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# Three-dimensional imaging of upward positive leaders in triggered lightning using VHF broadband digital interferometers

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[1] Upward positive leaders (UPLs) in two artificially-initiated lightning flashes were imaged in three dimensions using VHF broadband digital interferometers and a high-speed video camera with time-synchronized channel-base current measurements. Locatable VHF sources of the two UPLs began at 1.1 km and 1.5 km, a few milliseconds after the UPL inception, and ascended to 2.4 km and 3.7 km, respectively, with average 3-D speeds on the order of $10^6\ \mathrm{ms}^{-1}$. The initial stage currents for both flashes were unusually large and had peak values of 6 kA and 18 kA. VHF sources associated with positive leader propagation were located when the average current was higher than 3 kA and had significant pulse activity. The source altitudes and channel-base currents suggest that there might have been a region of significant negative charge at altitudes from 2 to 4 km, which is below the freezing level of typical thunderstorms in Florida. **Citation:** Yoshida, S., C. J. Biagi, V. A. Rakov, J. D. Hill, M. V. Stapleton, D. M. Jordan, M. A. Uman, T. Morimoto, T. Ushio, and Z.-I. Kawasaki (2010), Three-dimensional imaging of upward positive leaders in triggered lightning using VHF broadband digital interferometers, *Geophys. Res. Lett.*, *37*, L05805, doi:10.1029/2009GL042065.

## 1. Introduction

[2] Classical rocket-and-wire triggered lightning is typically initiated when an upward positive leader (UPL) develops from the top of the triggering wire and propagates upward toward overhead negative cloud charge. The UPL is followed by an initial continuous current (ICC), which in turn is often followed by one or more dart leader and return stroke sequences that transfer negative charge from cloud to ground [e.g., *Rakov and Uman*, 2003].

[3] Radio interferometry can provide the three-dimensional propagation characteristics of lightning channels, particularly inside the clouds where optical sensors are ineffective. There are varying reports regarding the strength of VHF emission from positive leaders. *Ushio et al.* [1997] reported that positive leaders produce no or relatively weak VHF radiation, making them difficult to detect and locate using VHF TOA methods or interferometry. *Shao et al.* [1996] specifically stated that upward positive leaders in New Mexico triggered lightning tended to be "quiet at VHF/UHF." Nevertheless, several researchers have reported detecting VHF radiation

from positive leaders. *Rhodes et al.* [1994] and *Shao and Krehbiel* [1996] reported observing in-cloud positive leaders that radiated at VHF at least as strongly as negative leaders. *Proctor* [1997] stated that positive stepped leaders emitted VHF-UHF pulses "rather more strongly" than negative stepped leaders. *Dong et al.* [2001] detected VHF radiation sources from an UPL in triggered lightning with a broadband VHF interferometer system installed 90 m away from the rocket launcher and presented a two-dimensional image of this UPL.

[4] Here we present VHF interferometeric source locations providing the first 3-D images of UPLs in artificially-initiated lightning flashes. These VHF source locations were obtained time-synchronized with high-speed video images and channel-base current measurements.

## 2. Instrumentation

[5] The observations presented in this paper are for two rocket-and-wire triggered flashes initiated on 30 June 2009 at the International Center for Lightning Research and Testing (ICLRT), located in north-central Florida, during an intense early morning multi-cellular thunderstorm. Channel-base current was measured at the launch tower with a 1-mΩ current-viewing resistor having an upper frequency response of 3 MHz and was digitized with 12-bit resolution at a sampling rate of 10 MHz. All reported currents correspond to negative charge moving downward or positive charge moving upward. High-speed video data for heights up to 350 m above ground level (AGL) were acquired using a Phantom v7.3 camera operating at a frame rate of 8 kfps and an exposure time of 120 μs (5 μs of dead time) that was located 440 m west of the launch tower. Rocket trajectory information was determined using the high-speed video data.

