The Need for an International Standard on Lightning Location Systems

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Abstract—The lightning flash density \( N_g \) so important in Lightning Protection standards for risk assessment calculations, should be replaced by the more suitable lightning strike-point density \( N_{sp} \). A factor 2 is proposed to relate \( N_g \) to \( N_{sp} \). More precise \( N_g \) values should occur from Lightning Location Systems (LLS), while improving their detection efficiency, location accuracy, and classification accuracy. A new IEC 62858 standard on LLS will be published soon, taking into account their performance characteristics.

Keywords—lightning flash density, lightning strike-point density, lightning location systems, standards.

I. INTRODUCTION


The lightning flash density \( N_g \) defined as the number of lightning flashes to ground per kilometer squared per year is the primary input parameter to perform such an evaluation. Nevertheless, it should be replaced by the lightning strike-point density \( N_{sp} \) related to \( N_g \) by a simple multiplication factor, taking into account not only the average number of multi-terminations flashes, but also the flash detection efficiency, location accuracy and misclassified events of the lightning location systems. Indeed, in many areas of the world \( N_g \) is derived from data provided by lightning location systems (LLS), but no common rule exists giving requirements neither for their performance nor for the elaboration of the measured data. In order to make reliable and homogeneous the values obtained from LLS in various countries using such systems, IEC TC81 (Lightning Protection) set up a new working group WG12, chaired by the author, to provide an international standard on LLS.

The purpose of the proposed standardization is to promote the harmonization of the national specifications and practices concerning the lightning location systems, in order to give a common and acknowledged validity to \( N_g \) values available in the various countries so that the risk evaluation would be harmonized not only as a procedure (IEC 62305-2, 2010) but also as results. The standard should specify the requirements and tests to be performed for Lightning Location Systems independently of the technology used for the hardware, relevant to:

a) the performance of the hardware, such as the detection efficiency of the LLS network, the location accuracy, the quality of the measured data;

b) the data processing, such as the sample data to be used, the grid cell size, etc.

The risk estimation will also incorporate the possibility that many lightning events may occur in a very short time, resulting damages being worsened by such a concentration.

II. LIGHTNING GROUND FLASH DENSITY

The ground flash density has first been estimated from records of lightning flash counters (LFC) in several countries and, more recently, from records of lightning location systems (LLS) in many countries. It can also potentially be estimated from records of satellite-based optical or radio-frequency radiation detectors, but it is worth noting that satellite detectors cannot distinguish between cloud discharges (CC : intra-cloud and cloud-to-cloud) and cloud-to-ground (CG) discharges and, hence, in order to obtain \( N_g \) maps from satellite observations, a spatial distribution of the fraction of discharges to ground (CG) relative to the total number (CG + CC) of discharges is needed. IEEE 1410 (IEEE, 2011) recommends, in the absence of ground-based measurements of \( N_g \), to assume that \( N_g \) is equal to one third of the total flash density (including both cloud discharges and cloud-to-ground discharges) based on satellite observations (Rakov, 2003).
The evaluation of the ground flash density \( N_g \) is not straightforward, though it is a crucial parameter related to the risk calculations. This is due to the following reasons (Bouquegneau et al., 2012):

- values of \( N_g \) result from LFC (lightning flash counters) and LLS (lightning location systems) data that so far are not accurate enough; the main problems are: detection efficiency, location accuracy (current LLS location error is in the range 500-1000 m), and misclassified events (Diendorfer et al., 2009); moreover, there is a lack of data in many regions of the world;

- depending on the country, maps of \( N_g \) sometimes refer to either maximum values or average values in a selected area which can be variously estimated (from a few \( \text{km}^2 \) to hundreds of \( \text{km}^2 \));

- in some countries, there is some confusion between flash density maps and stroke density maps and there is a flash multiplicity with an average of 2 to 3 strokes per flash in negative lightning discharges, a typical average value of the interstroke interval being around 60 ms (Rakov et al., 2013);

- damages are generally attributed to the first stroke though they could be also due or even made worse by subsequent strokes (particularly the second stroke or first subsequent stroke);

- moreover, almost one-half of all lightning discharges to ground, both single- and multiple-stroke flashes, strike ground at more than one point with the spatial separation between the multiple terminations of individual cloud-to-ground flashes ranging from some tens of meters to 8 km; the number of channels per flash (number of ground contacts or ground terminations related to multiple channel terminations on ground) is not taken into account, though the average number of ground contacts is between 1.5 and 1.7 (observed in USA, Brazil, Western Europe); before obtaining more accurate results, it is practical to estimate the ground strike-point density by multiplying the ground flash density by a correction factor of 1.5 to 1.7 (Diendorfer et al., 2009).

