IEC 62858

Edition 2.0 2019-10
REDLINE VERSION

INTERNATIONAL STANDARD

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Lightning density based on lightning location systems – General principles

IEC 62858:2019-10 RLV(en)

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INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 29.020; 91.120.40

ISBN 978-2-8322-7497-2

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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LIGHTNING DENSITY BASED ON LIGHTNING LOCATION SYSTEMS – GENERAL PRINCIPLES

FOREWORD

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International Standard IEC 62858 has been prepared by IEC technical committee 81: Lightning protection.

This second edition cancels and replaces the first edition published in 2015. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

Two informative annexes are introduced dealing with the determination of lightning density for risk calculation (Annex A) and ground strike point calculation methods (Annex B).

The text of this International Standard is based on the following documents:

FDIS	Report on voting
81/627A/FDIS	81/634/RVD

Full information on the voting for the approval of this International Standard can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

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INTRODUCTION

International standards for lightning protection (e.g. IEC 62305-2) provide methods for the evaluation of the lightning risk on buildings and structures.

The lightning ground flash density N_G, defined as the mean number of ~~lightning~~ flashes ~~to ground~~ per square kilometre per year, and the ground strike point density N_{SG}, defined as the mean number of ground strike points per square kilometre per year ~~is~~ are the primary input parameters to perform such an evaluation (see Annex A).

In many areas of the world ~~N_G is derived from~~ data for risk evaluation are provided by lightning location systems (LLSs), but no common rule exists defining requirements either for their performance or for the elaboration of the measured data.

LIGHTNING DENSITY BASED ON LIGHTNING LOCATION SYSTEMS – GENERAL PRINCIPLES

1 Scope

This document introduces and discusses all necessary measures to make reliable and homogeneous the values of ground flash density, N_G and ground strike point density, N_{SG}, obtained from lightning location systems (LLSs) in various countries. Only parameters that are relevant to risk assessment are considered.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 62305-1, *Protection against lightning – Part 1: General principles*

IEC 62305-2, *Protection against lightning – Part 2: Risk management*

3 Terms, definitions, abbreviated terms and symbols

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 62305-1 and IEC 62305-2 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

~~**3.1.1**~~
~~**cloud-to-ground lightning**~~
~~CG~~
~~discharge that is comprised of one or more cloud-to-ground lightning strokes that propagate from cloud to ground or vice versa and lead to a net transfer of charge between cloud and ground~~

~~Note 1 to entry: This note applies to the French language only.~~

~~**3.1.2**~~
~~**cloud lightning**~~
~~IC~~
~~discharge occurring within or among thunderclouds (intracloud), or between thunderclouds (intercloud), or between cloud and air, without a ground termination~~

~~Note 1 to entry: This note applies to the French language only.~~

~~**3.1.3**~~
~~**first return stroke**~~
~~first stroke to ground of a cloud-to-ground lightning discharge~~

~~Note 1 to entry: The stepped leader and attachment process precede the first return stroke.~~

~~**3.1.4**~~
~~**subsequent stroke**~~
~~subsequent stroke to ground that follows a previous (return) stroke in the same flash~~

~~Note 1 to entry: A subsequent stroke is preceded by a dart leader and may or may not have the same ground strike-point as any previous (return) stroke in the same flash.~~

~~**3.1.5**~~
~~**multiplicity**~~
~~number of first and subsequent strokes in a cloud-to-ground lightning flash~~

3.1.1
ground flash density
N_G
mean number of cloud-to-ground flashes per unit area per unit time (flashes x km^{-2} x year^{-1})

3.1.2
ground strike-point density
N_{SG}
mean of the number of strike-points to ground ~~or to ground based objects~~ per unit area per unit time (strike-points x km^{-2} x year^{-1})

3.1.3
lightning sensor
device that measures electromagnetic signals produced by lightning discharges

3.1.4
lightning location system
LLS
network of lightning sensors that work together to detect and geolocate lightning events within the area of the system's coverage

Note 1 to entry: This note applies to the French language only.

3.1.5
confidence ellipse
ellipse centred on the estimated ground strike-point, describing the degree of confidence of the location estimation (e.g. 50 %, 90 %, 99 %) based on sensor measurement errors

Note 1 to entry: The confidence ellipse is described in terms of the lengths of the semi-major and semi-minor axes as well as the bearing of the semi-major axis.

3.1.6
uptime
duration of fully functional operation of a lightning location system sensor, expressed as a percentage of the total observation time

3.1.7
stroke detection efficiency
flash detection efficiency
percentage of strokes or flashes detected as a percentage of the total number of strokes or flashes occurring in reality

3.1.8
median location accuracy
~~median~~ value of the distances between real stroke locations and the stroke locations given by the lightning location system

3.2 Abbreviated terms and symbols

CG cloud-to-ground ~~lightning~~

DE ~~flash~~ detection efficiency

GSP ground strike point

IC ~~cloud lightning~~ intra-cloud and inter-cloud

LA location accuracy

LLS lightning location system

N_G ground flash density

N_{SG} ground strike-point density

4 General requirements

4.1 General

The performance characteristics of a lightning location system (LLS) determine the quality of the lightning data available for calculating N_G ~~[3, 15]~~ [1][1]. A value of N_G with an error of ±20 % or less is deemed to be ~~acceptable~~ adequate for lightning risk assessment. Data from any LLS that is able to detect CG lightning and accurately determine the point of strike 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 adequate accuracy.

- Flash detection efficiency (DE): The value of the annual average flash detection efficiency of an LLS for CG lightning shall be at least 80 % in the region over which N_G has to be computed. This DE is usually obtained within the interior of the network. The interior of the network is defined as the region within the boundary defined by the outermost adjacent sensors of the network.
- Location accuracy (LA): The value of the median location accuracy of an LLS for CG strokes shall be better than 500 m in ~~all regions in~~ the region over which N_G has to be computed. This LA is usually obtained within the interior of the network.
- Classification accuracy: In a network with a flash DE meeting the criteria set for N_G calculation, erroneously low or high values of N_G will be identified ~~if~~ when too many CG strokes are misclassified as cloud pulses (or vice versa~~, this may lead to erroneously low or high values of N_G~~). This is especially true for single-stroke CG flashes. A classification accuracy (CG flashes not misclassified as IC) of at least 85% is required.

