Bayesian Analysis of the Detection Performance of the Lightning Imaging Sensors

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ABSTRACT: Identical Lightning Imaging Sensors (LIS) aboard the Tropical Rainfall Measuring Mission satellite (TRMM LIS, 1998–2015) and International Space Station (ISS LIS, 2017–23) have provided over two decades of lightning observations over the global tropics, with ISS LIS extending coverage into the midlatitudes. Quantifying the detection performance of both LIS sensors is a necessary step toward generating a combined LIS climatological record and accurately combining LIS data with lightning detections from other sensors and networks. We compare lightning observations from both LIS sensors with reference sources including the Geostationary Lightning Mapper (GLM) and ground-based Earth Networks Total Lightning Network (ENTLN), Earth Networks Global Lightning Network (ENGLN), National Lightning Detection Network (NLDN), and Global Lightning Dataset (GLD360). Instead of a relative detection efficiency (DE) approach that assumes the perfect performance of the reference sensor, we employ a Bayesian approach to estimate the upper limit of the absolute DE (ADE) of each system being analyzed. The results of this analysis illustrate the geographical pattern of ADE as well as its diurnal cycle and yearly evolution. Reference network ADE increased by ~15%–30% during the TRMM era, leading to a decline in TRMM LIS ADE. ISS LIS flash ADE has been relatively consistent at 61%–65%, about 4%–5% lower than TRMM LIS at the end of its lifetime.

KEYWORDS: Lightning; Thunderstorms; Remote sensing; Satellite observations; Bayesian methods

1. Introduction

Multiyear records of lightning observations from Earth-orbiting satellites enable the development of long-term global climatologies of lightning occurrence. The Tropical Rainfall Measuring Mission satellite carried a Lightning Imaging Sensor (TRMM LIS) that observed the global tropics from 1998 to 2015. The flight spare for LIS was launched to the International Space Station (ISS LIS) and operated from March 2017 to November 2023, extending the LIS observation record temporally and into the midlatitudes. TRMM LIS provided a highly valuable record of lightning occurrence for climatological studies (Cecil et al. 2015; Albrecht et al. 2016) that has been combined with data from the earlier Optical Transient Detector (OTD; 1995–2000; Cecil et al. 2014). Efforts are now ongoing to incorporate ISS LIS into this climatological record (e.g., Peterson et al. 2021), and the advent of additional lightning sensors aboard the Geostationary Operational Environmental Satellite (GOES-16, launched in 2016; GOES-17, launched in 2018; and GOES-18, launched in 2022), the Fengyun-4A (FY-4A) satellite (launched in 2016; Cui et al. 2022), and the Meteosat Third Generation (MTG) satellite (launched in 2022) brings further opportunities for multisatellite lightning sensor analysis.

A key initial challenge when seeking to compare and combine observations from multiple lightning sensors is quantifying their detection performance relative to each other. This question is not straightforward even for identical sensors such as TRMM LIS and ISS LIS. Nearly 2 years elapsed from the end of the TRMM era in April 2015 to the beginning of the ISS LIS record in March 2017. No other satellite lightning detector spanned that period. The best reference data available for comparison across that gap are from ground-based detection networks such as the Earth Networks Global Lightning Network (ENGLN), National Lightning Detection Network (NLDN), and Global Lightning Dataset (GLD360). However, these networks are not static; their performance has evolved over time due to processing improvements and network growth through the addition of new sensors. The challenge of comparison is further heightened by differences in the physical aspect of lightning detected by the various sensors (optical signals by LIS vs radio-frequency emissions by the ground networks), in the different viewing geometry from ground versus low-Earth and geostationary orbit, and in differing definitions of the recorded flashes [e.g., the truncation of flashes by the Geostationary Lightning Mapper (GLM) ground system, as discussed in Peterson (2019)]. In addition, TRMM LIS and ISS LIS had slightly different orbital altitudes and pointing geometries, both of which can influence the detection performance [e.g., contributing to the 30%–50% lower mean flash energy density for ISS LIS reported by Zhang et al. (2023)].

Detection efficiency (DE), defined as the percentage of true lightning discharges that can be detected, is a basic performance parameter for any lightning sensor or network. In the absence of a perfectly detecting reference system, DE can only be estimated. The most common method is the relative DE, calculated for system A as the probability that A detects a lightning discharge, given that system B detected that discharge (e.g., Rudlosky 2015; Rudlosky et al. 2017; Bateman...
and Mach 2020; Bateman et al. 2021; Zhu et al. 2022). This method assumes that system B detects all true lightning. An alternate statistic, introduced in Bitzer et al. (2016), is the absolute DE (ADE). Calculated using a Bayesian approach, ADE is defined as the probability that A detects a lightning discharge, given that any system involved in the analysis detects the discharge. This approach effectively assumes that the systems being analyzed collectively detect all true lightning discharges. This is still not wholly true; there will be some discharges below the detection threshold of all the systems. For this reason, Bitzer et al. refer to this statistic as the upper limit of absolute DE.

