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Upward Leader Currents Measured at the Kennedy Space Center Industrial Area Tower

A. Nag[1], K. L. Cummins[1,2], M. Plaisir[1], J. Wilson[3], D. Crawford[3], R. Brown[3], C. Noggle[1], H. K. Rassoul[1]
[1] Florida Institute of Technology, Melbourne, Florida, USA, [2] University of Arizona, Tucson, Arizona, USA, [3] NASA Kennedy Space Center, Florida, USA

***Abstract*—We present measurements of currents associated with unconnected upward leaders initiated from the Kennedy Space Center (KSC) Industrial Area Tower (IAT). Eight unconnected upward leaders (UULs) were initiated from the KSC-IAT between August 1, 2018 and November 15, 2019. All UULs were positive as they occurred in response to downward negative leaders that attached to ground near the tower. The KSC Mesoscale Eastern Range Lightning Information System (MERLIN) located these nearby strokes at distances ranging from 185 to 783 m from the tower, with the median being 538 m. The peak current for these strokes ranged from 13 to 69.3 kA, with the median being 26.7 kA. The durations of the eight UULs prior to current polarity reversal ranged from 116 µs to 1.15 ms, with the median being 789 µs. UUL-currents typically consisted of faster (ten-microsecond-scale) impulses overlaid on a slower (millisecond-scale) "background" current.**

Keywords-Instrumented tower; unconnected upward leaders; lightning; currents; charge transfer

I. INTRODUCTION

Measurements of lightning currents at instrumented towers are important for understanding the physics of various lightning processes. Current measurements of the first leader-return-stroke sequence in natural lightning can provide important insights into the characteristics of upward leaders and first return strokes. However, attachment of downward first strokes to tall, instrumented towers is relatively rare (e.g., Berger et al., 1975; Visacro et al., 2004, 2012; Takami and Okabe, 2007; Miki et al., 2019 [1-5]). The Industrial Area Tower (IAT) (Nag et al., 2021 [6]) at the Kennedy Space Center (KSC) is located in a region with flat ground experiencing lightning flash density in the range of 8 to 12 flashes/sq. km/year. A lightning current measurement system was installed on this 91.5 m tall tower supported by grounded guy wires and became operational on August 1, 2018. This relatively low-height (low enhancement) tower was selected in order to observe lightning attachment that exhibits the characteristics of natural lightning including short upward connecting and unconnected leaders in response to nearby downward leaders, natural first stroke onsets with slow-front and fast-transition characteristics, and natural first-stroke current waveforms. This is the only natural lightning-current measurement facility in the United States at present.

In this paper we examine the characteristics of the unconnected upward leaders (UULs) initiated from the KSC-IAT. Additionally, we analyze in detail the current-waveform characteristics of one of the UULs measured at this facility.

II. MEASUREMENT SYSTEM AND DATA

The measurement system consisted of a shunt and a Rogowski coil near the base of a 6.2-m tall mast and Franklin rod installed at the top of the tower (see Figure 1). Current from the base of the Franklin rod was brought by a down-conductor to the current measurement box at the tower top that contains the shunt and Rogowski coil. The current was measured in four separate channels, three from the shunt followed by electronic amplifiers, and one from the Rogowski coil followed by an integrator, resulting in broadband current measurements in the range of about 1 A to 200 kA. Table 1 shows the current measurement limits of each channel. Data in all channels were transmitted via fiber optic links from the tower-top to its base where they were digitized using a 12-bit oscilloscope at a rate of 25 MHz (sampling interval of 40 ns). The record-length was 2 seconds with a 750-ms pre-trigger. All data were GPS timestamped to allow correlation with other datasets.

Since the commencement of measurements at the tower, two downward negative flashes have attached to the tower. A high-speed video camera recorded the attachment of the upward and downward leaders in one of these flashes that occurred on July 26, 2019 (see Figure 2). Additionally, currents from eight UULs due to lightning in the close proximity of the tower have been recorded.

