On Lightning Incidence to Tall Structures

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***Abstract*—We compare in this paper direct measurements obtained at Tower 1 on Mount San Salvatore (Switzerland) and the Gaisberg Tower (Austria). They are situated in similar topographical environment but in different lightning activity zones. Direct measurements of lightning currents on these two towers have revealed a major difference in terms of the number of downward flashes. While Berger and co-workers obtained a significant number of downward flashes, more recent observations on Gaisberg and Peissenberg Towers were essentially composed of upward flashes. We use in this paper a new method to estimate the proportion of upward/downward flashes to a given tower, based on data from lightning location systems. The analysis using the proposed method explains the discrepancy in terms of the measured number of downward flashes in Gaisberg and in Monte San Salvatore.**

I. Introduction

Long-term observations and measurements of lightning discharges to tall structures have been conducted since 1930s following the construction of high-rise buildings and development of radio and television [1]. Skyscrapers and telecommunications towers have been widely used for lightning research, while some towers have been built and used exclusively for the measurements of lightning parameters (see Chapter 6 of [2]).

The design, installation and maintenance of lightning recording system on a tower present a very complex, expensive and challenging task. Among thousands of tall structures erected in Europe there are only a few equipped with lightning measurement system which are still in operation (e.g. Gaisberg Tower in Austria [3], Peissenberg Tower in Germany [4]), and most recently the Säntis Tower which was instrumented in 2010 [5].

Earlier in mid-20th century, long term observation of lightning currents using two instrumented towers in Monte San Salvatore (TI) resulted in a complete statistical characterization of lightning current parameters [6].

The number of flashes to a tall structure can be evaluated using the empirical formula proposed by Eriksson [8] based on experimental observations made at some tall structures

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

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

One important difference in the measurement results obtained at Monte San Salvatore and more recent data obtained at Gaisberg and Peissenberg towers concerns the ratio downward/upward flashes. While at Gaisberg and Peissenberg towers, downward flashes were rarely observed and constitute only about 1% of all recorded flashes [3], nearly 30% of the recorded flashes at Monte San Salvatore were of downward type [7].

The evaluation of lightning incidence to tall towers situated in mountainous regions is much more difficult than on flat ground due to the fact that topological factors will play a major role in the enhancement of the electric field at the top of the mountain. Therefore, the structure's actual height above ground level should be replaced with the effective height h_{eff}, whose evaluation is a very complex task [8, 9].

A summary of different techniques for the estimation of h_{eff} can be found in [9]. For the Monte San Salvatore towers (70-m tall located on a 910-m high mountain), the resulting effective height ranges from 198 m to 350 m. For the Gaisberg tower (100-m tall on a 1287-m high mountain), the obtained values for the effective heights range from 274 m to 1000 m.

In this paper, we will discuss the differences in the percentage of downward flashes observed in Monte San Salvatore and Gaisberg towers analyzing data from lightning location systems (LLS) and we will derive their effective heights.

TABLE I. LIGHTNING INCIDENCE TO THE SELECTED TOWERS

#	Object	Location	Period of observation	Object height, m	N_g, fl·km^{-2}·y^{-1}	Flashes per year		Upward negative flashes		Ref.
						↓	↑	ICC$_{RS, p}$, %	ICC$_{only}$, %	
1	Tower 1 on Mt. San Salvatore	45.977 N, 8.947 E	1955-1963 (9 years)	70	4	6	19	36	64	[7]
2	Tower 2 on Mt. San Salvatore		1955-1963 (9 years)	70	4	5	12			[7]
3	Gaisberg Tower	47.805 N, 13.112 E	2000-2007 (8 years)	100	2	1	57	52	48	[3]

Symbols: ↓ - downward flash, ↑ - upward flash, N_g – ground flash density in the region close to the object.

