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Key Points:
- Thirty-three percent of IC events (including preliminary breakdown in CG flashes) were detected and 86% were correctly classified as cloud discharge activity
- Seventy-three percent of complete IC flashes were detected and 95% were correctly classified
- Fourty-six percent of preliminary breakdown pulse trains in CG flashes were detected and 82% were correctly classified as cloud discharge activity

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A study of National Lightning Detection Network responses to natural lightning based on ground truth data acquired at LOG with emphasis on cloud discharge activity

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Abstract The U.S. National Lightning Detection Network (NLDN) detection efficiency (DE) and classification accuracy (CA) for cloud discharge (IC) activity (identified here by a sequence of non-return-stroke-type electric field pulses not accompanied by channels to ground) were evaluated using optical and electric field data acquired at the LOG (Lightning Observatory in Gainesville), Florida. Our ground truth "IC events" include 26 "isolated IC events" (complete IC flashes), 58 "IC events before first return stroke," and 69 "IC events after first return stroke." For the total of 153 IC events, 33% were detected by the NLDN, and the classification accuracy was 86%. For complete IC flashes, the detection efficiency and classification accuracy were 73% and 95%, respectively, and the average number of NLDN-reported cloud pulses was 2.9 per detected event. For 24 preliminary breakdown pulse trains in CG flashes, the detection efficiency and classification accuracy were 46% and 82%, respectively. We have additionally estimated the DE and CA for return strokes in CG flashes. Irrespective of stroke order and polarity, the DE was 92% (339/367), and the CA was also 92% (312/339). The DEs for negative first and subsequent strokes were 98% and 90%, respectively.

1. Introduction

The U.S. National Lightning Detection Network (NLDN) has more than 100 sensors installed in the contiguous USA with the typical separation distance of 300–350 km. Both the time of arrival (TOA) and magnetic direction finding (MDF) techniques are used. An overview of the evolution of the NLDN is given by *Orville* [2008]. The NLDN reports both cloud (IC) and cloud-to-ground (CG) lightning discharges, which are classified based on the magnetic field waveform criteria. In general terms, pulses wider than a certain threshold are interpreted as being produced by return strokes (RSs) in CG flashes and labeled "G," while narrower pulses are attributed to cloud flashes and labeled "C," although a new multiparameter classification method was implemented in the course of the 2013 upgrade. Since any CG flash involves some cloud discharge activity (notably the preliminary breakdown process), both "G" and "C" pulses can be reported by the NLDN during CG flashes. Due to a large variation of pulse parameters for either cloud or ground discharges, some pulses produced by return strokes are misclassified as "C" and some of those produced by cloud discharge activity as "G."

The detection efficiency is usually defined as the percentage of total ground truth events that were detected by the lightning locating system. For the CG lightning, estimation of the stroke detection efficiency is straightforward, since each stroke involves a cloud-to-ground channel, which can be observed in optical records. However, for cloud discharges, the detection efficiency is more difficult to define since they mainly occur inside the cloud and do not have readily identifiable features. *Rakov* [2013] stated that "if all cloud discharge pulses are accepted as 'counts,' the number of detected cloud discharges may be largely determined by the local noise level and lightning locating system's signal transmission rate limit."

Biagi et al. [2007], using video camera records, studied the performance characteristics of the NLDN in Southern Arizona, Oklahoma, and Texas. The ground flash detection efficiency was found to be 93% in Southern Arizona and 92% in Texas/Oklahoma, with the corresponding stroke detection efficiency being 76% and 85%. *Fleenor et al.* [2009], who additionally used electric field records from Los Alamos Sferic

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Table 1. Summary of the Ground Truth Data Set for IC Events

Event Type	Isolated IC Events	IC Events Before First RS	IC Events After First RS	All IC Events	PB Pulse Trains[a]	Regular Pulse Bursts RPBs[a]
Sample size	26	58	69	153	24	19
Geometric mean duration (ms)	504	23	69	64	2.7	1.3

[a]PB pulse trains and RPBs were not treated as separate IC events in calculating the DE and CA of IC events.

Array (LASA), conducted a similar field campaign in the region of Colorado-Kansas-Nebraska (U.S. Central Great Plains). They found, based on the LASA field waveforms, that 54% of NLDN-reported CG strokes were actually cloud pulses. *Cummins and Murphy* [2009] found that the NLDN classification accuracy varies from region to region and that for regions with higher frequency of positive lightning the classification accuracy tends to be lower. Also, rocket-triggered lightning data have been used to evaluate the NLDN performance characteristics in the Florida region [*Jerauld et al*., 2005; *Nag et al*., 2011; *Mallick et al*., 2014]. For 2004–2012, *Mallick et al*. [2014] found the ground flash and stroke detection efficiencies to be 94% and 75%, respectively. The strokes in rocket-triggered lightning are similar to regular subsequent strokes in natural lightning. Hence, the 75% stroke detection efficiency value cited above should be an underestimate for natural lightning, since the first strokes in natural lightning tend to be larger than subsequent ones.