  ~~It is not recommended to use N_G values having more than 2 decimals.~~

These performance characteristics of an LLS can be determined using a variety of methods including network self-referencing (using statistical analysis of parameters such as standard deviation of sensor timing error, semi-major axis length of the 50 % confidence ellipse, and the number of reporting sensors, which may be known from the LLS manufacturer or available from the LLS data) and comparison against ground-truth lightning data obtained using various techniques. These methods are discussed in Clause 5. A performance evaluation based on the methods described in Clause 5 and all the relevant basics of the network have to be provided on request.

The flash DE, LA, and classification accuracy of an LLS depend on a few fundamental characteristics of the network. LLS owners, operators, and data-providers should consider the following factors while designing and maintaining their networks to ensure that the lightning data are of adequate quality for N_G computation.

– Sensor baseline distance: The distance between adjacent sensors in an LLS ~~or~~ so called sensor baseline distance is influenced by the area of desired coverage and the sensitivity of individual sensors. Sensor baseline distance is one of the factors that determine the DE

[1] Numbers in square brackets refer to the Bibliography.

and LA of an LLS. The maximum sensor baseline distance of an LLS shall be such that the DE and LA of the network meet the criteria for N_G calculation described above.

– Sensor sensitivity: The sensitivity of sensors in an LLS primarily determines the ability of the network to detect lightning events of different peak currents. The sensitivity of sensors in an LLS shall be such that lightning events with peak currents in the range of 5 kA to 300 kA are detected and reported by the LLS. Sensor sensitivity is determined by various factors such as trigger threshold, electronic gain, sensor bandwidth, and background electromagnetic noise.
– Sensor uptime: The uptime of different sensors in a network determines the DE and LA of the network. The spatial and temporal variations of DE and LA are determined by the location of sensors that are up and contributing to the network. Hence it is important to guarantee that LLS sensors are up and running with no interruption.

4.2 Stroke-to-flash grouping

Return strokes detected by lightning location systems shall be grouped into flashes for N_G calculation. Multiple ground strike-points are included in the same flash. This grouping is done based on a spatio-temporal window.

A subsequent stroke is grouped with the first return stroke to form a flash if the following criteria are met:

a) the stroke occurs less than or equal to 1 s after the first return stroke;
b) the location of the stroke is less than or equal to 10 km from the first return stroke;
c) the time interval for successive strokes is less than or equal to 500 ms.

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

~~Multiple ground strike -points shall be included in the same flash using the above criteria.~~

~~Currently a multiplication factor of 2, relating~~ $\cancel{N_G}$ ~~to~~ $\cancel{N_{SG}}$ ~~shall be used [2].~~

Strokes can also be grouped into ground strike points to obtain N_{SG} based on different algorithms described in Annex B.

4.3 Minimum observation periods

A sufficiently long sampling period is required to ensure that short time scale variations in lightning parameters due to a variety of meteorological oscillations are accounted for. Additionally large scale climatological variations limit the validity of historic data. Some lightning detection networks have been recording lightning data for several decades and during this time there have been measurable changes to the ~~global meteorology~~ climate.

A set of lightning data for at least 10 full calendar years is required, with the newest data used not being older than five years. The data should be as continuous as possible, unless the data does not fulfil the performance requirements in some particular years which have then to be removed.

4.4 Observation area

The observation area is an area over which lightning data of quality as described above are available.

Different networks and sensor technologies will have different sensitivities with which they detect lightning. Network coverage falls off outside the boundaries of a network. In general, lightning data within half the average sensor baseline distance (distance between adjacent sensors in the network) from the boundary of the network should be of sufficient quality for N_G calculation ~~[11]~~.

4.5 Grid cell size

Ground flash density (N_G) values vary annually and regionally. Lightning data have to be evaluated as a raster map, i.e. a gridded array of cells constrained by a geographic boundary: the area of interest is divided into a regular grid (tessellation of the geographic area) and the N_G calculation function is applied to all the flashes occurring within the grid. The resulting value is then assumed to be the meaningful value within that area.

Grid size ~~shall~~ 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 from Formula (1), following Poisson distribution and the law of rare events, thus obtaining an uncertainty of less than 20 % at 90 % confidence level [~~8~~2].

$$N_G \times T_{obs} \times A_{cell} \geq 80 \quad (1)$$

where:

N_G is the ground flash density, in km^{-2} year^{-1};

T_{obs} is the observation period, in years;

A_{cell} is the area of each single cell, in km^2.

The data used in this analysis shall conform to the requirements of both 4.2 and 4.3. The minimum permissible cell dimension, irrespective of ground flash density and observation period, shall not be less than double the median location accuracy.

4.6 Edge effect correction

As defined in 4.5 the size of the smallest cell that can be considered should ~~be such that it contains~~ contain at least 80 flashes. In order to avoid edge effects for this cell the N_G value shall be obtained by integrating over a finer sub-grid of 1 km x 1 km resolution.

5 Validation of lightning location system performance characteristics

The performance characteristics of an LLS determine the quality of the lightning data available. These performance characteristics include:

– detection efficiency for IC and CG flashes and CG strokes;

– location accuracy;

– peak current estimation accuracy; and

– lightning classification accuracy.

