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

LIGHTNING-TRIGGERED UPWARD LIGHTNING FROM TOWERS IN RAPID CITY, SOUTH DAKOTA

Tom A. Warner[1*], Marcelo M. F. Saba[2], Scott Rudge[3], Matthew Bunkers[3], Walt Lyons[4], and Richard E. Orville[5]

1. Dept. of Atmospheric and Environmental Sciences, South Dakota School of Mines and Technology, Rapid City, SD, USA
2. National Institute for Space Research – INPE – Sao Jose dos Campos, Brazil
3. NOAA /National Weather Service, Rapid City, SD, USA
4. FMA Research, Inc., Fort Collins, CO, USA
5. Dept. of Atmospheric Sciences, Texas A&M University, College Station, Texas, USA

1. INTRODUCTION

Recent research efforts have shown that nearby flashes can trigger upward lightning from tall towers (e.g., *Wang and Takagi,* 2010; *Mazur and Ruhnke*, 2011; *Warner,* 2011, *Warner et al.,* 2011, and *Zhou et al.,* 2011). Findings from these studies suggest that these lightning-triggered upward lightning (LTUL) flashes are more common with summer thunderstorms, whereas self-initiated upward lightning (SIUL) flashes, where an upward leader initiates from a tall object without nearby preceding flash activity, favor less electrically active winter storms. For LTUL, a preceding positive cloud-to-ground (+CG) flash appears to be the dominant triggering flash type resulting in upward positive leaders (UPLs). However, the specific triggering flash component and mechanism has yet to be fully quantified. In this paper, we characterize the triggering flash types, components, and mechanisms responsible for LTUL during summer thunderstorms in Rapid City, South Dakota. We also characterize favorable storm types and regions.

2. LOCATION AND INSTRUMENTATION

Rapid City, South Dakota is located in the northern High Plains of the United States. A variety of storm types (e.g., singlecell, multicell clusters, supercells, squall lines, mesoscale convective systems, etc.) occur during the summer storm season, which lasts from April through September. Compared to the southern Plains, which are closer to the Gulf of Mexico, the northern High Plains experience a drier summer climate with dewpoints typically between 10-15ºC. As a result, cloud base heights during storms normally range between 2–4 km above ground level (AGL). A detailed description of this research location is found in *Warner et al.,* 2011.

Since 2004, 84 upward flashes from 10 towers (91–191 m AGL) have been observed using optical instrumentation. High-speed cameras were added in 2008 along with electric field sensing instrumentation in 2009, which allowed for coordinated measurements for some flashes. An analysis has shown that preceding visible flash activity triggered all but one upward flash.

The upward flashes discussed below were observed with up to three high-speed cameras operating between 1,000 and 67,000 images per second (ips). Fast electric field change data were collected using a modified whip antenna at a sensor site 1.2 km northwest of Tower 1 (*Mazur et al.,* 2011). The fast electric field antenna had a 10 µs time constant and the sample interval was also 10 µs (100,000 samples/s). All the instruments used GPS timing. Figure 1 shows 6 of the 10 towers as seen from a primary viewing location.

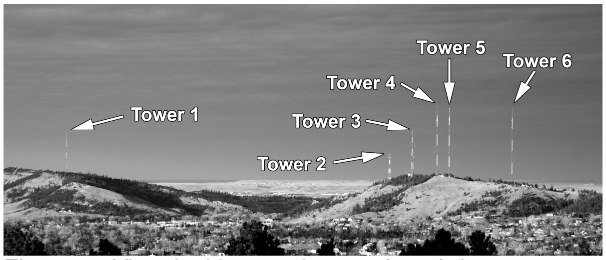

Figure 1. View looking northeast of 6 of the 10 towers located along a ridge that runs through Rapid City, SD.

3. OBSERVATIONS AND ANALYSIS

The following analysis will focus on three upward flashes that occurred on 17 June 2010 UTC. The first two analyzed upward flashes were the last two of eight occurring between 01:08:49 – 01:37:03 UTC. All eight were associated with a decaying multicellular storm cluster that moved northeast over the towers. The third analyzed upward flash was the first of two accompanying a cluster of strong multicellular storms that also moved northeast over Rapid City about 6.5 hours later.

---

*Tom A. Warner, South Dakota School of Mines and Technology, Dept. of Atmospheric and Environmental Sciences, Rapid City, SD 57702, tom.warner@ztresearch.com

3.1 *Flash 1, 01:30:48 UTC*

A single, highly branched upward leader (UL) formed from Tower 4 at 01:30:48.831 UTC, 63 ms after a +CG return stroke (RS) occurred 25.2 km north of the tower. The National Lightning Detection Network (NLDN, *Cummins and Murphy,* 2009) recorded an associated +62.9 kA estimated peak current +CG RS at 01:30:48.768 UTC. A high-speed camera operating at 1,000 ips (Phantom Miro 4, 997.5 µs exposure) recorded both the RS and UL. Two other high-speed cameras with narrower fields of view recording at 9,000 and 67,000 ips (110 µs and 14 µs respectively) captured the UL only. The UL exhibited extensive recoil leader (RL) activity suggesting it was positive polarity (*Mazur,* 2002 and *Saba et al.,* 2008) and lasted 748 ms without any subsequent dart leader/RS sequences following current cutoff. There were 3 –CG strokes recorded by the NLDN that were each associated with the connection of the negative end of a recoil leader with the main luminous positive channel prior to UL current cutoff (e.g., *Mazur and Ruhnke,* 2011; *Mazur et al.,* 2011). The three NLDN-indicated stroke locations were within 360 m of Tower 4.

