High-Speed Video Observations of Downward Negative Lightning Attachment to Tall Structures at the Kennedy Space Center

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Abstract

High speed video observations of downward negative lightning strikes that terminated on tall structures at the Kennedy Space Center in Florida are presented with particular emphasis on the time period of the attachment process. Close observations of aborted, unconnected, and connecting upward positive leaders from tall structures are reported and analyzed. Upward leader characteristics are analyzed as functions of structure height and geometry. Finally, the high-speed video data are used to perform measurements of the striking distance for lightning strikes to tall structures. These measurements are compared with those calculated using common IEC recommended formulation.

1 Introduction

Close-range, well-resolved high-speed video recordings of downward negative lightning strikes to tall structures are difficult to obtain, often requiring extended monitoring campaigns to acquire meaningful datasets. The value of such observations to the lightning protection community is significant because the characteristics of the attachment process between the downward stepped leader and the upward connecting leader (UCL) can be clearly and unambiguously determined. Such observations of the attachment process and the interaction of the lightning discharge with the structure can influence lightning protection design standards and methodologies, many of which are based on necessarily-simplistic models of the attachment process, which recent research has shown to involve a highly complex series of electrical breakdown processes (documented in [2][3][9][10][12], among others).

In the existing literature, most high-speed video observations of lightning striking tall structures document upward, structure-initiated lightning discharges [8][11], which are most common for structures greater than about 100 m in height. Recently [5] published detailed high-speed video observations of the attachment processes preceding the first return strokes of 24 downward negative lightning discharges that struck various tall structures in Guangzhou, Guangdong, China. The events reported by [5] generally attached to tall buildings and towers ranging in height from 300 m to 610 m. Based on their high-speed video observations, [5] documented three types of connection scenarios between the downward leader and the UCL.

The Kennedy Space Center (KSC) in Florida provides a unique opportunity to study the interaction of downward negative lightning with a variety of tall structures, many of which range in height from 100 m to 200 m. These structures include launch complex lightning protection systems, mobile launch support towers, vertical vehicle/payload integration facilities, and communications/weather towers. Further, unlike prior observations, which generally addressed lightning attachment to tall, pointed structures, many of the tall structures at KSC have extremely large footprints established by extensive overhead catenary wire and down-conductor lightning protection systems. Thus, it is possible to study not only the relationships between the lightning attachment process as a function of structure height, but also as a function of structure overall geometry.

This paper documents the attachment process of one particularly unique downward negative lightning discharge that terminated on the Launch Complex 39B (LC-39) lightning protection system [6]. The high-speed video data presented herein reinforce the complexity of the attachment process via multi-angle high-speed video observations recorded from much closer distance (< 300 m) than prior studies. Further, general qualitative and quantitative observations of the lightning attachment processes are provided, with particular focus on the relationship between structure height and geometry versus UCPL characteristics. Finally, striking distances are calculated for strikes to tall structures at KSC via the recommended formulation provided in the International Lightning Protection Standard, IEC-62305. The calculated striking distances are compared with the observed striking distances based on the high-speed video records.

2 Experimental Setup

The LC-39B lightning protection system consists of three, 181 m towers in a triangular orientation that support an overhead catenary wire system and a network of nine down conductors [6]. The catenary wire system and down conductors are isolated from the metallic towers via FRP insulating masts. The LC-39B lightning protection system is continuously monitored by a network of seven Phantom high-speed cameras, two located on each tower at the 147m level near the base of the FRP masts, and an additional camera located on the roof of the Vehicle Assembly Build-

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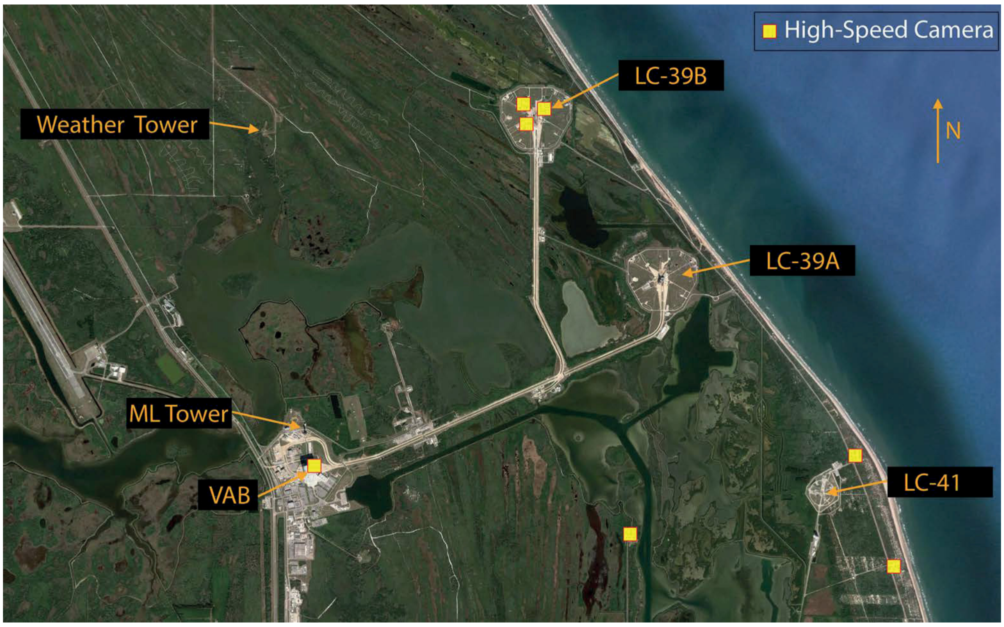

