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An "anomalous" triggered lightning flash in Florida

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[1] An "anomalous" rocket-and-wire triggered lightning flash, a flash whose leaders do not follow the triggering wire remnants to ground, is characterized via high-speed video images at 10 and 300 kilo-frames per second, still camera images, 66–72 MHz source locations from a Lightning Mapping Array, channel-base current, and electric field and electric field derivative (dE/dt) measurements. This is the first anomalous flash of about 410 classically triggered flashes in north-central Florida. The flash began with an upward positively charged leader (UPL) initiating from the tip of the upward-moving triggering wire about 280 m above ground level. All but the bottom 17 m of wire exploded (became luminous) 37.6 ms after UPL initiation. A stepped leader initiated, likely from the top of the wire remnants, 282 m above ground level about 1.3 ms after the wire explosion and propagated downward for 2.1 ms, attaching to the top of a grounded utility pole 117 m southwest of the launching facility. The line charge density on the stepped leader is estimated to be of the order of 10^{-3} C m^{-1}. Contrary to previously reported "anomalous" flashes in France and New Mexico (roughly 16% and 31%, respectively, of their triggered flashes), in our event, there was not a tens of milliseconds current-zero period preceding the stepped leader, there was no observed downward dart leader in the UPL channel prior to the stepped leader to ground, and there was a failed attempt to reestablish current in the exploded-wire channel between the UPL and ground.

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1. Introduction

[2] In classical (grounded wire) rocket-and-wire triggered lightning, a rocket with a thin metal grounded trailing wire is launched toward an overhead or nearby thunderstorm as illustrated in Figure 1(a). When the rocket reaches an altitude of typically 200 to 400 m, the enhanced electric field at the tip of the rocket is sometimes sufficiently strong to induce an upward positive leader (UPL) that propagates toward the negative cloud charge region above [*Rakov and Uman*, 2003]. As the UPL propagates, current flows through the channel formed by the UPL and the triggering wire. The current following the UPL period of perhaps tens of milliseconds is termed the initial continuous current (ICC). The transition from UPL to ICC is not well-defined. The UPL and the ICC along with any "precursor current pulses" [e.g., *Lalande et al.*, 1998; *Willett et al.*, 1999; *Biagi et al.*, 2009, 2012] measured on the ascending triggering wire form the initial stage (IS) of rocket-triggered lightning. On average, the wire explodes about 10 ms following the start of the UPL/ICC current flow [*Wang et al.*, 1999]. An abrupt decrease of current to zero or near zero generally accompanies this explosion and may be followed by several current impulses propagating downward from the top of the wire remnants in an attempt to reestablish current in the former wire channel [*Wang et al.*, 1999; *Rakov et al.*, 2003; *Olsen et al.*, 2006]. Current impulses that do not reestablish current flow in the channel are termed "attempted reconnection pulses" (ARPs), while those that do are termed "reconnection pulses" (RPs) [*Olsen et al.*, 2006]. Prior to the study by *Olsen et al.* [2006], ARPs and RPs were collectively referred to as "dart leader/return stroke-like sequences" by *Rakov et al.* [2003]. Following the end of the IS and a zero current period, one or more downward leader/return stroke sequences may traverse the remains of the channel between cloud and launching facility [*Rakov and Uman*, 2003]. These sequences are similar to subsequent strokes in natural lightning.

[3] Classical rocket-and-wire triggered lightning flashes whose leaders do not traverse the path of the wire remnants are referred to as "anomalous" flashes. Discussion of "anomalous" rocket-triggered lightning flashes in the published literature is confined to experiments performed in Massif Central (France) in the late 1970s and in New Mexico (USA) in the early 1980s [e.g., *Fieux and Hubert*, 1976; *Fieux et al.*, 1978; *Hubert and Mouget*, 1981; *St. Privat d'Allier Research Group*, 1982; *Hubert*, 1984; *Hubert et al.*, 1984]. Characteristics of these "anomalous" triggered lightning events are illustrated in Figure 1(b). The first

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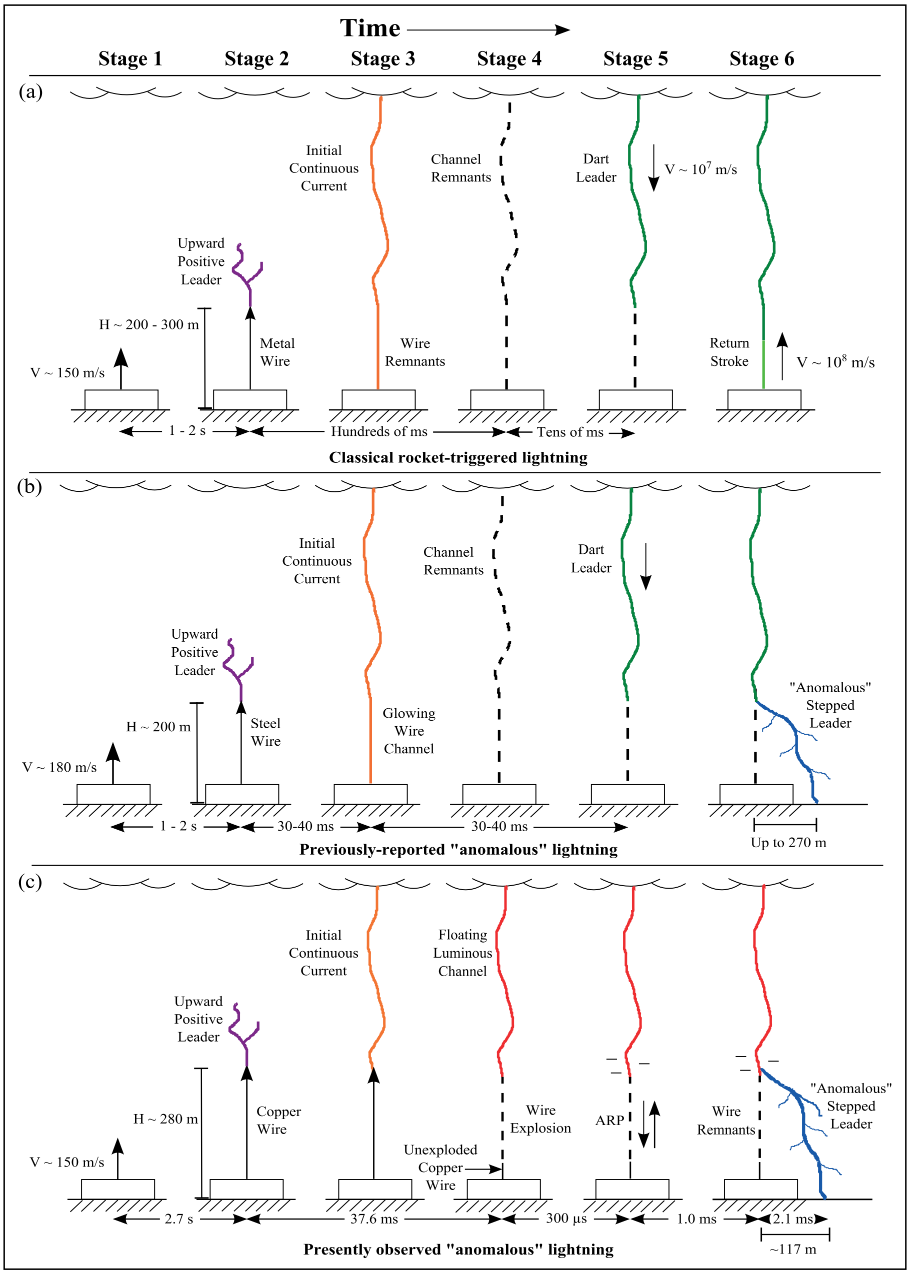

