0 V/m, and the IEC duration was 0.18 ms. Since the first LDAR2 event was time coincident with the beginning of the IEC, we assume that the same physical event caused the first LDAR2 event and started the IEC. This assumption is supported by two facts: (1) for 55% of 18 CG flashes analyzed, the first detected LDAR2 event of the flash was coincident with the beginning of the IEC and (2) no flashes had an LDAR2 event before the beginning of the IEC.

Figure 2 shows three additional examples of IEC's in CG flashes; these flashes occurred within ± 2 min of the flash shown in Figure 1. All three IEC's are quite similar to the IEC in Figure 1c, but a few differences are worth noting. In Figure 2b there is no LDAR2 event at the beginning of the IEC, but there is an LDAR2 event coincident with both a small negative pulse and a small change in slope of the IEC. Figure 2c has no coincident LDAR2 events, but the IEC does have an obvious change in slope at the time of a small negative pulse. The lack of an LDAR2 event coincident with the beginning of each IEC (and each slope change) is not surprising since the beginning pulse seems to be quite small even for a nearby sensor, making it less likely that enough of the widely distributed LDAR2 sensors would detect the pulse to obtain an LDAR2 location.

For the 18 CG flashes analyzed, the IEC values averaged 0.5 V/m with a median of 1.5 V/m and a range of 0.1 – 6.5 V/m (not distance-normalized). The IEC durations averaged 0.18 ms with a median of 0.16 ms and a range of 0.08 – 0.33 ms. The altitudes of the IEC's averaged 5.9 km with a median of 5.8 km and a range of 4.9 – 7.1 km. The horizontal distances between closest E-change sensor and the IEC events were 0.2 – 6.9 km. For all 18 CG flashes the IEC increased quasi-linearly with time up to the first IB pulse. The initial deflection of the first IB pulse was negative (which is the same polarity as the return strokes), but the electrostatic offset of the IB pulses was positive, like the IEC.

Initial E-changes of IC flashes

An example of the IEC in an IC flash is shown in Figure 3 with E-change data from the K02 and K14 sensors and with LDAR2 events plotted for their arrival time at the K02 sensor. The horizontal distances between the first LDAR2 event and the K02 and K14 E-change sensors were 0.5 km and 15.8 km, respectively; the altitude of the first LDAR2 event was 6.7 km. Figure 3a shows the first 200 ms of the flash with the initial LDAR2 event marked as the flash initiation. Since the K02 sensor was so close to the first LDAR2 event, the E-change at K02 was negative (within the reversal distance), while the E-change at the more distant K14 sensor was positive.

Figure 3b shows the first 4 ms of the flash including the IEC (described in the next paragraph) and the first 7 IB pulses, which are more clearly seen in the K14 E-change data. In fact the IB pulses in the K02 data are difficult to discern because they are distorted by the large net negative E-change (net negative offset) accompanying every IB pulse; these offsets are presumably due to electrostatic contributions (and possibly also to induction contributions) to the E-change data. Although not obvious in Figure 3b, there is a small positive offset in some IB pulses as seen at the K14 sensor (see example in Figure 3c).

Figure 3c shows 2 ms of data, including the IEC and the first IB pulse. The IEC of this IC flash has almost the identical shape as the IEC of the CG flash in Figure 1, except that it has opposite polarity, i.e., declining with time instead of increasing. The E-change falls rapidly for about 0.01 ms, then decreases at a slower steady rate for 0.37 ms, until an LDAR2 event is seen in the E-change data (marked with “begin E slope change”). After that LDAR2 event, the IEC decreases more rapidly for the last 0.08 ms. The IEC ends with the first IB pulse. The E-change of the IEC is -23.4 V/m, and the IEC duration is 0.46 ms. The magnitude of the IEC E-change is the largest of the 36 IEC’s in this study.