Information about NLDN responses to cloud discharge activity is rather limited compared to cloud-to-ground lightning and may be outdated due to system upgrades (particularly the latest one completed in 2013 [*Nag et al*., 2014]). As reported by *Cummins and Murphy* [2009], in 2006 the NLDN cloud flash detection efficiency was in the range of 10–20%. *Wilson et al*. [2013] reported that the NLDN typically detected one to three cloud pulses per flash prior to the 2013 upgrade. *Zhang et al*. [2015], who used video and VHF lightning mapping array (LMA) observations, reported that the NLDN cloud flash detection efficiency in 2012 was 29% and increased to 41% in 2013, after the upgrade. From a more recent study based on using LMA data as reference, *Murphy and Nag* [2015] reported the cloud flash detection efficiency in 2014 to be in the 50–60% range. *Nag et al*. [2010] found that the NLDN detection efficiency and classification accuracy for 157 compact intracloud discharges (CIDs) were 96% and 95%, respectively. Note that CIDs produce VLF/LF field pulses that are comparable in magnitude to higher-intensity return-stroke pulses.

The focus of this paper is on the NLDN detection efficiency (DE) and classification accuracy (CA) of cloud discharge activity based on the ground truth data set containing 153 IC events (identified by sequences of non-return-stroke-type electric field pulses not accompanied by channels to ground) recorded at the Lightning Observatory in Gainesville (LOG), Florida. Additionally, a ground truth data set of 367 CG strokes recorded at LOG will be used to evaluate the NLDN DE and CA for CGs after the 2013 upgrade. In this upgrade, the previous IMPACT (Improved Accuracy through Combined Technology) and LS7001 sensors were replaced by Vaisala's LS7002 sensors with enhanced sensitivity to low-amplitude signals. By using pulse onset corrections, the LS7002 can better determine the arrival time of electromagnetic pulse, which improves the location accuracy. Further, as noted above, a multiparameter classification method was implemented. Also, a new algorithm, called burst processing, is presently used to locate individual pulses in the pulse train. More detailed information on this upgrade can be found in the works of *Buck et al*. [2014] and *Nag et al*. [2014].

The scope of this study is limited to the NLDN. Information about other systems can be found in *Cummins and Murphy* [2009], *Betz et al*. [2009], *Rakov* [2013], and *Nag et al*. [2015].

2. Experimental Setup

Simultaneous electric field, electric field derivative (dE/dt), and high-speed (HS) video camera records were used in this study. All the records were obtained at the LOG, Florida, in the summer of 2014. The low-gain electric field measuring system includes a circular flat-plate antenna followed by an amplifier with an RC time constant of 10 ms. The high-gain electric field measuring system includes an elevated antenna with a different amplifier having a higher gain and an RC time constant of 440 μs, which allowed us to accentuate relatively small pulses. The bandwidths are 16 Hz to 10 MHz and 360 Hz to 10 MHz for the low-gain and high-gain electric field measuring systems, respectively. The upper frequency response of the dE/dt