Figure 1 Layout of the high-speed camera network at the Kennedy Space Center. Camera locations are shown in yellow squares while prominent launch complexes and other tall structures are annotated.

ing (VAB), located about 5 km to the southwest of LC-39B. The cameras record at a frame rate of 3,200 frames/second (312.5 µs frame interval).

A separate network of high-speed cameras provides continuous lightning monitoring for Launch Complex 41 (LC-41), where the Atlas/Vulcan series of vehicles are currently launched. In addition to capturing all lightning activity occurring in the vicinity of LC-41, this network of cameras also images direct lightning strikes to the VAB, Mobile Launch Tower (105m tower located adjacent to the VAB during the study period), Launch Complexes 39A/39B, and a 152m weather tower located west of LC-39B. The cameras record at frames ranges of either 3,200 frames/sec or 16,000 frames/sec (62.5 µs frame interval).

An overhead view of KSC showing the locations of all cameras and tall structures discussed in this paper is shown in Figure 1. Figure 2 shows an isometric view of the detailed geometry of LC-39B, including the lightning protection towers (Tower 1, Tower 2, and Tower 3), the overhead catenary wire system and down-conductors, and the locations of the high-speed cameras and peripheral down-conductor current and electromagnetic field measurements.

3 Direct Strike to LC-39B

The downward negative flash documented in this paper occurred at 18:02:54.543698 (UT) on March 29, 2014. The flash was recorded by all high-speed cameras on the lightning protection towers at LC-39B in addition to the camera on the VAB roof. Four 312.5 µs frames captured from the VAB roof camera are shown in Figure 3. Three sequential frames are shown prior to the attachment followed by a single frame following the attachment to illustrate the full geometry of the attachment region. The images have been inverted and contrast enhanced to more clearly show the leader propagation. The downward stepped leader propagated in a highly branched manner. In response to the downward stepped leader, two long sustained upward connecting positive leaders (UCPLs) were launched from the vicinity of Tower 2 and Tower 3, while a third upward positive leader (UPL) was launched from the vicinity of Tower1 (Figure 3, Frame -3). The upward leaders are labeled L1, L2, and L3 in Figure 3, corresponding to their general origination points at Tower 1, Tower 2, and Tower 3 (see Figure 2). At the end of the Frame -3, which ended about 136 µs prior to the attachment, L1, L2, and L3 had 2D lengths of about 106 m, 218 m, and 116 m, respectively. Leaders L2 and L3 both connected to different branches of the downward leader within a time period of a couple microseconds (Figure 3, Frame 0). The return stroke current due to the nearly simultaneous attachment points was directly measured at ground level on all nine LC-39B down conductors. The current waveforms are plotted in Figure 4 on a 40 µs timescale. The sum of the peak down conductor current waveforms totaled about -55.5 kA.

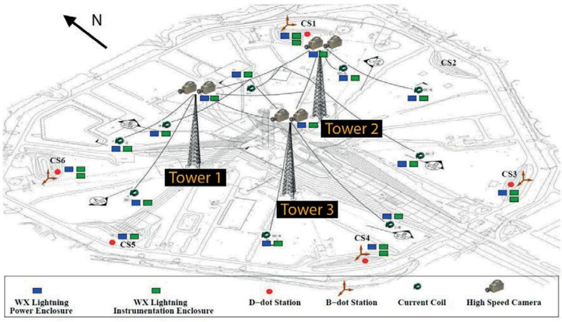

Figure 2 Geometry of the LC-39B lightning protection system. The towers, catenary wires, down-conductors, and instrumentation stations are annotated.

