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Close Observations of Forked and Upward-Illumination Return Strokes at the Kennedy Space Center/Cape Canaveral Air Force Station

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***Abstract*— A total of 232 well-resolved multiple ground contact flashes were recorded via high-speed video at the Kennedy Space Center (KSC)/Cape Canaveral Air Force Station (CCAFS) during 2014 and 2015. Of these 232 flashes, 58 flashes exhibited at least one clear instance of either forked or upward illumination (UI) return strokes. Characteristics of these 58 flashes are examined via close-range high-speed video recordings and time correlated rate of change of electric field (dE/dt) measurements. The dataset of forked strokes is subdivided into three separate classifications depending on inter-stroke interval and branching altitude. Inter-stroke intervals and distance separations between first and subsequent ground attachment points are evaluated for all classes of forked strokes and for UI strokes. The detection efficiency and peak current reporting of the National Lightning Detection Network (NLDN) is evaluated for all classes of forked strokes and for UI strokes.**

I. INTRODUCTION

Lightning researchers have observed and documented flashes having more than one ground contact point since the 1930's, initially using the streak-photographic technique (e.g., *Schonland,* 1935), then progressing to using standard video cameras (e.g., *Rakov and Uman,* 1994; *Valine and Krider,* 2002), and more recently, using high-speed digital video cameras (e.g., *Ballarotti,* 2005; *Campos,* 2014; *Kong,* 2009; *Stolzenburg,* 2012, 2013). These prior studies, among others, have shown that up to 50% of multi-stroke flashes exhibit more than one ground contact point. A subset of these flashes contain multiple return strokes that establish unique ground termination points on a millisecond or sub-millisecond time scale. This special classification of events is assigned various nomenclature in the literature include twin strokes, forked strokes, double-ground strokes, and multiple ground contact strokes. These flashes typically involve two (or occasionally more) spatially independent leader channels that contact ground separately within typically tens (e.g., *Guo and Krider,* 1982; *Willet,* 1995) to many hundreds (e.g., *Rakov and Uman,* 1994) of microseconds. Events with strokes terminating on ground within tens of microseconds have been attributed to competing branches of a common stepped leader contacting ground at nearly the same time (e.g., *Guo and Krider,* 1982; *Ballarotti,* 2005) while *Rakov and Uman* (1994) argued that the longer time durations between ground contact points observed in their study resulted from two sequential return strokes of the same flash initiated by different stepped leaders. Separation distances for strokes exhibiting multiple ground contact points have been shown to extend up to 5 km (e.g., *Thottappillil,* 1992), but are more typically of the order of about 1 km (e.g., *Campos,* 2014). Images of multiple ground contact strokes typically exhibit relatively uniform luminosity between ground and the branching point.

More recently, *Stolzenburg.* [2012, 2013] and *Campos* [2014] have reported on a new type of event involved in multiple ground contact flashes, termed the "upward Illumination (UI)" return stroke. *Stolzenburg* [2012, 2013] have shown that UI strokes occur when a branch of a stepped leader is effectively "cut off" electrically from the primary stepped leader channel, but still continues to propagate downward, eventually making contact with ground and initiating a weak return stroke. UI strokes have been shown to occur from several hundred microseconds up to nearly 3 ms following the initial return stroke of the flash. UI strokes typically exhibit comparatively weak luminosity to the initial return stroke, and unlike other multiple ground contact strokes, often exhibit non-uniform luminosity between the ground and the branching point (when visible). *Stolzenburg* [2012, 2013] reported observations of UI strokes where no luminosity existed between the primary leader channel and the apparently cut off branch, whereas *Campos,* [2014] reported cases where UI strokes occurred with dim optical channels still visible between the primary leader channel and the branch that supported the UI stroke. The later study utilized higher-resolution images and longer frame integration times, which may have allowed the camera to more clearly expose the dim connection region. The argument that UI strokes result from the stepped leader branch being electrically cut off from the main leader channel is supported by observations that the luminosity from the initial return stroke of the flash only illuminates the upper portion of the cut off branch, while the subsequent UI stroke only illuminates the branch from the ground upwards to the region where the branch is cut off from the primary leader channel (e.g., *Stolzenburg*, 2012). It is possible that the multiple ground contact flashes observed by *Rakov and Uman* [1994] that exhibited time durations between ground contact points of hundreds of microseconds were, in fact, due to a normal cloud-to-ground return stroke followed by a UI stroke.

In this study, time correlated high-speed video recordings and high-resolution rate of change of electric field (dE/dt) measurements are used to further examine strokes exhibiting multiple ground termination points, both of the "forked" and UI classifications (following the naming convention of *Campos* [2014]). During 2014 and 2015, a total of 232 flashes containing multiple ground termination points were imaged by the high-speed camera network at the Kennedy Space Center (KSC)/Cape Canaveral Air Force Station (CCAFS). Of these 232 flashes, 58 flashes (25%) contained at least one clearly imaged forked or UI return stroke.

II. Experiment

The high-speed camera network at KSC/CCAFS consists of 13 Phantom cameras configured to record cloud-to-ground return strokes in a localized area of about 10 km x 10 km. The cameras provide continuous lightning monitoring for the high-valued infrastructure and assets at KSC/CCAFS, including various launch complexes, space vehicle assembly buildings, and fabrication facilities. Many of the cameras are configured with intersecting fields of view to provide multi-angle video recordings of common lightning discharges. In addition, eight of the cameras are located on tall structures (> 150 m) in order to provide downward vantage points for accurate lightning strike point location. The high-speed cameras are triggered to record based on either the electric field, magnetic field, or optical output of nearby lightning return strokes. Eleven of the high-speed cameras record at a frame rate of 3,200 frames/s (exposure time of 312.5 µs) while two of the cameras record at 16,000 frames/s (exposure time of 62.5 µs). All cameras record at a resolution of 1280 x 800 pixels.

The high-speed camera data is supported by a network of six wideband (25 MHz, -3 dB) dE/dt sensors (e.g., *Hill*, 2016) that collectively form a time-of-arrival (TOA) network capable of determining the strike points of nearby lightning discharges with spatial and time accuracy of the order of 10 m and 100 ns, respectively. The digitization time bases of the six dE/dt sensors are synchronized with RMS timing accuracy of 15 ns. The accuracy of the TOA system has been independently verified using ground truth strike point data obtained by the high-speed video system in addition to Monte Carlo simulations.

The KSC/CCAFS area is also continuously monitored by the NLDN. The NLDN performance for the region has been recently evaluated using ground truth data collected at KSC/CCAFS by the aforementioned high-speed camera and dE/dt network by *Hill* [2016]. For the KSC/CCAFS region, the NLDN was shown to have median strike location accuracy of about 190 m.