Figure 1. Sequence of events (presented in stages) in three types of rocket-triggered lightning with time moving left to right: (a) Classical rocket-triggered lightning, (b) "Anomalous" triggered lightning in France and New Mexico, and (c) "Anomalous" triggered lightning in Florida. Total time duration is different for Figures 1a–c. In Figures 1b and 1c, the first return stroke occurs at the conclusion of Stage 6. The time elapsed between Stage 4 and Stage 6 in Figure 1c is several milliseconds and in Figure 1b is several tens of milliseconds. In stages 4–6 of Figure 1c, note the partially exploded kevlar-reinforced copper wire and ARP during flash UF 12–04.

discussion of anomalous triggered lightning was reported by *Fieux and Hubert* [1976] in the context of hazards encountered while triggering lightning in France. The authors reported that 6 out of 45 triggered flashes (13.3%) terminated on a ground location as far as 145 m from a launching facility, which was located 1100 m above sea level in Saint-Privat-d'Allier in central France. The authors stated that an anomalous flash typically exhibits upward leader propagation from the top of the wire and a faint wire "glow" and that after 40 to 80 ms, a downward leader traverses the existing natural channel to the top of the wire where it separates and traverses a path through virgin air to ground. *Fieux et al*. [1978] reported current, electric field, and video at 150 fps for an anomalous rocket-triggered flash. The authors reported that 8 out of 62 triggered events (12.9% and including the events described by *Fieux and Hubert* [1976]) were anomalous. The authors suggest that an anomalous rocket-triggered flash begins with an UPL emanating from the top of the wire, producing a current that increases to about 30 A in 40 ms. At approximately 40 ms

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after the start of the UPL, the wire begins to glow and then abruptly the current falls to zero. Then, 40 ms following the apparent cessation of current, a downward dart leader traverses the existing natural channel above the top of the wire. When the leader reaches the wire remnants, it chooses a path in virgin air, becoming a downward stepped leader to ground. *Hubert and Mouget* [1981] provide the most detailed published description to date of anomalous rocket-triggered lightning, building upon *Fieux and Hubert* [1976] and *Fieux et al*. [1978]. The process, according to the authors, begins as the majority of classical rocket-and-wire triggered lightning flashes: When the rocket is typically 150 to 400 m above ground level, a luminous UPL is launched from the wire top, producing a current of several tens of amperes at the ground. Once the wire melts, the current is abruptly cut off. A downward dart leader traverses the preexisting channel to where the wire remnants exist and then transitions to a stepped leader between the wire top and ground. The authors report that for French experiments through 1978, therefore including the data by *Fieux and Hubert* [1976] and *Fieux et al*. [1978], anomalous triggered flashes occurred in 14 out of 84 (16.7%) of all rocket-triggered flashes in France. *St. Privat d'Allier Research Group* [1982] reported that 15 out of 94 (16.0%) rocket-triggered flashes in France from 1973 through 1980 were "anomalous" flashes and that anomalous flashes attached to ground as far as 270 m from the ground launcher.

[4] In New Mexico, rocket-triggered lightning experiments were conducted near the summit of Mt. South Baldy near Socorro, New Mexico, in 1981 and 1982, at an altitude approximately 3200 m above sea level. *Hubert* [1984] and *Hubert et al*. [1984] report an identical sequence of events for anomalous rocket-triggered lightning in France and New Mexico, although in publications from both locations the accompanying image data do not appear sufficient to support the existence of a downward dart leader to the top of the wire remnants, only a time lag of tens of milliseconds between the cessation of current and the appearance of the stepped leader (see section 4: Discussion and Summary). In the New Mexico studies, 15 out of 48 (31.3%) of all rocket-triggered events were classified as anomalous, although a distinction is made between those anomalous flashes that do not terminate on the launcher and those that do not follow the wire remnants but do terminate on the launcher. The authors report that anomalous flashes terminate as far as 205 m from the ground launcher. Anomalous flashes that did not follow the wire remnants but did terminate on the launcher exhibited measured return stroke peak currents up to 35 kA.

[5] In this paper, data are presented from a nine-stroke "anomalous" classical rocket-triggered lightning flash that occurred on 15 May 2012 at the International Center for Lightning Research and Testing (ICLRT), a 1 km^2 facility located on the Camp Blanding Army National Guard base in north-central Florida. A sequential, graphical representation of the flash is illustrated in Figure 1(c). The flash is the only documented anomalous case in approximately 410 classical rocket-triggered lightning events at the ICLRT from 1993 to 2012, and it exhibited major features different from the earlier anomalous flashes in France and New Mexico. The elevation of the ICLRT is approximately 60 m above sea level, significantly lower than the sites in France and New Mexico. Further, triggered-lightning experiments in France and New Mexico used 0.2 mm diameter steel triggering wire, while the ICLRT experiments used 0.2 mm diameter kevlar-reinforced copper wire.

2. Experiment

[6] A satellite view of the ICLRT is shown in Figure 2 with annotations for the launching facility and strike point as well as the subset of the available measurements

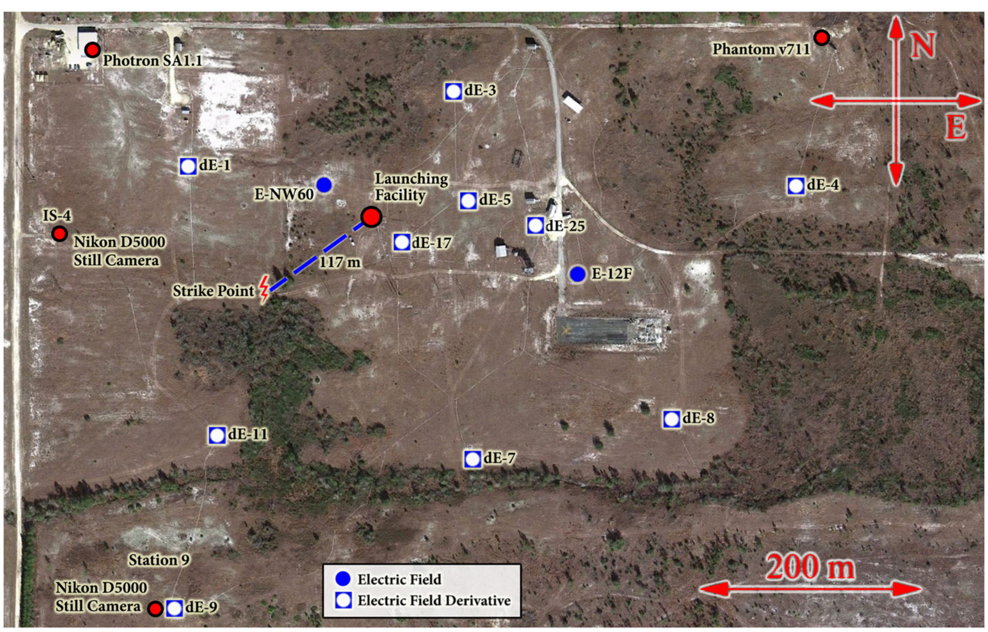

Figure 2. Aerial view of the ICLRT. The strike point of flash UF 12–04 is indicated by a red lightning, the launching facility by a red circle outlined in black. The 117 m distance between the strike point and the launching facility is shown. Electric field antennas are designated E and electric field derivative antennas dE.

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described here. The anomalous flash, designated UF 12–04, was triggered on 15 May 2012 at 17:45:04.709106 (UT) via a small fiberglass rocket carrying a 700 m spool of grounded kevlar-reinforced copper wire launched from a metallic rocket launcher, or launching facility, resting on ground level. The top of the launch tubes was 4 m above ground level. The rocket represented the fourth launch of the day and the first triggered flash with return strokes. The first three launches produced only "precursor current pulses" from the tip of the triggering wire, no sustained UPL, while the fifth launch resulted in a full IS process but no return strokes. The electric field at ground at the time of rocket launch was about +5.7 kV/m. The physics sign convention is used throughout this paper, that is, a positive electric field at ground corresponds to an upward-pointing electric field vector (the presence of negative cloud charge overhead induces a positive electric field).