III. CHARACTERISTICS OF UULS

A. "Triggering-Stroke" Characteristics

All eight UULs that were initiated from the KSC-IAT were positive as they occurred in response to downward negative leaders that attached to ground near the tower. The KSC

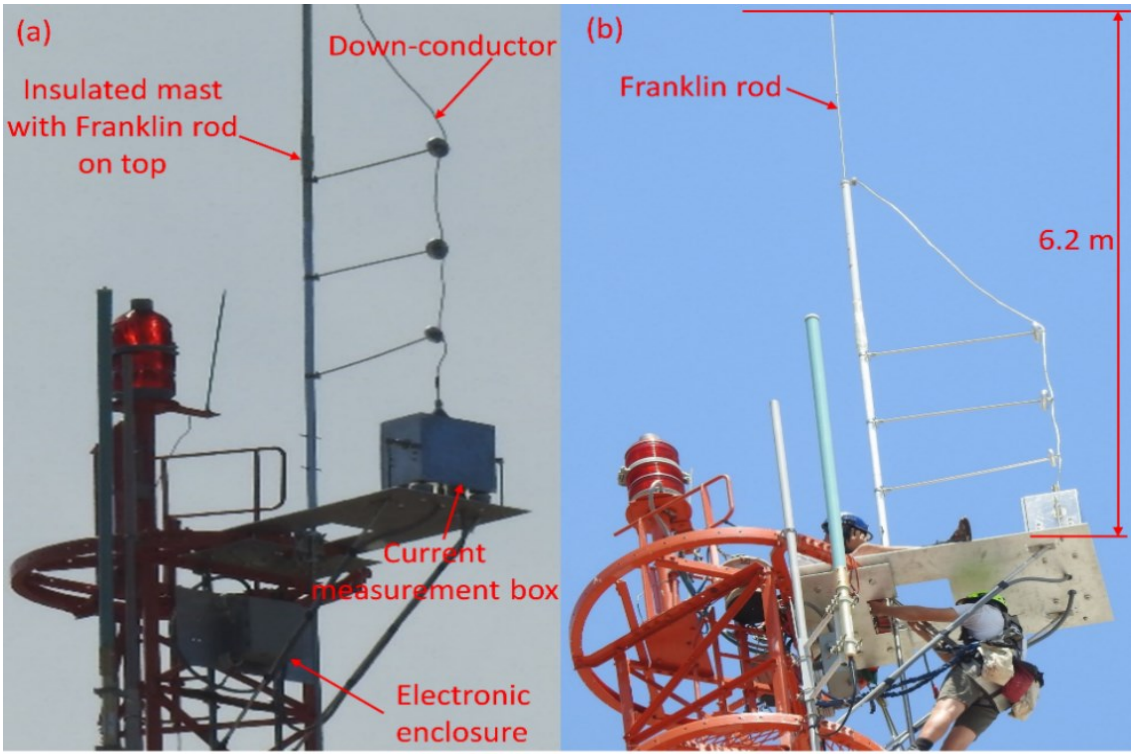

Figure 1. Pictures showing the current measurement system installed on top of the 91.5 tall KSC Industrial Area Tower. A shunt and Rogowski coil are in the current measurement box, labelled in (a), at the base of a 6.2-m tall mast and Franklin rod, labelled in (b), installed at the top of the tower.

