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Comments on Recent Observations of Faintly Luminous Formations (FLF) Captured Using Phantom High-Speed Cameras

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***Abstract*— During 2015, the high-speed camera network at Kennedy Space Center/Cape Canaveral Air Force Station was used to study a newly-reported optical phenomenon associated with the attachment process of lightning leaders to ground. This phenomena, termed the "Faintly Luminous Formation (FLF)" by researchers in the United States has significant implications on the definition of when and where the attachment process actually begins, important parameters that impact the design of successful lightning protection systems for assets and infrastructure. Five close (<1.5 km) lightning leader/return stroke sequences were simultaneously imaged by Phantom M310/V711 and V1610 high-speed cameras. In all cases, the M310/V711 cameras recorded FLF in a single pre-return stroke frame while the V1610 cameras recorded no evidence of FLF. The data provided in this paper indicates that FLF observations shown here and in recent studies in the United States and China may be digital camera artifacts as opposed to real lightning-related phenomena.**

I. Introduction

The growing availability of digital high-speed cameras has strongly influenced the lightning research community during the past ten years. Significant advances in the cumulative understanding of optical phenomena associated with lightning have been achieved via high-speed photography, including, but not limited to the physics of lightning leader propagation (e.g., *Biagi et al*., 2009, 2010, 2014; *Gamerota et al*., 2014b, 2015; *Gao et al*., 2014; *Hill et al*., 2011; *Petersen et al*., 2013, among others), processes associated with lightning initiation (e.g., *Campos et al*., 2013; *Petersen et al*., 2014, *Stolzenburg et al*., 2013, 2014, among others), and processes involving the lightning attachment process to ground or grounded objects (e.g., *Hill et al*., 2016; *Jiang et al*., 2015; *Lu et al*., 2013; *Tran et al*., 2014, 2015a, 2015b, among others).

During the past year, researchers in both the United States and China have focused their efforts on obtaining well-resolved high-speed video observations of the attachment of negative lightning leaders to ground, an inherently difficult process to study due to the microsecond timescale on which the attachment process occurs and the unpredictable nature of natural lightning, which poses significant difficulty for capturing high-fidelity video of the attachment process at close range. The attachment process consists of the interaction of the downward propagating, negatively charged leader with one or more positively charged, upward propagating leaders that initiate directly from the ground or grounded objects. The successful connection of the downward and upward connecting leader (UCL) results in the launching of a bi-directional return stroke current wave from the junction point (e.g., *Hill et al*., 2016; *Jerauld et al*., 2007; *Wang et al*., 1999, 2013, 2014). The ground-reflected downward propagating current wave and the initially upward propagating current wave together neutralize most of the negative charge deposited by the leader channel between the cloud and ground, effectively lowering negative charge to earth.

Tran et al. [2014] recorded high-speed video of a negative cloud-to-ground lightning flash in Gainesville, Florida that exhibited an unusual, weakly luminous and continuous path between the tip of the downward propagating leader and ground in the video frame prior to the frame containing the return stroke. The data were recorded using a Phantom V310 high-speed camera operated at a frame rate of 2,500 frames/s with exposure time of 30 µs per frame. The luminous channel, which the authors termed a "Faintly Luminous Formation (FLF)" had length of at least 50 m, uncharacteristically long for an UCL initiating from the ground or short grounded object. Further, the authors used time-correlated electric field records to determine that the video frame containing the FLF ended about 76 µs prior to the return stroke. The visible connection between the downward leader tip and ground existing for many tens of microseconds prior to the return stroke initiation was previously undocumented, although it had been previously observed at the Kennedy Space Center using Phantom M310/V310 cameras. Based on the time duration between the end of the FLF frame and the return stroke, the authors calculated the so-called "channel conditioning rate", the rate at which the faint, apparently weakly conducting channel was replaced by a hot, highly conducting plasma channel, to be about 6.6 x 10^5 m/s, comparable to the measured 2D speed of the downward leader channel. Based on the slow channel conditioning rate, Tran et al. [2014] characterized the FLF as a weakly conducting streamer zone that was a manifestation of the breakthrough phase of the attachment process (e.g, *Rakov and Uman,* 2003), in which the low-conductivity streamer zones of the downward and upward streamer zones initially interact, leading to the formation of a common streamer zone and ultimately resulting in the formation of the highly conducting return stroke channel. Based on the single observation, *Tran et al.* [2014] were unable to determine if the FLF originated from the descending leader tip, the tip of the UCL, or perhaps from both locations.

Tran et al. [2015a] conducted a focused, follow-up study on FLF observations, again using a Phantom V310 high-speed camera operated at frame rates of 2,500 to 3,600 frames/s and exposure times of typically 30 µs or 80 µs. The authors used short exposure times (and relatively long dead times within each frame) to help prevent the FLF from occurring in the same frame as the return stroke. A total of 18 instances of FLFs were photographed, all in the pre-return stroke frame, and were categorized into two primary classifications, group A events with continuous FLF between the downward leader tip and the visible strike point, and ground B events with FLF extending upward from the visible strike point but not in contact with the downward leader tip. The lower-bound lengths of the FLF channels for group A events ranged from 51-200 m. There was no evidence of UCLs photographed with any of the group A events. Two group B events developed from towers of 76 m and 58 m in height, with FLF extending upward 43 m and 71 m, respectively. In contrast, the authors state that FLF were never observed connected to the downward leader tip but unconnected from ground or grounded object, leading to the conclusion that FLF develop largely upward from the strike object. Luminous formations associated with leader stepping processes (space stems/leaders) were observed below the downward leader tips, but were much shorter than the observed FLFs. For the full dataset, the time intervals between the ends of the frames containing the FLF and the initiation of the return strokes, determined from time-correlated electric field waveforms, ranged from 9 µs to 139 µs. Corresponding channel conditioning rates (e.g., *Tran et al*., 2014) were calculated to be from 0.72-2.2 x 10^6 m/s. Similar to *Tran et al*. [2014], *Tran et a*l. [2015a] interpret the slow channel conditioning rates as the FLF being composed of low conductivity streamers and not hot leader channels capable of supporting return stroke current waves. For 75% of group A events observed, the authors reported pronounced fast electric field changes associated with leader stepping processes during the time interval between the end of the frame containing the FLF and the return stroke initiation. This is indicative that the leader continued to step through the weakly conducting FLF channel without the existing channel significantly affecting the leader dynamics. With the larger dataset of events compared to *Tran et al*. [2014], the authors state that the FLF can be viewed as an extended break-through phase process lasting many tens of microseconds in which the downward leader continues to move through the common streamer zone.