[7] Measurements obtained during this event include channel-base current, electric field, electric field derivative (dE/dt), 66–72 MHz VHF source locations from a local seven-station Lightning Mapping Array (LMA) network [*Rison et al.*, 1999; *Krehbiel et al.*, 2000; *Hill et al.*, 2012b], DSLR still camera images, and high-speed video images. Current at the triggered lightning channel base (launching facility) was directly measured using a T&M Research R-7000-10 noninductive current-viewing resistor with bandwidth from DC to 8 MHz. In all plots of the channel-base current, a positive current corresponds to downward-moving negative charge or upward-moving positive charge. The normal (vertical) component of the electric field was sensed using six inverted flat plate antennas of effective area 0.474 m^2 and one flat-plate antenna of area 0.155 m^2 located from 63 to 220 m from the launching facility. The electric field waveforms were digitized at 10 MS/s with 12-bit vertical amplitude resolution and were bandwidth limited to 3 MHz at the digitizer input. The derivative of the electric field was measured directly with

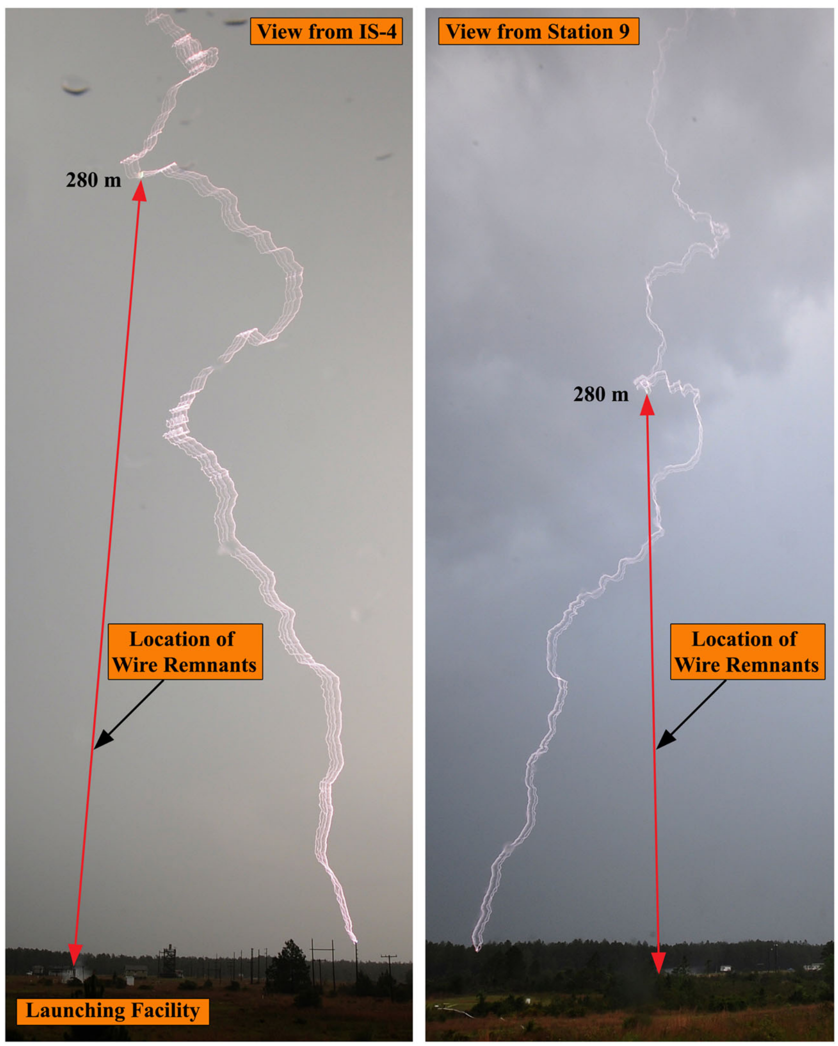

Figure 3. Still camera images of Flash UF 12–04: (left) View from IS-4 (278 m west of the launching facility) looking due east with vertical field of view of about 350 m, and (right) view from Station 9 (392 m southwest of the launching facility) looking northeast with vertical field of view of about 450 m. The vertical extent of each image is different. The launching facility is indicated. The red line denotes the location of the exploded triggering wire between the launching facility and the bottom of the UPL. See Figure 2 for aerial view of still camera locations. Note that the various strokes, nine total, are blown horizontally by the wind during the time exposure.

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flat-plate antennas of area 0.155 m^2 located at 10 stations at distances 27 to 391 m from the launching facility. The electric field derivative (dE/dt) measurements comprise the time-of-arrival (TOA) network described in *Hill et al*. [2012a]. Channel-base current and dE/dt waveforms were digitized in the field with HBM 7600 isolated digitizers at 100 MS/s with 14-bit amplitude resolution and bandwidth of 25 MHz and were recorded with a HBM GEN16t Transient Recorder.

[8] The LMA network surrounding the launching facility consists of seven stations at distances from 461 m to 9.6 km. Each LMA station recorded the time of peak power associated with VHF impulses from electrical breakdown processes associated with propagating lightning leaders occurring near or over the ICLRT. The system determined the three-dimensional source locations of the VHF impulses using the TOA technique described in *Thomas et al*. [2004]. VHF data were acquired during this event with continuous 10 μs data acquisition windows (note that *Hill et al*. [2012b] analyzed data from this LMA network in 80 μs data acquisition windows). The azimuth angles and distances from the triggering site to each LMA station are given in Table 1 and Figure 1 of *Hill et al*. [2012b]. Note that the LMA station nearest to the launching facility is 30 m northeast of the Vision Research Phantom v711 high-speed camera in Figure 2, a few meters outside the field of view.

[9] High-speed video images of the anomalous flash were acquired using both a Vision Research Phantom v711 and a Photron FASTCAM SA1.1 high-speed camera. The locations of both cameras are annotated in Figure 2. The Phantom v711 was located approximately 430 m northeast of the launching facility (top right of Figure 2) and was fitted with a 20 mm Canon lens set to an aperture of f/6.7. The camera recorded the anomalous triggered flash at 10 kilo-frames per second (kfps) with an exposure time of 98.6 μs per frame. The image resolution was 1280 × 304 pixels (vertical x horizontal), providing a 546 m vertical and 132 m horizontal field of view. The Photron SA1.1 was located 300 m northwest of the launching facility (top left of Figure 2) and was configured with a 20 mm Nikon lens set to an aperture of f/4. The Photron SA1.1 recorded a portion of the anomalous flash at 300 kfps, an exposure time of approximately 3.33 μs per frame. The resolution was 320 × 32 pixels (vertical × horizontal) providing a 133 m vertical and 13 m horizontal field of view. Both cameras recorded with 12-bit grayscale amplitude resolution and were synchronized to GPS time.

[10] Still camera images were acquired using two Nikon D5000 DSLR still cameras intended for wide-angle exposures of the lightning channel during rocket-triggered and nearby or on-site natural flashes. As shown in Figure 2, one D5000 was located 278 m west of the launching facility (view due east) at IS-4, and the other was located 392 m southwest of the launching facility (view northeast) at Station 9. Each camera was configured with a 10 mm lens set to an aperture of f/18 with an added six-stop neutral density filter and a circular polarizer. The cameras acquired continuous 5.8 s time exposures. Figure 3 depicts the low-altitude channel geometry of flash UF 12–04 with one image from each Nikon D5000 still camera location annotated in Figure 2.