III. Data

Most of the 58 flashes in the dataset containing at least one forked or UI return stroke were photographed at distances between about 500 m and 5 km, generally closer range than the prior studies, providing very high-resolution imagery of the optical processes with comparatively less image degradation due to the local atmosphere. Accurate strike point locations for both forked and UI strokes were determined by a combination of high-speed video recordings and dE/dt TOA measurements for 39 of the 58 flashes. Observations of four classes of multiple ground contact strokes will be analyzed in the subsequent sections, 1) forked strokes having long inter-stroke intervals (tens to hundreds of microseconds), 2) forked strokes having short inter-stroke intervals (less than or equal to 10 µs), 3) forked strokes having both short inter-stroke intervals and abnormally low-altitude branch points (often referred to as "root branches"), and 4) UI strokes. The performance of the National Lightning Detection Network (NLDN) will be evaluated for all four classes of events.

A. Forked Strokes with Long Inter-Stroke Intervals

A total of 33 forked strokes having long inter-stroke intervals were captured via high-speed video recordings. This classification of multiple ground contact stroke was the most commonly photographed in the dataset. For the 33 forked strokes, the average time separation between ground contact points was 177 µs (determined by measuring the time between return strokes on close dE/dt waveforms) with a range from 13 µs to 790 µs. These values are in reasonable agreement with those recently published by *Campos* [2014], who measured mean forked stroke inter-stroke intervals for a 16 stroke dataset of 118.7 µs with a range from 5.31 µs to 554.3 µs. Accurate strike point locations were determined for 28 of the 33 forked strokes. From these locations, the distances between subsequent ground contact points were calculated. The average distance separation for the 28 forked strokes was 1272 m, with a range from 414 m to 3528 m. *Campos* [2014] reported a mean distance separation for forked strokes of about 1200 m and did not observe stroke separations greater than 4 km, both statistics in good agreement with the results of this study. A total of 31 of the 33 forked strokes exhibited two independent ground contact points while two events contained three ground contact points. For two events, forked strokes were imaged for a first and subsequent return stroke.

Example high-speed video data of a typical forked stroke are shown in Fig. 1A,B while an aerial plan view of the strike locations is shown in Fig. 1C. Corresponding dE/dt waveform data are shown in Fig. 2. The high-speed video data were recorded from a camera located on the roof of the Vehicle Assembly Building (VAB) while the dE/dt data were recorded by an antenna located at the Beach House camera site located

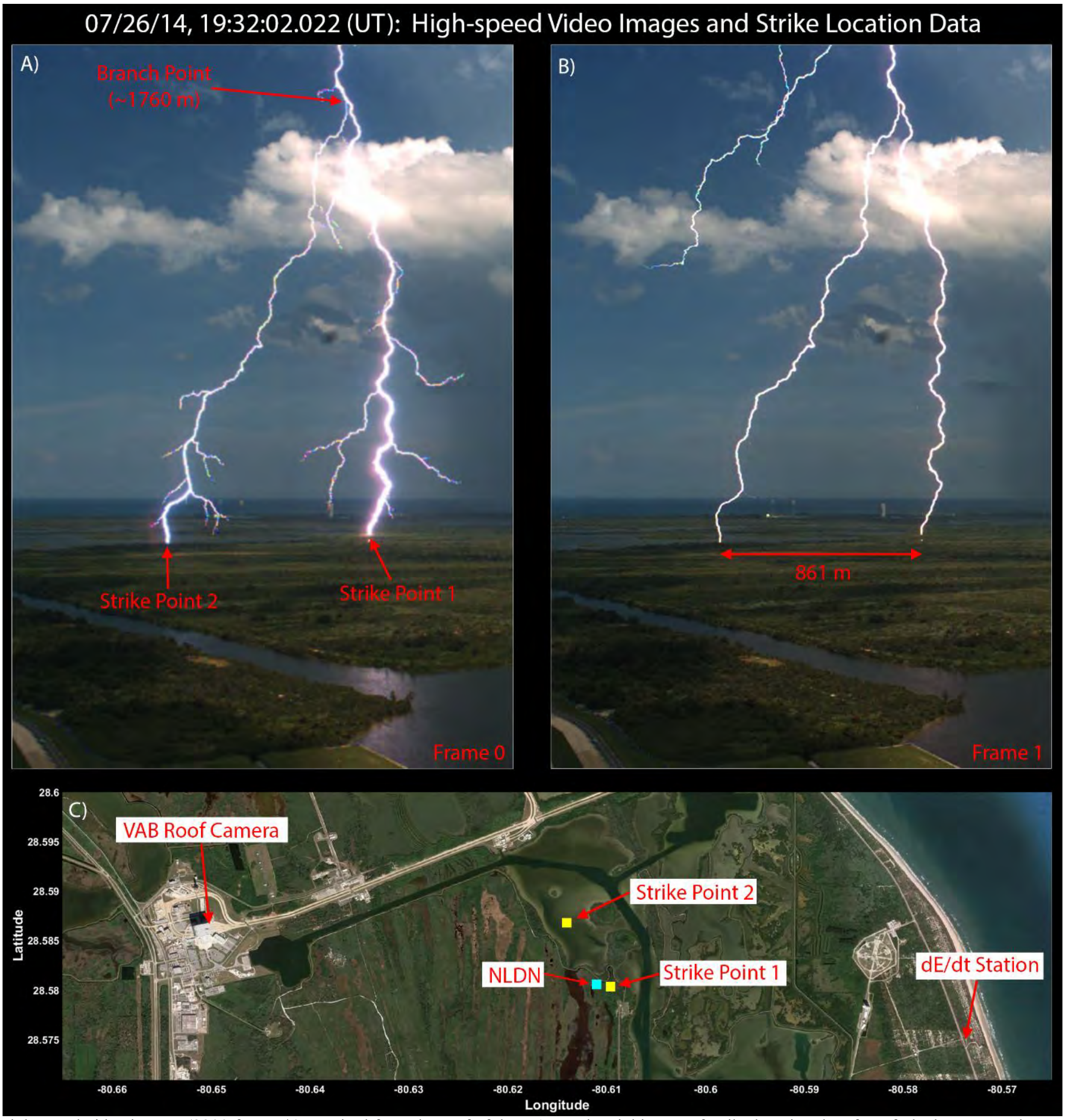

Figure 1. High-speed video images (3200 frames/s) acquired from the roof of the VAB and aerial image of strike location data for a forked return stroke on 07/26/14 at 19:32:02.022 (UT). The two ground terminations occurred 68 µs apart and were separated by 861 m. The altitude of the branch point was about 1760 m.

about 3.5 km southwest of the strike points. The forked stroke struck ground about 3.5 km east of the VAB. The branch point of the forked stroke is clearly visible in this example, and is located at an altitude of about 1760 m (determine via photogrammetry). Both stepped leader branches contacted ground during Frame 0, initiating return stroke current waves in both branches. The two ground contact points were separated in time by 68 µs and in distance by 861 m. For both channels to ground, the observed luminosity during and after the return stroke is continuous and generally uniform between the ground and the branch point, characteristic of forked strokes.