[6] VHF broadband digital interferometers were operated at two sites, one 3.2 km west (Site A) and the other 3.1 km south (Site B) of the launch tower. Each interferometer consisted of three capacitive electric field sensors placed in a right-angle-isosceles triangle with two legs of 10 m length and a hypotenuse of $10\sqrt{2}$ m. The signals from each of these sensors were band-pass filtered to 20–80 MHz and recorded with 10-bit resolution at a sampling rate of 200 MHz. The interferometers provided elevation and azimuth angles of the VHF sources. The interferometers exhibit significant errors in VHF source locations at low elevation [*Mardiana and Kawasaki*, 2000], in our experiment below about 1 km. Significant location errors would also be expected for sources above 15 km. For the VHF radiation that was detected by both interferometers, 3-D source locations were determined by first triangulating a single horizontal (x-y) location, and the resultant horizontal location was used to calculate a source

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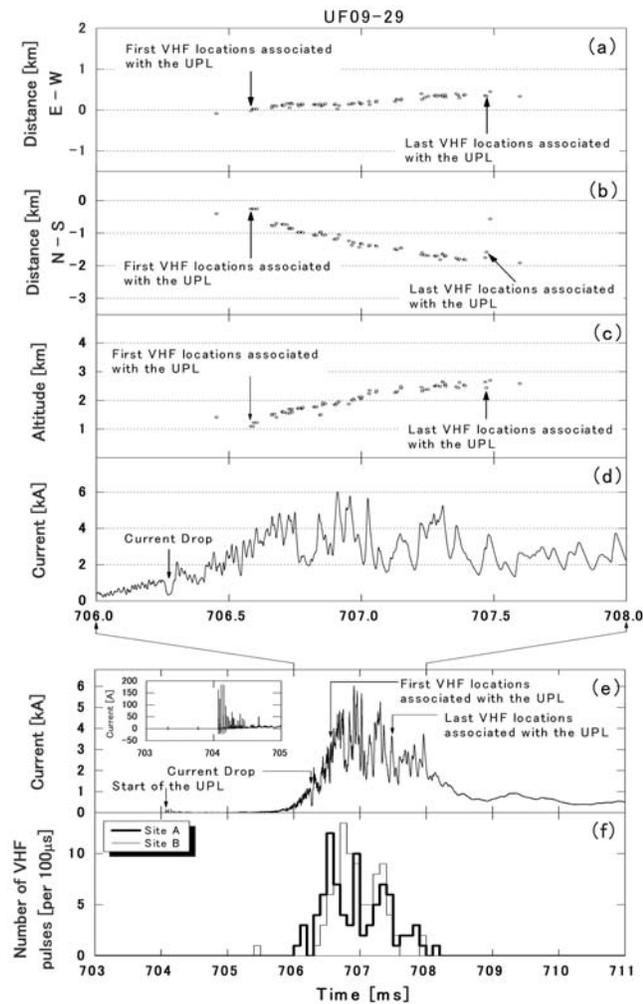
**Figure 1.** VHF source locations and channel-base current versus time for event UF 09–29, the (a) E–W, (b) N–S, and (c) altitude progressions of the VHF sources versus time on a 2-ms time scale, (d) the current during the time when the VHF sources were located on the same 2-ms time scale, (e) a current record centered on the peak VHF radiation on an 8-ms time scale (with an inset showing 2-ms expanded view of the beginning of the UPL), and (f) the number of the VHF pulses recorded by each VHF station per 100 $\mu$s. Note that east and north correspond to positive values in Figures 1a and 1b, respectively.

altitude (z-coordinate) for each interferometer [*Morimoto et al.*, 2004]. Sources were considered as being located only if they were recorded within 60 $\mu$s by the two interferometers, and if the two calculated altitudes were within 1500 m of each other, where upon the two altitudes were averaged. We estimate that the error in elevation could be a maximum of 1500 m. It was possible to locate a maximum of 2048 sources at a maximum rate of 1 source per 3.5 $\mu$s.