I. SELECTED TOWERS AND DIRECT LIGHTNING INCIDENCE OBSERVATIONS

Table I presents a summary of the parameters for the selected towers (Monte San Salvatore and Gaisberg) and the observed annual incidence of upward and downward flashes. The selected towers listed in Table I are located in somewhat similar topographic conditions, namely situated at the top of the mountains as shown in Figure 1a and Figure 2a. The second Berger's tower has been dismantled and its approximate location is shown in Figure 2a.

Matrices containing the elevation data were extracted from ASTER Global Digital Elevation Model (property of METI and NASA) and then averaged to produce the cells of 1×1 km shown in Figures 1b and 2b.

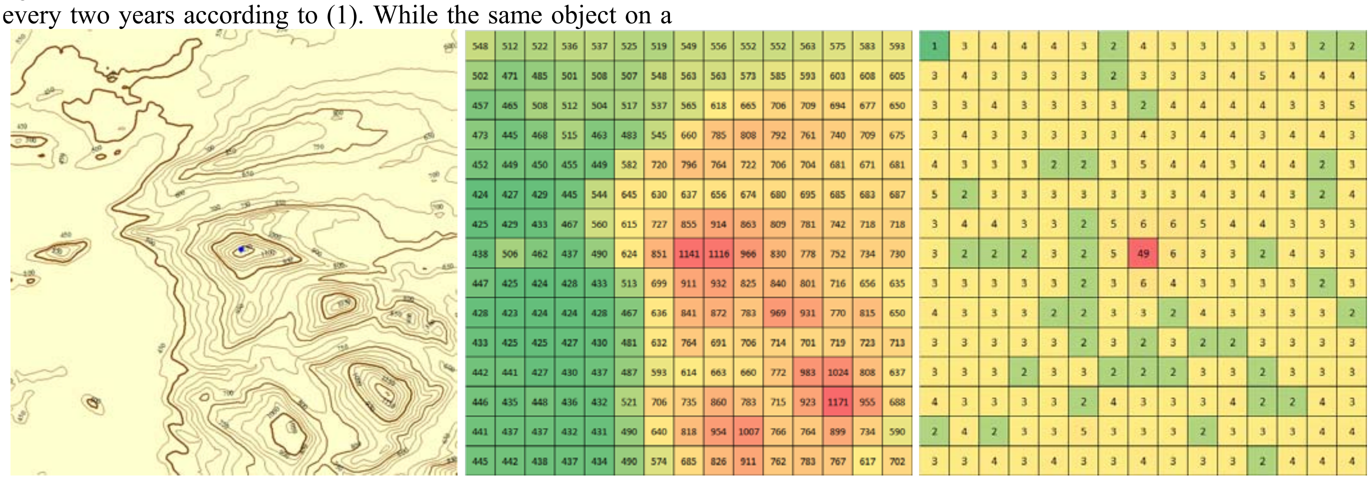
Mount San Salvatore is situated in a region with high lightning activity: the average annual lightning flash density is 4 flashes·km^{-2}·y^{-1}. Gaisberg Tower is located in a region with moderate lightning activity (2.4 flashes·km^{-2}·y^{-1}).

A structure with the same height as one of the Berger's towers but situated on a flat surface (in an area where N_g = 4 flashes·km^{-2}·y^{-1}) will be struck approximately once every two years according to (1). While the same object on a mountain top could get struck 17 to 25 times annually (see Table I). As mentioned earlier, this is mainly due to the increment of the electric field introduced by the mountain resulting in the initiation of upward flashes.