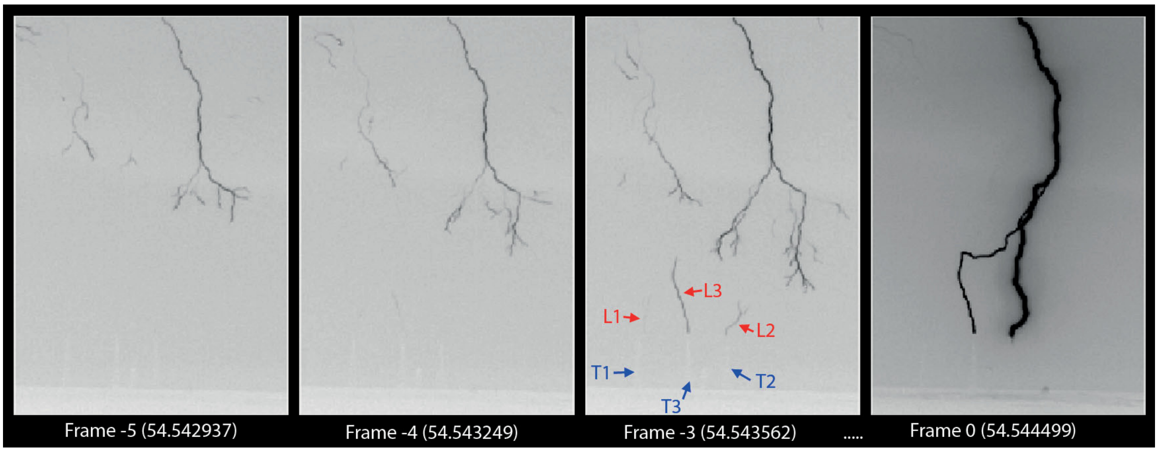

Figure 3 High-speed video frames recorded of the direct strike to LC-39B from the VAB roof.

The view of the attachment process from a distance of 5 km (Figure 3) provides a macroscopic window into the complex series of electrical breakdowns that occur at or near where the three sustained upward leaders initiated. The high-speed cameras located on the lightning protection towers at LC-39B provide much higher fidelity views of the attachment process at distances ranging from about 190 m to 275 m.

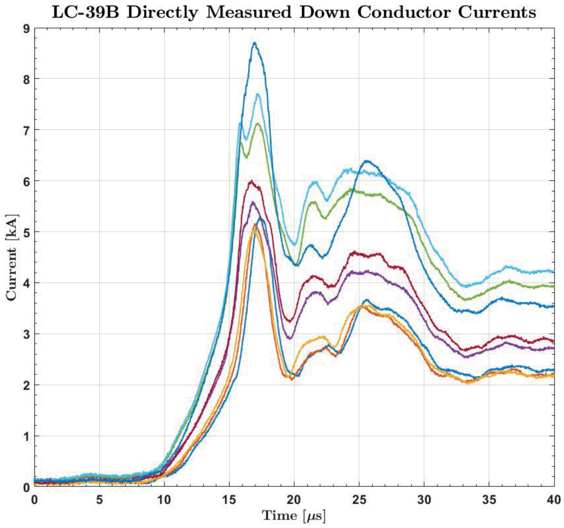

Figure 4 Directly-measured LC-39B down-conductor current waveforms.

3.1 Tower 1 Data

Ten consecutive 312.5 µs frames captured by the high-speed camera on Tower 2 that views Tower 1 are shown in Figure 5. The images have been inverted and contrast enhanced. The images were recorded at a distance of about 272 m. The return stroke occurs about 167 µs prior to the end of Frame -2. The first visible response of the catenary wire system to the downward stepped leader occurs in Frame -9, which ended about 2.02 ms prior to the return stroke, and when the stepped leader was at an altitude of about 700 m above Tower 1. In Frame -9, a 4.4 m UPL is launched from the air terminal atop Tower 1. Interestingly, the UPL that initiated from the air terminal, which is the highest point on the lightning protection system and where the local electric field enhancement might be expected to be the greatest, appears to die after Frame -9 and is not imaged through the return stroke. An additional aborted UPL is initiated in Frame -8 from the catenary wire that connects Tower 1 to Tower 2. This leader also dies by the end of Frame -7. In Frame -6, the long, sustained UPL that was imaged from the VAB roof camera is initiated from the catenary wire. The point where the long UPL is initiated is about 20 m from the air terminal atop Tower 1. An additional aborted UPL is visible in three frames coincident with the sustained UPL (Frame -6 through Frame -4). The sustained UPL continues to propagate towards the downward stepped leader (Figure 3) until the return stroke, which occurs in Frame -2.

