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A New Method for the Estimation of the Number of Upward Flashes from Tall Structures

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***Abstract*—A new method to estimate the number of upward flashes from tall structures is presented. The method is based on the analysis of the data provided by lightning location systems (LLS) and thus could be applied for any tall structure located in the region covered by a LLS. About 80 tall objects in Europe with heights ranging from 100 m to 300 m were selected for the analysis. LLS data for a period of 10 years on flashes within circles of 8 km around each object were exported from the EUCLID network database and analyzed. The number of upward flashes for each considered structure was estimated and the obtained results were compared with those calculated using the empirical formula of Eriksson. For towers located on hilly terrain, the physical height of the structure was replaced by its effective height determined according to the IEC recommendation. The obtained results follow the trend predicted by Eriksson's formula. However, significant dispersion is observed. This dispersion might be attributed essentially to meteorological and geological factors associated with different objects.**

Keywords-Tall structure, upward flashes, lightning location systems

I. Introduction

The design of a lightning protection system should be based on the risk of lightning striking the structure in question. This risk is a product of the annual number of dangerous events to the structure, the probability of damage to the structure and the consequent loss [1]. The evaluation of the number of lightning strikes depends on the height of the object, the local topography and the local level of lightning activity.

Free-standing structures with heights over 100 m experience both upward and downward flashes [2]. The number of upward flashes for a structure could be estimated using several methods, for example [3] by

- recording lightning current passing through the structure and analyzing its waveform,
- analyzing photographic or video records of the flashes to the object.

Both methods require the installation of complex and expensive equipment on the object and/or in its vicinity and thus they cannot be used widely.

Eriksson [4] analyzed experimental observations made at some tall structures and proposed the following empirical formula for evaluating the total number of flashes N_{all} to a tall structure:

$$N_{all} = N_g \cdot 24 \cdot h^{2.05} \cdot 10^{-6}, \qquad (1)$$

where h is the structure height in meters and N_g is the ground flash density in km$^{-2}\cdot$year^{-1} of the region where the object is situated.

The proportion of upward flashes was also given in [4]:

$$pu = 52.8 \cdot \ln(h) - 230. \qquad (2)$$

Therefore, the number of upward flashes can be estimated as follows:

$$N_{up} = N_{all} \cdot \frac{pu}{100}. \qquad (3)$$

Figure 1 illustrates the variation of the total number of flashes N_{all} and the number of upward flashes N_{up} as a function of the structure height, based on the expressions (1) – (3).

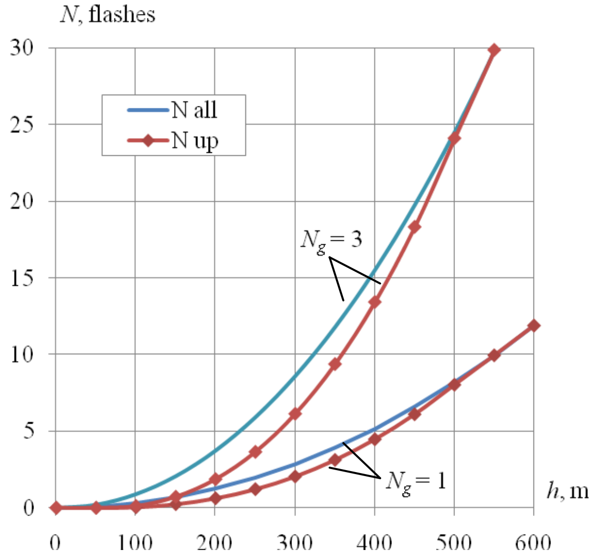

Figure 1. Variation of the total number of flashes and the upward flashes as a function of the structure height h and considering two values of ground flash density N_g, based on equations (1)-(3).

It can be seen from Figure 1 that the difference between N_{all} and N_{up}, which is the number of downward flashes, becomes insignificant for tall structures, for which upward flashes are predominant and therefore their estimation is of crucial importance for lightning risk analysis.

It is interesting to note that the first factor N_g on the right hand side in (1) is related to both downward and upward flashes. Downward flashes attracted by the object are proportional to the lightning flash density through

$$N_{down} = N_g \cdot \pi \cdot R_a^2 , \quad (4)$$

where R_a is the attractive radius.

