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Evaluating Location Accuracy of Lightning Location Networks Using Tall Towers

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***Abstract*- Historically, assessment of the location accuracy of the U.S. National Lightning Detection Network (NLDN) and other Lightning Location Networks has required either rocket-triggered lightning events or a system of cameras imaging towers or other objects known to be frequently struck by lightning. With recent improvements in the NLDN, it is now possible to use tall towers without supporting cameras. This allows for continuous verification of the location accuracy of the network in a large number of regions, rather than a few specific locations. While ground truth using towers is not new, the use of a large number of towers across a wide geographical area has not been previously reported. Results are presented for 22 towers in 12 states, including periods before and after the recent upgrade to the NLDN. Relative location accuracy has steadily improved over the last 4 years. 15 of the 22 towers have median location errors less than 100 m for 2013, with all having better than 250 m median error.**

Keywords – Ground truth, Tower strikes, triggered lightning

I. INTRODUCTION

Improvements in detection efficiency and location accuracy of the U.S. National Lightning Detection Network™ (NLDN) prompted an investigation into the use of tall towers to measure relative improvements in location accuracy. Use of towers for ground truth is a common practice, having been employed for many years. In most cases, single well known towers, such as the CN Tower in Toronto, Ontario [Lafkovici et al., 2008] and the Gaisberg Tower in Austria [Diendorfer 2010] have been used. Tall radio towers have not been used as frequently. In this work 22 radio towers of varying heights have been examined in multiple locations in the United States. A comparison of median location accuracy from 2010 through 2013 is presented. A simple method for calculating the probability value associated with the smallest error ellipse encompassing a known strike location is also presented.

II. METHOD

Most tower studies utilize video or radiation field waveforms with accurate time stamps to establish the precise time of individual strikes. Since this study includes a large number of “towers of opportunity” in several states throughout the U.S., video information was not available. Instead, flashes with high multiplicities whose locations were consistently close to the subject tower were examined. A methodology for eliminating events that did not strike the tower was developed. For the set of events that had a high probability of striking the tower in question, a median error was computed. By comparing values for thousands of flashes from individual years, the relative improvement in location accuracy can be accurately measured.

It is important to note that the triggered events examined in this manner have characteristics that are not typical of natural cloud-to-ground lightning. Due to the segment of the channel that propagates through the tower, where the propagation velocity is essentially the speed of light, these events tend to exhibit a very short and simple rise-time, which allows for a somewhat more accurate location estimate. However, this issue does not impact our assessment of relative improvements in location accuracy. In addition, as noted in the work of Pavanello et al. [2009] and others cited therein, the higher return stroke velocity in the tower results in artificially high peak radiation fields for events striking tall towers. This in turn means that more sensors will report these return strokes, as compared to subsequent strokes on nature CG flashes, again contributing to better location accuracy.

