2012
22nd International Lightning Detection Conference
2 – 3 April • Broomfield, Colorado, USA
4th International Lightning Meteorology Conference
4 – 5 April • Broomfield, Colorado, USA

CHARACTERISTICS OF UPWARD LEADERS FROM TALL TOWERS

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1. INTRODUCTION

Although scientific literature contains observed characteristics and behavior of upward lightning (e.g., *Rakov and Uman,* 2003, Ch 6), the integration of high-speed digital cameras into continued research on the topic has allowed for new insight and comparison (e.g., *Diendorfer et al.,* 2003; *Flache et al.,* 2008; *Lu et al.,* 2009; *Mazur and Ruhnke,* 2011; *Wang and Takagi*, 2010; *Zhou et al.,* 2011; *Hussein et al.,* 2011; *Warner*, 2011, and *Warner et al.,* 2011)

In this paper, we present characteristics and behaviors of upward positive leaders (UPLs) from 10 tall towers in Rapid City, South Dakota observed using high-speed cameras and other optical sensors along with coordinated electric field instrumentation. All observations were made during the summer thunderstorm season (April – September).

2. LOCATION AND INSTRUMENTS

Upward lightning from 10 tall towers in Rapid City, SD, USA has been observed since 2004 using GPS time-stamped standard-speed videography (60 images per second, ips) and still image photography. In 2008, high-speed video capability was added resulting in optical observations up to 7,207 ips. The addition of electromagnetic sensing equipment (fast antenna and electric field meter) in 2009 allowed for coordinated observations with high-speed optical assets. By the end of 2011, high-speed optical observations were made at up to 100,000 ips.

A detailed description of this research location, optical and electric field instrumentation and the towers can be found in *Warner*, 2011, *Warner et al.,* 2011, and *Mazur et al.,* 2011. The atmospheric electricity sign convention will be used in this paper, and all reported speeds and lengths are 2-dimensional. Some of the optical assets were located at varying angles from the towers. This allowed us to evaluate UPL 3-dimensional geometry and determine which leaders were suitable for 2-dimensional speed measurements.

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3. OBSERVATIONS AND ANALYSIS

A total of 84 upward flashes have been optically observed since 2004. 46% (39/84) had upward leaders (ULs) develop from more than one tower resulting in a total of 141 optically observed ULs. 138 of the 141 optically observed ULs were recorded with cameras that had a field of view extending from the horizon to at least cloud base (2 - 4 km above ground level, AGL). In most cases, an all-sky standard-speed camera provided a view from the local horizon (including all 10 towers) overhead to the overlaying clouds. High-speed cameras operating at 1,000 ips or greater captured 55 of the 141 ULs. These high-speed cameras were typically located at an observation point optimizing the view of the northern 6 towers. From this location, Tower 1 was 7.15 km away and Tower 6 was 4.63 km away (See Figure 1). Lenses were chosen to provide a field of view from the horizon up to at least cloud base over the towers. During a few storms, high-speed cameras was positioned as close as 600 m from some of the towers.

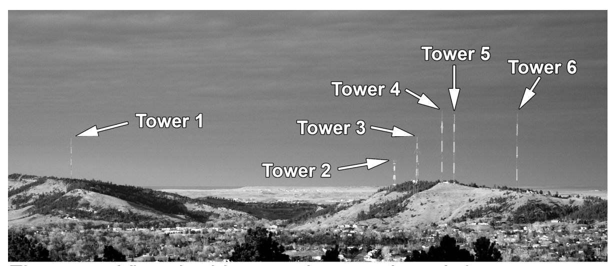


Figure 1. View looking northeast of 6 of the 10 towers located along a ridge that runs through Rapid City, SD.

The characteristics and behaviors determined from the analysis of 138 ULs are presented below. Complete quantification and statistical analysis of the observed characteristics is ongoing and will be reported in future work. This paper provides an overview.

None of the 10 towers have current sensing instrumentation, so the UL polarity classification was based on optical characteristics, electric field response and/or correlated National Lightning Detection Network (NLDN)-indicated events. 88% (121/138) of the ULs exhibited recoil leader (RL) activity, which is associated with positive leader (PL) development (e.g., *Mazur,* 2002; *Saba et al.,* 2008; *Mazur and Ruhnke,* 2011). Of the remaining 17 ULs, one had correlated negative

NLDN-indicated events at the tower location indicating an UPL (*Cummins and Murphy*, 2009). For one other UL that did not produce RLs, a positive field change indicated a developing PL. There were no positive NLDN-indicated events located at the towers, and none of the ULs recorded with high-speed cameras exhibited optical characteristics of negative polarity leaders (e.g., erratic leader tip directional change, localized branching and sustained stepping). For those flashes with correlated electric field data, all impulsive leader connections that occurred on branches or at tower tips generated positive field changes indicating UPL development. We, therefore, consider the reported characteristics and behaviors to be for UPLs.