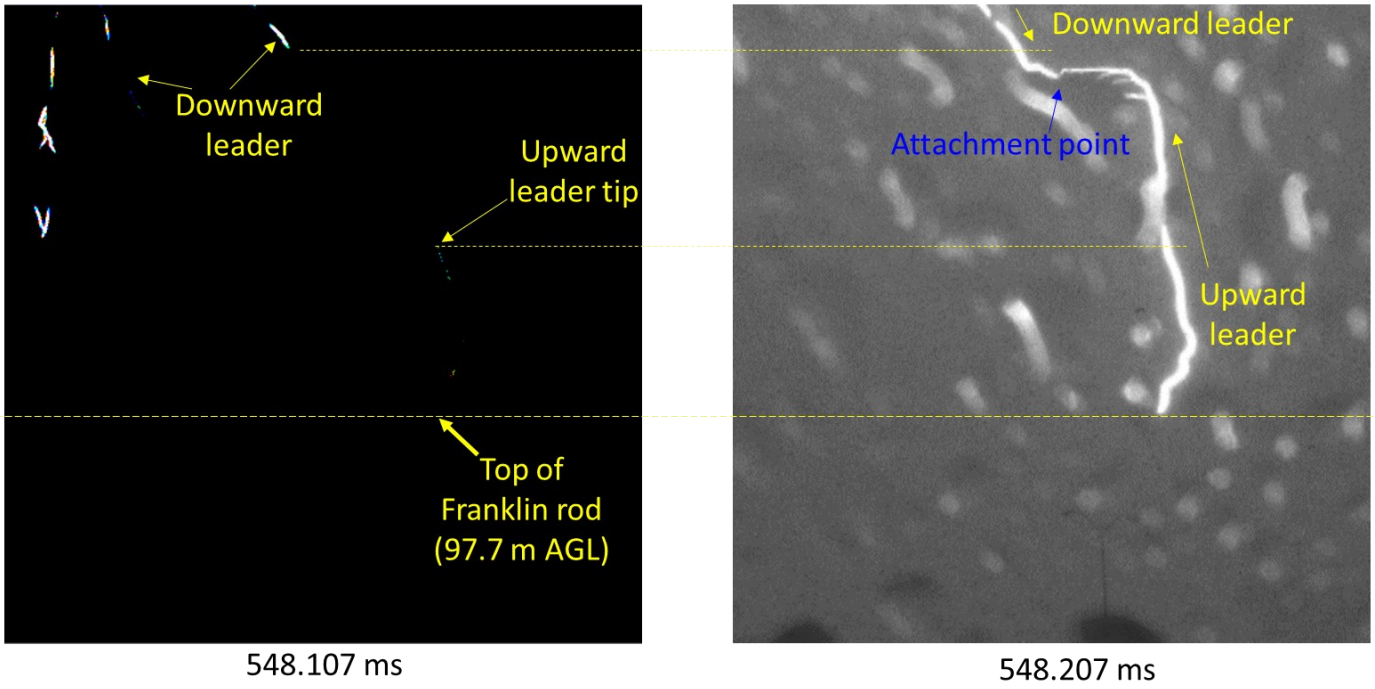

Figure 2. High speed video camera frames showing lightning striking the KSC IAT on July 26, 2019. These were captured from a distance of 700 m at 10,000 frames per second, so the inter-frame interval was 100 us and the exposure was 99.00 µs. The top of the Franklin rod, tip of the upward connecting leader (UCL) and the branches of the downward leader are indicated in the video camera frame shown in the left panel. The next video-camera frame, in the right panel, shows the return stroke as well as the inferred attachment-point of the upward and downward leaders.

TABLE I. CHARACTERISTICS OF THE FOUR CURRENT-MEASUREMENT CHANNELS AT THE KSC IAT.

Current Measurement Device	Frequency Bandwidth	Current Saturation	RMS Noise Floor with Full Bandwidth	RMS Noise Floor with 1 MHz Bandwidth
Shunt	DC – 10 MHz	±600 A	1.73 A	0.64 A
		±24 kA	33.8 A	12.9 A
		±120 kA	440 A	146 A
Rogowski coil	0.05 Hz – 10 MHz	±200 kA	4.05 kA	1.23 kA

