2016 24th International Lightning Detection Conference
18 - 19 April | San Diego, California, USA
6th International Lightning Meteorology Conference
20 - 21 April | San Diego, California, USA

Photo of Cloud-to-Ground Lightning Showing Multiple Upward Leaders

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***Abstract*— On 10 July 2015, a lightning flash that produced two ground terminations was photographed from inside the safety of a truck in southern New Mexico. An analysis of archived NLDN data show that this was a two-stroke flash, and a close-up view of the first stroke shows that it initiated at least 12 unconnected, upward leaders (or "streamers") near the ground termination. No unconnected upward leaders were seen near the second ground attachment. After combining an analysis of the photograph with detailed analyses of the NLDN data, we infer that the first stroke was of negative (normal) polarity and struck about 460 m (± 40%) from the camera. Attachment occurred when an upward-propagating positive leader reached an inferred height of about 20 m. The second stroke struck ground about 1.5 km from the camera, and the height of its attachment leader is estimated to be 28 m. The estimated lengths of the unconnected upward leaders in the 2-D plane of the first stroke range from 2 to 8 m, and all appear to be located within 20 m (2-D) of the main ground termination. Many of the unconnected upward leaders exhibit multiple upward branches, and most of the branches have upward-directed forks or splits at their ends. None of the upward leaders can been seen to emanate from tall, isolated, or pointed objects on the ground, but they likely begin on small plants or perhaps even flat ground. In terms of lightning safety, this photo clearly demonstrates (a) that a plethora of upward leaders can be produced near a lightning "strike point" and (b) that lightning can affect or directly damage more than one specific point on the ground.**

Keywords—Cloud-to-ground lightning; upward leaders; lightning attachment

I. Introduction

The physics of lightning attachment to ground is currently an active and important area of research [Cooray et al., 2007; Tran and Rakov, 2015; Hill et al., 2016; Jiang et al., 2015; Wang et al., 2015]. Additionally, unconnected upward leaders (UULs, sometimes referred to as "streamers") associated with lightning attachment have been identified as one of the five main causes of lightning injuries [Cooper 2002; Cooper et al. 2008]. A preliminary estimate of their frequency, in order from most to least common, are earth potential rise (including surface arcing), side flash/splash, contact potential, upward streamers/leaders, and direct strikes [Cooper et al. 2008]. Of these, unconnected upward leaders are the least understood, and their frequency and spatial distribution are not well known. A high-resolution digital photograph recently taken by Mike Olbinski, and analyzed in detail in this work, is one of the best examples of multiple UULs obtained to date.

II. Location and Photograph

Fig. 1 shows the photograph that was obtained by the first author at about 2128 MDT on 10 July 2015, while a dissipating supercell-type thunderstorm was moving to the northeast

Fig. 1. Full view of two lightning channels striking ground in southern New Mexico. The total exposure time was about 10 s, and the stroke (channel) on the right occurred first and produced multiple, unconnected upward leaders (or "streamers") near the attachment to ground (see also Figs. 3 and 4).

between Silver City and Deming, New Mexico. Note that two bright channels (or strokes) contact ground, and the stroke on the right also has multiple UULs near its point of attachment (see also Figures 3 and 4 to follow).

The 35 mm SLR camera (a Canon EOS 5D Mark III) had 5760 x 3840 pixels in the image plane, and operated with a 50 mm lens using an aperture ratio of f/6.3. The camera was tripod-mounted, and the shutter was triggered remotely from inside the safety of a truck. The duration of the exposure in Figure 1 was about 10 s, and loud thunder was heard at the time of the event.

A plan view of the photo site and estimates of the stroke locations are shown in the Google Earth (GE) image in Fig. 2. The camera location (Photo Site) is indicated by the white arrow, and the camera field of view (FoV) was between the two red lines. The yellow line shows the direction to our best estimate of the first stroke location based on a detailed analysis of the photograph together with the GE imagery.