Figure 2 shows the total electric field change (atmospheric electricity sign convention) as integrated from the fast antenna data. The time (decay) constant of the fast antenna was 10 µs as was the sample interval, and the integration procedure removed any change caused by the decay constant. Starting from a zero value, the electric field decreased to approximately -6 kV/m during the leader development that preceded the +CG RS. The rapid negative field change from the RS decreased the total electric field change to -13 kV/m. Following the saturating brightness from the RS, negative leaders (NLs) were visible just below cloud base propagating toward the tower (between 48.778–48.814 s). Figure 3 shows a visible NL propagating toward the tower. This was followed by in-cloud brightening overhead the towers from 48.820–48.831 s. The electric field continued to decrease during this period and at 48.831 s, an UPL developed from Tower 4. As the leader grew, the total electric field change leveled and reversed direction due to the increasing influence of the developing UPL. Small magnitude, abrupt positive steps in the total electric field are visible starting at 48.955 s and these correspond to RL connections with the main luminous UPL channel (*Mazur et al.,* 2011).

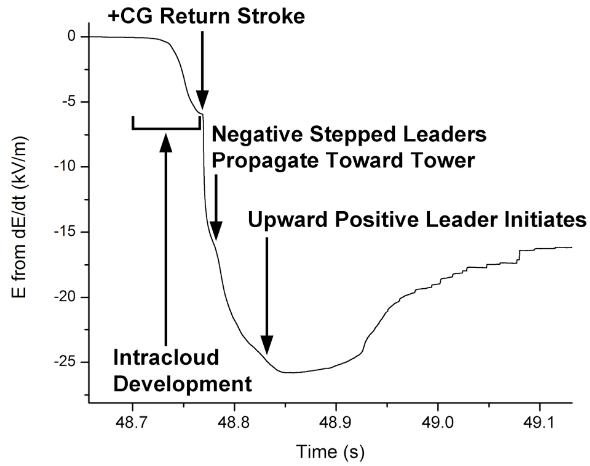

Figure 2. Total electric field change as integrated from the fast antenna data for Flash 1 (17 June 2010, 01:30:48 UTC).

Figure 4 shows the radar reflectivity from the KUDX WSR-88D weather radar located 34 km east of the towers. Data is from the 1.3º tilt volume scan beginning at 01:28:20 UTC. A north-south oriented cluster of strong multicellular storms approached Rapid City from the southwest, and the segment that passed over the towers had weakened significantly. There was a broad area of weak reflectivity (20-30 dBZ) that stretched north-south over the towers in between two stronger cells. The preceding +CG stroke at 48.768 s (shown as a solid white circle) was located in the stronger reflectivity (>50 dBZ) of the northern cell. There was an NLDN-indicated +IC event recorded about 1 km north of the +CG location at 48.784 s, 16 ms after the RS. This event, which took place while NLs where seen propagating toward the towers, was associated with an in-cloud brightness pulse observed by the Miro 4 close to the RS location.

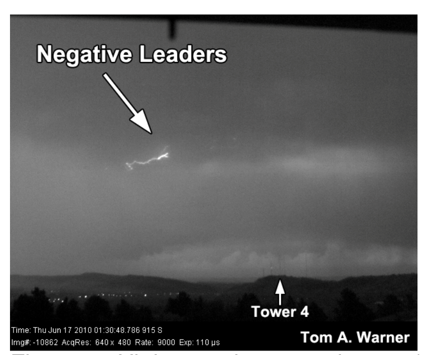

Figure 3. High-speed camera image (9,000 ips, 110 µs exposure) showing a NL propagating toward the towers following a +CG RS.

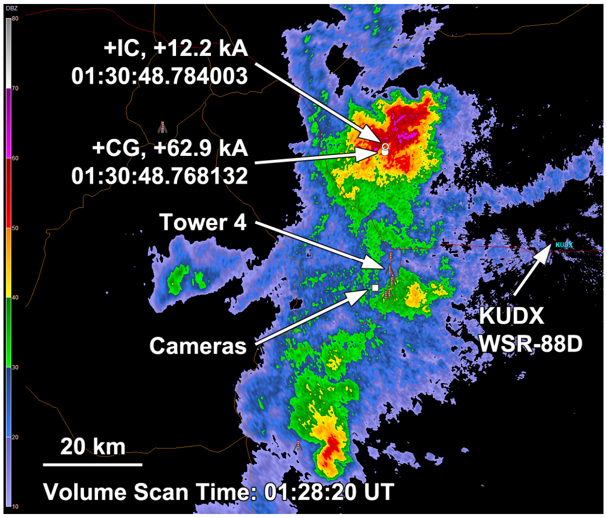

Figure 4. KUDX WSR-88D weather radar reflectivity from the 17 June 2010, 01:28:20 UTC volume scan (1.3º tilt).

3.2 *Flash 2, 01:37:03 UTC*

The second upward flash also followed a +CG flash. In this case, however, UPLs developed from seven towers instead of one, and initiation immediately followed the second of two spatially separated +CG RSs.