Bitzer et al. (2016) initially applied this Bayesian approach to compare TRMM LIS with Earth Networks Total Lightning Network (ENTLN) and reported ADE values for 2013 of 40.9% for ENTLN and 80.9% for TRMM LIS near North America and 10.8% for ENTLN and 94.8% for TRMM LIS globally. A follow-up study by Bitzer and Burchfield (2016) focused on ground-based lightning location systems, reporting global ADE of 56.8% for ENTLN, 59.8% for NLDN and GLD360 combined, and 7.9% for the World Wide Lightning Location Network (WWLLN). Since that time, the Bayesian approach has been applied to compare ISS LIS and the ground-based European Cooperation for Lightning Detection (EUCLID) network (Poelman and Schulz 2020) as well as NLDN, GLD360, and the GOES-16 GLM (GLM16; Murphy and Said 2020). There has, however, been no published analysis comparing the DE performance of TRMM LIS and ISS LIS, although Zhang et al. (2023) analyzed the differences in their group and flash parameters. Nor are updated ADE statistics available for the ground-based networks operated by Earth Networks (ENTLN and ENGLN) and Vaisala (NLDN and GLD360) in comparison to each other.

The purpose of this paper is fourfold: to expand the Bayesian analysis of TRMM LIS and reference network performance first presented in Bitzer et al. (2016); to characterize and compare the performance of both TRMM and ISS LIS by analyzing them with the same ground-based reference datasets; to provide updated statistics on the relative performance of the major ground-based networks, which have evolved over the years since they were analyzed by Bitzer and Burchfield (2016); and to provide the first ADE comparison of LIS with another satellite-borne lightning sensor. After describing the lightning sensors and methods in more detail (section 2), we investigate the geographic patterns and overall statistics of ADE during the TRMM LIS (section 3) and ISS LIS (section 4) eras. We then consider temporal variations in satellite and ground network performance (section 5), examining yearly trends and diurnal variability.

2. Data and methods

a. Data sources

The data analyzed in this study are summarized in Table 1. The satellite-borne sensors LIS (Blakeslee et al. 2020; Blakeslee 2021a,b) and GLM (Goodman et al. 2013; Rudlosky et al. 2019; GOES-R Algorithm Working Group and GOES-R Series Program 2018) monitor the 777.4-nm wave band to detect momentary cloud-top illumination produced by lightning. These sensors sample at approximately 500 frames per second. If pixel brightness in a 2-ms frame exceeds the dynamically varying background, LIS and GLM report an event. In the ground processing system, events in contiguous pixels within a single frame are clustered into groups, and groups are clustered into flashes using a weighted Euclidean distance (WED) method with time offsets of 330 ms and x and y offsets of 5.5 km (TRMM LIS and ISS LIS; Mach et al. 2007) and 16.5 km (GLM; Mach 2020). For example, for LIS,

\[ \text{WED}^2 = \left(\frac{X}{5.5}\right)^2 + \left(\frac{Y}{5.5}\right)^2 + \left(\frac{T}{330}\right)^2, \]

where \(X\) (\(Y\)) is the east–west (north–south) distance in kilometers between the group centroids, and \(T\) is the time difference in milliseconds. The difference in the distance weighting parameter reflects the spatial resolution of each sensor. LIS detects using a 128 × 128 pixel charge-coupled device (CCD) and, on TRMM, operated at 402.5-km altitude following an orbit boost in August 2001, ISS likewise operates near 400-km altitude. Pixels on both LIS instruments thus observe a similar sized region of Earth’s surface, roughly 4 km at nadir (Blakeslee et al. 2020). GLM is a 1372 × 1300 pixel CCD imager with variable pitch, which reduces the variations in pixel size. GLM pixels are ~8 km at nadir ranging to ~14 km near the limb (Rudlosky et al. 2019). Geographically, TRMM’s orbital inclination was 35° (Kummerow et al. 1998) such that TRMM LIS observed the global tropics up to ~38° latitude, while ISS orbital inclination is 51.6° (DeLucas 1996) such that ISS LIS observes the global tropics and midlatitudes. GLM16 observes the Western Hemisphere from its location at 75.2°W (Rudlosky et al. 2019).

ENTLN grew to over 800 sensors in 2015 (Bui et al. 2015), and today, it consists of over 1800 sensors in over 100 countries (Earth Networks 2009; Zhu et al. 2022). These wideband sensors (1 Hz–12 MHz) detect waveforms produced by intra-cloud (IC) pulses and cloud-to-ground (CG) strokes, which are then geolocated using a time-of-arrival technique. ENTLN’s detection capabilities have improved over time with the expansion of the sensor network and with various upgrades to the data processing algorithms, including a new processor launched in December 2021 (Zhu et al. 2022). To improve its global coverage, Earth Networks sensor pulse detections were combined with WWLLN stroke detections (Abarca et al. 2010) to create ENGLN (Earth Networks 2014). In this study, we analyze 5 years of ENTLN data followed by over 8 years of ENGLN data (Table 1).

