A Performance Study of Earth Networks Total Lighting Network (ENTLN) and Worldwide Lightning Location Network (WWLLN)

Vy Bui[1], Lin-Ching Chang[1], Stan Heckman[2]
[1]Dept. of Electrical Engineering and Computer Science, The Catholic University of America, Washington, District of Columbia, USA
[2]Earth Networks, Germantown, Maryland, USA
01bui@cardinalmail.cua.edu, changl@cua.edu, sheckman@earthnetworks.com

***Abstract* — Lightning observations from lightning detection networks are useful for severe weather forecasting. As these networks are constantly expanding and their detection capabilities are improving, it is critical to understand the performance of these networks. However, system performance evaluation is challenging because the true times and locations of lightning flashes are unknown. In this paper, we propose a method to calibrate a network and apply it to study the performance of two lightning detection networks, ENTLN and WWLLN, using observed multi-year's lightning data (2009-2014). The results can help to calibrate WWLLN and estimate its performance when new sensors are added, and to assist scientists in weather forecasts and to conduct reliable storm warning models.**

Keywords—Lightning; Detection Efficiency; Location Accuracy; ENTLN; WWLLN

I. Introduction

The Earth Networks Total Lightning Network (ENTLN), formerly WeatherBug Total Lightning Network (WTLN), and the Worldwide Lightning Location Network (WWLLN), are ground-based lightning detection networks operating in the United States and in a number of countries all over the globe. ENTLN is managed by Earth Networks and WWLLN is managed by the University of Washington. These lightning detection networks are increasingly used in many meteorological applications such as severe storm prediction [1], and the search for sprite-induced signatures of middle atmospheric NO_2 [2]. The reliability of these meteorological applications is correlated to the understanding of the capabilities of these lightning networks. Efforts in evaluating the performance among different lightning networks have been made, however, previous works focused only on a region or using a shorter period of data [3-5]. Moreover, the lightning detection technology has been improved and the numbers of sensors/stations in both networks have been increased in the past few years.

The goal of this paper is two folds. Firstly, we propose a method that can be used to calibrate a system when data was observed independently by two or more systems but no ground truth data is available. Secondly, we apply the proposed method to study the performance characteristics between two ground-based lightning detection systems using the observed multi-year's lightning data (2009-2014) reported by both networks, namely, ENTLN and WWLLN. Two performance metrics, relative detection efficiency, and mean location accuracy are used for the performance evaluation.

The rest of the paper is organized as follows. Section II will provide some background information on the two networks. The datasets used in this study, the detailed description of the proposed algorithm, and two performance metrics are presented in Section III. The results and discussion are provided in Section IV, followed by conclusions in Section V.

II. Ground-Based Lightning Detection Networks

Ground-based lightning detection networks using multiple antennas can calculate the direction and severity of lightning produced by thunderstorms from a given location. Frequencies emitted by lightning can be used to analyze its characteristics. In this section, we will provide the background information of the two networks under our investigation.

A. ENTLN

The Earth Networks Total Lightning Network (ENTLN) uses time-of-arrival detection methodology with GPS technology and sophisticated algorithms to accurately locate and classify lightning types. A sensor includes an antenna, a GPS receiver, a nano-second GPS-based timing circuit, a digital signal processor (DSP), onboard storage and internet communication equipment. There are more than 800 ENTLN wideband electrical field recorders (frequency ranging from 1HZ to 12MHZ) deployed globally nowadays. As a result of the advanced predictive abilities of ENTLN, it has the potential to significantly improve severe weather warning times over radar and other technologies [8].

B. WWLLN

The ground-based World Wide Lightning Location Network (WWLLN) detects very low frequency (VLF) radio waves (3-30 kHz) emitted by a lightning strike [6]. Most ground-based observations in the VLF band are dominated by impulsive signals from lightning discharges called "sferics". Significant radiated electromagnetic power exists from a few hertz to several hundred megahertz, with the bulk of the energy radiated at VLF. WWLLN began with 11 sensors during 2003 [7] and steadily increased to more than 70 sensors by January 2013 [8].