An examination of data reported by the U.S. National Lightning Detection Network (NLDN) [Cummins and Murphy, 2009] in the interval/region of the exposure shows that a negative, two-stroke cloud-to-ground flash occurred at an appropriate time and location. The NLDN reported no other candidate strokes in this region during the interval of the exposure. The NLDN stroke information is provided in Table 1. The angle and range in Table 1 are for our best estimates of the strike locations relative to an origin at the Photo Site, as described below. Note that both strokes had estimated peak currents that were lower than the expected medians for first strokes and for subsequent strokes that create new ground contacts in southern Arizona [see Table 5 in Biagi et al., 2007]. Since the spatial accuracy of the NLDN locations is limited to hundreds of meters [Nag et al. 2014], we have not used the NLDN location to estimate the true position of the first stroke (i.e. the one closest to the camera). Note that the original NLDN location for this stroke (NLDN 1st Stroke) was outside the FoV of the camera, and this clearly cannot be correct. A "reprocessed" NLDN location for this 1st stroke was computed after excluding a distant NLDN sensor in the central Rocky Mountains, and this provided more confidence that this was the proper 1st stroke in the flash, since the reprocessed location is within 400 m of the "Likely First Stroke Location" that was derived using Google Earth and camera information and shown in Fig. 2.

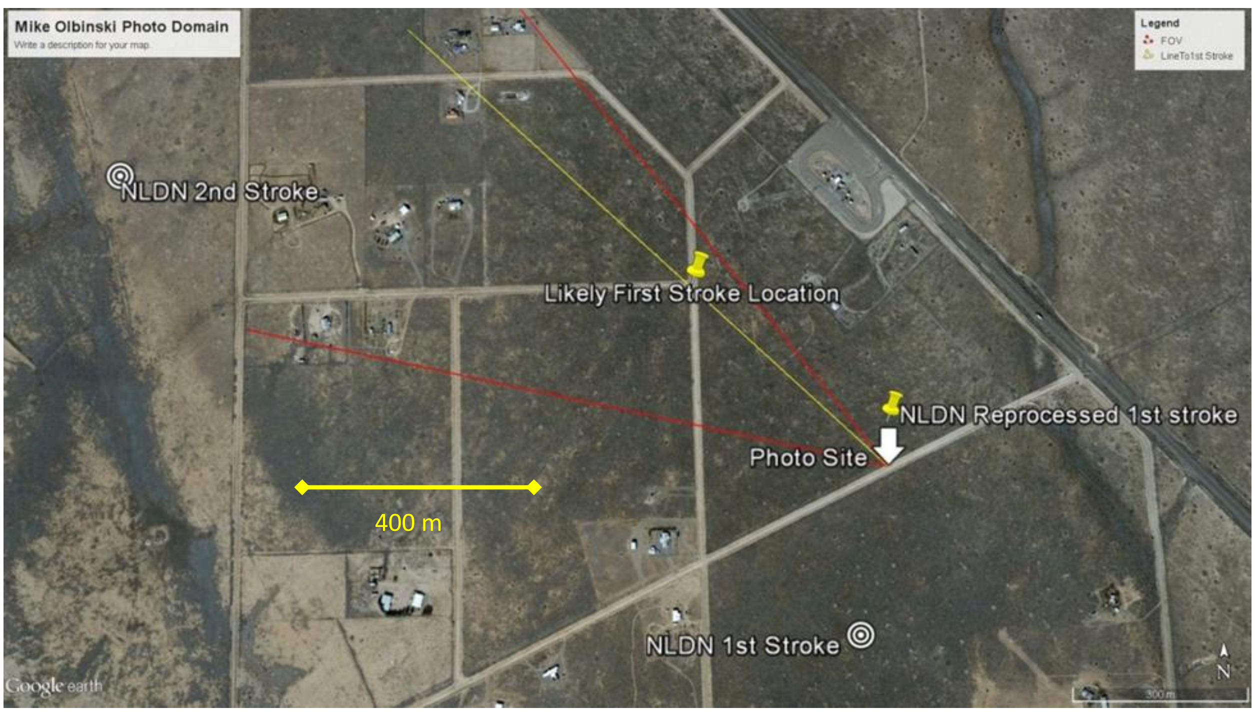

Fig. 2. Plan view of the camera site and field-of-view together with the original NLDN locations of the first and second strokes; the reprocessed NLDN position of the first stroke; and the likely location of the first stroke.

Table 1. NLDN parameters for the strokes shown in Fig. 1. SMA is the median estimated location error; Chi-square is a quality measure (should generally be less than 3.0); NSR is the number of sensors reporting the event. The Azimuth and Range values are for our best estimates of the strike locations relative to the Photo Site shown in Fig. 2.