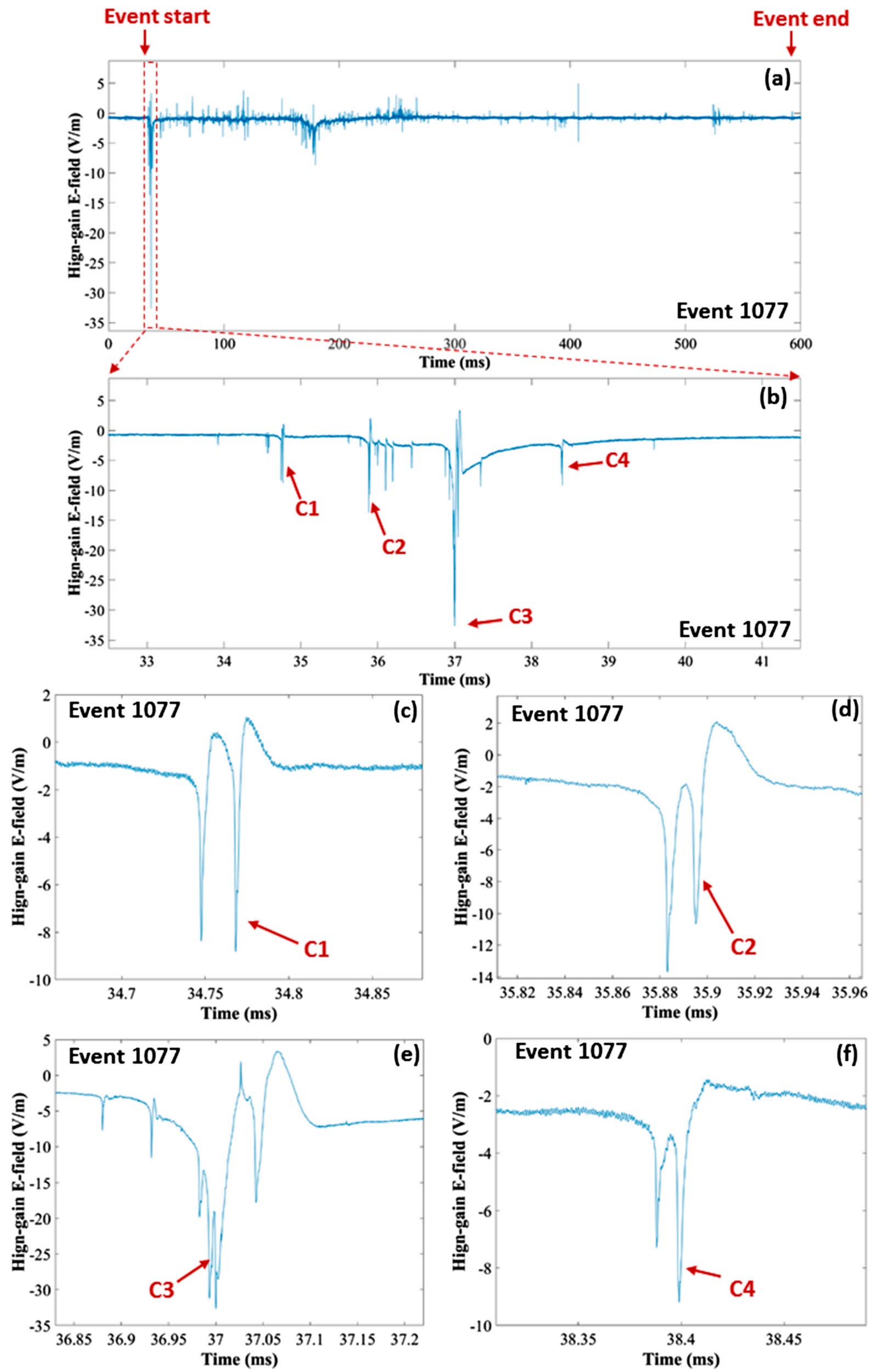

Figure 1. Example of an isolated IC event. No channel to ground was observed in the corresponding high-speed video camera record. (a) The overall record of the event. (b) Four NLDN-detected cloud pulses, labeled C1 to C4, clustered in the initial portion of the event. (c–f) Expansions of the four NLDN-detected pulses. The pulses were located by the NLDN at distances of 22 to 28 km from the LOG.

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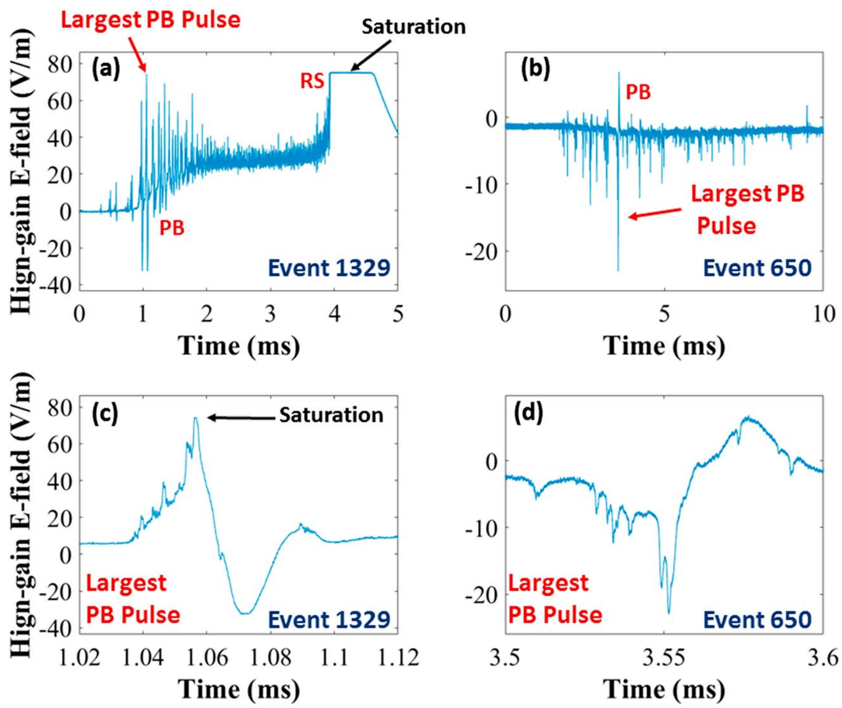

Figure 2. Examples of PB pulse trains in (a, c) negative and (b, d) positive CG flashes. The top row shows the PB pulse trains in their entirety. The bottom row shows the largest pulses in those two trains on an expanded (100 μs) time scale. The pulses shown in Figures 2c and 2d were located by the NLDN at 20 and 30 km from LOG, respectively, and were both misclassified as CGs.

measuring system is 10 MHz. The HS video data were obtained using a Megaspeed HHC-*X*2 video camera operated at 1000 frames per second with resolution of 832 × 600 pixels. It was equipped with a fisheye lens in order to have a wider (about 185°) field of view. The length of optical records was 1.2 s with 200 ms pretrigger. The length of field records was 1 s with 100 or 200 ms pretrigger.

