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**Key Points:**

- Natural and rocket-triggered lightning ground truth data acquired at LOG and CB were used for testing ENTLN responses to CG discharges
- CG detection efficiency and classification accuracy, as well as errors in location and current estimates were examined
- The results are needed for proper interpretation of ENTLN data used in a variety of meteorological and geophysical applications

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# Evaluation of ENTLN Performance Characteristics Based on the Ground Truth Natural and Rocket-Triggered Lightning Data Acquired in Florida

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**Abstract** The performance characteristics of the Earth Networks Total Lightning Network (ENTLN) were evaluated by using as ground truth natural cloud-to-ground (CG) lightning data acquired at the Lightning Observatory in Gainesville (LOG) and rocket-triggered lightning data obtained at Camp Blanding (CB), Florida, in 2014 and 2015. Two ENTLN processors (data processing algorithms) were evaluated. The old processor (P2014) was put into use in June 2014 and the new one (P2015) has been operational since August 2015. Based on the natural-CG-lightning data set (219 flashes containing 608 strokes), the flash detection efficiency (DE), flash classification accuracy (CA), stroke DE, and stroke CA for the new processor were found to be 99%, 97%, 96%, and 91%, respectively, and the corresponding values for the old processor were 99%, 91%, 97%, and 68%. The stroke DE and stroke CA for first strokes are higher than those for subsequent strokes. Based on the rocket-triggered lightning data set (36 CG flashes containing 175 strokes), the flash DE, flash CA, stroke DE, and stroke CA for the new processor were found to be 100%, 97%, 97%, and 86%, respectively, while the corresponding values for the old processor were 100%, 92%, 97%, and 42%. The median values of location error and absolute peak current estimation error were 215 m and 15% for the new processor, and 205 m and 15% for the old processor. For both natural and triggered CG lightning, strokes with higher peak currents were more likely to be both detected and correctly classified by the ENTLN.

## 1. Introduction

The Earth Networks Total Lightning Detection Network (ENTLN) consists of more than 1500 wideband (1 Hz to 12 MHz) sensors deployed in more than 40 countries around the world, including North and South America, Europe, Africa, Asia, and Australia. More than 900 sensors are presently installed in the contiguous United States. The sensors record electric field waveforms produced by lightning and send them to the central server via the Internet. By using the time-of-arrival technique, the ENTLN can report location and time of each lightning-produced pulse it detects. For each pulse, the polarity (positive or negative) and type of discharge (CG or IC) are determined based on the electric field pulse polarity (initial half cycle for bipolar pulses) and wave shape. All waveforms from ENTLN sensors are saved and can be processed using a different algorithm (different processor) in the future. More information on the ENTLN can be found in Liu and Heckman (2011).

Mallick et al. (2015) evaluated the ENTLN performance by using as ground truth rocket-triggered lightning data acquired in Florida in 2009 to 2012. Two different ENTLN data sets were evaluated in that study. The first data set was produced by the old processor (P2009) that was in service in June 2009 to August 2012. The second data set was produced by rerunning the same raw data (saved electric field waveforms) through the new processor (P2012) that was put in service in November 2012. Note that the term "processor" here means an algorithm that uses as inputs electric field waveforms recorded by individual ENTLN sensors and whose outputs include times and locations of lightning events, their type, peak current estimates, and location uncertainties. Mallick et al. (2015) found that the stroke detection efficiency and classification accuracy were 49% and 40% for the old processor and 67% and 48% for the new one. For the new processor, the medians of the location error and peak current estimation error were found to be 760 m and 19%, respectively.