The longest period of ground-based lightning data available for this study is the 16-yr record of NLDN (Vaisala 1995). Vaisala sensors detect lightning discharges in the very low-frequency (VLF) and low-frequency (LF) radio wavelengths (~500 Hz–~500 kHz), and the detected waveforms are geolocated using both time of arrival and magnetic direction-finding methods (Cummins and Murphy 2009). NLDN has evolved during the period of record of this study, with significant changes including a network-wide sensor upgrade that completed in 2013, a central processor upgrade in 2015, and additional central processing system improvements in 2018 (Murphy et al. 2021). Additional
upgrades and changes to NLDN prior to 2013 are detailed in Koshak et al. (2015). We further analyze 9 years of GLD360 stroke data (Table 1; Vaisala 2014), primarily after the network software upgrade in 2015 (Said and Murphy 2016). GLD360 also geolocates strokes using both time of arrival and magnetic direction-finding, but it employs a different sensor design restricted to detection in VLF (Said et al. 2010, 2023).

Timing agreement between ENGLN pulses and GLD360 strokes is at least submillisecond (Virts and Koshak 2023). Close geolocation agreement is also observed in areas such as CONUS and Brazil where the sensor network is dense, and peak distance offsets over most of our analysis domain are ~4 km or less (Virts and Koshak 2023). The same study reported submillisecond timing and ~3–5-km agreement between GLM16 and the ground-based networks, although larger distance offsets are observed near the GLM16 limb due to parallax (Virts and Koshak 2020).

### b. Methodology

Bitzer and Burchfield (2016) demonstrated that in a comparison of lightning detected by three systems (datasets A₁, A₂, and A₃), the unconditional probability that a discharge is observed by detection system A₁, or its absolute detection efficiency \( P(A_1) \), is related to the probability of detection by any system \( P(A_1 \cup A_2 \cup A_3) \) by

\[
P(A_1) = \frac{P(A_1 \cup A_2 \cup A_3)}{\alpha_1},
\]

where

\[
\alpha_1 = 1 + \frac{P(A_2 | A_1)}{P(A_2 | A_1) - 1} + \frac{P(A_3 | A_1)}{P(A_3 | A_1) - 1} + \frac{1}{P(A_2 | A_3)} (1 - P(A_2 | A_3)) - 1 + P(A_2 | A_3),
\]

and \( A_{23} \) is the intersection of datasets \( A_2 \) and \( A_3 \). For further details on this derivation, see Bitzer et al. (2016) and Bitzer and Burchfield (2016).

The probability of detection by any system \( P(A_1 \cup A_2 \cup A_3) \) cannot be known. As stated in section 1, for our analysis purposes, we assign it as 100%. This assumption, although necessary, has two key limitations:

1) If the universe of observed detections expands or contracts, due, for example, to changes in one detection system’s sensitivity, the reported ADE for other systems is affected even if they have not changed. As will be seen in section 5, this limitation is likely relevant to our analysis.

2) All detections reported by the contributing systems are assumed to represent real lightning, such that any non-lightning sources or artifacts produced by one system are accounted as missed detections by the other systems. Bateman et al. (2021) reported a flash false alarm rate (FAR) of just over 5% for GLM16 for the period August 2019–January 2020, and the FAR would have been slightly higher prior to implementation of the blooming filter in July 2019 (Edgington et al. 2019; Rudlosky and Virts 2021). The ISS LIS FAR is less than 5% (Blakeslee et al. 2020), and while no published statistics on the reference network FAR are available, examination of the data indicates the FAR is likely less than 1%.

For this study, stroke or pulse data from each ground-based network are clustered into flashes using the same clustering criteria employed for LIS [Eq. (1) above; Mach et al. 2007]. This clustering was performed across discharge types reported by the ground-based networks. Because we do not differentiate between CG strokes and IC pulses, we refer collectively to subflash illuminations or discharges as strokes except when observations from Earth Networks or LIS/GLM are being specified. In such cases, we use the “pulse” and “group” terminology that is standard for those sensors while acknowledging that all these systems detect both CG strokes and IC pulses. We calculate ADE at the stroke level, for direct comparison with earlier work by Bitzer et al. (2016) and Bitzer and Burchfield (2016), and at the flash level, to lay a basis for future climatological studies.