Similar observations for first return strokes were reported in China by *Jiang et al*. [2015] at the Shandong Artificially Triggering Lightning Experiment during the summer of 2013. *Jiang et al*. [2015] used both Phantom V711 and M310 high-speed camera to capture weakly luminous channels between the tip of the downward leader and ground in the frame prior to the return stroke frame. *Jiang et al*. [2015] categorize the events as UCLs instead of FLF because they observed clear upward propagation in one particular case.

Both *Tran et al*. [2015b] and *Jiang et al*. [2015] also reported FLF events associated with subsequent return strokes. *Tran et al*. [2015b] examined 13 subsequent strokes that exhibited FLF in a single pre-return stroke frame. The authors found that the FLF lengths ranged from 130 m to 908 m, considerably longer than the FLF imaged for first strokes in *Tran et al*. [2015a]. Channel conditioning rates (e.g., *Tran et al*. [2015a]) were found to generally follow the speed of the downward leader, whether of the dart stepped or dart leader classification. For dart-stepped leader events, the stepping of the leader was found to be unaffected by the presence of the visible FLF. Based on the low mean value of the electric field calculated along the channel, 28 KV/m via empirical techniques, *Tran et al*. [2015b] state that the FLF observed with subsequent strokes are not streamers, but instead may be associated with ampere-scale conduction currents in the poorly conditioned channel between the leader and ground established by the increasing electric field of the descending leader.

The FLF observations reported by *Tran et al.* [2014, 2015a, 2015b] and *Jiang et al*. [2015] have important implications for understanding the attachment process of lightning to ground or grounded structures. As noted by *Tran et al*. [2015a], the fact that the downward leader is apparently connected to ground many tens of microseconds prior to the return stroke when the leader is up to many hundreds of meters above ground clearly influences the existing concept of the striking distance. The concept of striking distance is a critical parameter in the design of effective lightning protection systems for highly valued assets and structures, such as many of the launch complexes and vehicle fabrication/integration facilities at the Kennedy Space Center (KSC)/Cape Canaveral Air Force Station (CCAFS) in Florida. During the summer of 2015, existing lightning experiments were modified to image FLF events at KSC/CCAFS. The high-speed camera network at KSC/CCAFS consists of a total of 13 cameras, many with intersecting fields of view to capture multi-angle views of common discharges. Many cameras are located on tall structures, which affords unobstructed fields of view of nearby lightning events. The camera network consisted of seven Phantom V310s, two Phantom V711s, two Phantom M310s, and two Phantom V1610s. The V1610s sample at 16,000 frames/second while the remaining cameras sample at 3,200 frames/second. In all cases, the exposure was set to the reciprocal of the sample rate. In addition, supporting wideband (25 MHz, -3 dB) electric field change waveforms (dE/dt) were recorded at six independent locations.

TABLE 1. SUMMARY INFORMATION ON FIVE FLF EVENTS CAPTURED AT KSC/CCAFS DURING SUMMER 2015

	Date	Time (UT)	Distance [m]	FLF Length [m]	ΔT [μs]
Event 1	08/20/2015	18:22:38.699	590 (VAB) / 531 (LCC)	98	189
Event 2	08/20/2015	18:23:18.695	1,361 (VAB) / 1,391 (LCC)	63	43
Event 3	08/26/2015	20:52:00.225	741 (VAB) / 735 (LCC)	171	91
Event 4	08/30/2015	12:11:22.438	756 (VAB) / 746 (LCC)	172	≥ 26
Event 5	10/11/2015	21:03:01.062	718 (SB) / 1,296 (BH)	75	37

II. DATA

The high-speed camera network at KSC/CCAFS captured many FLF events during summer 2015 at distances less than 1.5 km. The characteristics of these events generally mimicked those observed in the prior studies. Further analysis revealed a set of lightning events recorded by a Phantom V711 or M310, the cameras used in the prior studies, in addition to a Phantom V1610. In each case, the FLF imaged by the M310/V711 was not evident in the video captured by the V1610 camera. The V1610 cameras were configured with exposures a factor of five less than the V711 or M310, however, the V1610 lens apertures were set a minimum of four f-stops lower than the lenses mounted on the V711 or M310 cameras, making the V1610 more light sensitive than the other cameras. Five unique examples of this observation are shown in this paper with important parameters of each event summarized in Table 1. The "Distance" column in Table 1 provides the distance between the ground truth strike location of the discharge and the camera locations, with the M310/V711 distance and location given first and the V1610 distance and location given second. Events 1-4 were recorded by a M310 camera located on the roof of the Vehicle Assembly Building (VAB) along with a V1610 located on the second floor of the adjacent Launch Control Center (LCC). Event 5 was recorded by a V711 camera located at the South Beach (SB) camera site east of Launch Complex 41 (Atlas V), and a V1610 camera located at the Beach House (BH) camera site southeast of Launch Complex 41. FLF lengths given in Table 1 do not account for three-dimensional geometry, and are thus lower bound measurements. The "ΔT" column of Table 1 provides the time duration between the end of the M310/V711 frame containing the FLF and the dE/dt return stroke peak measured at the closest sensor to the strike location.

