High-Speed Video Camera and Geostationary Lightning Mapper Measured Signatures of Cloud-to-Ground Strokes with and without Significant Continuing Current

Megan D. Mark[1,2], Amitabh Nag[1,2], Kenneth L. Cummins[2], Mathieu N. Plaisir[2], Dylan J. Goldberg[2], Abdullah Y. Imam[2], Hamid K. Rassoul[2]
1. Los Alamos National Laboratory, Los Alamos, New Mexico
2. Florida Institute of Technology, Melbourne, Florida, USA

Abstract

Cloud-to-ground lightning return strokes are sometimes immediately followed by relatively slowly varying currents with durations that can last for hundreds of milliseconds, called continuing current. Duration of continuing current can be measured directly using high-speed video cameras and/or return-stroke channel-base current measurements. Data from the Geostationary Lightning Mappers (GLM), onboard the GOES satellites, has been suggested for use in previous studies for estimating continuing current duration using its detection of lightning optical emissions. In this study, we investigate the GLM responses to 173 negative cloud-to-ground strokes in the Space Coast of Florida from 2018-2023. We compare directly measured continuing current durations to those estimated from the GLM data. The detection efficiency of the GLM was 50.3% for cloud-to-ground strokes, with a lower detection efficiency for first strokes (31.3%) compared to subsequent strokes (62.3%). The estimated GLM continuing current durations seemed to be unrelated to those measured using high speed video cameras and/or channel-base current measurements and were significantly underestimated. It is possible that the significant underestimation found in this study compared to prior studies is due to algorithmic changes in the onboard processing of the GLM data.

1 Introduction

Since the 1920s, cloud-to-ground (CG) lightning flashes have been recorded, initially using streak (Boys) cameras [1] [2], and more recently using video cameras [3] [4] [5] [6] [7], resulting in great insights. As technologies improve, capabilities to record more detailed characteristics of lightning flashes increase, including the ability to measure individual processes within a CG flash. CG flashes typically contain multiple return strokes which effectively transfer charge to ground [8] (see book section 4.1). Sometimes, immediately following the impulsive flow of current during a return stroke, charge is transferred to ground by a lower amplitude (few amperes to few kiloamperes), longer duration (tens of milliseconds to hundreds of milliseconds) continuing current (CC) [8] [9] [10] [11]. Long CC is of interest to the greater community because of its relationship to lightning damage due to heating. This impacts electric power lines [12], initiation of forest fires [9] [13] [14] [15], and infrastructure protection in general.

Unfortunately, CC durations remain difficult to measure via most existing ground-based lightning locating systems (which focus on geolocating the impulsive component of the return stroke). Some studies have suggested methods for using space-based measurements to estimate CC durations [9] [12] [15] [16] [17]. Using space-based optical lightning detection to estimate CC duration was initially suggested by Christian et al. [17] and used the Lightning Imaging Sensor (LIS). Fairman and Bitzer [16] suggested a model to detect CG flashes with continuing current using the space-based Geostationary Lightning Mapper (GLM) with a probability of detection of 78% and a false alarm rate of 6%. They also showed that flashes with a high probability of producing CC tended to have brighter optical emissions over a long distance. The GLM is comprised of two space-based optical sensors on the GOES satellites that record continuously over the western hemisphere [18]. The sensors have a charge-coupled device (CCD) that records transient optical pulses at the 777.4 nm neutral oxygen emission line triplet and are capable of detecting optical emissions from lightning at any time of day throughout the field of view (FOV) [18] [19]. The GLM operational Lightning Cluster-Filter Algorithm (LCFA) sorts groups (localized ~2 ms optical emissions) within 330 ms in time and 16.5 km in space using the weighted Euclidean distance between groups into a flash [18] [20]. The data from the GLM is publicly available and many tools exist to download and identify GLM events, groups, and flashes [21].