All but one of the upward flashes had optically observed preceding nearby flash activity suggesting the UPLs were triggered (lightning-triggered upward lightning, LTUL). A comparison of high-speed optical observations with NLDN data (*Warner et al.,* 2011) and electric field records (*Warner,* 2011) supports this notion. *Warner et al.,* (2012) further suggested that the UPLs were triggered by either 1) the approach of horizontally propagating negative stepped leaders associated with either intracloud development or following a +CG return stroke or 2) a +CG return stroke as it propagated through a previously formed leader network that was near the towers. Initial analysis of upward flashes observed for the first time in Brazil utilizing both a high-speed camera (4,000 ips) and a Lightning Mapping Array appears to support these proposed triggering methods (*Saba et al.,* 2012).

3.1 Initial Development

Short duration (and length) attempted leaders occasionally preceded sustained UL development. These precursors (*Willett et al.,* 1999; *Biagi et al.,* 2009) were similar in brightness to sustained UL, but typically lasted only one image (14 µs). Sustained ULs would develop initially with weak luminosity that was sometimes below the optical threshold of the high-speed cameras. Those that did not branch shortly after initiation typically developed luminosity pulses/steps (when observed at 54,000 ips, 18 µs exposures or faster) that would originate at or near the tip of the leader, with an increased luminosity front that travelled down the leader toward the tower tip. When compared to negative leader stepping observed at the same temporal resolution, the pulsing of the PL appeared more irregular with wider luminosity variation. This pulsing would continue until the full length of the UL brightened significantly at which point the pulsing frequency would diminish and the leader would continue in a nearly continuous manner. On average, the pulsing terminated within 8 ms of UL initiation and within 600 m of the tower tip. Similar initial pulsing/stepping has been observed with UPLs in rocket-triggered lightning (e.g., Idone, 1992; Biagi et al., 2011). *Biagi et al.,* (2011) as well as *Mazur* (personal communication, 9 February 2011) suggested the transition to a more continuous development is likely due to increasing channel resistance as the leader grows longer. Irregular luminosity variations lasting either 10s of microseconds or 1s of milliseconds frequently followed this transition to a more continuous propagation. The luminosity increase associated with short duration variations initiated at the UPL tip whereas the channel luminosity along the entire UPL length appeared to increase uniformly during the longer lasting variations.

For those leaders that branched shortly after initial development (within 300 m), the branching tended to become prolific with the branched leader network luminosity remaining very low in the newly formed branches. The branch luminosity would frequently remain below detection thresholds of the faster high-speed cameras (e.g. greater than 20,000 ips). Pulsing similar to that seen with the non-branched ULs was not apparent in these cases.

3.2 Corona Brush

Non-branched leaders tended to be brighter than those that branched and frequently a corona brush was visible at the tip of a non-branched bright leader as it propagated. A similar corona brush was seen with a bright non-branched downward propagating PL associated with a +CG flash as well. The corona brush would change angle width and direction as the leader followed a tortuous path and would split prior to an unsuccessful (or successful) branch attempt. On a few occasions, a corona brush was visible at the tip of multiple bright branches for those UPLs that branched only a few times. Figure 2 shows the corona brush at three different times along an UPL's travel. Interestingly, *Berger et al.,* (1967) reported that corona brush was visible in one upward negative leader filmed with a streak camera, but not with any of the observed UPLs.

Often, when a corona brush was visible, bright and very short length leader segments that extended outward at an upward angle from the leader channel in trail of the leader tip would pulse without growing in length (See Figure 3). The shape of these short pulsing segments where descriptively similar in appearance to thorns on a rose stem. Close inspection of the location of these short pulsing leader segments showed that they formed at unsuccessful branches as indicated by corona brush splitting. On one occasion, a short-lived leader branch developed from one of these "thorns" after multiple previous pulses.

