Evaluating EUCLID's location accuracy using lightning strikes to tall structures

Dieter Roel Poelman
Royal Meteorological Institute of Belgium
Brussels, Belgium
dieter.poelman@meteo.be

Hannes Kohlmann
Austrian Lightning Detection and Information System (ALDIS)
Vienna, Austria
h.kohlmann@ove.at

Wolfgang Schulz
Austrian Lightning Detection and Information System (ALDIS)
Vienna, Austria
w.schulz@ove.at

***Abstract*— This study evaluates the location accuracy (LA) of the European Cooperation for Lightning Detection (EUCLID) network by analyzing lightning strikes recorded near tall structures over a 13-year period from 2012 to 2024. Structures selected for this analysis, either exceeding 150 meters in height or situated on prominent terrain like mountain tops, serve as ground truth for assessing the network's performance. The methodology involves calculating the ratio of lightning strike densities within 500 m of each structure to those within the surrounding ring (500 m to2 km). Structures with ratios below a defined threshold are excluded from further analysis, as the absence of elevated lightning density near the structure suggests it does not significantly attract or initiate lightning and is therefore unsuitable for our methodology. Subsequently, a density-based clustering algorithm is used to identify the most likely cluster of lightning events that struck the tower, and can therefore be used in the analysis of location accuracy. Results indicate a median LA of 130 m and a 95th percentile of 260 m.**

Keywords—location accuracy, tall structures, LLS

I. Introduction

Lightning location systems (LLSs) are crucial tools for various applications, ranging from power grid protection and operational safety to meteorological monitoring and research. For such systems to be reliably used, their performance—especially in terms of location accuracy (LA) and detection efficiency (DE)—must be well understood and validated. Although network intercomparisons [1,2] are sometimes used to estimate LLS performance, they rely on the implicit assumption that one network can serve as ground truth — an assumption that is not entirely valid. Consequently, the most direct and reliable approach involves comparing LLS data against independent ground-truth references.

Over the years, several methodologies have been employed to provide such ground-truth data, including lightning discharges to instrumented towers [3] rocket-triggered events [4, 5], and observations from high-speed video and electric field recordings [6, 7]. Each of these approaches comes with its own strengths and limitations. Instrumented towers and triggered lightning offer precise location data, but their validity is inherently local and often limited to a handful of sites.

High-speed video methods, with frame rates of at least a few hundred frames per second, can provide more spatially distributed performance estimates, yet are resource-intensive and typically confined to limited temporal and geographic windows. Further, his method does not provide the absolute location accuracy, but the relative location accuracy. This is because it relies on multiple discharges striking the same ground strike point, which is discernible through video observation, while the absolute location bias from the true ground strike point is not known.

The European Cooperation for Lightning Detection (EUCLID), has been periodically assessed using these methods [8]. However, such studies tend to be based on a small number of fixed locations and are not necessarily representative of the system's performance across its entire spatial coverage. These constraints highlight the need for alternative validation approaches. In this context, the current study explores the use of lightning data associated with numerous tall structures, such as towers, masts, and chimneys, across Europe as reference points for lightning impact locations to assess location accuracy on a much broader spatial scale and over a longer period. By systematically comparing lightning strikes near selected tall structures over a thirteen-year period, a spatially extensive and statistically robust assessment of location accuracy is provided. In doing so, the study provides insight into EUCLID's performance and its evolution over time.

II. Data and Methodology

A. Lightning Location System

EUCLID maintains a widespread lightning detection network comprising more than 170 sensors across the European continent, as shown in Figure 1. The primary objective of this network is to detect and classify both cloud-to-ground (CG) strokes and intracloud (IC) pulses operating in the very low and low frequency bands. Lightning event locations are determined using a combination of time-of-arrival (TOA) methods and magnetic direction finding (MDF) techniques. Readers interested in further details may consult https://www.euclid.org.