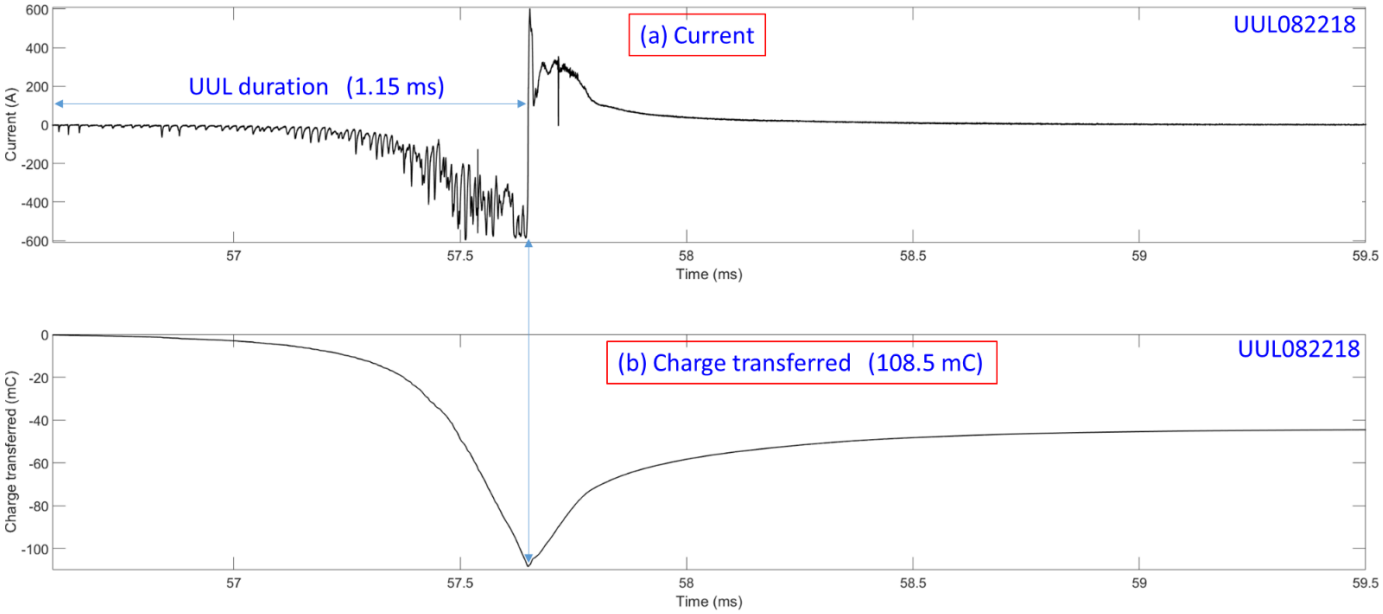

Figure 3. (a) The current waveform of a UUL that occurred on August 22, 2018 shown on a 2.9-ms time window. (b) The time-evolution of the charge transferred to ground by the UUL. The polarity of the current indicates the polarity of charge effectively transferred to ground. The duration of this UUL (at the time of current polarity reversal) was 1.15 ms and the charge transferred (prior to current polarity reversal) was 108.5 mC. Distance from tower to "triggering-stroke" for this UUL was 393 m. The MERLIN-reported peak current of the "triggering-stroke" was -20.1 kA.

Mesoscale Eastern Range Lightning Information System (MERLIN) (e.g., Hill et al., 2016 [7]) located these nearby strokes at distances ranging from 185 to 783 m from the tower, with the median being 538 m. The peak current for these strokes ranged from 13 to 69.3 kA, with the median being 26.7 kA. Figure 3a shows the current waveform of a UUL that occurred on August 22, 2018. Note that the polarity of the current shown in this figure indicates the polarity of charge effectively transferred to ground, which for all our UULs is negative.

B. Current Waveform Characteristics

Currents associated with UULs were recorded using the most sensitive current measurement channel with a measurement range of 0.64 A to 600 A (see Table 1). The duration of an UUL was defined as the time-interval between the inception of current in this channel and current polarity-reversal (see Figure 3a). This switching of current polarity was due to the reversal of the electric field at the time of the inception of the nearby return-stroke which was part of the "triggering" leader-return-stroke sequence. The durations of the eight UULs ranged from 116 μs to 1.15 ms, with the median being 789 μs. Also, generally speaking, pulse amplitudes are larger, background currents are higher, and interpulse intervals are shorter at later times during UULs as seen from Figure 3a.

C. Charge Transfer

From the perspective of charge transferred UULs can be considered as a bipolar lightning phenomenon; they transferred negative charge to ground between the inception of their current and the current-polarity reversal, following which, they effectively transferred positive charge to ground. We labeled the former as the UUL development phase and the latter as the collapse phase. Figure 3b shows the time-evolution of the charge transferred to ground by the UUL that occurred on August 22, 2018. Charge transferred by UULs in the time-interval between the inception of current and current polarity-reversal ranged from 0.5 to 109 mC, with the median being 6.3 mC.

D. Comparison of UUL Characteristics

Figure 4a shows the scatter plot of the MERLIN-reported peak currents for "triggering-strokes" versus the distance from the tower of the strokes' MERLIN-estimated ground-attachment points for the eight UULs. In general, triggering-strokes with higher peak currents attached to ground at farther distances from the tower. Figure 4b and c show the scatter plots

of the charge transferred by UULs versus their duration during the development and collapse phases, respectively. While more data is needed to quantify a relationship between these two parameters, it appears that charge transferred increases non-linearly with increasing duration, at least during the UUL development phase.

