2014 International Conference on Lightning Protection (ICLP), Shanghai, China

Number of Lightning Strikes to Tall Structures - Comparison of Calculations and Measurements using a Modern Lightning Monitoring System

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***Abstract*— Using a state-of-the-art lightning monitoring system LM-S with lightning detection sensors based on the Faraday effect the lightning currents caused by direct strikes to different buildings can be analyzed. The lightning monitoring system measures different current parameters, e.g. amplitude, charge, specific energy, time of strike. The measured data are compared with the expected number of strikes calculated based mainly on the international standard for risk management IEC 62305-2 Ed.2:2010 [1].**

Keywords; Lightning monitoring; measurements of lightning current parameters; calculations of expected number of strikes; comparison of measurement and calculations

I. INTRODUCTION

Measurements of lightning currents is an essential part of scientific work on lightning phenomenon from Franklin's kite experiment to scientific measuring sites in our time all over the world [2, 3]. Most of the past and present scientific lightning current measurement investigations are focused on various lightning parameters to understand the physics and the threat of lightning strikes. The used measuring technique is of scientific accuracy to understand each detail of the lightning discharge and to compare measurements with simulation results from high voltage discharge models. Due to the cost of the high precision measuring equipment the number of these sites is not high and statistic evaluation of the results is mostly based on a small number of measured lightning events.

A new Lightning Monitoring System developed for the preventive maintenance of wind turbines gives the opportunity to measure lightning currents in a huge number of sites and to evaluate the results on a statistical basis with a high number of measured events.

For marketing purpose the Lighting Monitoring System has been installed in several extraordinary and famous structures all over the world. In this paper five of these structures are analyzed and the calculated number of strikes is compared to the number of the measured lightning strikes. As the installations of the Lighting Monitoring System are just one to two years old, the presented results are only the beginning of a long term experiment which long term results will be continuously presented.

Since the 1990 the risk analysis for lightning threats has been investigated. Risk management for lightning and overvoltage protection is an essential tool, to estimate the vulnerability of a structure and the people and content inside against lightning and overvoltage threat and to ensure, that the necessary and most effective protection measures are selected in the required quality.

The first technical report in the frame of standardization dealing with risk analysis was published in 1995 as IEC 1662 [4]. Further development in this subject and the use of this publication then lead to the 1st edition of the lightning protection standard IEC 62305-2 in 2006. Risk management investigations were then performed for a great number of structures. The worldwide experiences lead to further improvement. In 2010 the 2nd edition of the international standard IEC 62305-2 [1] was published.

The methods and parameter values given by this standard are used for the purpose of this paper, to estimate the expected number of strikes. For very tall structures the expected number of strikes is estimated using a special, but well-established relationship.

II. LIGHTNING MONITORING SYSTEM LM-S

A. Motivation

The Lightning Monitoring System LM-S has originally been developed for the detection of lightning strikes into the rotor blades of wind turbines. Whereas the electric and electronic equipment of wind turbines can be protected by comprehensive surge protective measures the outer structures and particularly the rotor blades can be hit by direct lightning strikes. In defined maintenance cycles these damages are inspected and repaired in costly operations. With an integrated lightning monitoring system it is possible to adapt the maintenance cycle times to the real number and to the energy of the measured lightning strikes. Compared to scientific measurement devices the LM-S is less accurate (+/- 10%) but very easy to install and on an appropriate cost level.

B. *Polarimetric Current Sensor*

The function principle of polarimetric current sensors is based on the use of the Faraday Effect. This means that the magnetic field of a current has influence on a polarized light beam in an optical material crossing the magnetic field. The polarization angle of a linear polarized light wave in a special optical medium is turned by the presence of a magnetic field. This turning angle is depending on the Verdet-constant and the length of the optical material and on the magnetic field strength, which is a direct measure of the flowing current value. If linearily polarized light is coupled into a faraday-active crystal, the polarization angle is turned depending on the magnetic field through this crystal (Fig. 1).