A. Event 1

The first event studied occurred at 18:22:38.699 (UT) on August 20, 2015. The flash had two ground termination points, with the second ground termination point occurring within the field of view of both the M310 located on the VAB roof and the V1610 located in the LCC. The flash struck ground about 590 m east of the VAB camera. The pre-return stroke frame captured by the M310 is shown in Fig. 1A, while the two pre-return stroke frames captured by the V1610 are shown in Fig. 1B and Fig. 1C, respectively. The IRIG-B times corresponding to the end of each frame exposure are provided beneath each image. These times are expected to be accurate to within a few microseconds. Fig. 1A shows a continuous FLF channel (group A event from *Tran et al.* [2015a]) between the tip of the downward leader and ground. The FLF channel has lower bound length of 98 m with the M310 frame ending 189 μs prior to the dE/dt return stroke peak. The corresponding dE/dt waveform measured 3.62 km southeast of the strike location is also shown in Fig. 1. The V1610 image shown in Fig. 1B recorded two frames prior to the frame containing the return stroke and with higher sensitivity than the M310 image shown in Fig. 1A shows no evidence of FLF between the tip of the downward leader, located at an altitude of 87 m, and the ground. Note the V1610 frame exposure ended 42 μs after the M310 exposure shown in Fig. 1A. The downward leader propagated to an altitude of 52 m in Fig. 1C, again with no FLF channel visible. The V1610 image shown in Fig. 1C ended 102 μs following the M310 frame containing the FLF. The V1610 image in Fig. 1C also shows a short luminous channel segment separated from the downward leader tip, likely a space stem/leader associated with the negative leader step formation process (e.g., *Biagi et al.*, 2009, 2010; *Hill et al.*, 2011). The corresponding dE/dt waveform also clearly shows impulsive leader stepping activity between the end of the M310 frame and the return stroke peak, similar to the characteristics reported by *Tran et al.* [2014, 2015a, 2015b]. In this case, there was no UCL imaged by either the M310 or the V1610, likely indicative that the UCL occurred during the return stroke frame and was therefore masked by the return stroke luminosity.

B. Event 2

Event 2 was recorded 40 seconds after Event 1, at 18:23:18.695 (UT) on August 20, 2015. The first stroke terminated on ground 1,361 m to the NE of VAB camera. Fig. 2A shows a continuous FLF channel between the tip of the downward leader and the strike point with length of about 63 m. The second frame prior to the return stroke (Fig. 2B) recorded by the V1610 in the LCC ended with the downward leader at an altitude of about 115 m, while the pre-return stroke frame (Fig. 2C) ended with the downward leader at about 65 m altitude, just above the ending location in space of the downward leader captured by the M310 in Fig. 2A. There is no evidence of any FLF channel in either of the pre-return stroke frames captured by the V1610. The V1610 pre-return stroke frame in Fig. 2C ended 9 μs prior to the end of the M310 pre-return stroke frame in Fig. 2A, so it is possible (yet unlikely)