3.2 Tower 2 Data

In Figure 6, 10 video frames (312.5 µs frame interval) are shown that were recorded by the high-speed camera on Tower 1 that views Tower 2. Figure 6 shows the nine frames prior to the return stroke and a single frame following the return stroke (when the image was not fully saturated). The images have been inverted and contrast enhanced. The first UPL activity was recorded in Frame -11, when a 7 m long UPL was launched from the air terminal atop Tower 2. At the end of Frame -11, about 2.6 ms prior to the return stroke, the downward stepped leader was at an altitude of about 757 m above Tower 2. There was no visible leader activity in the vicinity of Tower 2 for the next two frames. In Frame -8, three short aborted UPLs were launched from the catenary wire that connects Tower 2 to Tower 1. The two aborted UPLs towards the top of Frame -8 are not imaged in the subsequent frames, while the UPL at the bottom of Frame -8 is imaged in Frame -6 and Frame -5 (although the leader does not appear to extend). The UCPL is initiated in Frame -6, which ends about 1 ms prior to the return stroke, and when the downward stepped leader is at an altitude of about 391 m. Like the case of Tower 1, the UCPL is not initiated from the air terminal, but instead from the catenary wire about 8 m from Tower 2. The UCLP propagated towards and connected to

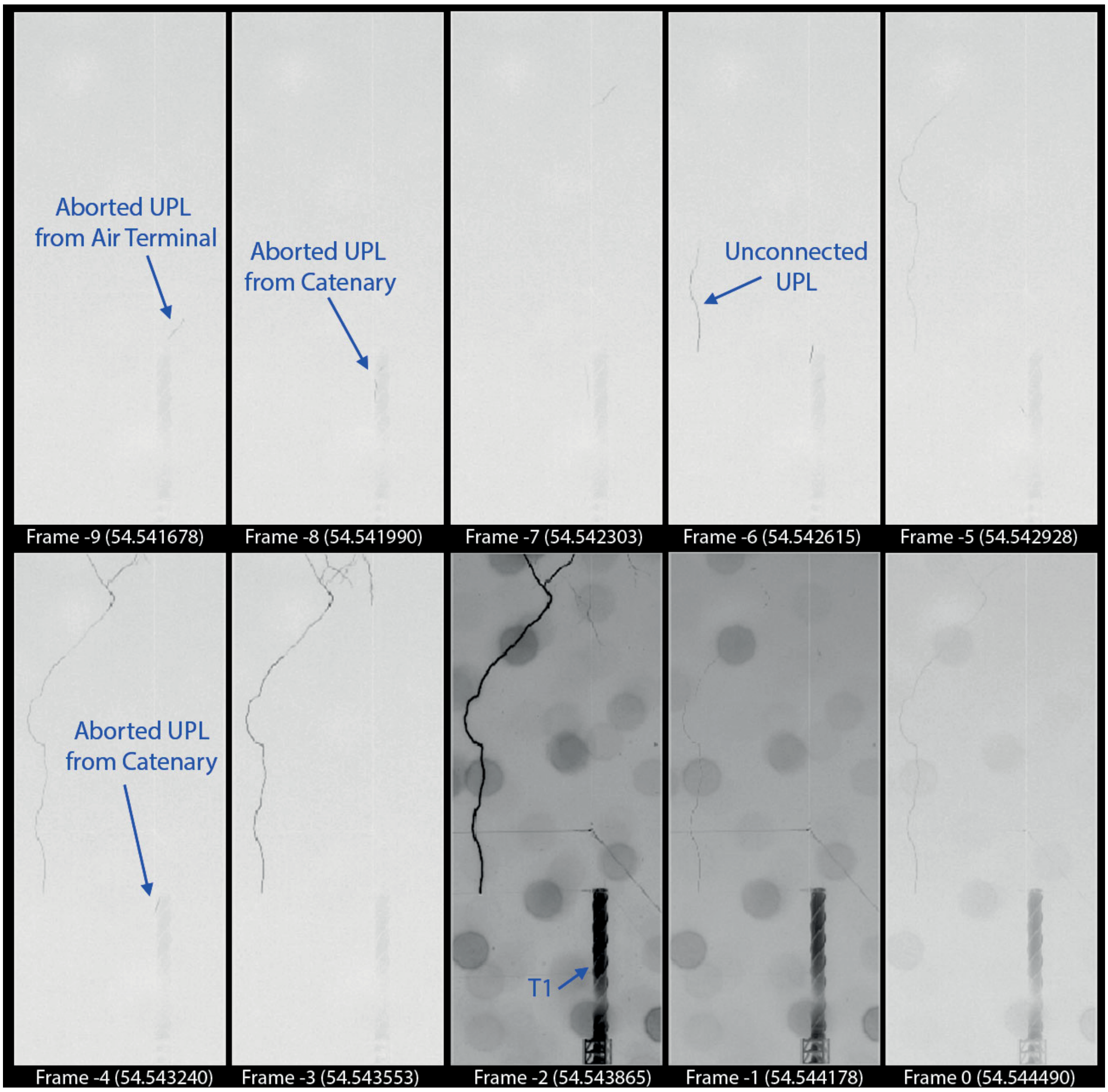

Figure 5 Upward leader activity imaged in the vicinity of Tower 1. The long sustained UPL initiated from a point about 20 m from the Tower 1 air terminal.

the rightmost branch of the stepped leader (Figure 3).

3.3 Tower 3 Data