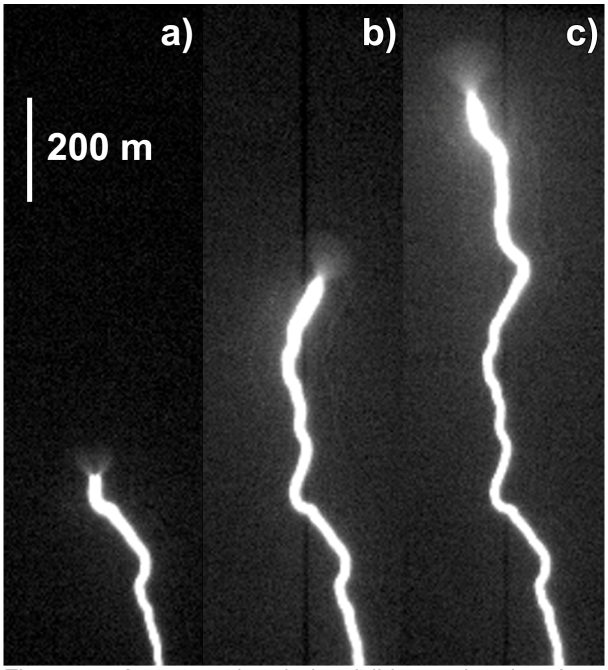


Figure 2. A corona brush is visible at the tip of an upward propagating PL. In a) the brush splits during an unsuccessful branch attempt. The brush grows in length and brightness as it propagates. The corona brush length at b) is 83 m and 121 m at c).

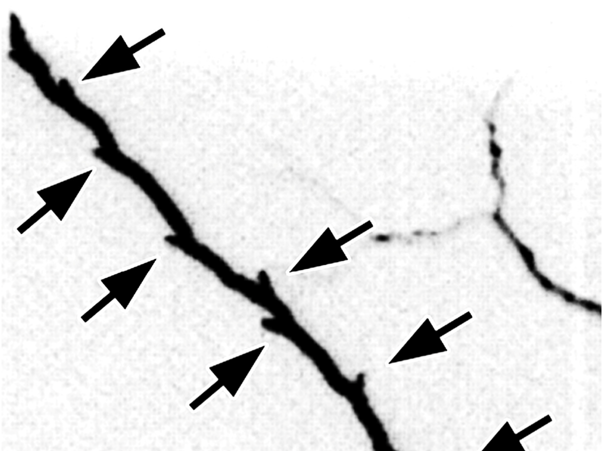


Figure 3. Time-integrated image from high-speed camera (9,000 ips, 110 µs exposure) showing short attempted leader segments that pulse repeatedly as the leader continues to grow.

3.3 Branching and Leader Geometry

Ninety-three percent (129/138) of the analyzed ULs branched with 59% (82/138) branching within 300 m of the tower tip. When branching occurred shortly after initiation, the UL tended to become widely branched with numerous weakly luminous branches. Often, one branch became dominantly brighter and branched significantly less than the weaker branches. The brightness of a dominant branch typically faded with time with a different branch becoming dominantly bright in the following time period. This transition of luminosity dominance to other branches usually continued throughout the flash. However, not all of the branches became bright over the course of the flash.

Interestingly, 57% (78/138) of the ULs transitioned to horizontal propagation just below cloud base. This region also appeared favorable for branching as 49% (68/138) of the ULs exhibited further (and sometimes intensified) branching coincident with or immediately following the transition to horizontal propagation. In fact, 16 out of the 129 branched leaders did not start branching until approaching cloud base and the branches then propagated horizontally (See Figure 4).

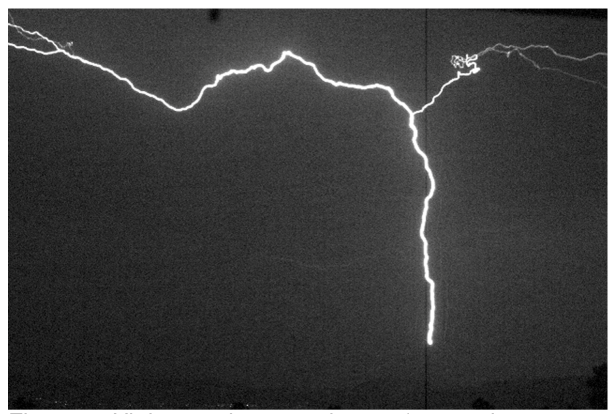


Figure 4. High-speed camera image (10,000 ips, 100 µs exposure) showing an UPL with horizontal branches just below cloud base.

When a bright leader channel branched, the two new leader segments would each exhibit luminosity pulsing/stepping similar to that seen during initial development. However, the pulse brightening would alternate between the two new branches. One of the new branch segments would brightening via a luminosity pulse that originated at or near the tip of the leader branch. As the pulse luminosity decayed, the other branch would develop a similar pulse, which would then decay before the first branch would again produce another pulse. As the leader branches grew, the pulsing frequency would diminish and the apparent interdependence between the two branches would also decrease. The branches would then continue to develop independently in a near continuous fashion.

We have observed alternating stepping between newly formed downward negative leader branches as well, but negative leaders did not transition to a more continuous development like the PLs.