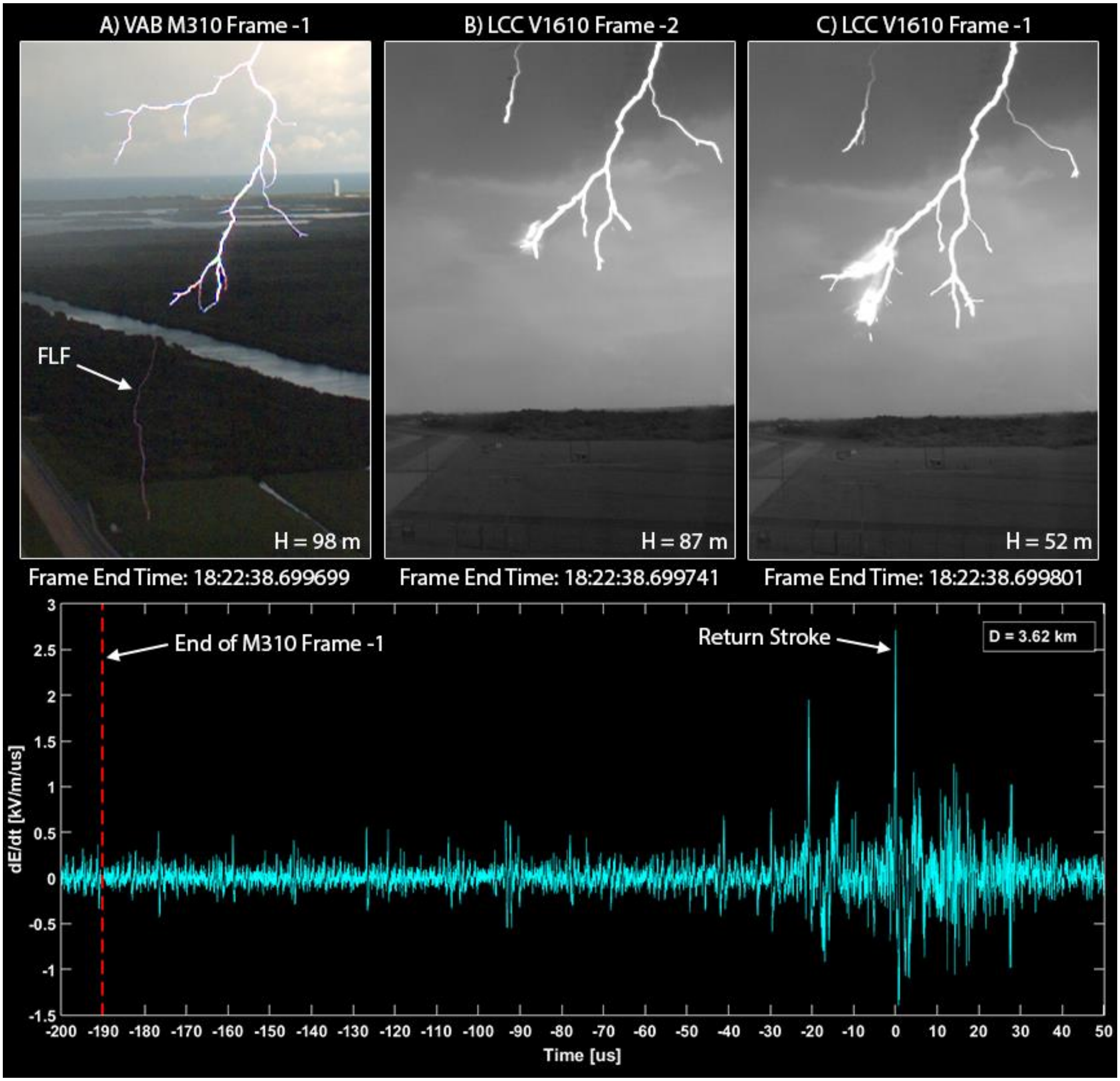

Fig. 1. Event 1 high-speed video images and dE/dt waveforms recorded on August 20, 2015 at 18:22:38.699 (UT), A) VAB M310 pre-return stroke frame showing FLF, B-C) consecutive LCC V1610 pre-return stroke frames not showing FLF.

that the FLF developed completely in this 9 μs time window, and was thus undetected by the V1610. Like Event 1, the dE/dt record measured 3.48 km to the southeast of the strike location shows clear evidence of leader stepping between the end of the pre-return stroke frame captured by the M310 and the dE/dt return stroke peak. No UCL was imaged in this case by either the M310 or V1610.

C. *Event 3*

The third FLF event was recorded on August 26, 2015 at 20:52:00.225 (UT) by the M310 on the VAB roof. The strike terminated on ground about 741 m east of the VAB. In Fig. 3A, the continuous FLF channel appears to extend 171 m between the tip of the downward leader and ground. The M310 exposure ended about 91 μs prior to the return stroke dE/dt peak shown in Fig. 3. The two frames prior to the return stroke recorded by the V1610 in the LCC are shown in Fig. 3B and Fig. 3C,

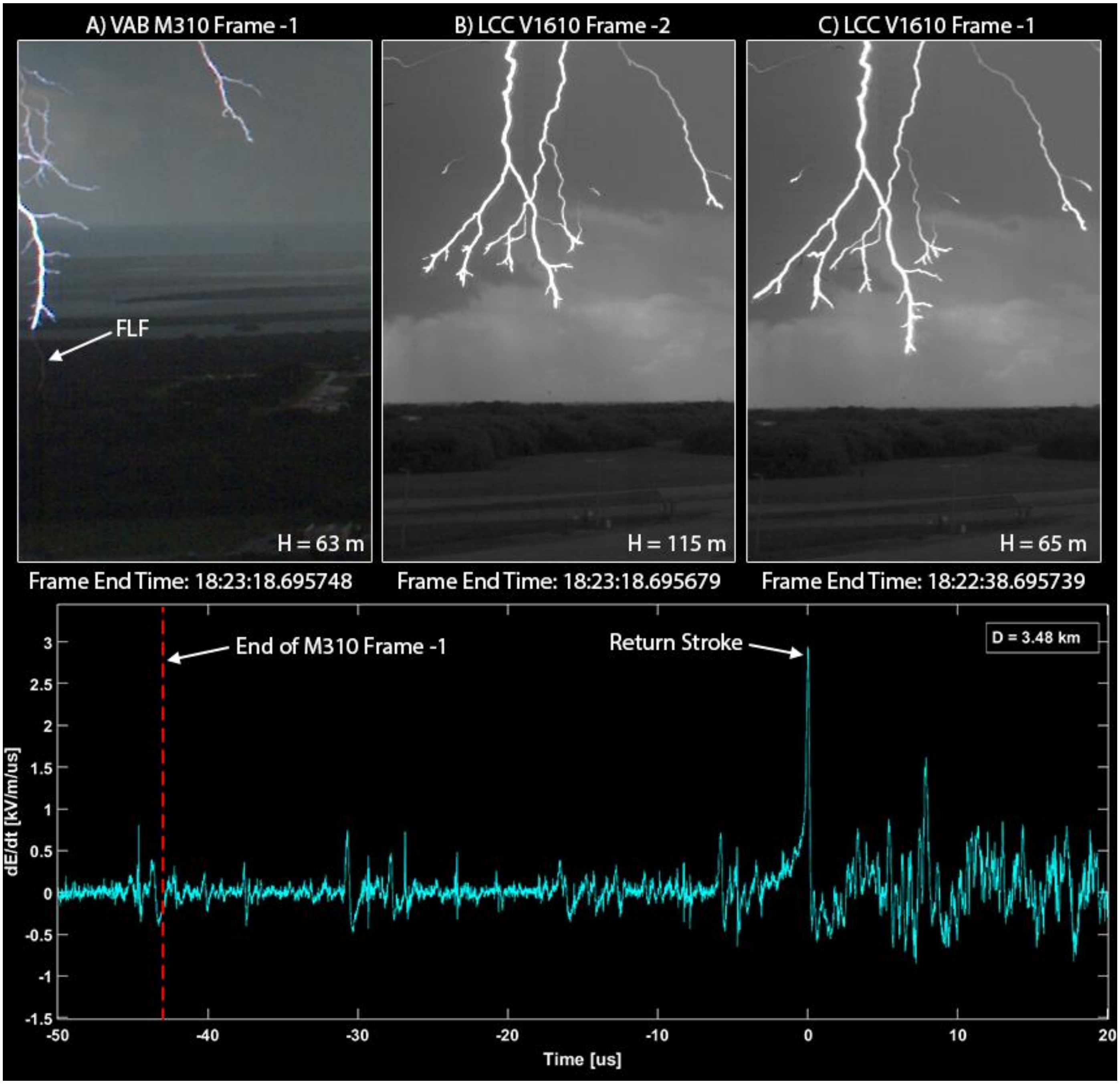

Fig. 2. Event 1 high-speed video images and dE/dt waveforms recorded on August 20, 2015 at 18:22:38.699 (UT), A) VAB M310 pre-return stroke frame showing FLF, B-C) consecutive LCC V1610 pre-return stroke frames not showing FLF.

respectively. The V1610 frame shown in Fig. 3B ended only 2 μs prior to the M310 pre-return stroke frame shown in Fig. 3A, yet no evidence of FLF is visible in the V1610 exposure. The leader propagated downward to an altitude of about 88 m at the end of the V1610 exposure shown in Fig. 3C, again with no FLF present between the leader tip and ground. The exposure shown in Fig. 3C ended 58 μs following the end of the M310 pre-return stroke frame. Based on the dE/dt leader steps waveforms shown in Fig. 3, the stepped leader clearly continued to propagate downward through the spatial region shown to be occupied by the FLF channel in Fig. 3A without being affected.

