Review of CIGRE Report "Cloud-to-Ground Lightning Parameters Derived from Lightning Location Systems – The Effects of System Performance"

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Abstract: CIGRE TF C4.404 has recently submitted a comprehensive report for publication, dealing with the effects of performance characteristics of lightning location systems (LLS) on lightning parameters based on data from such systems. This paper will provide an overview and summary of this extensive report.

Lightning parameters are essential input variables to procedures for estimating the lightning performance of transmission lines. Parameters that are typically derived from LLS observations are the ground flash density (GFD), ground stroke density (GSD), peak current distribution, flash multiplicity, and polarity. LLS upgrades and/or LLS expansions are causing changes in the network performance that result in changes in LLS-inferred lightning parameters.

The CIGRE report discusses the effect of using different location methods in terms of required number of sensors to obtain a location. For example, median peak current (absolute value) increased by 47%, from -9.8 kA to -14.4 kA, when data from combined direction-finding and time-of-arrival sensors were reprocessed using only the time information and requiring 4 sensors to compute a location. This effect is reduced with shorter sensor baseline distances, or (equivalently) with greater sensor sensitivity.

Direct measurements of currents in lightning striking instrumented towers or in triggered lightning allow estimation of all three major performance characteristics of LLS's - detection efficiency (DE), for strokes and flashes, location accuracy, and peak current estimation errors. By deploying most recent technology of sensors a flash DE of 95% or higher is achievable. In a network with small sensor baselines and low sensor threshold a flash DE close to 100% is possible. Corresponding stroke DE is generally lower, but can reach values in the range of 80-90%.

Peak current estimates given by LLS in the United States (NLDN) and Austria (ALDIS) are on average in reasonable agreement with the directly measured peak currents in triggered lightning and at electrically short towers, respectively, although significant differences (up to 50%) are observed for individual strokes, likely caused by the natural variation in return stroke speed.

Keywords: Lightning, Lightning Detection, Detection Efficiency, Location Accuracy, Peak Current Estimate

1. INTRODUCTION

The report has been developed in the framework of CIGRE Task Force C4.404 "Lightning Location System Data" and is a logical continuation of [1] and [2]. Lightning parameters are essential input variables to procedures for estimating the lightning performance of transmission lines.

This document begins with a comprehensive overview of lightning flash properties and parameters. A few of these lightning parameters, particularly those of main importance for power engineering, can be derived from data recorded by Lightning Location System (LLS). LLS data have the enormous advantage of covering extended areas up to continental scale on a continuous basis and can therefore observe the related exposure of technical services to the lightning threat. Parameters that are typically derived from LLS observations are the ground flash density (GFD), ground stroke density (GSD), peak current distribution, flash multiplicity, and polarity. These lightning parameters can vary significantly from storm to storm or between seasons.

The remainder of this paper briefly presents some of the key elements of the 117-page Technical Brochure No. 376. Many details have, by necessity, been left out of this overview. The report is available from CIGRE.

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The most fundamental performance parameters of a LLS are:

- Detection Efficiency (DE): We have to distinguish between flash detection efficiency (DE_f) and stroke detection efficiency (DE_s), where DE_f is typically higher than the DE_s, because a flash is successfully located whenever at least one of the strokes within a multi-stroke flash is located.
- Location Accuracy (LA): LLS-reported locations are defined by the centroid of the LLS error ellipse. For a given stroke, the distance between the LLS location and the ground truth striking point is defined to be the stroke location error.
- Peak Current Estimate: LLS infer peak currents from measured peak fields. Simple models to account for field attenuation are partially integrated into the lightning location software (see Eq.2). It is important to distinguish between the ability of a LLS to infer the correct peak current for a given stroke and the ability to provide correct values for peak current distributions. The former are typically used for case studies (e.g. investigation of power line flashover caused by a given lightning stroke) whereas peak current distributions are used in lightning protection standards and many lightning related statistical analyses.