Figure 4 shows three additional examples of IEC’s in IC flashes. All three are similar to the IEC in Figure 3c, but none of these IEC’s began with an LDAR2 event. In fact only 4 of the 18 IEC’s in IC flashes began with a coincident LDAR2 event (compared to 10 of 18 IEC’s of CG flashes). Some other differences in Figure 4 are worth noting. In Figure 4a there were two small electrostatic offsets during the IEC that were coincident with LDAR2 events; the slope of the E-change became more negative after the first of these, but did not change after the second. The IEC in Figure 4a also had the longest duration, 5.7 ms, of the 36 IEC’s in this study. The IEC in Figure 4b had a smoothly decreasing slope rather than 1-3 linear slopes seen in most other IEC’s. The IEC in Figure 4c had two slope changes, but no coincident LDAR2 events.

For the 18 IC flashes analyzed, the IEC values averaged -6.1 V/m with a median of -3.9 V/m and a range of -0.7 to -23.4 V/m (not distance-normalized). The IEC durations averaged 1.53 ms with a median of 0.92 ms and a range of 0.09 – 5.7 ms. The altitudes of the IEC’s averaged 8.3 km with a median of 8.4 km and a range of 6.6 – 9.6 km. The horizontal distances between the closest E-change sensor and the IEC events were 0.5 – 6.2 km. For all 18 IC flashes the IEC decreased, usually quasi-linearly, with time up to the first IB pulse; i.e., the IEC had a net negative E-change. The initial deflection of the first IB pulse was positive (except for the IEC in Figure 3c), but the electrostatic offset of the IB pulses detected at the close E-change sensor was negative, like the IEC.

CONCLUSIONS

To learn more about lightning initiation, we have studied the initial E-change data of 18 CG and 18 IC lightning flashes. The flashes were chosen because one of our E-change sensors was located close enough (within 7 km horizontally) to detect small initial E-changes. The data indicate that there is charge motion preceding the first initial breakdown pulse in a developing lightning flash. We have called this earliest charge motion the initial E-change or IEC. The beginning of the IEC was time coincident with the first LDAR2 event detected in the flash in 55% of the 36 flashes studied; we assume that the same physical event caused the first LDAR2 event and started the IEC. The source of the charge that moves during an IEC is unknown. The abstract gives the details of the net E-change and total duration of the 36 IEC's studied. The average duration of the IEC's is substantially shorter in CG flashes than in IC flashes; the average magnitude of the IEC is substantially smaller in CG flashes than in IC flashes. Further study of IEC's may explain the differences between IEC's in CG and IC flashes, may provide clues to the generation mechanism of the initial charge, and may explain how an IEC is connected to the first initial breakdown pulse in a flash.