For the example forked stroke shown in Fig. 1, the NLDN reported the first ground contact point within 117 m of the strike location determine by the local TOA network. The reported peak current was -8.8 kA. The second ground contact point was not reported by the NLDN. These observations were representative of the NLDN performance for the dataset of 33 forked strokes. For all but two cases, the NLDN reported the first ground contact point of the forked stroke, but did not report the subsequent contact point(s). Perhaps not coincidentally, the two cases where the NLDN reported both ground contact points of a forked stroke corresponded to the events with the longest

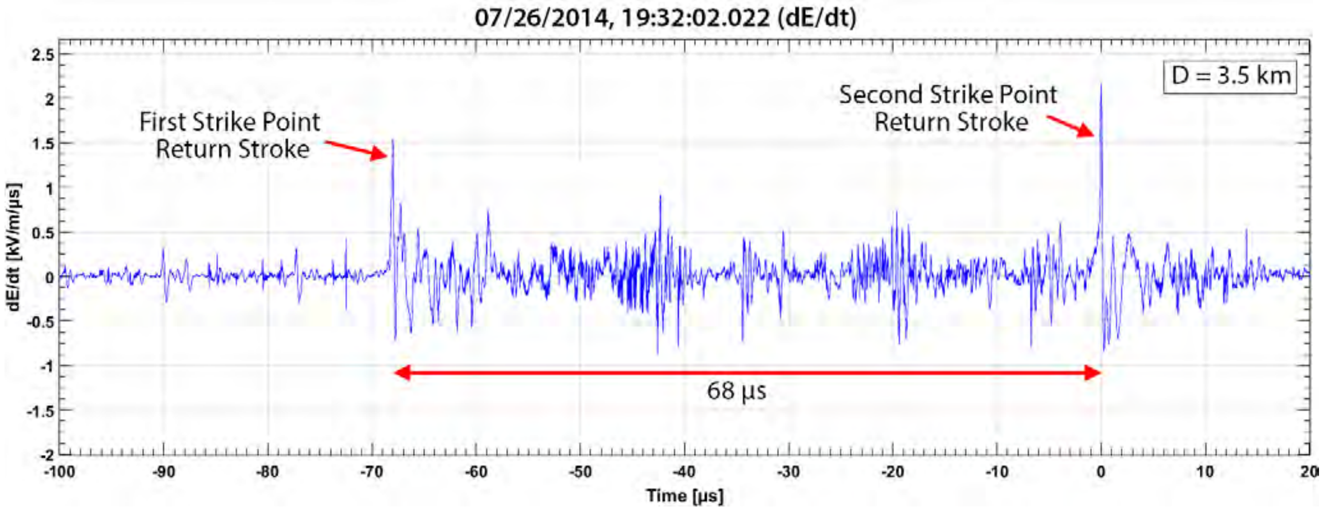

Figure 2. dE/dt waveform recorded at a distance of 3.5 km for a forked return stroke on 07/26/14 at 19:32:02.022 (UT). The two ground terminations were separated in time by 68 µs.

inter-stroke intervals (453 µs and 790 µs). The return stroke peak currents reported by the NLDN for forked strokes with long inter-stroke intervals averaged -22.5 kA, in good agreement with the overall average peak current of -21 kA for negative first strokes reported by *Nag* [2014]. For properly classified events, NLDN peak currents for forked strokes ranged from -8.4 kA to -66 kA. Three forked strokes were misclassified by the NLDN as cloud discharges.

B. *Forked Strokes with Short Inter-Stroke Intervals*

Forked strokes were classified as having short inter-stroke intervals if the time between ground-contact points was less than or equal to 10 µs. This type of forked stroke was previously reported by *Willet* [1995], who found three such cases among 32 flashes in their data set with ground terminations separated by 6.7 µs, 8.4 µs, and 9.9 µs. A total of 19 forked strokes with short inter-stroke intervals were recorded in the present data set. For these events, the average inter-stroke interval was 4.75 µs with a minimum of 1 µs and maximum of 10 µs. The distances between subsequent ground contact points could be accurately determined for 11 events. The lower percentage of accurately located strokes for this subset of data is due primarily to insufficient data resulting from unplanned power outages at the dE/dt measurement stations. The average distance separation for forked strokes with short inter-stroke intervals was 419 m, with a range from 30 m to 1094 m. In 18 of 19 cases, the forked strokes had two ground contact points, and in one case, three ground contact points.

An example dataset for a forked stroke with short inter-stroke intervals is shown in Fig. 3. The flash occurred on July 19, 2015 at 21:52:18.089 (UT) and had three termination points, the first to the southeast lightning protection system mast at Launch Complex 41 (LC-41), the second to ground 298 m south between LC-41 and the Vertical Integration Facility (VIF), and the third to ground 697 m southeast of the first termination point. High-speed video images of the three terminations are shown in Fig. 3A,B, with all three attachments occurring during Frame 0. The video images were recorded from the Beach House camera site located about 1.2 km southeast of LC-41. A dE/dt waveform recorded 2.5 km west of the strike location is shown in Fig. 4. Prominent return stroke field changes corresponding to the three termination points are labeled in Fig. 4. The three terminations occurred during a time-span of about 9 µs.

The NLDN successfully reported the first stroke of all forked strokes with short inter-stroke intervals. For the example shown in Fig. 3, the NLDN reported a single location for the three terminations, located about 338 m southwest of the first termination point (Fig. 3C). The average NLDN peak current for forked strokes with short inter-stroke intervals was -64.7 kA, almost a factor of three higher than the average peak current for negative first strokes reported by *Nag* [2014]. It is possible that this observation is coincidental considering the relatively small sample size. However, due to the microsecond-scale inter-stroke intervals measured for these events, it is also plausible that the distant NLDN sensors are recording a peak field that is actually a superposition of the fields radiated by the individual ground contact points. A higher measured peak field would likely translate into a larger estimated peak current considering the NLDN uses a field to current conversion equation to calculate the return stroke peak current. Two of the lower peak current events reported by the NLDN (-19.3 kA and -23.1 kA) were misclassified as cloud discharges.