D. Event 4

Event 4 occurred on August 30, 2015 at 12:11:22.438 (UT). The discharge struck ground 756 m east of the VAB and was imaged by both the M310 on the VAB roof and the V1610 in the LCC. High-speed video images are shown in Fig. 4. The pre-return stroke frame captured by the M310 in Fig. 4A shows a FLF channel extending from ground up to an altitude of 172 m. Unlike Events 1-3, the FLF channel in this case does not

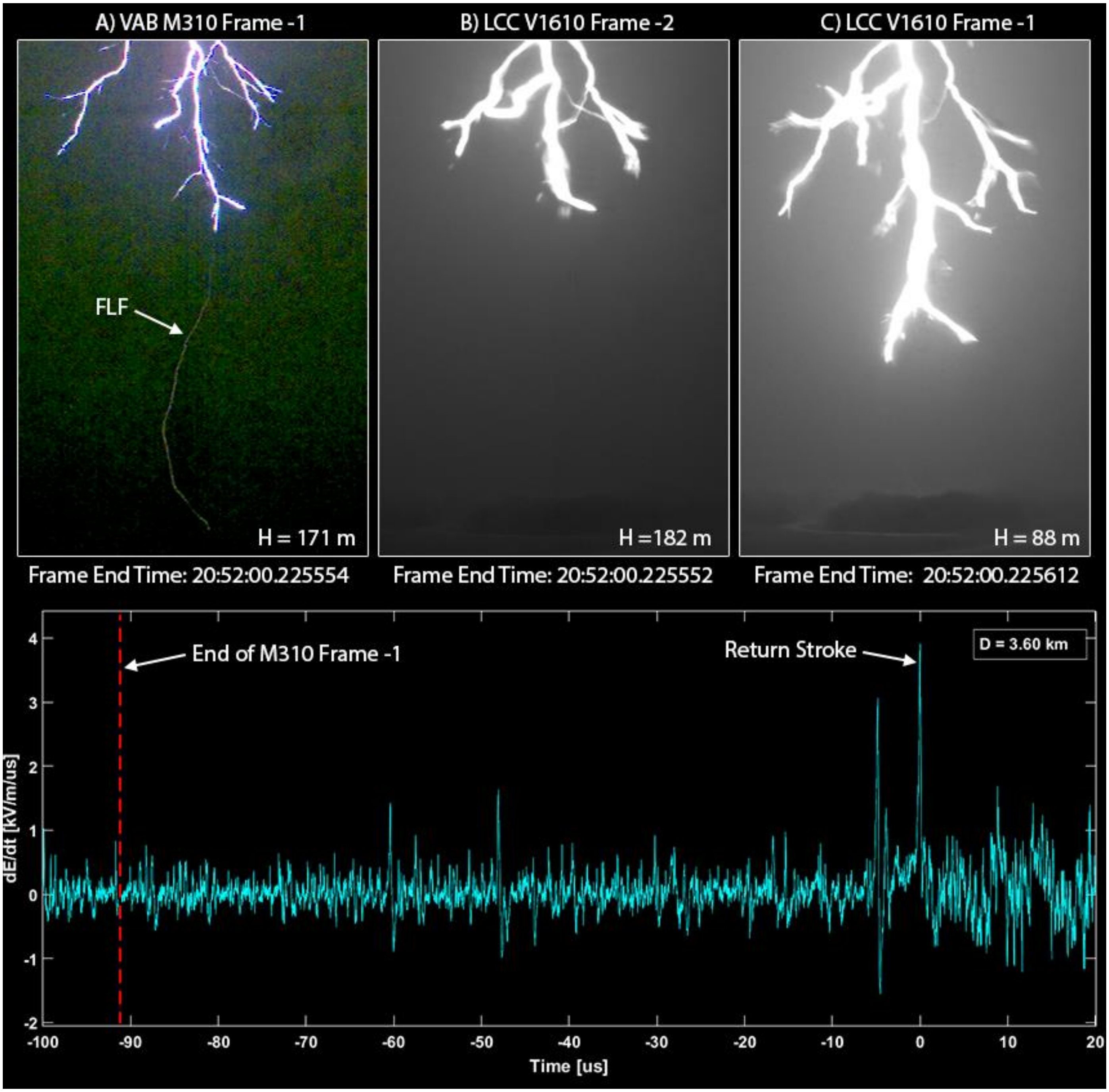

Fig. 3. Event 3 high-speed video images and dE/dt waveforms recorded on August 26, 2015 at 20:52:00.225, A) VAB M310 pre-return stroke frame showing FLF, B-C) consecutive LCC V1610 pre-return stroke frames not showing FLF.

