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Evaluation of the National Lightning Detection Network Upgrade Using the Lightning Imaging Sensor

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***Abstract*— We compared lightning data that was obtained using NASA's Lightning Imaging Sensor (LIS) and the U.S. National Lightning Detection Network™ (NLDN) prior to and after a network-wide NLDN upgrade completed in August 2013. This work includes analysis from 5 days in March, 2013 before the upgrade and 11 days in September after the upgrade. A total of 3,804 NLDN cloud pulses and cloud-to-ground strokes within the LIS field-of-view, and an overall 25,070 LIS groups (which are the "optical equivalent" to cloud pulses and/or strokes in the NLDN reports) in 1,874 flashes from the LIS have been evaluated. Overall, the post-upgrade detection efficiencies of the NLDN relative to the LIS increased from 6.4% to 9.9% at the group level, and from 42.9% to 48.7% at the flash level. On the other hand, the detection efficiencies of the LIS relative to the NLDN decreased from 55.6% to 52.9% at the group level and from 75.6% to 68.3% at the flash level, which are mainly due to the enhanced cloud pulses detection of the NLDN. This work also explores various spatial, temporal, and flash level characteristics of these two systems.**

Keywords—Lightning Detection; National Lightning Detection Network; Lightning Imaging Sensor

I. INTRODUCTION

Lightning emits a wide range of electromagnetic signatures through different processes, which can be detected by different lightning measurement systems. Currently, satellite-based measurements observe the optical signatures produced by lightning discharges, whereas most ground-based systems provide information about lightning processes by measuring electromagnetic emissions from very low frequency to very high frequency. Each sensor has its unique skill in providing information on certain processes within a lightning flash. For instance, a very low frequency or low frequency sensor is ideally suited to detect the first return stroke and subsequent strokes in cloud-to-ground (CG) flashes. On the other hand, a very high frequency sensor designed to measure signal time-of-arrival is more sensitive to the breakdown processes that extend a few hundreds of meters [Cummins and Murphy, 2009]. Therefore, combining these complementary satellite- and ground-based technologies [Nag et al., 2015] can help us detect most of the lightning discharges and build up our knowledge on the nature of lightning, even though any one system reports only a fraction of the lightning processes within a single lightning flash.

The Lightning Imaging Sensor (LIS) and Optical Transient Detector (OTD) are widely used satellite-based sensors, both of which were low Earth orbit instruments that observed optical pulses around the globe produced by both CG flashes and so-called IC flashes (those that do not include return strokes to ground). Climatologically, IC flashes occur 3-10 times more frequently than CG flashes [Boccippio et al., 2001].

The shortcoming of an orbital satellite sensor is that it observes a small area on the Earth for only a short period of time (a few minutes). The chances of a lightning-producing region being observed by a consistently moving satellite are very low. In the near future, the Geostationary Lightning Mapper (GLM), which will be onboard the GEOS-R satellite, will provide continuous observations over a large area [Goodman et al., 2013], and hence, improve our understanding of thunderstorm evolution and lightning activity over the Americas and adjacent oceans.

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Another limitation of optical satellite instruments is their limited ability to determine the flash type for individual flashes, although statistical retrieval methods can be used to discriminate flash types based on the distributions of the mean optical characteristics [Koshak 2010; Koshak et al., 2015a].

On the other hand, wide-area ground-based systems have relatively lower detection efficiencies for IC flashes compared to satellite-based sensors. Normally, ground-based measurements, such as those made by the U.S. National Lightning Detection Network™ (NLDN), have much higher detection efficiencies for CG strokes than for IC pulses. More details are provided in the methods section.

This paper will focus on the cross-validation between the ground-based NLDN system and the LIS sensor, and evaluate the NLDN performance before and after its upgrade completed in August 2013 [Nag et al., 2014] by comparing it to LIS. The detection efficiencies of one relative to the other will be reported, both before and after the recent NLDN upgrade. An assessment of the temporal differences between detected discharges and flashes and the spatial distances between detected discharges by the two systems will also be provided.

II. DATA AND METHODOLOGY

A. Lightning Imaging Sensor

The Lightning Imaging Sensor (LIS), which was designed to study thunderstorm processes and lightning climatology, was onboard the Tropical Rainfall Measuring Mission (TRMM) satellite [Christian et al., 1999, 2000] which ended observations on April 8, 2015. TRMM was a low-Earth orbital satellite, of which the inclination was 35 degree after levitating the orbit to 400 km on February 20th, 2001 [Cecil et al., 2014]. LIS used a 128×128 charge coupled device (CCD) array to view an area of 580 km × 580 km from above the cloud. The spatial resolution of each pixel of CCD array was about 5 km × 5 km. LIS detected the optical signatures from lightning discharges and identified lightning discharges by using a dynamic background tracking technique. LIS integrates the optical signals for 1.8 ms [Bitzer and Christian, 2015], and the result is read-out using a real-time processor that compares the optical intensity of each pixel with the background image. When the difference of the pixel intensity in the consecutive image exceeded a certain value, the processor identified this pixel as an LIS event, which is the most fundamental level of the LIS-reported data. It is possible that multiple optical pulses occurring within the frame integration time will contribute to one event [Mach et al., 2007]. Above-threshold detection of events in adjacent pixels during this frame integration time are defined as a LIS group, which can be associated with either a CG stroke or a high-current "cloud pulse", and is equivalent to an NLDN-reported discharge (see more in section II.B). Once a group is identified, a group centroid is then geo-located by spatially weighting the event locations by their radiance, representing the center of an optical pulse. Groups that occur within 330 ms and 5.5 km are weighted to interpret a LIS flash if their temporal and spatial properties are consistent [Mach et al., 2007]. As is done for groups, a flash centroid is geo-located by all the included groups. More details of the geolocation of a LIS group and flash will be discussed in section C. The instrument characteristics including pixel integration time, pixel spatial resolution and signal-to-noise ratio can all affect this clustering [Mach et al, 2007]. Finally, it is important to note that the light produced by an individual NLDN stroke or cloud pulse may be reported by LIS over more than one 1.8 ms frame integration time. This will be relevant to our interpretation of "time coincidence" between the two systems, discussed in Section II.C.