C. *Forked Strokes with Short Inter-Stroke Intervals and Low-Altitude Branch Points*

A smaller subset of forked strokes with short inter-stroke intervals exhibit a characteristic that can only be distinguished from photographic measurements at very close distance where the strike point is clearly visible. Occasionally, a forked stroke will exhibit one or more branches that originate at very low altitude (less than a hundred meters or so), producing additional

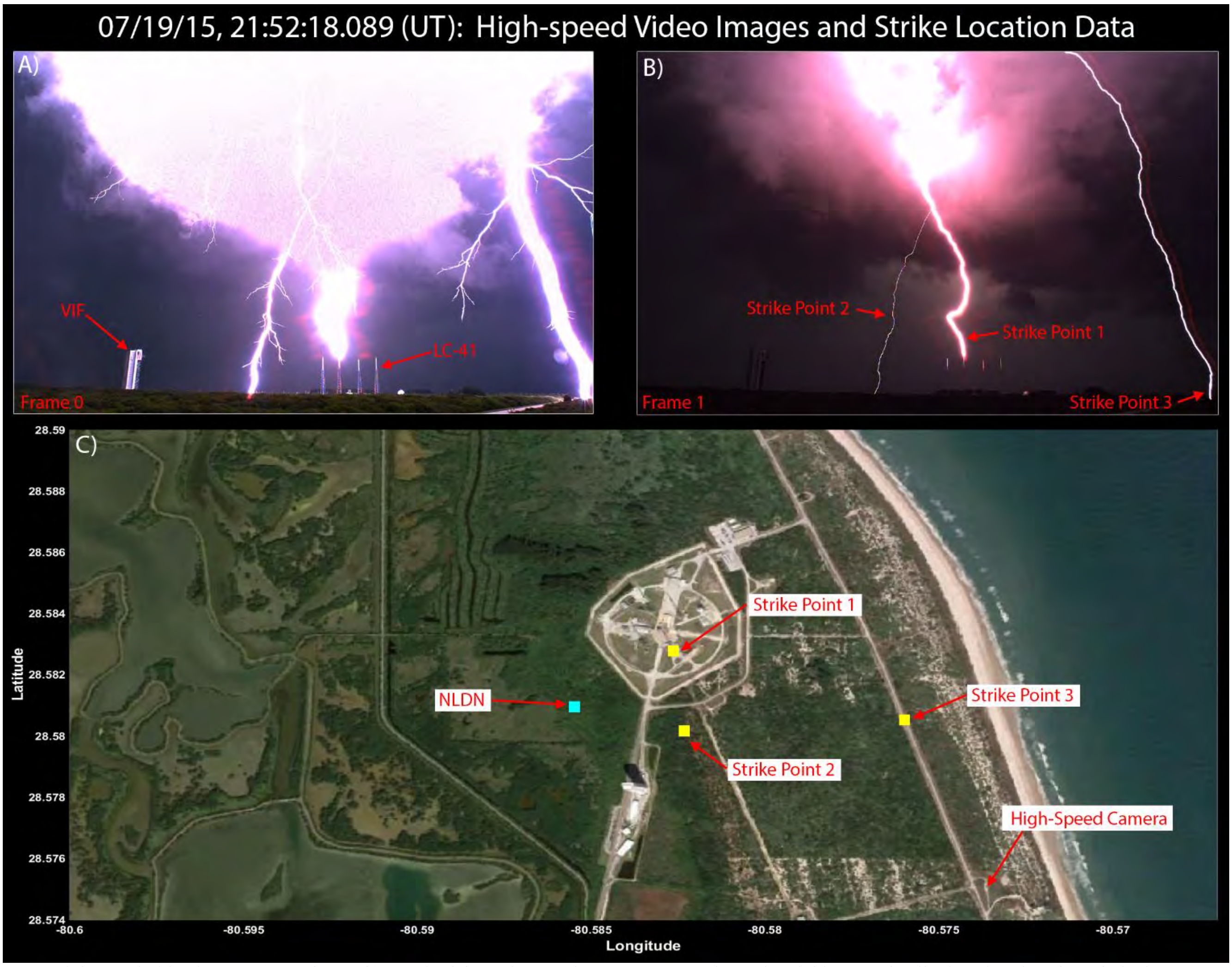

Figure 3. High-speed video images (3200 frames/s) acquired from the Beach House camera site and aerial image of strike location data for a forked return stroke with short inter-stroke interval on 07/19/15 at 21:52:18.089 (UT). The three terminations, one to the LC-41 lightning protection system and two to ground, occurred in a time-span of less than 10 µs.

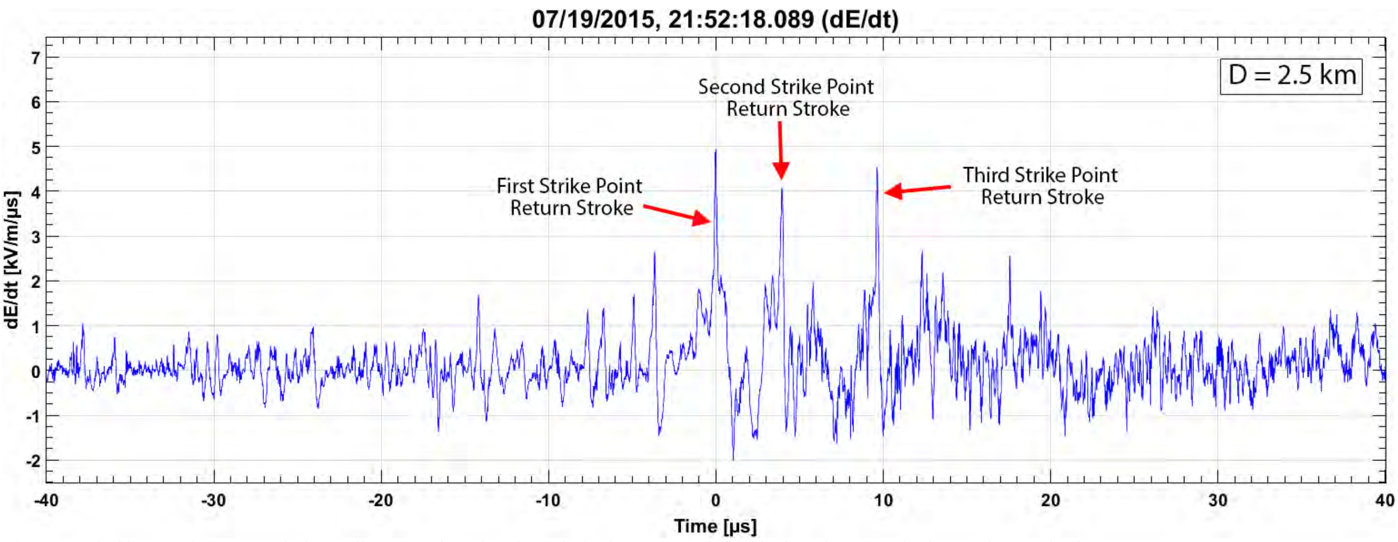

Figure 4. dE/dt waveform recorded at a distance of 2.5 km for a forked return stroke with short inter-stroke interval on 07/19/15 at 21:52:18.089 (UT).