The matching windows employed in this study differ for flash-level and stroke-level analyses. For flash-level analysis, the matching criteria are ±330 ms (i.e., from 330 ms before the flash starts to 330 ms after the flash ends) and 50 km between flash centroids. The temporal window is broader than that used by Zhang et al. (2019) but matches the flash clustering definition employed for LIS and GLM (Mach 2020). Recent simulation work by Virts and Koshak (2023) suggests that a broader matching window on the order of ±1 s provides a more accurate estimate of aggregate GLM performance; however, a similar simulation analysis has not been

### Table 1. Satellite and ground-based lightning data available for Bayesian analysis. Acronyms are defined in the text.

<table>
<thead>
<tr>
<th>Source</th>
<th>Lightning data</th>
<th>Time period</th>
<th>Domain</th>
</tr>
</thead>
<tbody>
<tr>
<td>GLM16</td>
<td>Event, group, flash</td>
<td>Dec 2017–present</td>
<td>Western Hemisphere</td>
</tr>
<tr>
<td>ISS LIS</td>
<td>Pulse</td>
<td>Jan 1998–Apr 2015</td>
<td>Global tropics</td>
</tr>
<tr>
<td>TRMM LIS</td>
<td>Stroke</td>
<td>Sep 2014–Present</td>
<td>Global</td>
</tr>
<tr>
<td>ENGLN</td>
<td>Stroke</td>
<td>Jan 2007–present</td>
<td>CONUS</td>
</tr>
<tr>
<td>ENTLN</td>
<td>Stroke</td>
<td>Mar 2017–Nov 2023</td>
<td>Global tropics + midlatitudes</td>
</tr>
<tr>
<td>GLD360</td>
<td>Stroke</td>
<td>Jun 2014</td>
<td>Global</td>
</tr>
<tr>
<td>NLDN</td>
<td>Stroke</td>
<td>Ash Dec 2017</td>
<td>Present Global</td>
</tr>
<tr>
<td></td>
<td>Stroke</td>
<td>Midlatitudes</td>
<td>Present Global</td>
</tr>
<tr>
<td></td>
<td>Stroke</td>
<td>Dec 2017–present</td>
<td>Present Western Hemisphere</td>
</tr>
</tbody>
</table>
performed for LIS to date. The distance matching window is broader than the flash clustering definition for either LIS or GLM but permits more successful matching for extensive flashes where the centroid reported by various sensors may be geographically displaced. More restrictive matching criteria of $\pm 10$ ms and 25 km are applied for stroke-level analysis, similar to the criteria used by Zhang et al. (2019). In this case, the temporal window accommodates a timing bias in the TRMM LIS data of about 2–2.5 ms compared to the ground networks (not shown). ISS LIS group timing offsets from the reference sensors are smaller, peaking from 0 to 1 ms (Blakeslee et al. 2020). Our temporal matching window also permits multi-frame illuminations such as the series defined by Peterson et al. (2017) to successfully match. Multiple matches are allowed, in accordance with previous studies of the detection performance of these sensors (e.g., Bateman and Mach 2020; Bateman et al. 2021). Allowing multiple matches not only may overestimate the resulting DE during periods of high
local flash rates but also helps to compensate in situations where a less sensitive sensor misses weaker strokes within a flash. Unlike Zhang et al. (2019), our flash- and stroke-level matching are performed independently of each other for simplicity.

Two spatial domains are employed in this study. For GLM16 and the global sensors and networks, analysis is for a partial “Western Hemisphere” domain defined as 25°S–37.5°N, 150°–30°W, and excluding areas outside the nominal GLM16 field of view (FOV). This is the largest region for which data from all sources are available to the authors. Analysis involving NLDN is also limited to areas south of 37.5°N and to data within CONUS borders, as the performance of NLDN is known to deteriorate outside U.S. borders.

c. Evolution of lightning detections

Daily lightning detection counts from each sensor and network reveal a similar annual cycle with maximum lightning occurrence during Northern Hemisphere summer (Fig. 1). GLM16 exhibits a slightly later peak during Northern Hemisphere late summer/early fall and Southern Hemisphere spring. The satellite optical sensors exhibit the largest group: flash ratios, detecting 16.0 (GLM16), 12.4 [TRMM LIS, similar to the 12.3 previously reported by Beirle et al. (2014)], and 10.3 (ISS LIS) groups per flash on average. In contrast, the mean stroke:flash ratios for the ground networks when averaged across flash types range from 1.6 (GLD360) to 2.4 (ENGLN).

Operating in low-Earth orbit, LIS observes only a ~600 km × 600 km region at any given time; thus, the TRMM LIS and ISS LIS lightning counts are ~2–3 orders of magnitude lower than the other sensors, which simultaneously observe much larger regions. Within the TRMM or ISS era, the number of lightning detections is largely stable from year to year. Figure 1 indicates a substantial decrease in daily LIS flash counts for the ISS era compared with the TRMM era. ISS spends less time than TRMM over the tropics, which comprise most of our analysis domain and where the global lightning hotspots are located (Zipser et al. 2006). ISS LIS also experiences a 1-s packet dropout about once per minute, which reduces the observing time by about 1.7%. Finally, ISS LIS periodically experiences partial obstruction of its FOV by ISS solar panels/radiators. Further comparison of the TRMM and ISS eras is explained in section 5a.

