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# Striking Distance of Vulnerable Points to be struck by Lightning in Complex Structures

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***Abstract*—The optimum location of air terminals is one of the main objectives of engineers during the design of lightning protection systems. It is based on the location of vulnerable places to be struck by lightning and on the determination of the striking distance and attractive radius from those points. Traditionally, the location of such probable strike points has been performed by using the Rolling Sphere Method but for the analysis of complex structures, there are still doubts about the sphere radius to be used. Recently, a physical leader inception model that can be used for calculations in structures with and without symmetry (including buildings and complex structures) was used to locate vulnerable places to be struck by lightning in actual buildings. To complement that analysis, the presence of a downward coming leader is considered in this paper. Thus, the striking distances for different buildings struck by lightning in Kuala Lumpur have been computed. It has been found that the striking distance depends also upon the XY position of the downward stepped leader respect to the analyzed strike point and that the attraction zone of the corners in a building is not a circular region as generally supposed. The maximum extension of the attraction zone is reached at points outside the perimeter of the building while shorter striking distances are obtained when the downward leader is located above the structure. This result clearly shows that the lightning attractiveness of corners of buildings cannot directly be evaluated with the existing methods, including the widely used rolling sphere method.**

***Index Terms*—Lightning protection, Leader inception model, Lightning attachment, Numerical simulation.**

## I. Introduction

The location of the most vulnerable places on the structure to be struck by lightning is the first step on the design of the external lightning protection system. Traditionally, the Rolling Sphere Method [1] has been used to locate of the probable lightning strike points on buildings. The radius of the fictitious rolling sphere is given by an empirical correlation with the prospective return stroke current. This empirical method comes from the electrogeometric method derived for power transmission lines [2, 3] and it has been extended to lightning studies in other structures without a deep analysis. Moreover, the used sphere radius does not consider any of the physical processes related to lightning attachment and it is the result of compromises in standardization committees [4].

In spite of this fact, the analysis of the lightning attractiveness of complex structures has not been deeply studied from a physical stand point. It is mainly because the existing upward leader inception models have not been properly adapted to be used in a practical way [5]. In a first attempt, D'Alessandro [6] used the collection volume concept proposed for free standing rods and transmission lines by Eriksson [7] to the analysis of buildings. He linked this concept with the field intensification method [8] to compute the striking distance. Even though the method is claimed to be validated with field observations [9], there are doubts in the lightning community about the convenience and validity of this collection volume/field intensification method to evaluate air terminals [10, 11].

In order to give a more physical approach on the evaluation of the conditions required for the inception of upward leaders from grounded structures with and without symmetry, a leader initiation model was recently proposed by Becerra and Cooray [12]. Later, it was successfully implemented in [13] to compute the background electric fields required to initiate upward leaders from the corners of some complex buildings in Kuala Lumpur. A good correlation between the corners with the lower background leader inception electric fields and the observed lightning strike points was found. The strike points were also observed to be influenced by the geometry of the structure as well as by the surroundings and not only on the prospective return stroke current as the rolling sphere method predicts. However, a comparative analysis of the results obtained with the physical leader inception model and the rolling sphere method could not be performed. It was mainly because of

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the fact that the downward stepped leader was not considered in that analysis and therefore the striking distances from the studied points could not be computed.
In order to overcome some restrictions of the analysis presented in [13], the downward leader channel is considered in the present paper. Thus, the leader inception condition is statically evaluated [12] and the striking distance from the corners of some complex structures in Kuala Lumpur are evaluated. The analysis is performed by moving the downward leader on the XY horizontal plane and at each position the distance required to incept a stable upward leader from the downward leader tip to the analysed corner is computed.

## II. EVALUATION OF THE LEADER INCEPTION CONDITION FOR COMPLEX STRUCTURES

### A. Leader inception model

The leader inception model devised by Becerra and Cooray [12] simulates the first propagation meters of an upward leader initiated from structures with and without axial symmetry. It is performed through an iterative geometrical analysis of the potential distribution in front of the studied point in the structure. This leader inception model assumes that a stable self-propagating upward leader is initiated at the moment when the conditions are enough to guarantee its advancement at least during the first meters. For sake of simplicity, it is assumed that the electric field produced by the downward leader does not change considerably during the time required for the inception of the upward leader. Therefore, the complexity of a full dynamic leader inception model [14] is avoided by considering this static condition. In addition, it is supposed that the initiation of streamers occurs before the leader inception takes place (condition satisfied for corners with tip radius shorter than some tens of centimeters). The discussion of these assumptions and the advantages of the leader inception model are addressed elsewhere [12-14].