In addition to the direct lightning observations, the LIS instrument provides one-second data to indicate the status of the instrumentation and the usability of the lightning data. It consists of 4 parameters, each of which is an 8-bit flag that depicts the status of the LIS/TRMM instrument, platform, external and processing, respectively, as "warning", "fatal" or "indifference" during that one second period [Boccippio et al., 1998; Christian et al., 2000]. Lightning data during the periods with a "fatal" flag or a selected subset of "warning" flags are not included in this study.

Overall, the model-predicted LIS flash detection efficiency of total lightning including cloud-to-ground (CG) and intra-cloud (IC) flashes was claimed to be 88%±9 [Boccippio et al., 2002], and afterwards validated as between 75%-90% depending on the local time of day [Cecil et al., 2014], whereas the NLDN has relatively lower detection efficiency of IC flashes.

B. National Lightning Detection Network

The ground-based NLDN, which is owned and operated by Vaisala, provides measurements of very low frequency (VLF) to low frequency (LF) emissions from lightning. The contiguous U.S., is uniformly covered by roughly 100 LS7002 sensors [Nag et al., 2014]. The detection efficiency of the U.S. NLDN has been evaluated by using various datasets including video observations [Biagi et al., 2007; Cummins et al., 2014; Zhang et al., 2015], tower data [Lafkovici et al., 2006, Cramer and Cummins, 2014], triggered lightning data [Jerauld et al., 2005; Nag et al., 2011; Mallick et al., 2014] and others. The NLDN is able to discriminate CG and IC discharges with roughly 90% accuracy. During the period of 2003 through 2012 it reported 90-95% of all CG flashes, and some IC flashes (10-20%). In 2013 (mainly from April till August), the U.S. NLDN underwent a system-wide upgrade [Nag et al., 2014; Murphy and Nag, 2015], focused on improving IC flash detection. Recent studies have shown an increase of the IC flash detection efficiency to 45-60% after this upgrade [Murphy and Nag, 2015].

When a CG or IC discharge is detected, the NLDN reports the discharge with the primary information of its time (accurate to the microsecond), location, peak current and discharge type (IC or CG). Additionally, the NLDN clusters the discharges into flashes based on its grouping algorithm described in Murphy and Nag, [2015]. It should be noted here that an NLDN discharge (either a cloud pulse or a ground stroke) is essentially equivalent to a LIS group (which is a cluster of LIS events), not a single LIS event. To be more precise, we will use "group level" to indicate the analysis between LIS groups and NLDN-reported discharges, and "flash level" to indicate the analysis between LIS flashes and NLDN flashes. Given that a LIS event is a single "lit-up" pixel in a 1.8 ms time period, and has no equivalent structure in an NLDN report, LIS events are not considered in this analysis.

Note that the NLDN detection efficiency gradually decreases close to the southern U.S. border and coastal areas [Nag et al., 2014] which are near the edge of the network. Thus, we restrict our studied regions to be within 33-37.5°N, 85-115°W to eliminate the areas where the NLDN detection efficiency is lower due to the network edge-effects, and limit to the LIS viewing latitudes.

C. Match Methodology

The TRMM orbited the Earth 16 times per day and visited any one location a few times a day (depending on the latitude), leading to limited observation duration over our studied region. Therefore, to precisely calculate the detection efficiency of LIS relative to the NLDN at both the group and flash levels, only the NLDN discharges that occurred within the LIS field of view (FOV) can be used.

Earlier work suggests that detection efficiency may be relatively low within a few pixels along the four edges of the FOV [Franklin 2013, Fig. 4.3]. In order to avoid this possible problem, we limited the data in an inner box from which 30 km was cut off from all the four edges. Only data in this reduced FOV were used in this study.

Since neither system (LIS or NLDN) is capable of detecting all of the lightning discharges, it is more accurate and robust to investigate the detection efficiency of each system with respect to the other (see Section II.D for detailed calculation).The most-fundamental comparison is NLDN-reported discharges (hereafter NLDN discharge) with LIS groups. We consider an NLDN stroke or pulse to be matched if it was correlated with a LIS group in both time and space. To be more specific, for each “good” (not flagged) LIS group, a time window from 10 ms before the LIS group occurrence to 10 ms after it was open for use, and we determined if there was an NLDN discharge that occurred during this time window. If any NLDN discharge did occur, we marked it as a “time-matched” discharge. Then the “time-matched” NLDN discharge was used to examine if its spatial location was related to the LIS group centroid location. If the two locations were within 20 km, this NLDN discharge and the LIS group were considered as “matched”. This is the temporal and spatial matching criteria that were used in Franklin [2013], except that they allowed multiple LIS groups to match a single NLDN discharge, whereas we only allowed one LIS group to match an NLDN discharge.

The flash-level analysis is more complicated. Given that the NLDN and LIS detect different signatures produced by lightning flashes, and they have their own clustering algorithms for grouping flashes, the cross validation between the two systems at flash level requires larger temporal and spatial constraints. Previous studies [Boccippio et al., 2000; Franklin, 2013] have used different criteria for the flash matching algorithm. Using data obtained from the OTD sensor, Boccippio et al., [2000] compared the NLDN first return stroke time and nominal OTD flash time, and considered a temporal window of 300-600 ms and a spatial constraint of 200 km to determine a coincident flash. It is known that the lightning optical signals can occur before the first return stroke, and the discharges can extend to tens of kilometers away from the preliminary ones. Therefore, using the first return stroke as the start time of the flash will lead to a need for looser time and space constraints. In addition, OTD had more spatial and temporal uncertainty than the LIS instrument. Recent work by Franklin [2013] compared LIS and NLDN discharges, both at the flash and group levels. Instead of using a single NLDN flash time for temporal constraint in the flash matching algorithm, Franklin [2013] used a dynamic time window with a minimum of 300 ms that extended longer if there were more than 5 strokes in the NLDN flash. This dynamic time window was not used for this study, due to the fact that (1) only NLDN discharges that were within the reduced FOV were considered, and (2) our correlation was at the group level, as described below.