During two upward flashes, new bipolar/bidirectional leaders formed near a UPL that had transitioned to horizontal propagation just below cloud base. The negative end of the new leader clearly stepped and branched while the positive end did not branch and exhibited a more continuous propagation. In both cases, the new leader's negative end connected with the established UPL forming a new branch well behind the UPL's tip. Fast electric field measurements from both cases showed a sharp positive field change coincident with the connections (see Figure 5).

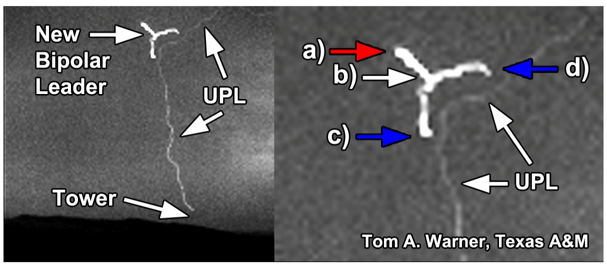


Figure 5. Shows a bipolar/bidirectional leader that initiated near an established UPL. The new leader positive end at a) propagated continuously away from the initiation point shown at b). The negative end stepped and branched forming the two branches seen at c) and d). The negative branch at c) connected with the UPL and formed a new PL branch, which continued to propagate for the remainder of the flash.

3.4 ***Recoil Leaders***

Recoil leaders (RLs) developed on weakly luminous PL branches that became cutoff from the main upward channel from which they branched (*Mazur,* 2002; *Saba et al.,* 2008; and *Mazur and Ruhnke*, 2011). Initially, a weakly luminous branch would grow from the branch point with luminosity visible from the branch point to the growing branch tip. As the branch extended further, the luminosity beginning from the branch point outward would fade below the camera-sensing threshold even though the growing tip was still visible. A bright bidirectional leader (recoil leader) would initiate at a point that lagged behind the tip of the advancing PL branch. The RL would expand bidirectionally with the negative end propagating toward the branch point and the positive end toward the branch tip. Most of the time, the RL would decay before the positive end reached the branch tip or the negative end reached the branch point. For those that did not fade, the recoil leader positive end (RLPE) would typically reach the tip of the leader branch before the recoil leader negative end (RLNE) reached the branch point. The RLPE arrival at the PL tip many times caused the illumination of a short, forked leader segments that would then decay within 10s of microseconds following the RLPE arrival. It is unclear if this forked segment was already formed and illuminated by the RLPE or a new forked segment formed due to (and therefore following) the arrival of the RLPE.

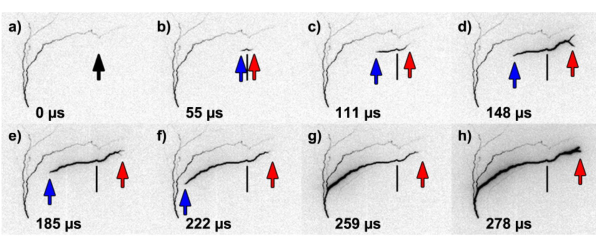
When the RLNE connected with a bright main luminous channel at the branch point, the branch luminosity would rapidly increase from the branch point outward toward the branch tip. When the luminosity front reached the branch tip, the forked tip would rebrighten, and frequently additional forks or short branches near the branch tip would illuminate within 250 µs following the front's arrival.

The behavior of the main channel stem (branch point to tower tip) following the RLNE arrival at the branch point varied. At recording speeds up to 67,000 ips (14 µs exposure), a RLNE connection at the branch point appeared to cause a bright main channel to brighten evenly along the entire segment no matter how high the connection. However, the luminosity increase rate (rise time) for the main channel was slower with higher connections. Furthermore, the brightness in the reconnected branch would rise faster and to a higher value than the main channel stem, and the stem would peak at a lower brightness value after the reconnected branch's luminosity began to decay. In some cases, the brightness increase in the stem was negligible, even when the reconnecting branch experienced a very bright pulse that far exceeded the main channel's luminosity.

As the brightness of the main channel decreased during the course of the flash, there was a point at which the connection of a RLNE at the branch point would fail to produce a luminosity increase. Instead, the RLNE would travel from the branch point down toward the tower tip along the weaker, but still luminous main channel. The RLNE luminosity front would lengthen and travel faster on the more conductive main channel, and a bright luminosity increase would occur when the front reached the tower tip. The luminosity increase would travel back up the path traversed by the RL This process was similar to a dart leader/return stroke sequence except that the main channel was still luminous and therefore current was not completely cutoff. *McEachron* (1936) described a similar observation after filming upward lightning from the Empire State Building using Boys cameras. In all our observed cases, the luminous main channel segment from the branch point upward (i.e., the main leader segment above the branch point and not part of the cutoff branch) did not brighten and appeared to not participate in nor be affected by the connections.

