The initial stage processes of rocket-and-wire triggered lightning as observed by VHF interferometry

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[1]   We examine VHF interferometric images, channel-base currents, and broadband electric field waveforms of the initial stage (IS) in two rocket-and-wire triggered lightning flashes. Two types of negative leaders, termed "long-duration" and "short-duration" leaders, were imaged by the VHF interferometers during the IS of the two flashes. There were three leaders that had relatively long durations of more than a few milliseconds. These three leaders were not accompanied by a significant change of channel-base current during their early stages of development, indicating that they corresponded to intracloud (IC) discharges that were not connected to the grounded triggered-lightning channel. Two of these three leaders eventually connected to the triggered-lightning channel and initiated initial continuous current (ICC) pulses. The third long-duration leader apparently developed from the vicinity of an isolated negative charge region toward an upper-level positive charge region and toward a branch of the grounded channel; it served to bridge the positive charge region and the triggered-lightning channel, resulting in the opposite polarity portion of the bipolar ICC. The short-duration negative leaders had durations of some hundreds of microseconds. These negative leaders apparently recoiled along the conductive channels created by branches of the upward positive leader (UPL); they initiated ICC pulses when the grounded channel was sufficiently conductive. It follows that ICC pulses can be initiated either by recoil leaders or via interception of separate in-cloud leaders by a grounded current-carrying channel.

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1.   Introduction

[2]   Artificially initiated lightning involves processes that are similar to those of natural downward lightning, including leader-return stroke sequences, continuing currents, and M-components, making it a useful technique to study lightning [e.g., *Fisher et al.*, 1993; *Jordan et al.*, 1995; *Rakov et al.*, 2001; *Biagi et al.*, 2009] and the interaction of lightning with various objects or systems [e.g., *Barker and Short*, 1996; *Fernandez et al.*, 1998; *Rakov*, 1999; *Mata et al.*, 2000]. Classical negative rocket-and-wire triggered lightning has several stages, including: the upward positive leader (UPL) that develops from the grounded triggering wire and

travels to the negatively charged cloud above; the initial continuous current (ICC); and, in many cases, one or more downward-negative leader/return-stroke sequences [*Rakov and Uman*, 2003]. The UPL and ICC together comprise the initial stage (IS) of a classically triggered lightning flash, which has a duration from some tens to hundreds of milliseconds.

[3]   Current impulses are often superimposed on the ICC, referred to as "ICC pulses." *Wang et al.* [1999] reported distributions and geometric mean (GM) values of ICC pulse parameters observed in three triggered lightning campaigns. The characteristics of the ICC pulses resemble the M-components that occur during continuing currents following return strokes [*Thottappillil et al.*, 1995].

[4]   Several researchers reported on the initiation of M-components in the cloud from observations of cloud-to-ground (CG) flashes using VHF interferometry. *Shao et al.* [1995], observing two CG flashes with a VHF interferometer and electric field change recording in Florida, reported that fast negative leaders with estimated speeds of about 10^6 m s^{-1} to 10^7 m s^{-1} developed prior to M-components, and asserted that the fast negative leaders initiated the M-component upon connection of the leader to the existing continuing current channel. *Mazur et al.* [1995], employing

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VHF interferometry observations with high-speed camera and electric field measurements in Florida, also reported that fast negative in-cloud leaders appeared to initiate M-components. *Shao et al.* [1996] observed a rocket-and-wire triggered CG flash with a New Mexico Tech VHF/UHF lightning interferometer at Langmuir Laboratory and reported that several short negative leaders approached the primary channel of the triggered lightning during the IS. They speculated that these negative leaders followed channels previously established by positive leaders, later connecting to the main ICC channel and producing ICC pulses.

[5] Due to the relatively fast propagation speeds (10^6 to 10^7 m s^{-1}) of M-component initiating leaders, the reports mentioned above [*Mazur et al.*, 1995; *Shao et al.*, 1995; *Shao et al.*, 1996] support the interpretation of *Mazur et al.* [1995] that: (1) the fast negative leaders retrace channels previously created by the upward positive leader, (2) the fast negative leaders connect to ICC or continuing current channels and, (3) the subsequent current waves produced by this connection are recognized at ground as an ICC pulse or an M-component when it occurs during an ICC or a continuing current, respectively. Another possible M-component initiation process, in which an upward-progressing leader intercepts a cloud discharge channel is considered by *Rakov and Uman* [2003].

[6] In this paper, we examine rocket-and-wire triggered lightning observations using VHF broadband digital interferometers along with measurements of channel-base currents and broadband electric fields in order to understand further the initiation mechanism associated with the ICC pulses. We determine the VHF source locations that occurred during the IS, and examine the relationship between in-cloud negative leader development and ICC pulses. Furthermore, we identify a lightning process termed here a "combined lightning," which we define as a connection between two or more separate discharges that can produce ICC pulses or an ICC polarity reversal in triggered lightning and, by extension, M-components.

2. Instrumentation

[7] The observations presented in this paper are from rocket-and-wire triggered flashes that were initiated in June and July of 2009 at the International Center for Lightning Research and Testing (ICLRT). The experiment has been previously described in *Yoshida et al.* [2010]. Channel-base currents were measured at the launch tower with a 1-mΩ current-viewing resistor having a flat frequency response from DC to 8 MHz. The remote electric fields were sensed with three flat plate antennas having different gains. These were located at distances of (in order of increasing sensitivity) 92 m (E-5), 357 m (E-6), and 156 m (E-2) from the launch tower. The E-2, E-5, and E-6 sensors had decay time constants (the decay time to 1/e for a step function input) of about 1 ms, 357 ms and 10 ms, respectively. The current and electric field measurements all had a 3-dB upper frequency response of 3 MHz, and all were digitized with 12-bit amplitude resolution and a sampling rate of 10 MHz. In this paper, positive current corresponds to negative charge moving downward or positive charge moving upward, and we use the atmospheric sign convention for electric fields (a positive electric field change corresponds to the dominant

addition of positive charge above the ground). All presented current or field risetimes are the time intervals from 10% to 90% of the pulse peak values, with the 10% level measured with respect to the immediately preceding background current or field level.

[8] VHF broadband digital interferometers were operated at two sites, one located about 3.1 km south (Site 1) and the other about 3.2 km west (Site 2) of the launch tower. The interferometers provided elevation and azimuth angles of the VHF sources. It was possible to locate a maximum of 2048 sources at a maximum rate of 1 source per 3.5 μs. Since positive breakdown generally produces weaker VHF radiation than negative breakdown [e.g., *Kawasaki et al.*, 2002], it is difficult for VHF mappers to locate positive leaders except under special conditions that involve large impulsive currents, during UPLs [*Yoshida et al.*, 2010], or immediately after return strokes [*Shao et al.*, 1995]. Unfortunately, most VHF source locations that we show in this paper developed between Sites 1 and 2, where the 3D image cannot be obtained clearly by triangulation. Furthermore, in some instances, the number and density of VHF 3D source locations was insufficient to determine the direction and speed of the causative breakdown. Except for one series of VHF sources that was particularly well located and had a rather long duration, we do not show VHF source locations in 3D. We instead show VHF sources in an elevation-azimuth format centered on Site 1 and Site 2. We define the duration of a leader as the time between its first VHF pulse and the last VHF pulse recorded by either of the two interferometers.