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III. METHODS

In this section, the proposed method to calibrate a system when no ground truth data is available is presented. We describe the data used in this paper, and the algorithm developed to identify the coincident flashes between two networks. We also provide the definitions of two metrics which will be used to evaluate the performance of these two networks and how to compute both metrics.

A. Calibrate a system when ground truth data is unavailable

The main objective of this paper is to calibrate the WWLLN lightning network so that we can foresee how its performance changes when new sensors will be added to the network later this year and within the next few years. However, this task appears challenging to make fine adjustments because the accurate times and locations of all lightning flashes are unknown. Therefore, we can only compare one imperfect network to another one using the data reported by both networks. We will first identify all coincident flashes between two networks within a timeframe, and then we can measure the mean location errors for a network indirectly. In other words, we compute the distance of matched flashes between a WWLLN location and an ENTLN location, so we can compute the average location error by summing all of the WWLLN location errors and the ENTLN location errors instead of measuring the location error of either system individually. In addition, we cannot measure the detection efficiency of a network directly but we can measure the fraction as the number of lightning flashes observed by WWLLN that ENTLN also observed, or the number of flashes observed by ENTLN that WWLLN also observed.

Nevertheless, by doing this for several years, we can see the effects of adding new Earth Networks sensors during those years, thus we can build tools that will help us in estimating the effects of adding new WWLLN sensors in the coming years.

B. Data

The data used in this study was the lightning flashes detected by ENTLN and WWLLN in the following four years: 2009 (only from May to December), 2011, 2012 and 2014. The data covers the regions through 90°S to 90°N and 180°E to 180°W. The total numbers of lightning flashes detected by both networks are reported in Table 1.

TABLE I. TOTAL NUMBER OF LIGHTNING FLASHES REPORTED BY ENTLN AND WWLLN

Years	*ENTLN*	*WWLLN*
2009 (May–Dec)	61,951,376	30,562,751
2011	42,471,715	49,321,913
2012	211,975,191	151,991,142
2014	376,768,497	212,565,304

Each flash detected by ENTLN is stored in a comma-delimited format with the order: UTC (Universal Time Coordinate) date, UTC time, latitude of flash, longitude of flash. Each flash detected by WWLLN is also stored in a comma-delimited format with the same order. The data is available (free of charge for scientific use and fee applied for commercial use) from Earth Networks. Readers who are interested in using the lightning data may contact Earth Networks directly.

C. Algorithm

Identifying coincident lightning is performed by making direct comparisons between lightning flashes located by ENTLN and WWLLN. The implementation detail of the proposed algorithm is shown in Figure 1.

Input:
All flashes reported by WWLLN within a month are denoted by *wwllnFlash* in the algorithm; All flashes reported by ENTLN within the same month are denoted by *entlnFlash*; Latitude of flashes read from WWLLN data are denoted by *wwllnLatitude*; Longitude of flashes read from WWLLN data are denoted by *wwllnLongitude*; Hours read from WWLLN data are denoted by *wwllnHour*; Time read from WWLLN data are denoted by *wwllnTime*;

Output:
The counts of lightning flashes observed by WWLLN that are also observed by ENTLN satisfied the criteria of coincident lightning in a given month

Algorithm: Coincident Lightning Identification

```
for each month in data
 allocate a 5-D unsigned integer array with size of
 180×360×6×31×24;
  for each flash in wwllnFlash
    latBin ← 90+floor(wwllnLatitude)
    lonBin ← 180+floor(wwllnLongitude)
    hourBin ← wwllnHour
    time ← wwllnTime
    for each temporal window size (i.e., windowBin):
      dt ← 0.1^windowBin
      enFlashes = entlnFlash between (time-dt, time+dt):
      for each flash in entlnFlash
        distances ← distance(wwllnFlash, entlnFlash)
        closestDistance ← min(distances)
        distanceBin ← floor(closestDistance)
        if distanceBin > 29:
          distanceBin ← 30
        end if
 coincident flash found at this location
 counts[latBin][lonBin][hourBin][windowBin][distanceBin]++
      end for
    end for
end for
Write out counts to a file.
```

Fig. 1. Algorithm of identifying coincident flash between two networks.