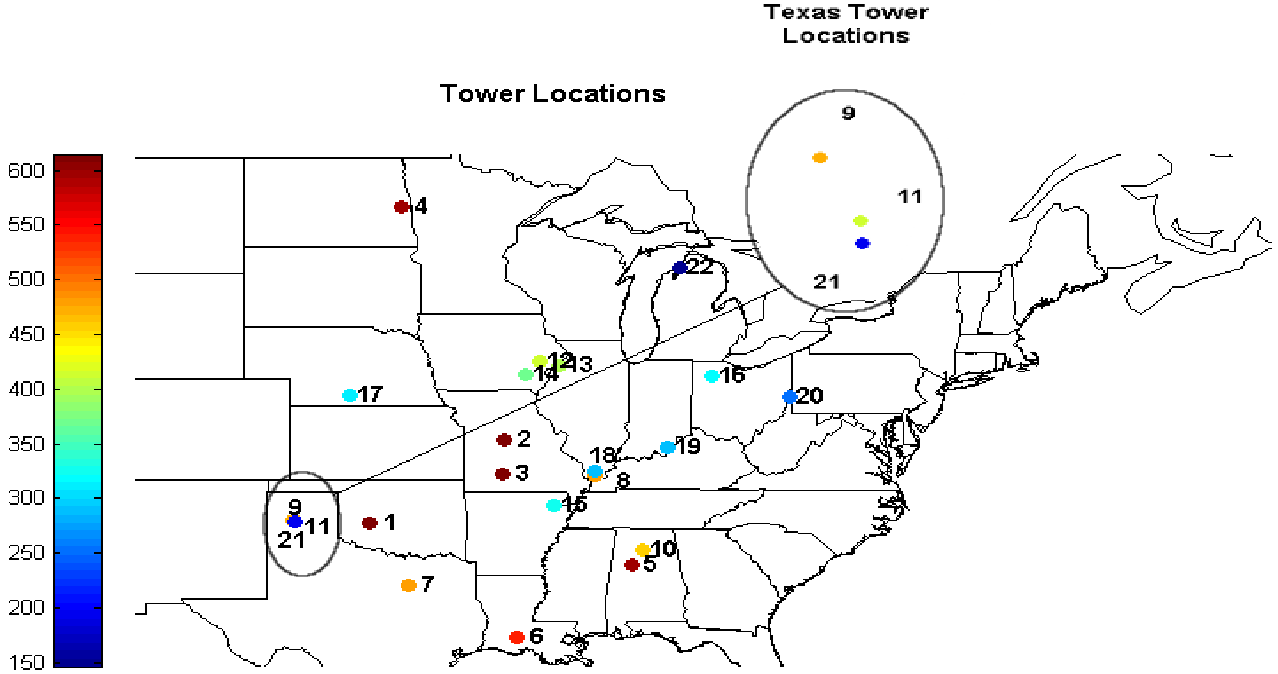

Fig. 1. Tower Locations

To develop a method to identify events that likely struck a given tower, we start by examining all events within a reasonable distance of the tower. A radius of 10 kilometers was selected; this ensures that even a strike with very poor accuracy will be included. This also allows the inclusion of a large number of events that did not strike the tower. As a first attempt to discriminate the valid (tower strike) events from nearby events, we utilized location error ellipse parameters that are normally calculated for each strike [Cummins et al., 1998]. First, the size of the ellipse was scaled so that the location of the tower lay on the ellipse. The corresponding probability value of this ellipse is computed (See appendix I for the details of this calculation). Events that required ellipses in excess of 95% were assumed to have not struck the tower, and were removed from the dataset. While this procedure eliminated most nearby (non-tower) events, some remained. In an effort to eliminate these events, only flashes which had 3 or more strokes with computed locations less than 500 meters from the tower were examined. To prevent bias caused by this requirement, an additional requirement, a minimum overall stroke count of 7 was implemented. The combination of these three requirements eliminated virtually all of the events that did not strike the tower without biasing the results.

III. RESULTS AND DISCUSSION

The locations of the 22 towers used in this investigation are shown in Fig. 1. Towers identifiers (numbers) are organized from tallest to shortest. Towers 9, 11 and 21 are relatively close together; their relative positions are shown in the inset. The distance between tower 11 and tower 21 is approximately 3.2 km.

Since direct evidence of attachment to these towers is not available, it is necessary to validate the method described above. As an initial step, all data from 2013 within 10 kilometers of each tower was compared to the stroke candidate dataset. 2013 was selected because it was expected that it would have the best location accuracy, and provide the clearest

validation The average stroke density for all 22 towers was calculated for both datasets, including 2022 strokes to the towers and 159,559 total strokes. Fig. 2 shows these results. Notice that the stroke density is presented on a logarithmic scale, and virtually all of the candidate stroke events were within 600 m of the towers . Only a small population of the total strokes was in the 500-1000 m range, seen in the "All Strokes" curve. Considering the 2022 strokes to the tower, the median location error was 82.8 meters and the mean was 138.0 meters.

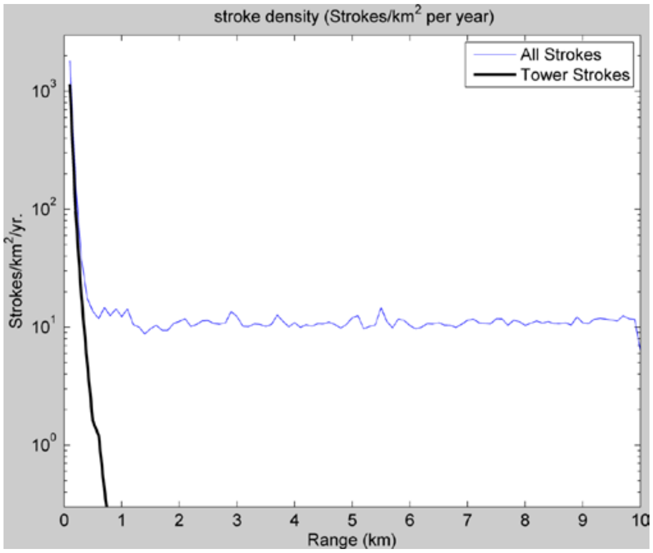

Fig. 2 Tower Stroke Density vs. Stroke Density within 10 km (2013 data).