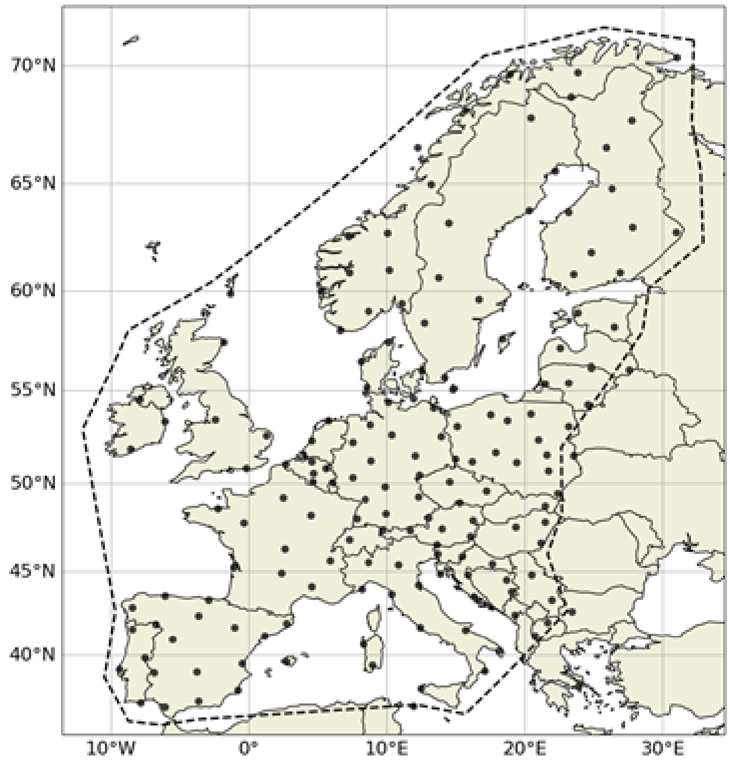

Fig. 1: Distribution of sensors in the EUCLID lightning detection network as of 2023. Quantitative analysis is limited to the area outlined by the dashed polygon.

Existing performance evaluations are based on a combination of direct lightning observations from instrumented towers and supplementary video and electric field measurements at selected sites. Analyses of tower data from 2007 to 2014 indicate a location accuracy on the order of 100 m [8]. Thanks to ongoing network upgrades, a steady improvement in location accuracy has been observed over time. Regarding detection efficiency, data from instrumented towers suggest values of 70% for negative CG strokes and 96% for flashes. However, broader studies using video and E-field data from the periods 2008–2012, 2011, and 2012–2013 yield higher DE values of 84% for strokes and 98% for flashes, as reported by [8, 9]. The slightly lower DE observed in tower-based studies likely stems from the fact that towers predominantly record subsequent strokes, which have weaker peak currents and are therefore more difficult to detect. More recent investigations by [10] using ground-truth data from Austria (2015, 2017, 2018) confirm stroke detection rates between 76% and 85.6%. The consistency of these performance metrics, despite the continuous changes in hardware and configuration over the years, highlights the reliability and robustness of the EUCLID system.

Large structures are known to occasionally initiate upward lightning discharges. When captured by a lightning location system (LLS), these events often exhibit a combination of intracloud (IC) pulses and cloud-to-ground (CG) strokes. This mixed signature depends both on the underlying physical processes within the flash and on possible misclassification by the detection system [11]. Therefore, as detailed below, both IC and CG discharges are included in the location accuracy analysis, and no selection criteria, e.g., peak current thresholds, were applied.

B. Structure Selection

To assess the location accuracy of the EUCLID lightning detection network, a database of tall structures; including towers, guyed masts, chimneys, and similar installations, is compiled across Europe to serve as so-called ground-truth reference points. The aim is not to create an exhaustive inventory of all existing tall structures, but rather to assemble a sufficiently large and spatially well-distributed sample within the EUCLID coverage domain to enable statistically meaningful analysis.