In this study, we use 77 negative CG flashes recorded using high-speed video cameras and geolocated by the National Lightning Detection Network (NLDN) as ground-truth. For a subset of these flashes, we also measured channel-base currents. This ground-truth dataset is then compared to the responses of the GLM and to CC estimations using the GLM.

2 Measurements and Methods

In the ground-truth dataset, 173 negative strokes (67 first and 106 subsequent) in 77 flashes that were captured on high-speed video and geolocated by the NLDN. Note that, not all first and subsequent strokes in the 77 flashes

Table 1 Stroke Characteristics of the Dataset

Characteristic		Sample size	Minimum	Maximum	Median
NLDN-reported peak current (kA)	First strokes (including single-stroke flashes)	67	-5	-228	-36
	Subsequent strokes in new channel	14	-11	-65	-25.5
	Subsequent strokes in pre-existing channel	92	-5	-82	-22
	First strokes in single-stroke flashes only	10	-5	-64	-20.5
CC duration (ms)	First strokes (including single-stroke flashes)	67	0.28	685	2.6
	Subsequent strokes in new channel	14	0.5	15.9	1.96
	Subsequent strokes in pre-existing channel	92	0.3	289	2.47
	First strokes in single-stroke flashes only	10	0.89	685	3.69
First-stroke to last-stroke time interval (ms)*		68	17.3	964	252
Interstroke time interval (ms)*		179	0.36	521	58.1
NLDN stroke distance to camera (km)		173	0.33	29.5	6.79

were recorded due to them being outside the camera's FOV or limited record length. The stroke characteristics are shown in Table 1; for computing the interstroke intervals, all NLDN-reported strokes were considered regardless of them being captured on high-speed video. Discussions on our CC duration estimation techniques and interpretation of the durations are found in Section 2.4.

2.1 High-Speed Video Camera Measurements

The strokes in this study were captured using Phantom high-speed video cameras that are a part of the Melbourne Lightning Observatory (MLO) at Florida Institute of Technology [22]. One of the video cameras recorded lightning strikes to the Industrial Area Tower (IAT) at Kennedy Space Center (KSC), which was instrumented to measure CG lightning channel-base currents [23] [24]. The frame rates of the cameras ranged from 10,000 frames per second (fps) to approximately 793,650 fps [22]. The regions around the MLO and KSC have mostly flat ground and experience lightning flash density in the range of 8-12 flashes/square kilometer/year [25] [26].

2.2 Channel-base Current Measurements

We analysed channel-base currents for 6 first and 14 subsequent strokes measured at the IAT. Only one first stroke and one subsequent stroke in this subset did not have high-speed video. The current measurement system consisted of a shunt and Rogowski coil installed near the base of a 6.2-m tall mast and Franklin rod at the top of the 91.2-m tall tower [24] [23]. The system is capable of measuring current in four separate channels, three from the shunt and one from the Rogowski coil, allowing for broadband current measurements from less than 1 A to 350 kA [26] [24]. Data is transmitted via fiber optic links, digitized with a 12-bit oscilloscope with a 50 MHz sampling rate and is GPS time-stamped [26] [24].

2.3 Geolocation of Recorded Strokes

Our dataset only included strokes geolocated by the NLDN; the NLDN-stroke time was used as a reference when examining the responses of the GLM using different criteria. For each flash, all reported GLM groups within -1 to +2 seconds of the NLDN-reported first-stroke time and within 30 km of the NLDN-reported first-stroke location were considered. A stroke was considered to be detected by the GLM if groups were reported within +/-4 ms of the reported NLDN stroke-time. Additionally, the spatial criteria was varied between 10 km and 30 km (as shown in Table 2) to examine its effect on the stroke detection efficiency. We found that the stroke detection efficiency did not change significantly for the different spatial matching criteria, so 30 km was used as the "standard" in the analysis presented in this paper. We examined the GLM reported groups separately for first strokes, subsequent strokes in new channels, and subsequent strokes in the same channel as the prior stroke.