Date	Time (UTC)	Latitude	Longitude	Peak Current (kA)	SMA (km)	Chi-square	NSR	Azimuth (degrees)	Range (m)
2015-07-11	03:30:09.275	32.4882	-107.9792	-14.8	0.2	0.9	8	315	460
2015-07-11	03:30:09.327	32.4955	-107.9925	-12.0	0.2	0.4	5	291.6	1410

III. Analysis of Photograph

The ground strike location for a negative lightning stroke is determined by the location where an upward connecting leader (UCL, which is positive in the case of negative return strokes) is initiated on the ground. The total height of the UCL is defined by the altitude at which this upward positive leader and the tip of a descending, negative stepped-leader channel join (the attachment point). This point can often be identified in still photographs as the location between faint branches that point upward and/or downward on the bright return stroke channel. The height of the UCL is often assumed to be roughly one half of the striking distance, or the height at which a downward stepped-leader pauses just before the UCL is initiated [Golde, 1945; Cooray, et al., 2007; Rakov and Uman, 2003; Uman, 2008]. Fig. 3 shows a portion of the image in Fig. 1 together with the estimated heights of the UCLs; they are 21.4m and 29.8m, in attachments 1 and 2, respectively.

Further magnified views of the first ground attachment (on the right-side of Fig. 1), are given in Figs. 4a and 4b. Note that there are at least 12 UULs that emanate from the ground in well-defined channels on both sides of the very bright return-stroke channel. The visible UULs are labeled in Fig. 4b, and note how most have upward-directed branches and how the branches frequently have forks or splits on their upper ends. Fig. 4 shows that none of the UULs appear to emanate from tall, isolated, or pointed objects on the ground; rather, all appear to be initiated by small features on the surface, plants or possibly even by flat ground.

Using our best estimate of the most likely first stroke location together with the optical properties of the digital camera, we have computed the length and spacing of the upward leaders (in a 2-dimensional plane at the source). The required camera properties include the focal length of the lens, the dimensions of the image plane, and the number and location of the exposed pixels. The MATLAB Image Processing Toolkit was used to process the digital image and to identify the desired pixel properties.

The results of these estimates are summarized in Table 2. The maximum brightness produced by the three UULs highlighted in gold were the largest (saturated at 255), and they were also the tallest (6.8 to 8.0 m) and had the largest number of branches (4-6). Note also that the faintest UUL (#5) is one of the shortest. If the horizontal distances between the UULs toward or away from the strike point are isotropically distributed, this will add an additional spatial uncertainty of about +/- 20m, which is about 5% of the likely range from the ground termination to the camera.

Table 2. Upward Leader Characteristics

ID	#Branches	Height (m)	Horizontal Dist. (m)	Brightness (0-255)
1	2	5.0	14.0	234
2	5	7.3	12.5	255
3	1	2.8	11.8	242
4	1	4.2	11.5	246
5	1	2.4	7.3	206
6	4	8.0	4.0	255
7	1	2.0	3.2	223
8	1	3.5	3.0	228
9	6	6.8	6.2	255
10	1	2.7	6.9	217
11	2	1.8	10.9	221
12	2	3.1	14.4	236

Fig. 3. Zoomed view of Fig. 1 showing the estimated location of the height of the upward connecting leaders (UCL) for the two ground contacts.