To determine which events are coincident events, it is necessary to establish a temporal and a spatial window within which events are reported by both networks. In our experiments, six different temporal windows are tested that are within 1 second, 100 milliseconds, 10 milliseconds, 1 millisecond, 100 microseconds and 10 microseconds, and 30 kilometers is used as the spatial window. For example, one scenario is: if there is a flash reported by WWLLN and the closest flash reported by ENTLN is within 20 kilometers and is within a chosen temporal window, say 100 milliseconds, a coincident flash is identified and counted at the location reported.

Figure 2 demonstrates how a coincident lightning is identified using the scenario we just described. Using this example, ENTLN flash is considered as coincident with WWLLN flash if it satisfies the following two conditions. First, if ENTLN flash occurs within 100 ms before WWLLN flash to 100 ms after the duration *d* of the WWLLN flash. Second, the distance between two stations that recorded the flashes must be less than 30 kilometers. As a result, the ENTLN flash occurs at t_1 will be determined as coincidence with the WWLLN flash at t_0 while the ENTLN flash occurs at t_2 will be identified as no matching flash because it took place after 100 milliseconds of the WWLLN event.

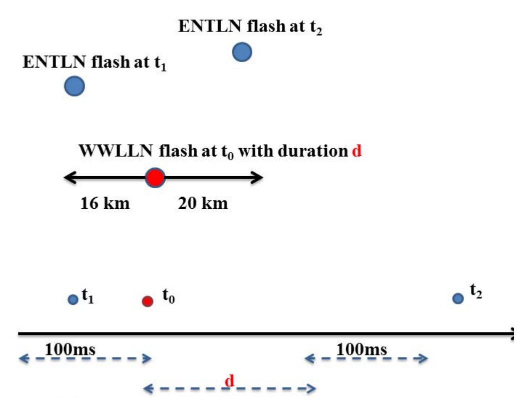

Fig. 2. An example of identifying coincident flash between two networks.

D. Performance Metrics

Utilizing lightning networks requires a comprehensive understanding of what the networks can detect and their limitations. In this paper, we use two performance metrics: the relative detection efficiency and the mean location accuracy.

The direct flash-by-flash comparisons described in the previous section allow us to measure the probability of the detection rate and the location differences between pairs of matched flashes. We now describe the relative detection efficiency (RDE) and the mean location accuracy (MLA) in more detail.

1) Relative Detection Efficiency (RDE): the detection efficiency is a function of the temporal and the spatial windows. For a choice of the temporal and the spatial windows, we measure the fraction of flashes observed by both networks. In other words, the ENTLN's relative detection efficiency will be computed as the number of WWLLN flashes coincident with one or more ENTLN flashes divided by the total number of WWLLN flashes.

2) Mean Location Accuracy (MLA): In addition to the relative detection efficiency, flash-by-flash comparisons can also disclose the location differences between the matched flashes. The location accuracy can be measured by the total number of the matched flashes at a given temporal window and the spatial difference between the sensor locations. The average location accuracy therefore can be presented using a histogram of all matched flashes and the computed distances between WWLLN and ENTLN stations for a choice of temporal window.

IV. Results and Discussions

As described in the method section, six different temporal windows were examined in order to determine the best matching criteria for performance comparison. First, we computed the relative detection efficiency as WWLLN flashes detected by the ENTLN, and ENTLN flashes detected by the ENTLN, i.e., the number of matched flashes between two networks divided by the total flashes (matched + unmatched). We have computed the performance metrics using a very tight temporal window (10 µs) to a broader temporal window (1 second), and we found that changing the temporal window size in matching criteria produced very small differences in the performance metrics estimated. Thus, we only show the results with the temporal window of 10 µs and the spatial window of 30 km. If a region on the map has a relative detection efficiency of 100%, it implies that the network is able to detect all of the flashes occurring within the region that are also seen by the other network.