As stated in Clause 4, for N_G and N_{SG}, the determination of ~~CG flash~~ DE, LA, and lightning classification accuracy is of primary importance. These performance characteristics can be evaluated using a variety of techniques which are summarized below.

a) Network self-reference: In this technique, statistical analysis of parameters ~~(e.g. [11])~~ such as standard deviation of sensor timing error, semi-major axis length of the 50 % confidence ellipse, and the number of reporting sensors, is used to infer the LA and DE of an LLS. Examples of such studies are found in [3], [4] and [~~7~~5]. This method requires data collected by the network after it has been properly calibrated. It can provide a good estimate of the network's performance in a cost-effective, practical manner.

b) Rocket-triggered lightning and tall object studies: This method uses data from rocket-triggered lightning experiments or lightning strikes to tall objects (e.g. instrumented towers) as ground-truth to evaluate the performance characteristics of an LLS within whose coverage area the triggered lightning facility or the tall object is located. The LA, DE, peak current estimation accuracy, and lightning classification accuracy of an LLS can be measured using this method. ~~Examples of studies using rocket-triggered lightning for~~

~~LLS performance evaluation include [6], [8], and [12], [13]. While these methods provide the best ground-truth data for performance characteristics validation for CG lightning (and are the only ways to directly validate peak current estimation accuracy of an LLS), they may be very expensive, may not be practical for all regions (as there are only a few triggered lightning facilities and instrumented towers across the world), and are a valid indicator of LLS performance only for the region where the rocket-triggered lightning facility or tall object is located (especially in cases where the performance of the LLS is expected to vary significantly from region to region).~~ Examples of studies using rocket-triggered lightning or lightning to tall structures for LLS performance evaluation include [6], [7], and [8]. These methods provide the best ground-truth data for performance characteristics validation for CG lightning. In addition, these methods are the only ways to directly validate peak current estimation accuracy of an LLS. However, they may be very expensive and may not be practical for all regions. There are only a few triggered lightning facilities and instrumented towers across the world. The results obtained from these methods are valid indicators of LLS performance only for the region where the rocket-triggered lightning facility or instrumented tower is located. Additionally, rocket-triggered lightning provides data for return strokes similar to only subsequent strokes in natural lightning. No data for first strokes in natural lightning can be obtained using this technique. This is also often the case for lightning strikes to tall objects depending upon the height of the object, local terrain, storm type, and other factors. Since first strokes in natural lightning are expected to have, on average, peak fields and currents that are a factor of two larger than those for subsequent strokes (e.g. [9]), CG flash and stroke DE estimated for an LLS using these methods may be somewhat of an underestimate.

c) Video camera studies: Lightning data obtained using video cameras can be used as ground-truth to evaluate the performance characteristics of an LLS within whose coverage area the lightning discharges occur. The LA, DE, and lightning classification accuracy of an LLS can generally be estimated using this method. Examples of studies using video cameras for LLS performance evaluation include [~~1~~8] and [~~14~~9]. In this method, data collection can be time consuming and challenging because the exact locations of lightning discharges to be captured on video cannot be predicted. Additional instrumentation such as antennas measuring the electric field from lightning discharges is often required for this technique.

d) Inter-comparison among networks: The performance of one LLS that is being tested can be compared against another LLS that may be used as reference, as long as the reference LLS is extremely well calibrated and its performance has been characterized independently. This method allows inferences to be made about the detection efficiency and location accuracy of the test LLS relative to the reference LLS. If the reference network provides VHF lightning mapping, inference about the test network's IC detection ~~efficiency~~ capability can be made, for example on plausibility of IC pulses or IC-CG discrimination. Examples of such studies include [10]. One limitation of this technique is that the test and reference networks have to overlap substantially and the results are only valid for the overlapping region. Further, if the performance of the reference network is unknown or if the reference network is not well calibrated, any inferences about the test network's performance are invalid.

While one or a combination of the above techniques can be used to evaluate the performance characteristics of an LLS, it is important to understand the strengths and weaknesses of the methods used, in order to obtain reliable estimates of LLS performance characteristics.

Annex A
(informative)

Determination of lightning density for risk calculation

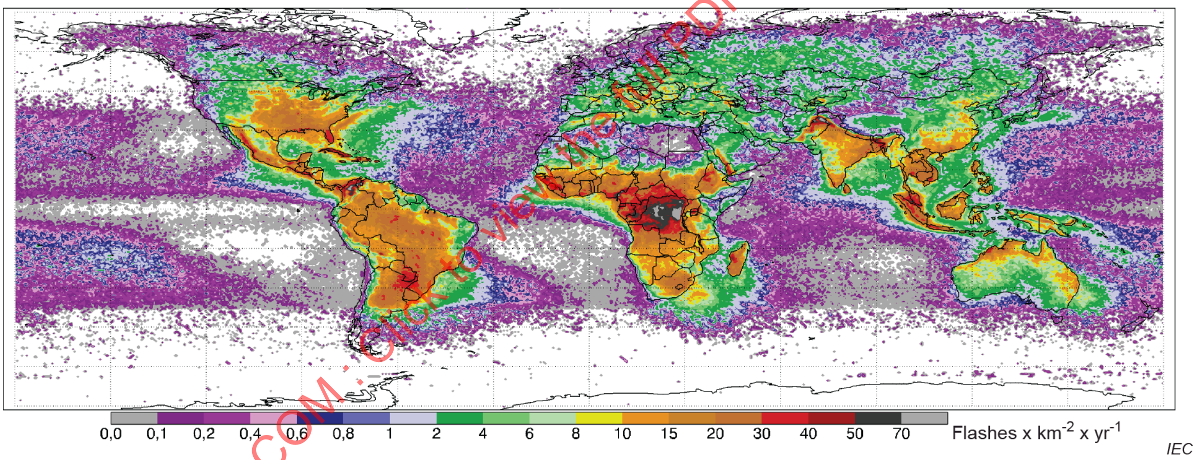
The lightning ground flash density N_G is the number of lightning flashes per square kilometre per year. In many areas of the world this value can be derived from data provided by local lightning location systems (LLSs) according to this document.

Historically N_G was determined from thunderstorm days or with the data of lightning flash counters. Because nowadays more accurate methods to determine N_G exist, the usage of thunderstorm days or data from lightning flash counters is no longer recommended.