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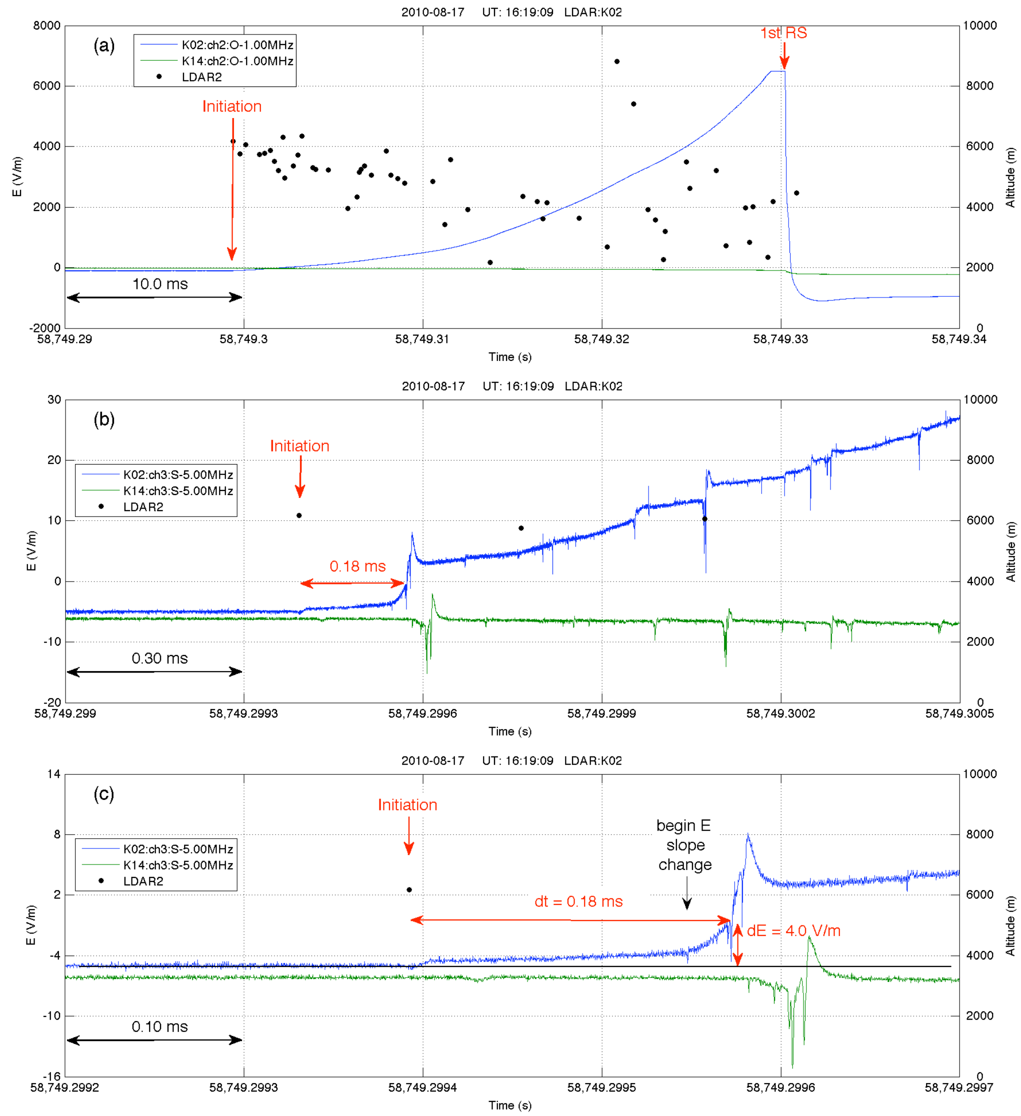

Figure 1. Example of IEC in a CG flash: E-change versus time for two sensors, K02 and K14, and LDAR2 events plotted as altitude versus time (using right vertical axis). The (x, y) position of the first LDAR2 event (marked with the red "Initiation" arrow) was at horizontal ranges of 3.2 km and 16.3 km, respectively, from the K02 and K14 sensors. (a) Overview of 50 ms including the first return stroke (RS). (b) First 1.5 ms showing IEC and several IB pulses. (c) Expanded view (500 µs) showing details of IEC and first IB pulse.