3. Results

[11] Flash UF 12–04 had nine return strokes as determined from on-site electric field measurements while the National Lightning Detection Network under-reported that the flash had six return strokes, with a first return stroke peak current

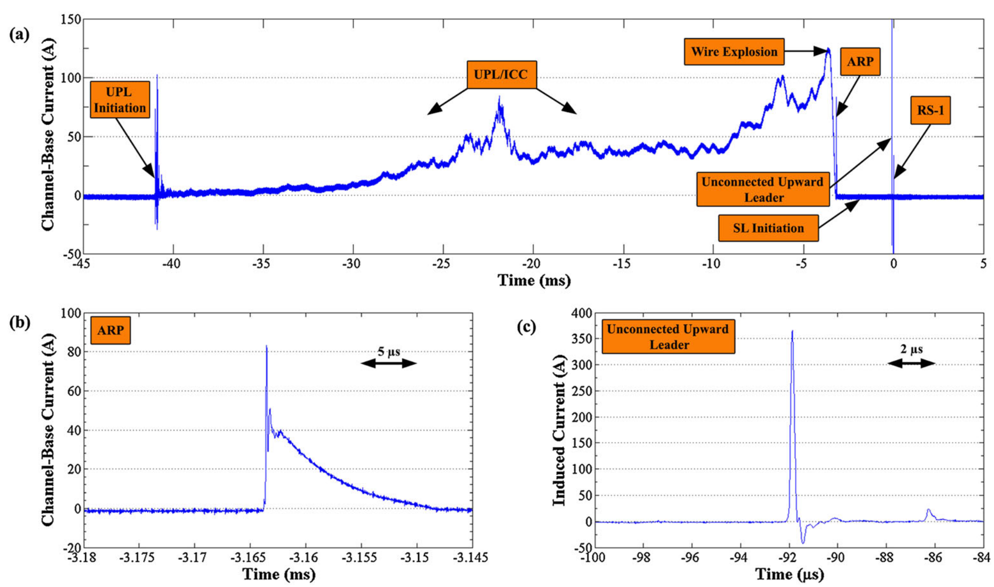

Figure 4. Current measured at the launching facility (ground) during flash UF 12–04: (a) Current plotted with full-scale amplitude of 450 A and a duration of 50 ms, (b) a 35 μs record containing the ARP, (c) a 16 μs record containing the current of the unconnected upward leader. The time scale of the bottom plots correlate to the time scale of the top plot. The unconnected upward leader and RS-1 are separated by about 90 μs and are not easily distinguishable on the time scale in Figure 4a. Note that the measured current due to RS-1 is induced from the return stroke which strikes nearby (117 m away). Time is relative to the return stroke.

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of 10.7 kA. Results presented here are primarily for the IS, attempted stepped leaders, and the primary stepped leader of the flash. Regarding Figure 3, the filters mounted on the Nikon D5000 cameras reduce the light throughput to the image sensor by a factor of about 250, and this reduction in light intensity coupled with the relatively short (37.8 ms) and a relatively dim IS process (discussed below) accounts for the absence of a clear luminous channel of the exploded triggering wire in the still photographs. The luminous wire explosion was nevertheless captured on high-definition video at 30 fps (not shown here) and on high-speed video, and its remnants are evident in Figure 6.

[12] The UPL and ICC portions of the IS had a maximum current amplitude of 125 A and average amplitude of 32 A, transferring 1.2 C of negative charge to ground. In Figure 4, a current waveform measured at ground during UF 12–04 is shown. The channel-base current steadily increases after the initiation of the UPL/ICC, abruptly dropping to less than two Amperes (the noise level of the digitization system) concurrent with the wire explosion, 37.8 ms after UPL initiation. One ARP, whose current at ground is shown in Figure 4(b), with peak amplitude of 85 A, occurs 62.5 μs after the current drops below the threshold of the measurement. An RP is not observed. When the rocket was at an altitude of approximately 282 m above ground level, all but the bottom 17 m of the trailing wire exploded. The 37.6 ms time duration between UPL initiation and wire explosion is longer than the mean of 8.6 ms reported by *Wang et al.* [1999], and the 282 m altitude at wire explosion is about average for classical rocket-triggered flashes at the ICLRT. Partial explosion of the trailing wire occurs relatively infrequently at the ICLRT. In a few previous events with partial explosions of the trailing wire, in addition to a current that falls below the threshold of the most sensitive measurement available, the bottom 10 m or so of the wire explodes tens of milliseconds following a reestablishment of the lightning channel between the bottom of the UPL and ground. During UF 12–04, the bottom 17 m of trailing wire did not explode, and there was no reestablishment of current to ground in the wire to cause it to do so after the top part exploded. Following the ARP, no steady channel-base current was measured at the launching facility, although one induced transient electrical discharge did occur during the stepped leader process and another occurred during the return stroke, both discussed below.

[13] Beginning 600 μs prior to the sustained downward stepped leader development, attempted stepped leader channels (luminous steps emanating from the UPL channel above the wire remnants) are observed in three locations in the Phantom v711 high-speed video. The three locations of attempted stepped leaders are at about 0, 5, and 20 m above the initiation point of the UPL and will be referred to as Locations 1, 2, and 3, respectively. These locations and attempted stepped leader channels are illustrated in the sequential image frames of Figure 5. The original images were inverted, equally contrast enhanced, and cropped to provide an optimal view of the attempted stepped leader channels. In Figure 6, 22 sequential Phantom v711 high-speed video frames (2.2 ms time duration) show the full stepped leader descending from an altitude of approximately 282 m to 10 m (the top of the utility pole) above ground level. The images shown in Figure 6 were equally contrast enhanced. In Figures 5 and 6, time progresses from left to right. The first attempted stepped leader occurs at Location 2 in Frame 2 of Figure 5, 600 μs (six frames) prior to sustained stepped leader development. The second attempted stepped leader occurs 400 μs prior to sustained stepped

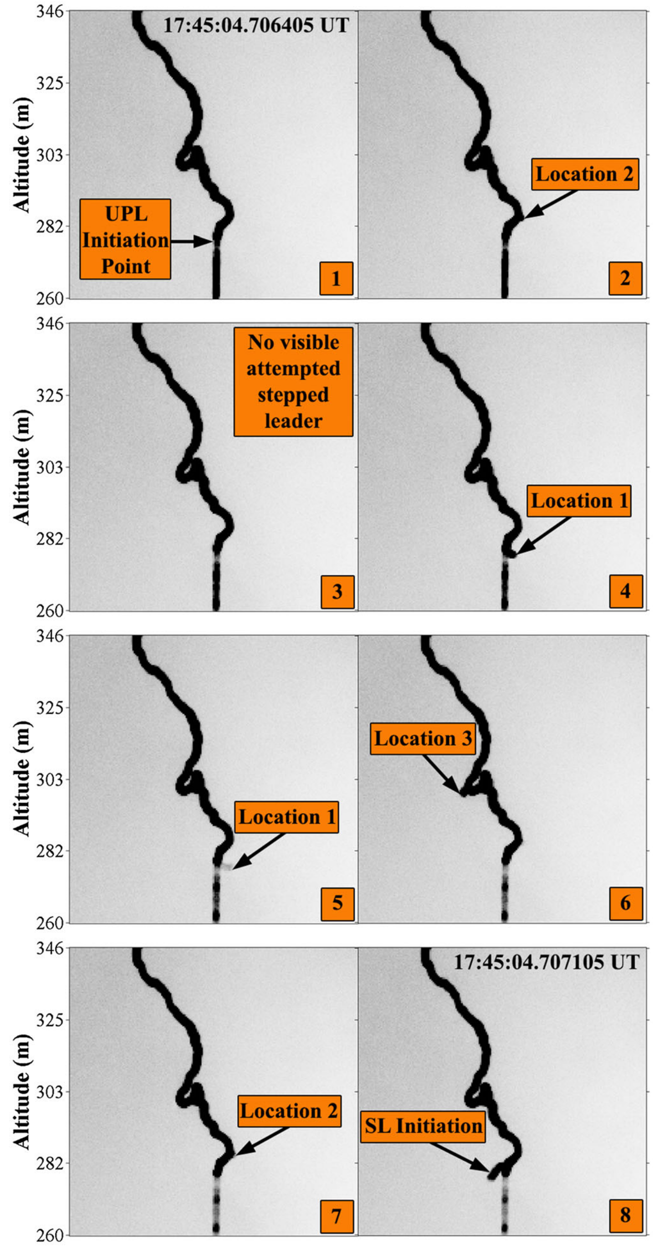

Figure 5. Eight high-speed video frames (10 kfps) depicting three attempted stepped leaders. Frame 1 is seven frames (~700 μs) prior to sustained stepped leader initiation, and 2.8 ms prior to the first return stroke. The images were captured by the Phantom v711 high-speed camera, located in the northeast corner of Figure 2. Time progresses from left to right across each row of video frames. Relative frame numbers are indicated in the bottom right corner of each image. The UPL initiation point is indicated in Frame 1. Black arrows indicate the first appearance and location of an attempted stepped leader. The sustained stepped leader of the flash begins during Frame 8. Altitude given is above ground level.