Unlike the flash matching method used in Franklin [2015], we compared the LIS groups and the NLDN discharges for the flash level analysis, but with larger temporal and spatial constraints than were used for the group level analysis. Instead of using 10 ms and 20 km as used in the group level analysis, 100 ms and 30 km were employed to allow (primarily) for matching non-coincident reports by the two systems that were within time:space bounds of a LIS flash. When a LIS group was matched, then we identified the flash that this group belonged to, using its parent ID which is a parameter provided by LIS to point out this group and flash relationship. If any group in the same flash had a match, this LIS flash became a matched flash. Likewise, the NLDN flash was called a match if any NLDN discharge in the same flash had a matched LIS group. A "matched" flash can have one or more "matched" discharges (if it was an NLDN flash) or groups (if it was an LIS flash). Note that this method could miss a small set of flashes that had more than 100 ms between all of its LIS groups and any NLDN strokes and/or pulses.

In this work, we have found that even though the matched NLDN discharges and the LIS groups have the same total count (one of each per match), when they point back to the flash level, the flash count could be different due to their different flash matching algorithms (see Section III.A for the flash counts). For instance, a LIS flash can last longer than one second, whereas an NLDN flash cannot. If both of the first and the very last optical signals in this longer-than-one-second LIS flash had an NLDN coincidence, there will be two “matched” NLDN flashes and only one “matched” LIS flash. Alternatively, LIS might combine multiple flashes into one due to its large (~ 5km) spatial footprint. This phenomenon can affect the relative detection efficiencies at the flash level, though it will not affect the relative detection efficiencies at the group level. These possible flash-count differences have motivated us to compare the matched flash counts for both NLDN and LIS, which will be shown in Section III.A.

D. Bayesian Approach

Previous works by Rubinstein, [1994] and Bitzer et al., [2016] have used probabilistic approaches to estimate the relative stroke detection efficiencies of two independent lightning locating systems, and to set bounds on the “true” detection efficiency for each system. The basic approach is described below.

Let S be the set of all the lightning discharges in the studied area; let A be the set of discharges detected by the NLDN; let B be the set of discharges detected by the LIS (see Fig. 1). Normally, S is larger than or at least equal to the union of A and

B (A U B). The ideal case would be the latter when LIS and NLDN combined together detected all of the lightning discharges. In reality, however, S is unknown, since no system can capture all of the lightning discharges. For practical purposes we assume a lower bound on the number of lightning discharges in the area of S to be m; which is the union of the number of the lightning discharges in set A (n_A) and set B (n_B). The unconditional probabilities, which represent the absolute detection efficiencies of the individual systems can be expressed as:

$$P(A) = \frac{n_A}{m} \leq \frac{n_A}{n_A + n_B - n_A \cap n_B} \tag{1}$$

and

$$P(B) = \frac{n_B}{m} \leq \frac{n_B}{n_A + n_B - n_A \cap n_B} \tag{2}$$

where $n_A \cap n_B$ denotes the intersection of the sets A and B, which represents the discharges that were detected by both systems. Equality is only valid when all of the unique lightning detected by system A and B include all of the lightning discharges that occurred in this area. In addition, the conditional probabilities

$$P(A|B) = \frac{n_A \cap n_B}{n_B} \tag{3}$$

and

$$P(B|A) = \frac{n_A \cap n_B}{n_A} \tag{4}$$

are the relative detection efficiencies of system A with respect to B and system B with respect to A, respectively.

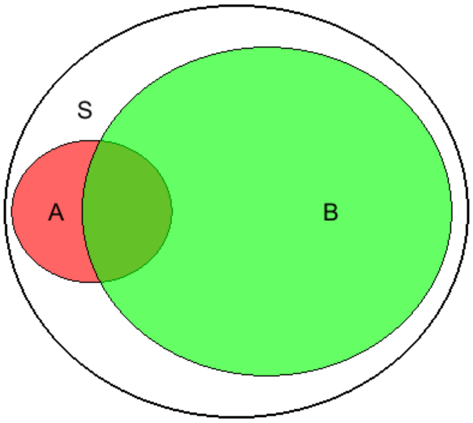

Fig. 1 A Venn diagram -illustrating set S (total lightning discharges), A (lightning discharges detected by NLDN) and set B (lightning discharges detected by LIS)

In Bayes theorem, the posterior probability is the consequence of prior (conditional) probability and a "likelihood function", and it can be simply expressed as:

$$P(B|A) = \frac{P(A|B)P(B)}{P(A)} \tag{5}$$

where the unconditional probability P(B) is the prior probability; P(A|B) is the likelihood of A given B; P(A) is the probability of A; and the conditional probability P(B|A) is the posterior probability, or the probability of B given A.

In our case, P(A) denotes the probability of detecting a lightning discharge (i.e. could be group-level or flash-level) by the NLDN, and P(B) the probability of detecting a lightning discharge by LIS. P(A|B) and P(B|A), therefore, stand for the relative detection efficiencies of NLDN and LIS given the other. Since the actual P(A) and P(B) are unknown, these calculated P(A) and P(B) provide upper bounds on the absolute detection efficiencies of these systems.

It is obvious that the estimated detection efficiencies of system A and B will be closer to the true values as the union of A and B are closer to, or even equal to, the total set S. In other words, the higher the true absolute detection efficiency of a system is, the more accurate the estimate of absolute detection efficiency is. Moreover, including additional (3 or more) lightning locating systems can provide complementary information, as suggested by Bitzer et al. [2016]. The union of those systems will be closer to S than the union of only A and B, which will result in more accurate estimates of all the absolute detection efficiencies.