As a starting point, a list was compiled consisting of several dozen structures, identified through internal discussions, particularly focusing on tall towers located along the ridges of the Alps, Apennines, and Pyrenees. To expand this list, Wikipedia was systematically queried for tall towers, radio masts, and similar structures with a physical height of minimum 150 meters. Wikipedia was chosen as the primary source due to the lack of a centralized, publicly available European equivalent to, for example, the U.S. Federal Aviation Administration's Obstacle Database, which has been used in related studies over the United States [12]. While other potential sources exist, such as databases from national aviation authorities, or various geospatial data repositories, Wikipedia offers the advantage of broad accessibility and rapid data extraction, which is sufficient given that the study does not require completeness. In addition to structure height (when known), ground elevation above sea level (ASL) was retrieved for each site using the Google Elevation API to complement the dataset. The initial list consisted of more than 1,300 entries, with the majority of them extracted from Wikipedia. Subsequently, the dataset was filtered to retain only those structures with a minimum separation of 2 km from any other structure in the list. This separation ensures that individual lightning strike clusters can be confidently attributed to a single structure, supporting a robust evaluation

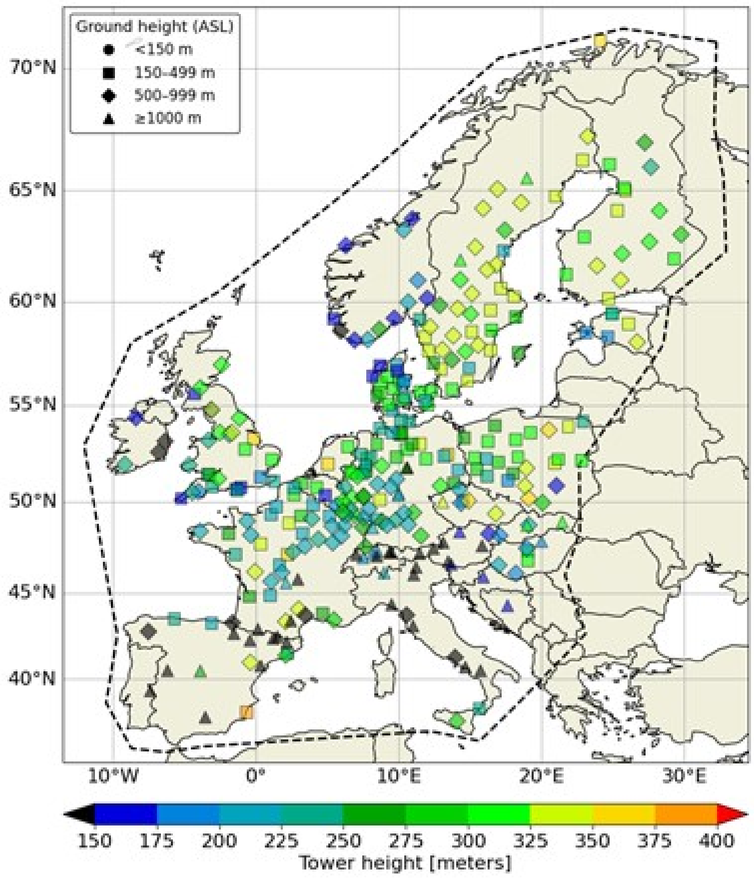

Fig. 2: Geographic distribution of selected structures used in the analysis. Marker color indicates structure height, while marker shape reflects the ground elevation category, as labeled in the plot. For some structures, height information is unavailable; however, these are typically located in high-elevation areas such as mountain ridges or summits, as evident from their symbol type.

of the network's geolocation capabilities. Nevertheless, smaller structures, i.e., typically wind turbines, may still be located within 2 km of a larger object. An example and the potential consequences of such proximity will be briefly discussed in the next section.

Even after applying the initial spatial and height-based filters, not all structures were retained for the final analysis. Some towers, despite meeting the structural criteria, were found to lack sufficient associated lightning data or did not exhibit a clear enhancement in strike density relative to their immediate surroundings. For this, an additional filtering step was introduced based on the spatial distribution of lightning discharges near each tower. Specifically, the ratio of lightning strike density within a 500 m radius of each structure to the density within an annular ring extending from 500 m to 2 km is calculated. If a threshold is applied to this ratio, i.e., retaining only towers with values above the threshold, then setting it too high will limit the dataset to only a few towers, while setting it too low will include towers that do not show a meaningful lightning enhancement. In this study, structures with a density ratio below 1.5 are excluded from further analysis, as they do not appear to significantly influence local lightning activity. In the end, in total, 315 structures were retained for further analysis. Their locations and heights are shown in Fig. 2. For structures shown in black, height information is unavailable; however, their symbol type (diamonds and triangles) indicates that they are typically situated in high-elevation areas such as mountain ridges or summits.