2. LIGHTNING DETECTION METHODS

Since an analysis of Cloud-to-Ground (CG) lightning parameters is the primary objective of the report, the discussion is limited to detection methods that operate on surface-propagated VLF/LF signals produced by CG discharges. The sensors in these systems are typically separated by 50-400 km, employing measurements of the radiation magnetic and/or electric field. CG discharges are located in terms of their ground strike points using various forms of magnetic direction finding (MDF), time-of-arrival (TOA), and combinations thereof. More comprehensive discussions including other detection methods and frequency ranges can be found in [3] and [4]. Methods and effects discussed in this report are generally applicable for any network technology that is based on surface-propagating EM-field measurements in the VLF/LF frequency range.

2.1 Grouping CG Strokes into Flashes

Various methods can be used to group strokes into flashes, and this will affect several derived lightning parameters. In the past an angle-based algorithm was employed where each direction finder (DF) counted all strokes that occurred within ±2.5 degrees of the first stroke for a period of one second after the first stroke, and the flash multiplicity was simply the largest number of strokes detected by any DF. Today's employed grouping algorithms group strokes into flashes using a spatial clustering algorithm. Strokes are added to any active flash for a specified time period (usually 1 second) after the first stroke, as long as the additional strokes are within a specified clustering radius (usually 10 km) of the first stroke and the time interval from the previous stroke is less than a maximum interstroke interval (usually 500 ms). Depending on the system configuration, strokes may be counted in the multiplicity even if they have a polarity that is opposite that of the first stroke. Clearly, the grouping algorithm can have an effect on the measured flash multiplicity, which will be very dependent on subsequent stroke detection efficiency too. Based on video studies there appears to be on average about 1.5-1.7 strike points (ground attachment points) for each CG flash. Hence, for a complete evaluation of the threat from CG lightning, one should use the area density of ground strike points as GFD. At the moment, commercial LLS's are limited in that they can resolve only strike points that are separated by several hundred meters, but this is already much less than the 10 km radius used for clustering the strokes of the meteorological flash (thunder) event.

2.2 Peak current estimate

LLS infer the peak current from the range normalized peak fields (range normalized signal strength RNSS) by using Eq.(1). The field-to-current conversion constant SNF in Eq.(1) is typically set to 0.23 or 0.185.

$$I[kA] = SNF * \overline{RNSS} \qquad (1)$$

$\overline{RNSS}$ is the mean of the range normalized signal strength (RNSS) values of all sensors participating in the location.

It is worth to note that the linear relationship (1) used to infer the peak current from the peak field is not solely based on the Transmission Line (TL) model. Existence of a linear relationship has been validated by simultaneous measurements of currents and fields from triggered lightning and lightning to towers. In these studies the necessity to take into account the propagation effects was also realized and hence attenuation models in form similar to Eq.(2) are implemented in today's lightning locating software

$$RNSS = SS * \left(\frac{r}{100}\right)^{b} * \exp\left(\frac{r-100}{L}\right) \qquad (2)$$

In the CIGRE report, the procedure to find the "best" value for the space constant L in Eq.(2) is described and demonstrated using data from the European lightning location system EUCLID.

It is worth noting that the field-to-current conversion procedure used by LLS for all types of strokes has been validated (using rocket-triggered lightning and tower lightning) only for negative subsequent strokes with peak currents lower than 60 kA, and is not necessarily applicable to negative and positive first strokes, as well as positive subsequent strokes. Additional experimental data are needed in order to validate (1) the field-to-current conversion ratio for first negative and positive strokes, and (2) the theoretical models that predict the effect of the increased attractive radius of high objects on the resulting peak current distribution for first strokes.

3. DETECTION EFFICIENCY (DE)

3.1 Model-Based Detection Efficiency of CG Lightning Strokes

DE is defined as the percentage (or fraction) of discharges (of any given type) that are reported by the LLS. Numerous factors determine the DE of a lightning location system.