appear to be connected to the downward leader tip, which is located at an altitude of 202 m. *Tran et al.* [2015a] classified this type of FLF as a "group B" event. The FLF image shown in Fig. 4A also shows a complex optical signature from 17 m to 33 m above ground level with multiple loops in the FLF channel. Images such as this exhibiting low-altitude loops in the channel are typically associated with the attachment region, as shown by *Howard et al.* [2010], *Jerauld et al.* [2007], and *Rakov and Uman* [2003]. In this case, the FLF channel extends for 140 m above the looped section of the channel and the downward leader tip is located nearly 170 m above the visible channel loops. The V1610 frame acquired two frames prior to the return stroke is shown in Fig. 4B. At the end of the frame, which occurred 34 μs prior to the end of the M310 frame shown in Fig. 4A, the downward leader tip was located at an altitude of 270 m. No FLF were visible below the downward leader tip. At the end of the V1610 pre-return stroke frame shown in Fig. 4C, the downward leader had descended to an altitude of 149 m, below the top of the FLF region shown in Fig. 4A. The V1610 frame shown in Fig. 4C ended 26 μs following the end

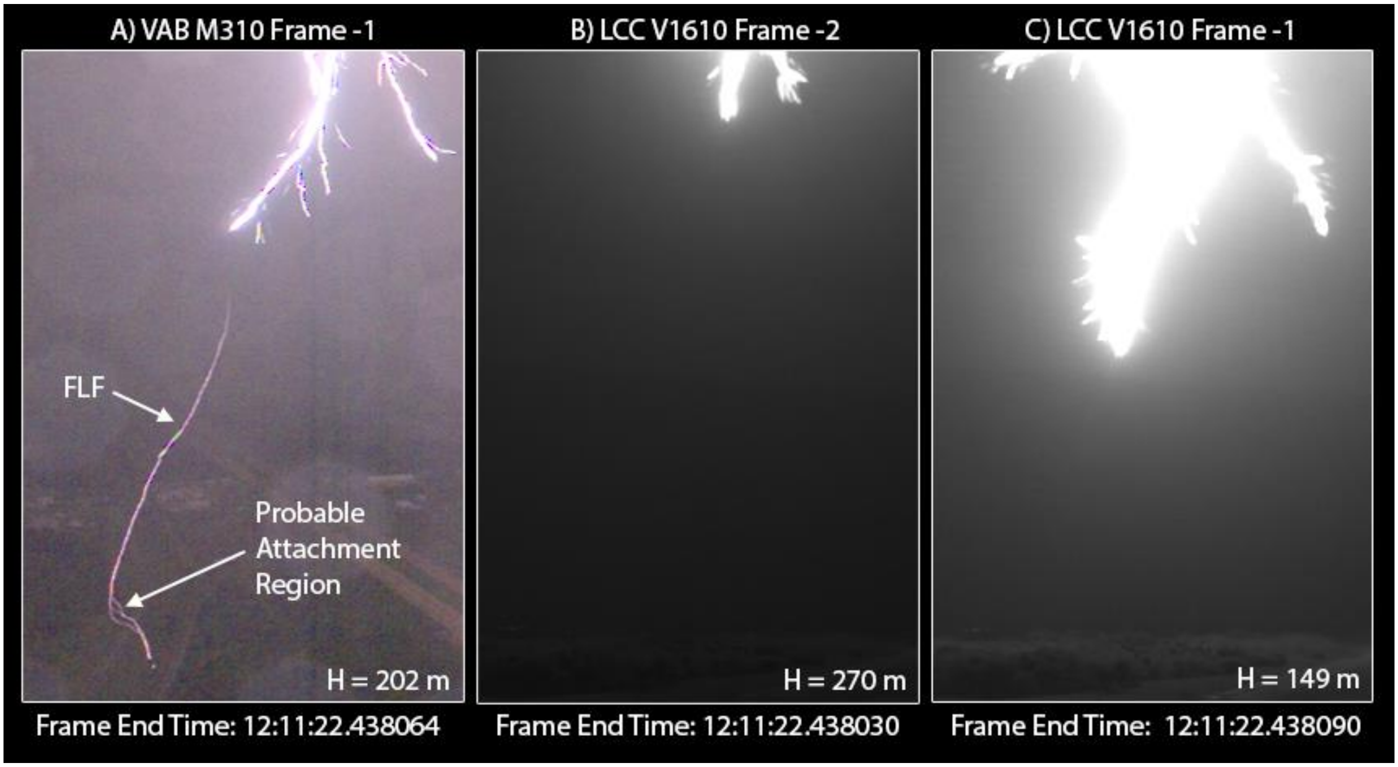

Fig. 4. Event 4 high-speed video images recorded on August 30, 2015 at 12:11:22.438, A) VAB M310 pre-return stroke frame showing FLF, B-C) consecutive LCC V1610 pre-return stroke frames not showing FLF.

of the M310 pre-return stroke frame shown in Fig. 4A, but no FLF channel is visible. No dE/dt waveform data were available for this event.

E. Event 5

The final FLF presented in this paper was photographed at 21:03:01.062 on October 11, 2015. The stroke attached to the southwestern lightning protection system mast at Launch Complex 41. A V711 high-speed camera recorded the event from the South Beach camera site, located 718 m northeast of the strike location, while a V1610 recorded the stroke from the Beach House camera site, located 1,296 m to the southeast of the strike location. The V711 pre-return stroke frame in Fig. 5A shows the FLF connecting the top of the mast to the downward leader tip. In this case, the FLF channel exhibited a pronounced sharp bend. The total length of the FLF channel was about 75 m, with the leader tip about 50 m above the strike location. The V711 pre-return stroke frame also shows unconnected upward leaders initiating from the northwestern lightning protection system mast as well as the overhead catenary wire system and down conductors. The V711 pre-return stroke frame ended about 37 µs prior to the return stroke dE/dt peak shown in Fig. 5. The two V1610 frames captured prior to the return stroke are shown in Fig. 5B and Fig. 5C. In Fig. 5B, the downward leader descended to an altitude of about 58 m above the strike location. The frame also captured an upward leader propagating from strike location with length of about 22 m. No visible connection was present between the downward and upward leaders at the end of the exposure in Fig. 5B, which ended about 34 µs prior to the end of V711 pre-return stroke frame in Fig. 5A. Additional unconnected upward leaders are also shown in Fig. 5B. Fig. 5C shows the downward leader descending to an altitude of 40 m above the strike location, with the upward leader extending 32 m above the strike location. Though difficult to resolve in Fig. 5C, there is a faint connection between the upward and downward leaders that is likely the initial interactions of the streamer zones prior to the full attachment. The V1610 pre-return stroke frame in Fig. 5C ended 29 µs following the end of the V711 pre-return stroke frame shown in Fig. 5A. As with the prior four events, the downward leader continued to propagate in a stepping manner following the establishment of the FLF shown in Fig. 5A.