C. *Clustering Algorithm*

A density-based spatial clustering algorithm was applied to identify the most probable group of lightning events physically associated with the structure. DBSCAN (Density-Based Spatial Clustering of Applications with Noise) works by identifying clusters of closely spaced points based on two key parameters: the maximum distance (*eps*) within which points are considered neighbors in the clustering process, and the minimum number of neighboring points (*min_samples*) required to form a cluster. Note that the distance parameter *eps* does not explicitly account for a physical attachment distance between a lightning strike and a structure. The algorithm is well-suited for this application as it allows for the separation of high-density clusters—likely representing lightning strikes attracted to a specific tower—from surrounding noise.

A basic sensitivity check was carried out by running the DBSCAN algorithm with various combinations of the *min_samples* and *eps* parameters, and visually inspecting the resulting clusters for each structure. For instance, setting *eps* too large can produce overly broad clusters that include discharges unrelated to the structure, while too small a value might exclude relevant strikes. Similarly, if *min_samples* is set too high, the algorithm may fail to identify any cluster. That said, the overall outcome of the location accuracy analysis showed only moderate differences across a range of realistic parameter choices. In the end, the *eps* value was fixed at 100 meters across all regions, while the *min_samples* parameter

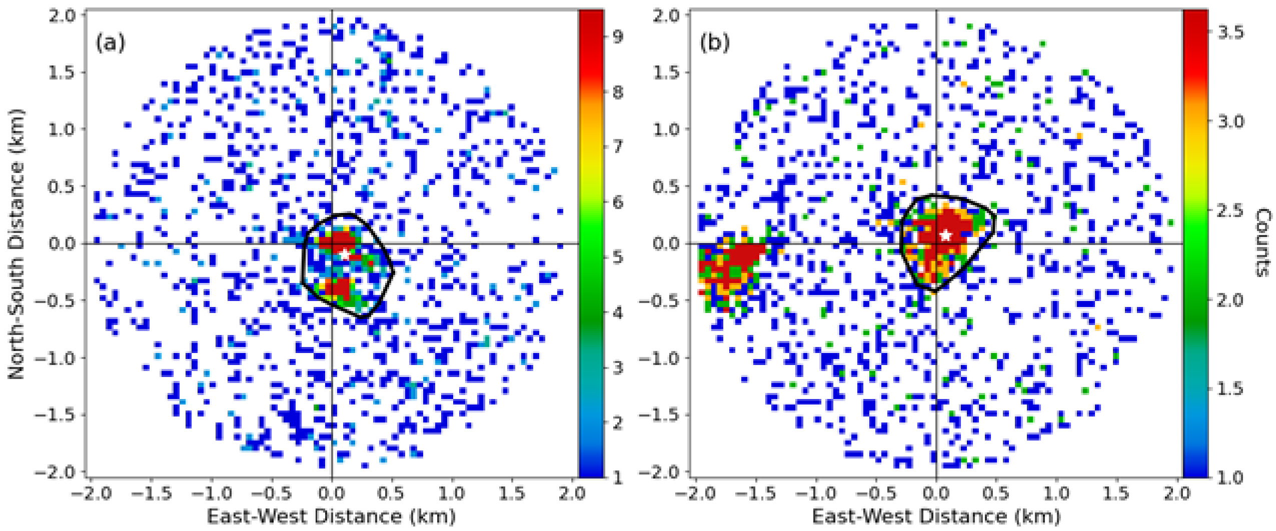

Fig. 3: Lightning density around a structure, shown for two different situations (a and b). The structure is centered at (0,0) in both panels. Lightning event density is color-coded, with red indicating higher densities. The black outlined polygon shows the cluster of lightning events identified using DBSCAN, which are subsequently used for the location accuracy (LA) calculation. The white star denotes the gravitational center of the cluster.

varied based on the number of lightning discharges within a 500-meter radius. For structures with at least 100 discharges within the 500-meter radius, *min_samples* is set to 20. In less active regions, such as Scandinavia, where this threshold was not always reached, *min_samples* was reduced to 5 to enable reliable clustering under sparse data conditions.