3. Results

3.1. Triggered Lightning UF09–30

[9] The first lightning flash discussed in this paper, UF09–30, was triggered on 30 June 2009 at approximately 14:01:14 (GMT). UF09–30 had a bipolar IS followed by a single downward leader/return stroke sequence. Figures 1a–1d show the elevation and azimuth, respectively, of the VHF sources from Sites 1 and 2; Figure 1e shows the channel-base current; Figure 1f shows the waveform of electric field change; Figures 1g and 1h show the overall waveforms of channel-base current and electric field change of this event, respectively. The launch tower corresponds to 355 degrees from Site 1 and 87 degrees from Site 2 in azimuth, respectively, and azimuth increases clockwise. *Yoshida et al.* [2010] described in detail the UPL development in UF09–30 and presented high-speed video images of its lower 350 m of development (in Figures 2 and 3 of *Yoshida et al.* [2010]). The UPL began to propagate 854 ms after the rocket was launched, when the wire top height was 123 m above ground level. In a time of 4.3 ms, the channel-base current increased through a series of kilo-ampere-scale impulses to a peak of 18 kA (at 20.8 ms in Figure 1) [*Yoshida et al.*, 2010]. Following the peak, current impulses of 1 to 2 kA magnitude were measured at the channel base for another 20 ms, after which the current became steady at a level of about 1 kA, apparently beginning the ICC. The ICC continued to flow for about 210 ms, during which time two ICC pulses occurred (labeled "ICC pulse i" and "ICC pulse j" in Figure 1e) with peaks at 87.5 ms and 116 ms. The current range displayed in Figure 1e has been limited to ± 6 kA to better show these two ICC pulses. The peak current and the
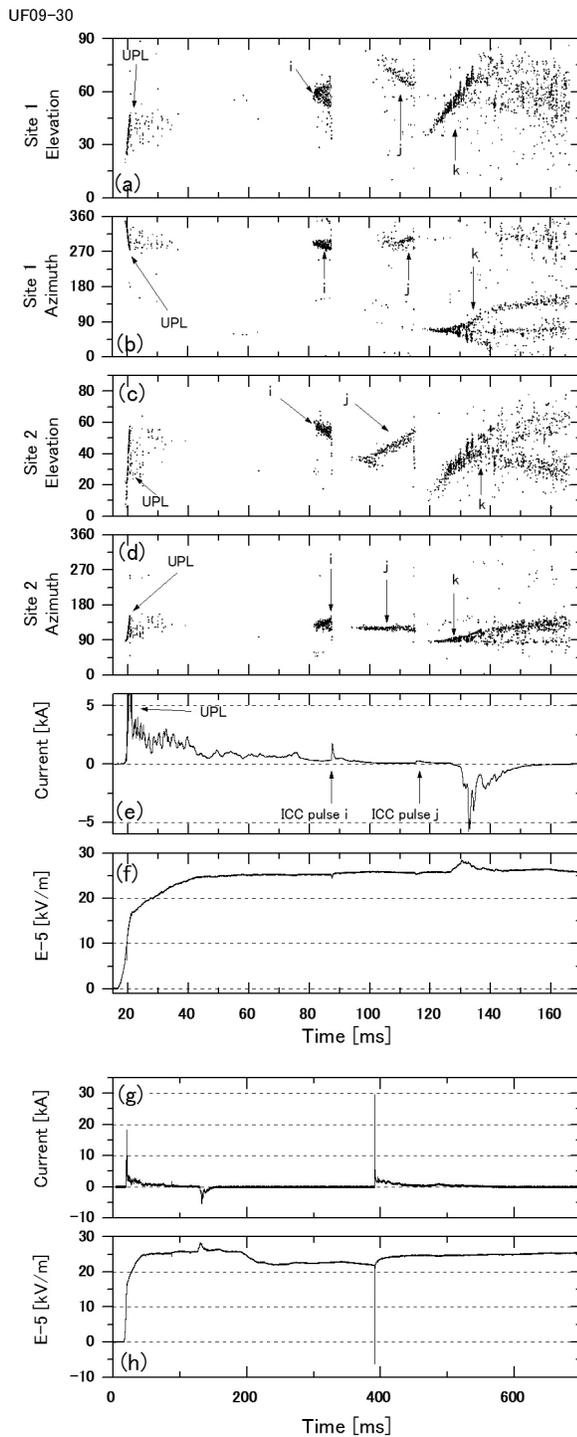
Figure 1. The two-dimensional imaging of VHF source locations, channel-base current and, electric field change versus time for event UF09–30, the (a) elevation, (b) azimuth progression of the VHF sources from Site 1, (c) elevation, (d) azimuth progression of the VHF sources from Site 2, (e) channel-base current, and (f) electric field change (E-5). Also shown are the overall waveforms of the (g) channel-base current and (h) electric field change (E-5) of this event. Note that true north corresponds to 0. The launch tower corresponds to 355 degree and 87 degree in azimuth from Sites 1 and 2, respectively, and the azimuth increases clockwise.

risetime of the ICC pulses 'i' and 'j' are summarized in Table 1a. Following the positive ICC pulses, the ICC began to decrease more rapidly at 126.6 ms and negative current began to flow at 127.3 ms. Then, the ICC exhibited several negative current pulses, the largest one at 132.7 ms having a peak of −5.5 kA. A total of 29 C of charge was transferred to ground by the negative ICC between 127.3 ms and 166.3 ms. The channel-base current switched polarity again (not resolvable in Figure 1e), becoming positive at 161 ms, and then decreased to zero in about 95 ms. A no-current interval of about 140 ms followed the IS, after which a single sequence of negative, downward dart leader and upward return stroke occurred, with a peak current of 29.6 kA at 392 ms.

[10] VHF source locations for UF09–30 are divided into four groups. The first group ('UPL' in Figures 1a–1d) corresponds to the UPL and the following breakdowns between 19 ms and 37 ms. The second and the third correspond,
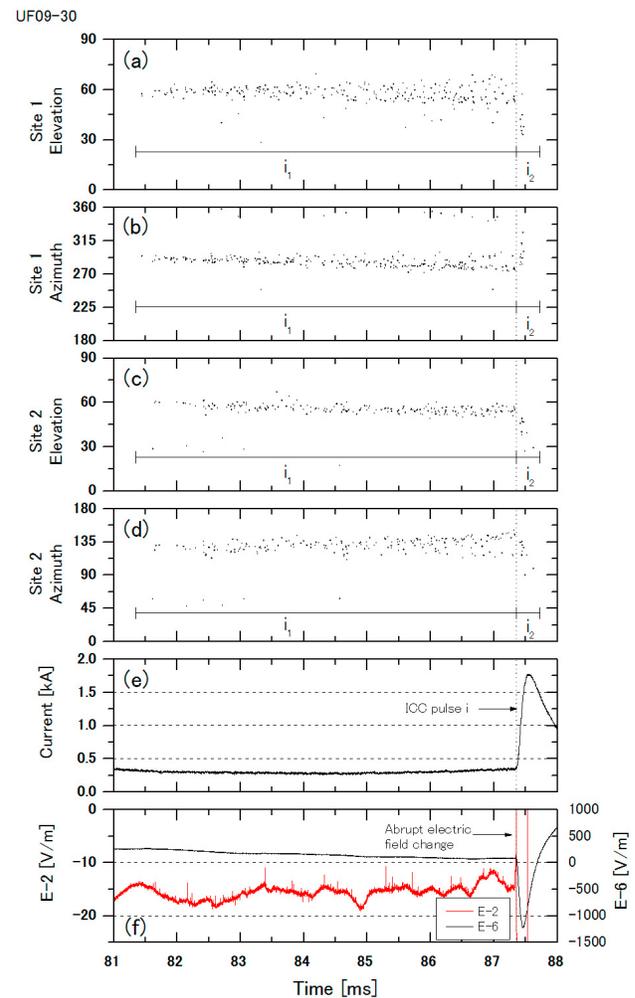

Figure 2. An expanded view of interferometer observations with electric field change and channel-base current versus time around ICC pulse 'i' between 81 ms and 88 ms for event UF09–30; (a) elevation, (b) azimuth progression of the VHF sources from Site 1, (c) elevation, (d) azimuth progression of the VHF sources from Site 2, (e) channel-base current, and (f) electric field change (E-2 and E-6).
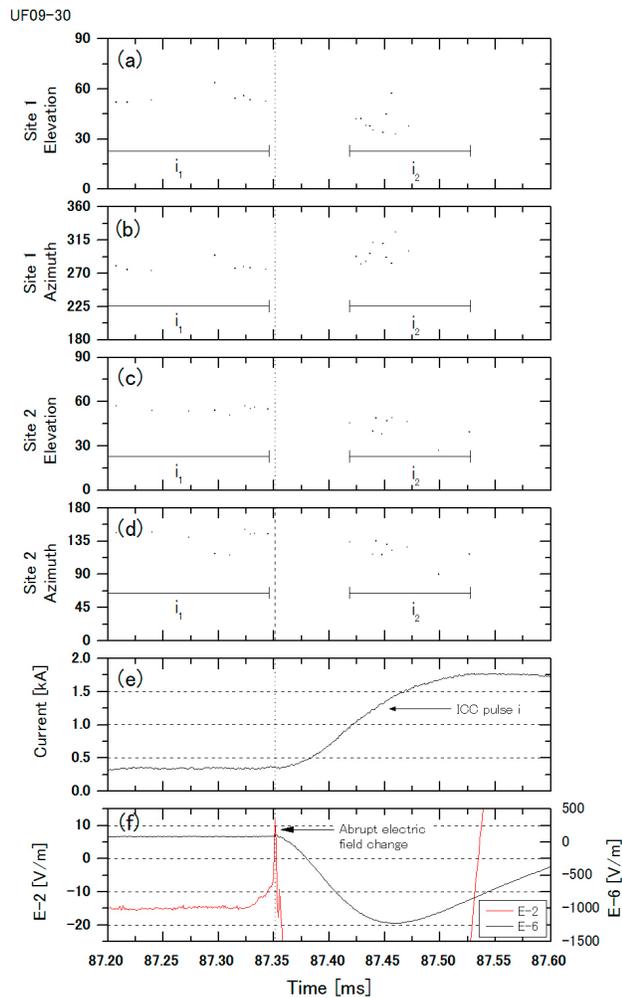
Figure 3. An expanded view of interferometer observations with electric field change and channel-base current versus time around ICC pulse 1 between 87 ms and 87.6 ms for event UF09–30; (a) elevation, (b) azimuth progression of the VHF sources from Site 1, (c) elevation, (d) azimuth progression of the VHF sources from Site 2, (e) channel-base current, and (f) electric field change (E-2 and E-6).