At 01:37:03.120 UTC, a single high-speed camera (Phantom v310, 9,000 ips, 110 µs exposure) observed a +CG RS that was correlated with an NLDN-indicated +29.4 kA estimated peak current +CG stroke located 32.5 km north-northeast of Tower 1. Following the RS, there was periodic in-cloud brightening and the RS channel luminosity remained visible for 103 ms. In-cloud flash activity continued after the RS channel was no longer observed by the v310. Three in-cloud brightness pulses were visible between 3.480–3.545 s near the RS location, and a NL was briefly visible just below cloud base following the last pulse at 3.541 s (421 ms after the RS). This leader briefly propagated southwest toward the towers following the pulse. Weak, periodic in-cloud brightness fluctuations continued until 3.719 s, after which pulsing in-cloud brightening, characteristic of NLs observed at 9,000 ips, propagated from the north-northeast toward the towers. The leader development passed just east of the northern towers based on an all-sky, standard-speed camera positioned 0.6 km south of Tower 6.

At 3.796 s (676 ms after the RS) the v310 observed a RL just below cloud base north-northeast of the towers and along the path traversed by the apparent NLs. Additional RLs formed in the same area and a downward propagating positive leader (PL) became visible at 3.806 s. A second PL propagated below cloud base 13 ms later to the right (southeast based on an all-sky camera) of the first. The second PL only branched twice and grew much brighter than the first. It also did not exhibit any RL activity, which is characteristic of bright PLs. Unlike the first PL, the second propagated nearly horizontal just below cloud base. Figure 5 shows an image from the v310 at 3.861 s, 1.3 ms prior to the second RS. The two PLs are beyond (north-northeast) the towers.

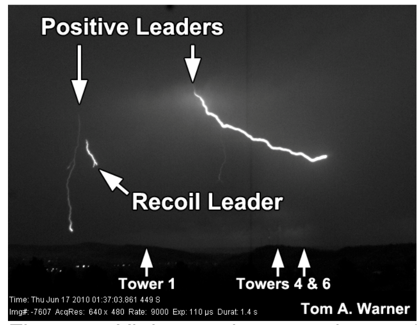

Figure 5. High-speed camera image (9,000 ips, 110 µs exposure) showing two downward propagating PLs. A RL is visible near the left PL.

The first PL grew brighter and accelerated as it approached the ground while its weak branches continued to cutoff and produce RLs (e.g., *Saba et al.,* 2008). The first PL connected with ground at 3.863 s (743 ms after the first RS), and the NLDN recorded an associated +96.0 kA estimated peak current, +CG stroke 6.54 km north-northeast of Tower 1. As the RS's saturating brightness subsided, already developing ULs were visible (less than one ms after the RS). ULs appeared to initiate nearly simultaneously from Towers 1,3,4,6,7,8, and 10 all within 3 ms of the RS. However, due to the RS's saturating brightness, it was impossible to determine the exact initiation times for the individual ULs.

The Miro4 (1,000 ips, 997.5 µs exposure) had a wide field of view that encompassed Towers 1-8. All the ULs exhibited RL activity suggesting that they were positive polarity. A portion of the UL from Tower 10 came into the Miro4's field of view as well, and it too produced RLs.

Figure 6 shows the total electric field change as integrated from the fast antenna (dE/dt) data. The integration began at 3.100 s and there was a slight negative field change (-0.5 kV/m) prior to the approach of the NLs that followed the first +CG RS. The time in Figure 6 starts at 3.620 s in order to focus on the details preceding UL initiation. At 3.680 s, the field began a shallow negative change, which steepened approximately 300 ms later corresponding to the approaching visible NLs and pulsing in-cloud brightening seen by the high-speed cameras. The total field change leveled at -7.5 kV/m and then rose slightly coincident with the development of downward propagating PLs. The RS resulted in a sharp negative field change to a value near -17.5 kV/m at which point the UPLs initiated. The total electric field change continued a downward trend to -24.7 kV/m by 3.888 ms before reversing direction and starting a sustained positive change due to the developing UPLs.

Figure 7 shows the UPLs that developed from Towers 1, 4, and 6 along with the +CG RS channel. Tower 3 also initiated a weakly luminous UL, but it had decayed by this point. The second PL that developed below cloud base prior to the RS is still visible beyond the ULs from Towers 4 and 6. This leader's luminosity weakened significantly coincident with the +CG RS; however, it reilluminated 12 ms later and continued to propagate horizontally for the remainder of the flash.

Based on high-speed observations of Towers 1-8, the longest UL lasted 439 ms (Tower 7). The NLDN recorded 4 -IC events at Tower 1 and one –CG at Tower 8. These events were associated with impulsive RL connections prior to current cutoff, and the NLDN locations were within 480 m of the respective towers.

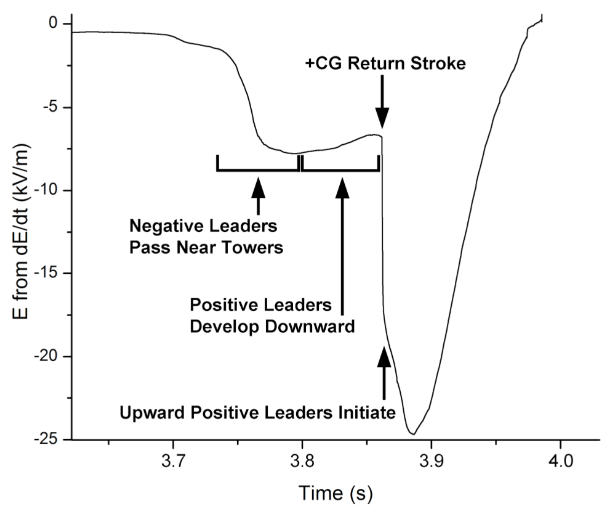

Figure 6. Total electric field change as integrated from the fast antenna data for Flash 2 (17 June 2010, 01:37:03 UTC).