II. DETERMINATION OF LIGHTNING INCIDENCE TO THE TOWERS USING LIGHTNING LOCATION SYSTEM

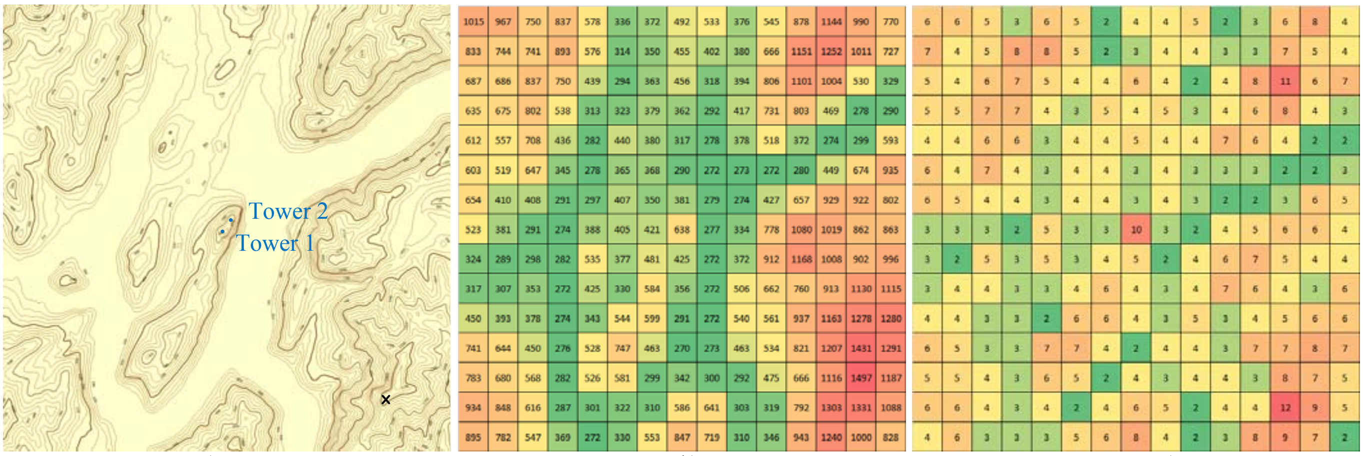
Lightning location systems (LLS) are an excellent tool for studying the lightning distribution in different regions. Several tens of sensors joined in the EUCLID network [4] record lightning flashes over the whole Europe. The assessment of the performances of lightning location systems can be evaluated by means of directly measured events provided by either instrumented towers (e.g. [10, 11]) or rocket-triggered lightning [12].

Direct observation on Gaisberg tower was used to evaluate the performance of EUCLID network [13]. The flash detection efficiency was found to be more than 97% for peak currents greater than 5 kA. The median location accuracy was 368 m with standard deviation of 768 m.



a) b) c)

Figure 1. Mountain Gaisberg region, the North is on the top. Each figure covers the same area of 15×15 km. a) Elevation contours, the position of the Gaisberg tower is shown with a blue dot. b) Approximated elevation terrain model, values inside each cell represent the average absolute height within the cell in meters. c) Lightning flash density registered by EUCLID LLS is given in flashes·km^{-2}·y^{-1}. Period of observation: 2000-2009.



a) b) c)

Figure 2. Mountain San Salvatore region, the North is on the top. Each figure covers the same area of 15×15 km. a) Elevation contours, the positions of Berger's towers are shown with blue dots. Monte Generoso Tower is shown with a cross. b) Approximated elevation terrain model, values inside each cell represent the average absolute height within the cell in meters. c) Lightning flash density registered by EUCLID LLS is given in flashes·km^{-2}·y^{-1}. Period of observation: 2000-2009.

Nevertheless, it is important to realize that lightning location systems are not able to capture all lightning flashes due to several reasons. Upward lightning flashes could be composed of initial continuing current only (ICC_{only} type) with amplitude up to several hundred amperes. These flashes do not produce significant electromagnetic radiation to be captured by the sensors far away from the tower and therefore cannot be detected remotely.