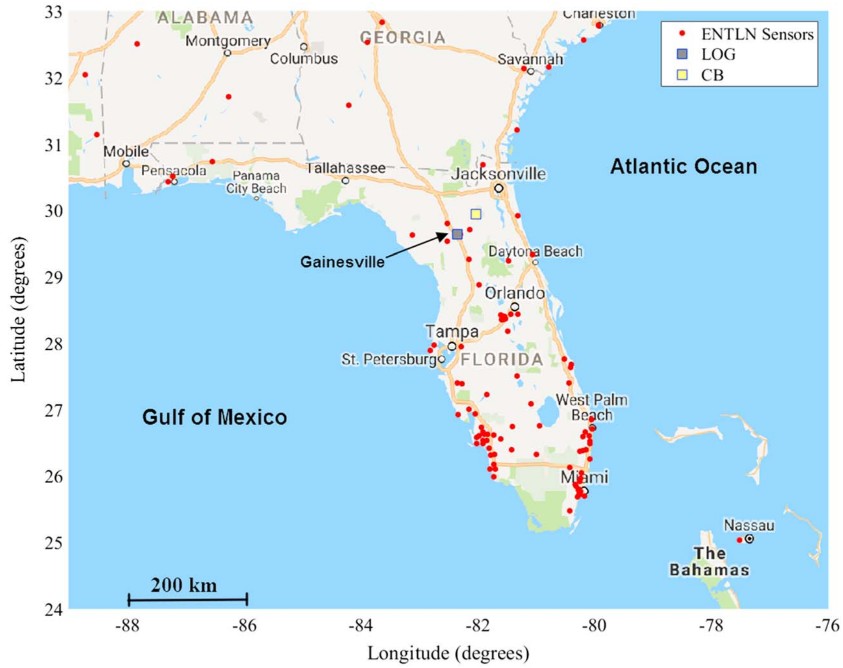


**Figure 1.** Locations of LOG (gray square), CB (yellow square), and ENTLN sensors (red circles) in the Florida region. The number of ENTLN sensors shown in this figure is 84, with the total number of sensors in the contiguous United States being more than 900.

In this study, the term "old processor" is used to denote the ENTLN processor (P2014) introduced in June 2014. Compared to previous ENTLN processors, this one had a decreased time window for searching for pulses, which served to increase the number of events seen by the ENTLN. The term "new processor" in this study refers to the ENTLN processor (P2015) that was put in service in August 2015. This latter (currently operating) processor features a new lightning classification algorithm, which uses multiple waveform parameters to distinguish between CGs and ICs.

In this paper, the ENTLN performance in the Florida region is evaluated by using natural cloud-to-ground lightning data recorded at the Lightning Observatory in Gainesville (LOG), Florida, in 2014 and 2015. Additionally, rocket-triggered lightning data acquired at Camp Blanding (CB), Florida, during the same time period were used for evaluation. The locations of LOG and CB (45 km apart) are shown in Figure 1. Also shown are the locations of ENTLN sensors deployed in the Florida region. The total number of sensors in Figure 1 is 84. Similar to the work of Mallick et al. (2015), two data sets produced using two processors were evaluated. The same originally recorded field waveforms were used as input to the two processors. The flash detection efficiency (DE), flash classification accuracy (CA), stroke DE, and stroke CA were examined for both natural lightning and rocket-triggered lightning, while the location errors and peak current estimation errors could be estimated only for rocket-triggered lightning. The results are important for proper interpretation of ENTLN data that are used in a variety of meteorological and geophysical studies and amount to the calibration of the network against the ground truth data. The developed methodology can be applied to other lightning locating systems.

## 2. Experimental Setup

### 2.1. Lightning Observatory in Gainesville (LOG)

Simultaneous electric field, electric field derivative (d$E$/d$t$), and high-speed (HS) video camera records, obtained at LOG, were used as ground truth natural lightning data in this study. 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-plate antenna with a different amplifier having a shorter RC time constant of 440 μs and a higher gain, which allowed accentuation of

**Table 1**
*Summary of Ground Truth Data Sets for Natural and Rocket-Triggered Lightning Acquired in Florida and Used in This Study*

| | Natural lightning | | Rocket-triggered lightning | |
|---|---|---|---|---|
| Year | Number of flashes | Number of strokes | Number of flashes | Number of strokes |
| 2014 | 134 | 367 | 18 | 78 |
| 2015 | 85 | 241 | 18 | 97 |
| Total | 219 | 608 | 36 | 175 |

relatively small pulses. The bandwidths are 16 Hz to 10 MHz and 360 Hz to 10 MHz for the low-gain and high-gain systems, respectively. The upper frequency response of the d*E*/d*t* measuring system is 10 MHz. The HS video data were obtained using a Megaspeed HHC-X2 video camera operated at 1000 frames per second with a resolution of 832 × 600 pixels. It was equipped with a fish-eye 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 a precision better than 1 ms. All systems were triggered when the electric field exceeded a preset threshold. The gains of the field measuring systems were such that they allowed us to record lightning up to some tens of kilometers from LOG.