In order to evaluate whether a stable leader is incepted or not under the influence of a downward leader whose tip is at a given height, the next analysis is performed:

a) The background potential distribution $U_1$ is calculated following the methodology presented in Section 2.B. Then, the obtained potential $U_1$ is approximated to a straight line (Figure 1) with slope $E_1$ and intercept $U'_0$ such that:

$$U_1^{(0)}(z) \approx E_1 \cdot z + U_0' \tag{1}$$

b) The charge $\Delta Q^{(0)}$ and position $l_s^{(0)}$ of the second corona are computed by using (2) and the parameters shown in Table 1:

$$\Delta Q^{(0)} \approx K_Q \cdot \frac{{U'_0}^2}{2 \cdot \left(E_{str} - E_1\right)} \tag{2.a}$$

$$l_s^{(0)} = \frac{U_0'}{E_{str} - E_1} \tag{2.b}$$

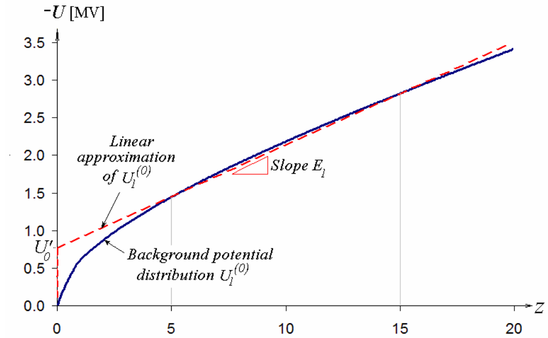


Figure 1. Example of the linear approximation of a background potential distribution.

If $\Delta Q^{(0)} < 1\mu C$, the leader inception condition is not fulfilled and the analysis stops. Otherwise, the simulation of the leader propagation starts $i$=1 with an initial length $l_L^{(1)}$ by evaluating the following steps:

c) Then, the potential at the leader's tip $U_{tip}^{(i)}$ at the current simulation step $i$ is computed as:

$$U_{tip}^{(i)} = l_L^{(i)} \cdot E_\infty + x_0 \cdot E_\infty \cdot \ln\left[\frac{E_{str}}{E_\infty} - \frac{E_{str} - E_\infty}{E_\infty} \cdot e^{-l_L^{(i)}/x_0}\right] \tag{3}$$

d) The position and charge of the corona zone in front of the leader tip are calculated as:

$$l_s^{(i)} = l_s^{(0)} + \frac{E_{str} \cdot l_L^{(i)} - U_{tip}^{(i)}}{E_{str} - E_1} \tag{4.a}$$

$$\Delta Q^{(i)} \approx K_Q \cdot \left\{\left(E_{str} \cdot \left(l_L^{(i)} - l_L^{(i-1)}\right) + U_{tip}^{(i-1)} - U_{tip}^{(i)}\right) \cdot \left(l_s^{(i-1)} - l_L^{(i)}\right)\right\} \tag{4.b}$$

e) The leader advancement distance $\Delta l_L^{(i)}$ and the new leader length $l_L^{(i+1)}$ is evaluated by using:

$$\Delta l_L^{(i)} = \frac{\Delta Q^{(i)}}{q_L} \tag{5.a}$$

$$l_L^{(i+1)} = l_L^{(i)} + \Delta l_L^{(i)} \tag{5.b}$$

where the constant parameters used in the previous equations are shown in Table 1.

