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On the effective height of instrumented towers for negative cloud-to-ground lightning: MCS case

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***Abstract*— The effective height of instrumented towers for negative CG lightning is discussed under the conditions of channel formation from the development of a bidirectional bipolar leader. The results developed for the conditions of Morro do Cachimbo Station exhibit significant differences in relation to those published in literature.**

Keywords*— *Effective tower height, Negative CG lightning

I. INTRODUCTION

In negative cloud-to-ground lightning, the quantity governing the initiation of the propagation of a stable positive upward leader from the top of elevated structures is the intensity of the electric field above it. The knowledge of this field intensity is very important for lightning protection, as it allows determining the striking distance (SD), defined in this work as the distance between the tip of the negative leader and the structure upon the initiation of the upward leader propagation, according to the primary concept given by Golde [1].

The position of instrumented towers, used for measuring lightning currents, at the top of mountains influences the intensity of the electric field above the tower tip, leading to higher values with increasing mountain height. Thus, it is usual to refer to an effective height of tower to consider the effect of the mountain height. In other words, this effective height corresponds to the height of an equivalent tower placed at a flat ground that would reproduce the condition for initiation of the upward-leader propagation of the instrumented tower, in terms of field intensity.

Several works addresses the determination of the effective height of instrumented towers, for instance those by Zhou et al. [2] and Smorgonskiy et al. [3]. A common feature of both works consists in attributing the entire source of the electric field at the tower top to the cloud charges and the charges they induce in the ground. Although this assumption reproduces approximately the conditions under the initiation of self-initiated upward lightning, it does not correspond to the conditions observed under the initiation of negative CG lightning. In this case, the charge distributed along the negative leader has major influence on the electric field above grounded structures, notably in the final stage preceding the positive upward leader initiation.

Presently, it is accepted by most researchers that the process leading to the formation of the lightning channel in negative CG lightning initiates with the creation of a bipolar and bidirectional floating leader with null net charge in the region between the negative layer and the lower positive charge region inside the cloud. This is followed by this bipolar leader development towards both the ground and the top of the cloud. In this case, the electric field above the ground results from both the cloud charges and from the distribution of charges along the floating negative leader, along with the effect of the Corona layer produced above the ground surface by the background field.

Presumably, in this condition, the resulting electric-field intensity above the grounded structures upon the initiation of the upward leader propagation is different from that resulting from assuming only the cloud charges as the source of this field, as in [2] and [3]. And this is expected to lead to different effective heights for instrumented towers.

In this scenario, this paper presents preliminary results of an investigation about the effective height of instrumented towers under typical conditions of negative CG lightning formation. First, data of measurements of the tower of Morro do Cachimbo Station (MCS) and the geometry of ground relief in the station surroundings are considered for providing references for the conditions required for initiation of the upward positive leader. Following, sensitivity analyses are developed to consider how the tower and the mountain heights affects the effective height of towers.

II. MODELING AND METHODOLOGY

A. Basic Considerations

The methodology of calculation and the modeling of the physical system involved in the lightning channel formation are the same described in [4], whose basic contents are reproduced below.

B. Methodology

An electrostatic model, based on Kasemir approach [5], applied consecutively at a very short time interval (in the range of microseconds) is able to indicate the evolution of the electric quantities involved in the formation of the lightning channel. It starts inside the cloud, as a bidirectional and bipolar leader with null net charge, which is following extended until it configures a lightning channel that transfers positive charge from the ground to the cloud effectively [6].

The methodology applied in this work consisted in developing this model based on assumed geometric distributions of charges in the cloud and induced at conductive bodies (leader, structures, ground). By using the Charge Simulation Method [7], the charges were calculated at each simulated step, corresponding to the consecutive leader geometries, to track the time evolution of the electrical quantities involved in the process. Mazur and Ruhnke firstly developed the ideas conducted in this work[6].

Each simulated step consists of an electrostatic "photograph" of the system that exhibits the state of the involved quantities. The electric potential along the leader is considered constant and is calculated at each step as the average potential generated in the same region by the charges of the storm cloud (in the absence of the leader). The electric potential at ground and grounded structures is assumed null.

C. Modeling the Physical System

The simulated system comprises a charged cloud over the ground, the tower, and the negative floating leader. Points of charge are distributed in the volumes corresponding to each one of these components. The charges distributed in the cloud are assumed to be constant, whereas those distributed along the other elements are variable and have their values determined at each simulated step.

1) Thundercloud model

The charged thundercloud was represented according to the structure given in [4], consisting of uniform cylindrical distributions of charges with lower base positioned at 2.4 km.

Figure 1 represents the cloud, with a 5-km radius and a vertical extent of 10 km. It comprises two main charged regions: the first one is positive, with a total charge of 50 C, located at the top of the cloud between 9.4 and 12.4 km of altitude. The second one is negative; it has -80 C and extends from 2.4 km to 9.4 km high. Two layers represent a small region of strong electrification, described as the storm cell by [4]. The inner cylinder has a diameter of 1 km. The negative inner layer of -10 C extends from 5.4 to 9.4 km of altitude, while the positive, with 3 C, from 2.4 to 5.4 km. Though this model does not represent the real distribution of charges inside the cloud, it is able to yield a distribution of electric potential along the vertical line (at the axis of the charged cylinders), which reproduces the typical distribution of atmospheric potential in thunderstorms.