sources reached their maximum elevation, multiple VHF breakdowns were located near the UPL path.

[12] Figures 2 and 3 show expanded views of Figures 1a–1f around ICC pulse 'i', between 81 ms and 88 ms, and between 87.2 ms and 87.6 ms, respectively. Figure 4 shows projection planes of the VHF source locations located by the VHF interferometers at Site 1 (Figure 4a) and Site 2 (Figure 4b). We divide the VHF source locations 'i' into negative leaders 'i_1' and 'i_2', based on whether they occurred before or after the abrupt E-field change indicated by the arrow in Figures 2f and 3f. The negative leader 'i_1' developed during a time of 5.9 ms. At the time when the negative leader 'i_1' launched, no significant change of the channel-base current was detected. It is evident in Figure 2f that many

respectively, to the VHF source locations around ICC pulse 'i' (labeled 'i' in Figures 1a–1d) and ICC pulse 'j' (labeled 'j' in Figures 1a–1d). The last group corresponds to well-defined VHF development 'k' (labeled 'k' in Figures 1a–1d). Note that the recording of the VHF pulses ended at 166 ms because the A/D converter ran out of memory.

[11] The VHF source locations associated with the UPL extended with an average 3D speed of 3.3×10^6 m s^{-1}, as reported in *Yoshida et al.* [2010]. After the UPL VHF
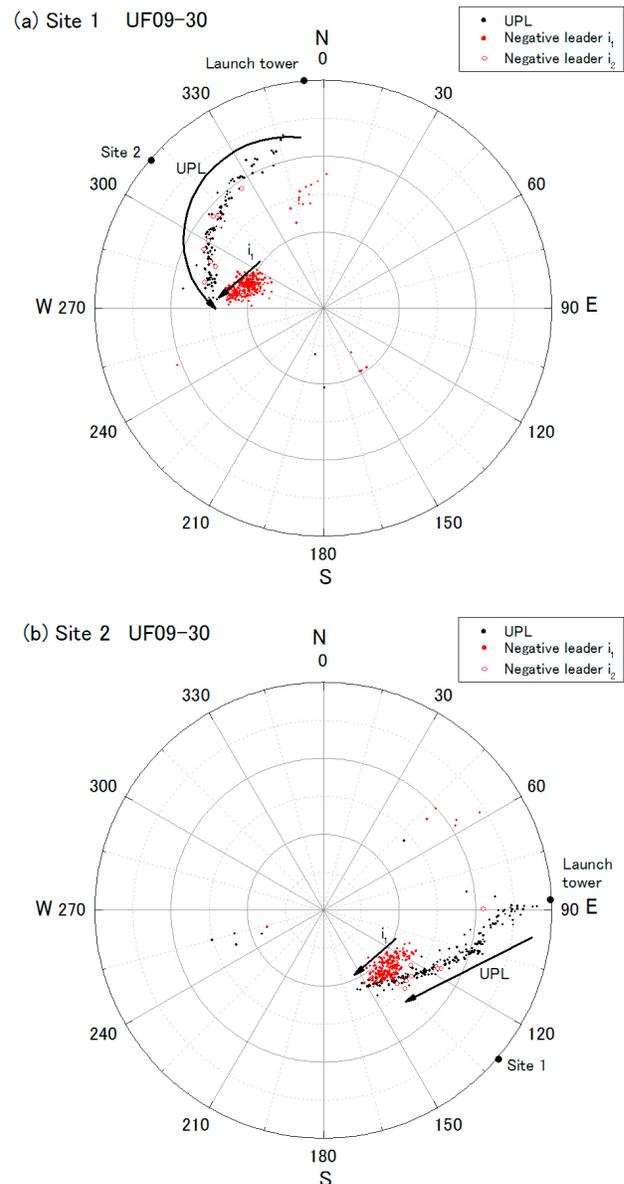

Figure 4. Projection planes of VHF source locations for the UPL and the negative leaders from (a) Site 1 and (b) Site 2. The black arrows indicate the propagation direction of the UPL and the negative leader 'i_1'.
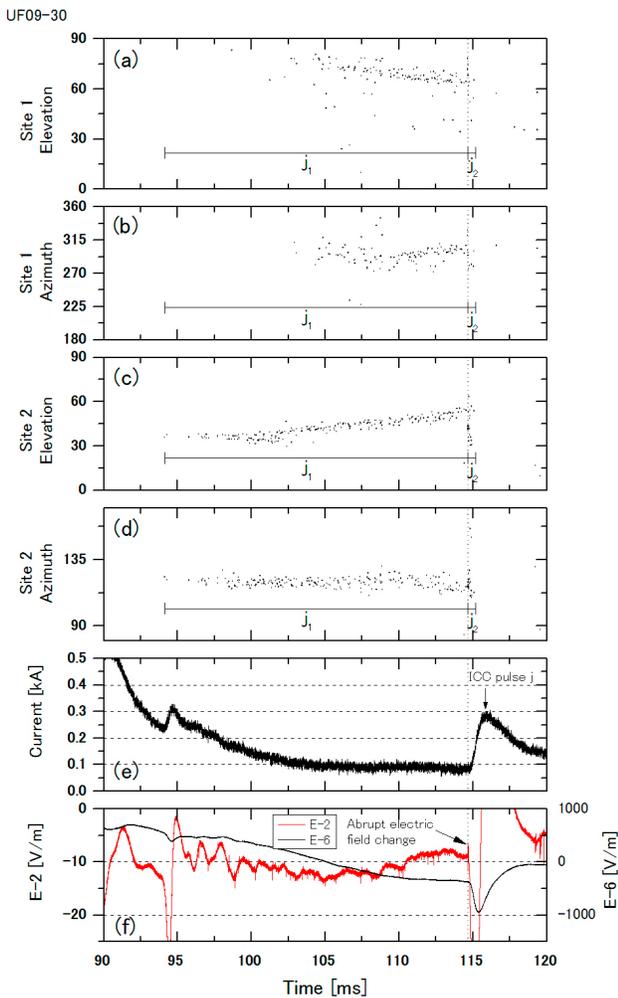
Table 1a. Current Amplitudes and 10–90% Risetimes of ICC Pulses in UF09–30

	ICC Pulse	
	i	j
Current amplitude (A)	1400	219
10–90% Risetime(μs)	109	603

Figure 5. An expanded view of interferometer observations with channel-base current and electric field change versus time around ICC pulse 'j' between 90 ms and 120 ms for event UF09–30; (a) elevation, (b) azimuth progression of the VHF sources from Site 1, (c) elevation, (d) azimuth progression of the VHF sources from Site 2, (e) channel-base current, and (f) electric field change (E-2 and E-6).

pulses are superimposed on the waveform of the electric field change when the locations of the leader 'i₁' were detected. Most of these pulses are positive unipolar or bipolar with positive initial half-cycle, indicative of negative charges propagating upward or, alternatively, moving away horizontally from the sensor [*Nag et al.*, 2009].