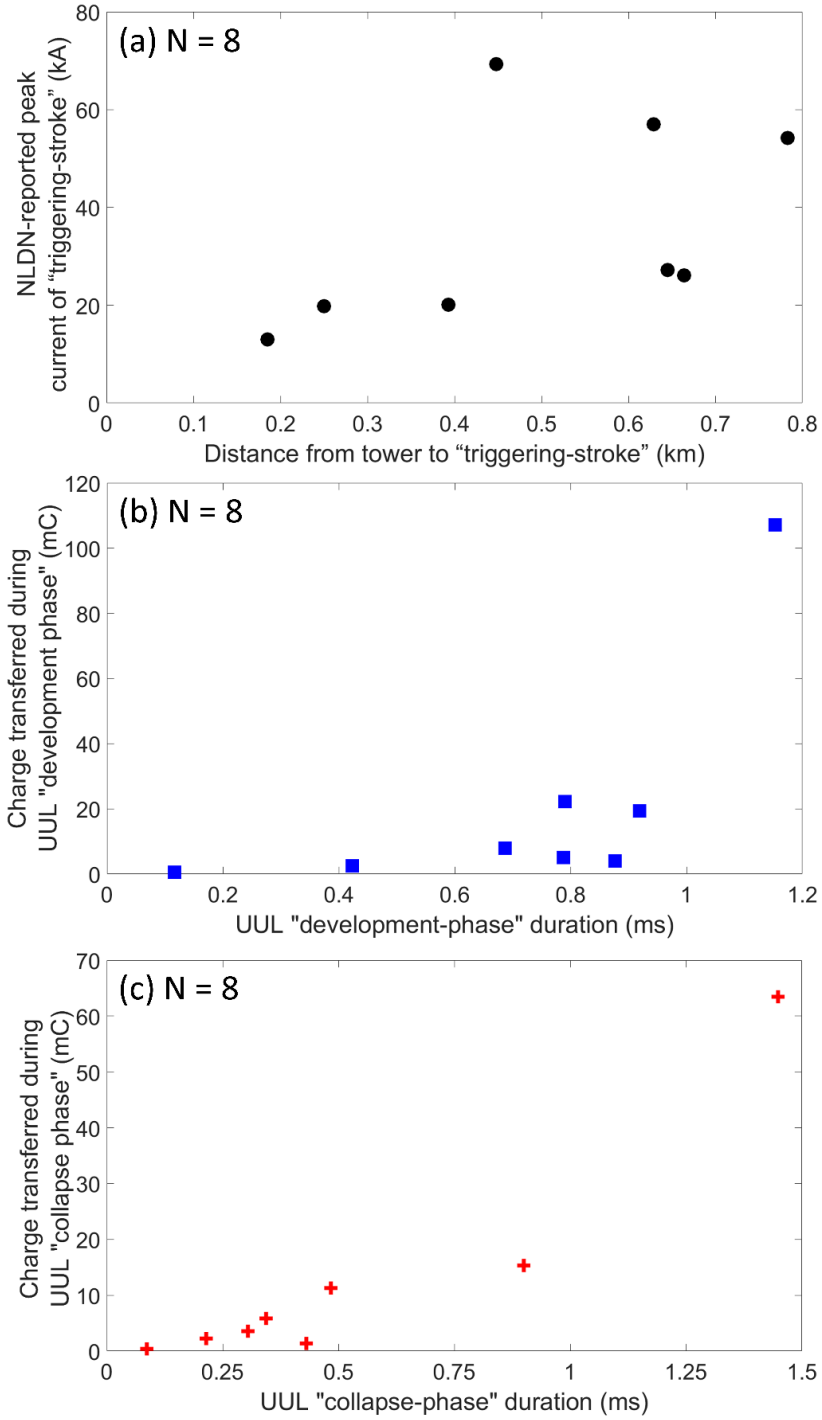

Figure 4. Scatter plots for eight UULs in our dataset showing (a) MERLIN-reported peak currents for "triggering-strokes" versus the distance from the tower of the strokes' MERLIN-estimated ground-attachment points, (b) charge-transferred by UULs during their development phase versus their development-phase duration, and (c) charge-transferred by UULs during their collapse phase versus their collapse-phase duration. Note that negative (blue squares in (b)) and positive (red plusses in (c)) charges were transferred to ground during the UUL development and collapse phases, respectively; only the charge magnitudes are shown in (b) and (c).