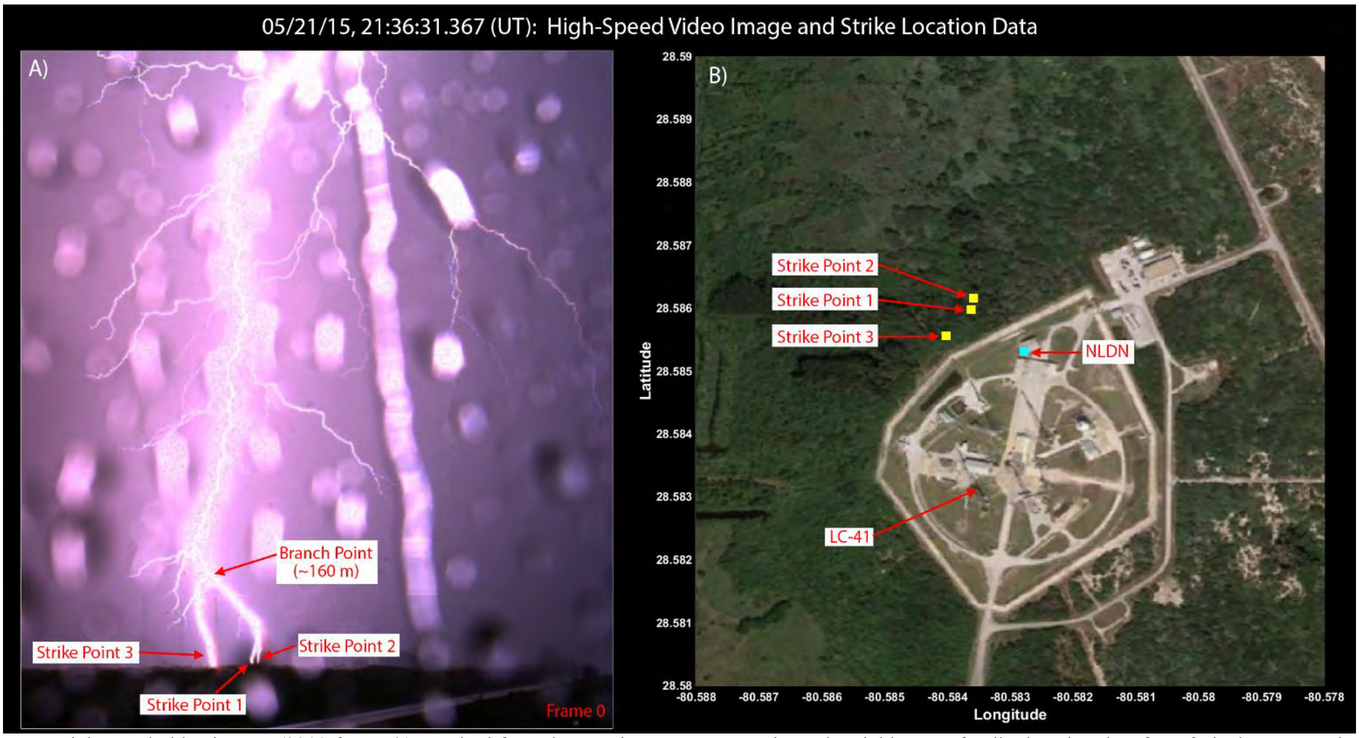

Figure 5. High-speed video images (3200 frames/s) acquired from the Beach House camera site and aerial image of strike location data for a forked return stroke with short inter-stroke interval and low-altitude branch point on 05/21/15 at 21:36:21.367 (UT). The three terminations, all to ground immediately north of LC-41, occurred in a time-span of about 4 µs. The two terminations associated with the root branch were separated by only 17 m.

ground contact points that occur both in close time succession and spatial relation to the ground attachment of the primary leader channel. These additional ground attachments are sometimes referred to as root branches. Eight forked stroke events exhibited this low-altitude branching characteristic. In six cases, a single low altitude branch accounted for both ground termination points. For two cases, the primary leader channel branched at higher altitude (like a more typical forked stroke), and then one of the two branches exhibited a second fork at very low altitude (tens of meters). These two flashes contained three ground contact points. For the eight total events that demonstrated abnormally low-altitude branching, the average time separation between ground contact points was 2.13 µs, with a range from 1 µs to 5 µs. The strike point locations were determined accurately for seven of the eight events. For these seven events, the subsequent ground contact points were separated by an average of 144 m with a range from 17 m to 308 m.

High-speed video and strike location data are shown in Fig. 5 for one of the two flashes that exhibited both a higher-altitude branch point along with a low-altitude branch, leading to three ground termination points. Corresponding dE/dt waveforms recorded 5 km north of the strike location are shown in Fig. 6. The flash occurred on May 21, 2015 at 21:36:31.367 (UT) with all three strike points terminating on ground immediately north of LC-41. The high-speed video image shown in Fig. 5 was acquired from the Beach House camera site, located about 1.3 km to the southeast. The main stepped leader channel forked at an altitude of about 160 m. The easternmost branch then forked again several tens of meters above ground level, producing two ground contact points separated in time by 1 µs and 17 m. The westernmost branch made ground contact about 3 µs later, 78 m southwest of the first strike point. The dE/dt return stroke peaks corresponding to the three attachment points, separated in time by a total of about 4 µs, are very clearly defined in Fig. 6.