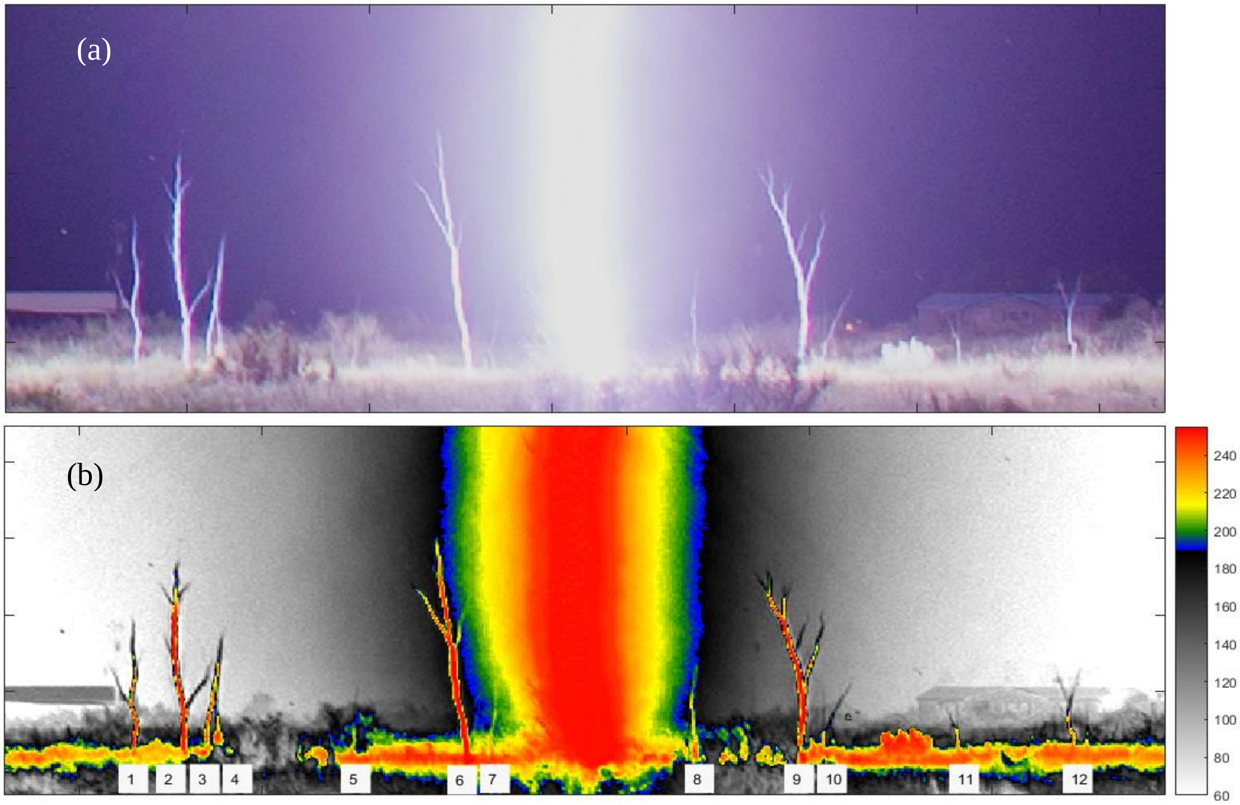

Fig. 4. (a) Additional magnification of the attachment on the right-side of Figure 1 showing multiple unconnected upward leaders (UULs) emanating from the ground; (b) The twelve UULs are labeled in this false color enhancement of (a). The scale on the right shows the brightness.

IV. Discussion

Previously published lightning photographs showing unconnected upward leaders near the ground termination have been described by Krider and Ladd [1975], Krider and Alejandro [1983], Krider and Wetmore [1987], Faidley and Krider [1989], Uman [1991] and others; more recent work has been listed in the Introduction. The photos in these papers show unconnected upward leaders in various configurations, shapes, and sizes emanating from trees, tall towers, or mountainous terrain. The estimates of the overall length, spacing, and brightness parameters of the UULs in this literature are generally comparable to our photograph. The main difference is that our photo shows that a multiplicity of upward leaders can be initiated by very small objects that do not appear in our photograph. If the electric fields produced by a downward-propagating leader are large enough, perhaps UULs can even be initiated on flat ground. Once they begin, the UULs clearly develop with multiple, upward branches that are of the order of meters in length, and this in turn suggests that their development may be in the form of a rapid succession of intermittent steps [Biagi et al., 2011]. The currents in well-developed positive leaders range from ten to hundreds of amperes [Lalande et al., 1998; Biagi et al., 2011; Uman 2008, Ch. 7], but those in UULs are not known.

As was stated in the Introduction, from the point of view of lightning safety, UULs are thought to be one of the five main causes of lightning injuries and possibly deaths [Cooper 2002; Cooper et al. 2008]. Unfortunately, their frequency of occurrence and electrical characteristics are still not well understood; therefore, lightning phenomena such as these clearly merit further study.

Acknowledgment

We thank Chris Biagi for helpful discussions during the writing of this manuscript.

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