Based on model calculations we show in the report for a simple network geometry depicted in Fig.1 the significant effect of applied location method (2, 3 or 4 sensors required to get a location) and sensor baseline. The highest DE (97 %) is achieved by the 150 km baseline network when only 2 sensors are required (combined MDF/TOA sensors), whereas the lowest DE (56 %) is estimated for a network of 300 km baseline, when 4 reporting sensors are necessary to get a location – which is generally required for TOA-only networks to avoid ambiguous locations. DE of a network requiring 4 sensors is obviously much more affected by any changes of baseline length or outage of a sensor.

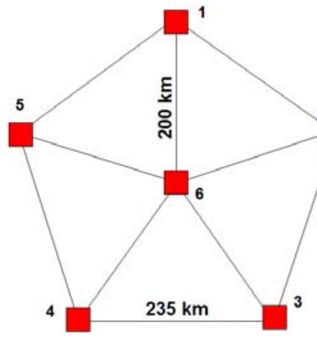

Fig.1: Example of a six sensor network configuration used for model DE calculations, where sensors are located at the corners and centre of a pentagon

These results are in good agreement with experimentally derived results shown in the CIGRE report. It should be noted that this effect will be reduced if the baselines distance is small compared to the effective range of the sensor, which is determined by the sensitivity (detection threshold level) of the sensor.

3.2 Effect of Detection Efficiency on CG Lightning Parameters

The primary factor influencing the accuracy of estimated ground flash density (GFD), peak current distributions, and flash multiplicity distributions is DE. Location accuracy – a statistical measure of the position difference between the actual ground strike location and the location provided by the network – has a weak secondary effect on these parameters.

Estimation of Ground Flash Density

Ground flash density (GFD), typically presented as the number of CG flashes per square km per year, is affected by LLS performance in rather direct ways. If the flash DE is low and nearly constant over longer time periods but can be estimated, then the actual GFD can be estimated by dividing the measured GFD by an estimate of flash DE. Flash DE is usually rather constant over moderate-sized regions (radius of 100-200 km for LLS networks with 200-300 km sensor baselines), making it practical to apply regional DE corrections. Methods for producing DE corrections are presented in section 5 of this paper.

Additionally, since about one half of all multi-stroke negative flashes are thought to have two or more ground attachment points separated by a few 10s of meters to over 7 km [5], the traditional GFD underestimates lightning-damage risk associated with a CG flash. Given that current LLS location error is in the range of 500-1000 m (median), the most practical method to estimate ground strike-point density (GSPD) is to multiply the GFD by 1.5 - 1.7, based on multiple strike point statistics accumulated to date.

Estimation of peak current parameters

Shape and parameters (e.g., mean, median) of LLS inferred lightning peak current distributions are extremely sensitive to the detection efficiency of the employed LLS.

To demonstrate the effect of different network settings - resulting in different DE - on the peak current and multiplicity distribution we have reprocessed data of the Austrian Lightning Detection & Information System (ALDIS) from summer 2001 (July and August 2001) with different configurations. Fig.2 shows a comparison of the resulting normalized peak current distributions for the LLS_8AT (8 IMPACT sensors combining angle (A) and time (T)) versus the LLS_8T/4 network, where angle information is disabled and therefore the sensors act like TOA sensors and 4 sensors are required to compute a location. Obviously the LLS_8AT configuration detects more flashes with small peak currents, when compared to the LLS_8T/4 configuration. A higher peak current is required in order to exceed the detection threshold at 4 or more sensors, therefore the resulting peak current distribution for this configuration is biased towards higher values.