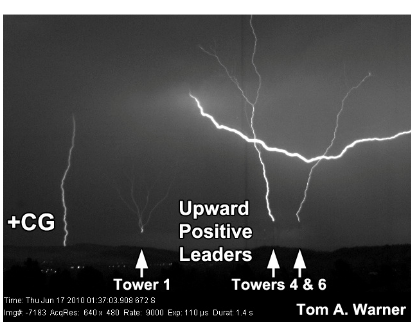

Figure 7. High-speed camera image (9,000 ips, 110 µs exposure) showing UPLs from three towers during Flash 2. The +CG RS channel is visible on the left side of the image, and a horizontally propagating PL that emerged below cloud is beyond the UPLs.

Figure 8 shows the weather radar 1.3º tilt reflectivity scan from the volume scan that began at 01:37:36 UTC. The first of the two +CG strokes was located in the higher reflectivity region (>50 dBZ) of the northern cell similar to the previous flash. However, the second +CG stroke was located in weaker reflectivity (20-30 dBZ) in a straight line between the first stroke and the towers.

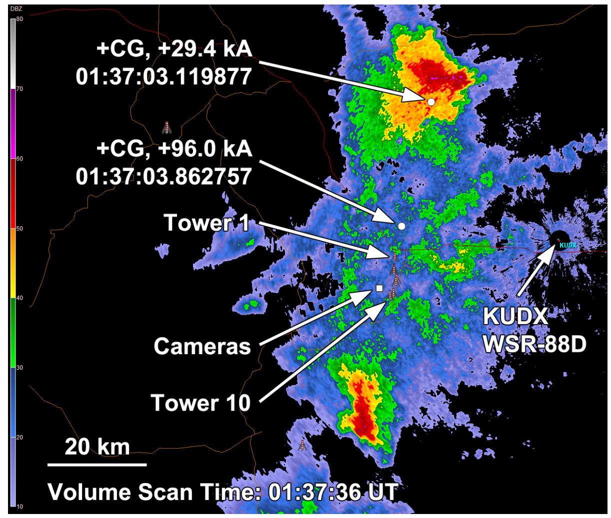

Figure 8. KUDX WSR-88D weather radar reflectivity from the 17 June 2010, 01:37:36 UTC volume scan (1.3º tilt).

3.3 *Flash 3, 08:04:45 UTC*

The third flash occurred later during the night as a second cluster of multicellular storms moved northeast over Rapid City. In this case, the storm cells had greater areal coverage and were scattered in a disorganized cluster. As the storm moved northeast, the higher reflectivity regions remained just east of Rapid City and a stratiform precipitation area passed over the towers. Two upward flashes occurred during the passage of this second storm system. Two high-speed cameras (Miro 4 and v310) were recording at 1,000 and 10,000 ips respectively with the Miro 4 again using a wide field of view.

At 08:04:44.907 UTC in-cloud brightness was observed beyond (northeast) of the towers, and at 44.919 s a bright cloud pulse with a short bright leader segment was visible just below cloud base, which lasted only one 100-µs exposure image. The NLDN recorded an associated +IC event with an estimated peak current of +8.2 kA, located 14.8 km northeast of Tower 6. A weakly luminous, non-branched PL became visible propagating to the left (north or northwest) from the location of the bright leader segment. This leader remained just below cloud base as it propagated horizontally. At 44.993 s (86 ms after the first visible flash activity), in-cloud brightness pulses became visible from the same area the PL emerged below cloud. This in-cloud brightening moved westbound toward the northern towers, and at 45.003 s, an UL initiated from Tower 6. The UL grew vertically without branching for 20 ms at which time it branched once with the two subsequent leader segments transitioning to horizontal propagation just below cloud base. Both segments branched further as it propagated with the additional branches remaining below cloud base. Some of the outermost UL branches developed RLs 73 ms after initiation.

At 45.020 s, while the UL was developing, additional PLs emerged below cloud near the area where the first PL was seen. Most of these propagated horizontally just below cloud base as well. 143 ms later one of the distant PLs connected with ground causing a +CG RS. The Miro 4, a standard-speed video camera (60 ips), and a digital still camera (20 s exposure) all recorded the RS and its channel, and the NLDN registered an associated +38.7 kA estimated peak current, +CG stroke located 16.6 km east-northeast of Tower 6. Figure 9 shows the digital still image of the entire flash.

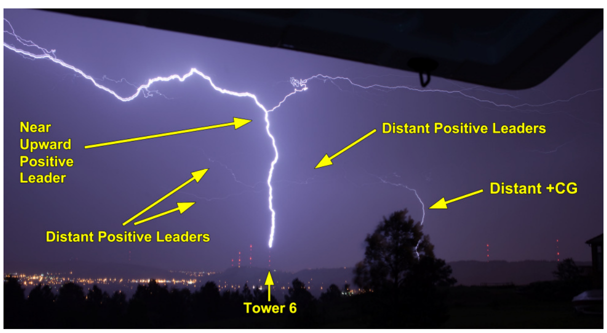

Figure 9. Digital still image (20 s exposure) showing a distant +CG RS channel, distant PLs, which propagated horizontally below cloud base, and a near UPL from Tower 6 during Flash 3.