### 2.2. Camp Blanding Lightning Triggering Facility

For rocket-triggered lightning, channel-base currents measured at Camp Blanding and their GPS times were used as ground truth data in this study. Also, the position of the rocket launcher (lightning termination point on ground) was known precisely and was used as ground truth for estimating location errors. The lightning triggering process is described in Rakov and Uman (2003, chapter 7). The channel-base current was measured using a 1 mΩ current-viewing resistor (CVR) with bandwidth from DC to 8 MHz. The signal from the CVR was transmitted to four separate sets of electronics (channels with different measuring ranges), which could collectively measure currents ranging from 1 mA to 60 kA (Ngin et al., 2014). The channel-base currents are recorded on several oscilloscopes, configured with different record lengths and sample intervals. For this study, the high-current channel (with highest measuring range) was used to record currents up to 60 kA with a resolution of 3 A, sampling interval of 10 ns, and record length of 2 s. Records from this channel were used to measure the peak current of each return stroke in this study. When the current magnitude exceeded 6 kA, a GPS time stamp was produced, which was used as the ground truth timing of the stroke. When the return-stroke current did not exceed the 6 kA threshold, the GPS timing of the stroke was determined from another current measuring system operated at CB by NASA.

## 3. Data and Methodology

The ground truth data sets for both natural lightning and rocket-triggered lightning are summarized in Table 1. In the summers of 2014 and 2015, electric fields for a total of 219 natural cloud-to-ground lightning flashes (175 negative, 39 positive, and 5 bipolar flashes) containing 608 strokes were recorded at LOG. The channel to ground was unambiguously documented for each of those strokes, although the termination point could be obscured by trees. No ground truth information on the strike point nor on peak current is available for natural lightning. Note that strokes with characteristic CG electric field waveforms but occurring outside of the field of view of our camera are not included in this study.

A total of 36 flashes containing 175 negative strokes were triggered at Camp Blanding in the summers of 2014 and 2015. Channel-base current records are available for 171 strokes. For one flash containing four strokes that were obtained from an altitude trigger (Lalande et al., 1998; Rakov et al., 1998) due to the breakage of the wire, no current record is available since the lightning channel did not attach to the instrumented launcher. These four strokes are not included in the evaluation of either current estimation errors or location errors. The histogram of ground truth peak currents for the 171 strokes in triggered lightning is shown in Figure 2. As noted in section 2.2, the position of the rocket launcher was used as the ground truth location of the channel termination point on the ground.

The methodology to determine the detection efficiency and classification accuracy for natural CGs used here has been developed by Zhu et al. (2016) and is shown in the form of a flowchart in Figure 3. Each ground truth

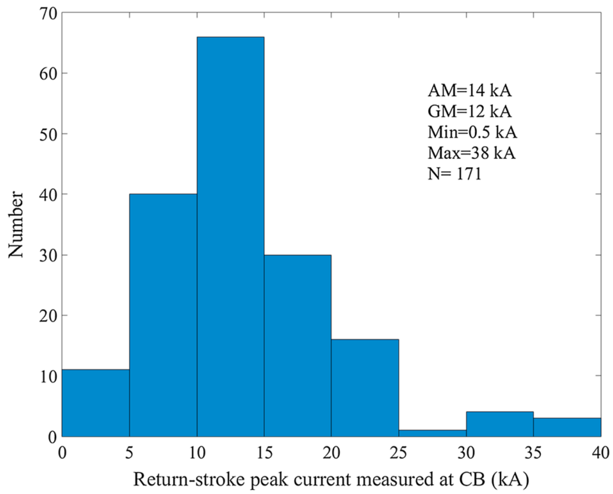


**Figure 2.** Histogram of magnitudes of peak current for 171 negative return strokes in 18 flashes triggered using the rocket-and-wire technique at Camp Blanding, Florida.

natural CG stroke had a clearly identified cloud-to-ground channel in the high-speed video record and characteristic features of cloud-to-ground stroke in the corresponding electric field waveform. Since most of our strokes were within 20 km of LOG, the return-stroke electric field waveforms had an initial (radiation) peak followed by an electrostatic ramp. The timing of the return stroke was determined by using the time of the pulse peak relative to the trigger time of the record, which was GPS time stamped. By using a 2 ms time window (±1 ms relative to the GPS time of ground truth stroke), we identified all the ENTLN-reported events (if any) in that time window and within 40 km of the LOG. The 40 km range was selected as optimal for the instrumentation setting used in this study. If no events were reported by the ENTLN in the search window, we regarded this stroke as a missed event. If a CG was reported in the window, we regarded this stroke as a correctly classified event. If a cloud pulse was reported in this window or the reported stroke was assigned incorrect (opposite) polarity, we regarded this stroke as a misclassified event. For the rare cases of multiple pulses reported by the ENTLN in the 2 ms window, we used the pulse whose timing (after accounting for the field propagation delay) was closest to that of the ground truth stroke. A similar methodology was used for the rocket-triggered lightning data set, except that the channel-base current records were used and the search area was centered at CB. Stroke DE is the percentage of ground truth strokes that were detected by the ENTLN. Flash DE is defined as the percentage of ground truth flashes in which at least one stroke was detected. The stroke CA is the percentage of ENTLN-detected ground truth strokes that were correctly reported as CGs. Flash CA is the percentage of ENTLN-detected ground truth flashes in which at least one stroke was correctly classified as a CG.