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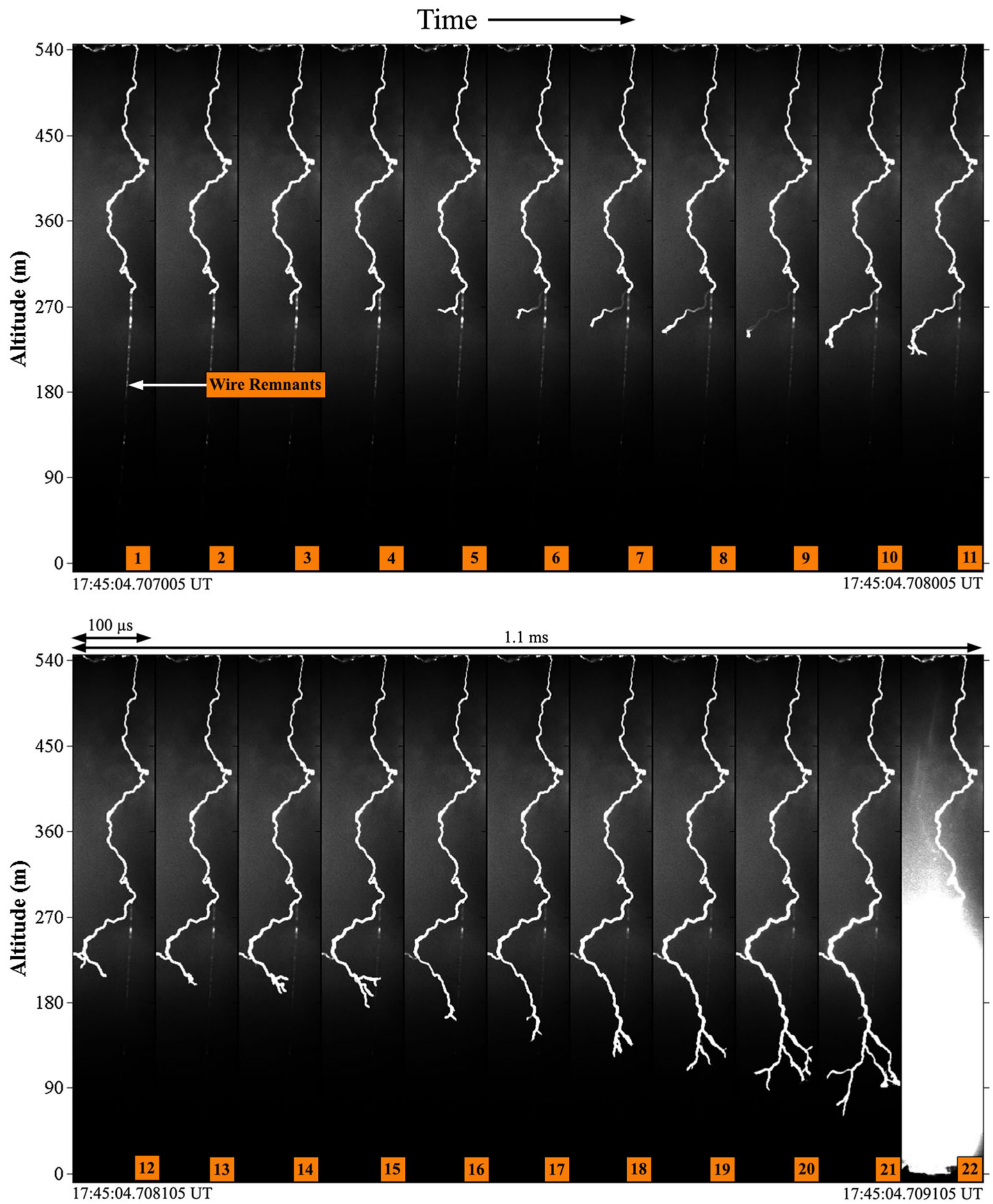

Figure 6. Twenty-two high-speed video frames (10 kfps) illustrating stepped leader development over a vertical range of about 270 m. The images were captured by the Phantom v711 high-speed camera, located in the northeast corner of Figure 2. The stepped leader separates from the UPL channel at about 282 m above ground level (Frame 2) and the strike point is about 10 m above ground level (Frame 22). Time progresses left to right across each row of video frames. The return stroke begins during Frame 22, corresponding to time t = 0 in Figures 4, 8, and 9. Frame 2 corresponds to Frame 8 in Figure 6 and "SL initiation" in Figures 7 and 9. The average speed of the main channel is 1.8×10^5 m/s.

leader development at Location 1 in Frames 4 and 5. The third attempted stepped leader occurs at Location 3 in Frame 6 simultaneously with a re-illumination of Location 2. Frame 7 shows a brightening of the first attempted stepped leader at Location 2. The sustained stepped leader is visible in Frame 8 at a height of about 282 m above ground level. Regarding Frame 8 of Figure 5, the point of sustained stepped leader initiation is approximately 2 m higher in altitude (282 m) than the point of UPL initiation (280 m). In the 38.9 ms between UPL initiation and appearance of the stepped leader, the rocket also ascended (and thus extended the triggering wire) about 2 m. The bottom of the UPL channel does not appear to move upward with the rocket during these 38.9 ms. The point of the sustained stepped leader initiation is probably the top of the wire remnants, 282 m above ground level. The stepped leader descends to ground in Figure 6 in 2.1 ms, attaching to a grounded, unused utility pole 117 m southwest of the launching facility. The wire remnants remained faintly luminous throughout the stepped leader process and for approximately 10 ms following the onset of the first return stroke. Three-dimensional TOA locations for dE/dt pulses at times correlated with the optically observed attempted stepped leaders were found at altitudes from

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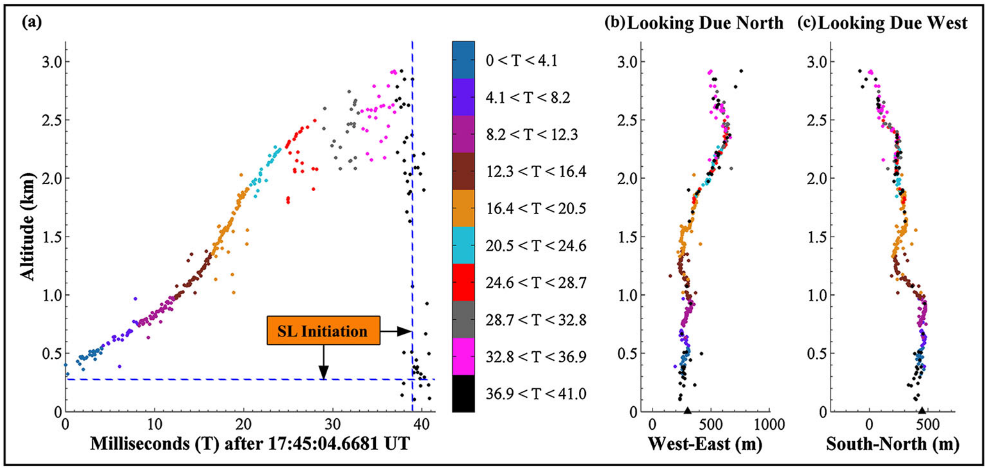

Figure 7. LMA source locations from the start of the UPL through the first return stroke for flash UF 12–04 on 15 May 2012: (a) altitude versus time plot, (b) a west-east versus altitude plot, (c) a south-north versus altitude plot. The sources span 41 ms beginning at 17:45:04.6681 UT, the time of UPL initiation. Time t = 41 ms corresponds to the first return stroke of UF 12–04. The sources are color coded with time according to the key in Figure 7a using 4.1 ms time windows.