Ten consecutive images (312.5 µs frame interval) captured by the high-speed camera on Tower 2 that views Tower 3, a distance of about 275 m, are shown in Figure 7. The images have been inverted and contrast enhanced. Like the observations at Tower 1 and Tower 2, the first leader activity from Tower 3 originates from the air terminal in Frame -9. Frame -9 ends about 2.2 ms prior to the return stroke when the downward leader is at an altitude of about 690 m above Tower 2. In this case, the initial leader is actually the UCPL that eventually connects to the downward stepped leader. At the end of Frame -9, the UCPL is about 1.5 m in length. No leader activity is visible in Frame -8. In Frame -7, the UCPL from the air terminal extends slightly and another UPL is initiated from the catenary wire adjacent to the Tower 3. The UCPL begins to accelerate in Frame -6. In Frame -6 and Frame -5, there are several additional aborted UPLs that originate from the catenary wires in close proximity to Tower 3. Following Frame -6, the UCPL continues to propagate upward and connects to the downward stepped leader in Frame -1.

4 Discussion

The response of the LC-39B lightning protection system to the downward stepped leader was highly complex, resulting in two UCPLs and a long unconnected UPL that each extended more than 100 m from the initiation point. In addition, the high-speed video images of three tower tops (Figure 5, Figure 6, and Figure 7) showed many additional short aborted UPLs that failed to transition to propagating leaders. Saba et al. [2017] have recently reported on similar aborted UPL observations from common buildings in Brazil. It is important to note that such observations of the attachment process, which are rare in the literature, can only be recorded from very close distance where pixel resolution and local atmospheric conditions do not significantly impact the image fidelity. For all three towers, the