As noted above, two different ENTLN processors (P2014 and P2015) were evaluated in this study. The ENTLN data sets used for evaluation were produced by running the old/new processor with the same field waveforms recorded by individual sensors in 2014 and 2015 as input, as if each of those processors was in service during the time period when our ground truth data were collected.

## 4. Results

### 4.1. Natural Lightning

Following the procedure outlined in Figure 3, flash DE, flash CA, stroke DE, and stroke CA were estimated using ground truth data for 219 natural lightning flashes containing 608 strokes for old and new ENTLN processors. The results are summarized in Table 2. For the old processor, the ENTLN flash DE, flash CA, stroke DE,

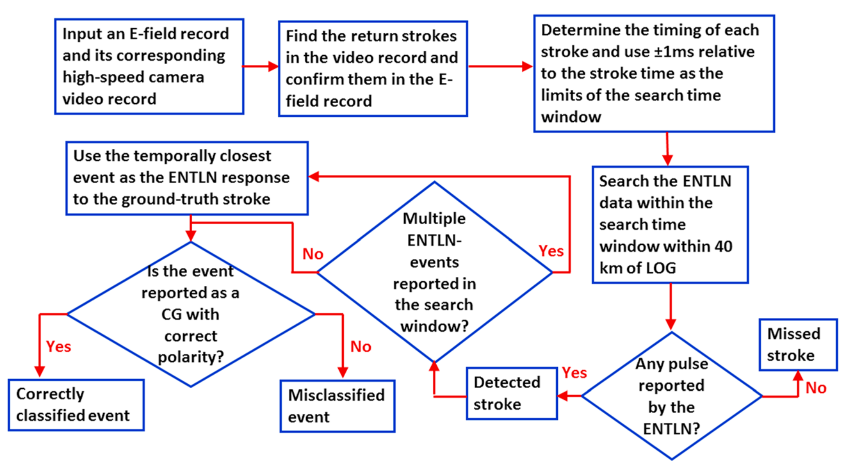


**Figure 3.** Flowchart showing the methodology to determine the detection efficiency and classification accuracy for natural cloud-to-ground lightning.

**Table 2**
*Summary of the ENTLN Performance Characteristics Evaluated Using Natural Lightning Data*

| Processor | Old | New |
|---|---|---|
| Number of flashes | 219 | 219 |
| Number of strokes | 608 | 608 |
| Flash DE | 99% | 99% |
| Flash CA | 91% | 97% |
| Stroke DE | 97% | 96% |
| Stroke CA | 68% | 91% |

and stroke CA were found to be 99%, 91%, 97%, and 68%, respectively, and for the new processor they were 99%, 97%, 96%, and 91%, respectively. Note significant improvement in the flash/stroke CA, while the flash/stroke DEs remain essentially the same. The average number of strokes per flash for ground truth natural lightning data set is 2.8, which is smaller than the 4.6 reported for negative CG flashes in Florida by Rakov and Uman (1990).

Stroke DE and stroke CA for different types of strokes in natural lightning are summarized in Table 3. Also given in Table 3 is the geometric mean (GM) peak current reported by the ENTLN for detected strokes (including misclassified ones). Both DE and CA for first strokes (positive and negative strokes combined) are higher than those for subsequent strokes (positive and negative strokes combined), which is likely to be due to the higher peak current for the first strokes. For the new processor, the GM peak currents for ENTLN-detected first strokes and subsequent strokes are 34 kA and 18 kA, respectively. The GM ENTLN-reported peak currents for misclassified strokes were 11 kA ($N$ = 189) for the old processor and 8 kA ($N$ = 52) for the new processor, while the corresponding values for correctly classified strokes were 30 kA ($N$ = 399) and 24 kA ($N$ = 532). It appears that strokes with higher peak currents (inferred from measured electric field peak) are more likely to be both detected and correctly classified by the ENTLN. One possible reason could be that return strokes with higher peak current have wider field waveforms at the measurement threshold level. Also, field waveforms of strokes with higher peak currents are less affected by noise, so that more accurate waveform characteristics can be obtained, which should improve classification accuracy.