## 3.  Results

### 3.1.  Triggered Lightning UF 09–29

[7]  The first of the two UPLs discussed here initiated a five-stroke flash at 13:49:16.704 (GMT). Figure 1a–1c

shows the E-W, N-S, and altitude progressions of the VHF sources on a 2-ms time scale, respectively; Figure 1d shows the current during the time that VHF sources were located on the same 2-ms time scale; Figure 1e shows the overall initial-stage channel-base current on an 8-ms time scale (with inset showing a 2-ms expanded view of the beginning of the UPL); and Figure 1f the number of the VHF pulses recorded by each VHF station per 100 $\mu$s. The UPL began 950 ms after the rocket was launched (704.1 ms in Figure 1e) when the wire-trailing rocket was at a height of 110 m and ascending at a speed of about 190 ms$^{-1}$. The channel-base current of the UPL began with 150 A or so damped-oscillatory current pulses. Each current pulse corresponds to a single UPL step, and the oscillatory nature of the initial pulses is attributed to the current reflecting off the impedance discontinuities at the ground and top of the wire. As the UPL channel lengthened and the leader-channel resistance increased, these current oscillations at ground became increasingly damped, and the current pulses transitioned to being unipolar [*Lalande et al.*, 1998; *Willett et al.*, 1999]. The current then increased steadily to 1.1 kA during a time of 2.19 ms, after which the wire explosion produced a current decrease (labeled "Current Drop" in Figures 1d and 1e) to 330 A during a time of 18 $\mu$s. After the current drop, the current increased to a peak of 6 kA during a time of 620 $\mu$s (at time 706.9 ms in Figures 1d and 1e), with several large pulses having magnitudes of about 2 to 4 kA occurring during this rise.

[8]  The interferometers located 71 sources associated with the UPL during a time of 889 $\mu$s (706.6 to 707.5 ms in Figures 1a, 1b, and 1c). The first and the last two VHF source locations were away from the other VHF locations, possibly because the locations were erroneous, or they were sources not associated with the UPL. In any case, we do not regard these sources as being associated with the UPL in our analysis. The first source associated with the UPL was located 2.2 ms after the initiation of the UPL from the triggering wire, and 185 $\mu$s after the start of the current drop when the current level had reached 3.3 kA. There were more VHF sources than current pulses. During the time between the first and last located VHF sources, the average current was 3.3 kA, and a total charge of 2.9 C was transferred. A relatively steady current less than 2 kA flowed for about 400 ms after the time when the last VHF source was located. The VHF sources moved from an altitude of 1.1 km to 2.4 km and over a horizontal distance of 1.4 km with an average 3-D speed of 2.2 x 10$^6$ ms$^{-1}$. In Figure 1f, the number of the VHF pulses recorded by each station decreases after the last VHF locations associated with the UPL, even though some large current pulses were recorded. The Phantom high-speed video camera was triggered immediately after the wire destruction, and hence too late to record the UPL development, but the images it recorded showed that the channel was approximately vertical (in the north-south oriented vertical plane) from the launcher height up to the top of its field of view (325 m). This observation is consistent with the initial VHF sources being located only 500 m south of the launch tower.