In areas without ground-based lightning location systems, the recommended estimate of ground flash density [11] is:

$$N_G = 0,25 \times N_t \quad \text{(A.1)}$$

N_t being the total (CG + IC) density of optical recorded flashes per km^2 per year, obtained through the NASA website (https://lightning.nsstc.nasa.gov/data/data_lis-otd-climatology.html). Figure A.1 gives an overview of total densities N_t all over the world.



SOURCE: https://ghrc.nsstc.nasa.gov/pub/lis/climatology/LIS-OTD/HRFC/browse/HRFC_COM_FR_V2.3.2015.png reproduced with the permission from the authors.

Figure A.1 – High resolution full climatology (HRFC) N_t data

NOTE In most areas of the world, an indication of lightning activity can be obtained from observations of lightning optical transients. Satellite-based sensors respond to all types of lightning with relatively uniform coverage. 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 + IC).

Often flashes exhibit multiple ground strike-points. Modern LLSs may provide N_{SG} directly according to one of the methods described in Annex B. In case of availability of N_{SG} from LLSs, using this data is recommended if the overall N_{SG} results were independently validated.

Annex B
(informative)

Ground strike points (GSPs) explanations and calculation methods

About half of negative cloud-to-ground lightning flashes exhibit several ground strike points. This happens when a given dart leader partly follows the preceding return stroke channel, ending by creating its own path to the ground. Every ground strike point represents a threat and should be accounted for in the lightning risk calculation.

Based on high resolution lightning location data it becomes possible to identify almost all the different attachment points in a cloud-to-ground lightning flash.

There are different algorithms available to determine ground strike points for LLS data with advantages and disadvantages:

- Cummins [12] employed discriminant analysis to create a "vote count" based on several parameters, including location difference and other parameters that can help identify new ground strike points, for example rise time. This method has the potential to identify new ground strike points when the location uncertainty is larger than the separation distance. The "vote" approach weakens the location difference analysis when the locations are well-known. This method is highly dependent on the quality of the rise-time parameter but some LLS technologies may not provide the rise time and peak-to-zero time information at all.
- Pédeboy [13], [14], [15] implemented a reliable clustering algorithm based on the k-means method. This algorithm does not employ a complete statistical treatment of the error geometry embodied in the error ellipses (it is just scaled by the size of the confidence ellipse) and has no mechanism to distinguish between individual ground strike points when the location uncertainty is larger than the separation distance of the ground strike points.
- Campos [16], [17] does a rigorous statistical job of evaluating the location uncertainty by using the geometry of the error ellipse in the full latitude/longitude space, while embracing the strengths of the k-means approach developed by Pédeboy. This method has the same potential weakness as the approach from Pédeboy, in that it has no mechanism to "refine" the classification when the location uncertainty is larger than the separation distance.

After applying one of these algorithms to LLS data, the ground strike point density can be determined spatially according to the same rules as the ground flash density.

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IEC 62858

Edition 2.0 2019-10

INTERNATIONAL STANDARD

NORME INTERNATIONALE

colour inside

Lightning density based on lightning location systems – General principles

Densité de foudroiement basée sur des systèmes de localisation de la foudre (LLS) – Principes généraux

IEC 62858:2019-10(en-fr)

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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LIGHTNING DENSITY BASED ON LIGHTNING LOCATION SYSTEMS – GENERAL PRINCIPLES

FOREWORD

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International Standard IEC 62858 has been prepared by IEC technical committee 81: Lightning protection.

This second edition cancels and replaces the first edition published in 2015. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

Two informative annexes are introduced dealing with the determination of lightning density for risk calculation (Annex A) and ground strike point calculation methods (Annex B).

The text of this International Standard is based on the following documents:

FDIS	Report on voting
81/627A/FDIS	81/634/RVD

Full information on the voting for the approval of this International Standard can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

International standards for lightning protection (e.g. IEC 62305-2) provide methods for the evaluation of the lightning risk on buildings and structures.

The lightning ground flash density N_G, defined as the mean number of flashes per square kilometre per year, and the ground strike point density N_{SG}, defined as the mean number of ground strike points per square kilometre per year are the primary input parameters to perform such an evaluation (see Annex A).

In many areas of the world data for risk evaluation are provided by lightning location systems (LLSs), but no common rule exists defining requirements either for their performance or for the elaboration of the measured data.

LIGHTNING DENSITY BASED ON LIGHTNING LOCATION SYSTEMS – GENERAL PRINCIPLES

1 Scope

This document introduces and discusses all necessary measures to make reliable and homogeneous the values of ground flash density, N_G and ground strike point density, N_{SG}, obtained from lightning location systems (LLSs) in various countries. Only parameters that are relevant to risk assessment are considered.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 62305-1, *Protection against lightning – Part 1: General principles*

IEC 62305-2, *Protection against lightning – Part 2: Risk management*

3 Terms, definitions, abbreviated terms and symbols

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 62305-1 and IEC 62305-2 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1.1
ground flash density
N_G
mean number of cloud-to-ground flashes per unit area per unit time (flashes x km^{-2} x year^{-1})

3.1.2
ground strike-point density
N_{SG}
mean of the number of strike-points to ground per unit area per unit time (strike-points x km^{-2} x year^{-1})

3.1.3
lightning sensor
device that measures electromagnetic signals produced by lightning discharges

3.1.4
lightning location system
LLS
network of lightning sensors that work together to detect and geolocate lightning events within the area of the system's coverage

Note 1 to entry: This note applies to the French language only.

3.1.5
confidence ellipse
ellipse centred on the estimated ground strike-point, describing the degree of confidence of the location estimation (e.g. 50 %, 90 %, 99 %) based on sensor measurement errors

Note 1 to entry: The confidence ellipse is described in terms of the lengths of the semi-major and semi-minor axes as well as the bearing of the semi-major axis.