All the records were GPS time stamped. The field measuring system was synchronized with the high-speed video camera with precision better than 1 ms. The measuring system and high-speed camera were triggered when the electric field exceeded a preset threshold. The gains of field measuring systems were such that they recorded lightning within a few tens of kilometers of LOG.

3. Data and Methodology

We identified the “cloud discharge activity” or IC event by a sequence of electric field pulses produced by either IC or CG flash that (1) had waveshapes clearly different from those characteristic of close return strokes and (2) were not associated with channels to ground in the corresponding HS video camera record (the camera had about 185° wide field of view). The characteristic features of close RS electric field waveform include the initial (predominantly radiation) peak and the following electrostatic ramp. In order to be counted as a pulse in a given sequence, the pulse had to meet two requirements: (1) the amplitude of the pulse exceeds twice the noise level and (2) the time separation from the preceding pulse is less than 200 ms. We assumed that the interpulse interval in an IC event was unlikely to exceed 200 ms since the total cloud flash duration is usually less than some hundreds of milliseconds [*Rakov and Uman*, 2003, chapter 9]. In the case of CG flashes, there could be multiple IC events in a single 1 s record, when they contained multiple strokes. In the latter case, pulse sequences occurring between the return strokes and after the last stroke were treated as individual IC events after the first return stroke. In the case of IC flashes, there was always a single IC event in a 1 s record. Our ground truth IC events (see Table 1) include 26 isolated IC events that can be viewed as complete IC flashes and 127 IC events that occurred in 76 CG flashes (70 negative and 6 positive). Out of the latter 127 IC events, 58 were IC events before first RS and 69 were IC events after first RS (including pulses occurring between strokes and after the last stroke).

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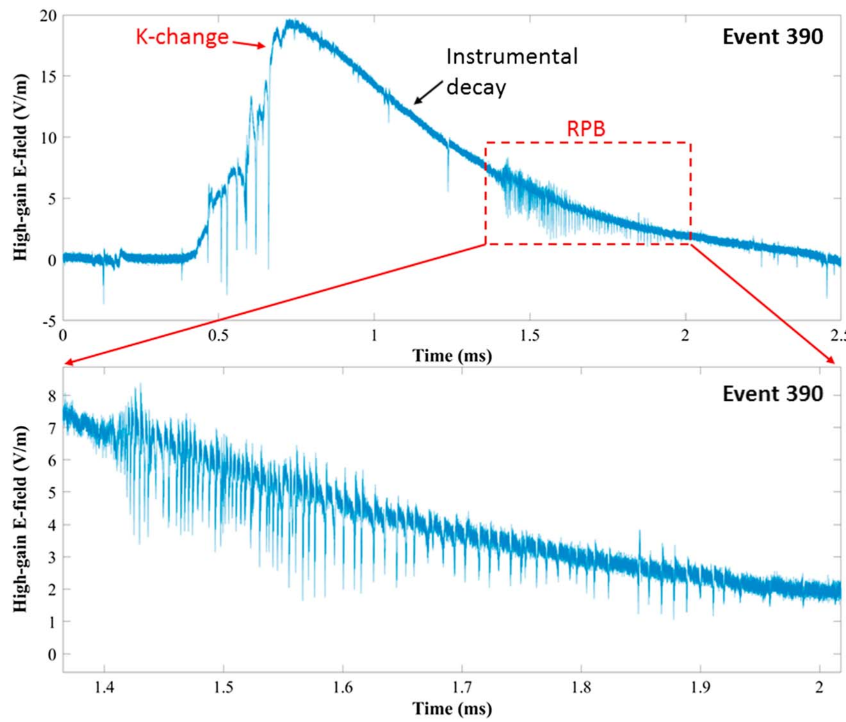

Figure 3. An example of regular pulse burst (RPB) that occurred in the later stage of a K change. No RPBs were recorded by the NLDN.

We additionally identified 24 preliminary breakdown (PB) pulse trains within IC events before first return stroke and 19 regular pulse bursts (RPBs), studied by *Krider et al*. [1975] and *Rakov et al*. [1996], within IC events after first return stroke and isolated IC events. The DE and CA for these two types of IC events were computed separately, in addition to the three main IC event categories; that is, PB pulse trains and RPBs were not treated as separate IC events in calculating the DE and CA of IC events.

Examples of isolated IC events, PB pulse trains, and regular pulse bursts are shown in Figures 1–3, respectively.