Sometimes, fast pulses are superimposed with the initial continuing current (ICC_p type) or are followed by return strokes (ICC_{RS} type). The detection efficiency of ICC_{RS} and ICC_p flashes depends strongly on the peak current. As can be seen in Table 1, a considerable fraction of the upward flashes contain ICC_{only} discharges. In Monte San Salvatore, only 36% of the upward flashes contained either ICC_p and/or ICC_{RS}. This fraction was found to be higher for the Gaisberg Tower (52%). The annual number of upward flashes for each tower given in Table I comprises all types of flashes and should be corrected by the mentioned factors in order to be compared with the values obtained by LLS.

A map of lightning density around the Gaisberg Tower is shown in Figure 1c. The position of the grid was specially adjusted so that the tower is located exactly in the middle of the central cell. It could be observed that lightning flash density close to the tower differs greatly from the flash density at a distance from the tower. As suggested in [14], this difference is mainly due to the fact that an object placed on the mountain top initiate additional upward flashes.

Lightning flash density map shown in Figure 2c covers the region around Mount San Salvatore. There are three cells with significantly higher values of lightning flash density. The one in the centre correspond to the 70 m tower situated on the Mount San Salvatore. The cell in the right bottom angle (S-W direction) with the value of lightning flash density equal to 12 flashes·km^{-2}·y^{-1} is located close to the 49 m tower on Mount Generoso (1700 m). The last cell with higher value of N_g in the top-right corner could be due to the presence of several high structures: the church and the bell-tower of unknown height in Brè or the cross on the summit of Monte Boglia (1516 m).

In order to evaluate the number of upward flashes associated with a given object, we propose to use the method described in [14] which is based on the assumption that the number of downward lightning flashes in the vicinity of a tall structure is only marginally affected by the presence of the object. The method consists of considering two concentric areas shown in Figure 3: a circle with a radius r = 1 km enclosing the object and a ring with the inner radius r and the outer radius R typically 8-10 km.

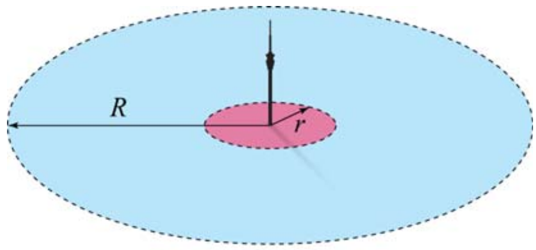


Figure 3. Areas used for the evaluation of the number of upward flashes form a tall structure.

The increment of the flash density in the inner circle is assumed to be 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 these downward flashes, however, are assumed to be detected by the LLS within the inner circle and, therefore, the presence of the tower does not increase the density of downward flashes.

III. Analysis of the Proportion of Upward Flashes

The overall number of flashes recorded by the LLS within the central circle (r = 1 km) is

$$N_{all} = D_1 \cdot S_1 = \pi \cdot D_1 \,, \qquad (2)$$

where D_1 is the lightning flash density in the central circle with the surface S_1.

We will now divide the number N_{all} into several components. It is evident that N_{all} is composed of the number of upward flashes N_{up} from the tower, downward flashes attracted to the tower N_{down_tower} and the rest part of downward flashes not attracted to the tower N_{down_out}:

$$N_{all} = N_{up} + N_{down\_tower} + N_{down\_out} \,. \qquad (3)$$

We assume that the number of downward flashes within the central circle will remain the same either when the object is present in the centre or not. It means that the number of downward flashes is determined by the value of ground flash density N_g around the tower. The overall number of downward flashes within this circle is limited by the value of N_g:

$$N_{down} = N_{down\_tower} + N_{down\_out} = S_1 \cdot N_g = \pi \cdot N_g \,. \qquad (4)$$

The exact value of downward flashes attracted to the tower N_{down_tower} is determined by the attractive radius R_a and there are several models to estimate this value [2]. We will not use those models to calculate the value of N_{down_tower}, instead we will consider it as a variable and will study the variation of the proportion of upward flashes as a function of the number of downward flashes to the structure.