NLDN strike locations were obtained for the first attachment points of all eight of the forked strokes in this subset of data. All strokes were correctly classified as cloud-to-ground strokes. For the example shown in Fig. 5, the NLDN strike location was 111 m southeast of the strike location produced by the local TOA network. In this case, the NLDN predicted that the discharge terminated within the LC-41 pad perimeter. The average NLDN reported peak current for the eight events was -83.9 kA, nearly a factor of four higher than the average peak current for negative first strokes reported by *Nag* [2014], and also higher than the average NLDN peak currents for the forked strokes with short inter-stroke intervals discussed in Section 3.2. Considering the average inter-stroke interval for the eight strokes in this subset of data was only about 2 µs, perhaps the field superposition effect discussed in Section 3.2 is further amplified, leading to even higher estimated peak currents.

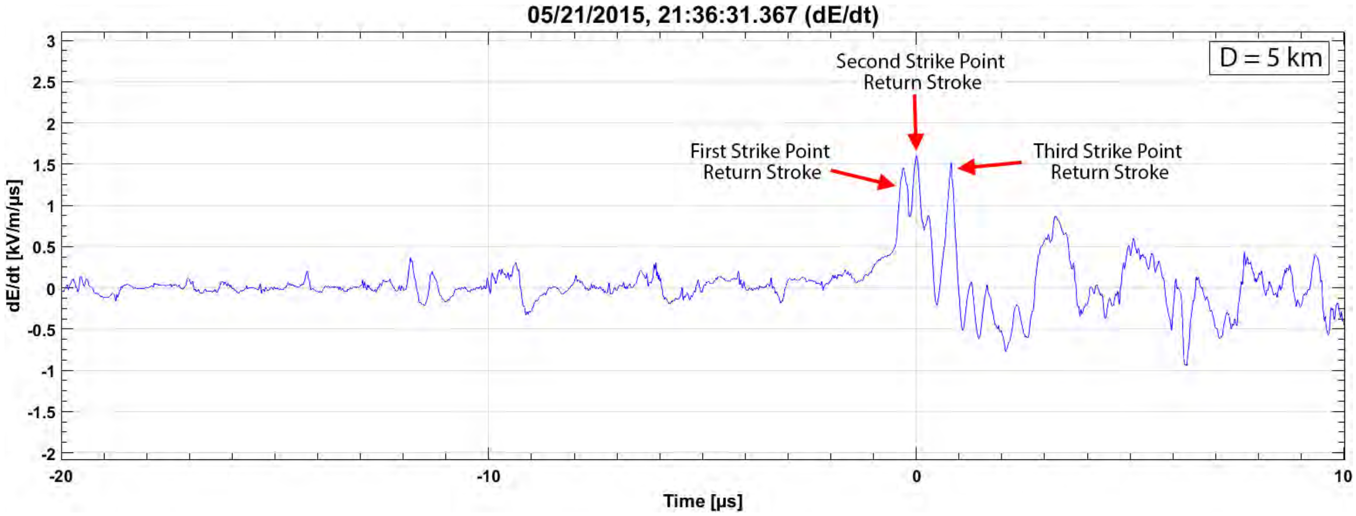

Figure 6. dE/dt waveform recorded at a distance of 5 km for a forked return stroke with short inter-stroke interval and low-altitude branch point on 5/21/15 at 21:36:21.367 (UT).

D. UI Strokes

UI strokes were principally differentiated from forked strokes by performing detailed analysis of the high-speed video images. As noted by *Stolzenburg* [2012, 2013] and *Campos* [2014], UI strokes tend to exhibit non-uniform luminosity in the channel segment traversed by the UI stroke. UI strokes are often imaged with decaying luminosity as a function of altitude. The channel segment that produces the UI stroke is either completed detached optically from the main stepped leader channel or is connected by a very thin, dim channel that is typically not illuminated by the upward propagation of the UI stroke following the ground attachment. A total of 32 UI strokes were imaged in this study. As with forked strokes, the time difference between the ground attachment of the primary leader channel and the subsequent UI stroke was measured from close dE/dt waveforms. For the 32 events, the average time difference between the primary leader channel ground attachment and the UI stroke was 836 µs with a range from 31 µs to 3.54 ms. 25% of the photographed UI strokes were separated in time from the primary leader channel ground attachment by more than 1 ms. For 12 UI strokes *Campos* [2014] found average inter-stroke intervals of 1.392 ms with times ranging from 254.1 µs to 2.648 ms. *Stolzenburg* [2012] found inter-stroke intervals ranging from 519 µs to 1.858 ms for four UI strokes. For 20 well-determined UI strokes, *Stolzenburg* [2013] reported inter-stroke intervals ranging from 180 µs to 3.99 ms with an average time separation of 1.25 ms. Both the average inter-stroke interval and range of inter-stroke intervals in this study are in reasonable agree with the prior studies. One notable difference is that five UI strokes were documented in this study with inter-stroke intervals less than 100 µs.

Accurate strike locations of main leader channel and subsequent UI stroke ground attachments were determined for 26 of the 32 events. For these events, the average distance separation between the main leader channel strike point and UI strike point were 1559 m, with distances ranging from 35 m to 4158 m. Half of the events had distances separations greater than 1 km. These statistics are in good agreement with prior studies (*Campos* [2014] reported average distances separation of 1250 m with range from 120 m to 3350 m and *Stolzenburg* [2013] reported average separation of 1.4 km with distances ranging from 0.4 km to 3.17 km).

High-speed video and strike location data of a well-resolved UI stroke are shown in Figure 7. The event occurred on July 3, 2015 at 19:11:09.225 (UT) with the primary leader channel and UI stroke attaching to ground north of Launch Complex 39B (LC-39B). In this case, the strike points of the primary leader channel and the UI stroke were separated by 3.32 km. In Frame 0, the primary leader channel attached to the ground, initiating a return stroke. A second downward branch is visible to the west of the primary leader channel. In Frame 1 (Figure 7B), the return stroke current wave propagated up the main stepped leader channel. A branch component is also visible in Frame 1, but note that the enhanced luminosity ceased at much higher altitude than the lower extent of the downward propagating branch. The western branch made ground contact in Frame 5 (Figure 7C), initiating the UI stroke. In Frame 6 (Figure 7D), the UI stroke propagated farther up the channel. In Frame 7 (Figure 7E), the enhanced luminosity of the UI stroke ceased propagating upward. Note the point where the UI stroke stopped propagating upward along the prior channel is at a similar location in space to where the branch component due to the primary leader channel return stroke stopped propagating downward in Frame 1 (Figure 7B). From these observations, it can be inferred that the leader branch that produced the UI stroke was effectively cut-off from the primary stepped leader channel at this point. Throughout the UI stroke process shown in Figure 7C-F, there is a faint optical connection between the inferred cut-off point and the primary leader channel. However, this section of channel does not experience any detectable change in luminosity due to the UI stroke process. Though