Table 1. Constant parameters used for the evaluation of the leader inception condition

| *Sym* | *Description* | *Value** | *Units* |
|---|---|---|---|
| $L_L^{(1)}$ | Initial leader length | $5\cdot10^{-2}$ | m |
| $E_{str}$ | Positive streamer gradient. Equations (2),(3),(4). | $4.5\cdot10^{5}$ | V/m |
| $E_\infty$ | Final quasi-stationary leader gradient. Equation (3). | $3\cdot10^{4}$ | V/m |
| $x_0$ | Constant given by the ascending positive leader speed and the leader time constant. Equation (3) | 0.75 | m |
| $q_L$ | Charge per unit length necessary to thermal transition. Equation (5) | $65\cdot10^{-6}$ | C/m |
| $K_Q$ | Geometrical constant that correlates the potential distribution and the charge in the corona zone. Equations (2), (4). | $4\cdot10^{-11}$ | C/V.m |

*Details about the chosen values can be found in [12].

f) If the leader length $l_L^{(i+1)}$ reaches a maximum value $l_{max}$, then the leader inception condition is fulfilled. If the leader advancement $\Delta l_L^{(i)}$ starts decreasing after some steps, then the leader will stop and leader inception is not reached. Otherwise, go back to *c)*. A typical value of $l_{max}$ equal to 2 meters was observed to be long enough to define the stable propagation of an upward leader when space charge pockets are not considered [12]. Larger values require more analysis steps $i$ and produce about the same result in that case.

*B. Potential distribution calculation*

As discussed in [13], the electrostatic calculation is the more demanding step in this kind of analysis. This is because of the fact that the solution of the Poisson equation in three dimensions (3D) requires a large amount of computational time and memory, despite of the powerful desktop computers and software nowadays available. Moreover, this problem becomes more relevant when the downward stepped leader is included in the analysis.

In this paper, a similar procedure as in [13] is used to compute the potential distribution from each corner in the analysed structure. However, the stepped leader is modeled instead of considering that the downward leader electric field is quasi-uniform over the grounded structure. The downward leader is assumed to be straight (without branching) and its charge is computed by using the charge density proposed by Cooray *et al*. [15]. Due to the restrictions in the number of mesh points, only a finite analysis zone is considered, omitting the upper part of the stepped leader, as can be seen in Figure 2. The analysis volume is thus limited to a rectangular zone whose external faces are far enough to assume that the tangential electric field on them is close to zero. In this way, the width of the analysis volume has to be at least several times larger compared with the structure. The analysis volume height is set equal to 600m since most of the analysed structures did not exceed 100m.

To compensate the contribution of the leader section that is not considered on the electric field calculation, an equivalent point charge placed at the upper part of the downward leader inside the analysis volume is used. The value of this equivalent charge is set in such a way that the electric fields obtained with the FEM model agree with the fields produced by the whole downward leader charge [15], as it can be seen in Figure 3. In addition, the contribution of the thundercloud electric field is computed in a separate analysis volume. A 10kV/m uniform background electric field is then assumed by setting the upper face of the geometry as a potential boundary. For sake of simplicity, the space charge layer created by corona at ground level is not considered, despite of the fact that it shields the thundercloud field and influences the computed striking distances [16].

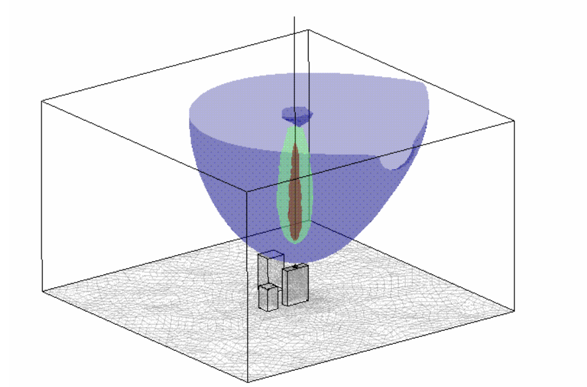

Fig. 2. Example of the isosurface plot of the potential for the FEM model of two bank buildings in Kuala Lumpur in presence of the downward leader.

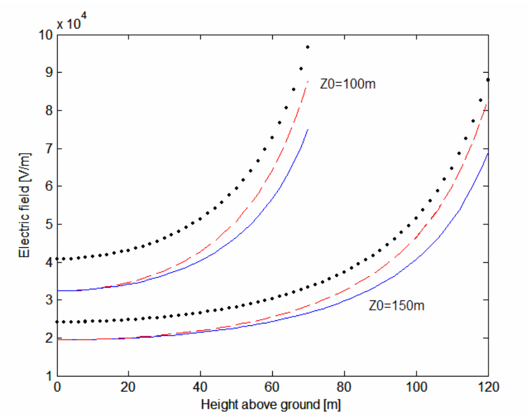


Fig. 3. Electric field below the downward leader tip computed by taking the total leader charge from its tip to the cloud base (solid line), the lower section of the leader below 600m only (dotted line) and the lower leader segment inside the analysis volume and the equivalent charge (dashed line). A 10kA downward leader channel whose tip is at 100m and 150m above ground is considered.