### 3.2.  Triggered Lightning UF 09–30

[9]  The second UPL initiated a one-stroke flash at 14:01:04.016 (GMT). Figure 2 shows (a)–(c) the N–S, E–W, and altitude progressions of the VHF sources on a 3-ms time
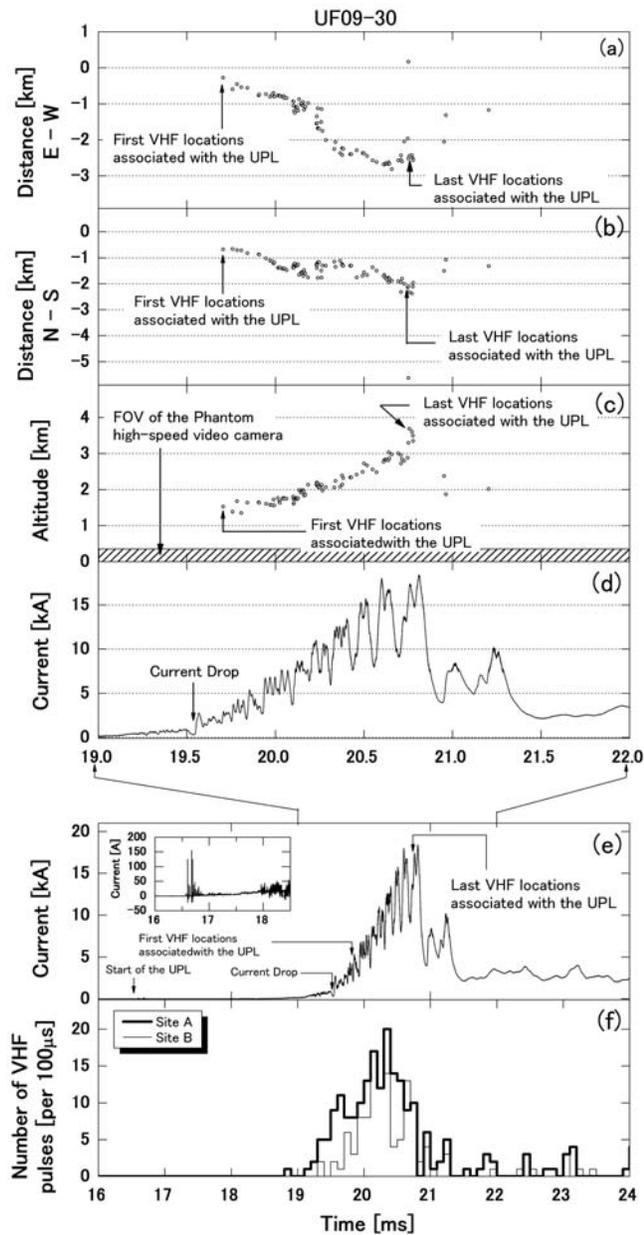
**Figure 2.** VHF source locations and channel-base current versus time for event UF 09–30, the (a) E–W, (b) N–S, and (c) altitude progressions of the VHF sources versus time on a 3-ms time scale, (d) the current during the time when the VHF sources were located on the same 3-ms time scale, and (e) current record centered on the peak VHF radiation on an 8-ms time scale (with an inset showing 2.5-ms expanded view of the beginning of the UPL), and (f) the number of the VHF pulses recorded by each VHF station per 100 $\mu$s. Note that east and north correspond to positive values in Figures 2a and 2b, respectively.

scale, (d) the current during the time that VHF sources were located on the same 3-ms time scale, (e) the overall initial-stage channel-base current on an 8-ms time scale (with inset showing a 2.5-ms expanded view of the beginning of the UPL), and (f) the number of the VHF pulses recorded by each VHF stations per 100 $\mu$s. The characteristics of the UPL are

very similar to that of UF 09–29. The UPL began 854 ms after the rocket was launched (at 16.5 ms in Figure 2e) with damped-oscillatory current pulses that later became unipolar (see Section 3.1) and exhibited a current drop (labeled "Current Drop" in Figures 2d and 2e). After the current drop, the current increased to a peak of 18 kA in 1.3 ms (at 20.8 ms in Figures 2d and 2e), with six large current pulses occurring during this rise, the largest one having an amplitude of 9.7 kA. After the overall current peak of 18 kA there were two more 4 kA pulses, and then the average current became steady near 2 kA.

[10] The Phantom camera imaged the UPL in eighteen video frames (2.25 ms). Four frames showing the UPL and an image from a later time showing the shape of the destroyed-wire channel section are depicted in Figure 3. The 2-D progression speed of the UPL estimated from the high-speed video images (in the north-south oriented vertical plane) varied, but generally increased from $1.2 \times 10^4 \, \mathrm{ms}^{-1}$ at 123 m AGL to $2.1 \times 10^5 \, \mathrm{ms}^{-1}$ at 325 m AGL. In each new frame, the UPL tip (newly-added upper section of the channel, labeled in Figure 3) was more luminous than the previously created channel. With each new frame, the newly-added channel sections were increasingly longer and more luminous, and the luminosity of the entire UPL channel increased. Note that the 120 $\mu$s frame time was longer than the expected interstep interval of some tens of microseconds.