Examination of daily time series from the ground-based networks reveals the networks’ improved detections over time due to the addition of sensors and improved processing methods. ENTLN lightning detections reveal a strong yearly increase (Fig. 1), spiking in mid-2014 at the end of the availability period. ENGLN lightning counts exceed those of ENTLN outside of those last few weeks and exhibit more consistent year-to-year behavior. Of the Vaisala networks, NLDN exhibits the greater detection improvement over time, with the most significant increase in lightning counts following the sensor upgrade in 2013 (Murphy et al. 2021). GLD360 detections exhibit the most year-to-year consistency of any of the ground networks.

For the remainder of this study, the viewtime variables included in each LIS science data file are used to identify which portion of Earth’s surface is in the nominal LIS FOV at any given time. GLM or ground network lightning observations outside the nominal LIS FOV are discarded; only reference observations in the nominal LIS FOV are used to evaluate LIS’ detection performance. All gridded plots are at 5° latitude × 5° longitude resolution, and all aggregates are calculated over the full domain (i.e., a flash-density-weighted ADE).

3. Absolute detection efficiency in the TRMM LIS era

The longest period of available ground network data during the TRMM era is for CONUS (Table 1), and ADE for a ~5.5-yr overlap period is shown in Fig. 2. In the aggregate, ENTLN exhibits the highest flash ADE of nearly 80%, followed by TRMM LIS at 68.4% and NLDN at 59.5%. At the stroke level, TRMM LIS has by far the highest ADE, at
76.0% compared with 39.7% for ENTLN and 20.4% for NLDN for the ground networks. These results reflect the observation in Fig. 1 that TRMM LIS was more sensitive to subflash components and thus detected more groups per flash than the ground networks. The results also compare qualitatively with Bitzer et al. (2016), who reported stroke ADE of 86.5% for LIS and 29.4% for ENTLN for a larger North America domain. Geographically, both ground networks exhibit higher ADE over the central and eastern Unites States, with flash ADEs as much as 40% higher than over the southwestern Unites States. The TRMM LIS pattern is more spatially consistent, though with some tendency for higher ADE near the CONUS perimeter where the ground network performance begins to decrease.

Earth Networks pulse counts increased dramatically during 2014 (Fig. 1), while NLDN flash and stroke counts nearly...
doubled compared with 2013. These improvements to ground network detection capabilities are reflected in the ADE during the brief ENGLN–NLDN–TRMM LIS overlap period (Fig. 3), where ENGLN flash ADE exceeded 95% and NLDN increased to 74.6%. ENGLN pulse ADE increased even more significantly, from ~40% to nearly 70%. In comparison, TRMM LIS ADE decreased by ~3% (flash) and ~14% (group), though remaining above 60%. Note, however, that this analysis period is brief (less than 8 months), spans Northern Hemisphere winter when lightning occurrence over CONUS is reduced, and includes many intervals of missing TRMM LIS data as the satellite neared the end of its lifetime. Hence, the sample size is almost two orders of magnitude smaller than for Fig. 2 and includes only ~11 000 LIS flashes in the CONUS domain.

With the advent of GLD360 during 2014, tri-network Bayesian analysis beyond the borders of CONUS is possible. Two brief overlap periods are available: ENTLN–GLD360–TRMM LIS for the first 6 months of 2014 (Fig. 4) and ENGLN–GLD360–TRMM LIS for the same 8-month period analyzed above (Fig. 5). ENTLN and ENGLN exhibit the greatest regional differences due to network sensor density, with flash ADE ranging from ~95% over CONUS to <20% over northern South America. Elevated ADE over 60%–70% is observed over the eastern equatorial Pacific, and higher values are also evident at the southern edge of the analysis domain, close to the dense sensor network in Argentina. Inclusion of WWLLN strokes in the ENGLN dataset in Fig. 5 provides greater global coverage compared with Fig. 4 that is not immediately obvious, given the lower aggregate flash ADE during the ENGLN period (45.8% vs 59.7%). However, the pattern of lightning occurrence also differs in these two periods, with 65% of flashes during January–June 2014 occurring in the Northern Hemisphere part of the domain and 63% of flashes during August 2014–April 2015 occurring in the Southern Hemisphere part of the domain. The seasonal shift in lightning occurrence away from the better-sampled Northern Hemisphere explains the counterintuitive decrease in flash ADE during the ENGLN period.