In mountainous regions, Rakov et al. (1989) found another factor of 1.7 higher average value of the ground flash density than for a plain terrain area, the two areas being about equally covered by the lightning location system.

The risk estimation should also incorporate the possibility that many lightning events may occur in a very short time (due to the relaxation time of the measuring system, some of them could be ignored), resulting damages being worsened by such a concentration.

III. THUNDERSTORM DAYS AND LIGHTNING GROUND FLASH DENSITY

The number of thunderstorm days per year (\( \text{year}^{-1} \)) \( T_d \) or keraunic level is the average number of days per year when thunder can be heard. It is not a good parameter. Indeed, in temperate regions, a frontal thunderstorm can go away after some minutes or can stay during several hours in full activity. Sometimes thunder can be heard at unusually large distances, say 40 km or even more, giving a strongly exaggerated impression of the lightning activity.

The keraunic level is an indicator of thunderstorm activity. It is not rigorous at all since it gives no indication of the number of lightning strikes to ground. That is why the concept of keraunic level was replaced by the ground flash density \( N_g \), number of lightning flashes to ground per kilometer squared per year (\( \text{km}^{-2} \cdot \text{year}^{-1} \)).

There are many factors influencing lightning incidence. The following parameters are important to be considered: topographical factors (soil humidity, thunderstorm corridors favoured by airstreams in valleys, lightning strikes on hillsides instead of mountaintops, etc.), geological and orohydrolithological factors (faults, crevices, cracks, water layers, etc.).

If no measurements of the ground flash density \( N_g \) for the area in question are available, this parameter can be roughly estimated from the annual number of thunderstorm days \( T_d \). Apparently the most reliable expression relating \( N_g \) and \( T_d \) is the one proposed by Anderson et al. (1984):

\[
N_g = 0.04 (T_d)^{1.25}.
\]

The observed variation in ground flash density from one region to another in the United States, and in many other countries, is more than two orders of magnitude.

Many flashes strike ground at more than one point. Most measurements of lightning flash density do not account for multiple channel terminations on ground. When only one location per flash is recorded, while all strike points are of interest, as is the case where lightning damage is concerned, measured values of ground flash density should, in general, be increased.

IV. GROUND FLASH DENSITY IN PRESENT LIGHTNING PROTECTION STANDARDS

In the risk calculation, Lightning Protection standards require the assessment of an annual number \( N \) of dangerous events (IEC 62305-2, 2010). This number of dangerous events due to lightning flashes influencing a structure to be protected depends on the thunderstorm activity of the region where the structure is located and on physical characteristics of the structure.

To calculate the number \( N \), one should multiply the lightning ground flash density \( N_g \) by an equivalent collection area of the structure, taking into account correction factors for the physical characteristics of the structure.

In countries where no LFC or LLS are installed, no map of \( N_g \) is available. In this case, lightning protection national standards generally apply an empirical formula relating the lightning flash density \( N_g \) to the annual number of thunderstorm days \( T_d \) in temperate regions \( N_g \) can be estimated by

\[
N_g = 0.1 \ T_d
\]

The value of the ground flash density \( N_g \) (\( \text{km}^{-2} \cdot \text{year}^{-1} \)) should be available from ground flash measurements with LLS and/or LFC. Nevertheless, these networks are not yet accurate enough, commercials announcing efficiencies as high as 98%, though the detection efficiency (DE), the location accuracy (LA), and the misclassified events probably induce at the best a total efficiency not greater than some 70 to 80%. Moreover low peak currents are never recorded and we mentioned that most measurements of lightning flash density do not sufficiently account for multiple channel terminations on ground.
We should include such distinctions in the concept of risk estimation (better than risk calculation). A first rough proposal to include these physical events could be to multiply \( N_g \) values (obtained from LLS measurements) by a factor of 2 for usual situations (flat grounds where the effective height could be considered as equal to the geometrical height; structures not taller than 60 m). This factor was proposed in the Belgian National Standard on values recorded from the Royal Meteorological Institute LLS network.

The accuracy of \( N_g \) mapping depends on the number of events per grid cell, which in turn depends on the grid cell size and period of observations (Diendorfer, 2008). It is recommended that the number of events per grid cell be at least equal to 80 (see Section VI).

In a lightning protection standard, what is important is not the ground flash density itself, but the ground strike-point density that we call \( N_{g_{	ext{sp}}} \).