2.4 Continuing Current Duration Estimations

Using the high-speed video camera records, we measured the time-period during which the cloud-to-ground channel was visible following the return stroke. The start time for this time-period was defined as the time of the first frame showing the downward leader attached to the upward leader (i.e. the first frame showing the leader-channel luminosity near ground abruptly increasing (compared to the previous frame). The end time was defined as the time of the frame in which the lightning channel could no longer be distinguished from the frame's background. For some flashes, only a section of the channel was within the FOV of the camera; in such cases the start time was defined as when the first frame showed an increase in luminosity of the channel-section within the FOV. First strokes were recognized by the significant branching and stepping observed as the downward leader approached ground in conjunction with a relatively slow (on the order of 10^5 m/s) leader-speed. Subsequent strokes were recognized by the lack of these characteristics along with a significantly faster (on the order of 10^7 m/s) leader speed. In cases where this rule could not be applied due to relatively large distance-to-channel, the re-illumination of the leader branching (generally not present in subsequent strokes) at the start of the return stroke was used to recognize first strokes. For strokes with channel-base current measurements, the CC duration was defined as the time-interval between when the return stroke current decayed to 10% of its peak value and when the current decayed to "zero" in the most sensitive current measurement channel. The "zero" was found by averaging the current waveform during the falling edge of the stroke in the most sensitive current measurement channel and identifying when the current decayed to within 1-3% of the average background noise level. Using these techniques, we found that for 61 (35.3%) of 173 strokes, the duration of post-return stroke luminosity or current was less than 3 ms. Conventionally [27] [28] [34, section 4.8], such short-duration currents are considered to be part of the tail-end of the falling edge of the return stroke current pulse rather than CC. However, we included in our analysis the measured durations (using the techniques described above) for all our strokes in order to examine their relationship to the GLM-estimated durations.

We estimated a CC duration from the GLM data for each of the detected strokes using the 4 ms-30 km time-space criteria (see section 2.3). The closest-in-time GLM group was selected to be matching the stroke. The time-contiguous GLM groups, after the matched one, with the same GLM Flash ID were used to determine the CC duration. These clustering criteria are similar to that used by Fairman and Bitzer [16]. Additionally, we also estimated the CC duration by allowing semi-contiguous-in-time groups (i.e., those with an inter-group interval of 2 ms or one GLM frame) with the same GLM Flash ID.

3 Results

As shown in Table 2, the GLM flash and stroke detection efficiencies for the 77 flashes and 173 strokes in our dataset were 80.5% and 50.3%, respectively. The detection efficiency for first strokes was 31.3%, which is lower than that for subsequent strokes (62.3%). Figure 1 shows the detection efficiency as a function of stroke order. For all space-time criteria used to match GLM groups with NLDN stroke-times and -locations, we found that the detection efficiency for higher order strokes was greater than that for first strokes. Note that the number of observations for each stroke order is included below the stroke-order (horizontal) axis.

Figure 2a shows a histogram of NLDN reported peak currents for strokes detected and not detected by the GLM; 50 and 50.6% of strokes with peak currents less and greater than 30 kA, respectively, were detected by the GLM. Figure 2b shows histograms of measured CC durations for strokes detected and not detected by the GLM. The GLM detected 38.5% and 65.8% of strokes with CC durations less than and greater than 3 ms, respectively. The

Table 2 GLM Detection Efficiencies (DE)

Event type	Matching criteria for GLM groups relative to NLDN strokes	GLM DE
All flashes	Within -1 and +2 s and 30 km	80.5%
All strokes	Within +/-4 ms and 30 km	50.3%
	Within +/-4 ms and 20 km	49.7%
	Within +/-4 ms and 15 km	48.0%
	Within +/-4 ms and 12.5 km	46.8%
	Within +/-4 ms and 10 km	41.6%
First strokes (including single-stroke flashes)	Within +/-4 ms and 30 km	31.3%
Subsequent strokes in new channel		50.0%
Subsequent strokes in pre-existing channel		64.1%
All subsequent strokes		62.3%
Single-stroke flashes		30%