3.1.6
uptime
duration of fully functional operation of a lightning location system sensor, expressed as a percentage of the total observation time

3.1.7
stroke detection efficiency
flash detection efficiency
percentage of strokes or flashes detected as a percentage of the total number of strokes or flashes occurring in reality

3.1.8
median location accuracy
value of the distances between real stroke locations and the stroke locations given by the lightning location system

3.2 Abbreviated terms and symbols

CG cloud-to-ground

DE detection efficiency

GSP ground strike point

IC intra-cloud and inter-cloud

LA location accuracy

LLS lightning location system

N_G ground flash density

N_{SG} ground strike-point density

4 General requirements

4.1 General

The performance characteristics of a lightning location system (LLS) determine the quality of the lightning data available for calculating N_G [1][1]. A value of N_G with an error of ±20 % or less is deemed to be adequate for lightning risk assessment. Data from any LLS that is able to detect CG lightning and accurately determine the point of strike 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 adequate accuracy.

[1] Numbers in square brackets refer to the Bibliography.

- Flash detection efficiency (DE): The value of the annual average flash detection efficiency of an LLS for CG lightning shall be at least 80 % in the region over which N_G has to be computed. This DE is usually obtained within the interior of the network. The interior of the network is defined as the region within the boundary defined by the outermost adjacent sensors of the network.
- Location accuracy (LA): The value of the median location accuracy of an LLS for CG strokes shall be better than 500 m in the region over which N_G has to be computed. This LA is usually obtained within the interior of the network.
- Classification accuracy: In a network with a flash DE meeting the criteria set for N_G calculation, erroneously low or high values of N_G will be identified when too many CG strokes are misclassified as cloud pulses (or vice versa). This is especially true for single-stroke CG flashes. A classification accuracy (CG flashes not misclassified as IC) of at least 85% is required.

These performance characteristics of an LLS can be determined using a variety of methods including network self-referencing (using statistical analysis of parameters such as standard deviation of sensor timing error, semi-major axis length of the 50 % confidence ellipse, and the number of reporting sensors, which may be known from the LLS manufacturer or available from the LLS data) and comparison against ground-truth lightning data obtained using various techniques. These methods are discussed in Clause 5. A performance evaluation based on the methods described in Clause 5 and all the relevant basics of the network have to be provided on request.

The flash DE, LA, and classification accuracy of an LLS depend on a few fundamental characteristics of the network. LLS owners, operators, and data-providers should consider the following factors while designing and maintaining their networks to ensure that the lightning data are of adequate quality for N_G computation.

– Sensor baseline distance: The distance between adjacent sensors in an LLS so called sensor baseline distance is influenced by the area of desired coverage and the sensitivity of individual sensors. Sensor baseline distance is one of the factors that determine the DE and LA of an LLS. The maximum sensor baseline distance of an LLS shall be such that the DE and LA of the network meet the criteria for N_G calculation described above.

– Sensor sensitivity: The sensitivity of sensors in an LLS primarily determines the ability of the network to detect lightning events of different peak currents. The sensitivity of sensors in an LLS shall be such that lightning events with peak currents in the range of 5 kA to 300 kA are detected and reported by the LLS. Sensor sensitivity is determined by various factors such as trigger threshold, electronic gain, sensor bandwidth, and background electromagnetic noise.

– Sensor uptime: The uptime of different sensors in a network determines the DE and LA of the network. The spatial and temporal variations of DE and LA are determined by the location of sensors that are up and contributing to the network. Hence it is important to guarantee that LLS sensors are up and running with no interruption.

4.2 Stroke-to-flash grouping

Return strokes detected by lightning location systems shall be grouped into flashes for N_G calculation. Multiple ground strike-points are included in the same flash. This grouping is done based on a spatio-temporal window.

A subsequent stroke is grouped with the first return stroke to form a flash if the following criteria are met:

a) the stroke occurs less than or equal to 1 s after the first return stroke;

b) the location of the stroke is less than or equal to 10 km from the first return stroke;

c) the time interval for successive strokes is less than or equal to 500 ms.

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

Strokes can also be grouped into ground strike points to obtain N_{SG} based on different algorithms described in Annex B.

4.3 Minimum observation periods

A sufficiently long sampling period is required to ensure that short time scale variations in lightning parameters due to a variety of meteorological oscillations are accounted for. Additionally large scale climatological variations limit the validity of historic data. Some lightning detection networks have been recording lightning data for several decades and during this time there have been measurable changes to the climate.

A set of lightning data for at least 10 full calendar years is required, with the newest data used not being older than five years. The data should be as continuous as possible, unless the data does not fulfil the performance requirements in some particular years which have then to be removed.

4.4 Observation area

The observation area is an area over which lightning data of quality as described above are available.

Different networks and sensor technologies will have different sensitivities with which they detect lightning. Network coverage falls off outside the boundaries of a network. In general, lightning data within half the average sensor baseline distance (distance between adjacent sensors in the network) from the boundary of the network should be of sufficient quality for N_G calculation.

4.5 Grid cell size

Ground flash density (N_G) values vary annually and regionally. Lightning data have to be evaluated as a raster map, i.e. a gridded array of cells constrained by a geographic boundary: the area of interest is divided into a regular grid (tessellation of the geographic area) and the N_G calculation function is applied to all the flashes occurring within the grid. The resulting value is then assumed to be the meaningful value within that area.

Grid size 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 from Formula (1), following Poisson distribution and the law of rare events, thus obtaining an uncertainty of less than 20 % at 90 % confidence level [2].

$$N_G \times T_{obs} \times A_{cell} \geq 80 \tag{1}$$

where:

N_G is the ground flash density, in km^{-2} year^{-1};

T_{obs} is the observation period, in years;

A_{cell} is the area of each single cell, in km^2.

The data used in this analysis shall conform to the requirements of both 4.2 and 4.3. The minimum permissible cell dimension, irrespective of ground flash density and observation period, shall not be less than double the median location accuracy.

4.6 Edge effect correction

As defined in 4.5 the size of the smallest cell that can be considered should contain at least 80 flashes. In order to avoid edge effects for this cell the N_G value shall be obtained by integrating over a finer sub-grid of 1 km x 1 km resolution.