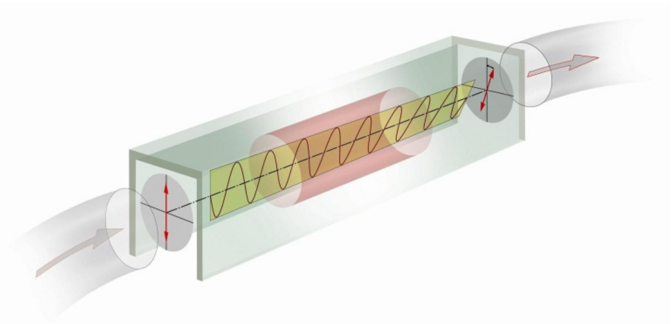

Figure 1. Faraday Effect: Turning of the polarization angle of linearily polarized light by an outer magnetic field

For the sensor setup (Fig. 2) the light beam of a light source is coupled by a lens system into an optical fiber and transferred to the sensor. In the sensor the light beam is polarized and goes through the faraday-active crystal. Along this distance the polarization angle of the light wave is turned, depending on the strength of the magnetic field influencing the crystal. A second polarizer at the light exit of the crystal converts the turning angle signal into an intensity signal. With no outer magnetic field no turning happens and the output intensity is at maximum. At a turning angle of 90° the output intensity signal will be zero which already describes the dynamic range of the sensor.

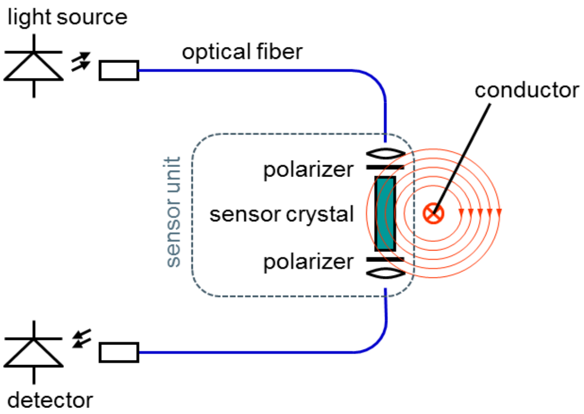

Figure 2. Sensor setup for polarimetric current measurement

Essential for the measurement of lightning currents is that the complete sensor unit (see Fig. 2) consists of only plastics, glass and ceramics. There is no conductive material and not any electronics directly in the sensor unit. It is a passive optical sensor which allows it to place it directly on any down conductor of a lightning protection system without any restrictions by required separation distances.

C. *System qualification*

The complete Lightning Monitoring System has been qualified in different laboratories to prove its applicability mainly for wind turbines. The accuracy of the measuring system in the temperature range of $-30°C \leq \vartheta \leq 60°C$ has been evaluated and the result is that in the measuring range for lightning current amplitudes of $5\ \text{kA} \leq \hat{I} \leq 200\ \text{kA}$ the current measuring error is less than 10%. Fig. 3 & 4 show a comparison of laboratory measurements of a lightning current with an amplitude of $I_{imp} = 30\ \text{kA}$, measured by the laboratory reference system (Fig. 3) and by the Lightning Monitoring System (Fig. 4).

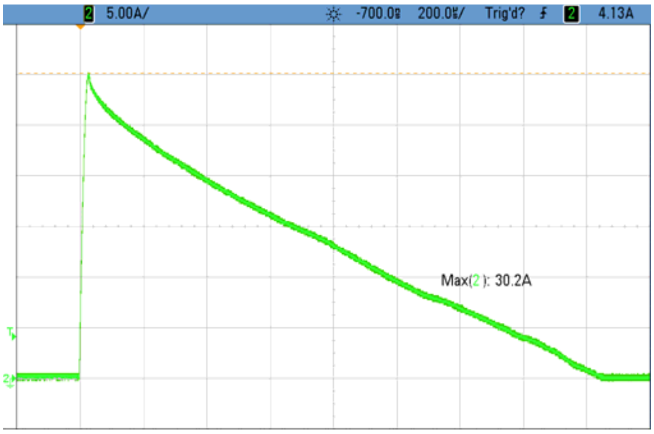

Figure 3. Measured lightning current impulse ($I_{imp} = 30$ kA) (calibrated laboratory measuring system)