Rubinstein [1994] suggested that the approach is not strictly valid for estimating flash detection efficiency, due to the indicated assumption of equal probability of detection for each stroke. The author concluded that the flash detection efficiency calculated by using this approach will be overestimated, because flashes with higher multiplicity would have higher chances to be detected by both systems. However, this assumption is not necessary for the Bayesian formulation by Bitzer et al. [2016].

For the 2-system case, if we use the assumption that the total set of lightning discharge is represented by the union of A and B, Bitzer et al. [2016] and Rubinstein [1994] provide an equivalent upper bound on P(A) and P(B).

III. RESULTS AND DISCUSSION

A. *Relative and absolute detection efficiencies*

In this study, we have analyzed 5 days in March and 11 days in September during 2013, selected for high LIS counts. A total of 25,070 (12,262 before the upgrade and 12,808 after the upgrade) LIS groups and 1874 (833 before and 1,041 after) LIS flashes, and 468,121 (99,878 before and 368,243 after) NLDN discharges were investigated. The total numbers of NLDN discharges that occurred within the reduced LIS FOV were 3,804 (1,402 before and 2,402 after). Since no single system is able to detect all of the lightning flashes or discharges, each dataset can provide complementary information for the whole set. To investigate how both systems performed during the two periods, the relative detection efficiencies of both P(NLDN|LIS), or NLDN with respect to LIS (N-to-L hereinafter) and P(LIS|NLDN), or LIS with respect to the NLDN (L-to-N hereinafter) were calculated and are shown in the tables below:

Table 1 NLDN detection efficiency relative to LIS at the group and flash levels

	Group Level	Flash Level
pre-upgrade (March 2013)	6.4% (780/12262)	42.9% (357/833)
post-upgrade (September 2013)	9.9% (1271/12808)	48.7% (507/1041)

Table 2 LIS detection efficiency relative to NLDN at group level

Group Level	Total	CG strokes	IC pulses
pre-upgrade (March 2013)	55.6% (780/1402)	48.6% (222/457)	59.1% (558/945)
post-upgrade (September 2013)	52.9% (1271/2402)	45.3% (445/982)	58.2% (826/1420)

Table 3 Same as Table 2, but at flash level

Flash Level	Total	CG Flashes	IC Flashes
pre-upgrade (March 2013)	75.6% (456/603)	78.1% (132/169)	74.7% (324/434)
post-upgrade (September 2013)	68.3% (575/842)	69.4% (134/193)	68.0% (441/649)

In the group level analyses, the pre- and post-upgrade N-to-L detection efficiencies were 6.4% (780/12262) and 9.9% (1271/12808), respectively. Since LIS did not undergo any modifications, we assume safely that the LIS DE did not change during the period. Therefore, this 3.5% increase in DE (55% improvement) supports an increase of the NLDN relative detection efficiency at the group level. It should be noted here that both our group-level N-to-L detection efficiencies are less than that was found by Franklin [Franklin, 2013] for the full-year of 2010. This is likely because they allowed the same NLDN-reported discharge to match more than one LIS group, whereas we did not. As mentioned earlier, the optical emission produced by an individual NLDN stroke or cloud pulse may be reported by LIS over more than one 1.8 ms frame time, which will affect this result. Our re-calculated group-level N-to-L detection efficiencies using the method of Franklin [2013] were 14.0% (1713/12262) before the upgrade and 17.9% (2294/12808) after the upgrade. Our pre-upgrade detection efficiency was somewhat higher than their result (10.1%), but our observation period was much shorter and was more recent. This maybe the result of a hardware upgrade in the NLDN that began in 2011 and improved sensitivity to low current discharges [Koshak et al., 2015b, Appendix A].

On the other hand, the pre- and post-upgrade L-to-N detection efficiencies at the group level were 55.6% (780/1402) and 52.9% (1271/2402), respectively, as shown in Table 2. This slight post-upgrade decrease is close to the measurement error, and is consistent with the enhancement of the NLDN system and its capability of detecting more lightning discharges due to the upgrade. Both L-to-N detection efficiencies of CG strokes and IC pulses showed a decrease (see Table 2).

For the flash level analysis, the N-to-L detection efficiency increased from 42.9% (357/833) before the upgrade to 48.7% (507/1041) after the upgrade. Given that the types of the flashes that LIS detected are unknown, there is no simple way to use this result to determine if this increase was mostly due to the improvement of IC flash detection by the NLDN. It might be possible to use climatological fraction of IC (or CG) flashes to statistically estimate the flash type [Medici, et al., 2015], but there is large variation throughout the U.S.. Insight into this issue is proved by the L-to-N flash analysis presented later in this section.

It should be noted here that the "matched" LIS flash count in the N-to-L analysis differs from the NLDN flash count in the L-to-N analysis, even though these analyses employ the exact same set of matched groups, strokes, and cloud pulses. Following the upgrade, Tables 1 and 3 show that the correlated groups were associated with 507 LIS flashes (using LIS flash algorithm) and 575 NLDN flashes (using the NLDN flash algorithm). Therefore, the NLDN views the correlated dataset as having 13.4% (575/507-100%) more flashes than LIS after the upgrade. Before the upgrade, NLDN reported 456 associated flashes, while LIS reported 357, which is 27.7% (456/357-100%) more flashes. These flash count differences are a result of either the NLDN flash algorithm separating the same flash as more than one, or the LIS flash algorithm grouping two individual but temporally and spatially close flashes together, or both. This is the first known report this flash count difference comparing flash grouping between the two systems, and it deserves further analyses. Moreover, the NLDN reported twice as many (27.6% vs. 13.4%) “excess” associated flashes before the upgrade than after; this is probably because the upgraded NLDN has reduced a break-up problem for some flashes.