As seen in Table 1, geometric mean durations for isolated IC events, IC events before first RS, and IC events after first RS were 504 ms, 23 ms, and 69 ms, respectively. The geometric mean duration for all the 153 IC events combined was 64 ms. For 24 PB pulse trains it was 2.7 ms and 1.3 ms for 19 RPBs. The IC event duration

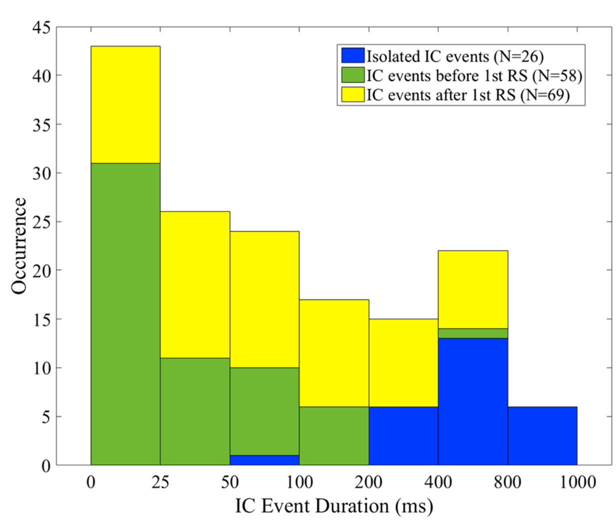

Figure 4. Histogram of durations of 153 IC events.

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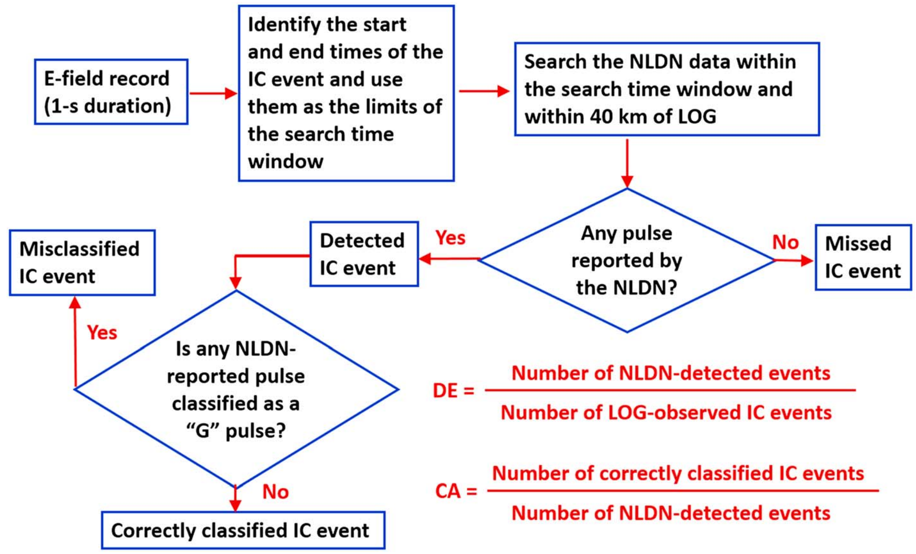

Figure 5. Flow chart used to determine the detection efficiency and classification accuracy for IC events.

was limited by the electric field record length, which was 1 s. The histogram of event duration is shown in Figure 4. Sources of most (85%) of the cloud pulses were reported by the NLDN to be at distances less than 30 km from the LOG. Note, however, that no ground truth information on source locations was available, and hence, the NLDN location accuracy for IC events could not be evaluated. Also, we do not know the distribution of source intensities for the events in our ground truth data set.

Our methodology was as follows (see Figure 5). We first identified in our 1-s long electric field records the start and the end of an IC event (a sequence of non-return-stroke-type pulses, for which no channel to ground was observed by our HS video camera). The onset of the first pulse and the end of the last pulse (each exceeding twice the noise level) in the pulse sequence were considered as the start and the end of the IC event, respectively (see an example in Figure 1a). Then we searched NLDN data within that time window (between the start and the end of the IC event) and within 40 km of the LOG. If the NLDN reported no pulses corresponding to the IC event, we regarded such an IC event as missed. If only C pulses (at least one) were reported, we regarded such IC event as correctly classified. If one or more G pulses were reported, we regarded such IC event as misclassified. The detection efficiency (DE) for IC events was defined as the fraction of LOG-observed IC events having as least one pulse reported by the NLDN (even if it was misclassified). The classification accuracy (CA) for IC events was defined as the fraction of NLDN-detected IC events for which the NLDN reported only C pulses and no G pulses.

NLDN responses to individual pulses in IC events were not evaluated in this study, since the number of ground truth events would be less certain than in the case of more readily identifiable multipulse IC events (pulse sequences). Such identification is particularly straightforward for PB pulse trains (see Figure 2) and RPBs (see Figure 3). Note that the NLDN data used in this study contained information for individual cloud pulses and CG strokes and that the NLDN did not group individual pulses into flashes or other multipulse events; this was done by us in the ground truth data and then NLDN responses (or lack of them) to those flashes/events were determined. Note also that our pulse-grouping algorithm, described at the beginning of this section, is different from that used by *Murphy and Nag* [2015].