In contrast, GLD360 exhibits more spatially homogeneous flash ADE during both overlap periods, ranging from ~50% to 70% over South America up to 70%–85% over much of CONUS and adjacent oceanic areas. The GLD360 stroke ADE also exhibits fewer regional variations, averaging 20%–40% over most of the domain. TRMM LIS, as expected for a satellite-borne sensor in low-Earth orbit, exhibits fewer regional variations still; the most noticeable tendency is for somewhat lower ADE over the well-sampled CONUS region. Aggregate flash and group ADE for the Western Hemisphere domain are 70%–71% and 74%–78%, respectively.

In a three-way ground network Bayesian analysis using 1 year of data near the end of the TRMM era, Bitzer and Burchfield (2016) reported global stroke ADEs for ENTLN and the Vaisala networks of similar magnitude of 56.8% and 59.8%, respectively. These values are significantly higher than the stroke ADEs shown in Figs. 4d, 4e and 5d, 5e. To first order, this discrepancy is due to the third sensor used in the comparison: in our case, TRMM LIS with its high group
ADE, while Bitzer and Burchfield compared with WWLLN, which had a stroke ADE of 7.9%. The inclusion of the much more sensitive TRMM LIS in our analysis expands the universe of all reported strokes, which would naturally lead to a lower reported ADE for the other networks involved in the comparison. It is worth noting that both our analysis and Bitzer and Burchfield’s report ENTLN and GLD360 stroke ADE within a few percent of each other during a similar time period (in their case, November 2014–October 2015).

After a nearly 2-yr gap following the end of the TRMM era, lightning detection from low-Earth orbit resumed in March 2017 with the advent of ISS LIS. In the following section, we explore the performance of ISS LIS with respect to the same ground-based reference networks along with GLM.

4. Absolute detection efficiency in the ISS LIS era

As demonstrated in Fig. 1, ISS LIS detects fewer flashes and fewer groups per flash than TRMM LIS, suggesting it has a higher minimum energy threshold for flash detection due to larger ISS LIS pixel size (Zhang et al. 2023). The Bayesian ADE statistics for a >5.5-yr overlap period with ground-based reference networks along with GLM.

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**Fig. 6.** As in Fig. 2, but comparing ENGLN, NLDN, and ISS LIS for the period 1 Mar 2017–31 Dec 2022.

**Fig. 7.** As in Fig. 4, but comparing ENGLN, GLD360, and ISS LIS for the period 1 Mar 2017–31 Dec 2022. The GLM16 nominal FOV is outlined in black.
networks over CONUS shown in Fig. 6 are consistent with a less sensitive ISS LIS, with flash ADE of 59.9% and group ADE of 53.8%, a decrease of ~5%–8% compared with the 8-month ENGLN–NLDN–TRMM LIS analysis in Fig. 3 and an even larger decrease compared with the ENTLN–NLDN–TRMM LIS analysis in Fig. 2. At the same time, NLDN aggregate ADE increased ~9%–11%, while Earth Networks ADE increased 11% (flash) and 27% (pulse) compared with Fig. 2. The temporal coevolution of LIS and ground network ADE will be explored in more detail in section 5. Spatially, the ISS LIS ADE is largely homogeneous, with some higher values near the edges of the CONUS domain. Both ground networks continue to exhibit higher ADE over the central and eastern United States, although this pattern is less prominent for ENGLN than previously.

Three sets of ISS LIS comparisons are possible for the Western Hemisphere domain, starting with an updated version (Fig. 7) of the analysis in Figs. 4 and 5. In spatial distribution and aggregate ADE, the results from the ISS LIS era mostly resemble those from the ENTLN–GLD360–TRMM LIS comparison during the first 6 months of 2014 (Fig. 4). Flash ADE values for the ground networks are ~4% higher in the later period, while LIS flash ADE is ~4% lower during the ISS era.

The presence of GLM16 in geostationary orbit from 2017 onward provides an unprecedented opportunity to apply the Bayesian ADE method to ISS LIS in comparison with another satellite-borne optical lightning detector. Figures 8 and 9 show the results of three-way Bayesian analysis of GLM16, ISS LIS, and either ENGLN or GLD360, respectively. In each case, GLM16 has the highest aggregate ADE of the three, with a flash ADE of 79%–80% and a group ADE of 76%–77%. The reference network ADE decreases by ~4%–9% (flash) and ~6%–7% (stroke) when GLM16 rather than another ground-based network is included in the analysis, while ISS LIS group DE is depressed even further (~12%). GLM16 is clearly more sensitive than ISS LIS overall; however, its performance is not as spatially consistent. Rather, it exhibits a dependence on zenith angle due to the increased pixel size near the limb and possibly other instrument effects (e.g., the narrowband filter cutoff; Wu et al. 2023): flash ADE is ~80%–90% over northern South America, the Caribbean, and the western Atlantic decreasing to 60%–70% over the Pacific intertropical convergence zone (ITCZ) and southeastern edge of the domain and to 35%–60% over the central and western United States. In addition to the effect of zenith angle, previous studies have also suggested the GLM16 DE is lower in regions that commonly experience thunderstorms with inverted polarity, such as Colorado (e.g., Rutledge et al. 2020; Murphy and Said 2020). These inverted storms tend to have higher flash rates that result in smaller flashes (Bruning and MacGorman 2013) that are less likely to be reported (Zhang and Cummins 2020). Taking Figs. 7–9 together suggests that a representative upper limit of ISS LIS ADE is in the range of 61%–65% (flash) and 57%–69% (group). This represents a decrease from the TRMM LIS ADE of ~70%–71% (flash) and ~74%–78% (group; Figs. 4 and 5). The question naturally arises whether this decrease was a step change from the TRMM to ISS era due to factors such as differing sensor sensitivity, pointing, or...
altitude; or improved reference network sensitivity; or if this change occurred gradually over time. The next section yields insight into this matter by presenting year-by-year analysis of LIS and reference network performance.