The pre- and post-upgrade L-to-N detection efficiencies at flash level were 75.6% (456/603) and 68.3% (575/842), respectively. Both CG and IC flash L-to-N detection efficiencies decrease after the upgrade. Moreover, the ratio of the total number of LIS flashes to the total number of the NLDN flashes also decrease from 1.4 (833/603) before the upgrade to 1.2 (1041/842) after the upgrade. These results indicate that LIS has reported fewer of the additional flashes that were reported by the NLDN after the upgrade, further supporting the improvement of the NLDN system and its increased detection capability.

The ratio of the total number of LIS groups to the total number of the NLDN discharges in the LIS FOV can be used to indicate the relative detecting capability of LIS relative to the NLDN. The averaged numbers in the pre- and post- upgrade periods were 8.7 (12262/1402) and 5.3 (12808/2402). It is clear that the NLDN was able to detect a much larger subset of lightning discharges following the upgrade. It should be noted that the decrease of this LIS/NLDN ratio (39% decrease) following the upgrade was greater than the decrease of the L-to-N detection efficiency (4.9% decrease). This indicates that although the NLDN was able to detect more lightning discharges, especially IC pulses because of its upgrade, many of these discharges were not reported by LIS.

Given equations (1) and (2), the upper bound on the estimated absolute flash detection efficiencies of each system can be calculated. In our case, set A (red circle) includes 842 flashes, while set B (green circle) includes 1041 flashes. The flash counts in the intersection (shaded area) based on the NLDN and LIS algorithms, however, are different. The flash count based on the NLDN algorithm was 575, whereas the flash count based on the LIS algorithm was 507. The NLDN flash counts employed in these calculations must be corrected by the 13.4% average higher flash counts reported by the NLDN, as identified earlier in this section Therefore, the estimated absolute total flash detection efficiencies of the NLDN and LIS are calculated as follows:

$$P(A) \le \frac{n_A}{n_A + n_B - n_A \cap n_B} = \frac{842/1.134}{842/1.134 + 1041 - 575/1.134} = 58.2\% \tag{6}$$

$$P(B) \le \frac{n_B}{n_A + n_B - n_A \cap n_B} = \frac{1041}{842/1.134 + 1041 - 507} = 81.5\% \tag{7}$$

This estimated post-upgrade detection efficiency of the NLDN (58.2%) is in agreement with Murphy's result of 45-63% total flash detection efficiency [Murphy et al., 2014].

This initial result of estimating the current LIS and NLDN detection efficiencies using the Bayesian approach does not partition the data as finely as desired. To be more accurate and precise in the future, P(B) at different local times and regions should be considered as well. Also, there are only two lightning locating systems in this study; a more accurate way to evaluate the absolute detection efficiency would be to consider and compare more systems as discussed in the section II.D.

B. *Multiplicity Comparison*

Due to the flash matching algorithms we discussed above, the N-to-L flash detection efficiency should depend on the multiplicity (number of groups per flash) of the LIS flashes. More specifically, for any group in a LIS flash that had a temporal and spatial correlation with as few as one NLDN discharge, the associated LIS flash was marked as "matched". Therefore a LIS flash which had more groups should have a higher chance to be "matched". Fig. 2 shows histograms of the fractional occurrence of multiplicity per flash for all of the LIS flashes and for matched LIS flashes. It is clear that the percentages for those greater multiplicity flashes are relatively higher in the matched flashes than the total flashes.

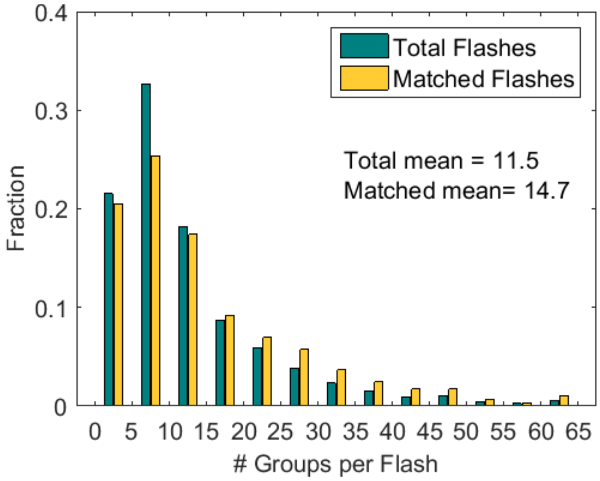

Fig.2 Comparison of fractional occurrence of multiplicity per LIS flashes between total LIS flashes and the matched LIS flashes.

C. *Time-related Comparisons*

The NLDN and LIS were developed to detect the very low and low frequency signals, and optical emissions from a lightning flash, respectively. Since these emissions come from somewhat different processes in a flash and have different geometrical properties, the time at which each of the system detects the same pulse or stroke could be different. The time differences between a reported NLDN discharge and its "matched" LIS group start time are shown in Fig. 3. LIS time is subtracted from NLDN time, so a negative value indicates that the NLDN reported earlier. The median time difference between an NLDN discharge and LIS group were -1.9 ms in March and -1.68 ms in September, respectively. Both months showed a negative bias, which indicates that NLDN discharges were normally reported earlier than its "matched" LIS group, and this bias can be as high as 10 ms. Although these long-delay cases were rare, they can still somewhat affect the matching results. The rather large median time shift is thought to be a LIS instrumentation issue and not due to differences in the physical processes, since light should be better time-correlated with the large electromagnetic fields associated with high-current discharges reported by the NLDN.