The ground truth data set for CGs includes 367 strokes recorded by both the electric field measuring systems and HS video camera. The channel to ground was unambiguously documented for each of those strokes.

Table 2. Summary of the Ground Truth Data Set for CG Strokes

Stroke Type	Negative First Strokes	Negative Subsequent Strokes	All Negative Strokes	Positive First Strokes	Positive Subsequent Strokes	All Positive Strokes	Total
Sample size	84	257	341	21	5	26	367

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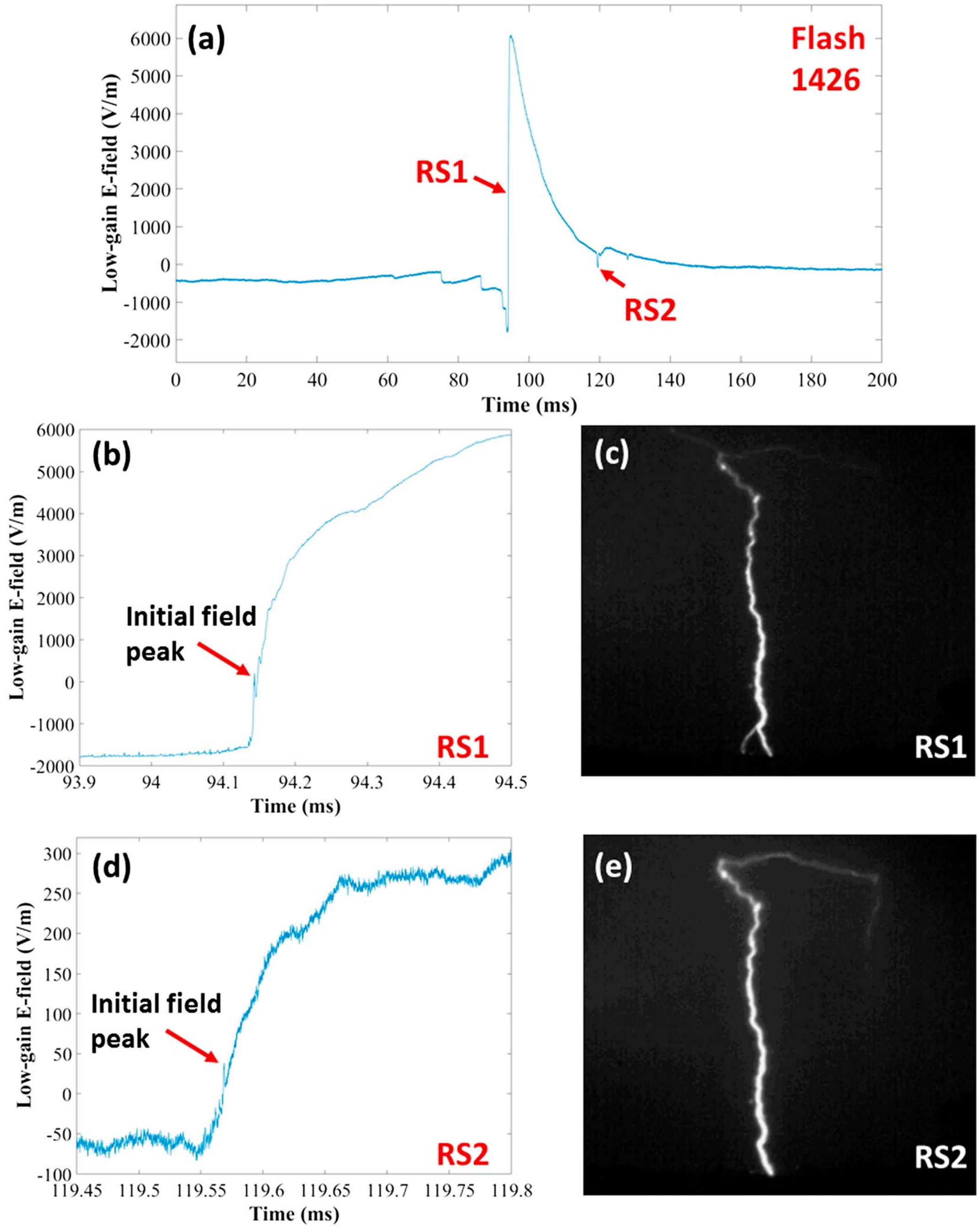

Figure 6. An example of ground truth data for a two-stroke CG flash. (a) The overall flash electric field record and expansions for the two return strokes (b) RS1 and (d) RS2) on 600 μs and 350 μs scales, respectively. (c and e) The corresponding video images (single frames). For the first stroke (RS1), the second frame is shown because the first frame is saturated. The NLDN reported that the RS1 occurred at 1.7 km and had peak current of −79 kA, while the second stroke (RS2) was missed. The peak current of RS2 was estimated to be −3.4 kA based on its field peak relative to that of RS1.