305 m to 280 m above ground level and from about 30 to 45 m west of the launching facility. The calculated sources had spatial uncertainties of the order of 1 m. Electric field derivative waveforms measured in association with stepped leader steps exhibited uncharacteristic oscillatory signatures without clearly defined dE/dt peaks, possibly a result of the reflection of the positively charged, upward-propagating wave following the formation of each step [e.g., *Hill et al*., 2011] from the UPL channel above. Without a well-defined dE/dt peak in the waveform, it was not possible to adequately locate the negative stepped leader sources of radiation.

[14] The LMA-located VHF sources shown in Figure 7 associated with the UPL [e.g., *Hill et al*., 2012b] increase in altitude to about 2.3 km above ground level followed by sources spread out about 700 m vertically above and below the apparent tip of the UPL as it continued to propagate. Two sources were located at 507 m and 242 m altitude about 60 μs following the onset of the ARP. These two sources were located along and near the bottom of the UPL channel and top of the wire remnants and are estimated to have an altitude uncertainty of about 25 m considering that the closest LMA station is 461 m from the channel base. Between the ARP and the sustained stepped leader (time duration of 1 ms), VHF sources are located at altitudes between 512 m and 2.8 km, as shown in Figure 7. The VHF sources occurring in this time period are perhaps indicative of charging of the UPL/ICC channel, that channel being unconnected to ground (floating in the ambient electric field), and contributing to an increasingly polarized UPL/ICC channel. Because the time resolution of the high-speed video is an order of magnitude less than the LMA system, it is difficult to establish a relationship between an attempted stepped leader pulse and VHF sources. Typical peak power of the located VHF sources appears to decrease by an order of magnitude from about 0 dBW to about −10 dBW between the wire explosion and initiation of the downward stepped leader. The strongest sources, measuring between 5 and 10 dBW, are associated with the stepped leader's descent to ground, presumably because negative breakdown radiates more powerfully than positive breakdown at VHF [*Edens et al*., 2012 and references therein].

[15] Approximately 90 μs prior to the first return stroke a positive polarity current pulse with peak amplitude of 365 A and pulse width of about 400 ns, shown in Figure 4(c) with polarity indicative of an unconnected UPL from the launcher, initiates from the top of the 17 m unexploded wire section. This electrical discharge and one branch of the downward stepped leader were simultaneously imaged in one frame of Photron SA1.1 high-speed video (captured at 300 kfps and not shown), with the descending stepped leader making a bright step during that frame. Luminosity was observed both a few meters above the launching facility and at the top of the remaining in-tact wire approximately 17 m above ground level. The luminosity observed a few meters above the launching facility may be a result of a small arc occurring between two pieces of unexploded wire. Luminosity was not observed on the in-tact wire. The wire remnants above 17 m, unlike the in-tact wire, are still slightly luminous at the time of this current pulse. The current amplitude of this upward unconnected leader is the largest current for such a discharge measured at the ICLRT [*Schoene et al*., 2008; *J. D. Hill*, private communication]. The three-dimensional location of the large dE/dt pulse associated with the upward unconnected leader was directly above the launching facility at an altitude of about 29 m with respect to local ground level, or about 12 m above the top of the unexploded wire segment. The altitude uncertainty of the dE/dt source location was 8.5 m. Prior to the upward discharge, a 1 to 2 m segment of channel was faintly luminous just above the launching facility and under the segment of in-tact wire, further suggesting that there may have been a small wire break at the bottom of the channel. From the Photron video, it is unclear if this is the same segment of channel illuminated during the discharge.

[16] For a time period of 14 μs (time t = −1 μs to t = 13 μs in Figure 8) surrounding the return stroke initiation, which

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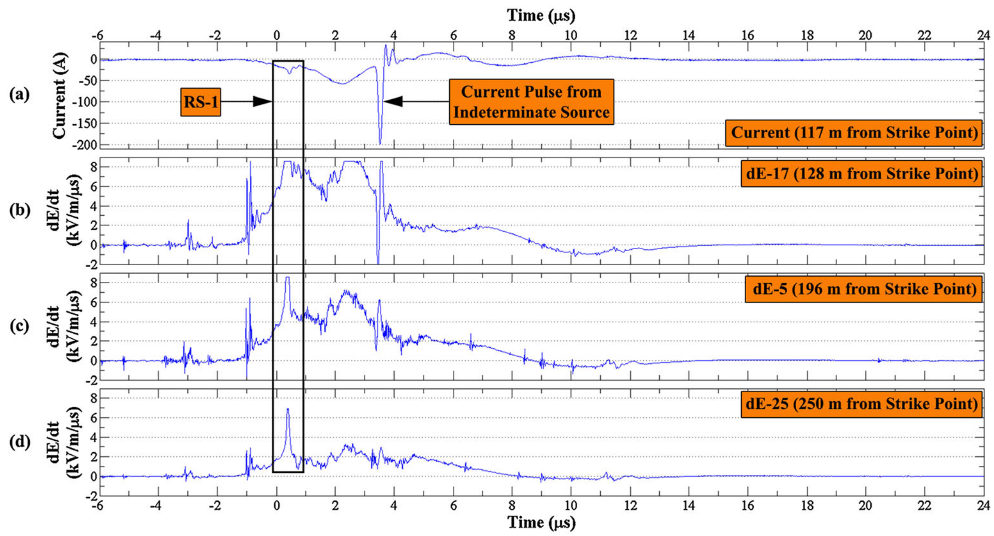

Figure 8. (a) Induced current at the launching facility during the first return stroke of UF 12–04 (strike point 117 m southwest—see Figure 1) spanning about 14 μs between $t = -1$ μs and $t = 13$ μs; (b) dE/dt at dE-17; (c) at dE-5; and (d) at dE-25. Distances from the strike point to the antennas are given. See Figure 2 for an aerial view of dE/dt locations. Time is relative to the return stroke.

terminated 117 m from the launching facility, induced current was measured on the launcher. Figure 8 illustrates this induced current of 14 μs duration along with dE/dt measured at three stations (dE-17, dE-5, and dE-25 in Figure 2) at distances of 128 m, 196 m, and 250 m, respectively, from the strike point. To time-align these measurements, propagation time assuming electric field wave propagation along ground and fiber delays were removed. The return stroke is indicated by the black rectangular box in Figure 8. If the current waveform is multiplied by −1, the current signature appears to follow the shape of the correlated dE/dt measurements, which is not unexpected considering the launching facility is acting as a large effective area dE/dt antenna in response to the radiated electric field. During the induced current shown, there is also a negative polarity current pulse with 10–90% rise-time of 90 ns and amplitude of 200 A about 3 μs following the return stroke signature which is marked as "Pulse from Indeterminate Source" in Figure 8. This pulse is discussed in greater detail at the end of section 4.

[17] A 5 ms electric field record is plotted in Figure 9 using data from two electric field antennas, E-NW60 and E-12F (see Figure 2), located 110 m northeast and 280 m due east, respectively, from the strike point. E-NW60 saturated 400 μs prior to the return stroke. E-12F had a sensitivity of 62 kV/m/V and time constant of 1.23 s, while E-NW60 had a sensitivity of 8.2 kV/m/V and time constant of 7.8 s, both with about 2 V of dynamic range. The time of the ARP, attempted stepped leaders, stepped leader initiation, possible unconnected upward leader, and first return stroke are annotated in Figure 9 based on frame times extracted from the high-speed video.

4. Discussion and Summary

[18] The images extracted from the Phantom v711 high-speed video and shown in Figures 5 and 6 are the first published images of an anomalous rocket-triggered flash that identify the top of the wire channel, thus unequivocally illustrating a downward stepped leader propagating from the top of the exploded triggering wire without an obvious downward leader preceding it. A likely explanation for this phenomenon and also for the appearance of attempted stepped leaders near the bottom of the UPL channel prior to the appearance of the stepped leader is the buildup of negative charge at the bottom of the UPL/ICC channel floating in the ambient electric field following the wire explosion and the ARP. In the present study, a negative charge near 1 C is shown in the following paragraphs to have resided at the bottom of the UPL/ICC after the isolated UPL/ICC has polarized in the ambient electric field. The near 1 C stepped leader charge source produced a negative line charge density of the order of 10^{-3} C/m along the stepped leader channel, as we shall also discuss below. Apparently, for reasons that are not clear, virgin air appears to be the preferred path to ground for the anomalous stepped leader rather than a path through the exploded triggering wire.