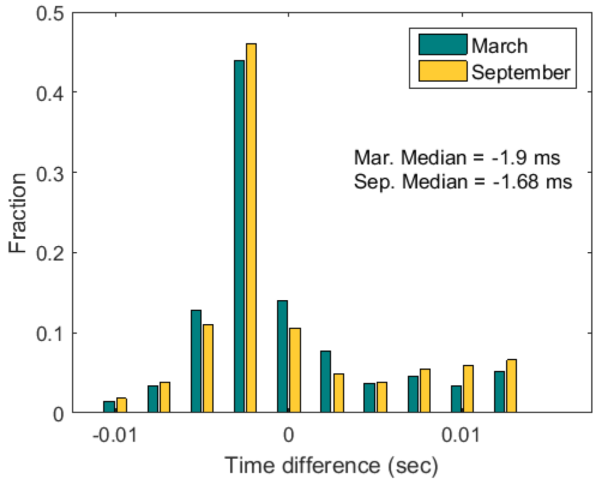

Fig.3 The time difference between NLDN discharges and time-matched LIS groups

For the flash level analysis, the duration of a flash can also be related to its ability to be detected. Both CG and IC flashes can last longer than 1 second. Although there is no time restriction on the duration of a LIS flash [Mach, et al., 2007], and a LIS flash could last longer than 1 s, the NLDN flash algorithm sets a 1-second limit on flash duration, as described earlier. Any CG strokes and/or IC pulses that occurs more than 1 s from the first one will be considered as the beginning of another flash in the NLDN dataset.

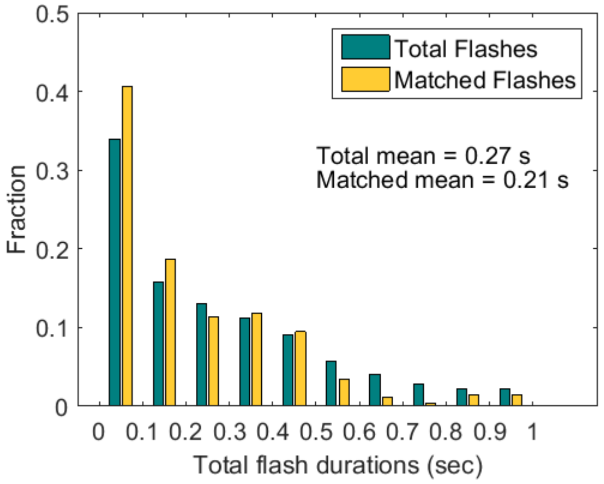

Fig. 4 Histograms of the NLDN reported total flash duration (including ICs and CGs). Left panel is all the NLDN reported total flashes, and right panel is matched flashes

Fig. 4 shows histograms of the durations of all (Total) flashes reported by the NLDN and those that were matched to LIS flashes. The durations were calculated as the time difference between the last NLDN discharge and the first discharge. Note the very high percentage of the flash durations in the smallest histogram bin (0-0.1 s); most of these cases had one discharge in the flash. It is clear that most of the NLDN reported flash durations are less than 0.5 s. The histogram for the total flash (IC+CG) durations (green) show a gradual decrease of the percentages when the flash durations increase. Likewise, the total IC flashes histogram shows a similar pattern (Fig. 5). Both matched total lightning flashes and total IC flashes (yellow) have shorter durations. The CG flash histograms (Fig. 6), however, shows that the matched CG flashes have higher percentage with longer durations. These findings suggest that the NLDN and LIS match better for long-duration (high multiplicity) CG flashes and short to moderate duration IC flashes.

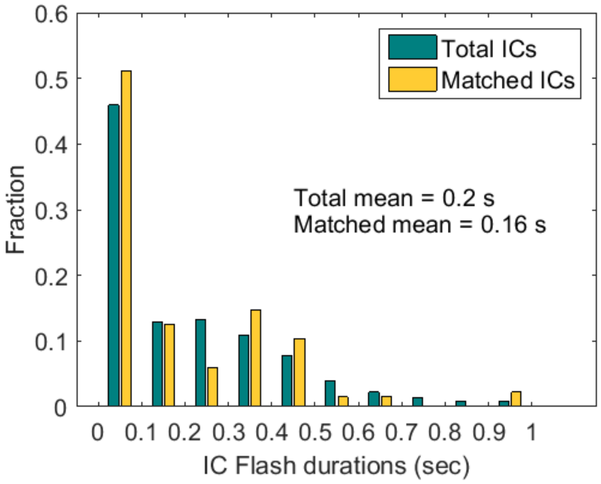

Fig. 5 Histograms of the NLDN reported IC flash durations. Left panel (green) is all the NLDN reported IC flashes, and right panel is matched IC flashes

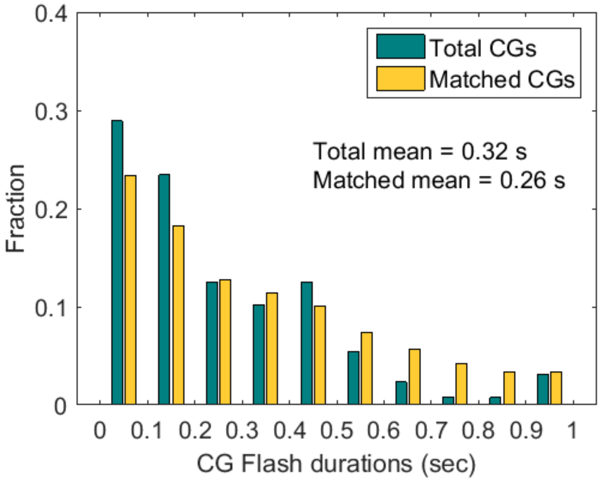

Fig. 6 Same as Fig. 5, but for CG flashes

D. *Location Comparison*

The location differences between the NLDN discharges and the centroids of their matched groups are shown in the histograms in Fig. 7. It is clear that the distance differences were generally less than 10 km, and the pre-upgrade and post-upgrade mean values were essentially the same (6.8 km and 7 km, respectively). Instead of decreasing monotonically, both periods showed a maximum occurrence in the 4-6 km range (about one pixel), which is comparable to the results from Thomas et al. [2000]. By further investigating the daily behavior of these distance differences (not shown in this paper), we observed transitions in the direction of the offset at specific times.