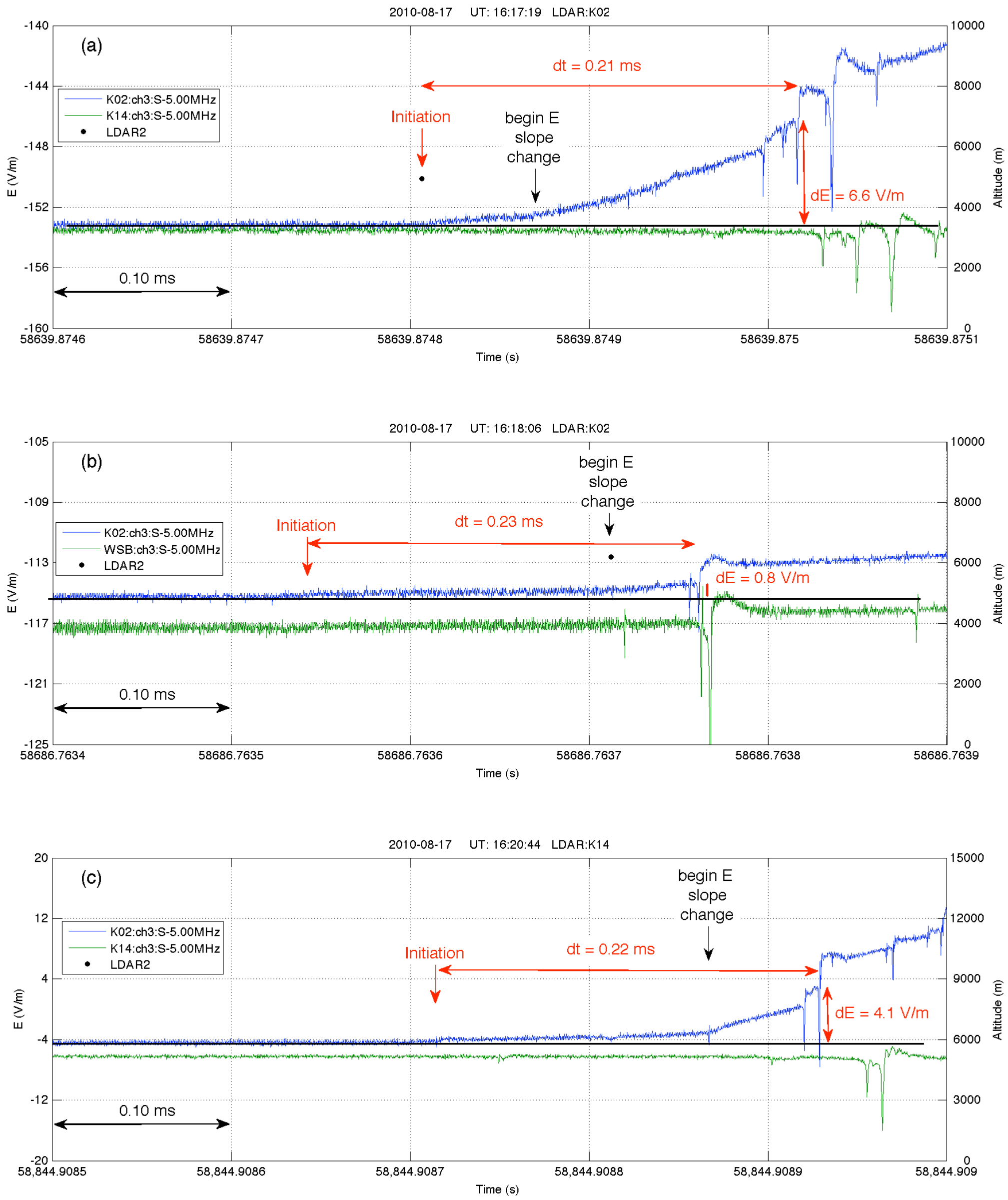

Figure 2. Similar to Figure 1c, showing three additional examples of the IEC versus time for CG flashes. The LDAR2 events are plotted for their arrival time at the K02 sensor. For Figure 2a the horizontal distance between the first LDAR2 event and the K02 and K14 sensors was 3.6 km and 16.6 km, respectively, in Figure 2b the distances were 3.8 km and 6.9 km from the K02 and WSB sensors, respectively, and in Figure 2c the distances were 2.9 km and 15.9 km from the K02 and K14 sensors, respectively.