Upward flashes initiated from the Gaisberg Tower (Austria) were found to be almost independent of lightning activity in the region nearby [5]. There could be different reasons for this phenomenon such as the difference in meteorological conditions in the vicinity of the Gaisberg Tower as compared to the surrounding area, namely the height of the cloud base. On the other hand, upward lightning observations on towers in Rapid City, South Dakota were correlated with nearby flash activity prior to upward leader initiation and the results were presented in [6].

In this paper, we present a new method to estimate the number of upward flashes from tall structures. Since the proposed method is based on the analysis of the data provided by lightning location systems (LLS), it can be applied to any tall structure located in a region covered by a LLS.

The paper is organized as follows. Section II describes the proposed method. Section III presents the application of the method to 77 tall objects in Europe (communication, TV, radio towers; power plant and factory chimneys) which were selected for the analysis. The structures' heights range from 100 m to 300 m. Section IV presents general conclusions.

II. Description of the Method

We will illustrate the proposed method through its application to a 100 m tall Gaisberg tower (47.804 N, 13.110 E) located on the mountain of 1280 m height. Figure 2 shows lightning flashes recorded by the EUCLID network during ten years in the region around the tower. In the figure, the tower is located in the center of the circle. Each dot in the figure represents the geographical position of a lightning flash, as located by the LLS. The lightning flash density close to the object and at different distances from it are compared by dividing the area of the study into 8 concentric rings, centered on the object.

Since the EUCLID network used in this study has a median location error of about 400 m [7], we have chosen the width of 8 rings to be 1 km so that practically all the flashes associated with the tower can be considered to be located within the first central circle.

The flash density in each ring can be evaluated as

$$D_i = \frac{N_i}{S_i \cdot T_{obs}} , \quad (5)$$

where

- N_i is the total number of flashes detected within each ring,
- S_i is the surface of the ring,
- T_{obs} is the observation period.

The obtained distribution $D_i = f(i)$ is presented in Figure 3. It can be seen that the values D_i for $i > 1$ remain essentially unchanged and correspond to the ground flash density in the vicinity of the tall object, usually expressed as N_g. In the first circle, on the other hand, the value D_1 is significantly higher than N_g.

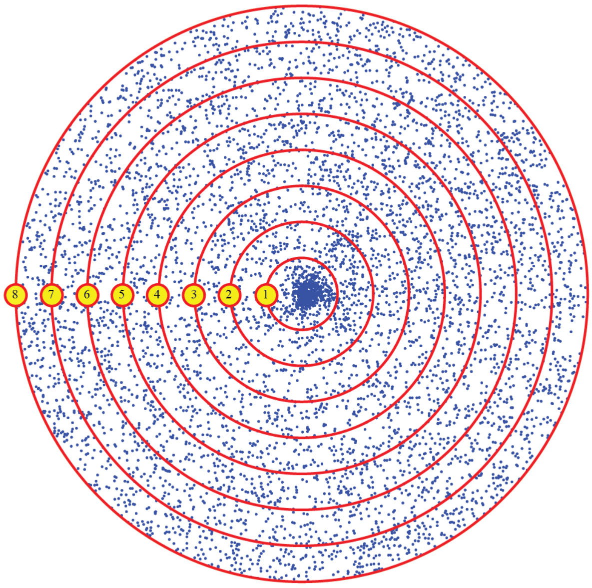

Figure 2. Lightning flashes detected during ten years within the circle of 8 km around a tower situated in the center.

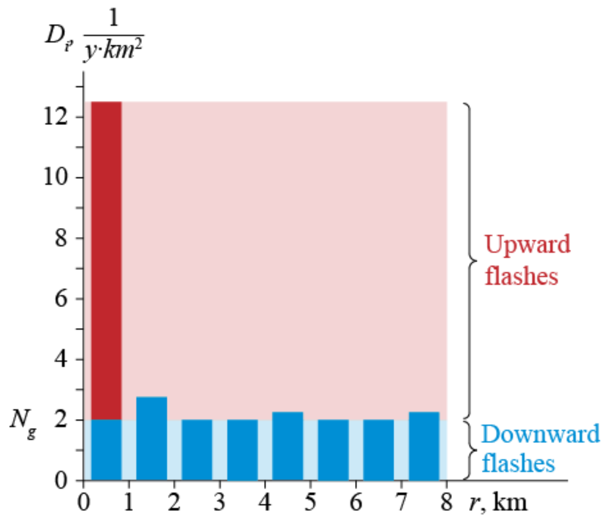

Figure 3. The lightning flash density within each ring, the tower is situated in the first one.