5 Validation of lightning location system performance characteristics

The performance characteristics of an LLS determine the quality of the lightning data available. These performance characteristics include:

- detection efficiency for IC and CG flashes and CG strokes;
- location accuracy;
- peak current estimation accuracy; and
- lightning classification accuracy.

As stated in Clause 4, for N_G and N_{SG}, the determination of DE, LA, and lightning classification accuracy is of primary importance. These performance characteristics can be evaluated using a variety of techniques which are summarized below.

a) Network self-reference: In this technique, statistical analysis of parameters such as standard deviation of sensor timing error, semi-major axis length of the 50 % confidence ellipse, and the number of reporting sensors, is used to infer the LA and DE of an LLS. Examples of such studies are found in [3], [4] and [5]. This method requires data collected by the network after it has been properly calibrated. It can provide a good estimate of the network's performance in a cost-effective, practical manner.

b) Rocket-triggered lightning and tall object studies: This method uses data from rocket-triggered lightning experiments or lightning strikes to tall objects (e.g. instrumented towers) as ground-truth to evaluate the performance characteristics of an LLS within whose coverage area the triggered lightning facility or the tall object is located. The LA, DE, peak current estimation accuracy, and lightning classification accuracy of an LLS can be measured using this method. Examples of studies using rocket-triggered lightning or lightning to tall structures for LLS performance evaluation include [6], [7], and [8]. These methods provide the best ground-truth data for performance characteristics validation for CG lightning. In addition, these methods are the only ways to directly validate peak current estimation accuracy of an LLS. However, they may be very expensive and may not be practical for all regions. There are only a few triggered lightning facilities and instrumented towers across the world. The results obtained from these methods are valid indicators of LLS performance only for the region where the rocket-triggered lightning facility or instrumented tower is located. Additionally, rocket-triggered lightning provides data for return strokes similar to only subsequent strokes in natural lightning. No data for first strokes in natural lightning can be obtained using this technique. This is also often the case for lightning strikes to tall objects depending upon the height of the object, local terrain, storm type, and other factors. Since first strokes in natural lightning are expected to have, on average, peak fields and currents that are a factor of two larger than those for subsequent strokes (e.g. [9]), CG flash and stroke DE estimated for an LLS using these methods may be somewhat of an underestimate.

c) Video camera studies: Lightning data obtained using video cameras can be used as ground-truth to evaluate the performance characteristics of an LLS within whose coverage area the lightning discharges occur. The LA, DE, and lightning classification accuracy of an LLS can generally be estimated using this method. Examples of studies using video cameras for LLS performance evaluation include [8] and [9]. In this method, data collection can be time consuming and challenging because the exact locations of lightning discharges to be captured on video cannot be predicted. Additional instrumentation such as antennas measuring the electric field from lightning discharges is often required for this technique.

d) Inter-comparison among networks: The performance of one LLS that is being tested can be compared against another LLS that may be used as reference, as long as the reference LLS is extremely well calibrated and its performance has been characterized independently. This method allows inferences to be made about the detection efficiency and location accuracy of the test LLS relative to the reference LLS. If the reference network provides VHF lightning mapping, inference about the test network's IC detection capability can be made, for example on plausibility of IC pulses or IC-CG discrimination. Examples of such studies include [10]. One limitation of this technique is that the test and reference networks have to overlap substantially and the results are only valid for the overlapping region. Further, if the performance of the reference network is unknown or if the reference network is not well calibrated, any inferences about the test network's performance are invalid.

While one or a combination of the above techniques can be used to evaluate the performance characteristics of an LLS, it is important to understand the strengths and weaknesses of the methods used, in order to obtain reliable estimates of LLS performance characteristics.

Annex A
(informative)

Determination of lightning density for risk calculation

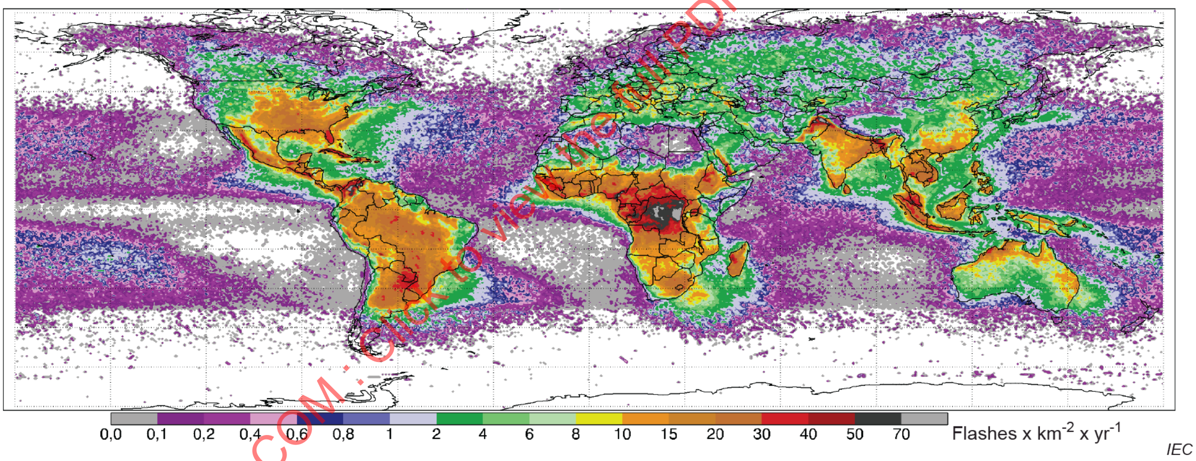
The lightning ground flash density N_G is the number of lightning flashes per square kilometre per year. In many areas of the world this value can be derived from data provided by local lightning location systems (LLSs) according to this document.

Historically N_G was determined from thunderstorm days or with the data of lightning flash counters. Because nowadays more accurate methods to determine N_G exist, the usage of thunderstorm days or data from lightning flash counters is no longer recommended.