Intense in-cloud brightness traveled from the +CG RS location westbound toward and over the towers immediately following the RS. This brightness increase retraced the path of the in-cloud brightness pulses that preceded UL initiation. NLs became visible just below cloud base north of the towers 20 ms after the RS and traveled southwest near the towers. The established UPL exhibited rapid brightening coincident with the passage of the intense in-cloud brightness that originated with the RS. The UPL appeared to brighten uniformly at first, and then RLs (much brighter than before the RS) initiated on the outer cutoff PL branches and connected with the main luminous branches, which further brightened the UL.

Figure 10 shows the total electric field change for this flash as integrated from the fast antenna data. A negative field change to -6 kV/m corresponded to the leader development (distant PLs below cloud and in-cloud brightening that approached the towers) that preceded the UPL initiation. The total field change then reversed direction from -9.3 kV/m at 45.013 s and increased steadily due to the developing UPL. The +CG RS caused a rapid -3.5 kV/m negative change with a positive change about 1/3rd that magnitude immediately following that spanned 6 ms. The total field change then increased with variable steepness for an additional 50 ms before resuming the established trend prior to the RS. The +CG RS channel was visible for 206 ms as observed by the Miro4.

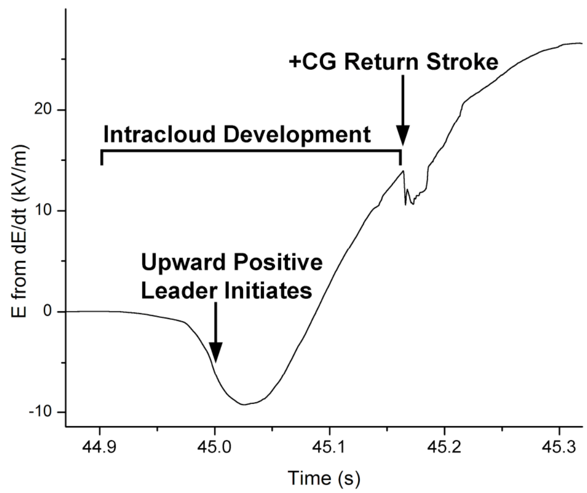

Figure 10. Total electric field change as integrated from the fast antenna data for Flash 3 (17 June 2010, 08:04:45 UTC).

The UL from Tower 6 maintained luminosity for 1.159 s. During the later portion of the flash, the NLDN recorded 2 -CG strokes and 3 -IC events that were associated with RL connections prior to current cutoff. The NLDN locations were within 270 m of Tower 6.

Figure 11 shows the reflectivity associated with the KUDX weather radar 1.3º tilt scan from the 08:02:50 UTC volume scan. The higher reflectivity cells were southeast of the towers, and there was a broad area of stratiform precipitation (35-45 dBZ) to the north that extended counterclockwise to the west of the cells. Both the preceding +IC NLDN-indicated event and following +CG stroke where located in this stratiform precipitation region, and the +CG stroke was 3.1 km east-southeast of the +IC event.

A SpriteNet camera (*Lang et al.,* 2011; *Lyons et al.,* 2011) operating at 60 ips (17 ms exposure) and located at Yucca Ridge near Ft. Collins, Colorado (444 km to the south), recorded a temporally and spatially correlated sprite triggered by this flash. The sprite was observed from 45.168 until 45.218 s, after the +CG RS at 45.163 s.

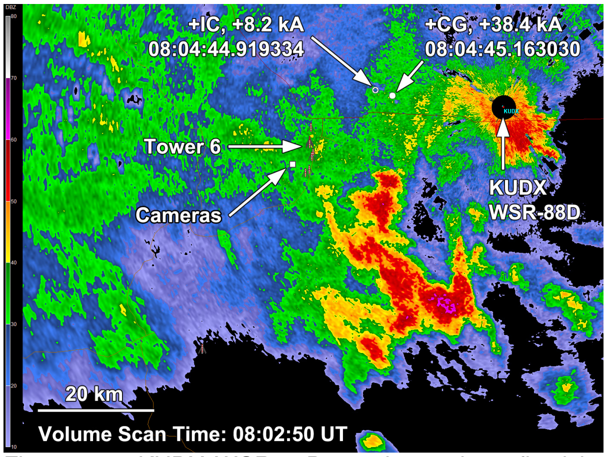

Figure 11. KUDX WSR-88D weather radar reflectivity from the 17 June 2010, 08:02:50 UTC volume scan (1.3º tilt).

4. DISCUSSION

4.1 *Flash 1*

Based on the associated high-speed optical and electric field data, the UPL from Tower 4 was triggered by the approach and passage of NLs that propagated horizontally just above cloud base near the towers following a +CG RS 25.2 km away. Since no in-cloud brightening was visible over the towers prior to the RS, and since the UL initiated 62 ms after the RS, it is likely that the RS reached the outer extent of the leader network that formed prior to the RS and caused new negative breakdown in virgin air that propagated toward the towers. It was not until the new leader development passed near the towers that the UPL initiated. If we make an assumption that the pre-RS leader network traveled no more than 5 km toward the tower, then the RS would reach the end of this network in approximately 50 µs (5 km / 1 x 10^8 m/s). Assuming a direct line path to the towers, NLs would have to travel at 3.2 x 10^5 m/s to then arrive over the towers 62 ms later (20 km / 62 ms), which is a reasonable speed for NLs (*Saba et al.,* 2008; *Rakov and Uman,* 2003).