Furthermore, in order to obtain the proper solution of the 3D geometry, it is necessary to use an adequate mesh and solver. For the former case, it is necessary to choose the mesh by compromising quality and number of elements. However, numerical experiments showed that there are not large differences between the results obtained with coarse and fine meshes for the model shown in Figure 2. In this paper, a normal mesh with maximum element size scaling factor, element growth rate, curvature factor and mesh curvature cut off equal to 1, 1.4, 0.4 and 0.01 respectively is used. In addition, to properly evaluate the downward leader charge when solving the geometry, a maximum element size of 4 m is defined along the edge that corresponds to the leader. On the other side, since the selection of the solver depends upon the problem type, different solvers and preconditioners were tested. The best performance is obtained by using the conjugate gradients iterative solver with algebraic multigrid preconditioner [17]. For the model shown in Figure 2, the solution of the model (including meshing) takes from 26 to 48 s CPU time in a PC Intel Pentium, 3.19GHz, 1.5GB RAM.

Once the potential distribution along the line from the analysed point position ($x_i$, $y_i$, $z_i$) to the leader tip ($x_0$, $y_0$, $z_0$) is computed, the upward leader inception analysis presented in section 2.1 is applied. Then, the highest position of the downward leader tip $z_0^{upward(i)}(x_0, y_0)$ that initiates an upward leader from the $i$-th corner is computed iteratively by using the bisection method [21]. Hence, the FEM model is rebuilt, remeshed and solved for all the heights $z_0$ evaluated in the iterative loop. In our calculations, up to 7 iterations are usually required to find $z_0^{upward(i)}$ for each case. Once ($x_0$, $y_0$, $z_0^{upward(i)}$) is found, the distance from it to the analysed corner ($x_i$, $y_i$, $z_i$) is defined as the striking distance.

Likewise, the location of the downward leader in the horizontal plane (XY) is changed around the analysed corner in order to evaluate the influence of the lateral distance on the striking distance. It is evaluated from the position of the analysed corner ($x_i$, $y_i$) outwards, forming radial lines spaced 45 degrees until inception is not reached. Hence, the computed places where the downward leader incepts an upward leader define the "*upward leader inception attraction zone*" from each corner. Even though this region does not correspond to the "effective attraction zone" of the structure to lightning flashes [7], the leader inception zone is the upper limit of it. This is because the effective attraction zone is also defined by the successful connection of both leaders, which is not evaluated here.

## III. Study Cases

In order to evaluate the striking distance of complex buildings, two of the study cases considered in [13] are modelled. Then, the analysis is performed for the vertices of each structure since more than 90% of the observed lightning strike points in buildings correspond to sharp and protruding corners [18-19].

The first study case corresponds to the Faber Tower Building shown in Figure 4. This structure is formed by two towers (H=90m, W=30m, L=70m) adjacent to each other and surrounded by another structure of similar height, 100m away. In this case, the striking distances are computed for the labeled corners shown in Fig. 4. The obtained position ($x_0$, $y_0$, $z_0^{upward(i)}$) of the downward leader tip required to initiate an upward leader from each corner are shown as asterisks. A prospective return stroke current of 15kA is considered.

Interestingly, the top view of the model (Figure 4.b) predicts that the leader inception attraction zone of the corners is not a symmetrical and circular region as it is assumed by the rolling sphere method [1], the collective volume concept [6] or the collection surface method [19]. Note that the larger area of the attraction zone of the corners corresponds to points around the outside to the building. This suggests that most of the upward leaders incepted from the corners are produced by downward leaders located outside the periphery of the structure. Whereas, the stepped leaders located above the building do not initiate connecting leaders from the corners and finally strike the roof. This fact indicates that the corners of buildings do not effectively protect the building as proposed in [20], even if air terminals or grounded metal caps are placed at them. In addition, note in Fig. 4.b that the corners seem to "attract" lightning flashes towards the structure. This result can explain the observed fact that corners of buildings in Kuala Lumpur and Singapure are struck by lightning even when air terminals are used in the center of the roof [18].