In areas without ground-based lightning location systems, the recommended estimate of ground flash density [11] is:

$$N_G = 0,25 \times N_t \qquad \text{(A.1)}$$

N_t being the total (CG + IC) density of optical recorded flashes per km^2 per year, obtained through the NASA website (https://lightning.nsstc.nasa.gov/data/data_lis-otd-climatology.html). Figure A.1 gives an overview of total densities N_t all over the world.



SOURCE: https://ghrc.nsstc.nasa.gov/pub/lis/climatology/LIS-OTD/HRFC/browse/HRFC_COM_FR_V2.3.2015.png reproduced with the permission from the authors.

Figure A.1 – High resolution full climatology (HRFC) N_t data

NOTE In most areas of the world, an indication of lightning activity can be obtained from observations of lightning optical transients. Satellite-based sensors respond to all types of lightning with relatively uniform coverage. 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 + IC).

Often flashes exhibit multiple ground strike-points. Modern LLSs may provide N_{SG} directly according to one of the methods described in Annex B. In case of availability of N_{SG} from LLSs, using this data is recommended if the overall N_{SG} results were independently validated.

Annex B
(informative)

Ground strike points (GSPs) explanations and calculation methods

About half of negative cloud-to-ground lightning flashes exhibit several ground strike points. This happens when a given dart leader partly follows the preceding return stroke channel, ending by creating its own path to the ground. Every ground strike point represents a threat and should be accounted for in the lightning risk calculation.

Based on high resolution lightning location data it becomes possible to identify almost all the different attachment points in a cloud-to-ground lightning flash.

There are different algorithms available to determine ground strike points for LLS data with advantages and disadvantages:

- Cummins [12] employed discriminant analysis to create a “vote count” based on several parameters, including location difference and other parameters that can help identify new ground strike points, for example rise time. This method has the potential to identify new ground strike points when the location uncertainty is larger than the separation distance. The “vote” approach weakens the location difference analysis when the locations are well-known. This method is highly dependent on the quality of the rise-time parameter but some LLS technologies may not provide the rise time and peak-to-zero time information at all.
- Pédeboy [13], [14], [15] implemented a reliable clustering algorithm based on the k-means method. This algorithm does not employ a complete statistical treatment of the error geometry embodied in the error ellipses (it is just scaled by the size of the confidence ellipse) and has no mechanism to distinguish between individual ground strike points when the location uncertainty is larger than the separation distance of the ground strike points.
- Campos [16], [17] does a rigorous statistical job of evaluating the location uncertainty by using the geometry of the error ellipse in the full latitude/longitude space, while embracing the strengths of the k-means approach developed by Pédeboy. This method has the same potential weakness as the approach from Pédeboy, in that it has no mechanism to “refine” the classification when the location uncertainty is larger than the separation distance.

After applying one of these algorithms to LLS data, the ground strike point density can be determined spatially according to the same rules as the ground flash density.

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COMMISSION ÉLECTROTECHNIQUE INTERNATIONALE

DENSITÉ DE FOUDROIEMENT BASÉE SUR DES SYSTÈMES DE LOCALISATION DE LA FOUDRE (LLS) – PRINCIPES GÉNÉRAUX

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La Norme internationale IEC 62858 a été établie par le comité d'études 81 de l'IEC: Protection contre la foudre.

Cette deuxième édition annule et remplace la première édition parue en 2015. Cette édition constitue une révision technique.

Cette édition inclut les modifications techniques majeures suivantes par rapport à l'édition précédente:

Introduction de deux annexes informatives, traitant de la détermination de la densité de foudroiement pour le calcul du risque (Annexe A) et des méthodes de calcul concernant les points d'impact au sol (Annexe B).

Le texte de cette Norme internationale est issu des documents suivants:

FDIS	Rapport de vote
81/627A/FDIS	81/634/RVD

Le rapport de vote indiqué dans le tableau ci-dessus donne toute information sur le vote ayant abouti à l'approbation de cette Norme internationale.

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INTRODUCTION

Les Normes internationales pour la protection contre la foudre (par exemple l'IEC 62305-2) fournissent des méthodes pour l'évaluation des risques de foudre sur les immeubles et autres structures.

La densité de foudroiement au sol N_G, définie comme le nombre moyen d'éclairs par kilomètre carré et par an et la densité de points d'impact au sol de la foudre N_{SG}, définie comme le nombre moyen de points d'impact au sol par kilomètre carré et par an, sont les paramètres d'entrée principaux pour effectuer de telles évaluations (voir l'Annexe A).

Dans de nombreuses régions du monde, les données d'évaluation des risques sont fournies par des systèmes de localisation de la foudre (LLS), mais il n'existe aucune règle commune définissant les exigences de performances ou d'élaboration des données de mesure.

DENSITÉ DE FOUDROIEMENT BASÉE SUR DES SYSTÈMES DE LOCALISATION DE LA FOUDRE (LLS) – PRINCIPES GÉNÉRAUX

1 Domaine d'application

Le présent document décrit et étudie l'ensemble des mesures nécessaires pour rendre fiables et homogènes les valeurs de la densité de foudroiement au sol, N_G, et de la densité de points d'impact au sol, N_{SG}, obtenues par des systèmes de localisation de la foudre (LLS) dans différents pays. Seuls les paramètres essentiels à l'évaluation du risque sont pris en compte.

2 Références normatives

Les documents suivants sont cités dans le texte de sorte qu'ils constituent, pour tout ou partie de leur contenu, des exigences du présent document. Pour les références datées, seule l'édition citée s'applique. Pour les références non datées, la dernière édition du document de référence s'applique (y compris les éventuels amendements).

IEC 62305-1, *Protection contre la foudre – Partie 1: Principes généraux*

IEC 62305-2, *Protection contre la foudre – Partie 2: Evaluation des risques*

3 Termes, définitions, termes abrégés et symboles

3.1 Termes et définitions

Pour les besoins du présent document, les termes et définitions donnés dans l'IEC 62305-1 et l'IEC 62305-2 ainsi que les suivants s'appliquent.