[19] The simple leader model described by *Uman* [1987] and *Rakov and Uman* [2003] relates the electric field change from the downward-moving leader to its causative charges. The elongating leader channel is assumed to be vertical and uniformly charged and to derive its charge from a point or spherical charge source at height *H*. The electric field change due to the elongating leader above a ground plane is given in equation (A.9) of *Uman* [1987]. The electric field due to the point or spherical charge source above a ground plane is given by equation (A.10) of *Uman* [1987]. The initial point charge source at height *H* decreases as charge is transferred from it to the vertical elongating channel below, producing a line charge density on the channel. When the leader touches ground, the product of the line charge density and the height *H* is equal to the original source charge. The total field change, the sum of *Uman's* [1987] equations (A.9) and (A.10), is given in *Uman* [1987], equation (A.11), and reproduced in equation (1)

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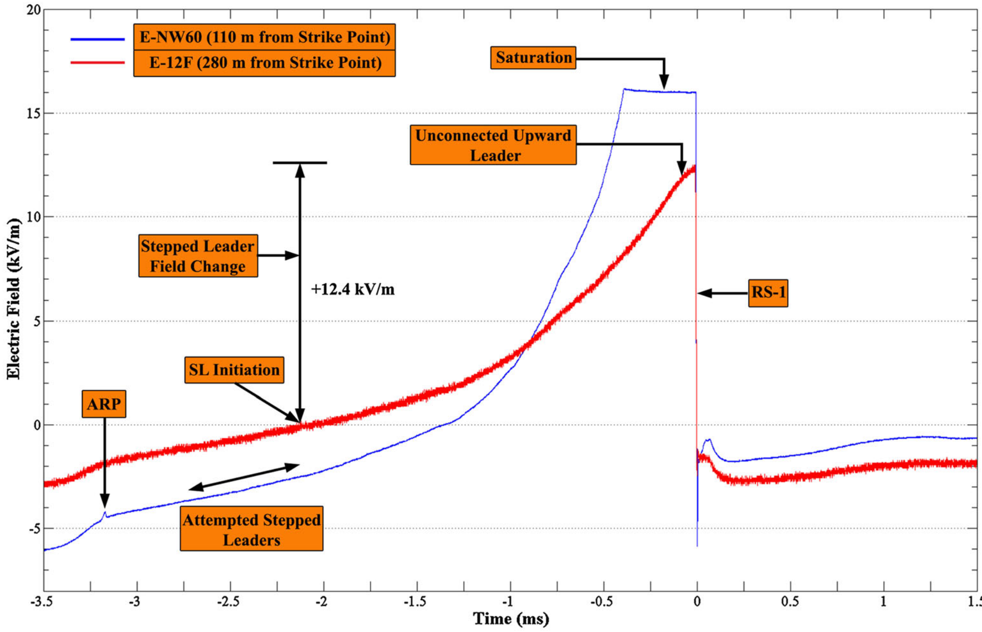

Figure 9. Electric field from two different stations during UF 12–04 (see Figure 1). E-NW60 is plotted in red, and E-12F is plotted in blue. Processes between the wire explosion and return stroke are annotated. Time in milliseconds is relative to the return stroke. Note that E-NW60 saturates. The stepped leader initiates 2.1 ms prior to the return stroke. The ARP occurs 3.1 ms prior to the return stroke (1.0 ms prior to the stepped leader). Attempted stepped leaders span approximately 600 µs prior to sustained stepped leader initiation. Time is relative to the return stroke.

with the physics sign convention at the time the leader touches ground, where $H_B = 0$

$$\Delta E = \frac{2|\rho_L|}{4\pi\epsilon_0 D}\left[1 - \frac{1}{\left(1+\frac{H^2}{D^2}\right)^{1/2}} - \frac{H^2}{D^2}\frac{1}{\left(1+\frac{H^2}{D^2}\right)^{3/2}}\right] \qquad (1)$$

[20] The measured stepped leader electric field change (see E-12F, plotted in Figure 9) is used with equation (1) to calculate the line charge density, ρ_L, of the channel, and the initial point charge source, $Q = \rho_L H$. The stepped leader channel of UF 12–04 is not vertical, but varies horizontally on the order of 100 m from the point of stepped leader initiation (see Figure 2) and has branches. Nevertheless, in the modeling, we assume that the channel is vertical. We calculate ρ_L and Q for two distances D in equation (1) that bracket the actual situation. In the first calculation, we assume there is a vertical channel at the ground strike point (117 m distant from the launching facility and 280 m from E-12F), hence D = 280 m and H = 282 m. In the second calculation, we assume there is a vertical channel above the launching facility (183 m from E-12F), hence D = 183 m and H = 282 m.

[21] The total change in electric field due to the descending stepped leader, ΔE, is found from measured E-12F to be +12.4 kV/m. In the first case with D = 280 m (distance from strike point to E-12F), we calculate a uniform charge density of 3.3×10^{-3} C/m and an initial source charge at H = 282 m of 0.93 C. In the second case with D = 183 m (distance from launching facility to E-12F), we calculate a uniform charge density of 1.7×10^{-3} C/m and an initial source charge at H = 282 m of 0.48 C. It follows that a reasonable range of ρ_L and Q for this event lies between the calculated values of 1.7 to 3.3×10^{-3} C/m and 0.48 to 0.93 C, respectively.

[22] *Hubert et al.* [1984] reported a 0.8 C median charge transfer deposited by the first return stroke of an anomalous flash from magnetic field measurements. The authors assumed the special case of a magnetostatic field produced by a vertical infinite length conductor, as given by their equation (1) and approximated the current waveform from a broadband magnetic field sensor located 191 m from the launching facility. Their 0.8 C median charge transfer value is within the 0.48 to 0.93 C range calculated above using the measured electric field, illustrating two very different techniques that resulted in the same approximate value of charge transfer for the stepped leader.

[23] Furthermore, *Schonland* [1953] found the average stepped leader charge lowered to ground per unit length in natural flashes to be on the order of 10^{-3} C/m, near our estimates for this present stepped leader. *Proctor* [1997] reported a line charge density of 10^{-3} C/m for stepped leaders that originate at altitudes between 1 and 7.4 km above sea level. *Proctor et al.* [1988] estimated the total charge deposited by 15 natural stepped leaders to have a median value of 11 C for stepped leaders with channels 3 to 13 km in length, with the charge being proportional to channel length. *Rakov and Uman* [2003] propose that a 7 km channel has a total charge of 5 C resulting in an average value of $\rho_L = 7.1\times10^{-4}$ C/m.

[24] Three major differences between anomalous rocket-triggered lightning in France/New Mexico and in Florida are now examined. First, in flash UF 12–04, there was an apparent absence of a downward dart leader from

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the cloud base to approximately the top of the wire remnants. A downward dart leader prior to initiation of a downward stepped leader was reported in all the earlier works. *Fieux et al*. [1978] report the first image of an anomalous rocket-triggered flash in their Figure 13, taken with video at 150 fps. The authors state that a downward leader traverses the existing path of the UPL/ICC channel to the top of the wire remnants. However, the wire's location is unclear in the image, and the rocket exhaust appears to travel above the field of view of the video camera, implying that the wire has also traveled above the video's field of view. *Hubert and Mouget* [1981] give two images of an anomalous rocket-triggered flash; but the top of the wire was not visible. *Hubert* [1984] gives three images of anomalous rocket-triggered flashes: In Figure 5, a downward stepped leader is associated with a rocket launch. The rocket exhaust has a vertical extent beyond the camera's field of view, but luminosity from wire remnants abruptly stops at an altitude within the field of view of the camera. There is no clear connection between the top of the wire channel in the image and the downward stepped leader. The other two images do not depict luminous wire remnants. It follows from the above that the previous literature on anomalous rocket-triggered lightning flashes does not clearly support via photography the claim of a downward leader traversing the path of the UPL. Rather, the primary evidence is the fact that there was a delay of tens of milliseconds after the wire explosion, characteristic of a normal interstroke interval that would be followed by a dart leader [*Rakov and Uman*, 2003].