Frequently, the reilluminated/reconnected branch would quickly lose its luminosity following a RL connection, and additional RL connections would occur along the same branch in a repeating cycle. The repeated RL connections gave the appearance that the branch was unstable and that the RL connections were trying to establish stable leader growth. On a few occasions, a leader branch would remain luminous following a connection and would then grow continuously without additional RLs forming.

Figure 6 shows the initiation and development of a RL that formed along a cutoff PL branch as captured by a high-speed camera (54,001 ips, 18 µs exposure). The RL developed bidirectionally and the RLNE connected with the main luminous channel causing a brightness increase from the branch point out the PL branch upon which the RL formed. The luminous main channel stem (between the branch point and tower tip) brightened more slowly and reached a lower peak luminosity value than the branch. *Mazur et al.,* [2011] conducted an analysis of this RL connection using correlated high-speed optical and electromagnetic field data and concluded that the polarity of the UL was positive and that a negative field change occurred as the RLNE propagated down the decayed PL branch towards the main luminous channel. The resulting positive field change that correlated with the RLNE connection with the main luminous positive channel supported the notion that the RL successfully reestablished (reionized) the PL branch that had become cutoff from the main channel. This connection would, therefore, result in a current pulse exceeding the slowly varying current resulting from the developing UL (e.g. *Flache et al.,* 2008; *Diendorfer et al.,* 2009). If the impulsive electric field change resulting from these connections exceeds the NLDN's sensing threshold, a negative polarity event (-CG or -IC) would be recorded. This was in fact the case for those connections exhibiting the brightest pulse luminosity as seen by the high-speed cameras (*Warner et al.,* 2011).



Texas A&M, Tom A. Warner / 54,001 ips / 18 µs exposure

Figure 6. High-speed camera image sequence (54,001 ips, 18 µs exposure) showing the bidirectional development of a RL. a) Black arrow shows the initiation point. b) RL develops bidirectionally with red arrow indicating the RLPE and the blue arrow indicating the RLNE. Black line remains at the initiation point. d) RLPE reaches the PL branch tip and illuminates short forked segment. g) The RLNE reaches the branch point on the main channel and the branch brightens toward the branch tip. Main channel stem between the branch point and tower tip begins brightening. h) Luminosity increase reaches the positive branch tip and branch extends with new forks visible.

Frequently, the RLs faded prior to connecting. On a few occasions, however, the RL faded prior to the RLNE reaching the branch point, but after a delay of a few 100s of mircoseconds, a brightly luminosity leader emerged from the branch point and propagated outward along the decayed branch path. It is unclear if this was a delayed connection by the RLNE that was still propagating but below the detection threshold of the high-speed camera or if the emerging leader from the branch point was induced (triggered) by the approaching RLNE. In one case, the RL faded nearly completely, except for a barely visible pulsing/stepping tip associated with the RLNE. This periodically visible tip eventually connected with the main channel at the branch point and produced a bright luminosity increase that travelled back out to the branch tip. The RLNE initially propagated at 40.0 x 10^5 m/s for 55 µs and then decelerated to 5.3 x 10^5 m/s in the following 56 µs. The speed then varied between 2.6 x 10^5 m/s and 8.3 x 10^5 (average 5.2 x 10^5 m/s) for 1.629 ms before accelerating from 5.6 x 10^5 m/s to 15.2 x 10^5 m/s in the 19 µs before connecting at the branch point. These apparent delayed (or induced) connections also occurred when the RLNE traveled past the branch point and toward the tower tip. For one case, the RLNE approached the tower tip with an average speed of 4.72 x 10^6 m/s. The RLNE faded and was no longer visible at 212 m above the tower tip. After a 462 µs delay, an upward propagating leader from the tower tip became visible. If the RLNE (with a luminosity below the high-speed camera's detection level) continued toward and connected with the tower tip, it would have required an average propagation speed of 4.59 x 10^5 m/s. This speed is only 12% less than the measured speed for a barely visible RLNE discussed earlier. We, therefore, suspect these cases represent delayed connections by weakened and therefore slowed RLNEs rather than induced leaders.

If a weak PL branch branched further before it became cutoff from a main channel, a RL would initiate above the multiple branches that had since decayed. As the RLNE traveled toward the original branch point along the main channel, it would pass by other decayed branch points. Quite often, the RLNE would travel out the decayed branch paths instead of continuing toward the main channel branch point forming a luminous "V" or "check mark" pattern (See Figure 7). When this occurred, the RL usually faded shortly after. On a few occasions, the RLNE would begin stepping as it traveled further out the secondary branch before fading. It is unclear why the RLNE would travel out the secondary branch instead of continuing toward the main channel. Possibly the conductivity was greater along the secondary branch path.