The key assumption of our method is that the number of downward lightning flashes in the region of a tall structure is unaffected or only marginally affected by the presence of the object and does not change significantly within the circular observation area. We assume therefore that the increment of

D_i in the inner circle is mainly due to the upward lightning discharges which were initated from the tower and thus could be observed only in that central circle. At the same time, some downward flashes within this circle are attracted to the tower (depending on their charge and distance from the tower) while some are not. All of these downward flashes, however, are assumed to be detected by the LLS within the innermost circle and, therefore, the presence of the tower does not increase the density of downward flashes.

These assumptions allow us to categorize the flashes detected within the first circle and estimate the number of upward flashes initated from the tall tower using

$$N_{up} = \left(D_1 - N_g\right) \cdot S_1 . \qquad (6)$$

III. Application

We have selected 77 tall objects in Europe (TV, radio, communication towers and power plant chimneys) with heights ranging from 100 m to 300 m. Their placement is shown in Figure 4. Structures on totally flat terrain are very rare. Therefore, we have also considered objects situated on hills or mountains where the object is located on the most prominent peak and not on a slope or in a valley.

In order to compare selected objects, we have used the simplified concept of the effective height illustrated in Figure 5. As suggested by IEC [8], the difference between the summit and the average surrounding ground level (shown as the lower horizontal dotted line in Figure 5) was assumed to be the height of the hill and was added to the physical height of the structure. We have selected only comparatively small mountains and hills with heights varying from 10 m to 450 m. Calculated values of effective heights are in the range between 120 m and 560 m.

Figure 4. Location of the tall structures selected for the analysis.

Data on stroke locations within the circles of 8 km around each object for a period of 10 years have been exported from the EUCLID network database, which is characterized by a median location error of 400 m [7].

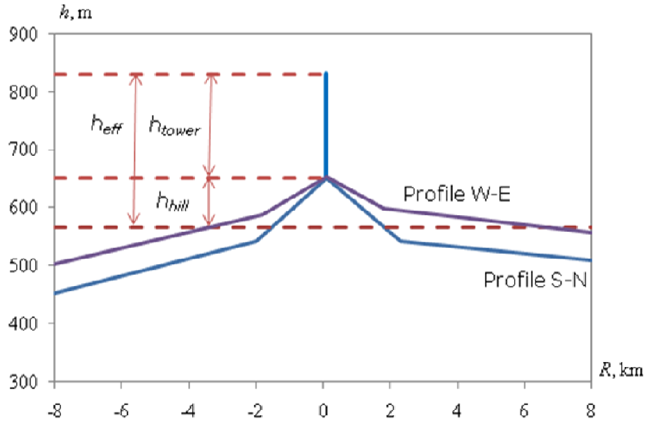

Figure 5. Illustration of the estimation of the effective height.

Note that only the upward flashes that contain return strokes or initial continuing current pulses are detectable by a LLS. Flashes without any fast pulses constitute almost half of the overall number of upward flashes that occured at the Gaisberg Tower [9] and couldn't be detected by LLS. We can therefore assume that the obtained values of upward flashes could be underestimated by about 40-50%.

The procedure described in Section II was then used to estimate the number of upward flashes initiated from the selected tall structures. The comparison between the obtained results and those predicted by Equation (3) is shown in Figure 6. Tall structures were divided according to the ground flash density N_g around them into three groups: N_{g1} = 0.5 – 1.5 flashes·km^{-2}·y^{-1}, N_{g2} = 1.5 – 2.5 flashes·km^{-2}·y^{-1}, N_{g3} = 2.5 – 3.5 flashes·km^{-2}·y^{-1}. In Figure 6 the values obtained with the new proposed method are shown. As discussed previously, they could be underestimated by the limited detection of upward flashes without any fast rising pulses, but more data on the proportion of undetectable flashes are needed to estimate the error correctly.

The results confirm the trend of Eriksson's expression (3), but at the same time significant dispersion of the data is present. The observed differences can be attributed essentially to the meteorological and geological factors associated with different objects. Part of the observed differences could also be due to the limitations of the proposed approach. As discussed earlier, the values of N_{up} determined by our method could be underestimated due to the limitations of LLS.

By comparing Figures 6a and 6c it can be seen that the number of upward flashes is lower in regions with less lightning activity N_g, but obviously more data are needed to confirm this hypothesis. Indeed, in Figure 6b, a large scatter of the values is observed within the biggest group of tall structures.

