Introducing the Concept of the Volume Lightning Strike Density

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***Abstract*—This letter introduces the concept of the volume lightning strike density (vLSD) and provides the mathematical framework for transitioning from a 2D to a 3D electrogeometric analysis; this may offer new insights into established methodologies for lightning incidence estimation and risk assessment. The feasibility of the vLSD idea is based on the intensive research conducted on emerging technologies of 3D reconstruction of lightning discharges path. Thus, based on the vLSD concept, a new lightning activity parameter N_V (strikes/km^3/yr), that is, the average number of lightning strikes with at least one leader branch per cubic kilometer per year in an area, can be quantified in light of the widespread installation of modern lightning discharge recording systems. This work may open new horizons on lightning activity characterization offering an alternative or complementary approach to the traditional concept of the ground flash density, N_G (flashes/km^2/yr); the proposed vLSD concept could also be applied in evaluating the lightning interception efficiency of traditional as well as advanced lightning protection systems especially at critical sites, where enhanced lightning protection is of importance.**

***Index Terms*—3D reconstruction, ground flash density, lightning incidence, lightning location systems (LLSs).**

I. Introduction

LIGHTNING activity characteristics significantly affect lightning incidence estimation to an object as well as the lightning performance of power systems [1]; thus, extensive research is still conducted so as to provide with up-to-date and reliable data on lightning parameters [2]. The latter mainly comprise, but are not limited to, information regarding the: (i) ground flash density, (ii) lightning peak current distribution, and (iii) ratio of negative to positive lightning flashes in a region as well as their seasonal and geographical variation [3], [4].

Lightning activity data are commonly obtained with the aid of lightning location systems (LLSs) installed in different parts of the world; these may comprise either well-established continental-scale or local-scale LLSs [2]. The development of LLSs or improvement of the performance of existing ones is a topic that attracts wide attention from academia and industry also considering the need for increased coverage around the world. LLS performance characteristics, i.e., flash detection efficiency, location accuracy, and classification accuracy are evaluated with the aid of ground-truth lightning data obtained from: (i) rocket-triggered lightning experiments, (ii) lightning strike measurements to tall-instrumented objects, and (iii) field observations employing high-speed video recording systems [2].

As for the ground flash density, N_G (flashes/km^2/yr), it is a parameter defined as the average number of flashes per square kilometer per year in an area. N_G is widely employed in lightning incidence estimation and lightning risk assessment studies; thus, accurate determination of the ground flash density per region around the world and its correlation with seasonal and topographical characteristics is of importance [1].

In this work, the volume lightning strike density (vLSD) concept is introduced, based on which a new lightning activity parameter is defined, N_V (strikes/km^3/yr), that is the average number of lightning strikes with at least one leader branch per cubic kilometer per year in a region; the fundamentals of this new parameter are based on 3D reconstruction of lightning discharges path and could be used as an alternative or complementary approach to the ground flash density, N_G (flashes/km^2/yr). vLSD considers the lightning activity in a region above ground surface taking advantage of the rapid advancements in the accuracy and efficiency of LLSs, high-speed video recording systems, and very high frequency (VHF) broadband digital interferometers.

The mathematical framework for lightning incidence estimation and lightning performance assessment to practical engineering applications based on the proposed concept is provided proposing a transition from a 2D to a 3D electrogeometric analysis approach. This work: (i) provides insights on establishing new techniques regarding lightning activity characterization that may form the basis for the use of an alternative or complementary concept and (ii) aims to introduce the vLSD concept to the scientific community so as to be considered on the research and development of emerging recording systems. The proposed vLSD concept, subject to validation against field observations and data and overcoming existing challenges that may prevent its universal application for the time being, could be integrated into international standards and guidelines on lightning protection systems in the forthcoming years involving traditional as well as advanced lightning interception technologies. Its use could be beneficial especially for critical sites, where enhanced lightning protection is needed and the additional expenses for complementary data collection based on advanced recording systems could be justified.