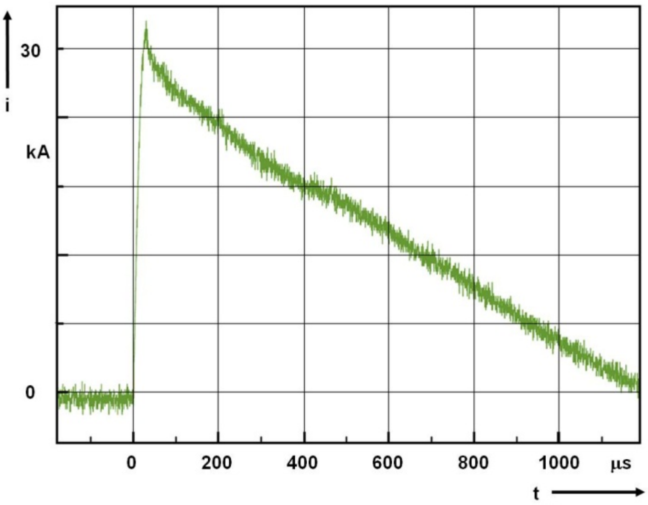

Figure 4. Measured lightning current impulse ($I_{imp} = 30$ kA) (Polarimetric current sensor LM-S)

III. INVESTIGATED STRUCTURES

Besides the installations in wind turbines the Lightning Monitoring System has been installed in more than ten famous structures all over the world. For the investigations according the expected and the measured strikes five representative structures are chosen.

A. Statue of "Herman the German", Detmold, Germany

Figure 5. LM-S installed at Herman the German Statue, Detmold, Germany

With an overall height of 53.46 m, Herman the German is the highest statue in Germany (Fig. 5). It reminds to the battle in Teutoburg Forrest in the year 9 p.C. against the Roman legion. It is built on the top of a hill and the sculpture is made of copper. The LM-S system is installed since July 2012 and all information is open to the public under www.blitze-am-hermann.de, but only in German language so far.

B. Burj Khalifa, Dubai, United Arab Emirates

Figure 6. LM-S installed at Burj Khalifa, Dubai, United Arab Emirates

The Burj Khalifa is the highest building in the world with a height of 828 m (Fig. 6). It is commercially used and contains offices, suites, hotels, restaurants and observation platforms. Elevators are going up to 638 m. For the LM-S installation the remaining distance up to the top must be climbed.

C. Great Belt Bridge, Denmark

The Great Belt Bridge in Denmark connects the Danish islands Funen with Zealand. With an overall length of 2694 m the biggest main span is 1624 m. The main pillars are 254 m high and the street runs about 70 m above sea level (Fig. 7).

Figure 7. LM-S installed at Great Belt Bridge, Denmark

D. Clock Tower, Graz, Austria

Figure 8. LM-S installed at Clock Tower, Graz, Austria

The Clock Tower is the famous landmark of the City of Graz in Austria (Fig. 8). It was built in the 13th century and has four dial plates with a diameter of more than 5 meters. The clocks were originally built with only one hand to point the hours as it was common in that time. The later installed hand for the minutes is shorter to distinguish it from the first one. So the length scheme of both hands is mixed up until today.

E. Wumen Gate, Forbidden City, Beijing, China

The Wumen Gate is one major entrance to the inner part of the Forbidden City (Fig. 9). The Forbidden City is an extraordinary complex of 890 Palaces on an area of more than 720,000 m^2 and since 1987 it belongs to the Cultural Heritage of the World.

Figure 9. LM-S installed at Wumen Gate, Forbidden City, Beijing, China

IV. EXPECTED NUMBER OF STRIKES - BACKGROUND

A. *Common structures*

The expected number of strikes is mainly calculated using the procedure described in the international lightning protection standard IEC 62305-2 Ed.2:2010 [1]. In Annex A of this standard, the number of direct strikes N_D is given as:

$$N_D = N_G \cdot A_D \cdot C_D \cdot 10^{-6} \tag{1}$$

where:

N_G is the lightning ground flash density at the location of the structure investigated ($1/(km^2 \cdot year)$);

A_D is the collection area of the structure (m^2);

C_D is the location factor of the structure.