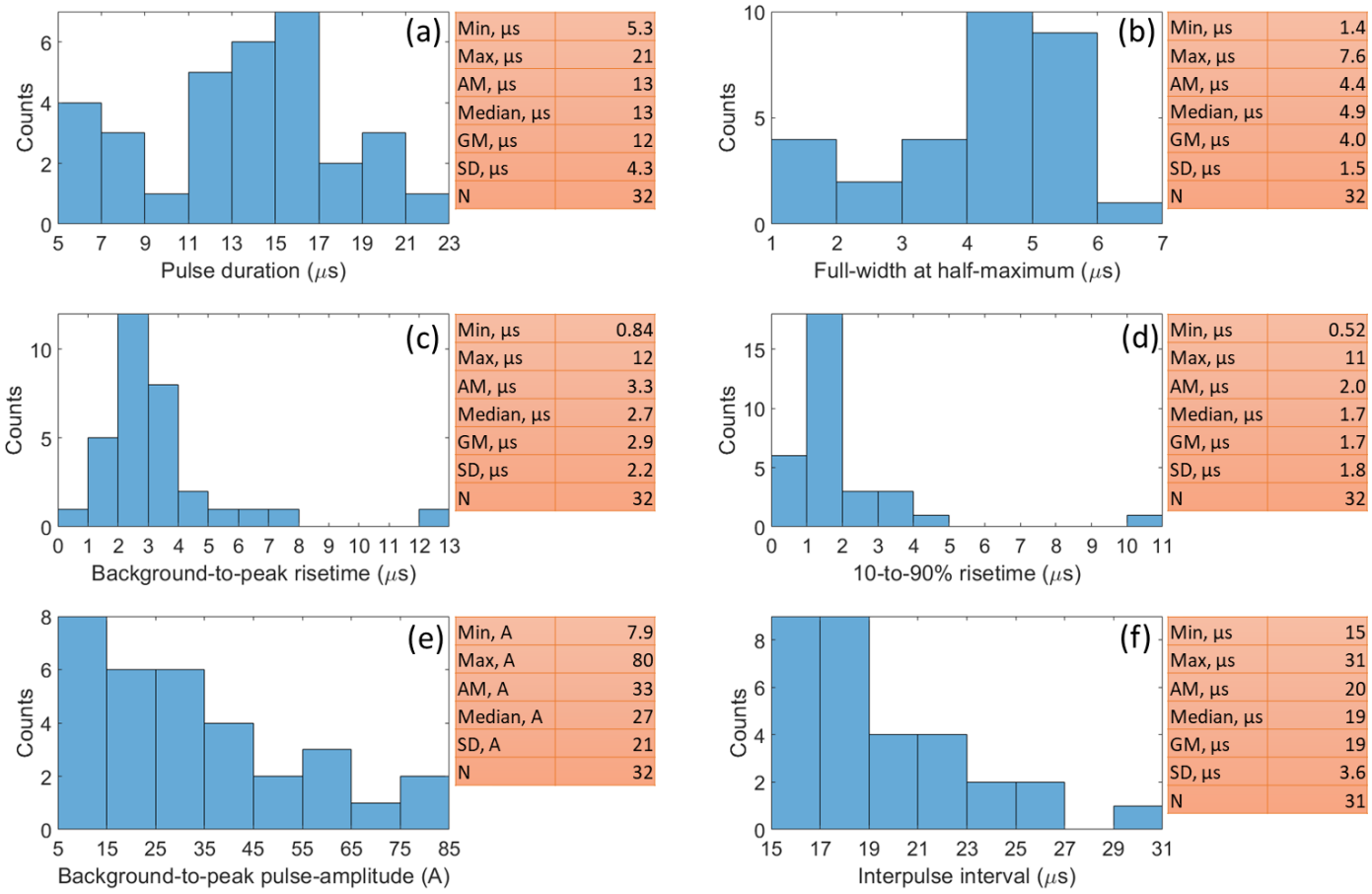

Figure 5. Histograms of (a) duration, (b) full-width at half-maximum, (c) background-to-peak risetime, (d) 10-to-90% ristime, (e) background-to-peak amplitude, and (f) interpulse interval for pulses occurring during an UUL whose current waveform is shown in Figure 3a.