Fig. 3 is a polar plot of all strokes which illustrates the same finding. In this case, data is limited to a 3 kilometer radius around the towers. Each range ring is 1 kilometer. Note the distinct clustering of points within 500 meters, and no clear spatial bias of the population (centered on the plot origin).

As noted earlier, each event that is geo-located by the NLDN includes information about the nature of the expected location error. This information is depicted by the median (50th percentile) confidence ellipse, which is characterized by its semi-major and semi-minor axes (in km), and by the orientation of the major axis relative to north-south (in degrees). The remainder of this analysis for the whole population of 22 towers is an assessment of the accuracy of these ellipse values for the tower strikes that occurred in 2013.

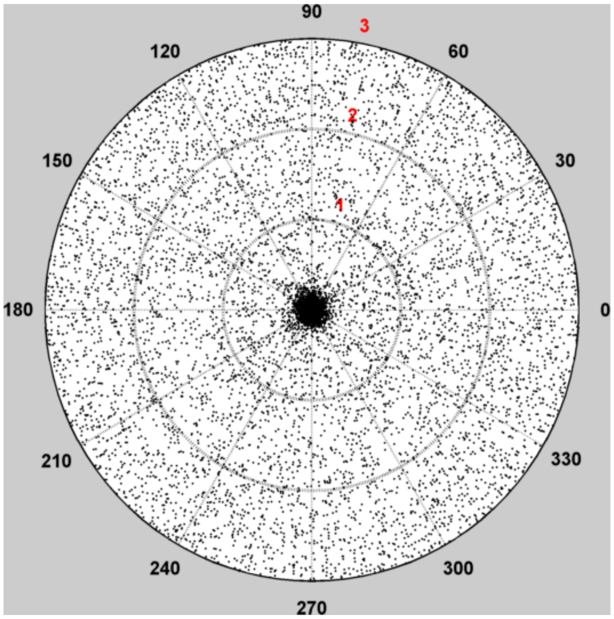

Fig. 3 Polar Plot of tower stroke events (2013 data)

The most-direct assessment of the nature of the error estimates employed by many authors [Idone et al., 1998; Jerauld et al. 2005; Nag et al. 2011 and others] is to plot a scatter-gram of the actual location error vs. the median (p=0.5) ellipse semi-major axis. If one assumes that the actual location error is in the direction of the semi-major axis, then a statistically-perfect error estimate would show half of the scatter-points above a slope=1 line on this plot, and half below. Assuming Gaussian errors, 90% of the scatter-points would be below a slope = 1.82 line, as shown in Nag et al., 2011 (their figure 9). For the NLDN, past studies have shown that actual errors are somewhat smaller than would be expected from the error ellipse parameters.

The data is this study is consistent with these previous studies. Fig. 4 shows this scatter-gram for the 2013 tower dataset, along with the slope = 1 line. Almost all of the errors fall below the line, indicating that the estimated error ellipse parameters are very conservative. In part, this is due to the “ease” of geo-locating tall towers, discussed above. More importantly, it reflects the conservative approach employed by Vaisala as steady improvements in location accuracy are developed. Based on these and other analyses, error ellipse “size” estimates will be reduced in the future.

In order to further quantify the results in Fig. 4, the errors were calculated in terms of the probability level of the scaled ellipse, as described in the Methods section and the Appendix. This analysis eliminates the assumption that the actual error is in the direction of the semi-major axis. The results are provided in Fig 5. The distribution of events as a function of the ellipse probability value is provided by the blue frequency (count) histogram. The most-probable value (largest count) is the lowest probability “bin”, with nearly-monotonically decreasing counts for higher probability values. Were the ellipse estimates less-conservative, this histogram would have had a uniform distribution over all probability values. The cumulative probability is shown as the solid blue line. For an arbitrary location with no tendency to attract lightning or a network with poor location accuracy, this cumulative probability curve would be linear, as all distances would be equally likely. This is shown as a dotted line in Fig. 5.

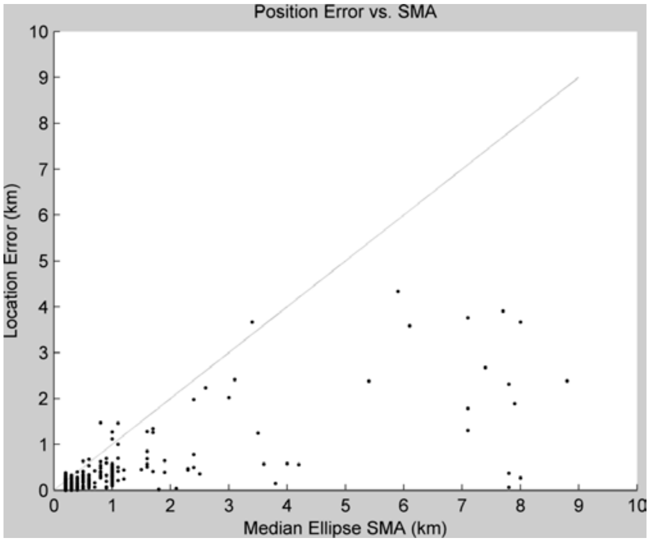

Fig. 4 Tower Strike Ellipse Semi-Major Axis vs Location Error (2013 data)