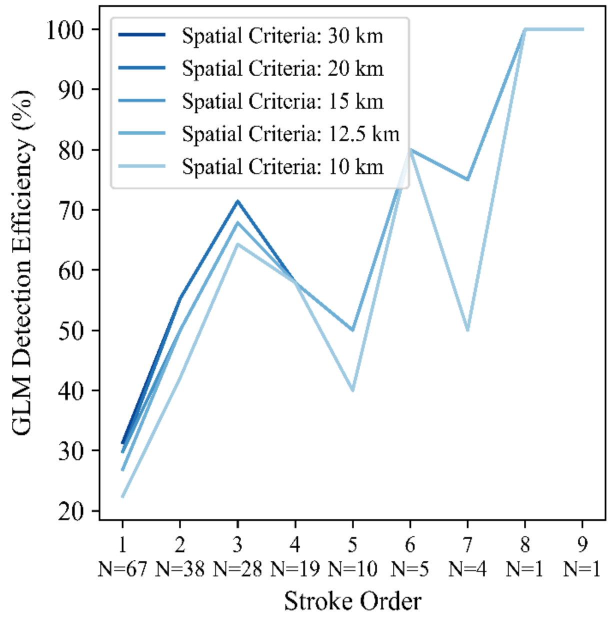

Figure 1 GLM detection efficiency for strokes of different order.

scatter plot of the measured (ground-truth) CC durations versus those estimated by the GLM is shown in Figure 2c. The GLM-estimated CC durations were unrelated to those measured using high-speed video or channel-base currents; the GLM-estimated CC durations were very significantly (as much as one to two orders of magnitude) underestimated for CC durations greater than 20 ms. No GLM-estimated CC duration was longer than 6 ms. When comparing the CC durations estimated using the contiguous and semi-contiguous GLM groups (Figure 2d), we found that the two criteria yielded very similar CC durations.

4 Discussion

The lower detection efficiency for first strokes than for subsequent strokes in our dataset from Florida are consistent with the findings in previous studies in New Mexico and Brazil [29] [30]. It should also be noted that the detection efficiency was about the same (approximately 30%) for single-stroke flashes as for all first strokes. Little variation in detection efficiency occurs with changing spatial criteria, indicating that for negative strokes in our dataset the GLM detected/reported groups relatively close to the