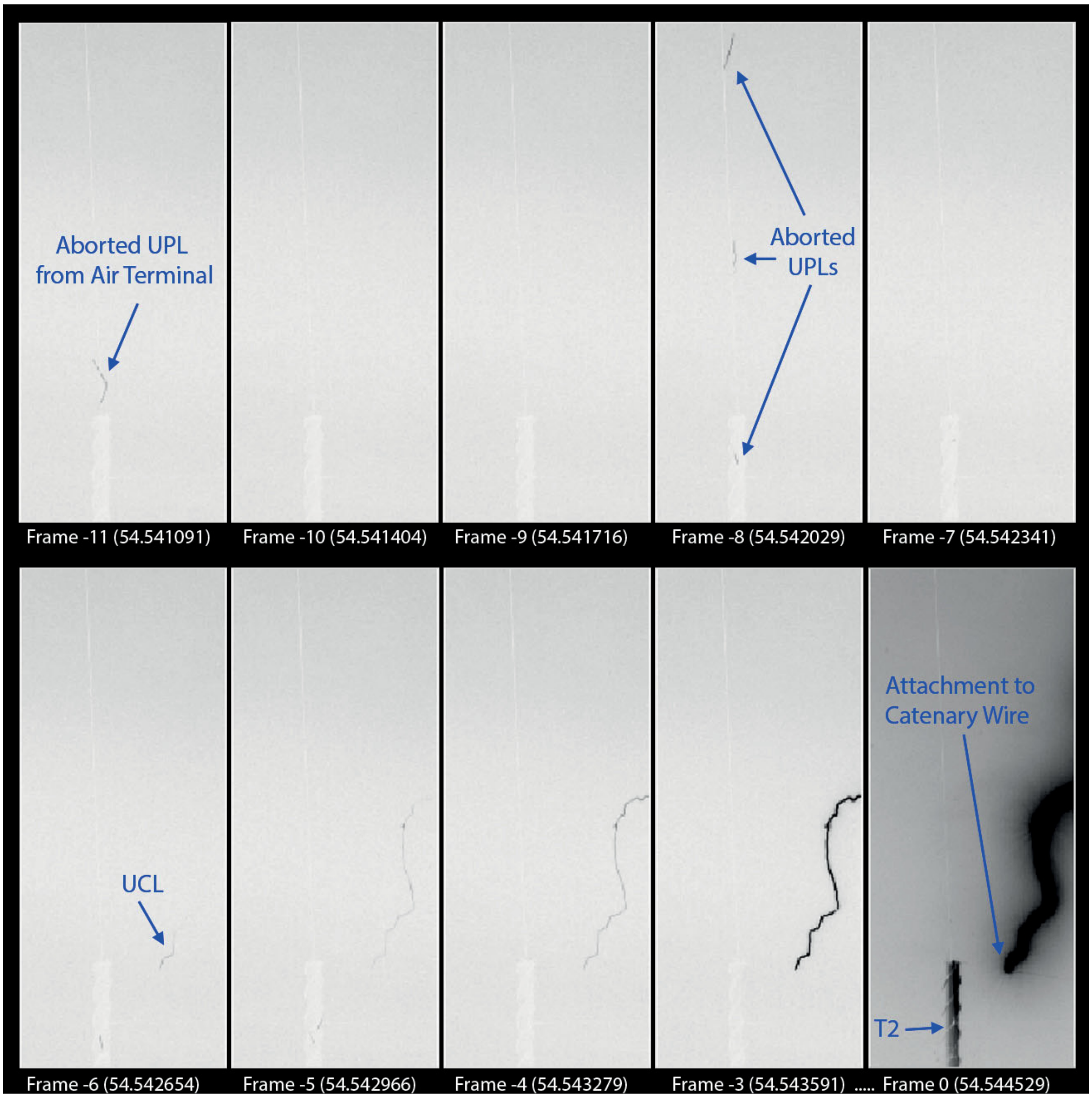

Figure 6 . Upward leader activity imaged in the vicinity of Tower 2. The long sustained UPL initiated from a point about 8 m from the Tower 2 air terminal.

initial upward leader activity occurred from the air terminal atop the tower from about 2-2.6 ms prior to the return stroke when the downward stepped leader was around 700 m in altitude above the lightning protection system. Interestingly, in only one case (Tower 3), the initial leader activity from the air terminal actually resulted in a propagating upward leader. For both Tower 2 and Tower 1, the long sustained upward leaders actually initiated from the catenary wires at distance of about 8 m and 20 m from the air terminals. These combined observations indicate that the initial electric field enhancement over the LC-39B lightning protection system was likely greatest at the air terminals (when the stepped leader was at higher altitude), perhaps due to the cumulative field from the highly branched stepped leader. However, as the stepped leader approached within a few hundred meters of the lightning protection system, the field enhancement due to the small-scale geometry of the stepped leader branches relative to the overhead lightning protection system, which is essentially a planar network of catenary wires at about 180 m altitude, appears to have superseded any local field enhancement that may have been present due to the 3-ft air terminal on each tower top. This suggests that the electric fields radiated by the stepped leader as it neared ground may have varied significantly over the top of the catenary wire system, and that strong local field enhancement due to individual leader steps may be responsible for the many upward leaders that were initiated from the catenary wires instead of the protruding air terminals. Note the catenary wires are relatively smooth stainless steel braided wire ropes without protrusions where significant field enhancement might be expected.

5 Striking Distance Observations

The high-speed video observations recorded at KSC provide a unique opportunity to measure the striking distance for direct strikes to tall structures. The IEC provides a recommended formula for striking distance according to Equation 1 as a function of return stroke peak current *I*,