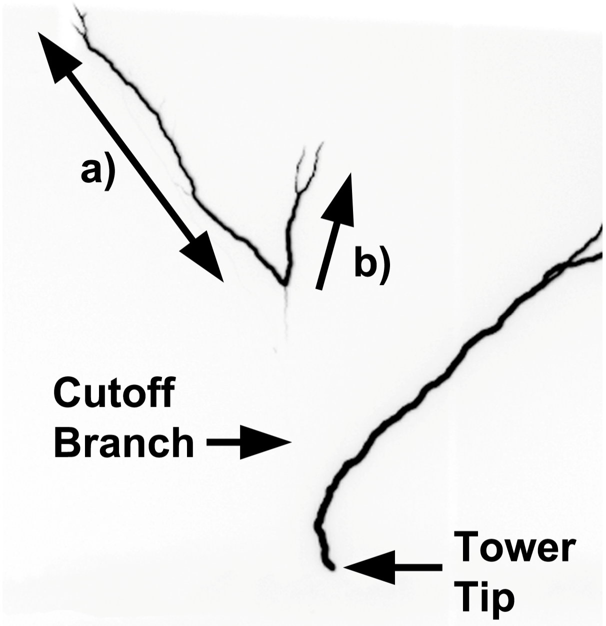


Figure 7. High-speed camera image (9,000 ips, 110 µs exposure) showing the development of a RL on an UPL cutoff branch. a) The RL initially grew bidirectionally. b) Upon reaching a decayed branch point, the RLNE traveled out the decayed branch forming a “check mark” pattern. Weak luminosity did extend a short distance down from the decayed branch point. The RL faded in the images that followed.

In cases where the RLNE did not deviate out a secondary branch path and made a successful connection with the main luminous channel, the secondary cutoff branches sometimes developed RLs during the period the primary branch was illuminated by the connection. The RLs on the secondary branches appeared to be initiated by the change in electric potential along the primary branch path due to the first RL connection. The negative end of the secondary RLs would frequently connect with the primary branch while the luminosity following the first RL connection was ongoing. These secondary connections rebrightened the leader segment between the secondary branch point and the tower tip causing additional fluctuations/pulses in the channel base luminosity following that generated by the first RL connection. Figure 8 shows the channel base brightness measured just above the tower tip for a RL connection in which a second RL formed on a secondary cutoff branch. The high-speed camera captured both the primary and secondary RL development. These “multi-pulse” connections were very common with the number of pulses per connection increasing with increasing flash elapsed time. This seems reasonable given the increasing number of branches that likely form as the UL grows. The secondary peaks followed within 1 ms of the primary peaks.

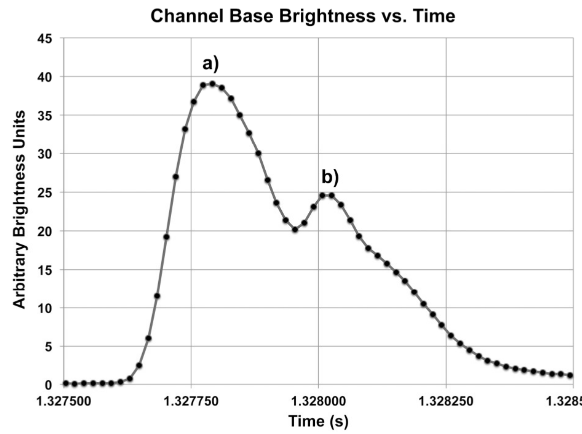


Figure 8. A plot of Channel Base Brightness vs. Time as measured just above the tower tip. a) shows the peak brightness from the first recoil connection. b) shows the subsequent peak from a second RL connection along a secondary cutoff branch. High-speed recording was made at 54,001 ips, 18 µs exposure.

On two occasions, a RLNE deviated off the previously formed (and now decayed) branch path as it propagated toward a main channel branch point. In both cases, the leader began stepping as seen with negative leader development in virgin air. In one case, the stepping RLNE connected with the PL at a point different than the original branch point. In the other case, the stepped RLNE eventually faded without making a connection.

RL development seemed proportional to the amount of branching. Weakly luminous PLs branched much more than bright PLs, and RLs formed on the weakly luminous branches that became cutoff from their branch point. Therefore, widely branched ULs usually produced numerous RLs. In some cases, numerous weak branches were not initially seen by the faster high-speed cameras, however, the subsequent and prolific development of bright RLs along the cutoff branch paths clearly showed where the branches had formed (see Figure 9).