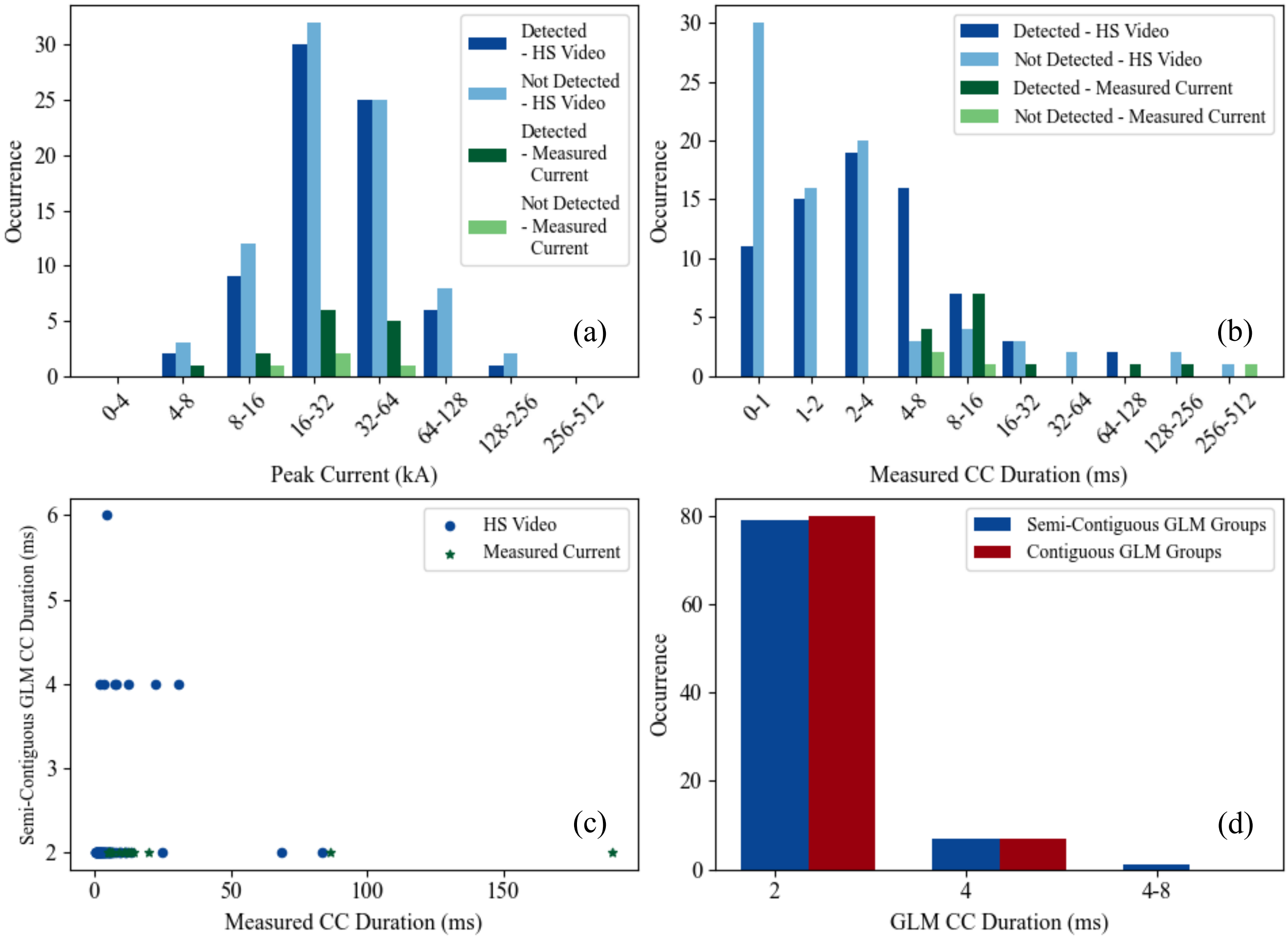

Figure 2 (a) Histogram of NLDN reported peak currents for strokes detected and not detected by the GLM. (b) Histogram of measured CC duration for strokes detected and not detected by the GLM. (c) Measured (ground-truth) CC durations versus those estimated by the GLM. (d) Histogram of CC durations using the two methods for GLM CC duration estimation.

NLDN stroke locations. Our finding that the GLM-estimated CC durations did not exceed 6 ms is inconsistent with the results of Fairman and Bitzer [16] who found that out of their 288 CG strokes, there were 152 CG strokes that had a GLM-estimated CC duration of 10 ms or greater.

One possible reason for the GLM not detecting first strokes and single-stroke flashes is that subsequent stroke channels may try to neutralize more distant pockets of charge by extending inside the thundercloud and perhaps reaching higher altitudes leading to optical emissions from near the cloud top (or cloud-edges) that are detectable by the GLM. On the other hand, studies using both ground-based photographs and space-based observations (from FORTE) have shown first strokes to be optically brighter than subsequent strokes [31] [32]. The missed single-stroke flashes and first strokes as well as the extremely underestimated CC durations could be due to algorithmic processing on-board the GLM [33] rather than being related to lightning or thundercloud characteristics.

5 Summary

Detection efficiencies for the GLM were found by using, as "ground-truth", a lightning dataset consisting of negative CG strokes in the Space Coast of Florida observed using high-speed video cameras from 2018-2023. The overall negative CG flash detection efficiency was 80.5%. The stroke detection efficiency was 50.3%, with it being 31.3% for first strokes and 62.3% for subsequent strokes. The detection efficiency for single-stroke flashes was 30%. The GLM's detection of a stroke was not dependent on the CC duration or the NLDN-reported peak current. The GLM-estimated CC durations were significantly underestimated and unrelated to those measured from video camera or channel-base current records. Recent upgrades to the GLM data processing could probably be preventing the detection of first strokes and reporting of groups during continuing currents in CG strokes.