### 4.2. Rocket-Triggered Lightning

Flash DE, flash CA, stroke DE, and stroke CA were examined for 36 rocket-triggered lightning flashes containing 175 negative strokes. The results are summarized in Table 4. The ENTLN detected all the flashes with both old and new processors. For the new processor, only one flash was misclassified versus three for the old processor. Compared to the old processor, the new-processor stroke DE increased from 94% to 97% and the stroke CA increased from 42% to 86%. It is known that negative strokes in rocket-triggered lightning are similar to regular subsequent negative strokes in natural cloud-to-ground lightning (Rakov & Uman, 2003, chapter 7). The new-processor stroke DE (97%) for rocket-triggered lightning is slightly higher than that (95%) for subsequent negative strokes in natural lightning, as seen in Table 3. The new-processor stroke CA for rocket-triggered lightning is 86%, which is lower than 91% for the subsequent negative strokes in natural lightning. As seen from Table 4, the GM ground truth peak current for detected strokes is about a factor of 5 greater than that for undetected strokes. Similarly, the GM ground truth peak current for correctly classified strokes is about twice higher than that for misclassified strokes.

For rocket-triggered lightning strokes, peak current estimation errors and location errors were also examined. The histograms for absolute (unsigned) peak current estimation error ($|I_{ENTLN} - I_{CB}|/I_{CB}$), and signed peak current estimation error ($(I_{ENTLN} - I_{CB})/I_{CB}$), are shown in Figure 4. Figure 5 shows the scatterplots of the

**Table 3**
*Summary of the Estimated Values of ENTLN Stroke DE and CA for Different Types of Strokes in Natural Lightning*

| | | Stroke DE | | Stroke CA | | GM peak current for ENTLN-detected strokes (kA) | |
|---|---|---|---|---|---|---|---|
| Stroke type | Number of strokes | Old processor | New processor | Old processor | New processor | Old processor | New processor |
| First negative strokes | 139 | 99% | 99% | 86% | 96% | 31 | 30 |
| First positive strokes | 40 | 98% | 98% | 85% | 90% | 47 | 47 |
| Subsequent negative strokes | 419 | 96% | 95% | 60% | 91% | 18 | 18 |
| Subsequent positive strokes | 10 | 100% | 100% | 60% | 60% | 26 | 25 |
| All first strokes | 179 | 99% | 99% | 86% | 95% | 33 | 34 |
| All subsequent strokes | 429 | 96% | 95% | 60% | 90% | 18 | 18 |
| All negative strokes | 558 | 97% | 96% | 67% | 92% | 20 | 21 |
| All positive strokes | 50 | 98% | 98% | 80% | 84% | 41 | 41 |
| All strokes combined | 608 | 97% | 96% | 68% | 91% | 21 | 22 |

**Table 4**
*Summary of the ENTLN Performance Characteristics Evaluated Using Rocket-Triggered Lightning Data (All Strokes Transported Negative Charge To Ground)*

| Processor | Old | New |
|---|---|---|
| Number of flashes | 36 | 36 |
| Number of strokes | 175 | 175 |
| GM channel-base peak current (kA) | 11.6 | 11.6 |
| Number of detected flashes | 36 | 36 |
| Number of correctly classified flashes | 33 | 35 |
| Number of detected strokes | 169 | 169 |
| Number of correctly classified strokes | 71 | 145 |
| Flash DE | 100% | 100% |
| Flash CA | 92% | 97% |
| Stroke DE | 97% | 97% |
| Stroke CA | 42% | 86% |
| GM ground-truth peak current for undetected strokes (kA) | 2.6 | 2.4 |
| GM ground-truth peak current for detected strokes (kA) | 12.2 | 12.3 |
| GM ground-truth peak current for misclassified strokes (kA) | 9.8 | 6.5 |
| GM ground-truth peak current for correctly classified strokes (kA) | 16.5 | 13.6 |
| Median absolute current estimation error | 15% | 15% |
| Median location error (m) | 205 | 215 |