[13] The E2 electric field change in Figure 3f exhibits the large abrupt positive change followed by an abrupt and much larger negative change. The abrupt positive electric field change with a risetime of 0.4 μs is comparable to a typical electric field change when a return stroke occurs in downward negative lightning [e.g., *Rakov and Uman*, 2003]. As seen in Figure 4, the negative leader 'i₁' moved away from the electric field sensors located near the launch tower in a few kilometers and approached the vicinity of the upper end of the UPL. The abrupt electric field change occurred right after the negative leaders 'i₁' ended. These facts

indicate that the negative leader 'i₁' connected to the existing UPL channel, which was electrically connected to the ground, at the time of or a few microseconds before the abrupt E-field change. As noted earlier, the abrupt positive electric field change was followed by the much larger and longer negative electric field change, and a current pulse was detected at the wire base after the abrupt electric field change. These observations indicate that a negative current wave flowed to the ground via the UPL conductive channel after the connection of the negative leaders and the UPL. These electric field and current waveforms are similar to those for M-components described by *Rakov et al.* [1995], who inferred that a negative current wave was injected into the continuing current channel propagated toward ground when the large negative electric field change was recorded. The VHF radiation was absent for the 67 μs after the abrupt E-field change. It seems that the negative leader 'i₂' developed along or near the channels of the UPL and the negative leader 'i₁' and toward the launch tower during a time of 108 μs.

[14] Figures 5 and 6 show expanded views of the data in Figures 1a–1f between 90 ms and 120 ms, and between 114 ms and 115.5 ms, respectively. Figure 7 shows projection planes of the VHF sources located by the VHF interferometers at Site 1 (Figure 7a) and Site 2 (Figure 7b). We divide the VHF source locations 'j' into negative leaders 'j₁' and 'j₂', based on whether they occurred before or after the abrupt E-field change indicated by the arrow in Figures 5f and 6f. The negative leader 'j₁' locations detected by Site 2 started about 3 ms before the first locations detected by Site 1; that is, the interferometer at Site 1 failed to detect the first 3 ms of the leader. It seems that the negative leader 'j₁' was launched directly overhead at Site 1, where the interferometers could not locate lightning development well. In Figure 5f, many pulses are superimposed on the waveform of the electric field change, as was the case for the negative leader 'i₁'. However, most of the pulses are negative unipolar or bipolar with negative initial half-cycle, indicative of the negative leader moving toward the sensor [*Nag et al.*, 2009], the opposite of the pulse polarity seen in the electric field associated with ICC pulse 'i'. A current pulse began to rise about 130 μs after the leader 'j₁' had initiated. As in Figure 7a, the initiation point of the negative leader 'j₁' is away from the UPL when it began. Therefore, the negative leader 'j₁' at that time apparently was not connected to the UPL channel. The duration of the negative leader 'j₁' was 20.4 ms. The electric field change in Figure 6f shows the large burst of bipolar pulses occurring almost simultaneously with the start of the negative leader 'j₂', followed by a relatively slow negative change. In Figures 7a and 7b the negative leader 'j₁' propagated toward the origin of the negative leader 'i₁'. The negative leader 'j₁' apparently attached to the channel of the negative leader 'i₁', which itself had already connected to the existing UPL, at or a few microseconds before the time of the abrupt positive electric field change. The abrupt electric field change is followed by larger and longer negative field change, as was the case for ICC pulse 'i'. The negative leader 'j₂' was located along or near the channels of previous VHF source locations. It appears that the negative leader 'j₂' developed toward the launch tower during a time of 449 μs, although the VHF source locations are somewhat scattered.
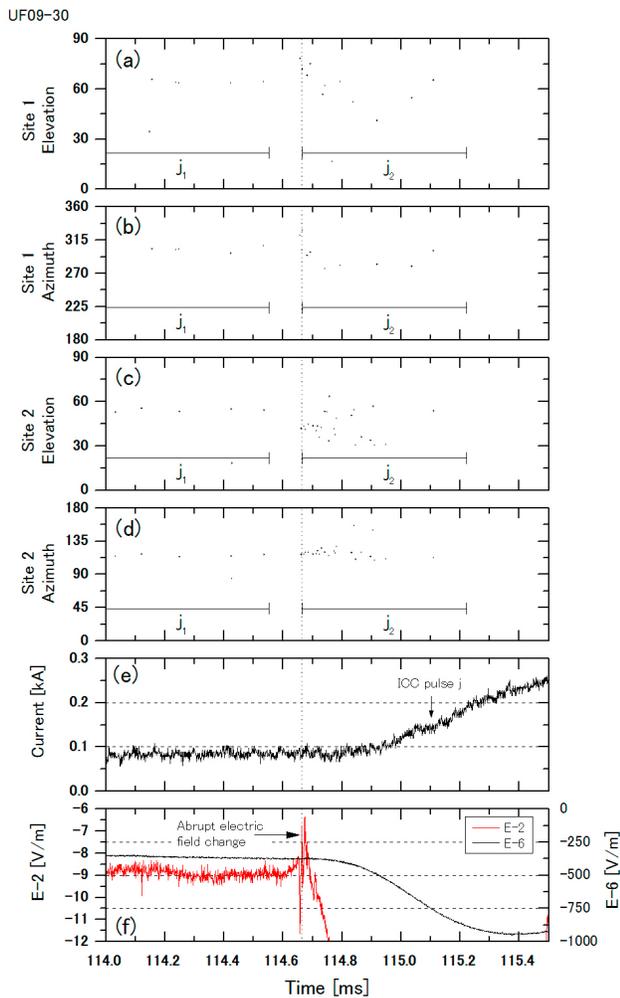
Figure 6. An expanded view of interferometer observations with channel-base current and electric field change versus time around ICC pulse 'j' between 114.0 ms and 115.5 ms for event UF09–30; (a) elevation, (b) azimuth progression of the VHF sources from Site 1, (c) elevation, (d) azimuth progression of the VHF sources from Site 2, (e) channel-base current, and (f) electric field change (E-2 and E-6).

[15] The channel-base current exhibited positive value after the ICC pulse 'j', and then the current decreased more rapidly around 126.6 ms and exhibited negative peaks, the largest one at 132.7 ms. As seen in Figure 1, a long and intense negative leader, labeled 'k', began to propagate at 119 ms. Figure 8 shows an expanded view of the data in Figures 1a–1f around the beginning of the negative leader 'k' between 118 ms and 128 ms. Figure 9 shows the projection planes of the negative leader 'k' and the VHF locations prior to the negative leader 'k' from Sites 1 and 2. As can be seen in Figures 8 and 9, the negative leader 'k' launched from the east of Site 1, 7.6 ms before the time when the current began to decrease more rapidly, and propagated toward Sites 1 and 2. The negative leader 'k' had at least two branches over Site 1.

[16] During the time when the negative leader 'k' was located, many negative unipolar or bipolar electric field

pulses occurred with risetimes ranging from a few hundred nanoseconds to 10 μs. These pulses are similar to large bipolar electric field pulses associated with IC discharges [e.g., *Nag et al.*, 2009]. No significant channel-base current change was recorded when the VHF sources and electric field pulses associated with the leader 'k' began. Further, the negative leader 'k' began separately from the VHF source locations of the previous lightning processes such as the UPL, the leaders 'i$_1$' and 'j$_1$' in Figure 9. For the negative leader 'k', the two VHF broadband digital interferometers at Sites 1 and 2 located some tens of VHF sources at 75 degree or more in elevation, indicating that one of the two branches of the negative leader 'k' developed upward to at least 9 km.
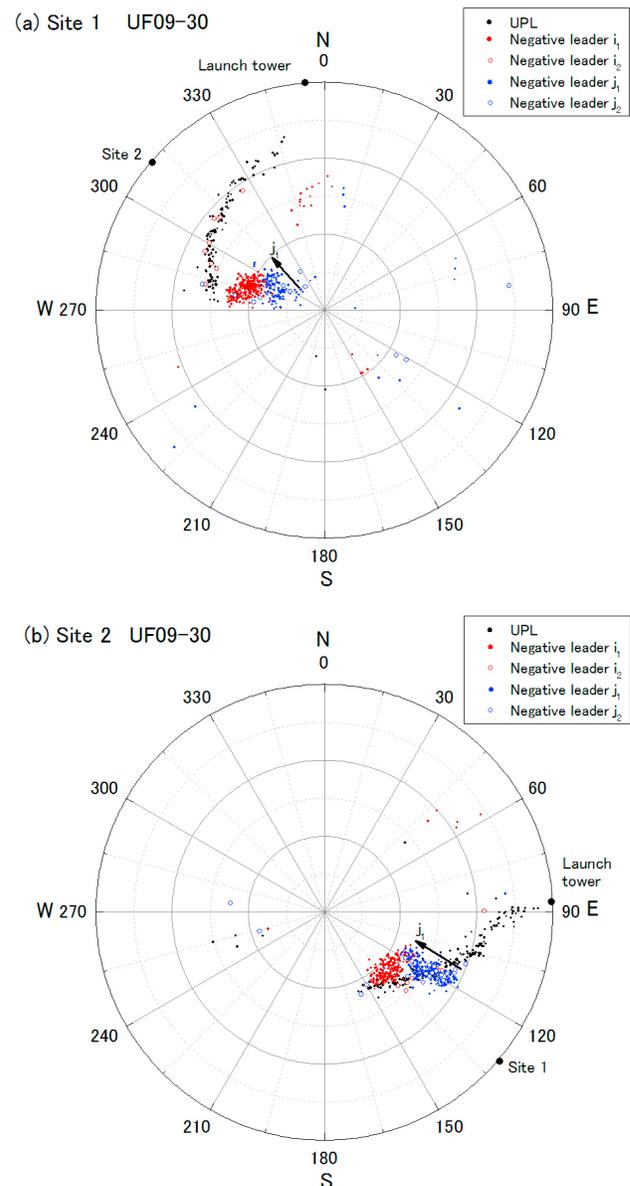