Literature

[1] N. Clarence and D. Malan, "Preliminary discharge processes in lightning flashes to ground," *Q.J.R. Meteorol. Soc.,* 1957.

[2] C. Boys, "Progressive lightning," *Nature,* pp. 749-50, 1926.

[3] R. D. Brantley, J. A. Tiller and M. A. Uman, "Lightning properties in Florida thunderstorms from video tape records," *J. Geophys. Res.,* 1975.

[4] W. Winn, T. V. Aldridge and C. B. Moore, "Video tape recordings of lightning flashes," *J. Geophys. Res.,* p. 4515–4519, 1973.

[5] M. M. F. Saba, M. G. Ballarotti and O. Pinto Jr., "Negative cloud-to-ground lightning properties from high-speed video observations," *J. Geophys. Res.,* 2005.

[6] L. Z. Campos, M. M. Saba, T. A. Warner, O. Pinto Jr., E. P. Krider and R. E. Orville, "High-speed video observations of natural cloud-to-ground lightning leaders – A statistical analysis," *Atmospheric Research,* 2014.

[7] M. D. Tran and V. A. Rakov, "Initiation and propagation of cloud-to-ground lightning observed with a high-speed video camera," *Scientific Reports,* 2016.

[8] V. A. Rakov, Fundamentals of Lightning, United Kingdom: Cambridge University Press, 2016.

[9] P. M. Bitzer, "Global distribution and properties of continuing current in lightning," *J. Geophys. Res.: Atmospheres,* 2017.

[10] L. Z. Campos, M. M. Saba, O. Pinto Jr. and M. G. Ballarotti, "Waveshapes of continuing currents and properties of M-components in natural negative cloud-to-ground lightning from high-speed video observations," *Atmospheric Research,* 2007.

[11] L. Z. S. Campos, M. M. F. Saba, O. Pinto Jr. and M. G. Ballarotti, "Waveshapes of continuing currents and properties of M-components in natural positive cloud-to-ground lightning," *Atmospheric Research,* 2009.

[12] J. Montany`a, J. L´opez, O. van der Velde, G. Sol`a, D. Romero, C. Morales, S. Visacro, M. Saba, S. Goodman, E. Williams, M. Peterson, N. Pineda, M. Arcanjo and D. Aranguren, "Potential use of space-based lightning detection in electric power systems," *Electric Power Systems Research,* 2022.

[13] D. Latham and E. Williams, "Chapter 11 - Lightning and Forest Fires," in *Forest Fires Behavior and Ecological Effects*, Academic Press, 2001, pp. 375-418.

[14] N. Pineda, J. Montanyà and O. A. van der Velde, "Characteristics of lightning related to wildfire ignitions in Catalonia," *Atmospheric Research,* 2014.

[15] F. J. Pérez-Invernón, J. V. Moris, F. J. Gordillo-Vázquez, M. Füllekrug, G. B. Pezzatti, M. Conedera, J. Lapierre and H. Huntrieser, "On the Role of Continuing Currents in Lightning-Induced Fire Ignition," *J. Geophys. Res.: Atmospheres,* 2023.

[16] S. Fairman and P. Bitzer, "The Detection of Continuing Current in Lightning Using the Geostationary Lightning Mapper," *J. Geophys. Res.,* 2022.

[17] H. Christian, R. Blakeslee and S. Goodman, "Lightning imaging sensor (LIS) for the earth observing system," 1992.

[18] S. J. Goodman, R. J. Blakeslee, W. J. Koshak, D. Mach, J. Bailey, D. Buechler and G. Stano, "The GOES-R geostationary lightning mapper (GLM)," *Atmospheric Research,* 2013.