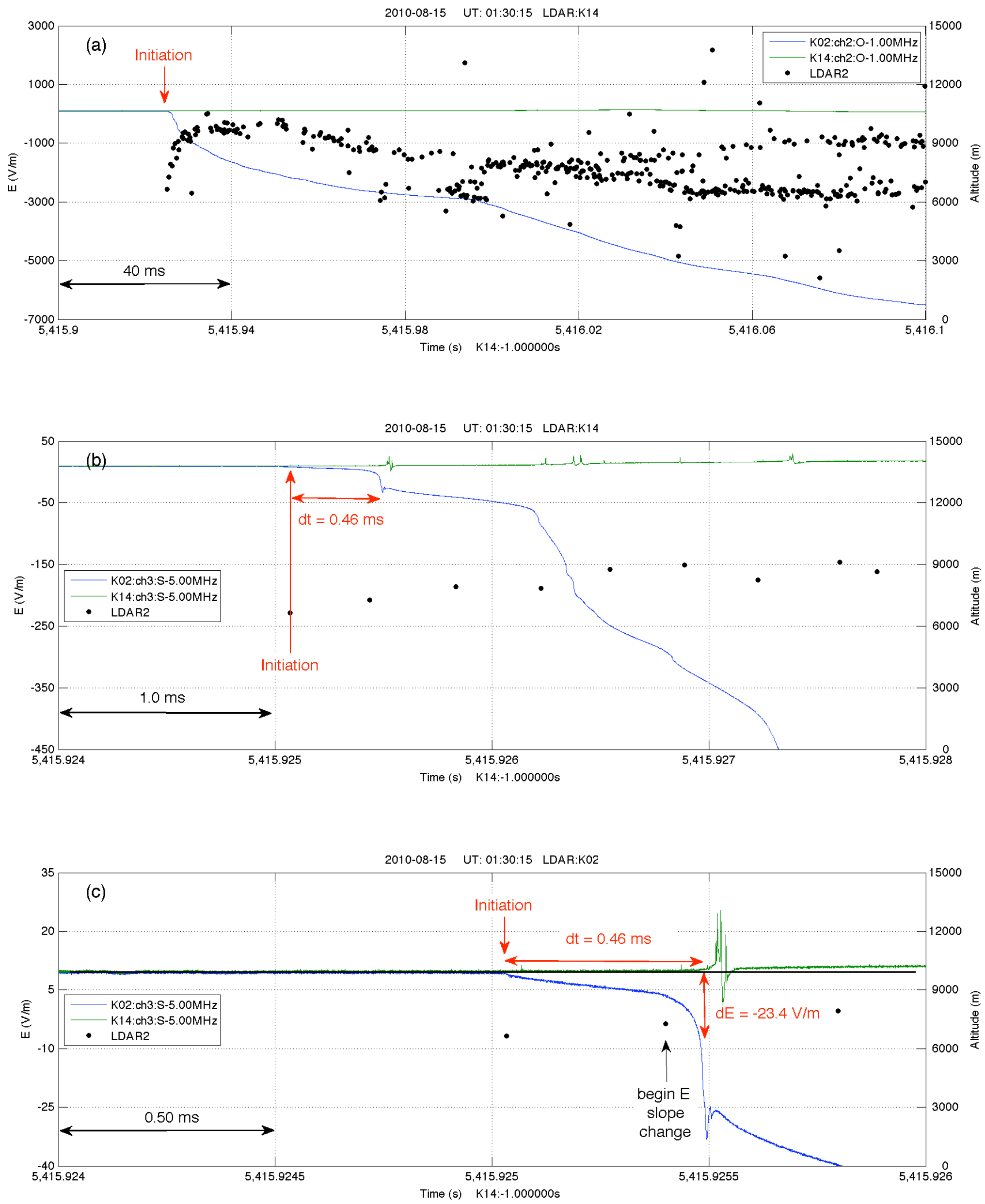

Figure 3. Similar to Figure 1, showing the IEC in an IC flash. The horizontal position of the first LDAR2 event (marked with the red "Initiation" arrow) was at ranges of 0.5 km and 15.8 km, respectively, from the K02 and K14 sensors. The LDAR2 events are plotted for their arrival time at the K02 sensor. Figure 3a: Overview of first 200 ms of flash. Figure 3b: First 4 ms showing the IEC and several IB pulses. Figure 3c: Expanded view (2 ms) showing details of the IEC and the first IB pulse.