When applying DBSCAN to EUCLID observations near a structure, multiple clusters may be identified. In such cases, the cluster closest to the structure's location is assumed to contain the lightning events that struck the structure. This can happen, for instance, when another structure—such as a wind turbine—is located nearby but was not included in the original structure list. As a result, the primary structure may have passed the initial criterion of having no other tall structures within a 2 km radius. In these situations, the closest cluster to the tower was selected for analysis, under the assumption that it is most likely associated with the structure in question. However, it is important to note that no additional filtering was applied to explicitly remove nearby structures like wind turbines from the analysis domain. As a result, the possibility remains that some lightning discharges may be misattributed to the reference tower. This introduces a potential positive bias in the estimated location errors, meaning that the reported location accuracy values should be interpreted as upper-bound estimates under the applied methodology.

An example of the output of the DBSCAN clustering algorithm is shown in the Fig. 3. In both subplots, the lightning activity around the reference structure—located at the origin (0, 0)—is represented as a color-coded 2D histogram. The number of lightning discharges falling within each spatial bin (pixel) is indicated by the color scale, with higher counts shown in red. The black polygon delineates the spatial extent of the DBSCAN cluster that was retained for the analysis, while the white star marks the gravity center of the identified cluster. Fig. 3a illustrates a case where two spatially distinct dense areas are present within the same DBSCAN cluster close to the reference structure in the middle of the plot. The central peak is clearly associated with the tower at the origin, but a secondary peak is visible just to the south. This secondary maximum corresponds to a nearby wind turbine, which was not explicitly removed from the dataset—likely because the initial tower list only included structures exceeding 150 m and did not specifically target wind turbines. Because the turbine is close enough to the tower, both sets of discharges are grouped into a single DBSCAN cluster, shifting the gravity center slightly southward. In contrast, Fig. 3b shows a tower with a nearby wind turbine located farther away—approximately 1.5 km to the west. Although two dense areas are again visible, the DBSCAN algorithm only selects the cluster centered on the reference tower, as the discharges associated with the wind turbine lie outside the specified eps radius for clustering. This illustrates that the spatial proximity of such nearby sources is critical: if they fall within the clustering radius, they may be inadvertently included in the analysis. This example highlights a limitation of the methodology. While DBSCAN effectively groups high-density lightning discharges, it does not distinguish between discharges caused by the tower and those attracted to nearby structures such as wind turbines, which are not accounted for in this study. Nonetheless, because no explicit removal of surrounding structures was performed, the resulting location accuracy metrics should be interpreted as upper-bound estimates—they may be biased towards higher values due to the inclusion of unrelated discharges in the cluster.

Not shown in this study, the robustness of the clustering approach was evaluated by applying the methodology to ground-truth data from the instrumented Gaisberg and Säntis towers, where each lightning strike is independently recorded with GPS-synchronized timing. The resulting median location accuracy (LA) values obtained with the clustering method show very good agreement with previously published results for these towers, including those reported by [8] and [13]. This close correspondence demonstrates that the proposed methodology is capable of reliably identifying tower-related lightning events and reproducing known trends in network location performance, thereby supporting its applicability to the broader dataset analyzed in this study.

III. RESULTS

Figure 4 shows the median location accuracy for each tower in the dataset, indicated by the color of the circle markers. The color scale ranges from 0 to 350 m, with red