II. Proposed Concept vs Conventional Approach

A. Ground Flash Density

The ground flash density, N_G (flashes/km^2/yr), is used to reflect the lightning activity at a region. N_G can be obtained [2]:

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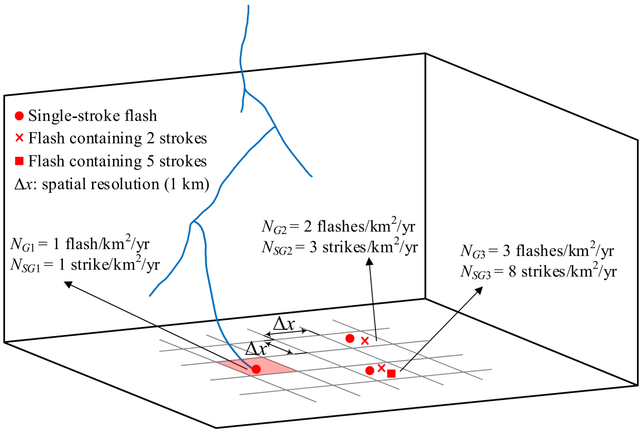

Fig. 1. Schematic representation of the ground flash density, N_G, concept; Δx is the spatial resolution. Red symbols denote lightning flashes termination points within one year comprising either single-stroke or multi-stroke flashes.

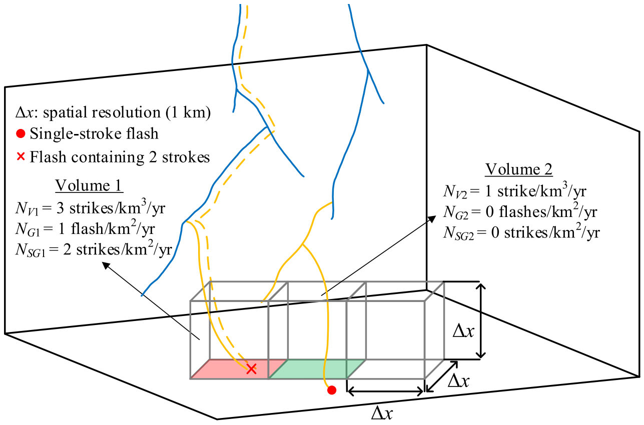

Fig. 2. Conceptual visualization of the volume lightning strike density; Δx is the spatial resolution. The average number of lightning strikes with at least one downward leader branch located in a cube of size Δx (denoted with orange color) are counted within one year. With solid lines the stepped leaders of first strokes and with dashed lines the dart leaders of subsequent strokes.

(i) from the keraunic level, based on empirically given correlations between thunderstorm days or hours and N_G, (ii) with the aid of lightning flash counters, and (iii) in recent times with the use of LLSs comprising either satellite-based or the more reliable ground-based LLSs. The latter employ the so-called time-of-arrival and/or direction-finding techniques to detect lightning and estimate its peak value and termination point.

In addition, the concept of the ground strike point density, N_{SG} (strikes/km^2/yr), has been introduced to consider the multiple strokes per flash and the possible different termination points at ground level between first and subsequent strokes [5]. This can be achieved due to the improved efficiency and performance of LLSs able to distinguish between different individual ground strike points with high accuracy.

Fig. 1 depicts a schematic representation of the conventional concepts of ground flash density and ground strike point density. The number of lightning flashes per year terminating at ground within a square defined by the selected spatial resolution are counted (red symbols in Fig. 1). The spatial resolution, Δx, used for grid discretization takes typical values between 1–10 km; in general, a minimum cell dimension is selected that is larger than double the median value of the location accuracy of the employed LLS [2]. Hence, an average N_G estimation for the region under study can be concluded on an annual basis. For the illustrative example of Fig. 1, indicative values of N_G (flashes/km^2/yr) are shown for each rectangle assuming that Fig. 1 refers to the recorded lightning activity of a single year and $\Delta x = 1$ km. It is noted that N_{SG} may take higher values as every flash typically contains more than one stroke; flash multiplicity as also N_G may vary significantly both seasonally and geographically.

B. Volume Lightning Strike Density (vLSD)

Based on the concept of the vLSD, the lightning activity parameter N_V (strikes/km^3/yr) is introduced that is defined as the average number of lightning strikes with at least one downward leader branch per cubic kilometer per year in a region.