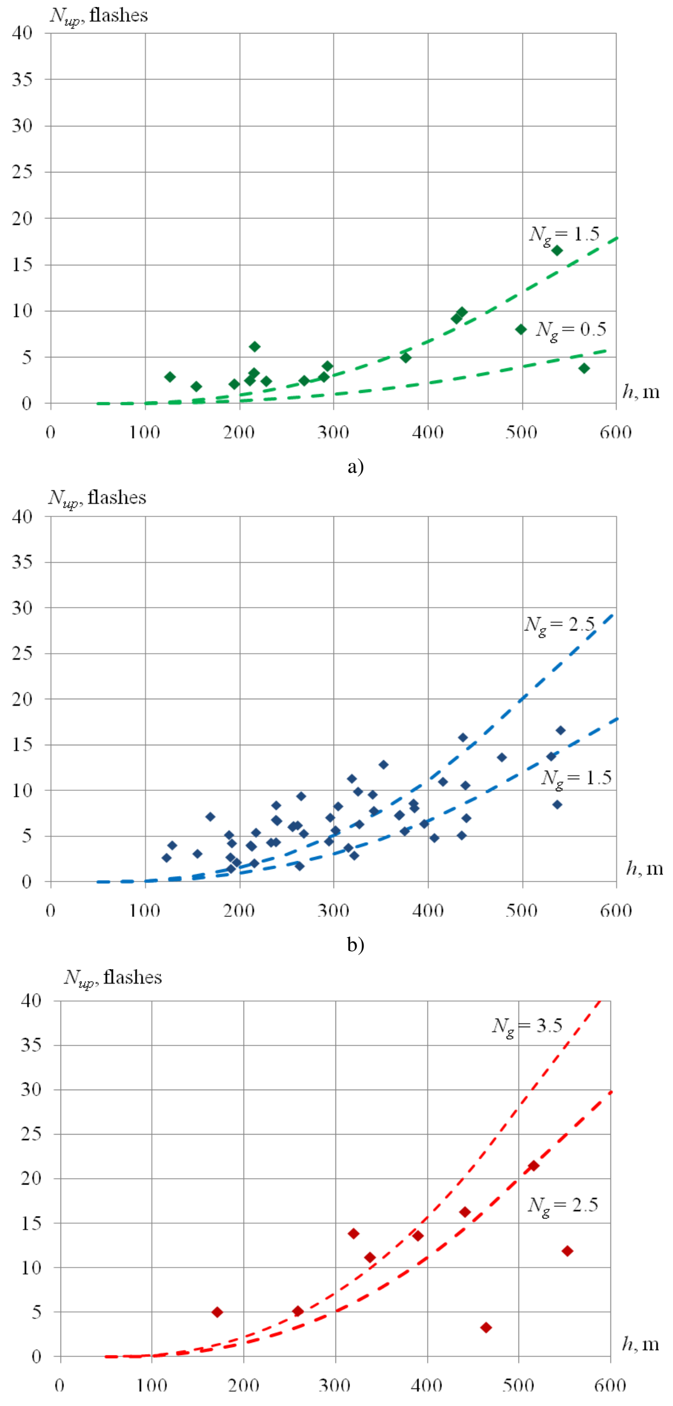

Figure 6. Number of upward flashes from the structures of different height situated in the regions with a) $N_g = 0.5\text{-}1.5$, b) $N_g = 1.5\text{-}2.5$, c) $N_g = 2.5\text{-}3.5$ flashes·km^{-2}·y^{-1}. In each figure, we have also presented the results obtained using Eriksson's formula for the corresponding values of N_g.

IV. Conclusions

In this paper, we presented a new method to estimate the number of upward flashes from tall structures. The proposed method is based on the analysis of the data provided by lightning location systems (LLS) and thus could be applied for any tall structures located in the region covered by a LLS.

For the analysis we have selected 77 tall objects in Europe (TV, radio, communication towers and power plant chimneys) with heights ranging from 100 m to 300 m were selected. Data on flashes within circles of 8 km around each object for a period of 10 years were exported from the EUCLID network database and the number of upward flashes from each considered structure was estimated.

The obtained results were compared with the results obtained using the empirical formula of Eriksson. For towers located on hilly terrain, the physical height of the structure was replaced by its effective height determined according to the IEC recommendation.

The obtained results confirm the trend predicted by Eriksson's formula, even though significant dispersion was observed. This dispersion might be essentially attributed to meteorological and geological factors associated with different objects.

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