Similar to IC events, no independent information on actual source location and its intensity was available. We believe that our requirement of simultaneous capturing of CGs by both optical and electric field measuring systems serves to reduce any potential bias. Most of the CG strokes were reported by the NLDN within 20 km of LOG. A summary of the CG data set is given in Table 2. The 367 strokes were from 112 negative, 20 positive, and 2 bipolar CG flashes. The percentage of positive flashes was 15%, higher than average for summer thunderstorms. Note that the number of negative first strokes (84) is smaller than the number of

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Table 3. Summary of the NLDN Detection Efficiency (DE) and Classification Accuracy (CA) for IC Events

Type of IC Event	DE	CA	AM Number of NLDN-Reported Cloud Pulses per Detected Event	Maximum Number of NLDN-Reported Cloud Pulses per Detected Event
Isolated IC events	73% (19/26)	95% (18/19)	2.9	12
IC events before first RS	28% (16/58)	88% (14/16)	1.4	7
IC events after first RS	22% (15/69)	73% (11/15)	1.9	7
All IC events	33% (50/153)	86% (43/50)	2.1	12
PB pulse trains[a]	46% (11/24)	82% (9/11)	1.0	4
RPBs[a]	0% (0/19)	-	-	-

[a]PB pulse trains and RPBs were not treated as separate IC events in calculating the DE and CA of IC events.

negative flashes (112) due to the fact that some first return strokes were not included in the ground truth data set since they were outside the field of view of our HS video camera, even though they were identified in our electric field data. An example of ground truth negative CG flash (both video and electric field records) is shown in Figure 6. Out of the 367 strokes, 39 were from single-stroke flashes and the other 328 strokes were from multiple-stroke flashes. Single-stroke flashes constituted 20% of the negative CGs and 85% of the positive CGs.

By using a 2 ms time window ($\pm$1 ms relative to the GPS time of ground truth stroke), we identified all the NLDN-reported events (if any) in that time window and within 40 km of the LOG. If no events were reported by the NLDN in the search window, we regarded this stroke as a missed event. If a G pulse was reported in the window, we regarded this stroke as a correctly classified event. If a C pulse was reported in this window or the reported G pulse was assigned incorrect (opposite) polarity, we regarded this stroke as a misclassified event. For the rare cases of multiple pulses reported by the NLDN in the 2 ms window, we used the pulse whose timing was closest to that of the ground truth stroke.

It is worth making a comment regarding our selected 40 km search radius. Strictly speaking, we cannot rule out the situation when the source that produced the electric field pulse in our record was farther than 40 km from LOG. The trigger threshold of our electric field measuring system was empirically set to provide triggering by lightning events within 20 km or so. We have chosen the 40 km search radius to cover the expected source locations with a significant "safety margin." But it is still possible that some intense events could have occurred outside the 40 km search radius. If this did happen and the event was reported by the NLDN, the detection efficiency estimated in our study would be somewhat underestimated.

4. Analysis and Discussion

4.1. Detection Efficiency and Classification Accuracy of IC Events

Out of the total of 153 IC events, 26 were isolated IC events that could be viewed as complete IC flashes, one example of which is shown in Figure 1, 58 were IC events before first return stroke, and 69 were IC events after first return stroke. The overall detection efficiency and classification accuracy of IC events were 33% and 86%, respectively. More detailed results for the DE, CA, and the average numbers of NLDN-reported cloud pulses per detected IC event (minimum number of pulses is 1) are given in Table 3. DE for isolated IC events was 73%, which is 2–3 times higher than that for the other two IC event categories. The DE for cloud flashes reported by *Murphy and Nag* [2015] was about 50–60%, which is somewhat lower than the 73% found for our complete IC flashes but higher than the 33% for all IC events in our study. The average number of NLDN-reported cloud pulses per detected IC event was found to be 2.1.

For complete IC flashes, the average number of NLDN-reported cloud pulses was 2.9 per detected event, and the maximum number of reported pulses was 12, these numbers being higher than their counterparts for the other two IC event categories. Classification accuracies for isolated IC events, IC events before first RS, and IC events after first RS are 95%, 88%, and 73%, respectively. Note that our sample sizes are not very large, especially for isolated IC events, so further studies are needed to reduce statistical uncertainties.

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Table 4. Summary of the NLDN Detection Efficiency (DE) and Classification Accuracy (CA) for CG Strokes

Stroke Type	DE	CA
Negative first strokes	98% (82/84)	96% (79/82)
Negative subsequent strokes	90% (231/257)	90% (208/231)
Positive first strokes	100% (21/21)	95% (20/21)
Positive subsequent strokes	100% (5/5)	100% (5/5)
All negative strokes	92% (313/341)	92% (287/313)
All positive strokes	100% (26/26)	96% (25/26)
All first strokes	98% (103/105)	96% (99/103)
All subsequent strokes	90% (236/262)	90% (213/236)
All strokes combined	92% (339/367)	92% (312/339)

Due to very small pulse amplitudes, none of the 19 regular pulse bursts (in both IC and CG flashes) was detected by the NLDN. Out of the 24 preliminary breakdown pulse trains in CG flashes, 11 (46%) were detected and 9 (82%) of the 11 were correctly classified as cloud events. The two misclassified events are relatively high-intensity PB pulse trains, one of which preceded the negative return stroke and the other one occurred before the positive return stroke. Those misclassified PB pulse trains are shown in Figures 2a and 2b. The largest pulses (shown in Figures 2c and 2d) were incorrectly reported by the NLDN as a 45 kA negative CG stroke and a 30 kA positive CG stroke, respectively.