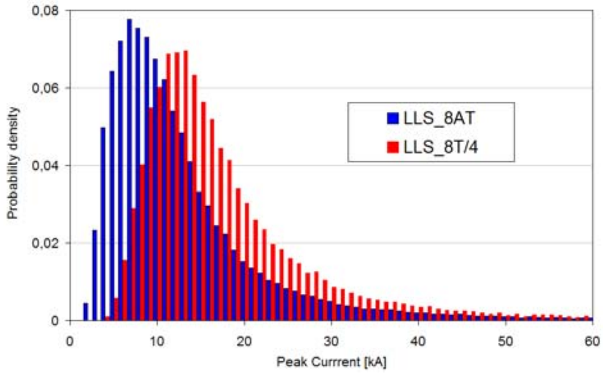

Fig.2: Comparison of the resulting peak current distributions for the LLS_8AT and LLS_8T/4 (relative DE 69%) network settings

It is interesting to note that the pure TOA system of equal baseline and requiring 4 measurements (LLS_8T/4) detects only 43% of the flashes of the EUCLID reference network, whereas the reduction in flash DE for the LLS_8AT is only -11%. LLS_8AT shows a median negative peak current (-9.8 kA) compared to -14.4 kA (+47% increase) for the LLS_8T/4 network. These variations of current distributions resulting from DE differences (when different sensor types are employed) would be sufficient to “mask” any likely regional peak current differences resulting from “real” climatological differences.

Estimation of Multiplicity parameters

Earlier work [6], [7] have shown that the overall stroke DE (computed including both first and subsequent strokes) has a strong influence on the measured multiplicity distribution, and that the “true” multiplicity distribution determines the relationship between flash DE_f and overall stroke DE_s.

However, it is well accepted that first stroke DE (DE_1) differs from and is generally higher than subsequent stroke DE (DE_{su}). A more general model for the multiplicity distribution that separates out these two DE terms, assuming that all subsequent strokes have equal detection probability, is described in the CIGRE report.

The importance of using this more-general model is illustrated in Fig.3. Two conditions are shown – both of which result in a flash DE_f of 89%. One condition employs the same DE (60%) for first and subsequent strokes. The other condition has a significantly higher first stroke DE_1 (70%) and a lower subsequent-stroke DE_{su} (40%). Note that the percentage of single-stroke flashes is significantly lower in the condition with equal DE (DE_1 = DE_{su}). Table 1 summarizes these results, and also provides the average multiplicity values associated with the various conditions. In this example, the average measured multiplicity differed by nearly 30% (3.1 vs. 2.4), with no change in flash DE_f.

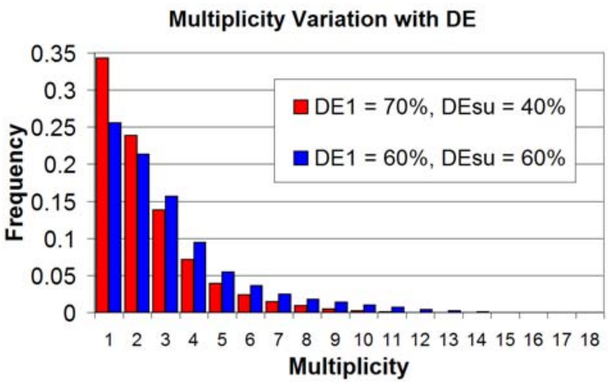

Fig.3: Multiplicity histograms for two different detection efficiency conditions. Both conditions result in flash DE_f of 89%.

TABLE 1: FLASH DE_F, PERCENT OF SINGLE-STROKE FLASHES, AND MULTIPLICITY FOR THREE DETECTION EFFICIENCY CONDITIONS.

DE_1 : DE_{su}	Flash DE_f	% Single-stroke	Multiplicity
100% : 100%	100%	17%	4.5
60% : 60%	89%	26%	3.1
70% : 40%	89%	34%	2.4

It is clear from Fig.3 and Table 1 that it is important to consider different DE values for first and subsequent strokes, and that detection efficiency can have a significant effect on measured multiplicity parameters.

4. GROUND TRUTH REFERENCES

For the evaluation of these LLS performance parameters reference data are either obtained from direct current measurements on instrumented towers such as the Gaisberg Tower in Salzburg (Austria) and CN Tower in Toronto (Canada), or from triggered lightning or video observations.

From different studies presented in detail in the CIGRE report the following conclusions for the major LLS performance criteria are drawn:

By deploying most recent technology of sensors a DE_f of 95% or higher is achievable. In a network with small sensor baselines and low sensor threshold settings (requires sensor sites with low electromagnetic background noise) a DE_f close to 100% is possible. DE_S is generally lower than DE_f and can reach values in the range of 80-90%, where most likely strokes of very small peak currents are missed by the LLS.