Since we know the total number of downward flashes within the central circle we can finally estimate the number of upward flashes associtaed with a tall structure as proposed in [14]:

$$N_{up} = N_{all} - N_{down} \,. \qquad (5)$$

Table II. Estimation of the Number of Upward and Downward Flashes for the Tower 1 on Monte San Salvatore and the Gaisberg Tower

Tower (from Table I)	Estimations form LLS data					Data from direct measurements		
	N_g, flashes·km^{-2}·y^{-1}	D_1, flashes·km^{-2}·y^{-1}	N_{all}, flashes	N_{down}, flashes	N_{up}, flashes	N_{upward} × % $ICC_{RS,p}$ flashes	$N_{downward}$, flashes	N_{up}, %
1	3.9	5.4	17	12	5	7	6	54
2						4	5	44
3	2.4	12.4	39	8	31	31	1	97

The results of the estimations using (2) – (5) are given in Table II for the Tower 1 on Mount San Salvatore and the Gaisberg Tower. For example, for the case of Gaisberg Tower the total number of flashes registered by LLS within the circle of 1 km is 39. According to the value of N_g and (4) there were 8 downward flashes recorded within this circle. Therefore the number of upward flashes is 31 and all of them are assumed to be initiated from the tower. We should then calculate the number of downward flashes attracted to the tower. And, finally,

$$N_{up}, \% = \frac{N_{up}}{N_{up} + N_{down\_tower}} \cdot 100 \,. \qquad (6)$$

As was suggested before, we will not use some specific value of R_a, but will study the variation of N_{down_tower}. The results are presented in Table III for the Gaisberg Tower.

Table III. The percentage of upward flashes estimation for the Gaisberg Tower.

N_{all}	N_{down}	N_{up}	N_{down_tower}	N_{down_out}	N_{up}
flashes					%
39	8	31	1	7	97
39	8	31	2	6	94
39	8	31	3	5	91
39	8	31	4	4	89
39	8	31	5	3	86
39	8	31	6	2	84
39	8	31	7	1	82

For the Tower 1 on Mount San Salvatore similar calculations have been done and the comparison with the Gaisberg Tower is shown in Figure 4.

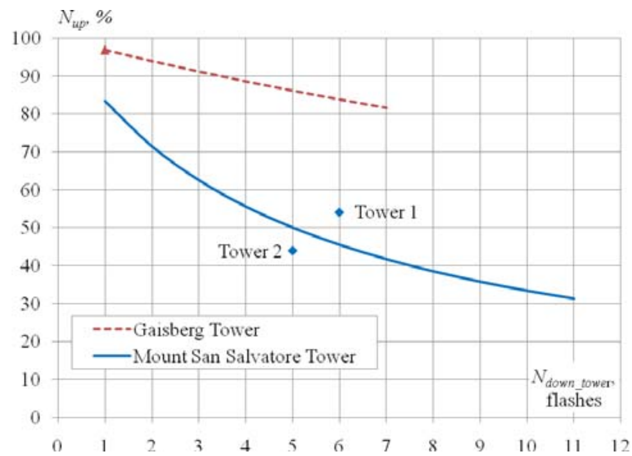


Figure 4. Proportion of upward flashes as a function of the number of downward flashes to the structure (triangle corresponds to the Gaisberg

Tower direct measurements data, diamond points to the direct measurements data from the towers on Mount San Salvatore).

It could be seen from Figure 4 that the value of N_{up}, % for the Gaisberg Tower is higher than for the Tower 1 on Mount San Salvatore irrespective of the value R_a and the number of downward flashes to the tower.

It was mentioned before that ICC_{only} flashes affect the results of LLS observations. Therefore we have excluded them from our analysis in order to compare the percentage of upward flashes obtained from direct measurements with the values obtained by analyzing the LLS data. The corrected values are given in Table II and are also presented in Figure 4 (dotted line).

This observation by means of the new method based on the lightning flash densities obtained from LLS data explains the discrepancy in terms of the measured number of downward flashes in Gaisberg and in Monte San Salvatore.

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