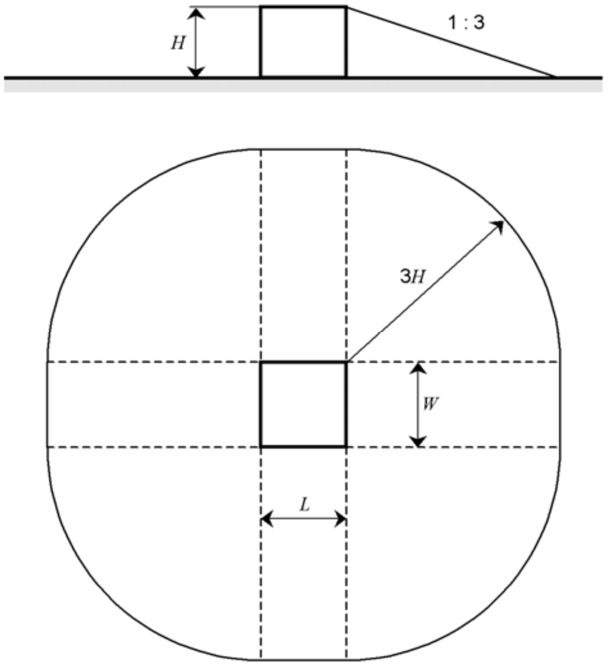

Figure 10. Collection area A_D of an isolated structure

For isolated structures on flat ground, the collection area A_D is the area defined by the intersection between the ground surface and a straight line with 1/3 slope which passes from the upper parts of the structure (touching it there) and rotating around it. For an isolated rectangular structure with length *L*, width *W*, and height *H* on flat ground, the collection area is then equal to:

$$A_D = L \cdot W + 2 \cdot (3 \cdot H) \cdot (L+W) + \pi \cdot (3 \cdot H)^2 \tag{2}$$

where *L*, *W* and *H* are expressed in meters (Fig. 10).

The value "3" in (2) is valid for a typical height of the structure of 20 m. However, the use of this value underestimates the number of strikes for lower structures and overestimates the number of strikes for structures with a height of more than 20 m [5]. Therefore, for structures exceeding a height *H* of 20 m, the value 3 is replaced by *m* given as:

$$m = 13.4 \cdot H^{-0,5} \tag{3}$$

The relative location of the structure, compensating for surrounding structures or an exposed location, will be taken into account by a location factor C_D (Table I).

TABLE I. STRUCTURE LOCATION FACTOR C_D

Relative location	C_D
Structure surrounded by higher objects	0.25
Structure surrounded by objects of the same height or smaller	0.5
Isolated structure: no other objects in the vicinity	1
Isolated structure on a hilltop or a knoll	2

A more precise evaluation of the surrounding objects' influence generally can be obtained considering the relative height of the structure with respect to the surrounding objects or the ground within a distance of $(3 \cdot H)$ from the structure and assuming $C_D = 1$.

B. *Very tall structures*

For very tall structures the method given by IEC 62305-2 seems not to be sufficient. Here, according to Eriksson [6, 8], the total number of flashes N_{Tall} is given by

$$N_{Tall} = N_G \cdot 24 \cdot H^{2.05} \cdot 10^{-6} \tag{4}$$

where:

H is the effective height of the structure.

The relationship in (4) was evaluated for structures with effective heights in the range of 100 m … 550 m. The term "effective height" takes into account that tall structures, like towers, may be located on top of a hill or a mountain, so that the height of the tower is superimposed by the additional influence of this position. However, in case of tall structures located on a flat ground, the effective height corresponds to the structure's height.

In case of very tall structures also upward lightning discharges occur. The percentage of upward lightning discharges increases with increasing height of the structure. To estimate this effect, the percentage of upward flashes P_U as a function of the structure's effective height H can be calculated according to [7, 8]:

$$P_U = 52.8 \cdot \ln(H) - 230 \tag{5}$$

However, the distinction in downward and upward lightning discharges is necessary only, if the lightning current parameters are investigated in detail. If only the total number of strikes is investigated, the results given by (4) are sufficient, because the number N_{Tall} contains both discharge types.

V. EXPECTED NUMBER OF STRIKES FOR THE INVESTIGATED STRUCTURES

A. *Statue of "Herman the German", Detmold, Germany*

The statue of Herman can be estimated as a sharp needle with a height of 53.5 m (tip of the sword) and negligible length and width. It is located solely on top of a hill. The flash density is coming from the German lightning detection network BLIDS. The data for the calculation are given in Table II.

TABLE II. DATA FOR CALCULATING N_D FOR "HERMAN THE GERMAN"

L	*W*	*H*	C_D	N_G
1 m	1 m	53.5 m	2	2.6/(km^2·year)

Using (3) results in m = 1.83. According to (2) this leads to a collection area of A_D = 30,570 m^2. Finally, with (1) the number of direct strikes is N_D = 0.159/year, i.e. a direct strike occurs every 6.3 years.

