21, rue d'Artois, F-75008 PARIS
http : //www.cigre.org

International Colloquium
on Lightning and Power systems

INSA LYON
France

LIGHTNING STRIKE-POINT DENSITY FOR RISK ASSESSMENT

C. BOUQUEGNEAU
University of Mons
Belgium

A. ROUSSEAU
SEFTIM
France

SUMMARY

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_{sg}. A factor 2 is proposed to relate N_g to N_{sg}. More precise N_g values should occur from Lightning Location Systems (LLS), while improving their detection efficiency, location accuracy, and classification accuracy. A new standard on LLS (IEC 62858) is under consideration.

KEYWORDS

Lightning, risk, flash density, strike-point, lightning location system, standards**.**

Christian.bouquegneau@umons.ac.be.

I - Lightning Ground Flash Density

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 risk assessment calculation. Nevertheless, it should be replaced by the lightning strike-point density N_{sg} 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 C. Bouquegneau, 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; [7]) 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.

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, [6]) 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, [8]).

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., [3]):

- 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., [5]); 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 km^2 to hundreds of 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., [9]) ;

- 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., [5]). Most measurements of lightning flash density do not account for multiple channel terminations on ground even of some LLS are able to discriminate such multiple strike points. 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.

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.

II - Ground Flash Density in Lightning Protection Standards

In the risk calculation, Lightning Protection standards require the assessment of an annual number N of dangerous events (IEC 62305-2, [7]). 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 keraunic level T_d; in temperate regions N_g can be estimated by

$$N_g = 0.1\ T_d \qquad (1)$$

The value of the ground flash density N_g ($km^{-2}\ year^{-1}$) 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 90%. 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).

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, [4]). It is recommended that the number of events per grid cell be at least equal to 80.

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_{sg}.

The choice of a specific value of N_{sg} 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 such as nuclear plants) 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.

$$N_{sg} = f\, N_g \tag{2}$$

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, [7]) but also for its results.

III - Ground STRIKE-POINT Density in Lightning Protection Standards

Following the proposal described with relation (3), by introducing a factor of 2 to N_g to take N_{sg} 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, [7]), to replace the actually poor information on N_g (text limited on comments to formula 1) by the following:

The lightning strike-point density N_{sg} 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

$$N_{sg} = 2\,N_g \qquad (3)$$

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

$$N_g = 0.25\,N_t \qquad (4)$$

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 .

It is likely that, when N_{sg} will be introduced, a revision of a few formulas will be needed in the lightning risk standard 62305-2 to take care of reality check.

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

IV - 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. [5] and the other one by Rakov et al. [9].

The performance characteristics of a Lightning Locating Systems determine the quality of the lightning data available for calculating N_g (Schulz, [10]). A value of N_g with a 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 detection efficiency (DE), the location accuracy (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_{sg} 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 strike-point. This performance should be taken into account in estimating lightning incidence to areas when performing risk calculations (for example in IEC 62305-2 [7]).

A sufficiently long sampling period is required to ensure that short time scale variations in lightning parameters due to variety of meteorological oscillations are accounted for.

Additionally large scale climatological variations limit the validity of historic data. Lightning data for a recent period of at least ten years is required.

The observation area is determined by area over which pertinent lightning data are available.

Ground flash density (N_g) values vary annually and regionally. Lightning data have to be evaluated inside a gridded array of cells constrained by a geographic boundary: the area of interest is divided into regular grids (tessellation of the geographic area) and an aggregation function is applied to all flashes occurring within the grid. The resulting aggregation value is assumed to be the meaningful value within that area.

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.

Grid size (Schulz et al., [10]) has to be chosen in such a way that the dimensions of each cell and the number of years considered both comply with the minimum requirements obtained by formula (6), following Poisson distribution and the law of rare events, thus obtaining an uncertainty of less than 20% at 90% confidence level (Diendorfer, [4]):

$$N_g \, T_{obs} \, A_{cell} > \text{or} = 80 \tag{5}$$

where:
N_g is the ground flash density (km^{-2} $year^{-1}$),
T_{obs} is the observation period (years),
A_{cell} is the area of each single cell (km^2).

TABLE I. GRID CELL CHARACTERISTICS

N_g (km^{-2} $year^{-1}$)	Square: dim. 1 km	Square: dim. 3 km	Square: dim. 10 km
	Min # of years	Min # of years	Min # of years
0,25	320	35	**3**
0,5	160	18	**2**
1,0	80	**9**	**1**
2,0	40	**4**	**1**

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 bold 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 admissible 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.

V - 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, Ed. 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.

Acknowledgment

The authors thank the following active members of IEC TC81 WG12 for their pertinent contribution: W. Schulz, S. Thern, A. Kern, H. Betz, J. Montanya, S. Pedeboy, M. Bernardi, A. Nag, M. Grant, and D. Poelmann.

References

[1] Anderson, R., et al. (1984), Lightning and Thunderstorm Parameters, in Lightning and Power Systems, London, IEE Conf. Publ. # 236.

[2] Bouquegneau, C., and Rakov, V. A. (2010), How Dangerous is Lightning?, Dover Publications, Mineola, New York.

[3] Bouquegneau C., Kern, A., and Rousseau, A. (2012), Flash Density applied to Lightning Protection Standards, Proc. Ground'2012 & 5th LPE, Bonito, Brazil, November 2012.

[4] Diendorfer, G. (2008), Some Comments on the achievable Accuracy of Local Ground Flash Density Values, Proc. 29th ICLP, Uppsala, Sweden, paper 2-8.

[5] Diendorfer, G., et al. (2009), Cloud-to-Ground Lightning Parameters Derived from Lightning Location Systems – The Effect of System Performance, CIGRE Report 376 (WG C4.404), April 2009.

[6] IEEE Guide for Improving the Lightning Performance of Electric Power Overhead Distribution Lines, IEEE (21 January 2011).

[7] International Electrotechnical Commission, IEC 62305 (Ed. 2, 2010), Protection against Lightning: (1) General Principles, (2) Risk Management, (3) Physical Damage and Life Hazard, (4) Electrical and Electronic Systems within Structures.

[8] Rakov, V. A., and Uman, M. A. (2003), Lightning: Physics and Effects, Cambridge Univ. Press, New York.

[9] Rakov, V. A., et al. (2013), Lightning Parameters for Engineering Applications, CIGRE Report C4.407; summary published in Electra, 2013.

[10] Schulz, W., et al. (2013), draft project of IEC 62858, Ed. 1.