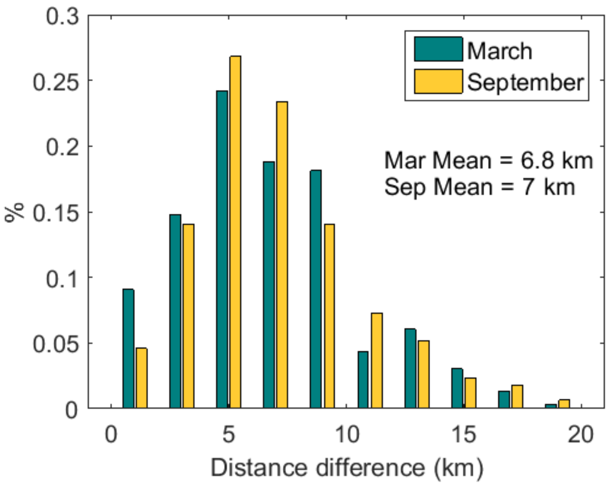

Fig. 7 Histograms of the distances between matched NLDN discharges and the closest group centroid. Left panel is before the upgrade, and right panel is after the upgrade

Following discussions with the LIS science team, it became clear that these transitions occurred whenever the TRMM satellite underwent its periodic "yaw maneuver" (the operational information including date, time and orbit # for these maneuvers are available at:

http://www.eorc.jaxa.jp/en/hatoyama/satellite/satdata/maneuver/Yaw_e.pdf)

We have evaluated the relative distance differences between "time-matched" LIS group centroids and NLDN strokes/pulses, and how this yaw maneuver has affected the spatial matching. During our studied time period, the yaw maneuver occurred twice. One of them occurred at 20:35:01 (orbit # 90164) on September 13th, 2013. Fig. 8 shows the comparison of the distance differences before and after the yaw maneuver. To make the work statistically meaningful, the data before the yaw maneuver are from 4 days (09/10, 09/11, 09/12, 09/13 before 20:30), while the data after the yaw maneuver is only from Sep. 13th (after 20:30) during a high flash-rate period. There were 317 time-matched samples (10 ms time window) before the TRMM yaw maneuver, and 869 after. The scatter plots are the four-quadrant distance difference between the LIS group centroids and their time-correlated NLDN strokes and/or pulses (NLDN minus LIS). The mean position bias and standard deviation around the mean locations are -4.66 km and 3.42 km before the yaw, while the mean and standard deviation after the yaw are 4.11 and 4.32, respectively, illustrated in Fig. 9. Note that the mean (bias) values mentioned above are in the Y (N-S) direction. The bias in the X direction is negligible comparing to the bias in the Y direction in both cases.

The other yaw maneuver occurred at 08:47:01 (orbit # 87554) on March 30th, 2013 (see Fig. 10 and Fig. 11). The data before the yaw maneuver are from 4 days (03/23, 03/24, 03/29, 03/30 before 08:30 am), while the data after the yaw maneuver is only from March. 31st (after 09:00). There were 425 and 1248 time-matched samples before and after the yaw, respectively. The mean and standard deviation in Y direction are 4.89 km and 4.71 km before the yaw, while the mean and standard deviation in Y direction after the yaw are -5.63 and 4.47, respectively.

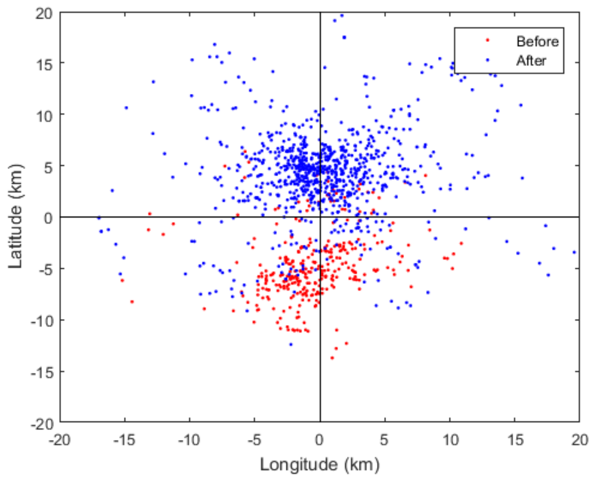

Fig. 8 Four-quadrant scatter plots of the distance difference between the time-matched NLDN and LIS. Blue dots are the distance difference (NLDN minus LIS). Red dots are before the yaw maneuver and blue ones are after. The yaw maneuver occurred at 20:35:01 on September 13th, 2013

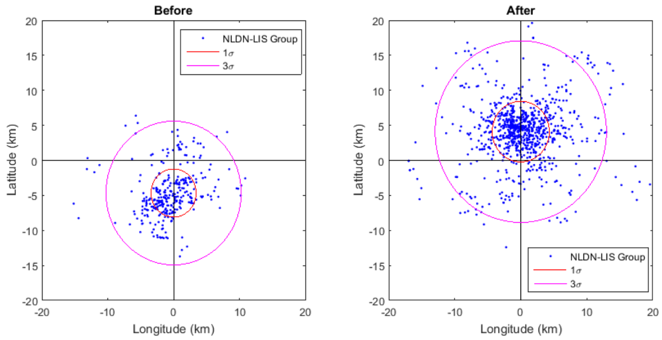

Fig. 9 Four-quadrant scatter plots of the distance difference between the time-matched NLDN and LIS. Blue dots are the distance difference (NLDN minus LIS). Red and pink circles represent the 1-standard deviation and 3-standard deviation areas (only in Y direction), respectively. Left panel is before the yaw maneuver, and right panel is after. The yaw maneuver occurred at 20:35:01 on September 13th, 2013

These results provide conclusive evidence that the LIS locations include a north or south positional bias of about 5 km, at least over the coterminous U.S., defined by the satellite orientation which changes with each yaw maneuver. This results in a 10 km average north:south shift of the LIS group centroid at the time of the maneuver. This positional bias is approximately one standard deviation of the random error, and should be correctable. To illustrate this, an average 5 km distance was used to correct this bias for all the matched groups in this study. For south-bias days, 5 km is added to the latitudes of all the matched LIS groups, while for north-bias periods, 5 km is subtracted from the latitudes of all the matched LIS groups. Fig. 12 shows a histogram comparing the distance differences with yaw maneuver corrected (yellow bars) and without corrected (green bars). The occurrence maximum between 4-8 km sections has been removed by the correction, and the fraction of matched groups gradually decreases as the corrected distance differences increases.