B. *Burj Khalifa, Dubai, United Arab Emirates*

The tower Burj Khalifa, of course, is a very tall structure. It can be estimated as a sharp needle with a height of 828 m (tip of the antenna). It is located on flat ground, therefore the effective height is identical to the height. Adjacent structures exist, but due to the enormous height of the tower they are neglected. The flash density is estimated from NASA's global map of lightning frequency. The data for the calculation are given in Table III.

TABLE III. DATA FOR CALCULATING N_{TALL} FOR BURJ KHALIFA

H	N_G
828 m	2.0/(km^2·year)

For Burj Khalifa as a very tall structure (4) is used. The total number of strikes to Burj Khalifa therefore results in an enormous number N_{Tall} = 46/year. According to (5) 125% of these are upward lightning discharges. This percentage obviously is not possible, but it shows, that a structure as high as the Burj Khalifa is clearly outside the validity range of (5). As a first approach, the percentage of upward lightning strikes is assumed to be 80%, i.e. 37/year.

C. *Great Belt Bridge, Denmark*

In case of the Great Belt Bridge, the two main pillars are of interest. These are equipped with the Lightning Monitoring System. Each of the two main pillars can be estimated as a thin structure (length 25 m, width 8 m) with a height of 254 m. Because of their distance they are assumed to act as independent structures on flat ground. The flash density is coming from the German lightning detection network BLIDS together with the European network EUCLID. The data for the calculation are given in Table IV.

TABLE IV. DATA FOR CALCULATING N_D AND N_{TALL}, RESP. FOR GREAT BELT BRIDGE

L	*W*	*H*	C_D	N_G
25 m	8 m	254 m	1	1.0/(km^2·year)

Firstly, each of the two pillars is assumed to be a common structure, i.e. the method of IEC 62305-2 is applied. Using (3) results in m = 0.84. According to (2) this leads to a collection area of A_D = 157,500 m^2. Finally, with (1) the number of direct strikes is N_D = 0.158/year, i.e. a direct strike occurs every 6.3 years.

If, secondly, each of the two pillars is assumed to be a very tall structure, (4) is used, and then the total number of strikes results in N_{Tall} = 2.04/year. According to (5) 62% of them are upward lightning discharges, i.e. 1.27/year.

This comparison shows the remarkable influence of the structure's height on the number of strikes, due to the large-area electric field enhancement of those structures, and especially the phenomenon of upward lightning discharges, which usually do not occur at common structures.

It is obvious [5, 6, 7, 8], that the two pillars have to be treated as very tall structures. With that, the latter value of the expected total number of strikes, N_{Tall}, is used further.

D. *Clock Tower, Graz, Austria*

The Clock Tower in a simplified approach is estimated to be a rectangular structure with a base of 8 m x 8 m and a height of 28 m. Modeling the structure's roof in a more detailed manner does not influence the results remarkably. The tower is located solely on top of a hill. The flash density is coming from the Austrian lightning detection network ALDIS. The data for the calculation are given in Table V.

TABLE V. DATA FOR CALCULATING N_D FOR CLOCK TOWER

L	*W*	*H*	C_D	N_G
8 m	8 m	28 m	2	2.4/(km^2·year)

Using (3) results in m = 2.5. According to (2) this leads to a collection area of A_D = 18,130 m^2. Finally, with (1) the number of direct strikes is N_D = 0.0870/year, i.e. a direct strike occurs every 11.5 years.

E. *Wumen Gate, Forbidden City, Beijing, China*

The Wumen Gate consists of a main structure with a base of 127 m x 37 m and a maximum height of 38 m. Two symmetric wings with comparable height and a length of 78 m are connected perpendicularly. With that an inner courtyard is created. However, the distance between the two wings is 78 m only. Therefore, in a simplified approach Wumen Gate can be estimated to be a rectangular structure with a base of 127 m x 115 m and a height of 38 m.

Wumen Gate is located on flat ground. Adjacent structures exist, but these are lower and mostly sufficiently far away from the gate, so that the investigated structure can be assumed as standing-alone. The flash density is estimated from NASA's global map of lightning frequency The data for the calculation are given in Table VI.