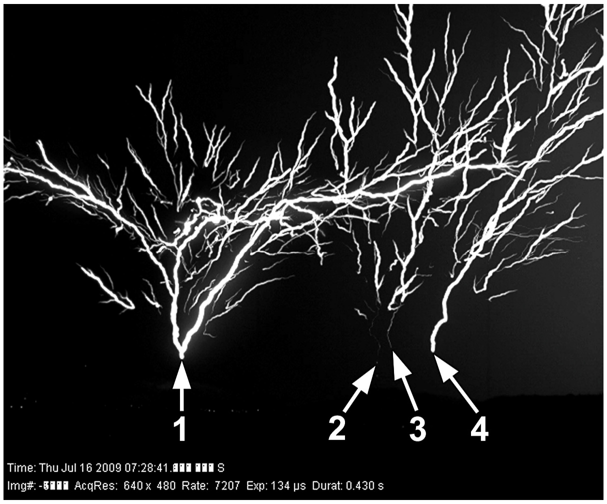


Figure 9. Time-integrated video segment from a high-speed camera (7.207 ips, 134 exposure) showing the prolific development of bright RLs on the weakly luminous branches of four UPLs. Many of the RLs faded prior to connecting to the main stem.

It is important to note, that RLs formed well before the UPLs reached cloud base. The minimum time between UPL initiation and the first observed RL was 6.2 ms with the average time 22.8 ms. The minimum height above tower tip elevation for the first RL was 155 m with an average of 539 m. The connection behavior visible below cloud remained unchanged for those UPLs that entered the cloud.

For those RLs favorable for 2-dimensional speed measurements, the minimum, maximum and average RLNE propagation speed was 3.82×10^4 m/s, 1.89×10^7 m/s and 4.53×10^6 m/s respectively. For two cases, RLPE propagation speed could be measured and the minimum, maximum and average speed was 7.85×10^5 m/s, 1.08×10^7 m/s and 3.75×10^6 m/s respectively. The relatively short distance typically travelled by RLPEs limited the number of measureable cases.

3.5 *Leader Behavior*

The individual branches of branched ULs exhibited a spectrum of leader growth behavior. During one upward flash that had two primary branches, one branch developed continuously and brightly with little additional branching (stable leader growth), whereas the other branch developed in a non-continuous manner (unstable leader growth) that included a series of strong RL connections some of which registered as –CG strokes by the NLDN. The bright stable leader branch grew significantly faster (average speed 9.39×10^4 m/s) than the RL-producing unstable branch (average speed 2.81×10^4 m/s). Additionally, the stable leader branch exhibited bright irregular luminosity variations along its entire length as it approached cloud base and transitioned to horizontal propagation. These luminosity variations were likely induced as the leader propagating through areas of varying ambient potential *(Mazur and Ruhnke,* 2011*)*. During the variations, which each lasted 1s of milliseconds, the entire leader, including the branch tip, was still visible and there were no impulsive branch connections along its length. These luminosity variations were observed during other upward flashes as the leaders developed below cloud base.

Typically, the behavior and geometry of all the ULs that occurred during the same storm were similar. If the first upward flash had an UL that did not branch until approaching cloud base, ULs from following flashes usually did not branch until cloud base as well. Figure 10 shows a composite image of three upward flashes that occurred within a 12-minute period. A single UPL developed from Tower 1 in each case, and all grew vertically without branching before transitioning to horizontal propagation below cloud base.

Figure 10. A composite image of three upward flashes photographed with a digital still camera (20 sec exposure). All three non-branched UPLs initiated from Tower 1 and transitioned to horizontal propagation below cloud base.

Incremental propagation speeds were measured for 18 UPLs. The minimum, maximum and average speed was 1.76×10^4 m/s, 5.97×10^5 m/s and 1.05×10^5 m/s respectively. 12 UPLs were bright enough to measure speeds from within 300 m of the tower tip to cloud base. The average initial speed for these cases was 5.48×10^4 m/s and the average speed at cloud base was 1.39×10^5 m/s.

3.6 *Multiple Upward Leader Flashes*

A multiple upward leader (MUL) flash is defined as an upward flash in which an UL develops from more than one tall object. The 10 towers in Rapid City provide a unique opportunity to observe these types of flashes. 46% (39) of the 84 upward flashes involved more than one tower with a maximum of seven ULs initiated during one flash.