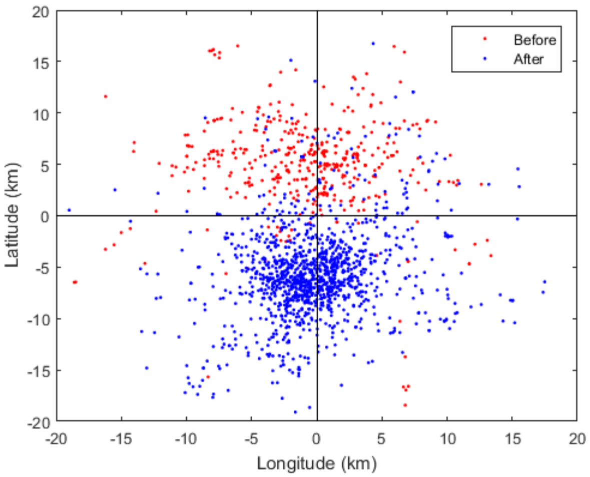

Fig. 10 Same as Fig. 8, but for the yaw occurred at 08:47:01 on March 30th, 2013

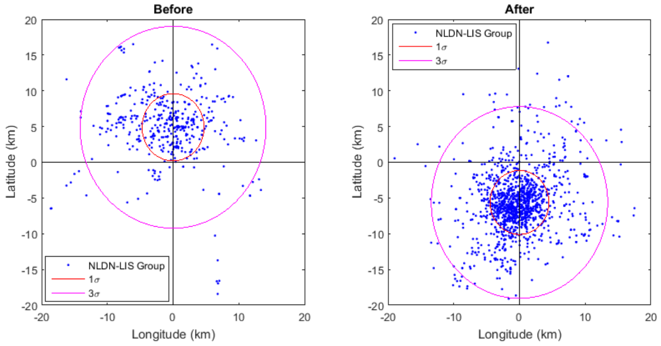

Fig. 11 Same as Fig. 9, but for the yaw occurred at 08:47:01 on March 30th, 2013

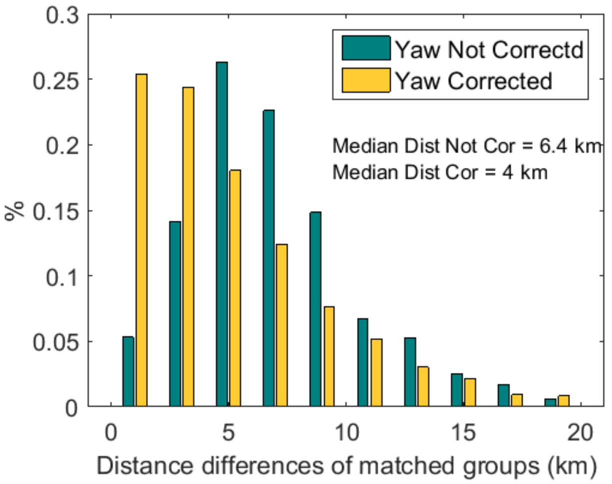

Fig. 12 Histograms of the all the matched groups distance without yaw maneuver corrected on left, and with yaw maneuver not corrected on right

IV. SUMMARY AND CONCLUSIONS

There is clear evidence showing an increase of detection efficiencies of the NLDN relative to LIS from 6.4% to 9.9% at group level and from 42.9% to 48.7% at flash level after its system-wide upgrade in 2013. These increases were the results of the enhanced IC flashes detection by the NLDN. On the other hand, the detection efficiencies of the LIS relative to the NLDN decreasing from 55.6% to 52.9% at the group level and from 75.6% to 68.3% at the flash level, and are thought to be due to the increased number of flashes detected by the NLDN.

The set theory and related Bayesian approach provides a more complete way to look at the relative and “absolute” detection efficiencies of lightning locating systems. In our study, the estimated (upper bound) “absolute” detection efficiencies of the LIS and the NLDN (post-upgrade) calculated by using this approach were 81.5% and 58.2%, respectively.

In addition, from the discussions above, there are several other main observations and conclusions:

1) Due to the different flash grouping algorithms, we found that the flash counts reported by LIS and NLDN based on the same correlated groups/events in the individual flashes are different. The correlated NLDN flash count was 575, which is higher than the correlated LIS flash count 507. The possible reasons for this count difference can be the separation of the detected NLDN flashes that either had few discharges or were longer than one second, and/or the merging of two or more LIS reported flashes as one. Further analysis is needed to characterize and understand this difference.

2) Results show that the NLDN discharges were normally reported earlier (less than 2 ms) than the correlated LIS groups. This finding is consistent with findings by Franklin [2013].

3) The nature of the flashes had an impact on detection efficiency. NLDN flashes with greater multiplicity have a higher chance to have temporal and spatial correlated LIS reports. Moreover, CG flashes with longer durations tend to have a higher chance to be detected by both systems. However, a large fraction of NLDN-detected IC flashes with correlated LIS reports had only one pulse in the individual flashes.

4) There is a roughly 5 km distance offset (north:south shifting) in the latitudinal location (longitudinal location offset is negligible) of the LIS group-level data, relative to the temporally and spatially correlated NLDN discharges. This offset is due to the TRMM satellite yaw maneuver, and is recommended to be corrected in order to better compare the LIS geolocations with other lightning locating systems.

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