[11] The interferometers located 80 sources associated with the UPL during a time of 1.05 ms (from 19.7 ms to 20.75 ms in Figure 2) beginning 950 $\mu$s after the UPL extended beyond the Phantom field of view at 325 m AGL, and 3.2 ms after the UPL initiation. The first source was located 3.1 ms after the initiation of the UPL and 260 $\mu$s after the start of the current drop when the current had reached 3.1 kA. Most of the VHF sources associated with the UPL were located during the time when the current was rising to 18 kA. In the time between the first and last located VHF sources the average current was 8.5 kA and a total charge of 8.9 C was transferred. Sources moved from an altitude of 1.5 km to 3.7 km and over a horizontal distance of 2.7 km with an average 3-D speed of $3.3 \times 10^6 \, \mathrm{ms}^{-1}$. In Figure 2f the number of the VHF pulses recorded by each station decreases after the last VHF locations associated with the UPL, even though some kiloampere-level current pulses were recorded. The final six source locations apparently progressed downward. These may have been associated with a separate UPL branch or with some recoil leader process [e.g. *Rakov et al.* 2003]. They could be also due to errors in estimating the vertical coordinates of VHF sources (see Section 2).

## 4. Discussion

[12] The VHF-imaged first and second UPLs, respectively, (1) began at about 185 $\mu$s and 260 $\mu$s after the current drops associated with the exploding of the wire and when the currents exceeded about 3 kA, (2) had average currents, 3.3 kA and 8.5 kA, during the time when VHF sources were located that were unusually large for UPLs in triggered lightning (see below), (3) exhibited superimposed large current pulses with amplitudes in the kiloampere range, and (4) ended when the currents dropped to appreciably lower levels, about 2 kA, and tended to have less significant variations. The average currents during the time when VHF
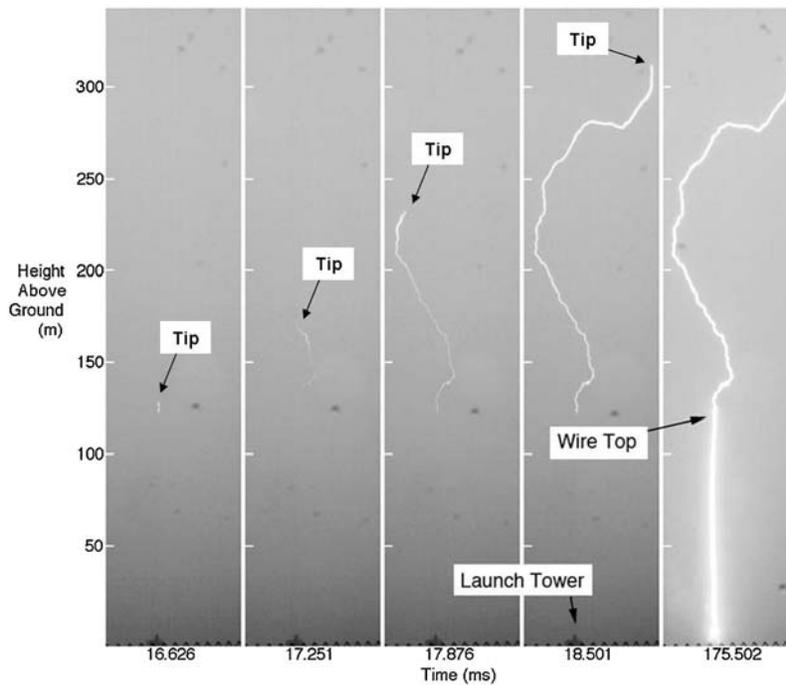
**Figure 3.** Four 125 $\mu$s frames recorded by the Phantom high-speed video camera from flash UF 09–30 showing the development of the UPL, and a fifth frame showing the shape of the bottom 350 m of channel, illuminated after the destruction of the triggering wire. The launch tower can be seen near the lower edge of each frame. The times when the frames were recorded are indicated beneath each frame and the height above ground scale is given on the left. Note that the fifth frame was recorded at 175.502 ms; that is, much later than the end of the VHF and current records shown in Figure 2.