The choice of a specific value of \( N_{g_{	ext{sp}}} \) related to the risk estimation of a given building or structure, applicable to the international and national lightning protection standards, could be defined as follows: choose the estimated average (or, maximum, better in critical structures) value of \( N_g \) on the ground flash density map of the region involved (on the condition that these values were confirmed during a recent period covering at least 10 years) in a circular area of at least 5 km radius around the building or structure to be protected, and, when estimating the lightning risk assessment, multiply this number by a factor of 2, i.e.

\[
N_{g_{	ext{sp}}} = f \times N_g \tag{3}
\]

where the proposed factor \( f \) is equal to 2.

Let us note that, when the LLS systems will directly give the ground strike-point density, such a correction factor will not be needed.

Inside IEC TC81, a new working group WG12 on Lightning Location Systems (LLS) was recently set up. Indeed so far no common rule exists giving requirements neither for the LLS performances nor for the elaboration of the measured data. In order to make reliable and homogeneous the values obtained from the LLS systems in various countries using such systems, a new international standard is needed. This standard shall promote the harmonization of the national specifications and practices concerning the LLS systems, in order to give a common and acknowledged validity to ground flash density values available in various countries so that the risk evaluation would be harmonized as well not only as a procedure (IEC 62305-2, 2010) but also for its results.

V. GROUND FLASH DENSITY IN PRESENT LIGHTNING PROTECTION STANDARDS

Following the proposal described with relation (3), by introducing a factor of 2 to \( N_g \) to take \( N_{g_{	ext{sp}}} \) into account instead of \( N_g \), WG12 suggested to IEC TC81 MT9 (Maintenance Team of the International Technical Committee on Lightning Protection, related to the risk management; see IEC 62305-2, annex A1, 2010), to replace the actually poor information on \( N_{g_{	ext{sp}}} \) (text limited on comments to formula 2) by the following:

The lightning strike-point density \( N_{g_{	ext{sp}}} \) is more reliable than the lightning ground flash density \( N_g \) when the lightning protection of a structure (building) is considered. To cover this effect, the value of \( N_g \) should be multiplied by 2.

In countries where the LLS systems will directly give the ground strike-point density such a factor 2 will not be needed. Then

\[
N_{g_{	ext{sp}}} = 2 \times N_g \tag{4}
\]

The \( N_g \) map should cover at least a recent period of ten years and it should display the mean value of \( N_g \) in a circular area of at least 5 km radius around the structure to be protected.

For critical structures, the maximum value may be used instead of the mean value, and the area may be larger. This could lead to higher risk levels.

In most areas of the world, an indication of lightning activity may be obtained from observations of lightning optical transients. Satellite-based sensors respond to all types of lightning with relatively uniform coverage in all areas. With sufficient averaging, optical transient density data provide better estimates of ground flash density than thunder observations, which have a wide range of relations between ground flash density and thunderstorm hours or thunderstorm days. There are also regional variations in the ratio of ground flashes (CG) to total flashes (CG + CC). A median value of 0.25 ground flashes to total flashes is recommended in temperate regions.

In areas without ground-based lightning location systems or lightning flash counters, the recommended estimate of ground flash density is

\[
N_g = 0.25 \times N_t \tag{5}
\]

where

\( N_t \) is the total (CG + CC) density of optical flashes per km\(^2\) per year, obtained through http://lightning.nsstc.nasa.gov/data/data_lis-otd-climatology.html.

WG12 members would deeply appreciate to get comments on this proposal.

VI. LIGHTNING LOCATION SYSTEMS CHARACTERISTICS

Lightning Location Systems (LLS) are currently used in many countries to acquire lightning data that can be used for mapping \( N_g \). Unfortunately, any LLS fails to detect relatively small cloud-to-ground flashes (particularly near the periphery of the network or some hundreds kilometers outside the antenna network) and fails to discriminate against some cloud flashes, unwanted in determining \( N_g \). The corresponding system characteristics, the detection efficiency and the selectivity with respect to ground flashes, are influenced by network configuration, position of the lightning relative to the network, system sensor gain and trigger threshold, sensor waveform selection criteria, lightning parameters, and field propagation conditions. The interpretation of system output in
terms of \( N_g \) is subject to a number of uncertainties, but multiple-station lightning locating networks are by far the best available tool for mapping \( N_g \). More detailed information about LLS is found in two CIGRE reports, one by Diendorfer et al. (2009) and the other one by Rakov et al. (2013).

The performance characteristics of a Lightning Locating Systems determine the quality of the lightning data available for calculating \( N_g \) (Schulz, 2013). A value of \( N_g \) with an maximum error of +/- 20% is deemed to be adequate for lightning risk assessment. Data from any LLS that is able to detect CG lightning and accurately determine the ground attachment point of CG strokes can be used for the purpose of \( N_g \) computation.