For this flash, therefore, we suggest that the triggering flash was a +CG flash and the triggering component was horizontally propagating NLs that developed after the RS reached the outer extent of the bipolar leader development that preceded the RS. The NLs then propagated near the tower causing a negative field change (the triggering mechanism), which initiated the UPL.

4.2 *Flash 2*

For Flash 2, seven UPLs initiated within a few milliseconds after the second RS of a +CG flash. Like Flash 1, the first +CG RS (32.5 km north-northeast of the towers) reached the outer extent of the preceding intracloud development and initiated new negative breakdown in virgin air that propagated near the towers. However, in this case, the resulting negative field change experienced at the towers did not initiate any UPLs. As the horizontal propagating NLs became cutoff from the rest of the leader network that extended back to the north-northeast, PLs developed on the cutoff ends reestablishing their bipolar nature (*Krehbiel,* 1981 and *Lu et al.,* 2009). One of the PLs developed downward and connected with the ground causing the second +CG RS 6.54 km from the towers. As the RS traveled upward from the ground connection point, through the PLs and then horizontally through the NL network that had passed near the towers 100 ms earlier, the rapid and intense negative field change caused a near-immediate initiation of the seven ULs.

For this flash, we again classify the triggering flash as a +CG flash, but the triggering component in this case was the RS as it traveled through the leader network that previously passed near the towers. The triggering mechanism was again the negative field change.

4.3 *Flash 3*

The correlated high-speed optical and electric field data for Flash 3 suggests that horizontal propagating NLs associated with bipolar leader development passed near the towers and initiated a single UPL from Tower 6. Since the PLs that emerged below cloud base approximately 15 km away did not approach the towers, the in-cloud NL development that did approach likely dominated the corresponding negative field change.

160 ms after the UPL initiated, one of the PLs associated with the preceding bipolar leader development connected with the ground 16.6 km northeast of Tower 6 forming a +CG RS. A corresponding rapid negative field change occurred with the RS followed by a rapid positive change 1/3rd the magnitude. The sharp positive electric field change that immediately followed the negative RS change may reflect an induced intensification in the UPL as the RS traveled through the previously formed bipolar leader network that extended near the towers. When the +CG RS occurred, the entire UPL attached to Tower 6 was still below cloud base. There were no apparent connections between the preceding leader network and the UPL either before or after the RS.

In this case, the triggering flash was a +CG flash with extensive pre-RS leader development. The triggering component was horizontally propagating NLs associated with the bipolar leader development that preceded the RS. The triggering mechanism was the negative field change at the tower caused by the NLs' approach. The RS was not part of the triggering component or mechanism.

This is a rare case only seen twice in the 84 upward flashes. More common is the triggering of UPLs by intracloud flashes with horizontally extensive NL development or by +CG flashes as discussed previously.

4.4 *Triggering Classification*

The preceding three cases, along with other analyzed cases, suggest two possible triggering flash types, two triggering flash components, and one triggering mechanism for lightning-triggered UPLs. The two triggering flash types are either an intracloud cloud flash (IC) or a +CG flash. The two triggering components are either horizontal propagating NLs or a +CG RS. The horizontal propagating NLs can form during the bipolar intracloud development of an IC flash or preceding a +CG RS as in Flash 3. They can also form after a RS reaches the outer extent of the leader network formed prior to the RS. In either case, however, the NLs need to pass near or over the towers for initiation to occur based on all-sky optical observations.

The +CG RS triggering component results from the propagation of the RS through the leader network that formed previously near or over the towers. Again based on all-sky optical observations, the location of the pre-RS leader network relative to the towers is critical for UL initiation. We have observed a significant number of nearby +CG flashes, which did not initiate ULs. In these cases, horizontally propagating in-cloud brightness following the RS was either not observed or propagated away from the towers.

When the triggering component is horizontal propagating NLs following a +CG, the delay between the +CG RS and UL initiation can be 10s to 100s of milliseconds depending on the distance between the towers and pre-RS leader network. However, when the RS triggers the ULs, the close proximity of the preformed leader network and the speed at which RS traverses the network results in ULs that are typically visible within a few milliseconds or as soon as the saturating brightness decays when observed with a high-speed camera.

In all cases, the triggering mechanism for UPLs is a negative electric field change at the tower locations that causes the initiation of UPLs. Statistical analysis of the range of field change rates and magnitudes are ongoing and will be reported in future work.

4.5 *Storm Classification*

There were a total of 34 storms that produced the 84 upward flashes. On average, 2.5 upward flashes were generated per storm with the maximum number being 10. Based on weather radar analysis of the 34 storms, the most common storm type was multicellular clusters (56%) followed by squall lines (35%). The remaining 9% were single cell storms. However, one storm that began as a single cell storm developed into a multicell cluster and produced upward flashes during both phases. The most common storm region favorable for upward lightning was an associated stratiform precipitation area that either led or trailed the storm convective region. Seventy-five percent (63/84) of the upward flashes occurred with a stratiform precipitation region over the towers and surrounding area. Weak convection ahead of a main convective region was present for 17% (14/84) of the cases. Only 7% (6/84) of the cases occurred with the convective region over the towers, and all these were during the passage of a squall line. For 4 of the 34 storms (12%), multiple upward flashes initiated as different storm regions passed over the towers (e.g., upward flashes occurred in the weak convection region ahead of the main convective core and also in the trailing stratiform precipitation area that followed).