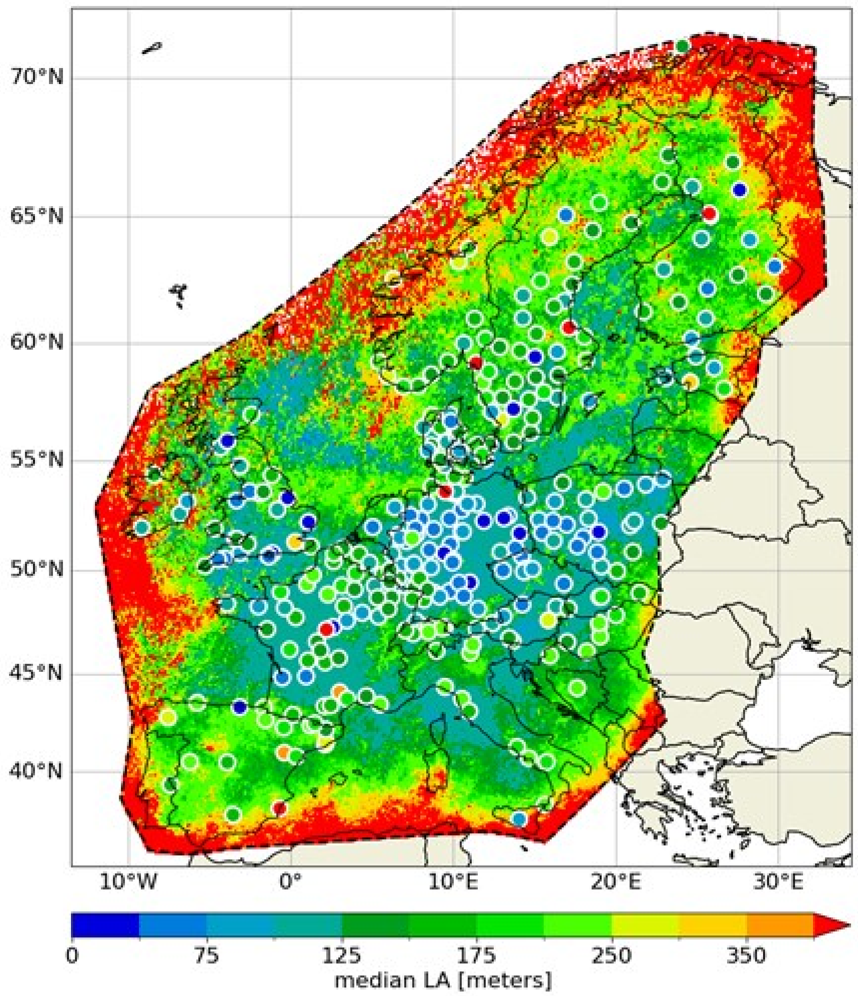

Fig. 4: Median location accuracy (LA) at each instrumented tower (colored circles), overlaid on the spatial distribution of the median semi-major axis (SMA) of the 50% error ellipse for EUCLID strokes from 2012–2024. The color bar indicates the scale in meters.

values representing towers with a median LA exceeding 350 m . Most towers fall within the green and blue categories, indicating relatively good geolocation performance across the network. Only a small number of towers exhibit red values, suggesting that high median LA is uncommon. Mean and median values of the LA found with the adopted methodology are 140 m and 130 m, respectively, with the 95th percentile at 260 m.

In the background of the figure, the underlying color field represents the spatial distribution of the median semi-major axis (SMA) of the 50% error ellipse assigned to each stroke by the EUCLID system. Interestingly, the spatial pattern of the median SMA aligns well with the tower-based median LA values. This consistency supports the representativeness of the SMA as a real-time proxy for geolocation quality. However, it is worth noting that the median SMA values tend to be somewhat larger than the tower-based median LA estimates.

It should be noted that EUCLID, like any operational lightning detection network, undergoes continuous technical upgrades, including the addition and relocation of sensors, hardware improvements, and central processing software updates. Consequently, network performance is expected to improve over time. Although the present study reports aggregated median LA values over the full analysis period, a time-resolved application of the methodology reveals a gradual shift toward lower median LA values in more recent years, consistent with ongoing network enhancements

IV. Summary and Discussion

The proposed methodology has demonstrated its effectiveness in evaluating lightning location accuracy using tall structures as reference points. Applying this approach yields mean and median location errors of approximately 140 m and 130 m, respectively, with a 95th percentile of about 260 m, confirming that the method provides a reliable basis for assessing network performance.