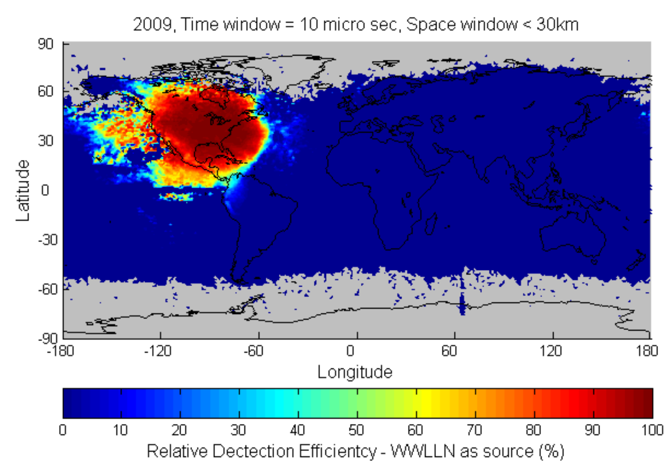

Fig. 3. ENTLN's Detection Efficiency in 2009 within 10 µs in time window and distances between station < 30 km.

Figures 3, 4, 5 and 6 show the ENTLN's relative detection efficiency of year 2009 (only May to Dec.), 2011, 2012 and 2014 respectively. In 2009, ENTLN has RDE values that ranged from 80% to 100% in North America, and ranged from 30% to 75% in the ocean along the West coast.

However, the RDE rate is better in the ocean along the East coast, i.e. 50% to 100% (see Fig. 3). Since ENTLN's sensors were deployed only in the United States in year 2009, this explains why the regions outside of the United States have the RDE equal to 0.

In 2011, the RDE values ranged from 50% to 95% in North America. This result is due to the total number of flashes detected by both networks being slightly lower than 2009 (see Table 1). However, numbers of ENTLN stations have been installed in other regions since then. For example, there were many new stations installed in Brazil, Europe, and Australia in 2011. As a result, the values of RDE computed were improved from 0% in 2009 to about 35% to 88% in 2011 in the southern of South America; 22% to 25% in the northern of South America; 37% to 75% in Europe; and 51% to 80% in Australia in 2011 (Fig.4).

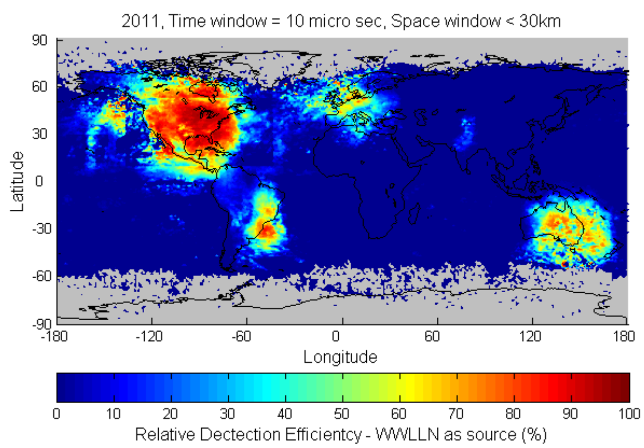

Fig. 4. ENTLN's Detection Efficiency in 2011 within 10 µs in time window and distances between station < 30 km.

Later in 2012, ENTLN has expanded its sensor coverage in South America, North Africa, Europe,and Asia. This reflected on the greater relative detection efficiency obtained on the world globe map for year 2012. ENTLN's RDE increased significantly in all continents in 2012 (ranged from 50% to 88%) and it can detect good amount of lightning flashes in the oceans (ranged from 39% to 81%). In some regions in South Africa and northern of South America, the detection rate is lower (ranged from 35% to 55%) (Fig. 5). This is simply due to the sensors' coverage of ENTLN at the time.