Figure 7. Projection planes of VHF source locations for the UPL and the negative leaders from (a) Site 1 and (b) Site 2. The black arrows indicate the propagation direction of the negative leader 'j$_1$'.
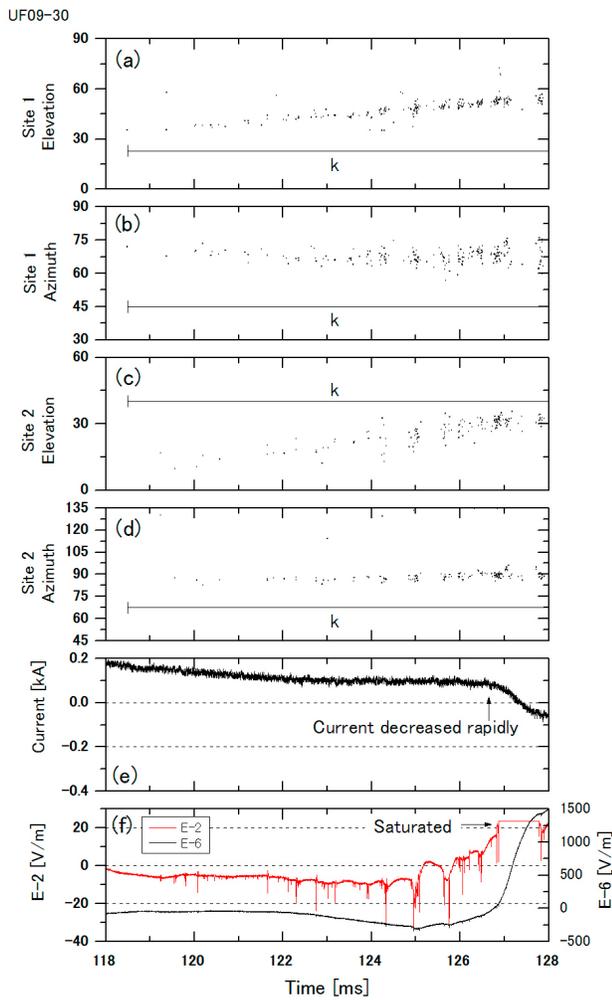
Figure 8. An expanded view of interferometer observations with channel-base current and electric field change versus time between 118.0 ms and 128 ms for event UF09–30; (a) elevation, (b) azimuth progression of the VHF sources from Site 1, (c) elevation, (d) azimuth progression of the VHF sources from Site 2, (e) channel-base current, and (f) electric field change (E-2 and E-6).

3.2. Triggered Lightning UF09–38

[17] The second lightning flash discussed in this paper, UF09–38, was triggered on 14 July 2009 at approximately 21:25:17 (GMT). UF09–38 transferred only negative charge to ground, and had a single sequence of downward negative dart leader and return stroke following the IS. Figures 10a–10d show the elevation and azimuth of the VHF sources from Site 1 and Site 2, respectively; Figure 10e shows the channel-base current; Figure 10f shows the electric field change. The channel-base current of the UPL increased steadily up to the first large current peak (1.2 kA) at 997.3 ms, followed by a decrease in 19 ms to about 50 A (at 1016 ms), and then by a 1.9 kA ICC pulse having a risetime of 230 μs. The interferometers at Sites 1 and 2 located 14 and 57 VHF sources, respectively, that were associated with the UPL during a time of 35 ms until the first peak of the current. During this period, only two VHF sources were

located in 3D by the triangulation with a 60 μs time window employed in previous paper [*Yoshida et al.*, 2010]. Following the 1.9 kA ICC pulse, the channel-base current became steady near 200 A with many superimposed ICC pulses having magnitudes of hundreds of amperes. After the end of the IS at 1489 ms, there was a no-current interval lasting about 31 ms, followed by the single return stroke at 1526 ms with a peak current of 25.5 kA. After the first return stroke, there was about 44 ms of continuing current with four M-components. The VHF interferometers at Sites 1 and 2 ceased to record the VHF radiations at 1633 ms and at 1845 ms, respectively, because the A/D converters had recorded their maximum number of locations.
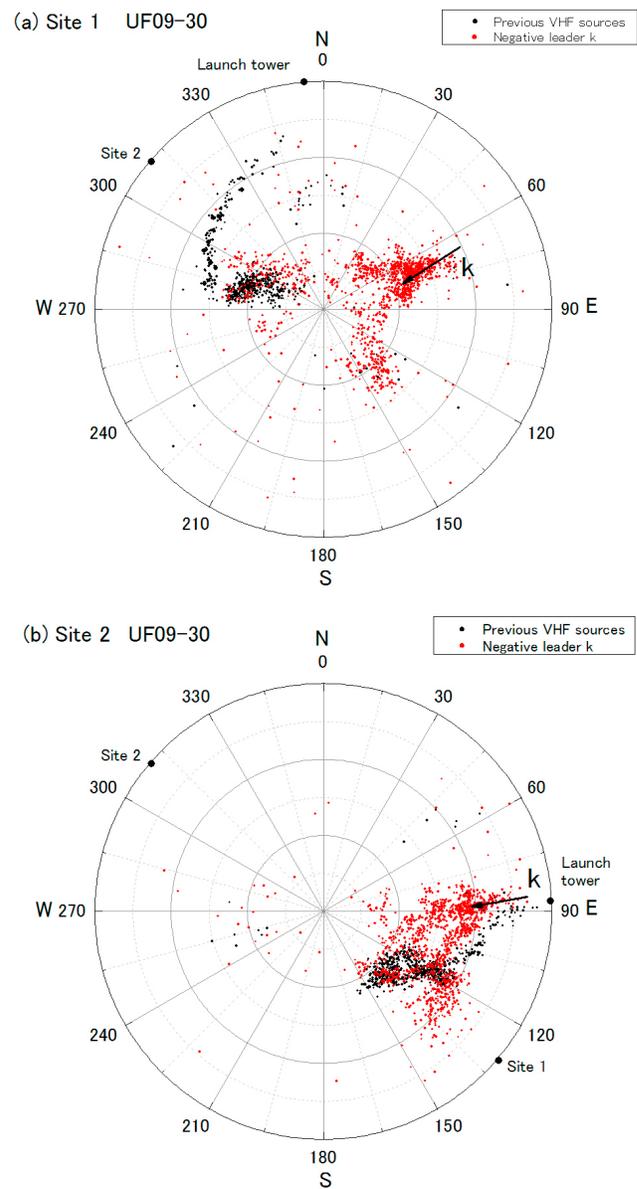