A common observation with upward lightning triggering is the presence of horizontally extensive flashes (both intracloud and +CG flashes) with NLs propagating just above cloud base. Also common is the tendency for PLs associated with triggering flashes and UPLs from the towers to propagate horizontally just below cloud base. These observations suggest that there is a region just above cloud base favorable for the horizontal propagation of NLs and a region just below cloud base favorable for the horizontal propagation of PLs. *Coleman et al.,* 2003; 2008 proposed that a horizontally stratified region of positive charge could act as a positive potential well (potential maximum) causing NLs to propagate horizontally into and through the well. Likewise, a horizontally stratified region of negative charge could act as a negative potential well (potential minimum) causing PLs to propagate horizontally in this region.

Positive charge generation due to aggregate shedding at the melting layer (e.g., *Stolzenburg et al.,* 1994; *Shepherd et al.,* 1996) may result in a positive charge region just above cloud base. Likewise, a negative screening layer at cloud base or negatively charged precipitation falling below cloud base (e.g., *Stolzenburg et al.,* 1994) may result in horizontal PL propagation. Continued analysis of these and future cases will seek to further characterize storm morphology and charge structures present during upward lightning.

4.6 *Coincident Transient Luminous Events*

On three different nights a SpriteNet camera near Ft. Collins, Colorado (444 km south of Rapid City) was able to observe storms that were producing upward flashes in Rapid City. Nine upward flashes were observed during this coordinated monitoring period and six of the upward flashes had associated sprites. The optical assets in Rapid City recorded a preceding +CG

RS for each case, and the NLDN recorded 5 +CGs and one +IC (even though there was a confirmed ground stroke). For 5 of the cases, both the UL and sprite initiation followed the +CG RS. For the remaining case, which is Flash 3 discussed in this paper, the UL initiated before the +CG RS and the sprite was observed after the RS. Unfortunately, the SpriteNet camera temporal resolution (17 ms) does not allow for adequate comparison between UL and sprite initiation times. We are working on obtaining coordinated high-speed optical observations both below and above cloud in the future.

Coincident sprite and UL observations suggest that the triggering storm and flash types are the same for both. There has been extensive research investigating the storm and flash types favorable for TLEs (e.g., *Lyons,* 1996; *Lyons et al.,* 2003; *Cummer et al.,* 2005; *Lyons et al.,* 2009; *Lang et al.,* 2010, 2011). Findings from these investigations show that stratiform precipitation areas of MCSs containing horizontally extensive +CG flashes with large charge moment changes are favored. It appears these conditions are also conducive to LTUL. More investigation is needed to determine if the triggering component(s) and mechanism for LTUL are the same for TLEs.

5. CONCLUSION

We present evidence from concurrent high-speed optical and electric field data that suggests that UPLs are triggered from tall towers in Rapid City, SD due to 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 propagates through a previously formed leader network that is near the towers.

We further suggest that storms that produce horizontally extensive flashes with NLs propagating near cloud base are the most likely to produce LTUL in the northern High Plains. Furthermore, the most favorable storm region for LTUL is a stratiform precipitation area with reflectivity less than 45 dBZ.

Ideally, coordinated observations using 3-dimensional lightning mapping instrumentation (e.g., Lightning Mapping Array, LMA or interferometer) along with existing assets would help to visualize triggering components and storm charge structure (*Cummins and Murphy,* 2009). Initial analysis of upward flashes observed for the first time in Brazil utilizing both a high-speed camera (4,000 ips) and an LMA supports the triggering methods proposed in this paper (*Saba et al.,* 2012). However, more observations are needed, and we plan to incorporate a 3-dimensional interferometer with future observations in Rapid City.

6. ACKNOWLEDGEMENT

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. 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.

7. REFERENCES

Coleman, L. M., T. C. Marshall, M. Stolzenburg, T. Hamlin, P. R. Krehbiel, W. Rison, and R. J. Thomas, 2003: Effects of charge and electrostatic potential on lightning propagation. *J. Geophys. Res.*, 108(D9), 4298, doi:10.1029/2002JD002718.

Coleman, L. M., M. Stolzenburg, T. C. Marshall, and M. Stanley, 2008: Horizontal lightning propagation, preliminary breakdown, and electric potential in New Mexico thunderstorms. *J. Geophys. Res.*, 113, D09208, doi:10.1029/2007JD009459.

Cummer, S. A., and W. A. Lyons, 2005: Implications of lightning charge moment changes for sprite initiation. *J. Geophys. Res.*, 110, A04304, doi:10.1029/2004JA010812.

Cummins, K. L., and M. J. Murphy, 2009: An Overview of Lightning Locating Systems: History, Techniques, and Data Uses, With an In-Depth Look at the U.S. NLDN. *IEEE Trans. Electromag. Compat.*, 51(3), 499-518.