ENTLN has continued to expand its sensor coverage to almost the whole globe. In 2014 (Fig. 6), ENTLN has its greatest detection rate of lightning flashes compared to WWLLN: the RDE values ranged from 85% to 100% in North, Central and South America; similar RDE values were found in Europe and Australia. For the same reason, the detection efficiency of 70% to 88% were observed in South Africa, South Asia; 10% to 63% in North Africa and Central Asia. In the Pacific Ocean, Atlantic Ocean, and North Indian Ocean, the estimated RDE values for ENTLN ranged from 50% to 100%. By comparing Figures 5 and 6, it is clear that most continents have experienced a significant RDE improvement compared to the previous years.

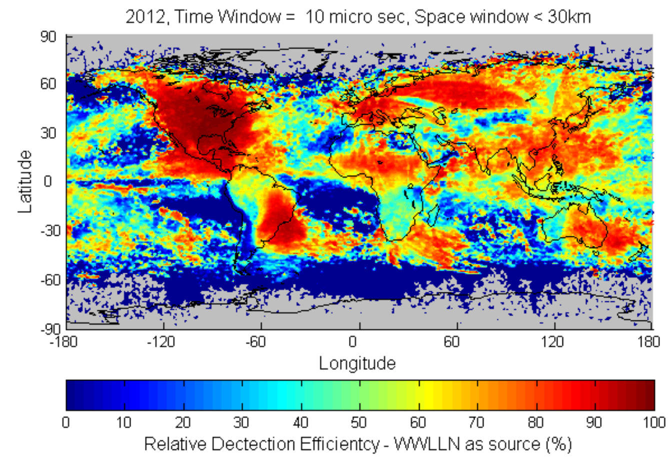

Fig. 5. ENTLN's Detection Efficiency in 2012 within 10 µs in time window and distances between station < 30 km.

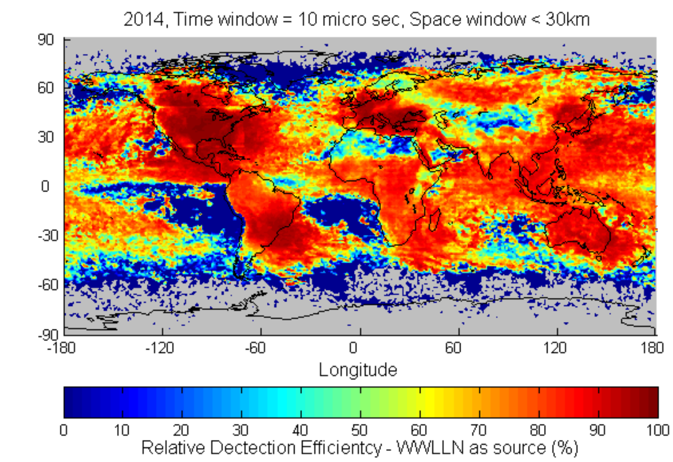

Fig. 6. ENTLN's Detection Efficiency in 2014 within 10 µs in time window and distances between station < 30 km.

Inspecting the relative detection efficiency is one method to describe the performance of a network. Nevertheless, such measures need to be used cautiously, as they often demand the assumption that the reference system is uniform and complete.

Second, we computed the location differences between the coincident flashes. The average location accuracy can be obtained using a histogram of all coincident flashes and the computed distances between WWLLN and ENTLN stations for a choice of temporal window.

Figures 7 through 10 show the estimated mean location accuracy in years 2009 (May to Dec.), 2011, 2012 and 2014, respectively, using the same temporal (10 µs) and spatial (30 km) windows as the matching critera.

In 2009 (Fig. 7), the number of matched flashes was 3.5 million when the distance between stations of ENTLN and WWLLN is set to 5 km. With the same condition, the matched flashes was more than 4 million in 2011 (see Fig. 8). When the distance between stations is broader, i.e., 17 km, the coincident flashes of both networks reduced to 500,000 in 2009 and 1 million in 2011. As the distance between stations gets wider, i.e., from 20 to 30 km, these numbers were further reduced; approximately 100-300 thousand flashes in 2009 and 300-500 thousand flashes in 2011.