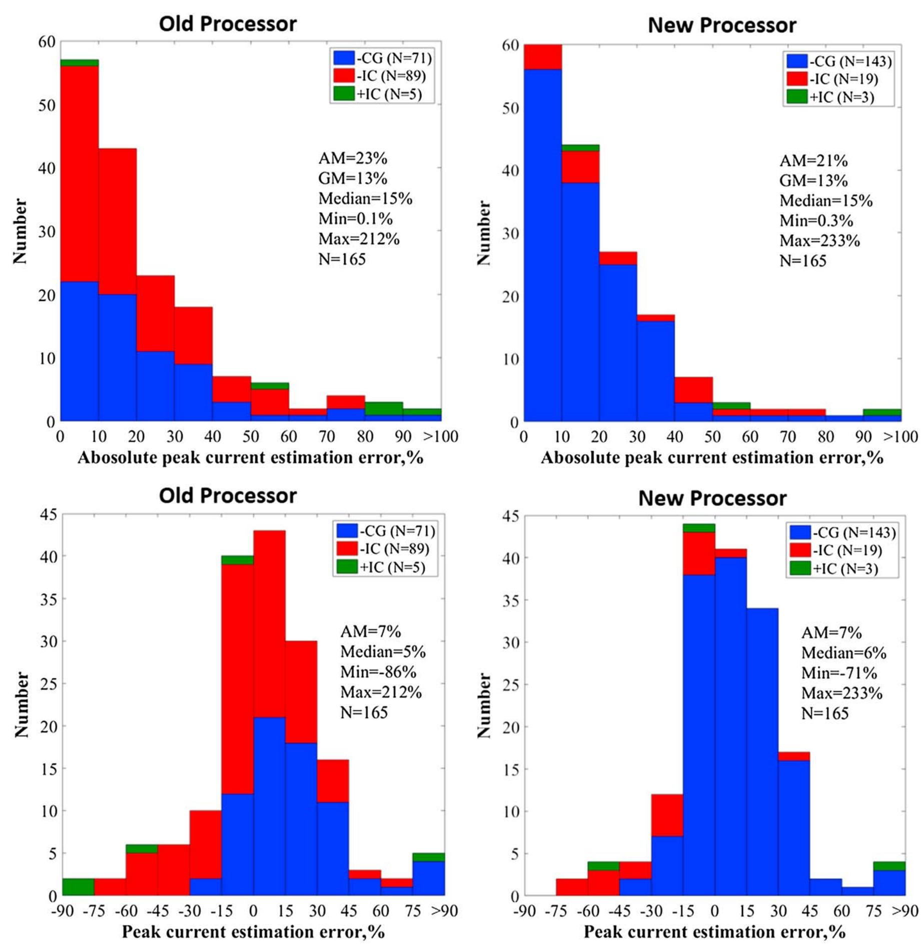


**Figure 4.** Histograms of (top row) absolute and (bottom row) signed peak current estimation errors for (left column) old and (right column) new processors.

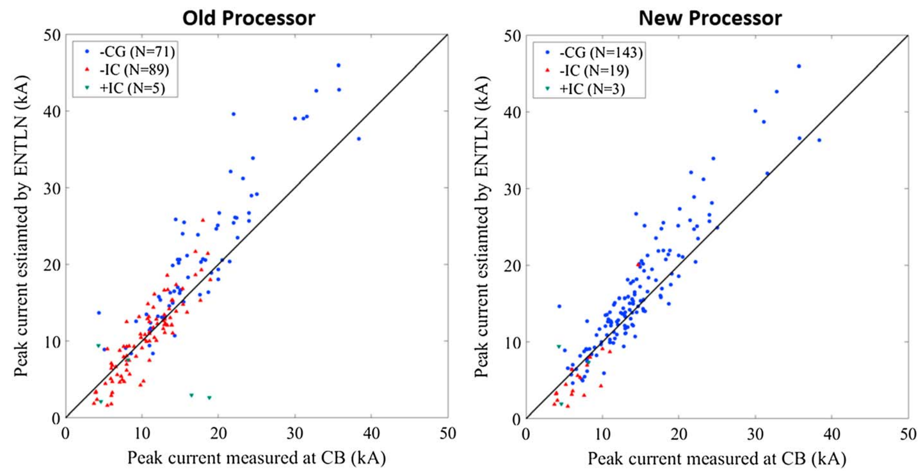


**Figure 5.** Scatterplots of the magnitude of peak current estimated by the ENTLN versus the magnitude of ground truth peak current measured at CB for (left) old and (right) new processors. Note that the type (−CG, −IC, or +IC) for each event was designated by the ENTLN and that the ground truth type for all the events is negative return stroke (−CG).