Figure 9. Projection planes of VHF source locations for the negative leader 'k' and previous breakdowns from (a) Site 1 and (b) Site 2. The black arrows indicate the propagation direction of the negative leader 'k' in its beginning stage.
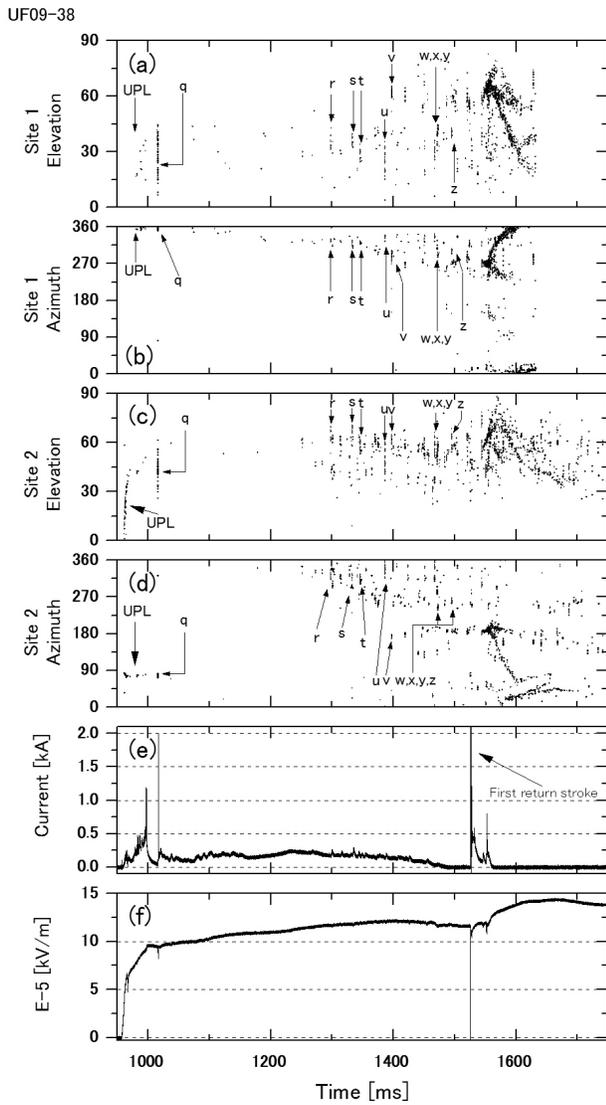
UF09–38

Figure 10. The two-dimensional imaging of VHF source locations, channel-base current, and E-field change versus time for event UF09–38, the (a) elevation, (b) azimuth progression of the VHF sources from Site 1, (c) elevation, (d) azimuth progression of the VHF sources from Site 2, (e) channel-base current, and (f) electric field change (E-5).

[18] As can be seen in Figures 10a–10d, after the first peak of the current, there were ten groups of VHF sources exhibiting well-defined propagation before the first return stroke (labeled 'q' through 'z'). Among the ten negative leaders, the first five negative leaders (from 'q' to 'u') were followed by ICC pulses (ICC pulse 'q' through 'u'), while the other five negative leaders (from 'v' to 'z') were not followed by ICC pulses above the noise level of the channel-base current, about 40 A.

[19] The current peaks and the risetimes of these ICC pulses are summarized in Table 1b. The geometric mean durations for the negative leaders followed by ICC pulses and not followed by ICC pulses in UF09–38 are 176 μs with a range of 115 μs to 786 μs and 232 μs with a range of 121 μs

Table 1b. Current Amplitudes and 10–90% Risetimes of ICC Pulses in UF09–30

	ICC Pulse				
	q	r	s	t	u
Current amplitude (A)	1944	84	107	51	63
10–90% Risetime(μs)	230	461	531	139	351

to 342 μs, respectively. The durations of the negative leaders in UF09–30 are greater than those in UF09–38.

[20] Figure 11 shows an expanded view of the data in Figure 10 around the first ICC pulse between 1015.5 ms and 1017.5 ms. This leader could be located in 3D by the same triangulation scheme employed in *Yoshida et al.* [2010]. Figures 11a–11c show the E-W, N-S, and altitude progressions of VHF sources; Figure 11d shows the channel-base current; Figure 11e shows the waveforms of electric field change. The downward negative leader 'q' had a 3D speed
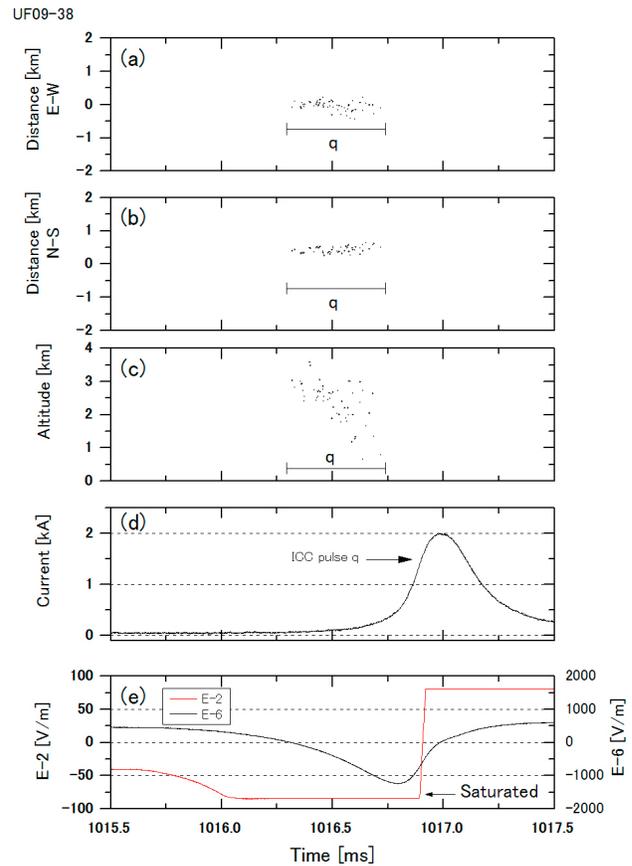
UF09–38

Figure 11. An expanded view of interferometer observations with channel-base current and electric field change versus time around the negative leader 'q' between 1015.5 ms and 1017.5 ms for event UF09–38; (a) E-W, (b) N-S, (c) altitude progression of the VHF sources, (d) channel-base current, and (e) electric field change (E-2 and E-6). The origin of Figures 11a–11c corresponds to the launch tower.
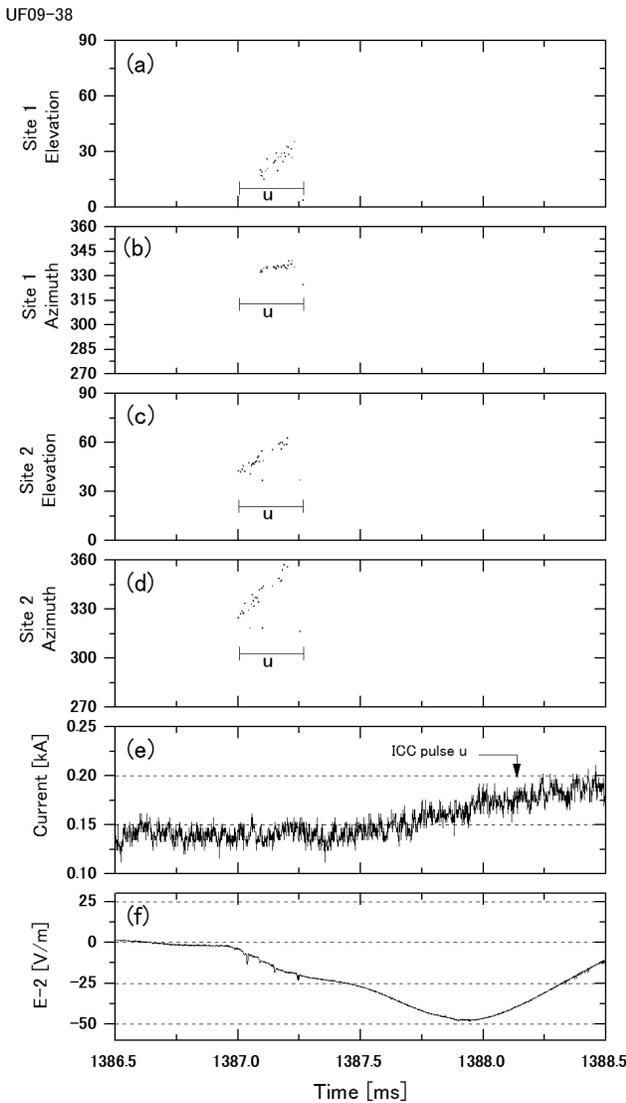
UF09–38

Figure 12. An expanded view of interferometer observations with channel-base current and electric field change versus time around the negative leader 'u' between 1386.5 ms and 1388.5 ms for event UF09–38; (a) elevation, (b) azimuth progression of the VHF sources from Site 1, (c) elevation, (d) azimuth progression of the VHF sources from Site 2, (e) channel-base current, and (f) electric field change (E-2).

of 5.6×10^6 m s^{-1} and lasted 786 μs. The negative leader apparently began propagation from directly above the launch tower at about 3.5 km altitude. The channel-base current for the ICC pulse shown in Figure 11 apparently began about 500 μs before the VHF sources appeared to have reached ground. At this time the VHF sources were located at about 1.5 km in altitude.