5. Temporal variability of absolute detection efficiency

a. Yearly evolution

The yearly coevolution of LIS, Earth Networks, and Vaisala lightning detection performance is shown in Fig. 10 for both the CONUS and Western Hemisphere domains, with vertical gray lines indicating discontinuities due to the availability of the underlying datasets. The analysis reveals a steady decrease in TRMM LIS flash ADE over CONUS from 75% to 64% during the initial 2009–14 overlap period, while during the same period, its group ADE decreased even more strongly from 87% to 60%. On the other hand, the same analysis indicates that NLDN ADE was roughly consistent from 2009 to 2012 before increasing by over 15% due to improvements to Vaisala sensors and signal processing (Murphy et al. 2021), while the ENTLN ADE increased by 30% or more during this 6-yr period. Bitzer et al. (2016) likewise reported lower ADE for TRMM LIS and higher ADE for ENTLN in 2013 compared with previous years. In contrast, the ADE for all sensors has been largely consistent over CONUS during the 6-yr ISS LIS record (Fig. 10). For the Western Hemisphere domain, ENGLN ADE increased by ~10% (flash) and 8% (pulse) during the ISS era while GLD360 and ISS LIS exhibited little overall change.

The results in Fig. 10 strongly suggest that the decline in calculated TRMM LIS performance was primarily due to the substantial improvement in ground network performance during the same period; i.e., that TRMM LIS itself was largely stable even though the estimate of its performance is not stable. A decrease in the sensitivity of the LIS sensor could produce a similar trend; however, a 13-yr stability analysis of the background radiance of deep convective clouds showed no discernible instrument degradation over the period (Buechler et al. 2014). The decrease in TRMM LIS ADE combined with the increase in ground network ADE further suggests that the ground networks are detecting “new” lightning that was previously below the detection threshold of either sensor. The results in Fig. 10 also give context to the decrease in ADE from the TRMM LIS to ISS LIS eras (e.g., Fig. 2 vs Fig. 6). The actual decrease in performance from the last 2 years of TRMM LIS to ISS LIS is ~4%–5%, which is consistent with the reduction in globally averaged flash rate reported by Blakeslee et al. (2020). A variety of factors may contribute to this decrease. First, ISS LIS may be less sensitive than TRMM LIS. A comparison of flash statistics between the two sensors suggests this is the case: ISS LIS reports fewer events per group (3.6 vs 4.6) and events per flash (35.4 vs 52.8) than TRMM LIS, and its flash durations are also shorter (0.246 vs 0.260 s). These values are consistent with the reductions in ISS LIS events per group and groups per flash reported by Zhang et al. (2023). Second, the ISS platform may contribute to fewer flashes:

1) The ISS platform is more canted than TRMM was. Moreover, the addition of a new Russian module in late July
2021 caused even more canting, such that LIS was pitched roughly 5° behind ISS. Internal analysis suggests that ISS canting caused a larger LIS footprint relative to TRMM, even with similar orbital altitudes, and addition of the 2021 module decreased overall LIS DE by an additional 2%.

2) The ISS solar panels rotated through the LIS field of view once per orbit. While the panels are masked out in the LIS viewtime variables, there may be some residual blockage given the comparative coarseness of the viewtime variables (0.5° resolution).