It can be noted that in both Figures 7 (2009) and 8 (2011), the histograms show fewer flashes with the distances between stations less than 4 kilometers. This result is expected because we were counting the flashes per range bin, not the flashes per square kilometer. The bin with distances between 3 and 4 kilometers has an area of $7\pi^2$ kilometers, while the bin with distances between 4 and 5 kilometers has an area of $9\pi^2$ kilometers, and the bin with distances between 5 and 6 kilometers has an area of $11\pi^2$ kilometers. At these distance settings, the offsets are essentially random, and there is more such area too, thus the average number of matched flashes decreased.

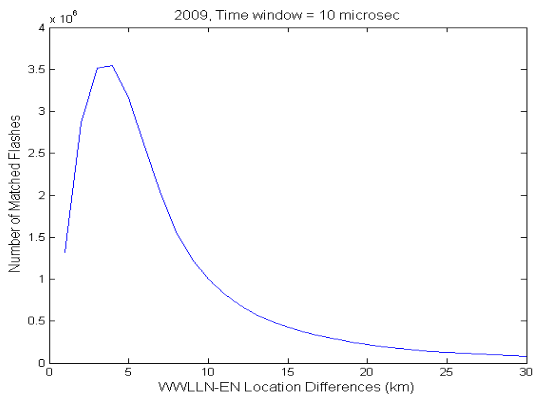

Fig. 7. Histogram of distances between WWLLN and ENTLN location in 2009 within 10 µs.

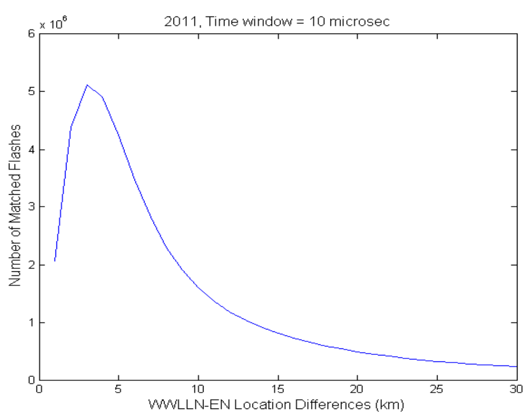

Fig. 8. Histogram of distances between WWLLN and ENTLN location in 2011 within 10 µs.

Figure 9 shows that the numbers of matched flashes in 2012 were increased significantly even if the distance between two stations of ENTLN and WWLLN was less than 3 km (ranged from 16 to 47 milion matched flashes). The numbers of matched flashes were further increased in 2014 (see Fig. 10) and ranged from 28 million to more than 70 million. When the distance was set broader (for example, 13 km), the numbers of coincident flashes of both networks were reduced drastically, i.e. from 10 million down to 4 million in 2012 and the similar rate was observed in 2014. As the distance gets even wider (i.e., greater than 15 km to 30 km), the numbers of matched flashes stay within 1-2 million in 2012 and 2014. It is worth pointing out that this number is double since 2011 and triple since 2009. As a result, ENTLN has demonstrated its capabilities as the lightning detection rate has been improving since then.

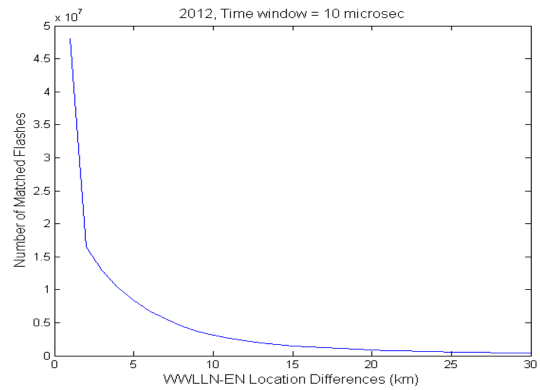

Fig. 9. Histogram of distances between WWLLN and ENTLN location in 2012 within 10 µs.