The following LLS performance characteristics are required for computation of \( N_g \) with an adequate accuracy:
- the annual average flash detection efficiency (DE) of an LLS for cloud-to-ground (CG) lightning should be at least 80\% in all regions within the interior part of the network;
- the median location accuracy (LA) of an LLS for CG strokes should be better (lower) than 1 km in all regions within the interior of the network;
- in a network with a flash DE that meets the criteria set for \( N_g \) calculation, if too many CG strokes are misclassified as cloud pulses, it may lead to erroneously low values of \( N_g \): a classification accuracy of at least 85\% is required.

The performance characteristics of LLS can be determined using a variety of methods including network self-referencing and comparison against ground-truth lightning data obtained using various techniques.

The flash DE, LA, and classification accuracy of LLS depend on a few fundamental characteristics of the network. LLS owners, operators, and data providers should consider the several factors related to the sensors (baseline distance, sensitivity, uptime) while designing and maintaining their networks to ensure that the lightning data is of adequate quality for \( N_g \) computation.

It is important to note that LLS record strokes, not flashes, and therefore estimation of \( N_g \) from LLS data depends on the method to group strokes into flashes. Return strokes detected by LLS shall be grouped into flashes for \( N_g \) calculation. This grouping is done based on a spatial-temporal window. A stroke is added to a flash if the following criteria are met:
- occurring less than or equal to 1 s after the first return stroke;
- stroke location is less than or equal to 10 km from the first return stroke; and
- time interval from previous stroke is less than 500 ms.

The flash position is assumed to be the location of the first stroke.

Multiple ground strike points will be included in the same flash using the above criteria; as proposed above a multiplication factor of 2 relating \( N_g \) to \( N_{gs} \) is necessary (see relation 4). Here, it must be distinguished between multiple terminations on ground for a single stroke (a pretty rare event), which is usually detected by the LLS as one ground strike-point, and a termination on ground for a subsequent stroke deviated from the termination of the previous stroke, which is usually detected from the LLS as a further ground

\[
\begin{align*}
N_g \times T_{obs} \times A_{cell} > & \text{ or } 80 \\
N_g & \text{ is the ground flash density (km}^{-2}\text{ year}^{-1}), \\
T_{obs} & \text{ is the observation period (years),} \\
A_{cell} & \text{ is the area of each single cell (km}^2\text{).}
\end{align*}
\]

Table I. Grid cell characteristics

<table>
<thead>
<tr>
<th>( N_g ) (km(^{-2}) year(^{-1}))</th>
<th>Square: dim. 1 km</th>
<th>Square: dim. 3 km</th>
<th>Square: dim. 10 km</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min # of years</td>
<td>Min # of years</td>
<td>Min # of years</td>
</tr>
<tr>
<td>0.25</td>
<td>320</td>
<td>35</td>
<td>-</td>
</tr>
<tr>
<td>0.5</td>
<td>160</td>
<td>18</td>
<td>-</td>
</tr>
<tr>
<td>1.0</td>
<td>80</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2.0</td>
<td>40</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The minimum observation period (years) for an estimated ground flash density \( N_g \) and cell dimensions (side of a square), for each grid element. The boxes in Table I with numbers in grass are the practical spatio-temporal grid cell characteristics.

The tessellation must be done such that the dimensions comply with the requirements of Table I. The minimum admisible cell dimension, irrespective of ground flash density and observation period may not be less than double the median location accuracy.

For any region, an elementary grid of 1 km x 1 km has to be used as an underlying grid for forming a grid cell that meets the above criteria for \( N_g \) calculation. To avoid edge effects, for
A given location at which the value of \( N_g \) is desired, the smallest grid cell surrounding that location containing at least 80 flashes should be considered for calculating an average value of \( N_g \) for that location.

VII. CONCLUSION

The evaluation of the ground flash density (\( N_g \)) is a crucial point related to the risk calculations especially in the Lightning Protection standards (IEC 62305, 2010). Data from LLS are not yet accurate enough; moreover, there is sometimes some confusion between stroke density, flash density, and ground strike-point density. Waiting for a better detection efficiency and a better location accuracy of LLS, taking into account all unknown or non-precise parameters, and wishing to stay on the safety side, we suggest to multiply the ground flash density (obtained from LLS) by a factor of 2 in the standards focusing on the lightning risk assessment. We also recommend to continue to work on the new international standard IEC 62858, Edition 1 (standard actually prepared by IEC TC81 WG12), essentially working so far on the lightning flash (and strike-point) density based on Lightning Location Systems.

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