magnitude of current estimated by the ENTLN versus the magnitude of ground truth peak current measured at CB, from which one can also see that the majority of misclassified events (red and green plot symbols) had peak currents <20 kA for the old processor and <10 kA for the new processor. The ENTLN overestimated the peak currents for most of the events with ground truth peak currents >20 kA. Histograms for ENTLN location errors and plots of ENTLN-reported stroke locations are shown in Figures 6 and 7, respectively. The median location errors for old and new processors are 205 m and 215 m, respectively. Note that in Figures 4–7, the discharge type (−CG, −IC, or +IC) for each event was designated by the ENTLN and that the ground truth type for all the events is negative return stroke (−CG).

In Table 5, the ENTLN performance characteristics evaluated using rocket-triggered lightning data in this study are compared with the results found in Mallick et al. (2015). Note that a total of four processors (P2009, P2012, P2014, and P2015) are compared in that table. One can see from Table 5 that the upgrade in November 2012 significantly decreased the current estimation error, which resulted from calibration of ENTLN peak-current evaluation formula against directly measured currents for rocket-triggered lightning (Mallick et al., 2013). Further, the upgrade in June 2014 greatly improved the detection efficiency and location accuracy. Finally, the upgrade in August 2015 notably increased the classification accuracy, due to the implementation of new multiparameter classification algorithm.