The effect of the number and type of sensors located within a few hundred kilometers around any strike point becomes obvious when we compare the DE results of lightning to the Gaisberg tower and triggered lightning in Florida. The stroke DE_S in the Gaisberg tower area is significantly higher, since 5 sensors are within a distance of 150 km. In the U.S. NLDN only one sensor is within 100 km from the Camp Blanding site and the 4 next nearest sensors are at distances between 200 and 250 km, resulting in predominantly poor detection of triggered strokes with small peak currents. In addition, when a subset of the nearby sensors only provide TOA information (as in the Florida area in 2001-2002), the LLS was not able to produce a position when only two sensors detected an event.

The different ground truth studies confirmed a location accuracy with a median location error in the range of 500 m, as predicted by model calculations. The most accurate locations are observed for peak currents in the intermediate peak-current range of 20-30 kA, since a sufficient number of sensors report the event and the peak field values are below the saturation limit of the nearby sensors. Roughly half of this error is a bias (spatial offset) resulting from propagation of the radiation field over different terrain, and has the potential to be corrected.

Triggered lightning and upward initiated lightning to elevated towers represents mostly same-channel subsequent strokes in natural downward lightning. First strokes in downward lightning typically have larger peak currents than subsequent ones and therefore the DE values based on triggered and tower lightning data represent lower bounds on DE for the given LLS.

Peak current estimates from LLS are dependent on the sensor calibration, the applied attenuation model and the field to current conversion factor. Some of the differences observed in the peak current estimate of triggered lightning located by the U.S. NLDN and strikes to the Gaisberg tower located by EUCLID are most likely caused by the different settings in the attenuation model and field to current conversion used in the two networks. An observed pronounced over-estimation of peak currents by the NALDN from lightning to the CN Tower appears to be caused at least partly by the so called tower effect (see e.g. [8, 9]).

5. METHODS FOR COMPENSATION OF RELATIVE NETWORK DETECTION EFFICIENCY

5.1 Stroke DE correction using peak current distributions

The effect of DE on peak current distributions shown in section 3.2 provides the rationale for a method to estimate the relative stroke DE between two regions or conditions (Reference and Test Conditions). This method is described in detail in the CIGRE report. If there is a specific peak current value (I_0) above which all events are seen in a Test condition (that peak current being higher than the I_0 value for a Reference condition that had higher stroke DE), then it is possible to represent the difference in the Test and

Reference conditions by "scaling" the Test distribution by a constant that is equal to the fraction of events detected by the Test network. The Test and Reference distributions should then be identical for peak currents greater then I_0. This fact is illustrated in Fig.4, where the Test distributions have been "normalized" by scaling them down to the known stroke DE values. Note that the curves are essentially identical for peak currents above 11 kA. Note also that the curves grow farther apart as peak current decreases, which reflects the variable (but decreasing) detection efficiency with decreasing peak current in the Test configuration. Fig.4 clearly shows that no flashes with peak currents below 4 kA were seen in the "75%" Test condition.

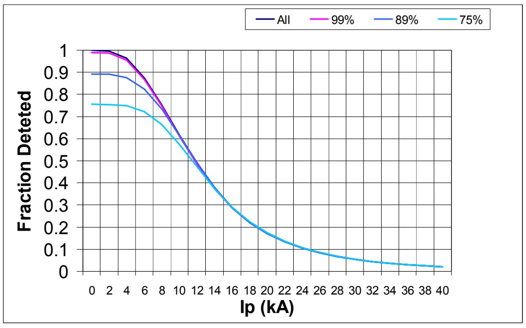

Fig.4: First stroke peak current distributions scaled by their associated relative first stroke DE values, for four different detection efficiency conditions in the central U.S. NLDN

5.2 Graphical Approach to DE Estimation

In addition to the more mathematically oriented procedure summarized in section 5.1 a graphical approach for DE correction is also presented in the report. When peak current distributions are plotted in semi-log format (see Fig.5), one can easily tell how to "adjust" the "Test" curve (green) for it to match the "Reference" curve (blue) for the higher peak-current values. A correction is determined sliding the test curve down in order for the Test and Reference curves to be aligned at higher-current levels (DE-corrected curve is shown in red). The relative DE of the test condition (compared to the Reference condition) can be read off of the y-axis (in this case, 80%).