3) The ISS environment may be noisier than that of TRMM due to experiments being changed out, astronaut activity, spacecraft docking, etc. The TRMM satellite, in contrast, was designed for weather observation.

b. Diurnal cycle

As an optical sensor, LIS detects lightning via the fleeting brightening of cloud tops. During daytime, the background itself is brighter due to reflected sunlight, and LIS has reduced sensitivity and ability to detect dim flashes. Hourly flash and stroke ADE are shown in Fig. 11 for the longer availability overlap periods, which provide sufficient sample sizes for hourly analysis. LIS exhibits a distinct diurnal pattern during each analysis period, with reduced ADE during the day. Daytime (0800–1700 LT) flash ADE over CONUS is 5.9% lower than nighttime (2000–0500 LT) ADE during the TRMM LIS era, while the daytime decrease during the ISS LIS era is slightly larger, 11.5% for CONUS and 8.7% for the Western Hemisphere domain. Similar daytime reductions are observed at the group level (6.6%, 11.5%, and 7.4%, respectively). These diurnal differences are on the lower end of the 12%–20% peak-to-peak diurnal variation in DE predicted for LIS by Boccippio et al. (2002) based on laboratory calibration. The ground networks also exhibit a diurnal cycle in ADE, with peak values occurring around 0700–0900 LT (Fig. 11) for reasons that are not well understood.
6. Conclusions

The Bayesian methodology introduced by Bitzer et al. (2016) provides a statistical quantification of the performance of a single lightning sensor or network as compared with the larger universe of lightning discharges detected by all sensors involved in the analysis, providing an upper limit of the absolute detection efficiency (ADE). This method is applied to compare satellite-based sensor and ground-based network performance during the last 5.5 years of the TRMM LIS era and the first 5.5 years of the ISS LIS era (Table 1).

The NLDN, GLD360, ENTLN, and ENGLN networks each spanned the ~2-yr gap between LIS missions, allowing a unique opportunity to compare both LIS sensors against the same reference sources. However, this comparison is complicated because these networks did not remain static but rather evolved with the addition of sensors and improvements to processing systems (sections 2a, 2c; Fig. 1). The >10% decrease in TRMM LIS flash ADE during the last 5.5 years of its lifetime must be understood to first order as reflecting the increased performance and sensitivity of the reference networks (>15% for NLDN and >30% for ENTLN; Fig. 10), which expanded the universe of detected lightning flashes. A comparison of the end of the TRMM LIS era and beginning of the ISS LIS era suggests that the actual difference in flash ADE is on the order of 4%–5%. ISS LIS appears to be less sensitive than TRMM LIS, detecting fewer events per group and flash and shorter flash durations, although factors relating to the ISS platform likely contribute to this reduced sensitivity (see discussion in section 5a). Overall, a representative upper limit of ISS LIS ADE is 61%–65% (flash) and 57%–69% (group; Figs. 7–9). Diurnal statistics suggest a daytime flash ADE suppression of approximately 6% during the TRMM era and 9%–12% during the ISS era (Fig. 11), slightly lower than predicted by laboratory calibration (Boccippio et al. 2002).

This study updates the statistical comparison of the detection performance of the major ground-based networks first performed by Bitzer and Burchfield (2016). ENGLN has the highest and most consistent detection performance over CONUS, detecting 91.7% of the combined lightning flashes compared with 70.9% for NLDN and 59.9% for ISS LIS (Fig. 6). When considering the larger Western Hemisphere domain, GLD360 has the higher flash ADE, 70.2% compared with 65.6% for ISS LIS and 55.6% for ENGLN (Fig. 7). GLD360 and ISS LIS also exhibit more geographically consistent performance, while that of ENGLN varies more with the density of the Earth Networks sensor network.

We also present the first direct Bayesian ADE comparison of ISS LIS with another satellite-borne sensor, the GLM on GOES-16 (Figs. 8 and 9). GLM16 is more sensitive overall
than ISS LIS, with a flash ADE of 79%–80% and a group ADE of 76%–77%, both of which exceed the GLM specifications of ≥70% DE (Goodman et al. 2013). However, GLM16 performance is a function of zenith angle and pixel size, decreasing from 80% to 90% over northern South America, the western Atlantic, and equatorial Pacific, to only 35%–60% over central and western CONUS where the view angle is greater and inverted-polarity storms are more frequent. ISS LIS performance exhibits fewer geographic variations, as expected for a sensor in low-Earth orbit, and as such, it is a valuable tool for evaluating the performance of geostationary lightning sensors such as the GLMs and the MTG Lightning Imager (MTG-LI). ISS LIS is a valuable extension of the global climatological lightning record, and efforts to generate a long-term climatology of TRMM LIS and ISS LIS lightning are ongoing.

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Data availability statement. TRMM LIS (http://doi.org/10.5067/LIS/LIS/DATA201) and ISS LIS data (http://doi.org/10.5067/LIS/LISSLIS/DATA109) are accessible through NASA’s Global Hydrometeorology Resource Center (GHRC) Distributed Active Archive Center (DAAC, ghrc.nsstc.nasa.gov). GLM data (http://doi.org/10.7289/V5KH0KK6) are accessible through the NOAA Comprehensive Large Array-data Stewardship System (CLASS; class.noaa.gov). Earth Networks and Vaisala Inc. collected and provided the ENTLN and ENGLN and the NLDN and GLD360 data, respectively, to GHRC as part of GLM cal/val activities.

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