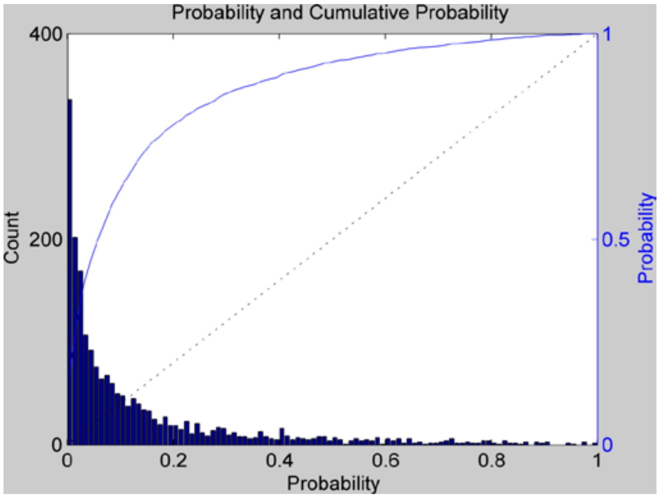

Fig. 5 Probability and Cumulative Probability, Tower Stroke Data (2013 data)

Median location accuracies for 2010-2013 for each of the towers are presented in histogram form in Fig. 6. It is clear that for most towers, there is a significant reduction in location error from 2010 to 2011, and less pronounced improvement in 2012. 2013 results are very similar to 2012. Two notable exceptions are tower 6 and tower 20, where very little improvement is observed. In an effort to understand the behavior at these two towers, the average chi-square values and semi-major axis values of the population of events within 10 kilometers of each tower were computed. Results for towers 6 and 20 were indistinguishable from the other towers. In the case of tower 6, it may be an edge-of-network effect. Research into the reasons for these larger errors is ongoing.

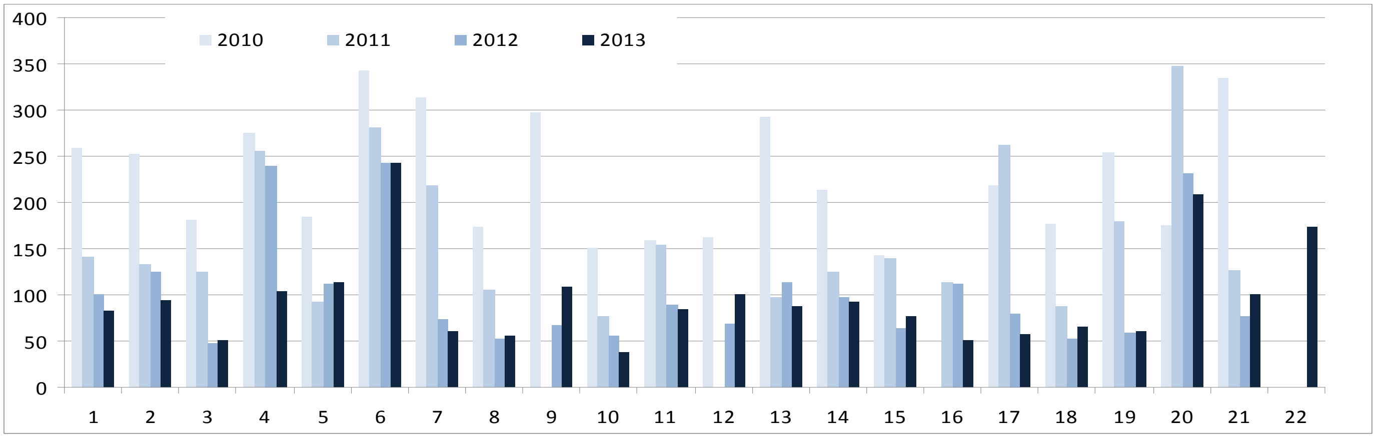

Fig. 6 Median semi-major error ellipse for each tower by year

The overall accuracy for the 22 towers is summarized in Table I. More than 1000 events were evaluated for each year, resulting in reliable cumulative statistics with uncertainty below the 1% level. There was a steady decrease in the overall median value over the four years, dropping to below 90m in 2013. For all years, the percentage of events with errors greater than 1 km was less than 0.5%. This percentage fell to 0.05% in 2013.