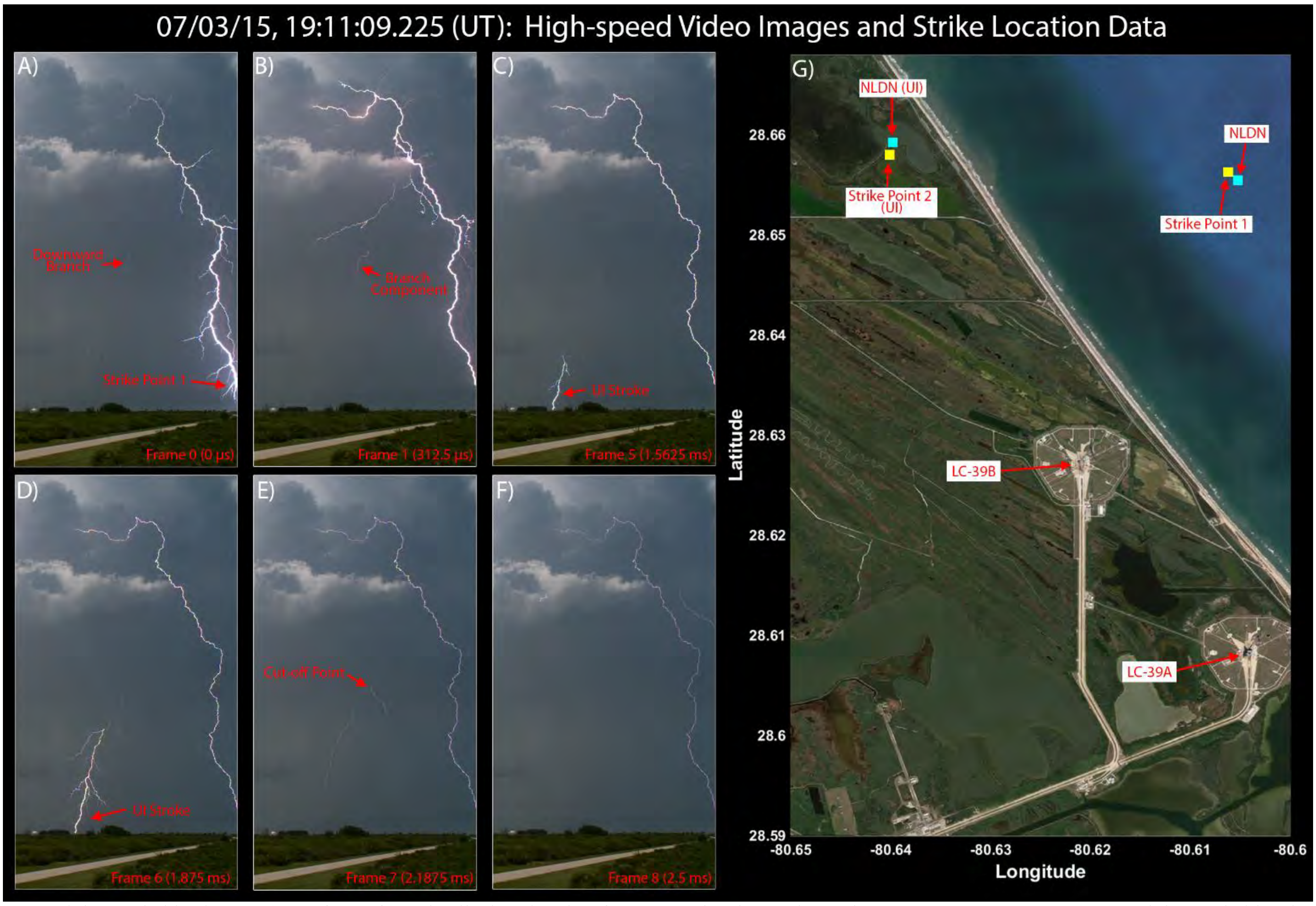

Figure 7. High-speed video images (3200 frames/s) and strike location data for a UI stroke observed on July 3, 2015 at 19:11:09.225 (UT). High-speed video data (3200 frames/s) were recorded from the Beach House camera site. The UI stroke occurred 1.67 ms after the first stroke at a distance of 3.32 km from the attachment point of the first stroke.

Stolzenburg [2012, 2013] reported actual gaps with no detectable luminosity between the primary leader channel and the cut-off leader branch that initiated the UI stroke, in this data set, a dim channel persists throughout the UI stroke process. As previously stated, this difference may be attributable to both the camera exposure and the distance (and resolution) at which the UI stroke processes were photographed.

Corresponding dE/dt waveforms measured about 4.5 km southeast of the strike location are shown for the example event in Figure 8. The UI stroke occurred about 1.67 ms following the attachment of the primary leader channel to ground (Figure 8A). Expanded timescale views of the first return stroke and UI return stroke are shown in Figure 8B and Figure 8C, respectively. The UI stroke radiated a more-or-less typical return stroke field change that is about a factor of 3 smaller than that radiated by the first return stroke.

The NLDN reported strike location data for 31 of the 32 events that exhibited both a first return stroke and a UI stroke. For 24 events, only the strike location of the first return stroke was reported. Both the strike locations of the first stroke and UI stroke were reported for seven events. Finally, for one event, only the strike location of the UI stroke was reported. For the example flash shown in Figure 8, the NLDN reported the first stroke about 74 m southeast of the strike location computed from the local TOA network. For the UI stroke, the NLDN strike location was located about 100 m northeast of the strike location obtained by the local TOA network. The 24 NLDN reports for the first strokes preceding the UI strokes had average peak currents of -23.5 kA, typical values for first strokes. Only one of the first strokes was misclassified as a cloud discharge. Out of the seven UI strokes reported by the NLDN, four were misclassified as cloud discharges. The average peak current for the seven UI strokes reported by the NLDN was -8.5 kA.