[21] Figures 12 and 13 show, as typical examples, expanded views of the data in Figure 10 around the negative leader 'u' between 1386.5 ms and 1388.5 ms, and around the negative leader 'v' between 1397 ms and 1399 ms, respectively. As can be seen in Figure 12f, the negative leader 'u'

caused a slow negative electric field change, indicating that it approached the E-2 sensor by the launch tower. The duration of the negative leader 'u' was 264 μs. The channel-base current began to increase about 140 μs after the negative leader 'u' ceased detectable VHF emission. Several negative pulses are present in the electric field change associated with the progression of negative leader 'u'. The other three negative leaders associated with ICC pulses also ceased detectable VHF emission some hundreds of microseconds before the beginning of the rise of the corresponding ICC pulses. In Figure 13, the negative leader 'v' propagated toward the launch tower with a negative regular

UF09–38

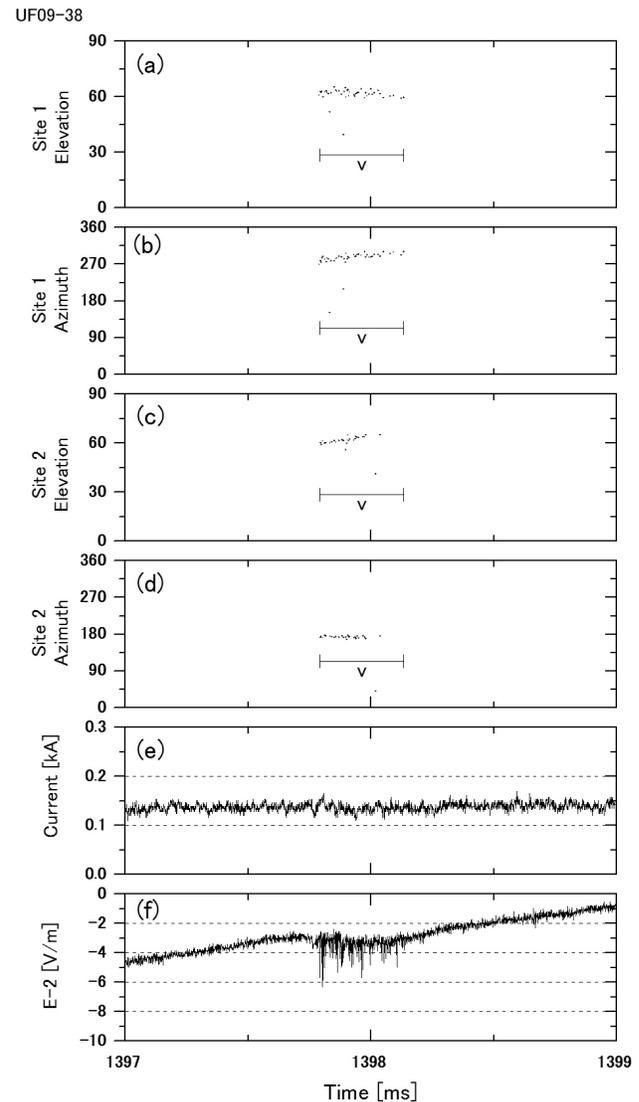**Figure 13.** An expanded view of interferometer observations with channel-base current and electric field change versus time around the negative leader 'v' between 1397 ms and 1399 ms for event UF09–38; (a) elevation, (b) azimuth progression of the VHF sources from Site 1, (c) elevation, (d) azimuth progression of the VHF sources from Site 2, (e) channel-base current, and (f) electric field change (E-2).

pulse burst in the electric field change waveform, similar to that studied by *Rakov et al.* [1996].

4. Discussion

4.1. Long-Duration Negative Leader Initiating ICC Pulses (UF09–30)

[22] The durations of the negative leaders 'i_1' and 'j_1' of UF09–30 are 5.9 and 18.7 ms, respectively. These durations are considerably larger than the typical dart leader durations reported by *Rakov and Uman* [1990]. If these negative leaders 'i_1' and 'j_1'developed with the typical dart leader propagation speeds of 1.1×10^7 m s^{-1} [*Orville and Idone*, 1982; *Idone et al.*, 1984], the negative leader channel lengths, respectively, would be 65 km for the negative leader 'i_1' and 224 km for the negative leader 'j_1', which are unreasonable for an ordinary lightning leader. If the negative leaders 'i_1' and 'j_1'developed with a speed of 2×10^5 m s^{-1}, which is the typical speed of initial, stepped leaders reported by *Shao et al.* [1995], their channel lengths would be 1.2 km and 4.1 km, respectively. The channels of the negative leaders 'i_1' and 'j_1' located by the VHF interferometers are somewhat scattered in Figures 4 and 7. According to *Yoshida et al.* [2012], channels of stepped leaders located by VHF interferometers are sometimes more or less scattered when stepped leaders develop in a heavily branched manner. Taking into account that the negative leaders 'i_1' and 'j_1' produced typical cloud pulse activity in the electric waveform, it is likely that the negative leaders 'i_1' and 'j_1' initiated separately from the UPL, requiring that they break down virgin air, and create channels that were separate IC discharges. The word "separate IC discharges" means an IC discharge that is not directly connected by previously created channels with another discharge. Another possible interpretation is that the negative leaders 'i_1'and 'j_1' were dart-stepped leaders initiated from a defunct channel produced by the UPL or previous lightning processes, as suggested by *Wang and Takagi* [2008]. Clearly, more research is needed.

[23] Although the time when the ICC pulse began to increase is not clear in Figure 3, it seems that the time difference between the rise of the ICC pulse 'i' and the abrupt positive E-field change is between 2 μs and 20 μs. Assuming that the distance between the source point and the electric field change antenna is 4 km, and that it took at least 12 microseconds for the radiation to traverse the two, the speed of the negative charge transfer from the junction point of the leader 'i_1' and the UPL to ground is estimated from 1.25×10^8 m s^{-1} to 2.86×10^8 m s^{-1}. The estimated speed is similar to the range of measured return stroke speeds [e.g., *Idone and Orville*, 1982; *Mach and Rust*, 1989; *Willett et al.*, 1988, 1989] and is consistent with the channel conductivity being high between the junction point and ground. On the other hand, propagation speeds of M-component waves are estimated to be between 10^7 and 10^8 m s^{-1} [e.g., *Rakov et al.*, 1995]. As seen in Figures 3a–3d, after the apparent connection of the negative leader 'i_1' to the UPL channel, the VHF broadband digital interferometers at Sites 1 and 2 did not detect any VHF signals for a time of 67 μs, after which negative leader 'i_2' was detected. This fact indicates that the existing channel transferring negative charge was of sufficient conductivity to not

involve the type of breakdown associated with VHF radiation, consistent with *Rakov et al.*'s [1995] inference that the M-component (and ICC pulse) is a guided–wave phenomenon.

[24] As seen in Figure 6, an abrupt electric field change was recorded about 130 μs prior to the beginning of the ICC pulse 'j'. Assuming that the connection between the negative leaders 'i_1' and 'j_1' was at an altitude of 4 km, it took a time of about 142 μs for the charge to reach ground with an inferred speed of 2.8×10^7 m s^{-1}, consistent with *Rakov et al.*'s [1995] modeling results for M-components. The estimated speed of the charge transfer associated with ICC pulse 'j' is about one order of magnitude slower than that of ICC pulse 'i'. It seems that the channel through which the negative charge associated with ICC pulse 'j' was transferred might have been less conductive than that of ICC pulse 'i'. The VHF radiation associated with the negative leader 'j_2' may be evidence supporting an idea that some M-components and ICC pulses are a composite effect of many waves by numerous breakdowns along a conductive channel [*Wang et al.*, 2007]. Further observations and research are needed to test the composite waves hypothesis and its applicability to M-components and ICC pulses.