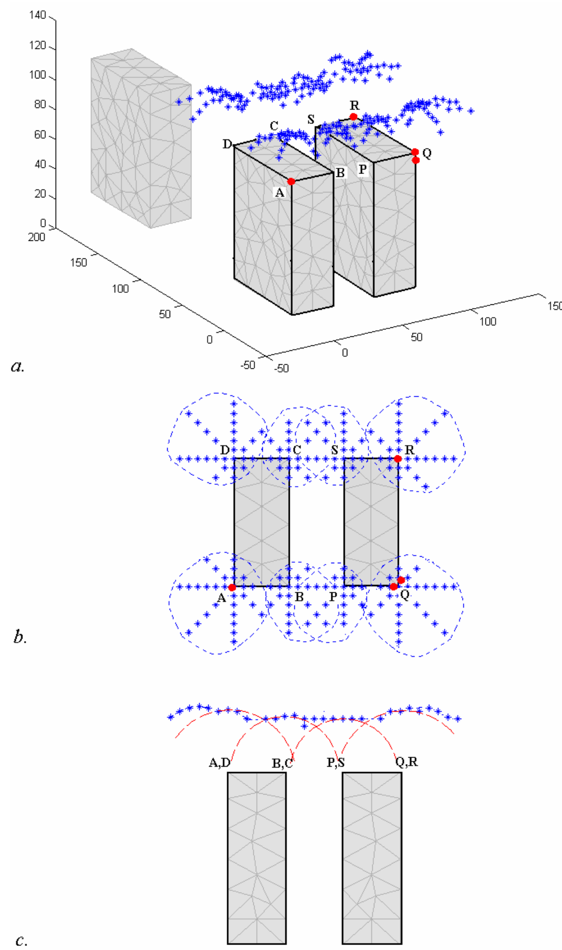


Fig. 4. Diagram of the FEM model, the observed lightning damaged points (dots) and the points of the downward leader tip where leader inception takes place (asterisks) from the corners of the Faber Towers Building, *a*) three dimensional 3D plot, *b*) top view, *c*) side view. The dotted lines define the upward leader inception attraction zone while the dashed lines define the hemispherical area from each corner usually assumed [18, 19].

Another important observed feature is that the larger striking distances do not correspond to the downward leaders located above the studied point (Figure 4.c). Thus, the computed leader inception points ($x_0$, $y_0$, $z_0^{Upward(i)}$) do not define the surface of an spheroid centered at the corners as it is predicted by the rolling sphere method [1] and derivates [5, 6, 18, 19]. This can be explained in terms of the electric fields produced by the downward leader at different positions respective to the corner of a grounded structure, as can be seen in Figure 5.

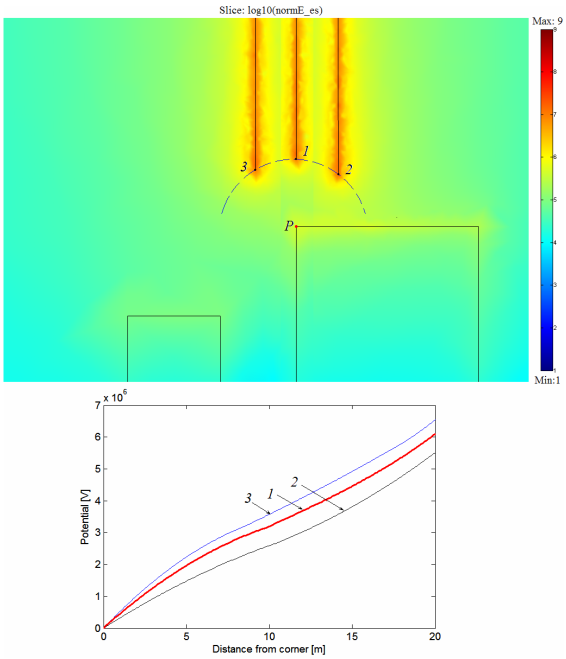


Fig. 5. Example of a slice plot of the electric field logarithm (upper plot) on the plane *Y*=0 produced by a 15kA downward leader at three different locations from the corner of a grounded structure. The potential distribution along the line that connects the corner *P* and each position of the downward leader tip (*1*, *2*, *3*) is also shown.