source were located are significantly larger than both the geometric mean and maximum of average initial stage currents in triggered lightning reported by *Wang et al.* [1999] (96 A and 1028 A, respectively), and *Miki et al.* [2005] (99.6 A and 316 A, respectively). Note that their average values include more of the relatively low steady currents at the end of the initial stage, while our averages only include the current during the times of significant pulse activity (when VHF sources were located). The maximum current pulse peaks during the initial stage reported by *Wang et al.* [1999] and *Miki et al.* [2005] were 2046 A and 2179 A, respectively. Additionally, *Rakov et al.* [2003] reported kA-level (apparently up to 5 kA) current pulses superimposed on slower-varying initial-stage current, similar to those reported here, and attributed them to UPL step formation processes. The ICC pulses occurring during the initial stage for UF 09–29 were mostly between 2 to 4 kA, and for UF 09–30 they were mostly between 5 to 10 kA. Our observations suggest that the VHF power emitted by positive leaders is sufficient for locating when some current level is exceeded and/or a stepping process is involved. It appears likely that the VHF emission from positive leaders can be stronger than has been generally thought if the current is sufficiently high (> 1 kA) and/or is impulsive. This observation has important implications for the interpretation of VHF lightning images, which are generally assumed to be entirely due to negative leader processes, in terms of both leader polarity and inferred cloud charge structure.

[13] The located VHF sources associated with the two positive leaders ascended to altitudes of 2.4 km and 3.7 km, which are below the typical freezing level altitude of 4 km in Florida storms [*Koshak and Krider*, 1989]. These altitudes

are also several km below the altitude, 7 to 8 km, where the center of the main negative charge region is thought to be located in a typical Florida thunderstorm [*Koshak and Krider*, 1989]. However, the storm from which the lightning flashes were triggered was not a typical convective Florida summer thunderstorm. It was an unusually intense and large multi-cellular system and hence it might have had an atypical charge structure, probably more like that of a mesoscale convective system. Using balloon-borne electric field meters launched into summertime thunderstorms in central Oklahoma, *Stolzenburg et al.* [2002] reported that mesoscale convective systems could have as many as five stratified charge layers outside the updraft region, with the bottom layer being negative between altitudes of 2 to 4 km AGL. Such a low-altitude negative-charge layer could limit the UPL upward extension. The unusually large channel-base currents during the time when VHF sources were located between altitudes of 1 to 4 km for the two UPLs indicate that the storm probably did have a low-level layer of significant negative charge similar to that reported by *Stolzenburg et al.* [2002].

[14] The UPLs in both flashes may have continued to propagate into regions of negative charge at higher altitudes, with a lower channel current, resulting in VHF emission that was undetectable. Alternatively and perhaps more likely, the VHF emission may have been lower and not locatable if the UPL began to propagate upward in a heavily branched manner as it ascended to higher altitudes, as was reported by *Proctor et al.* [1988]. Significant branching might both reduce the current and the transient VHF emission per branch and produce complex VHF source geometries that the interferometer could not resolve [*Kawasaki et al.*, 2002].

Figures 1f and 2f show that fewer VHF pulses were recorded after the last VHF locations associated with the UPLs, even though kiloampere-level current pulses were measured at the ground.

[15] For the UPL of UF 09–30, the initial 2-D speed that was observed optically was $3.0 \times 10^4$ ms$^{-1}$, which is similar to what *Biagi et al.* [2009] reported for the first 100 m of one UPL, $5.6 \times 10^4$ ms$^{-1}$. The UPL speed increased to $1.3 \times 10^5$ ms$^{-1}$ when the leader extended to 325 m AGL. The average 3-D speed of VHF sources between 1.5 and 3.7 km was $3.3 \times 10^6$ ms$^{-1}$, which is approximately an order of magnitude higher than the optically observed 2-D value at lower altitudes. The leader acceleration was likely caused by a combination of decreasing air pressure and increasing electric field intensity with increasing altitude [*Stolzenburg et al.*, 2002]. For the UPL of flash 09–30, the increasing length and luminosity of newly-added channel segments in successive high-speed video images indicate that the step lengths were increasing or were occurring at a faster rate because the electric field intensity was increasing with altitude.

## 5. Summary

[16] The first 3D VHF images of UPLs in triggered lightning are reported. It appears that VHF sources associated with positive breakdowns are locatable only when currents are in the kiloamperes range and/or a stepping process is involved. This observation is important for the interpretation of VHF radiation measurements.

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