[25] In the sense that the separate IC discharge became part of the existing triggered-lightning discharge, we refer to UF09–30 as a "combined lightning." *Yoshida et al.* [2009] observed an upward negative flash from a tall tower using a VHF interferometer in which two negative leaders occurred immediately prior to ICC pulses with relatively short rise-times of less than 10 μs. We re-examined these negative leaders and estimated their 2D speeds to be of the order of 10^5 m s^{-1}, that is, of the same order of magnitude as the speeds of typical stepped leaders. It seems that the upward flash in *Yoshida et al.* [2009] was similar to "combined lightning," although the durations of the two negative leaders are 470 μs and 860 μs. From multiple-station electric field change measurements, *Krehbiel et al.* [1979] inferred that subsequent leaders often originated away from the discharge activity near the upper (positive) end of the channel to ground, as opposed to being "recoils" resulting from that activity. This scenario is similar to that for initiation of our long-duration leaders (which do not appear to be "recoils"), although in our case the channel was grounded, while subsequent leaders in *Krehbiel et al.*'s [1979] study were launched when the channel was cut-off near ground. It is likely that the UPL of the rocket-and-wire triggered lightning changed the ambient electric field strength around an isolated negative charge region in the thundercloud, and subsequently caused a negative leader to launch from it. After that, the negative leader encountered the existing triggered-lightning channel.

4.2. Bipolar ICC (UF09–30)

[26] In the bipolar lightning UF09–30, a long and intense negative leader 'k' initiated (at 119 ms) 7.6 ms before the negative current began to flow. No significant channel-base current change was recorded when the VHF sources and electric field pulses associated with leader 'k' began, and it clearly began at a location that was separate from the VHF source locations of the previous lightning processes such as the UPL, the leaders 'i_1' and 'j_1'. These observations indicate
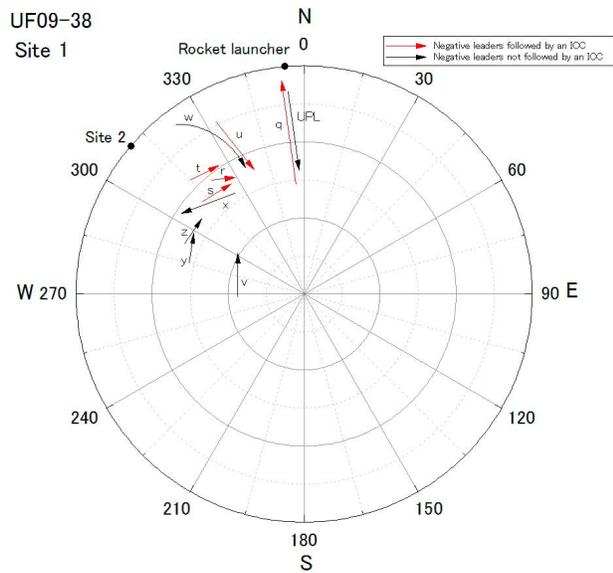
Figure 14. A projection plane of the propagation directions of the leaders of UF09–38 from Site 1. The arrows indicate the propagation directions of the negative leaders.

that the negative leader 'k' was a separate IC discharge that was initiated from an isolated negative charge region in the thundercloud and extended (via different branches) toward both an upward level positive charge region and the UPL. At the same time, a branch of the UPL may have propagated significantly toward the isolated negative charge region, but it was not of sufficient current intensity to produce detectable VHF radiation [e.g., *Kawasaki et al.*, 2002, *Yoshida et al.*, 2010]. We speculate that one branch of the UPL connected to one branch of the IC discharge, and that the IC discharge effectively bridged the upper positive charge region and ground. The positive charge flowed through this bridge to ground, producing the polarity reversal and large negative current during the ICC. It is likely that one of the many negative-polarity pulses in the electric field in Figure 8f, which are larger than the abrupt electric field changes associated with ICC pulses 'i' and 'j', correlates to the connection of the negative leader 'k' and the branch of the UPL.

[27] In this case, the connection between two separate discharges, or "combined lightning" caused the bipolar lightning. In the cases of the ICC pulses 'i' and 'j' in UF09–30, the separate IC discharges encountered the existing UPL channel but did not encounter positive charge regions. *Narita* [1989], recording nine bipolar current waveforms during winter thunderstorms in Japan, suggested that the bipolar current flowed through the same channel connecting two different charge regions in the thundercloud. A recent review of bipolar lightning is given by *Rakov* [2005]. The combined lightning concept may be a common feature of bipolar lightning that transfers both negative and positive charges to ground.

4.3. Short-Duration Negative Leader Initiating ICC Pulses (UF09–38)

[28] The leader durations of the negative leaders 'q' through 'z' in UF09–38 are more than one order of magnitude shorter

than the durations of the negative leaders 'i₁' and 'j₁' of UF09–30. Their durations are slightly less than one millisecond, or the typical durations of the dart leaders reported by *Rakov and Uman* [1990]. Their durations are comparable to the durations of fast negative leaders observed by *Mazur et al.* [1995], *Shao et al.* [1995], and *Akita et al.* [2010] to initiate M-components and K-changes. The short-durations of the negative leaders in UF09–38 suggest that the leaders developed with speeds of the order of 10^6 to 10^7 m s^{-1} in the channel which was previously created by the UPL.

[29] It is likely that the short-duration negative leaders that stopped radiating on VHF before the beginning of the rise of the ICC pulses in UF09–38 (leaders r, s, t, and u) are similar to the fast negative leaders reported by *Mazur et al.* [1995] and *Shao et al.* [1995] to occur prior to M-components. The short-duration negative leaders (v, w, x, y, and z) which were not associated with an ICC pulse appear to correspond to the attempted leaders or K changes reported by *Mazur et al.* [1995] and *Shao et al.* [1995]. Figure 14 shows a projection plane for the leader directions of the UPL and negative leaders 'q' through 'z' of UF09–38 from Site 1. All of the negative leaders, with the exception of negative leader 'x', propagated toward the launch tower or previous leaders. This result is consistent with the interpretation that the negative leaders 'recoiled' through the previously created UPL channel to the ground. The origins of the negative leaders moved away from the launch tower with time, indicating that the UPL developed within the negative charge regions to increasingly further distances. Furthermore, the negative leaders followed by ICC pulses occurred earlier than those not followed by ICC pulses. These facts suggest that the ICC channel became less conductive with the development of time, which is consistent with observations by *Mazur et al.* [1995] for M-components in natural lightning. Therefore, the short-duration and by inference fast negative leaders initiated the ICC pulses, as reported for M-components by *Mazur et al.* [1995] and *Shao et al.* [1995]. However, there is one exception. The negative leader 'q' in Figure 11 apparently ceased development some hundreds of microsecond after the beginning of the rise of the corresponding ICC pulse. Also, the current increase of the ICC pulse began before the VHF sources of the negative leader 'q' reached the ground. To understand these ICC pulses, additional data and analysis are needed.

5. Conclusions

[30] Interferometric observations in conjunction with channel-base current and electric field measurements enabled us to investigate the mechanisms of charge transfer from the cloud to the ground during the IS of the rocket-and-wire triggered lightning.

[31] Long-duration negative leaders (negative leaders 'i₁', 'j₁' and 'k' in UF09–30) had durations of a few milliseconds or more. The long-duration negative leaders were not connected to the grounded triggered-lightning channels when they began to propagate, indicating that these leaders propagated by breaking down virgin air, and that they were separate lightning processes from the triggered lightning when they began. When the negative leaders 'i₁' and 'j₁' in UF09–30 encountered the existing triggered-lightning channel, the negative charge was transferred to ground, causing the

channel-base current increases at ground level, that is, the ICC pulses. The negative leader 'k' in UF09–30 traveled both to an upper positive charge region in the thundercloud and to a branch of the UPL as an intracloud discharge, effectively bridging the positive charge region and the grounded channel. Positive charge was then transferred to ground, resulting in the opposite polarity portion of the bipolar ICC. In these cases, the intracloud discharges became part of rocket-triggered lightning, so that the overall flash can be viewed as a "combined lightning." To the best of our knowledge, this is the first observation of combined lightning.

[32] Durations of most negative leaders associated with ICC pulses observed in this campaign were of the order of hundred microseconds. These short-duration leaders resemble the fast negative leaders initiating M-components reported by *Mazur et al.* [1995] and *Shao et al.* [1995].

[33] Overall, our results indicate that ICC pulses, and by inference M-components, can be initiated either by recoil leaders or via the interception of separate in-cloud leaders by a grounded current-carrying channel.

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