For those MUL flashes observed with high-speed cameras, the longest delay between the first and last UL initiation was 10.2 ms. For this particular case, two ULs developed when horizontally propagating negative stepped leaders approached the towers following an NLDN-indicated +51.9 kA estimated peak current +CG return stroke 29 km away. High-speed cameras captured both the +CG return stroke and negative leader development that followed. The first tower to initiate the UL was 2.6 km closer to the approaching negative leaders. Both ULs were widely branched and produced RLs suggesting they were both positive. Interestingly, the speed required to travel 2.6 km in 10.2 ms is 2.55×10^5 m/s, which is a typical speed for negative stepped leaders (*Saba et al.,* 2008; *Rakov and Uman,* 2003). The behavior and geometry of all the ULs within a MUL flash was usually similar, however, the individual leader brightness and duration varied. If one of the ULs developed RLs, the others typically did as well. The optical observations suggest that all the towers involved in MUL flashes in Rapid City were influenced by the same triggering component, and therefore, develop MULs of the same polarity (i.e., positive). This was evident in the case examined in detail by *Warner,* (2011).

4. DISCUSSION

The wide field of view used with some of the high-speed cameras (up to 10.5 km vertical and 14 km horizontal in some cases), along with the high cloud bases common in the northern United States High Plains, allowed visualization of large portions of single and MUL networks. The coordinated assets provided for the observation and characterization of MUL development, leader propagation and branching, leader luminosity variations and impulsive connections. Although analysis of these data is ongoing, some of the observed behavior raise questions that should be addressed in future research.

Why is there a tendency for some UPLs to propagate horizontally just below cloud base? Is there a negative charge screening layer at cloud base that acts as a negative potential well (*Coleman et al.,* 2003; 2008) for horizontal PL propagation? Is negatively charged precipitation falling below cloud creating a potential well? The region that was favorable for horizontal propagation also appeared favorable for branching as well as new bipolar leader development. We have observed new bipolar leader development near horizontally propagating PLs just below cloud base during intracloud flashes and +CG flashes as well.

Why do a large majority of UPLs branch, and what conditions preclude branching? Multiple upward flashes that occurred during the same storm usually exhibited similar geometry and branching behavior. Does a certain charge distribution, triggering component or mechanism lend itself to this coherent behavior?

RLs frequently developed on highly branched UPLs. Is branching a necessary requirement for RL development? Can a RL form on a non-branched leader that decays and becomes cutoff from the tower tip? We have observed numerous downward propagating negative leaders and none have appeared to develop RLs. When negative leader branches decayed, redevelopment initiated at the branch point along the main luminous channel with a bright fast continuously propagating leader traveling toward the decayed branch tip. The continuously propagating leader would then begin stepping when it reached the end of the decayed branch. This behavior was clearly different than that observed with PLs.

There seemed to be a main channel luminosity threshold below which a RLNE would continue to the tower tip before initiating a luminosity increase that traveled back up the channel. Although this process resembled a dart leader/return stroke sequence, in these cases the main channel was still weakly luminous and therefore the current was not completely cutoff. What is this corresponding current threshold for this behavior and does it depend solely on the level of current in the main channel or does it also depend on the potential of the RLNE? This behavior was also seen with downward –CG flashes (*Saba et al.,* 2010).

A comparison between channel base brightness variation and leader behavior for 7 upward flashes showed that short duration (20 µs or less) luminosity pulses preceding and during the initial slow rise in luminosity were due to initial leader stepping. As the leader brightened and transitioned to a more continuous propagation, irregular luminosity pulses lasting 10s of microseconds occurred and were caused by luminosity increases originating at the leader tip. Slower luminosity variations lasting 1s of milliseconds, which did not initiate at the leader tip, appeared to be induced throughout the leader's length by varying ambient potential along the leader's path. Bright luminosity pulses with rise times in the 10s to 100s of microseconds (minimum high-speed camera exposure was 10 µs) were associated with RL connections, and connections made higher up a brightly luminous main channel tended to produce slower rise times in the channel base luminosity.

5. CONCLUSION

We have reported on UPL characteristics and behaviors from multiple towers in the northern High Plains of the United States. The ULs were initiated during electrically active summertime thunderstorms and triggered by nearby preceding flash activity. The optical assets wide fields of view and high cloud bases allowed observation of MULs and entire leader networks visible below cloud base. The use of high-speed cameras operating at up to 100,000 ips resulted in the sequential, time-resolved imagery of upward propagating leader channels and branches, RL and nearby new leader initiation, bipolar development and connection with main channels. The analysis of these observations helps quantify upward lightning behavior as well as suggest topics for further investigation.

6. ACKNOWLEDGEMENTS

We wish to acknowledge Vlad Mazur and Lothar Ruhnke for the use and analysis of their electric field data, and Vaisala, Inc. for providing the NLDN data. The first author would like to thank Mike Bickett for his help with the optical asset platforms. We also thank Christopher Redmond for help with photogrammetry. This study is part of a lightning program funded by the National Science Foundation (ATM - 0813672), and we thank Bradley F. Smull for his interest and support.

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