[19] H. J. Christian, R. J. Blakeslee and S. J. Goodman, "The detection of lightning from geostationary orbit," *J. Geophys. Res.: Atmospheres,* 1989.

[20] D. M. Mach, "Geostationary Lightning Mapper Clustering Algorithm Stability," *J. Geophys. Res.: Atmospheres,* 2019.

[21] E. C. Bruning, C. E. Tillier, S. F. Edgington, S. D. Rudlosky, J. Zajic, C. Gravelle, M. Foster, K. M. Calhoun, P. A. Campbell, G. T. Stano, C. J. Schultz and T. C. Meyer, "Meteorological imagery for the geostationary lightning mapper," *J. Geophys. Res.: Atmospheres,* 2019.

[22] H. Khounate, A. Nag, M. N. Plaisir, A. Y. Imam, C. J. Biagi and H. K. Rassoul, "Insights on Space-Leader Characteristics and Evolution in Natural Negative Cloud-to-Ground Lightning," *Geophysical Research Letters,* 2021.

[23] A. Nag, K. L. Cummins, M. N. Plaisier, R. G. Brown, J. G. Wilson, D. E. Crawford, R. C. Noggle and H. K. Rassoul, "Characteristics of upward-connecting-leader current leading to attachment in downward negative cloud-to-ground lightning strokes," *Atmospheric Research,* 2023.

[24] M. N. Plaiser, A. Nag, K. L. Cummins, D. J. Goldberg, C. J. Biagi, R. G. Brown and K. H. Rassoul, "The lightning attachment processes observed on a submicrosecond-scale: Measurements of current and video," in *International Conference on Grounding & Lightning Physics and Effects*, Belo Horizonte, Brazil, 2023.

[25] R. L. Holle, K. L. Cummins and W. A. Brooks, "Seasonal, Monthly, and Weekly Distributions of NLDN and GLD360 Cloud-to-Ground Lightning," *American Meteorological Society,* 2016.

[26] A. Nag, K. L. Cummins, M. N. Plaisir, J. G. Wilson, D. E. Crawford, R. G. Brown, R. C. Noggle and H. K. Rassoul, "Inferences on upward leader characteristics from measured currents," *Atmospheric Research,* 2021.

[27] M. M. F. Saba, O. Pinto Jr. and M. G. Ballarotti, "Relation between lightning return stroke peak current and following continuing current," *Geophysical Research Letters,* 2006.

[28] M. G. Ballarotti, M. M. F. Saba and O. Pinto Jr., "A new performance evaluation of the Brazilian Lightning Location System (RINDAT) based on high-speed camera observations of natural negative ground flashes," in *19th International Lightning Detection Conference*, Tuscon, Arizona, 2006.

[29] A. Leal, O. Cantrell, R. Sonnenfeld, G. Arcanjo Velasco dos Santos Ferreira, W. Matos, V. Rakov and M. Saba, "Observations and inferences of simultaneous records of cloud-to-ground flashes from space and ground over the American continent," in *AGU Annual Meeting 2023*, San Francisco, 2023.

[30] A. Leal and V. Rakov, "Processes in negative and positive CG lightning flashes detected from space by GLM," *Electric Power Systems Research,* 2024.

[31] D. M. Jordan and M. A. Uman, "Variation in Light Intensity With Height and Time From Subsequent Lightning Return Strokes," *J. Geophys. Res.,* 1983.

[32] T. Light, D. Suszcynsky and A. Jacobson , "Coincident radio frequency and optical emissions from lightning, observed with the FORTE satellite," *J. Geophys. Res.,* 2001.

[33] K. L. Cummins, C. Tillier, H. Christian, P. Bitzer, S. F. Edgington, T. Kpulun, A. Nag and M. Mark, *GLM Algorithm Update Discussions,* 2023.

[34] V. A. Rakov and M. A. Uman, Lightning Physics and Effects, Cambridge University Press, 2003.