Fig. 2 depicts a conceptual visualization of the vLSD. The number of lightning strikes with at least one downward leader branch located in a cube of size equal to the spatial resolution Δx are counted. Indicative average values of N_V are presented in Fig. 2; a value of $\Delta x = 1$ km is adopted to allow for a direct comparison of vLSD to the corresponding values of N_G and N_{SG} so as to stress the differences between the proposed and conventional concepts. It is important to note that although the ground flash density of the red area in Fig. 2 is $N_G = 1$ flash/km^2/year, N_V is equal to 3 strikes/km^3/yr (volume 1 in Fig. 2). Thus, vLSD can consider the intensity of lightning activity in a volume above earth surface, irrespectively of the lightning strike termination point, something that is inherently neglected by the traditional concept of N_G. vLSD takes into account the random growth and extensive branching of lightning leaders; the latter is expected to be higher for negative lightning polarity. It is noteworthy that it can also account for flash multiplicity as it considers the total number of stepped and dart leaders of first and subsequent strokes (volume 1 in Fig. 2).

C. Feasibility and Challenges of the Proposed Concept

N_V (strikes/km^3/yr) estimation based on the vLSD concept requires the accurate determination of downward leaders' location; the feasibility of the latter is supported by recent studies on leader branches and their trajectories [6]. This can be achieved by 3D reconstruction of the downward leader path employing high-speed video recording systems. Multiple high-speed video cameras strategically located could be used to perform 3D reconstruction of the leader path; work is in progress toward this direction [7]. Alternatively, three-dimensional imaging using VHF broadband digital interferometers [8] could be employed to achieve the intended leader path reconstruction. Hence, the number of lightning strikes with at least one downward leader branch passing through a specific observation volume, irrespectively of the lightning strike termination point (such as in the case of the green area of volume 2, Fig. 2), could be counted and

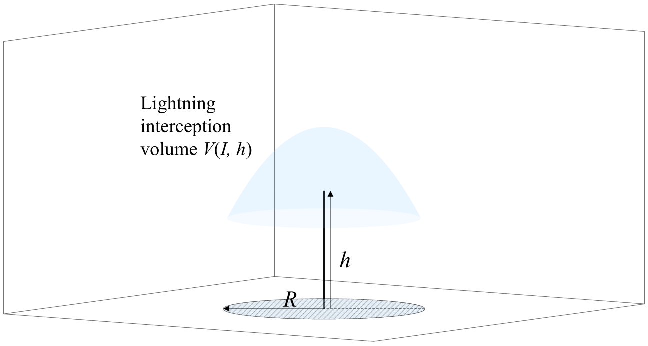

Fig. 3. Lightning attachment to a free-standing mast; *V* is the lightning interception volume. Blue solid and hatched zones denote the lightning interception volume and lightning interception area, respectively.

used for N_V estimation; the adopted Δx resolution is expected to be between 0.1 and 1 km. N_V maps could be developed based on sufficient observation years and validation covering different parts of the world in an analogous way to N_G.

It is noted that there exist several challenges and open topics regarding the vLSD concept associated with: (i) the required time for gathering reliable data on lightning leader branching to create a complete database at different heights, (ii) the effect of the selected spatial resolution Δx (size of volume cell) on the observation/interception volume since averaging the computed N_V values over a specified area may result in misestimation of lightning incidence to a structure; sensitivity analysis of the spatial resolution Δx on the estimated lightning incidence is of great importance, and (iii) capturing lightning channels of different brightness intensities as well as determining a meaningful camera sensitivity threshold.

III. APPLICATION OF VLSD TO LIGHTNING-RELATED ENGINEERING PROBLEMS

Based on the ground flash density, N_G, the annual number of lightning flashes to a free-standing mast is given as [9]:

$$N = N_G \pi \cdot \int_0^\infty R^2(I,\ h)\, f(I) dI \tag{1}$$

where *R* is the mast interception radius function of the lightning peak current *I* and mast height *h* (Fig. 3) and *f(I)* is the probability density function of the lightning stroke peak current distribution. Thus, lightning incidence estimation converts basically into a 2D computation procedure by considering the projection of the lightning interception radius to ground surface (blue hatched zone in Fig. 3), where N_G is defined (Fig. 1).