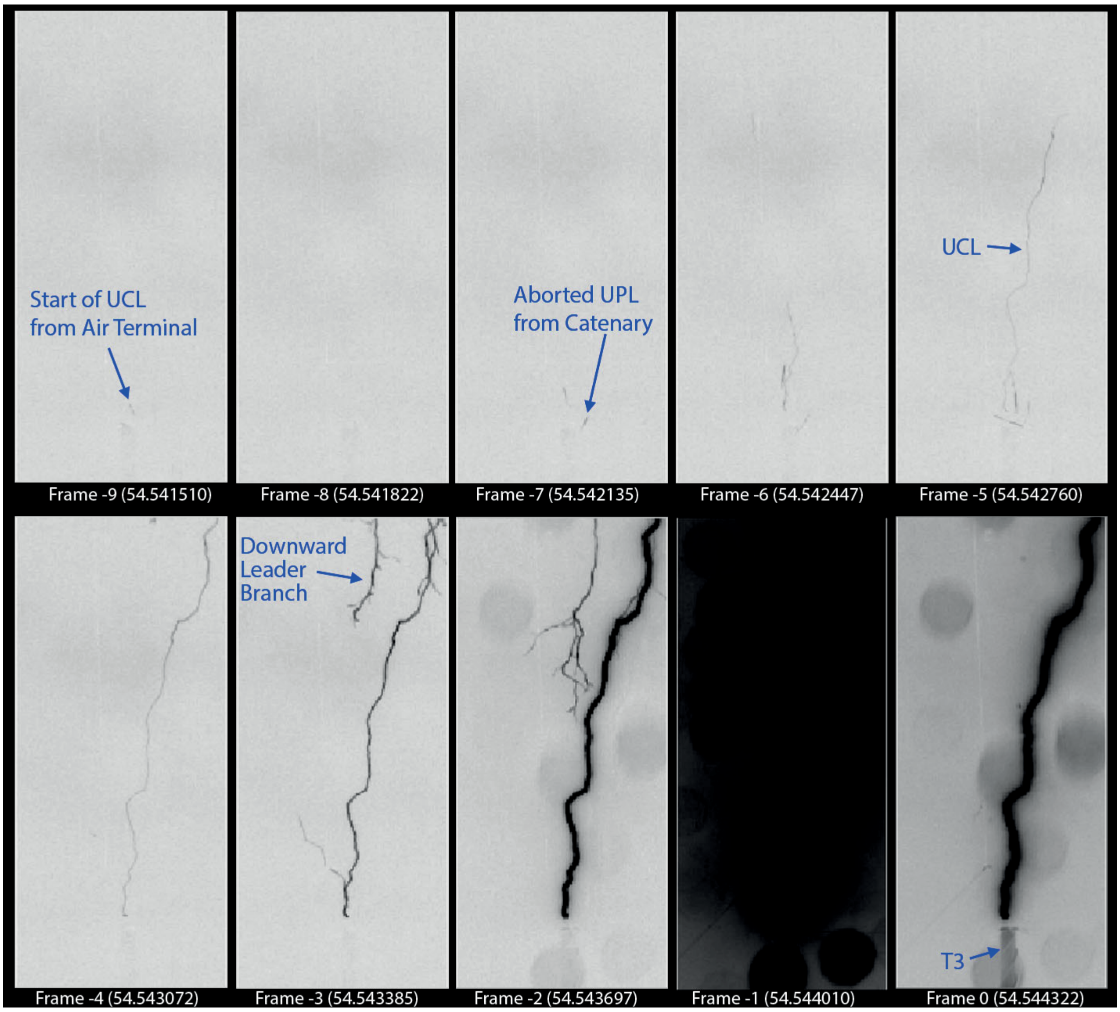

Figure 7 Upward leader activity imaged in the vicinity of Tower 3. The long sustained UPL initiated from the air terminal.

where I is in units of kiloamperes.

$$R_s = 10 \cdot I^{0.65} \tag{1}$$

The striking distance is defined as the distance between the downward leader tip and the structure or ground at the instant when the upward connecting leader is initiated. For the LC-39B direct strike discussed above, striking distances can be determined from the experimental data independently for the direct attachments to Tower 2 and Tower 3. For Tower 2, the UPCL initiated from the catenary wire when the stepped leader tip was about 391 m above Tower 2. For Tower 3, the UPCL initiated from the air terminal when the stepped leader tip was about 690 m above Tower 3. Recall that the measured peak current of the LC-39B direct lightning strike was about -55.5 kA. There is not a reliable method to determine how much current is attributable to each of the nearly simultaneous attachment points because the currents were measured at ground level, however, based on the high-speed video images (Figure 3), the attachment to Tower 2 conducted a larger current than the attachment to Tower 3. Interestingly, the sustained UCPL propagation initiated earlier from Tower 3 than Tower 2, despite that Tower 3 appears to have been associated with a lower current attachment. If we assume that Tower 2 conducted 60% of the current (about -33.3 kA) and Tower 3 conducted 40% of the current (about -22.2 kA), then the calculated striking distances are 97.6 m and 75.0 m, respectively. If a single striking distance is calculated assuming the full current of -55.5 kA, the calculated striking distance is 136.1 m. Compared to the measured striking distances of 391 m (Tower 2) and 690 m (Tower 3), the calculated striking distances, per the recommended IEC formula, are significantly lower.