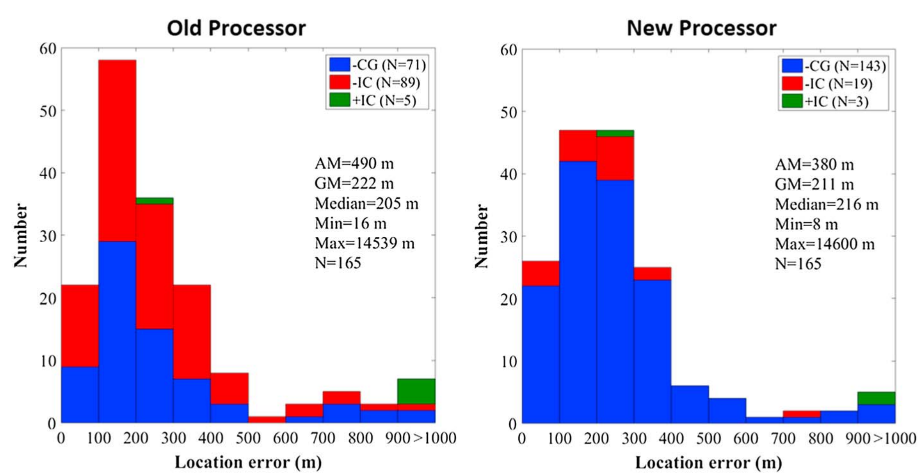


**Figure 6.** Histograms of location errors for the (left) old and (right) new processors.

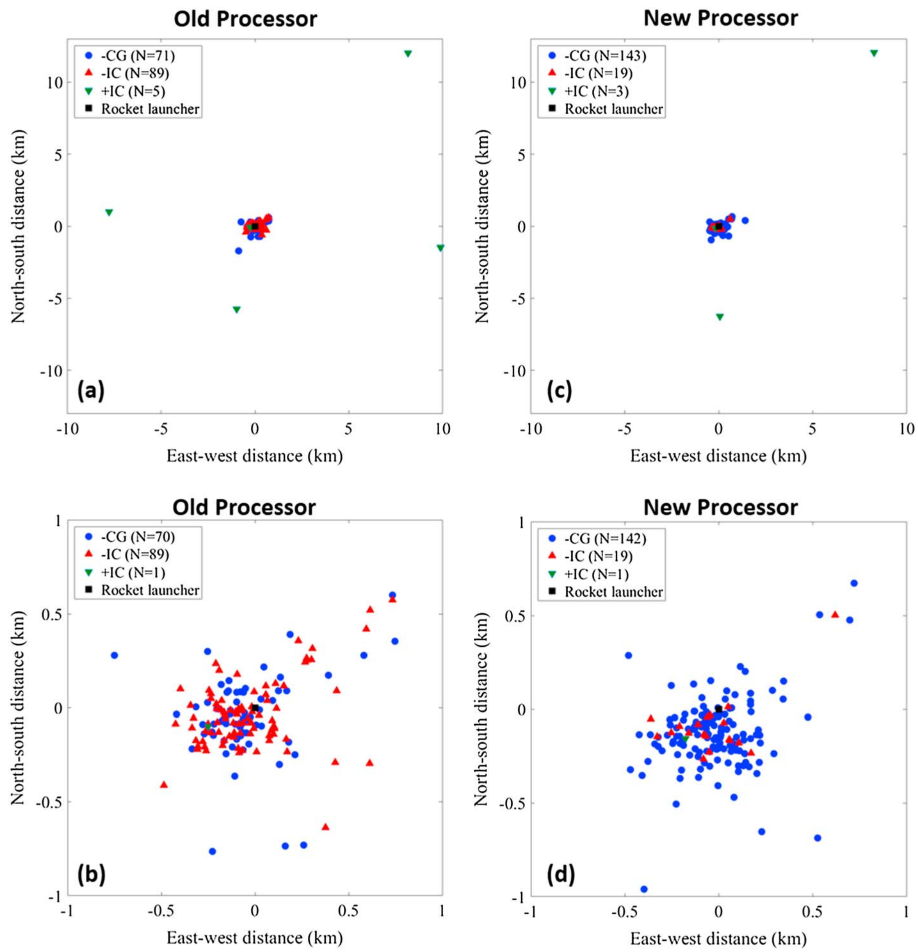


**Figure 7.** Plots of ENTLN-reported locations for (a, b) old and (c, d) new processors. Figures 7b and 7d are 2 km by 2 km zoom-ins of Figures 7a and 7c. The ground truth location (the position of the rocket launcher) is at the origin of coordinates [0,0].

**Table 5**
*Comparison of ENTLN Performance Characteristics Evaluated for Four Different Processors Using Rocket-Triggered Lightning Data Acquired in Two Different Time Periods*

| Reference | Mallick et al. (2015) | | This study | |
|---|---|---|---|---|
| Processor ID | P2009 | P2012 | P2014 | P2015 |
| Processor service time period | 2009 to Nov 2012 | Nov 2012 to Jun 2014 | Jun 2014 to Aug 2015 | Aug 2015 to present |
| Time period of ground truth data collection | 2009–2012 | 2009–2012 | 2014–2015 | 2014–2015 |
| Number of flashes | 57 | 57 | 36 | 36 |
| Number of strokes | 245 | 245 | 175 | 175 |
| Flash DE | 77% | 89% | 100% | 100% |
| Flash CA | - | - | 92% | 97% |
| Stroke DE | 49% | 67% | 97% | 97% |
| Stroke CA | 39% | 46% | 42% | 86% |
| Median location error (m) | 631 | 760 | 205 | 215 |
| Maximum location error (km) | 13.4 | 18.6 | 14.5 | 14.6 |
| Median absolute current estimation error | 51% | 19% | 15% | 15% |
| Maximum absolute current estimation error | 96% | 71% | 212%[a] | 233%[a] |

[a]The maximum absolute current estimation errors exceeding 200% are associated with the event represented in both panels of Figure 5 by a blue circle with $I_{ENTLN}$ ~ 14 kA and $I_{CB}$ = 4.4 kA. If that event were excluded, the maximum absolute current estimation error would be 119% for both P2014 and P2015.

## 5. Summary

The performance characteristics of the ENTLN were evaluated by using as ground truth natural lightning data recorded at LOG and rocket-triggered lightning recorded at CB in 2014 and 2015. For 219 natural CG lightning flashes containing 608 strokes and for the new processor (P2015), the flash DE, flash CA, stroke DE, and stroke CA were 99%, 97%, 96%, and 91%, respectively, while they were 99%, 91%, 97%, and 68% for the old processor (P2014). The stroke DE and stroke CA for first strokes are higher than those for subsequent strokes. For 36 rocket-triggered lightning flashes containing 175 strokes and for the old processor, the flash DE, flash CA, stroke DE, and stroke CA were 100%, 92%, 97%, and 42%, respectively, while their counterparts for the new processor were 100%, 97%, 97%, and 86%. The median values of location error and absolute peak current estimation error were 205 m and 15% for the old processor and 215 m and 15% for the new processor. For both natural and triggered lightning, strokes with higher peak currents (inferred or directly measured, respectively) were more likely to be detected and correctly classified by the ENTLN. Note that the results of the present study correspond to the Florida region and might not be representative of the entire ENTLN.

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