4.2. Detection Efficiency and Classification Accuracy of CG Strokes

Out of the 367 positive and negative CG strokes, 28 were missed by the NLDN. For the 339 detected strokes, 312 were correctly classified as CGs with correct polarity, and 27 were misclassified as cloud pulses. No CG strokes were reported with incorrect polarity. The resultant stroke detection efficiency (DE) is 92% and classification accuracy (CA) is also 92%. Our results for DE and CA for the different categories of CG strokes are summarized in Table 4. One can see from the table that both DE and CA of positive CGs are higher than those of negative CGs and that DE and CA of first strokes are higher than those of subsequent strokes. Both DE and CA for the only strokes in single-stroke flashes are 100% ($N = 39$), while for first strokes ($N = 78$) in multiple-stroke flashes they are 97% and 93%, respectively. For all strokes (first and subsequent strokes combined) in multiple-stroke flashes, the DE and CA are 92% and 91%, respectively.

NLDN DE and CA for CG strokes obtained in different studies are summarized in Table 5. Our results for negative subsequent strokes, DE = 90% and CA = 90%, can be compared with their counterparts (75% and 96%) for negative strokes in rocket-and-wire-triggered lightning [*Mallick et al.*, 2014], which are thought to be similar to subsequent strokes in natural lightning. For 231 NLDN-detected negative subsequent strokes in this study, the GM NLDN-reported peak current was 17 kA versus 12 kA for 290 strokes in rocket-triggered lightning studied by *Mallick et al*. [2014]. Thus, the higher DE in our study can be, at least in part, associated with higher peak currents in our ground truth data set. Another possible reason for this discrepancy is the fact that the NLDN was upgraded between 2004–2012 (the study of *Mallick et al*. [2014]) and 2014 (this paper).

Note that the classification accuracy for CG strokes found in this study cannot be generalized to the entire NLDN, since it is known to vary by region and by storm [e.g., *Cummins and Murphy*, 2009].

Table 5. NLDN DE and CA for CG Strokes Obtained in Different Studies

Reference	*Jerauld et al.* [2005]	*Biagi et al.* [2007]	*Biagi et al.* [2007]	*Fleenor et al.* [2009]	*Nag et al.* [2011]	*Mallick et al.* [2014]	This study
Type of lightning	Triggered	Natural	Natural	Natural	Triggered	Triggered	Natural
Time period	2001–2003	2003–2004	2003–2004	2005	2004–2009	2004–2012	2014
Region	Florida	Arizona	Texas-Oklahoma	Colorado-Kansas-Nebraska	Florida	Florida	Florida
Number of strokes	159 (negative subsequent[a])	3620 (positive and negative, first and subsequent)	882 (positive and negative, first and subsequent)	547 (positive and negative, first and subsequent)	139 (negative subsequent)	326 (negative subsequent)	367 (positive and negative, first and subsequent)
Stroke DE	60%	68%	77%	84%	76%	75%	92%
Stroke CA	-	-	-	44%	-	96%	92%

[a]Except for one positive subsequent stroke. All triggered lightning strokes are classified as subsequent.

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5. Summary

The NLDN detection efficiency (DE) and classification accuracy (CA) for cloud discharge activity (IC events) and CG strokes in Florida were estimated by using the electric field and optical data acquired at LOG. For 153 ground truth IC events, the DE and CA were 33% (50/153) and 86% (43/50), respectively. The average number of NLDN-reported cloud pulses per detected IC event was 2.1. Compared to IC events associated with CG flashes, isolated IC events (complete IC flashes) were found to have higher DE (73%), CA (95%), and average number of NLDN-reported cloud pulses (2.9). Out of the 24 preliminary breakdown pulse trains in CG flashes, 11 (46%) were detected and 9 (82%) of the 11 were correctly classified as cloud events. None of the 19 regular pulse bursts was detected.

For CG strokes, the DE and CA were both 92%. Both DE and CA for positive CGs were higher than those of negative CGs, and DE and CA for first strokes were higher than those for subsequent strokes. The DE for negative subsequent strokes was 90% (GM peak current = 17 kA), which is appreciably higher than the 75% estimated based on the rocket-and-wire-triggered lightning data (GM peak current = 12 kA). The CA for negative subsequent strokes in our study was 90%, which is somewhat lower than the 96% estimated using the triggered lightning data.

Note that the results of the present study correspond to the Florida region and to the NLDN configuration and settings that existed in the summer of 2014.

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