IV. Discussion and Concluding Remarks

Summary statistics for the four classifications of events discussed in this study are provided in Table 1. The forked and UI strokes presented in this paper comprised 25% of 232 total multiple ground contact flashes recorded at KSC/CCAFS during 2014 and 2015. The remaining 75% of multiple ground contact flashes exhibited strokes that appear to not have been associated with different branches of a common stepped leader,

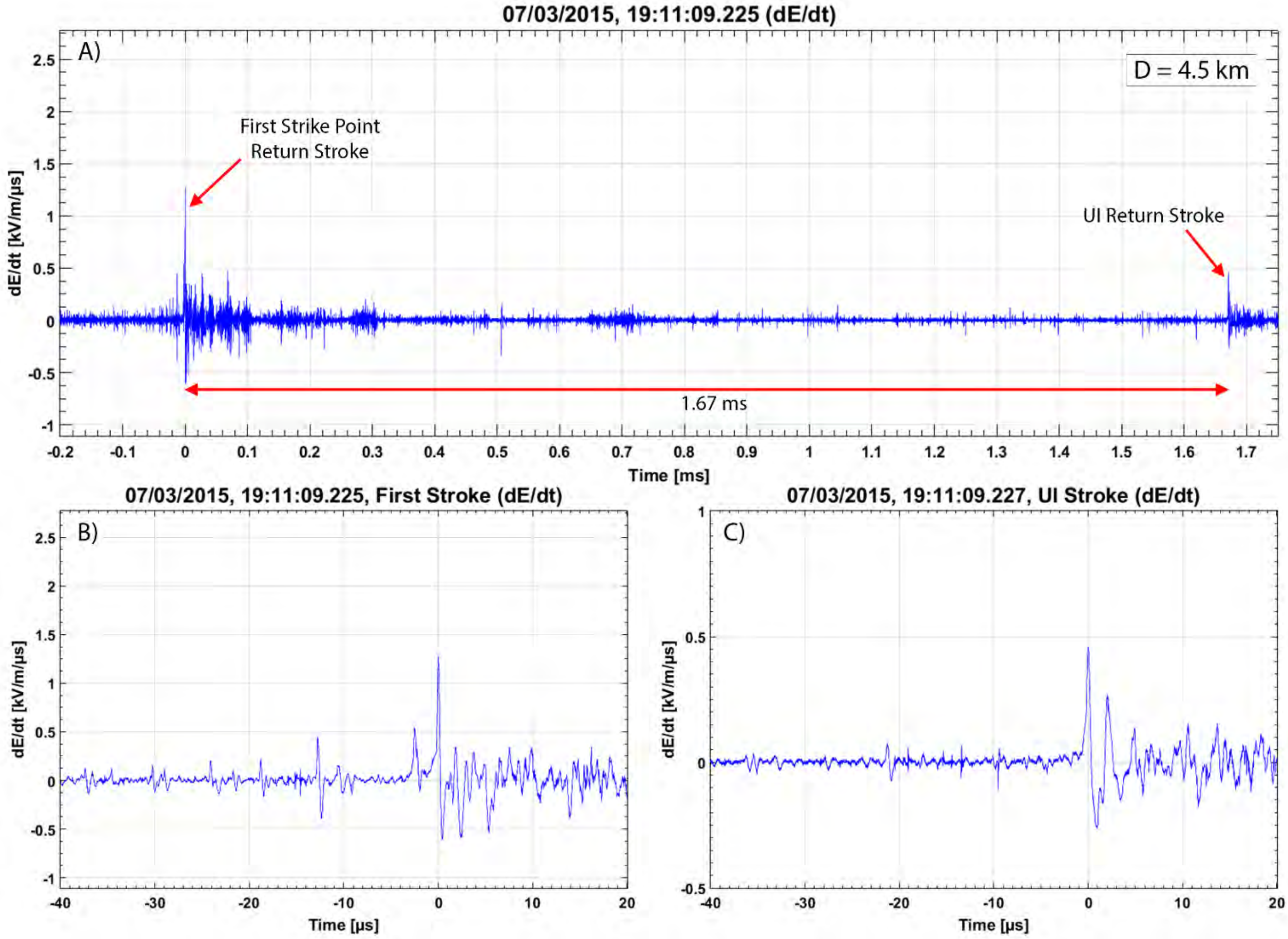

Figure 8. A) dE/dt waveform recorded at a distance of 4.5 km for a UI stroke on July 3, 2015 at 19:11:09.225 (UT). B-C) Expanded timescale view of the first return stroke and UI stroke.

but occurred in sufficiently close time succession (adopting the 1 s timing threshold proposed by *Valine and Krider* [2002]) to be associated with a common flash. Multiple ground contact flashes without forked or UI strokes exhibit longer time durations between subsequent strokes (up to several hundred milliseconds) and greater distance separations between new ground contact points (often many kilometers).

The results of this paper have shown that large coverage area lightning locations systems (such as the NLDN) struggle to resolve the multiple strike points that occur in close time succession with forked strokes. The return strokes generated from all ground connections of forked stroke flashes can carry significant currents of the order of typical first strokes. At facilities such as KSC/CCAFS where both the direct and indirect effects of close lightning return strokes can result in damage to high-valued and sensitive assets, the underreporting of the subsequent ground strike points in forked strokes is a definite concern, and also reinforces the need for supplementary localized lightning detection and reporting systems with sufficient resolution to fully resolve and characterize these events. Further, the observation that the NLDN may tend to significantly overestimate the peak currents of forked strokes occurring in microsecond time succession could also cause unwarranted alarm if such an event were to occur in an area where vehicle retest criteria are based on both the peak current and distance to nearby return strokes.

The data presented in this paper have shown that UI strokes are typically associated with relatively low peak currents, in agreement with prior studies. Like the case of forked strokes, large coverage area lightning location networks tend to accurately report the initial ground contact point in a flash containing a UI stroke. The subsequent UI stroke is often not reported or is misclassified as a cloud discharge. The low detection efficiency for UI strokes is likely more a function of their low peak currents than the inter-stroke interval (as is the case for forked strokes). UI strokes are less of a concern from a lightning protection standpoint than forked strokes due to their comparatively low peak currents.

TABLE 1. SUMMARY STATISTICS FOR THE FOUR CLASSIFICATIONS OF MULTIPLE GROUND CONTACT STROKES.

Event Class	N	Time Separation Avg, Range (µs)	Distance Separation Avg, Range (m)	First Attachment NLDN DE (%)	Average First Stroke NLDN Peak Current (kA)	Subsequent Attachment(s) NLDN DE (%)	Average Subsequent Stroke NLDN Peak Current (kA)
Forked Strokes with Long Inter-stroke Intervals	33	177 (13 - 790)	1272 (414 - 3528)	93.9	-22.5	6.1	-11.5
Forked Strokes w/Short Inter-Stroke Intervals	19	4.75 (1 - 10)	419 (30 - 1094)	100	-64.7	0	n/a
Forked Strokes w/Short Inter-Stroke Intervals and Low-Altitude Branch Points	8	2.13 (1 – 5)	144 (17 – 308)	100	-83.9	0	n/a
UI Strokes	32	836 (31 – 3540)	1559 (35 – 4158)	75	-23.5	25	-8.5

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