A second example case study is provided in Figure 8. Here, a downward negative lightning discharge attached to a 152 m weather tower at KSC. The 62.5 µs frame interval images in Figure 8 show the frame where the initial UCL was imaged from the top of the tower and the frame immediately prior to the attachment. In this case, the UCL extended more than 530 m before connecting to the downward stepped leader. The NLDN peak current for the stroke was -74.4 kA. Based on Equation 1, the calculated striking distance for this return stroke was 164 m. The experimentally-determined striking distance, based on the high-speed video image shown in Figure 8, is about 673 m, a difference of more than a factor of four. Note that this discharge was captured by a camera located at a distance of almost 10 km. It is likely that the UCPL initiated earlier

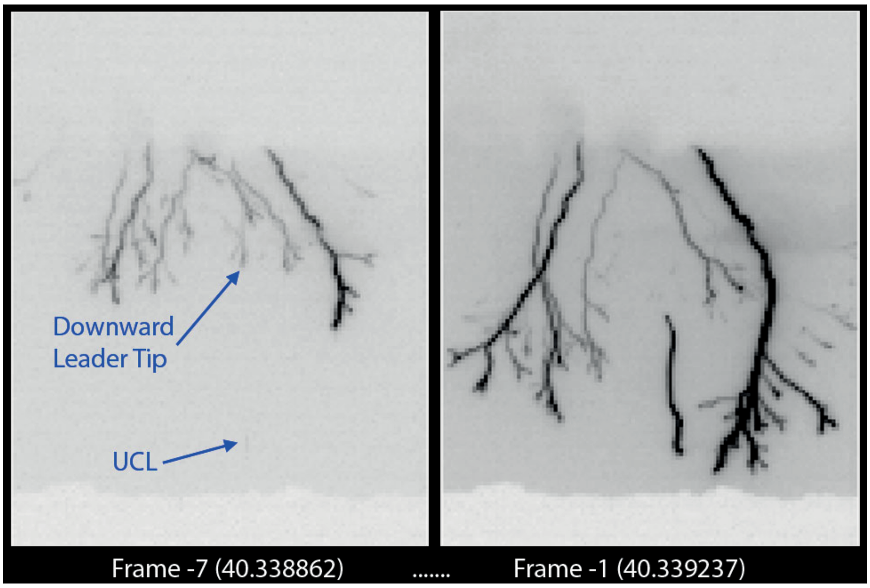

Figure 8 A direct strike to a 152 m weather tower at KSC. The UPCL extended to more than 530 m before connecting to the downward stepped leader.

than observed in the high-speed video images, and thus, the measured striking distance is likely an underestimate.

Previous studies have examined the relationship between UPCL characteristics and structure height [e.g., Cooray et al., 2014, Rakov and Lutz, 1990], and have suggested that the common striking distances formulation may be inadequate for determining the attractive radius for tall structures. The examples shown in this paper provide experimental data to support those claims. Based on these data and other similar observations at KSC, it is clear that structure geometry significantly impacts the point during the downward leader phase when the strike point is determined.

6 Literature

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Dr. Hill received his Ph.D. degree in Electrical Engineering from the University of Florida. His research at the ICLRT focused on the mechanisms and physics of natural and triggered lightning leader propagation and ground attachment, including the related high-energy physics. Dr. Hill has authored or co-authored more than 60 articles in peer-reviewed journals, more than 45 conference publications, and more than 50 technical reports. Dr. Hill spent four years working in Kennedy Space Center's Advanced Electronics and Technology Development Laboratory, where he specialized in the design and implementation of robust, highly-accurate lightning location systems, custom lightning monitoring systems, high-speed photographic and biological imaging systems, and electromagnetic sensors. He is now a Lightning Subject Matter Expert at Scientific Lightning Solutions, where he specializes in the design of state-of-the-art lightning instrumentation systems, design and testing of complex lightning protection systems, lightning damage mitigation, and standards compliance. Dr. Hill has extensive experience in custom software development with emphasis on lightning waveform and image analysis.

Dr. Mata received his Ph.D degree in Electrical Engineering from the University of Florida. He was the lightning subject matter expert and technical lead of Kennedy Space Center's Advanced Electronics and Technology Development Laboratory for 12 years. He directed the program that designed the lightning protection and lightning instrumentation systems for NASA's Launch Complex 39B, perhaps the most sophisticated lightning protection and monitoring system in the world. Dr. Mata is the recipient of many awards, including NASA's Distinguished Public Service Medal and the NASA KSC Engineer/Scientist of the Year Award. Dr. Mata has also worked extensively with the International Center for Lightning Research and Technology (ICLRT) to evaluate and refine lightning instrumentation systems used to monitor high-tech vehicles, payloads, and high-value assets at the Kennedy Space Center, Cape Canaveral Air Force Base, and other Department of Defense locations.