III. DISCUSSION

The fact that FLF events similar to those shown by *Tran et al*. [2014, 2015a, 2015b] and *Jiang et al*. [2015] were also imaged by the same model Phantom M310 and V711 high-speed cameras at KSC/CCAFS, but were not imaged by Phantom V1610 cameras operating with higher sensitivity raises the question of whether the FLF events are real lightning optical phenomena, or alternately, are actually digital camera artifacts. Certain characteristics of the FLF observations presented here and in the previous studies are difficult to interpret, most notably that the stepwise propagation of the downward leader appears to be unaffected by the presence of the apparently pre-conditioned FLF channel, and that the attachment process appears to begin many tens of microseconds prior to and at much higher altitude than well-documented examples of the natural lightning attachment process to ground shown in the literature. To address these concerns, the authors

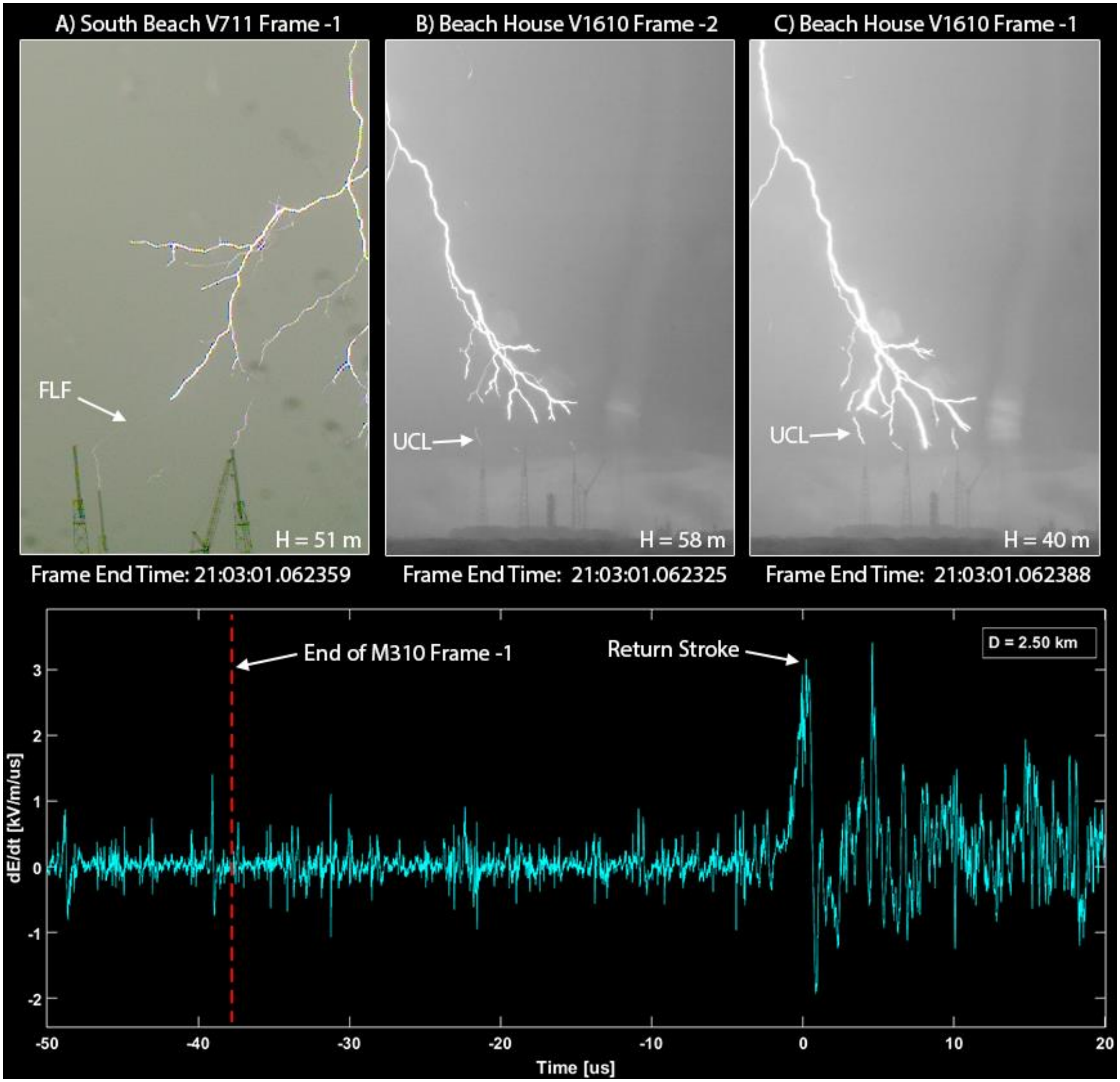

Fig. 5. Event 5 high-speed video images and dE/dt waveforms recorded on October 11, 2015 at 21:03:01.062 A) South Beach V711 pre-return stroke frame showing FLF and multiple unconnected upward leaders, B-C) consecutive Beach House V1610 pre-return stroke frames not showing FLF, but showing both a UCL and multiple unconnected upward leaders.

contacted Vision Research, the company that designs and manufactures the high-speed cameras used in the FLF studies. The raw camera .CINE files that produced the extracted images shown in this paper were sent to the engineering team at Vision Research for in-depth analysis. The response from Vision Research is quoted below:

"*There is a characteristic of digital sensors that have a pipelined architecture (that is, the ability to start acquiring a frame while the previous frame is being read out of the sensor) called parasitic light sensitivity or PLS. During the readout of a given frame, some charge can accumulate in pixels that are quickly and highly saturated by the next frame. This results in those pixels displaying some of what will occur in the subsequent frame--a quick peek into the future. There may be information in the artifact. In the case of these lightning strikes, the artifact shows the path of the leader as it contacts the ground, or perhaps a very short glimpse of the main discharge.*"

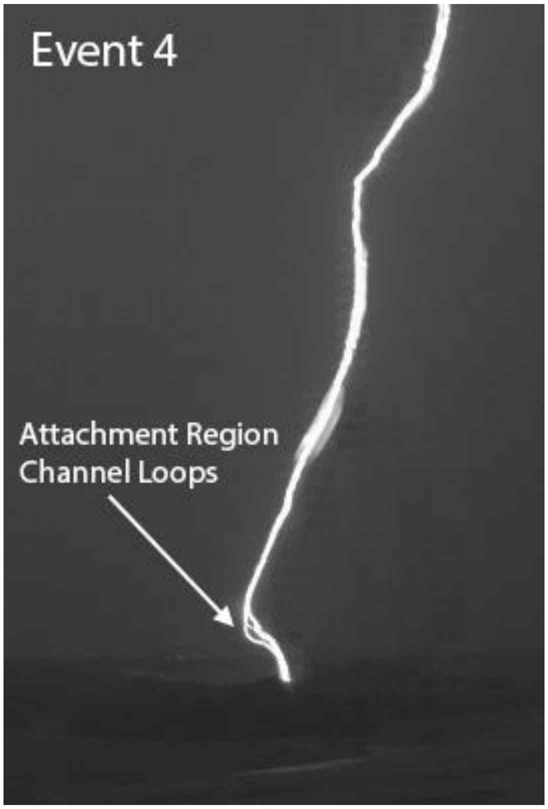

Fig. 6. Post return-stroke LCC V1610 frame recorded during Event 4 on August 30, 2015 at 12:11:22.438 showing channel loops from 17-33 m above ground level. The channel loops are typically indicative of the region where the attachment process occurred.

The authors believe the analysis performed by Vision Research suggests that the FLF observations presented here and in the prior studies are likely not real lightning optical phenomena. All FLF events recorded in this study and in *Tran et al*. [2014, 2015a, 2015b] were observed in a single frame prior to the frame containing the return stroke. In all cases, the return stroke channel produces a significant saturation of the camera sensor in the frame following the FLF observation. Based on the analysis conducted by Vision Research, it is likely that the bright light due to the return stroke produces parasitic light leakage onto the previous frame, as described in the quotation above. For Events 1-3 shown here, this light leakage effectively traced the exact path between the tip of the downward leader in the frame prior to the return stroke and the eventual strike point. For Event 4, the light leakage not only traced the path of the leader, but also showed complex characteristics of the attachment region that occurred a more-typical 17-33 m above the ground compared to the upper extent of the FLF region, which extended 172 m above the ground. A post-return stroke frame captured by the V1610 in the LCC is shown in Fig. 6. The attachment region channel loops shown in the M310 image of Fig. 4A are clearly present in the post-return stroke image as well. For Event 5, the light leakage traced the path between the downward leader tip and the strike point, and based on the two images captured the V1610 of the UCL propagation (Fig. 5B and Fig. 5C), likely also obscured the UCL captured by the V711. Note the V711 resolved multiple unconnected upward leaders prior to the return stroke for Event 5, but these leader paths were not overwritten by the highly-saturated return stroke channel in the subsequent frame.

Over the course of the summer and fall months of 2015, many hundreds of close (less than 3 km) cloud-to-ground lightning discharges were imaged by the network of M310 and V711 cameras at KSC/CCAFS. The majority of these events did not exhibit the FLF characteristics shown in Fig. 1-5 of this paper. This is likely a result of the relatively narrow lens apertures, which were typically set to *f*/11 in order to well-resolve the return stroke channels without over-saturating. In contrast, the FLF studies performed by *Tran et al*. [2014, 2015a, 2015b] and *Jiang et al*. [2015] were conducted with lens apertures set from typically *f*/1.8 to *f*/4. The prior studies recorded a much higher percentage of FLF events. Whether the M310 and V711 cameras produce the FLF characteristic shown in this paper and in the prior studies is likely dependent on many factors, including, but not limited to 1) the distance of the lightning channel from the camera, 2) the camera lens aperture, 3) the peak optical power radiated by the return stroke, 4) the time duration between the beginning of the return stroke frame and when the return stroke actually occurs within that frame, 5) the geometry and speed by which the sensor data are read following the end of the pre-return stroke frame exposure.

Phantom V310/M310 and V711 cameras utilize the same sensor, while the Phantom V1610 camera utilizes a different sensor. The sensor readout topologies are proprietary Vision Research information, although the results of this study suggest that the V1610 is capable of reading the sensor data sufficiently fast, and/or the electronic shutter is sufficiently opaque to avoid the light leakage issues experienced by the V310/M310 and V711 series cameras. The authors plan to work directly with Vision Research to test the camera models in question in a controlled environment in order to understand and better quantify the set of circumstances that lead to the recent FLF observations.

IV. SUMMARY

High-speed video images of five negative polarity lightning return strokes recorded by both Phantom M310/V711 and V1610 cameras at KSC/CCAFS during the summer and fall of 2015 were presented. The Phantom M310/V711 cameras showed FLF characteristics for each of these five events, while the Phantom V1610 cameras did not. Detailed analysis on the raw camera data by Vision Research, the designer and manufacturer of the high-speed cameras used in the present and prior studies, lead us to believe that the FLF observations are likely not real lightning optical phenomena, but are instead related to parasitic light leakage that occurs when the camera sensor is highly saturated by the return stroke during the readout period of the pre-return stroke frame. Future efforts will be conducted in collaboration with Vision Research to better understand and quantify the circumstances that allow this issue to occur.

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