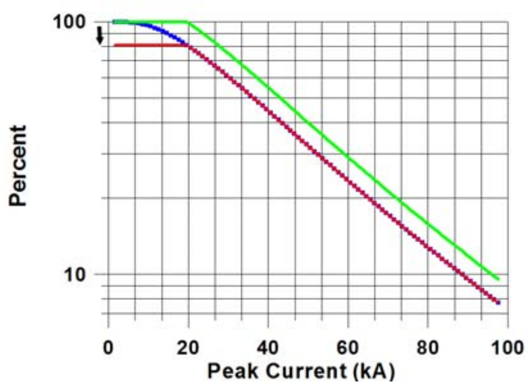

Fig.5: Distributions plotted in semi-log format for simulated long-normal peak current distribution (blue), same distribution after removing all events below 20 kA (green), and the DE-corrected distribution (red).

6. CONCLUSIONS

This reviewed CIGRE report provides a comprehensive overview about the effect of LLS performance on Cloud-to-Ground (CG) lightning parameters derived from LLS. An understanding of the ranges of uncertainties and errors of any derived lightning parameter is essential in order to avoid misinterpretation of results.

The available technology for detecting and locating lightning to ground has significantly improved over the last decade. LLS upgrades and/or LLS expansions are causing changes in the network performance that result in changes in LLS-inferred lightning parameters. These effects must be considered in order to allow data from different LLS to contribute to our understanding of true regional and climatological differences in lightning parameters.

References

(1) CIGRE Report 94: "Lightning Characteristics Relevant for Electrical Engineering: Assessment of Sensing, Recording and Mapping Requirements in the Light of Present Technological Advancements", TF 33.01.02, (1995).

(2) CIGRE Report 172: "Characterization of Lightning for Applications in Electric Power Systems", TF 33.01.02, (2000).

(3) Cummins, K. L. and M. J. Murphy: "Overview of Lightning Detection in the VLF, LF, and VHF Frequency Ranges", 16th International Lightning Detection Conference (ILDC), Tucson, Arizona, (2000).

(4) Rakov, V. A. and M. A. Uman: "Lightning: Physics and Effects", Cambridge University Press, (2003).

(5) Rakov, V. A., M. A. Uman, and R. Thottappillil: "Review of lightning properties determined from electric field and TV observations", J. Geophys. Res. 99: 10,745-50, (1994).

(6) Rubinstein, M.: "On the determination of the flash detection efficiency of lightning location systems given their stroke detection efficiency", EMC Conference Proceedings, Zurich, (1995).

(7) Rakov, V. A. and G. R. Huffines: "Return-stroke multiplicity of negative cloud-to-ground lightning flashes", J. Appl. Meteor., Vol. 42, No. 10, pp. 1455-1462, (2003).

(8) Lafkovici, A., A.M. Hussein, W. Janischewskyj and K. Cummins, "Evaluation of the performance characteristics of the North American Lightning Detection Network based on tall-structure lightning," IEEE Trans. on Electromagnetic Compatibility, vol. 5, no. 3, pp. 630-641, (2008).

(9) Pavanello, D., F. Rachidi, W. Janischewskyj, M. Rubinstein, V. O. Shostak, C. A. Nucci, K. L. Cummins, A. M. Hussein, and J.-S. Chang, "On the Current Peak Estimates Provided by Lightning Detection Networks for Lightning Return Strokes to Tall Towers", IEEE Transactions on Electromagnetic Compatibility, in press, (2009).