Note in this example that for three positions of the downward leader tip ($x_0$, $y_0$, $z_0$) equidistant to the corner *P*, the obtained potential distributions are different. Moreover, the potential produced by a downward leader placed outside the perimeter of the structure (case *3*) is larger that the one of the downward leader above the corner (case *2*). Since the potential distribution is used to evaluate the leader propagation during the first meters and to determine the leader inception condition, these differences are therefore reflected on the computed striking distances presented in this paper.

A similar analysis is applied to the corners of two bank buildings: Industry and Pembangunan, which have been struck by lightning two and five times respectively. The buildings have different height (70m and 110m) and are separated by about 30m. A difference with the previous case, there was an air terminal at the center of roof of the one of the buildings (Figure 6). First of all, note that the computed attraction zones are also not symmetrical regions, even for the air terminal (Figure 6.b). This result shows as in [13] that the analysis of air terminal efficiency in complex structures cannot be based on studies performed for free standing rods [7]. On the other hand, observe that in this case the attraction zone of the corners and the air terminal complemented each other, fully protecting the building (Figure 6.b). Moreover, the attraction zone of the corners *S* and *P* of the Pembangunam bank covers the corners *C* and *B* of the Industry bank as well. This is in agreement with the fact that there has not been any observed strike points in corners *C* and *B* during the study period [18]. This indicates that the corners in tall structures protect shorter adjacent structures or avoid lateral strikes to tall free standing buildings, in agreement with field observations [18, 19].

## IV. Conclusions

The striking distance from the corners of two complex structures are computed by using a physical leader inception model. It is found that the corners in grounded complex structures attract lightning flashes towards it but do not protect the roof where they are located. This is because the attraction zones of the corners are not symmetrical regions centered at them as it is generally assumed by the rolling sphere method [1], the collective volume concept [6] or the collection surface method [19].

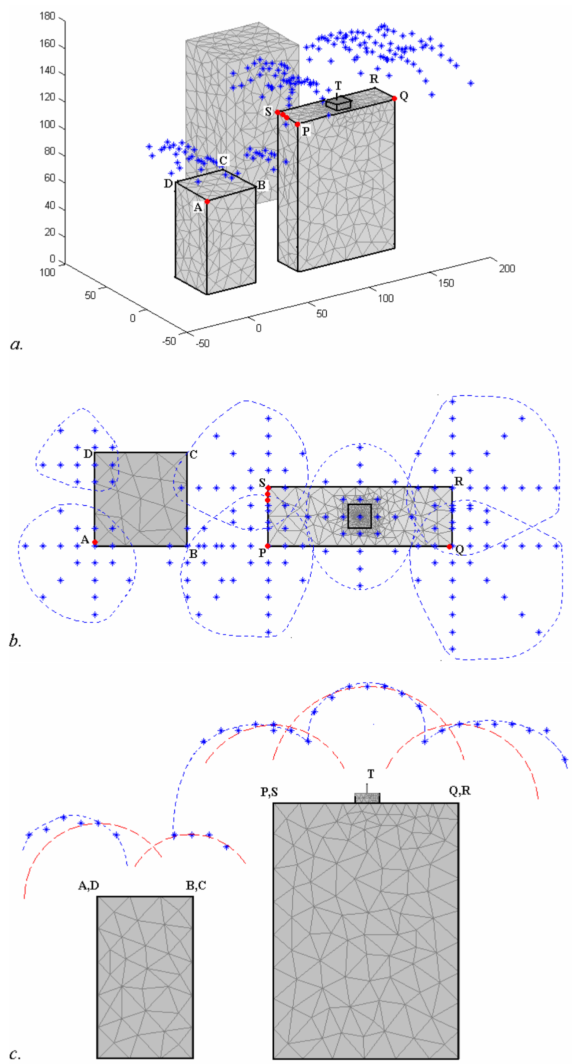


Fig. 6. Diagram of the FEM model, the observed lightning damaged points (dots) and the points of the downward leader tip where leader inception takes place (asterisks) from the corners of two bank buildings: Industry and Pembangunan, *a*) three dimensional 3D plot, *b*) top view, *c*) side view. The dotted lines define the upward leader inception attraction zone while the dashed lines define the hemispherical area from each corner usually assumed [18, 19].

## V. ACKNOWLEDGEMENT

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