[25] The second difference, related to the first, is the time duration between the cessation of current (wire explosion) and a downward leader, with UF 12–04 having about 1.3 ms before the initiation of the stepped leader at the wire top and the previous literature reporting an average on the order of 40 ms [*Fieux and Hubert*, 1976; *Fieux et al*., 1978; *Hubert and Mouget*, 1981; *Hubert*, 1984; *Hubert et al*., 1984]. Correlated dE/dt, channel-base current, and high-speed video explicitly show that UF 12–04 has a stepped leader that separates from the main lightning channel within 2 ms of an abrupt decrease in current to at or near zero. *Fieux et al*. [1978] reported electric field-mill data (their Figure 14) and current (their Figure 12), but they are not correlated in time. Their Figure 14 illustrates the only electric field data presented for an anomalous rocket-triggered flash in the literature, providing support for their reported tens of millisecond time duration between current cessation and return stroke.

[26] The final difference is our measurement of an ARP (a failed attempt to reestablish a conducting path between the bottom of the UPL channel and ground) within 100 μs after the wire explosion. In existing anomalous rocket-triggered lightning literature, no pulse with ARP characteristics is reported. *Fieux et al*. [1978], *Hubert and Mouget* [1981], and *Hubert et al*. [1984] report having current measurements with a time resolution on the order of 50–100 ns and report current measurements down to a few Amperes. ARPs measured at the ICLRT typically exhibit a 10–90% risetime of the order of 150 ns, decay to 50% times of the order of 2 to 3 μs, and peak amplitudes of about 90 A. All anomalous flashes reported in the literature occurred using 0.2 mm steel trailing wire that the authors refer to as "melting" or having a "glow", not "exploding." It is possible that the slower data sampling rate relative to ICLRT measurements and perhaps the slower disintegration of the steel wire led to the lack of apparent ARPs in the previous anomalous rocket-triggered lightning literature. Some rocket-triggered flashes at the ICLRT have exhibited an initial current variation in which the current drops to near zero without any ARPs. Thus, it is likely that previous anomalous flashes simply had no ARPs.

[27] The major differences in anomalous rocket-triggered lightning between prior experiments and UF 12–04 are described above. There are also three differences in experimental setup that could be significant in influencing the probability of an "anomalous" event. First, the grounded trailing wire attached to the rocket was 0.2 mm diameter steel for the previously reported events [e.g., *Fieux et al*., 1978] while it was 0.2 mm diameter kevlar-reinforced copper for UF 12–04. The physical characteristics of these two metals (e.g., electrical and thermal conductivity, specific heat, melting point) will play a role in the time duration of current flow through the wire necessary for wire explosion, the character of the explosion, and the characteristics of the wire remnants. It is not known how the different materials and character of the explosion will affect the potential current-zero or significant current decrease caused by the relatively high impedance of the exploding wire [e.g., *Vlastós*, 1973; *Zischank*, 1992]. Second, the experiment altitude above sea level and local topography widely vary. The studies in New Mexico and France were carried out in mountainous terrain 3200 m and 1100 m above sea level, respectively, while the ICLRT is situated on essentially flat land about 60 m above sea level on the Florida peninsula. *Hill et al.* [2012b] suggest this altitude difference may be a causative influence on the different UPL branching characteristics observed below the cloud base. Third, the climate of north-central Florida is generally more humid and warmer than those of south-central France and New Mexico. The effect of humidity on rocket-triggered lightning is poorly understood, but it may affect many aspects of the lightning discharge, including leader propagation and branching [*Hill et al*., 2012b] and perhaps the conductivity of the exploded triggering wire. Whether or not these environmental differences influence the probability of "anomalous" flashes, 13% and 31% of all rocket-triggered flashes in France and New Mexico, respectively, and less than 1% of all rocket-triggered flashes at the ICLRT (UF 12–04 is the one and only anomalous flash), is an open question.

[28] *Schoene et al*. [2008] examined lightning-induced currents in a buried loop conductor and a grounded vertical conductor for one natural and twelve rocket-triggered lightning flashes at the ICLRT. The grounded vertical conductor was 7 m long. According to *Schoene et al*. [2008], current may form in a vertical conductor through coupling of the lightning electromagnetic fields resulting in (1) induced current on the vertical conductor only or (2) current from a breakdown process at the top of the vertical conductor. In process (1), the current is confined to the system of vertical conductor and its grounding medium, while in process (2), the current also flows from the system into the ionized air above. The authors reported current waveforms of several positive-polarity current pulses with amplitudes of up to 140 A for a natural flash terminating 210 m from the vertical

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conductor, indicating that several unconnected upward leaders had initiated from the top of the vertical conductor, process (2). Flash UF 12–04 exhibited a stepped leader, like a natural flash, although it was initially triggered. The launch tubes were 4 m above ground level, and the anomalous flash terminated 117 m from the launching facility, producing a 365 A positive polarity electrical discharge at the launcher, about 2.5 times the maximum amplitude of those reported by *Schoene et al*. [2008].

[29] The Photron SA1.1 imaged one frame of the positive polarity discharge and a small portion of downward stepped leader during UF 12–04. The downward stepped leader shows a clear brightening when the positive polarity discharge occurs, although without the full stepped leader in the field of view of the camera, the relationship between the two processes is unclear. Given these observations and those described above, we infer that the discharge 17 m above the launching facility was an unconnected upward leader induced by the overhead charge in the downward stepped leader as described by process (2) above and in *Schoene et al*. [2008].

[30] *Schoene et al*. [2008], in their Figure 5, plot dE/dt and induced current (process (1) discussed above) on a grounded vertical conductor for several return strokes during a rocket-triggered flash. They conclude that a vertical conductor with grounding resistance at its base can act like a dE/dt antenna for nearby flashes. The data in Figure 8 support this conclusion: The slowly varying components of (a) are similar in waveshape to the dE/dt waveshapes in (b), (c), and (d). The return stroke-induced current (excluding the high-frequency pulse at time $t = 3.5$ µs in Figure 8) supports process (1) as described by *Schoene et al*. [2008], and lasted from $t = -1$ to 13 µs in Figure 8.

[31] The high-frequency negative polarity pulse (Pulse from Indeterminate Source) in Figure 8(a) at 3.5 µs has a 10–90% risetime of 90 ns and peak amplitude of about 200 A. There is a large dE/dt pulse that coincides with this current pulse. The dE/dt pulse associated with this current pulse is attenuated over distance faster than the return stroke dE/dt pulse, suggesting that its source is near ground level. The return stroke is outside the Photron high-speed video field of view. When the return stroke occurs, light is reflected off of the launching facility. High-speed video (3.3 µs frames at 300 kfps) reveals a very small discharge that occurs just above the top of the launching facility and lasts, at most, one frame. Given these two observations in addition to the remaining 17 m of in-tact wire, the 17 m unexploded portion of wire might have contributed to this large field change a few microseconds following the first return stroke, perhaps making the induced current in Figure 8 (a) a combination of process (1) and (2) described by *Schoene et al*. [2008]. Ultimately, the cause of the negative polarity of the large amplitude current pulse in Figure 8 is indeterminate. In Figure 8, a negative polarity pulse is indicative of downward-moving positive charge or upward-moving negative charge.

[32] Following manuscript acceptance, the authors discovered literature on seven “anomalous” rocket-triggered lightning flashes that were triggered during winter storms in Japan between 1977 and 1982 [*Horii and Ikeda*, 1985; *Horii and Sakurano*, 1985; *Kito et al.*, 1985]. Five of the seven “anomalous” flashes were triggered with mH inductor “protection devices for broadcasting” placed in series between the wire reel and earth ground and one had a “transformer” placed there. Apparently, in these tests the total grounding impedance, including the added inductive impedance, facilitated the “anomalous” behavior.

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