Krehbiel, P. R., 1981: An analysis of the electric field change produced by lightning, Ph. D. dissertation, Univ. of Manchester Inst. of Sci. and Technol., Manschester, U. K.

Lang, T. J., W. A. Lyons, S. A. Rutledge, J. D. Meyer, D. R. MacGorman, and S. A. Cummer, 2010: Transient luminous events above two mesoscale convective systems: Storm structure and evolution. *J. Geophys. Res.*, 115, A00E22, doi:10.1029/2009JA014500.

Lang, T. J., J. Li, W. A. Lyons, S. A. Cummer, S. A. Rutledge, and D. R. MacGorman, 2011: Transient luminous events above two mesoscale convective systems: Charge moment change analysis, *J. Geophys. Res.*, 116, A10306, doi:10.1029/2011JA016758.

Lu, G., S. A. Cummer, J. Li, F. Han, R. J. Blakeslee, and H. J. Christian, 2009: Charge transfer and in-cloud structure of large-charge-moment positive lightning strokes in a mesoscale convective system. *Geophys. Res. Lett.*, 36, L15805, doi:10.1029/2009GL038880.

Lyons, W. A., 1996: Sprite observations above the U.S. High Plains in relation to their parent thunderstorm systems. *J. Geophys. Res.*, 101, 29,641–29,652, doi:10.1029/96JD01866.

Lyons, W. A., T. E. Nelson, E. R. Williams, S. A. Cummer, and M. A. Stanley, 2003: Characteristics of sprite-producing positive cloud-to-ground lightning during the 19 July 2000 STEPS mesoscale convective systems. *Mon. Weather Rev.*, 131, 2417–2427, doi:10.1175/1520-0493

Lyons, W. A., M. Stanley, J. D. Meyer, T. E. Nelson, S. A. Rutledge, T. J. Lang, and S. A. Cummer, 2009: The meteorological and electrical structure of TLE-producing convective storms, in Lightning: *Principles, Instruments and Applications*, edited by H. D. Betz et al., pp. 389–417, doi:10.1007/978-1-4020-9079-0_17, Springer, New York.

Lyons, W. A., S. A. Cummer, S. A. Rutledge, T. J. Lang, T. Meyer, T. A. Warner and T. M. Samaras, 2011: TLEs and their parent lightning discharges. Paper presented at the 14th International Conference on Atmospheric Electricity, August 07-12, 2011, Rio de Janeiro, Brazil.

Mazur, V., 2002: Physical processes during development of lightning flashes. *C.R. Physique*, 3, 1393-1409.

Mazur, V., and L. H. Ruhnke, 2011: Physical processes during development of upward leaders from tall structures. *J. Electrostatics*, 69, 97-110.

Mazur, V., L. H. Ruhnke, T. A. Warner, and R. E. Orville, 2011: Discovering the Nature of Recoil Leaders. paper presented at the 14th International Conference on Atmospheric Electricity, August 07-12, 2011, Rio de Janeiro, Brazil.

Rakov, V. A., and M. A. Uman, 2003: Lightning: Physics and Effects. Cambridge Univ. Press, New York.

Saba, M. M. F., K. L. Cummins, T. A. Warner, E. P. Krider, L. Z. S. Campos, M. G. Ballarotti, O. Pinto Jr., and S. A. Fleenor, 2008: Positive leader characteristics from high-speed video observations. *Geophys. Res. Lett.*, 35, L07802, doi:10.1029/2007GL033000.

Saba, M. M. F., J. Alves, C. Schumann, D. R. Campos and T. A. Warner, 2012: Upward lighting in Brazil. Paper presented at the 22nd International Lightning Detection Conference, Apr 2 – 5, Boulder, Colorado, USA.

Shepherd, Tommy R., W. David Rust, Thomas C. Marshall, 1996: Electric Fields and Charges near 0℃ in Stratiform Clouds. *Mon. Wea. Rev.*, 124, 919–938. doi: http://dx.doi.org/10.1175/1520-0493(1996)124<0919:EFACNI>2.0.CO;2

Stolzenburg, M., T. C. Marshall, W. D. Rust, and B. F. Smull, 1994: Horizontal distribution of electrical and meteorological conditions across the stratiform region of a mesoscale convective system. *Mon. Weather Rev.*, 122, 1777–1797, doi:10.1175/1520-0493(1994)122<1777:HDOEAM>2.0.CO;2.

Wang D., and N. Takagi, Y. Takaki, 2010: A comparison between self-triggered and other-triggered upward lightning discharges. Proceedings of the 30th International Conference on Lightning Protection, Sep 13-17, Cagliari, Italy.

Warner, T. A., 2011: Observations of simultaneous upward lightning leaders from multiple tall structures. *J. Atmos. Res.*, doi:10.1016/j.atmosres.2011.07.004 (In press)

Warner, T. A., K. L. Cummins, and R. E. Orville, 2011: Comparison of upward lightning observations from towers in Rapid City, South Dakota with National Lightning Detection Network data - preliminary findings. Proceedings of the 3rd International Symposium on Winter Lightning, Jun 13-15, Tokyo, Japan.

Zhou, H., G. Diendorfer, R. Thottappillil, H. Pichler, and M. Mair, 2011: Close electric field changes associated with upward-initiated lighting at the Gaisberg Tower. Proceedings of the 2011 International Symposium of Lightning Protection (XI SIPDA), Oct 3-7, Fortaleza, Brazil.