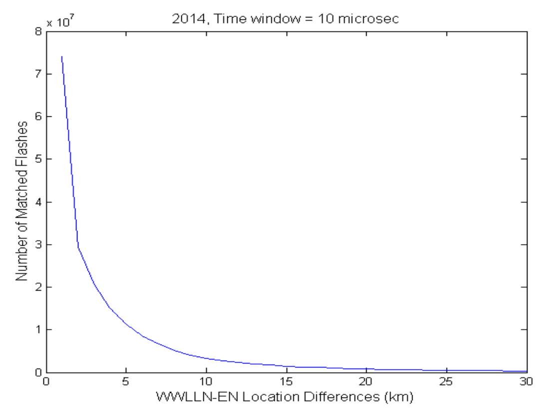

Fig. 10. Histogram of distances between WWLLN and ENTLN location in 2014 within 10 µs.

V. CONCLUSIONS

In this paper, we proposed a method to evaluate the performance a system when there is data observed independently by two systems, but no ground truth data is available. We have applied the method to study the performance characteristics between two ground-based lightning detection networks, namely, Earth Networks Total

Lightning Network (ENTLN) and Worldwide Lightning Location Network (WWLLN). The data used in this study is a multi-year lightning dataset that spans over four recent years, i.e., from May 2009 to December 2009, 2011, 2012 and 2014. Two metrics, relative detection efficiency, and the mean location accuracy, were used in the assessment of the network's performance.

Our results show that the lightning detection capabilities of ENTLN were improved strongly from 2009 to 2014. In 2009, our analysis showed that the relative detection efficiency (RDE) ranged from 80% to 100% in North America and 0% in other regions of the global. In 2011, the RDE values increased significantly in regions outside of North America. For examples, RDE was increased to 35% ~ 88% in the southern of South America; 37% ~ 75% in Europe; and 51% ~ 80% in Australia. Later in 2012, ENTLN's RDE was further increased in South America (i.e. to 50% ~ 64% in the north region and 50% ~ 100% in the south region); the RDE values ranged from 50% to 85% in Europe and North Africa; the same rate observed in Australia and part of Asia. This improvement is mainly due to the expansion of ENTLN in its sensor coverage. For the same reason, ENTLN has continued to improve its detection rate in 2014, i.e. 85% ~ 100% in North, Central and South America; similar rates were found in Europe and Australia; 70% ~ 88% in South Africa and South Asia; 10% ~ 63% in North Africa and Central Asia. In the Pacific Ocean, Atlantic Ocean, and North Indian Ocean, the estimated RDE values for ENTLN ranged from 50% to 100%. In summary, it is clear that most continents have experienced a significant RDE improvement compared to the previous years. The mean location accuracy in terms of the number of matched flashes was also increased substantially during our tested years. For example, using a very tight temporal window (i.e. 10 µs), the number of matched flashes was 3.5 million in 2009, 4 million in 2011, 14 ~ 45 million in 2012, and 28 ~70 million in 2014. The results indicate that both the relative detection efficiency and the mean location accuracy of ENTLN have been increased significantly in most of the continents over our study periods. The performance improvement of ENTLN is related to hundreds of new stations which were installed in the past few years.

The Earth Networks Total Lighting Network (ENTLN) has demonstrated an effective lightning detection rate across the United States and an increasing detection rate over the globe. The described capabilities of ENTLN in its continental scale and multiyear assessment suggest strong potential to assist operational weather forecasting in many modern meteorological applications. The analysis presented in this paper can help us to calibrate the WWLLN lightning network with the aim of predicting how its performance may change when hundreds of new sensors will be added to the network in the coming few years. These insights can also be used by lightning vendors to enhance their network performance, by weather experts to assist in weather forecasting and by scientists to conduct more reliable storm warning models.

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