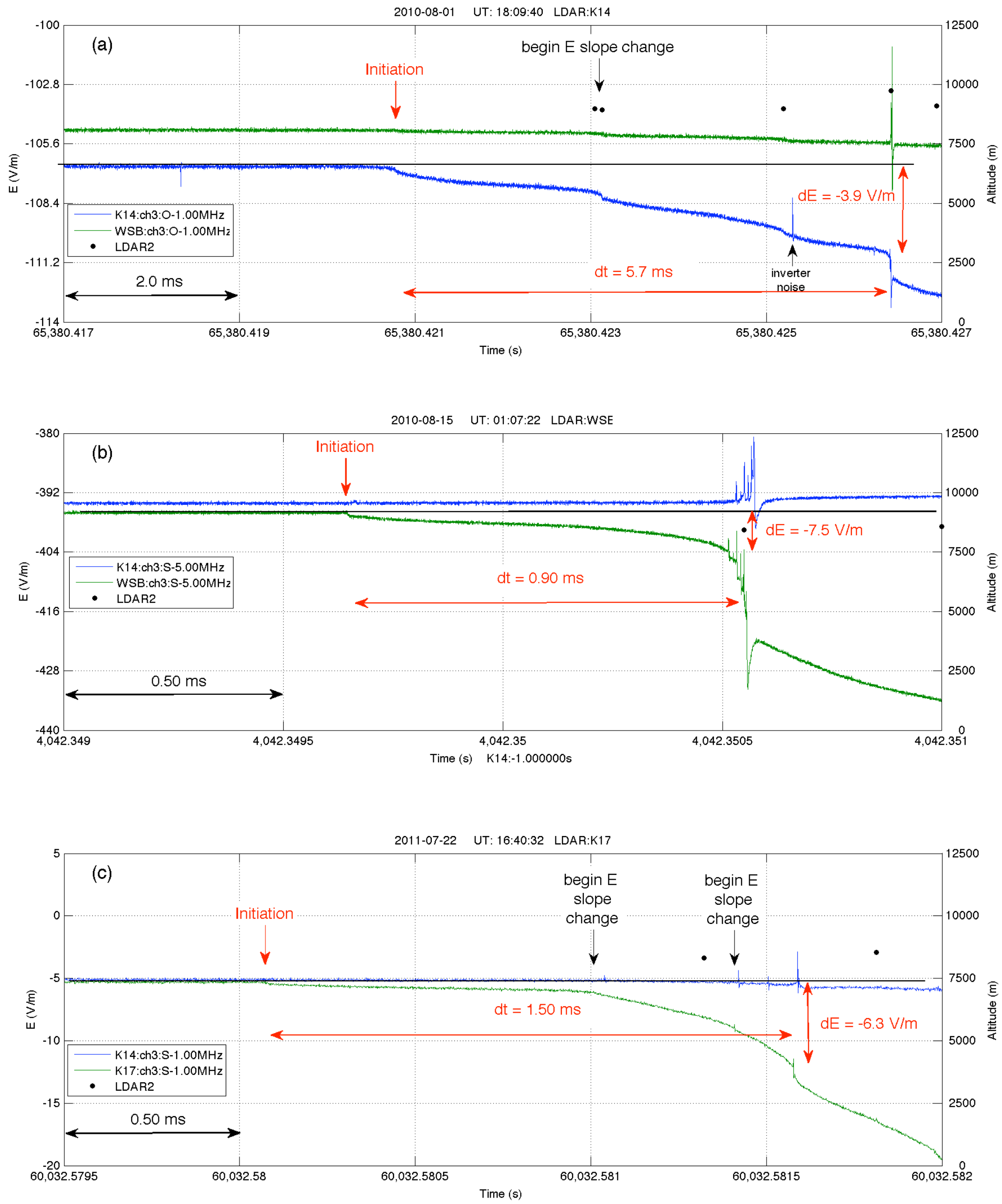

Figure 4. Similar to Figure 3c, showing three additional examples of the IEC versus time for IC flashes. For Figure 4a the horizontal distances between the first LDAR2 event and the K14 and WSB sensors were 5.3 km and 11.9 km, respectively, and the LDAR2 events are plotted for their arrival time at the K14 sensor. For Figure 4b the horizontal distances between the first LDAR2 event and the K14 and WSB sensors were 11.7 km and 4.3 km, respectively, and the LDAR2 events are plotted for their arrival time at the WSB sensor. For Figure 4c the horizontal distances between the first LDAR2 event and the K14 and K17 sensors were 9.4 km and 3.3 km, respectively, and the LDAR2 events are plotted for their arrival time at the K17 sensor.