IV. Case Study of UUL Occurring on August 22, 2018

We examined in detail the characteristics of current for the UUL that initiated from the KSC IAT on August 22, 2018. The current waveform for this UUL is shown in Figure 3a on a 2.9-ms time window and can be considered to be a typical example. The duration of the UUL-current was 1.5 ms during which it transferred 108.5 mC of negative charge to ground. As seen in Figure 3a, UUL-currents typically consist of faster (ten-microsecond-scale) impulses overlaid on a slower (millisecond-scale) "background" current. Figures 5a-f show the histograms of the characteristics of 32 pulses occurring during the UUL in Figure 3a. The median pulse duration and full-width at half-maximum were 13 and 4.5 µs, respectively. We measured the background-to-peak and 10-to-90% risetimes of the pulses whose medians were 2.7 and 1.7 µs, respectively. The median background-to-peak pulse amplitude was 27 A and the median interpulse interval was 19 µs.

V. Summary

The Industrial Area Tower at the Kennedy Space Center is located in a region with a lightning flash density of 8 to 12 flashes/sq. km/year. A lightning current measurement system was installed at the IAT in July-August 2018. The measurement system was operational on August 1, 2018. The measurement system consists of a shunt and a Rogowski coil near the base of a 6.2-m tall mast and Franklin rod installed at the top of the tower. Since the commencement of measurements at the tower, two downward negative flashes have attached to the tower. Additionally, currents from eight unconnected upward leaders due to lightning in the close proximity of the tower have been recorded. The following characteristics of UUL-currents were observed:

- Typical UUL duration was of the order of several hundred microseconds and each leader transferred several millicoulombs of charge.
- The UUL currents consisted of the "typical" faster modulations observed in such current waveforms overlaid on a slower "background" current.
- UUL current pulses were around 10 µs in duration and had risetimes of around 2-3 µs.
- Generally speaking, pulse amplitudes are larger, background currents are higher, and interpulse intervals are shorter at later times during UULs.

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REFERENCES

[1] K. Berger, R. B. Anderson, and H. Kröninger, "Parameters of lightning flashes," CIGRE Electra, vol. 41, pp. 23–37, 1975.

[2] S. Visacro, A. Soares, Jr., M. A. O. Schroeder, L. C. L. Cherchiglia, and V. J. de Sousa, "Statistical analysis of lightning current parameters: Measurements at Morro do Cachimbo Station," J. Geophys. Res., vol. 109, 2004, Art. no. D01105, doi: 10.1029/2003JD003662.

[3] S.Visacro, C. R. Mesquita, A. De Conti, and F.H. Silveira, "Updated statistics of lightning currents measured at Morro do Cachimbo Station," Atmos. Res., vol. 117, pp. 55–63, 2012, doi: 10.1016/j.atmosres.21011.07.010.

[4] J. Takami and S. Okabe, "Observational results of lightning current on transmission towers," *IEEE Trans. Power Del.*, vol. 22, no. 1, pp. 547–556, Jan. 2007.

[5] T. Miki, M. Saito, T. Shindo, M. Ishii, "Current observation results od downward negative flashes at Tokyo Skytree from 2012 to 2018," IEEE Trans. on EMC, Vol. 61, No. 3, June 2019, doi: 10.1109/TEMC.2019.2910319.

[6] A. Nag, K. L. Cummins, M. N. Plaisir, J. G. Wilson, D. E. Crawford, R. G. Brown, R. C. Noggle, H. K. Rassoul, "Inferences on upward leader characteristics from measured currents," Atmospheric Research, https://doi.org/10.1016/j.atmosres.2020.105420, 2021.

[7] J. Hill, C. Mata, W. Roeder, "Evaluation of the Performance Characteristics of MERLIN and NLDN Based on Two Years of Ground-Truth Data from Kennedy Space Center/Cape Canaveral Air Force Station, Florida," in: 24th International Lightning Detection Conference (ILDC) International Lightning Detection Conference. San Diego, 2016.