TABLE I. LOCATION ACCURACY SUMMARY

Year	**Total Count**	**Median Error meters**	**% With Error 0.5-1 km**	**% With Error >1.0 km**
2010	1480	226	7.4	0.5
2011	2216	130	2.4	0.1
2012	2496	95	1.4	0.06
2013	2022	83	1.1	0.05

IV. CONCLUSION AND FURTHER WORK

The results presented here represent only a subset of the towers observed to have high-multiplicity lightning events associated with them. The data presented in this manuscript suggest overall median network location accuracy has improved from ~ 500 meters in 2010 to about 150-200 meters in 2014. Use of tall towers is a valid method of determining relative improvements in location accuracy, although it will not directly provide an accurate measure of location accuracy for natural lightning.

Examination of data related to tall towers will continue. Investigation into the differences in location accuracy illustrated above, regional differences in tower strikes, relative effect of tower height, as well other topics will be investigated. A camera study would be useful to augment and validate the work presented here.

APPENDIX I: CALCULATING THE PROBABILITY LEVEL OF AN ELLIPSE WHICH INTERSECTS A POINT ASSET

Given a lightning event with a 50% probability ellipse oriented randomly with respect to the asset in question, the following derives the necessary procedure to determine the required scaling value that allows the asset to fall on the parameter of the ellipse.

The 50% ellipse is specified by semi-major length, semi-minor length, and the angle the semi-major makes with respect to true north. The first step is to transform from a cardinal direction based coordinate system to one based on the semi-major axis with the estimated location as the origin. Using the equation for the ellipse, the size of the modified semi-major and semi-minor ellipse can be computed. From these values, a scaling factor can be computed, and the probability level can be determined from this factor.

If A is the 50% semi-major axis length, B is the 50% semi-minor length, α is the angle the semi-major axis makes with respect to true north, r is the distance from the located event to the asset, and β is the bearing from the event to the asset with respect to true north, then

$$\varphi=\beta-\alpha \tag{1}$$

Is the angle between the semi-major axis and tower. Then the component of the distance from the strike to the asset in the semi-minor direction is

$$x = r\sin\varphi \qquad (2)$$

The corresponding distance in the semi-major axis direction would be

$$y = r\cos\varphi \qquad (3)$$

and the scaled semi-minor and semi-major axes are

$$b = \sqrt{\frac{ecc^2 x^2 + y^2}{ecc^2}}\ ,\ a = b(ecc) \qquad (4)$$

where ecc is the ratio of the semi-major to the semi-minor axis, b is the scaled semi-minor axis, and a is the scaled semi-major axis.

Sigma is the scaling factor multiplied by the sigma of the 50% ellipse:

$$\text{Sigma} = 1.177(\ b/B) \qquad (5)$$

and the probability level can be obtained directly from:

$$\text{prob} = 1 - e^{\frac{sigma^2}{2}} \qquad (6)$$

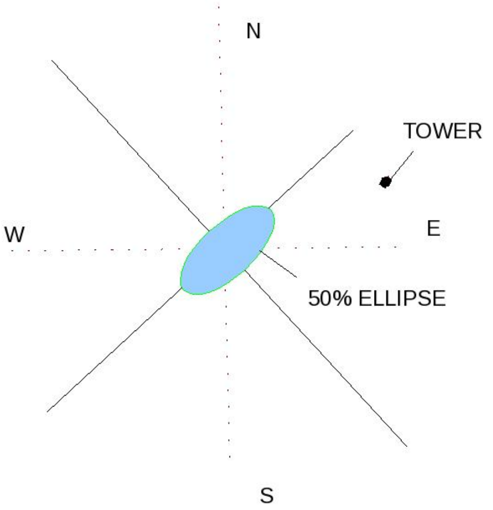

Figure 1. Ellipse and asset

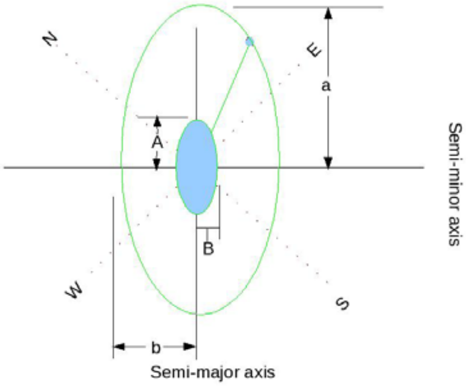

Figure 2. Ellipse and asset with scaled error ellipse

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