L'ISO et l'IEC tiennent à jour des bases de données terminologiques destinées à être utilisées en normalisation, consultables aux adresses suivantes:

- IEC Electropedia: disponible à l'adresse http://www.electropedia.org/
- ISO Online browsing platform: disponible à l'adresse http://www.iso.org/obp

3.1.1
densité de foudroiement au sol
N_G
nombre moyen d'éclairs nuage-sol par unité de surface et par unité de temps (éclairs x km^{-2} x an^{-1})

3.1.2
densité des points d'impact au sol
N_{SG}
moyenne du nombre de points d'impact au sol par unité de surface et par unité de temps (points d'impact de foudre x km^{-2} x an^{-1})

3.1.3
capteur de foudre
dispositif qui mesure les signaux électromagnétiques produits par les décharges de foudre

3.1.4
système de localisation de la foudre
LLS
réseau de capteurs de foudre fonctionnant ensemble pour détecter et géolocaliser les phénomènes de foudre dans la zone couverte par le système

Note 1 à l'article: Le terme abrégé "LLS" est dérivé du terme anglais développé correspondant "lightning location system".

3.1.5
ellipse de confiance
ellipse centrée sur le point d'impact au sol estimé; décrit le degré de confiance de l'estimation de localisation (50 %, 90 %, 99 %, par exemple) en se fondant sur les erreurs de mesure du capteur

Note 1 à l'article: L'ellipse de confiance est décrite par rapport aux longueurs du demi-grand axe et du demi-petit axe, ainsi qu'à l'orientation du demi-grand axe.

3.1.6
temps de disponibilité
durée de fonctionnement entièrement fonctionnel d'un capteur intégré à un système de localisation de la foudre, exprimée en pourcentage du temps d'observation total

3.1.7
rendement de détection des décharges
rendement de détection des éclairs
pourcentage des décharges ou éclairs détectés par rapport au pourcentage du nombre total de décharges ou d'éclairs qui se produisent réellement

3.1.8
précision de localisation médiane
valeur des distances entre les localisations de décharges réelles et les localisations de décharges indiquées par le système de localisation de la foudre

3.2 Termes abrégés et symboles

CG (cloud-to-ground)	éclair nuage-sol
DE (detection efficiency)	rendement de détection
GSP (ground strike point)	point d'impact au sol
IC (intra-cloud/inter-cloud)	nuage-nuage
LA (location accuracy)	précision de localisation
LLS (lightning location system)	système de localisation de la foudre
N_{G} (ground flash density)	densité de foudroiement
N_{SG} (ground strike-point density)	densité des points d'impact de foudre au sol

4 Exigences générales

4.1 Généralités

Les caractéristiques de performance d'un système de localisation de la foudre (LLS) déterminent la qualité des données relatives à la foudre qui sont disponibles pour le calcul de N_G [1][1]. Une valeur de N_G avec une tolérance de ±20 % ou moins est jugée adéquate pour une évaluation du risque de foudre. Les données de tout LLS capable de détecter les éclairs nuage-sol (CG) et de déterminer avec précision le point d'impact des décharges nuage-sol peuvent être utilisées pour calculer la valeur de N_G. Les caractéristiques de performance suivantes du LLS sont exigées pour un calcul de N_G avec une précision adéquate.

- Rendement de détection des éclairs (DE): la valeur du rendement de détection des éclairs moyen annuel d'un LLS pour les éclairs CG doit être d'au moins 80 % dans la région pour laquelle N_G doit être calculée. Ce DE est généralement obtenu à l'intérieur du réseau. L'intérieur du réseau est défini comme la zone située dans les limites établies par les capteurs adjacents les plus éloignés du réseau.
- Précision de localisation (LA): la précision de localisation médiane d'un LLS de décharges CG doit être supérieure à 500 m dans la région pour laquelle N_G doit être calculée. Cette LA est généralement obtenue à l'intérieur du réseau.
- Précision de classification: dans un réseau avec un DE des éclairs qui respecte les critères définis pour le calcul de N_G, des valeurs erronées (trop faibles ou trop élevées) de N_G sont identifiées lorsqu'un trop grand nombre de décharges CG sont identifiées par erreur comme des impulsions nuage-nuage (ou inversement). Cela est en particulier vérifié pour les éclairs CG à décharge unique. Une précision de classification (absence d'erreurs d'identification d'éclairs nuage-sol en tant qu'éclairs nuage-nuage) d'au moins 85 % est exigée.

Ces caractéristiques de performance d'un LLS peuvent être déterminées par différentes méthodes, notamment l'autoréférence du réseau (qui utilise l'analyse statistique de paramètres tels que l'écart-type des erreurs temporelles du capteur, la longueur du demi-grand axe de l'ellipse de confiance de 50 % et le nombre de capteurs de rapport, qui peuvent être obtenus auprès du fabricant du LLS ou des données du LLS) et la comparaison avec les données de terrain relatives à la foudre obtenues par différentes techniques. Ces méthodes sont examinées à l'Article 5. Une évaluation des performances fondée sur les méthodes décrites à l'Article 5 et tous les paramètres de base pertinents du réseau doivent être fournis sur demande.

Le DE des éclairs, la LA et la précision de classification d'un LLS dépendent de quelques caractéristiques fondamentales du réseau. Il convient que les propriétaires, les opérateurs et les fournisseurs de données du LLS tiennent compte des facteurs suivants lors de la conception et de la maintenance des réseaux, afin de garantir que la qualité des données relatives à la foudre est suffisante pour le calcul de N_G.

– Distance de base entre capteurs: la distance entre deux capteurs adjacents dans un LLS, appelée distance de base entre capteurs, dépend de la zone de couverture souhaitée et de la sensibilité de chaque capteur. La distance de base entre capteurs est l'un des facteurs qui déterminent le DE et la LA d'un LLS. La distance maximale de base entre les capteurs d'un LLS doit être telle que le DE et la LA du réseau satisfassent aux critères de calcul de N_G décrits ci-dessus.

[1] Les chiffres entre crochets renvoient à la Bibliographie.