TABLE VI. DATA FOR CALCULATING N_D FOR WUMEN GATE

L	***W***	***H***	***C_D***	***N_G***
127 m	115 m	38 m	1	10/(km^2·year)

Using (3) results in $m = 3.17$. According to (2) this leads to a collection area of $A_D = 76{,}020\ \mathrm{m}^2$. Finally, with (1) the number of direct strikes is $N_D = 0.76$/year, i.e. a direct strike occurs every 1.3 years.

VI. MEASUREMENT RESULTS

For the selected structures the results of the measurements are compared with the expected number of strikes. For the time being, the comparison is concentrated only on the number of strikes. Due to the short time of operation of the LM-S and therefore the limited number of strikes, it is not meaningful to analyze the current parameters amplitude, charge, specific energy, etc. For that a wider statistical base, i.e. a larger number of measured strikes, is necessary. This may be subject of further publications.

TABLE VII. OPERATION TIME OF INSTALLED LM-S

Investigated structure	***LM-S in operation since***	***Month of operation***
Herman, Detmold	July 2012 – June 2014	24
Burj Khalifa, Dubai	Aug. 2013 – Dec. 2013	4
Great Belt Bridge, Denmark	June 2013 – June 2014	13
Clock Tower, Graz	July 2013 – June 2014	12
Wumen Gate, Beijing	Aug. 2013 – June 2014	11

Table VII shows the operation time of the installed LM-S until the end of June 2014. Table VIII gives the number of measured lightning strikes since the start of the LM-S operation, together with the number of expected lightning strikes according to the calculation in chapter V.

TABLE VIII. MEASURED AND EXPECTED LIGHTNING STRIKES

Investigated structure	***Number of measured lightning strikes N_{Meas}***	***Number of expected lightning strikes N_{Exp}***
Herman, Detmold	0	0.32
Burj Khalifa, Dubai	4	15.3 - 3.0 downward - 12.3 upward
Great Belt Bridge, Denmark	1	4.4 - 1.7 downward - 2.7 upward
Clock Tower, Graz	0	0.09
Wumen Gate, Beijing	0	0.70

As it can be seen easily, the time of operation is too short for "common" structures to conduct a meaningful comparison of the measured and the expected number of strikes. As lightning strikes to such structures are rare events, a longer time period is necessary.

For the very tall structures, there are already data available. However, in both cases (Burj Khalifa and Great Belt Bridge) the measured numbers are smaller than the expected ones. Possible reasons for this deviation are, for example:

- Equation (4) overestimates the number of strikes in such a tall structure as the Burj Khalifa. The validity range of (4) may be lost for a more than 800 m tall structure.
- The lightning flash density in Dubai may be much less than expected from the NASA's global map of lightning frequency. This may be also valid for the Great Belt Bridge.
- The LM-S does not register all kind of lightning discharges with the same probability. The qualification of the system shows, that in the measuring range of $5\ \mathrm{kA} \leq \hat{I} \leq 200\ \mathrm{kA}$ the current measuring error is less than 10%. However, if an upward lightning discharge is not followed by a downward one, the triggering level in the range of 5 kA may not be reached. This may be essentially valid for a higher number of upward lightning discharges.
- If only the number of expected downward lightning discharges is compared with the measurements, there is a comparatively good agreement. This may be explained again with a higher number of upward lightning discharges being not registered by the LM-S.

Some of the questions may be answered (1) after a longer time of operation and (2) if the current parameters of the measured strikes are included in the investigation.

VII. CONCLUSION

A modern lightning monitoring system LM-S with lightning detection sensors based on the Faraday Effect has been installed in several extraordinary and famous structures all over the world. This includes "common" structures as well as very tall structures. The main issue of this LM-S is to deliver data for the preventive maintenance of wind turbines.

First measurements of the number of lightning strikes to the investigated structures are available. A comparison with the expected number of strikes shows, that for common structures the time of operation must be longer than only some months. For very tall structures the measured number of strikes is less than the expected one. This may be due to the high percentage of upward lightning discharges at such structures. Those upward lightning discharges possibly are not registered with the same probability than the downward lightning discharges.

It is planned to continuously report about the measurements with the LM-S. The long term results of the number of strikes and the lightning current parameters at the investigated structures may lead to better answers to some of the existing questions.

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