Acknowledgment

The authors are grateful to all the EUCLID members for being able to use the data for this study.

References

[1] Poelman Dieter R., Honoré F., Anderson G., Pedeboy S., 2013: Comparing a Regional, Subcontinental and Long-range Lightning Location System over the Benelux and France. J. Atmos. Oceanic Technol., 30, 2394-2405J. Clerk Maxwell, A Treatise on Electricity and Magnetism, 3rd ed., vol. 2. Oxford: Clarendon, 1892, pp.68–73.

[2] Poelman, D. R., Schulz, W. : Comparing lightning observations of the ground-based European lightning location system EUCLID and the space-based Lightning Imaging Sensor (LIS) on the International Space Station (ISS), Atmos. Meas. Tech., 13, 2965–2977, https://doi.org/10.5194/amt-13-2965-2020, 2020.

[3] Diendorfer, G., 2010: LLS performance validation using lightning to towers. Proc. 21st Int. Lightning Detection Conf., Orlando, FL, Vaisala, 15 pp.

[4] Jerauld, J., V. A. Rakov, M. A. Uman, K. J. Rambo, D. M. Jordan, K. L. Cummins, and J. A. Cramer, 2005: An evaluation of the performance characteristics of the U.S. National Lightning Detection Network in Florida using rocket-triggered lightning. J. Geophys. Res., 110, D19106, doi:10.1029/2005JD005924.

[5] Nag, A., and Coauthors, 2011: Evaluation of U.S. National Lightning Detection Network performance characteristics using rocket-triggered lightning data acquired in 2004–2009. J. Geophys.Res., 116, D02123, doi:10.1029/2010JD014929.

[6] Idone, V. P., D. A. Davis, P. K. Moore, Y. Wang, R. W. Henderson, M. Ries, and P. F. Jamason, 1998a: Performance evaluation of the U.S. National Lightning Detection Network in eastern New York: 1. Detection efficiency. J. Geophys. Res., 103 (D8), 9045–9055.

[7] Schulz, W., H. Pichler, and G. Diendorfer, 2010: Evaluation of 45 negative flashes based on E-field measurements, video data and lightning location data in Austria. Proc. 30th Int. Conf. on Lightning Protection, Cagliari, Italy, Power and Energy Society, 1011-1–1014.

[8] Schulz, W., Diendorfer, G., Pedeboy, S., and Poelman, D. R.: The European lightning location system EUCLID – Part 1: Performance analysis and validation, Nat. Hazards Earth Syst. Sci., 16, 595-605, doi:10.5194/nhess-16-595-2016, 2016.

[9] Diendorfer, G.: A review of 25 years of lightning research in Austria from 1991–2015, in: World meetingon Lightning, 6–8 April 2016, Cartagena, Colombia.

[10] Schwalt, L., Pack, S., and Schulz, W.: Ground truth data of atmospheric discharges in correlation with LLS detections, Elect. Power Syst. Res., 180, 106065, https://doi.org/10.1016/j.epsr.2019.106065, 2020.

[11] Paiva, Amanda & Saba, M. & Naccarato, Kleber & Schumann, Carina & Jaques, Robson & Ferro, Marco & Warner, Tom. (2014). Detection of upward lightning by lightning location systems. 2014 International Conference on Lightning Protection, ICLP 2014. 1824-1826.10.1109/ICLP.2014.6973425.

[12] Zhu, Y., Lyu, W., Cramer, J., Rakov, V., Bitzer, P., & Ding, Z. (2020). Analysis of location errors of the U.S. National Lightning Detection Network using lightning strikes to towers. Journal of Geophysical Research: Atmospheres, 125, e2020JD032530. https://doi.org/10.1029/2020JD032530

[13] Azadifar, M., F. Rachidi, M. Rubinstein, M. Paolone, G. Diendorfer, H. Pichler, W. Schulz, D. Pavanello, and C. Romero (2016), Evaluation of the performance characteristics of the European Lightning Detection Network EUCLID in the Alps region for upward negative flashes using direct measurements at the instrumented Säntis Tower, J. Geophys. Res. Atmos., 121, 595–606, doi:10.1002/2015JD024259.