Nevertheless, accurate estimation of lightning incidence to a mast calls for implementation of a 3D approach, as lightning interception points form an interception volume around the mast as depicted in Fig. 3. Thus, based on the concept of the vLSD, lightning incidence to a mast can be estimated as:

$$N = N_V \cdot \int_0^\infty V(I,\ h)\, f(I) dI \tag{2}$$

where *V*(*I*, *h*) is the lightning interception volume (Fig. 3); for example, *V*(*I*, *h*) can be computed following an analytical approach [10] or through advanced simulations [11].

It is noteworthy that knowledge of the number and position of lightning leaders in a volume above ground surface, by means of the vLSD concept, is important for lightning incidence estimation and consequently lightning risk assessment studies. This is due to the fact that the N_V parameter considers the lightning activity in a specific volume above ground surface, via the lightning leaders passing through this volume, that may affect lightning incidence to the object; this is of great importance especially for tall structures such as wind turbines. On the contrary, ground flash density only considers flashes at the ground level in the proximity of the air-terminal; thus, N_G may lead to an underestimation of the attractive effect of the air-terminal, as also depicted in Fig. 2.

Following a similar approach for the case of a practical engineering application, the shielding failure flashover and backflashover rate of an overhead transmission line can be formulated based on the concept of the vLSD as:

$$SFFOR = N_V \cdot \int_{I_C}^{I_{MSF}} V_{line} \cdot p_{SF} \cdot f(I) dI \tag{3}$$

$$BFR = N_V \cdot \int_0^\infty \int_{I_{BF}}^\infty V_{line} \cdot (1 - p_{SF}) \cdot f(I/t_f) \cdot f(t_f) dI dt_f \tag{4}$$

where N_V is the volume lightning strike density, *I* and t_f are the peak and time-to-crest values of the lightning stroke current, $f(I/t_f)$ and $f(t_f)$ are the conditional probability density function of the stroke current given the time-to-crest and the probability function of the time-to-crest, respectively [12], V_{line} is the total lightning interception volume of the power line, and p_{SF} is the shielding failure probability of the line, that is, the probability that lightning strikes entering V_{line} terminate to phase conductors. As for the critical currents I_C and I_{BF}, these are the minimum lightning peak currents causing shielding failure flashover and backflashover of line insulation [12], and I_{MSF} represents the maximum shielding failure current [12], which could be alternatively considered as infinite in (3) following a stochastic approach [11]. The main influencing parameters of V_{line} and p_{SF} are the power line geometry (phase conductors and shield wire(s) height, shielding angle, conductors' geometry and sag) and lightning peak current and polarity. I_C and I_{BF} depend mainly on t_f, basic insulation level of the line, power line geometry, and operating voltage; I_{BF} is also affected by the dynamic tower ground resistance. I_{MSF} depends on the power line geometry.

Eqs. (2)–(4) form the basis for the use of the vLSD: (i) as an alternative or complementary concept of lightning activity characterization to that of the well-established ground flash density and (ii) as a means of validation of lightning interception volumes defined by lightning attachment models against field observations. The vLSD concept could be also implemented in evaluating the lightning interception efficiency of traditional as well as emerging lightning protection technologies that are expected to be commercialized in near future, such as laser-based air-terminals [13].

IV. CONCLUSION

The volume lightning strike density concept has been introduced as an alternative or complementary approach to that of the ground flash density aiming at more comprehensive lightning risk assessment studies. The idea of this new lightning activity parameter is based on the possible quantification of lightning discharges' density in space above the ground surface. This could be achieved through the aid of emerging technologies on the 3D reconstruction of lightning discharges path taking advantage of the ongoing research on this topic employing high-speed video recording systems and very high-frequency broadband digital interferometers.

The mathematical background for lightning incidence estimation to a mast and lightning performance assessment of overhead lines has been established proposing a transition from a 2D to a 3D electrogeometric analysis approach and stressing the applicability of the volume lightning strike density concept to practical engineering problems.

This work aims to provide new insights on establishing novel techniques regarding lightning activity characterization, which form the basis for the use of an alternative method to evaluate the lightning interception efficiency of lightning protection systems that incorporate traditional as well as emerging lightning interception technologies; application of the proposed concept could be particularly beneficial for critical sites, where enhanced lightning protection is needed.

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