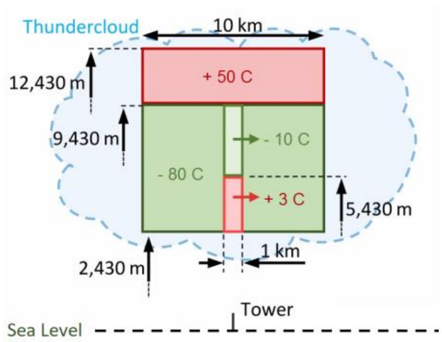

Fig. 1. Geometrical representation of elements that represent the charged cloud in simulations. Adapted from [4].

2) Grounded structure model

The short-instrumented tower at MCS was represented by a 60-m high and 20-cm radius cylinder with charges distributed each 20 cm along its axis. In the analyses, the tower height was varied from 10 m to 300 m, preserving the radius and the charge distribution.

3) Leader model

The single leader consisted in a long vertical bipolar floating conductor placed in the axis of the cylinder, with null net charge. It initiates at the point of highest negative E-field level, between the borders of the negative and positive inner layers (5.4 km), and propagates upwards and downwards. The downward negative leader (DNL) corresponds to the lower part of the floating leader.

The radius of the core of the ionized channel varies, on average, from 1 to 2 cm [6]. However, the charge stored in this core creates an electric field capable of exceeding the dielectric strength of the air around the channel, composing a corona envelope. It is assumed that the charge stored in the channel is mostly concentrated in the layer of ions around the channel core [7]. The value of the radius of the downward leader's potential was initially estimated at 1 m, corresponds to a discretization of one point charge per meter.

4) Corona layer above ground

The charge distribution in the cloud causes a slow-varying component of electric field at the ground level. This component is responsible for producing a corona layer at the ground that can extend to heights above 100 m [2]. The slowly-varying E-field at the ground is strongly affected by the corona layer. Amplitudes of about 50 kV/m expected to be produced at the ground by the cloud charges are typically reduced to about ± 5 kV/m due to this effect [8]. As the effect of the corona layer decreases the background field (due to the charges in the cloud), in the developed analysis, the values of E-field at the ground and at the top of the structures were entirely attributed to the charges deposited along the bipolar leader, whose inferior extremity approaches the ground.

5) Ground

The relief of the ground surrounding MCS was represented as perfectly conducting surface of null electric potential. For determining the effective tower height, a flat conductive ground with null potential throughout its extension was represented at the altitudes of 1000 and 0 m. The presence of ground was taken into account as images, consisting in induced charges distributed below the ground surface, whose values were determined at each processing step. The variation of the mountain height was implemented representing the ground surface as a half ellipsoid, whose radius at the flat ground level was 400 m.

6) Model processing

A sequence of static conditions configured after each step of the floating leader was simulated. Each condition corresponds to a specific length of the leader, determined by its consecutive steps (each 10-m elongation of the negative leader corresponds to a 50-μs step interval).

At each step, the leader potential, assumed constant and equal to the average value yielded by the cloud charges (and their images in the ground) along the leader length, was calculated using the Charge Simulation Method. Finally, the values of charges distributed along the leader length and along the grounded structure (to make the resulting potential equals to, respectively, the leader potential and null potential) are determined.

III. RESULTS

Three main results simulated according to the modeling and methodology described in Section II are presented next. First, the effective height of MCS tower is determined and compared with that produced when only the background field is considered. Following, sensitivity analyses were developed to assess the influence of mountain height in the process to determine the effective height of towers. Finally, the effect of the altitude of the flat ground is assessed.

A. *Condition for initiation of the UCL propagation*

The condition required for initiation of the upward connecting leader propagation was defined based on the value of the electric field estimated 1.5 m above MCS tower $E_{T1.5}$ during this initiation. This value was determined multiplying the average electric field at the ground E_{G50} (50m from the tower) at this initiation (64.4 kV/m for 9 events measured at MCS [8]) by the ratio between $E_{T1.5}$ and E_{G50}. This ratio was found to be 8.9 for a real first return stroke, which transferred 5.98 C [4].

This condition (573-kV/m electric field, 1.5 m above the tower top) was defined as the threshold for the initiation of the positive upward leader propagation. Note that this threshold would have general validity as criterion for initiation of UCL propagation, whatever the ground relief.

For the analyses of this work, we considered a vertical bipolar leader along the axis of the cloud, whose lower negative tip approaches the ground. This would lead to a SD of 150 m (distance between the DNL and the top of the tower at the instant the threshold field is reached 1.5 m above the tower) and to a transferred charge of about 5.65 C (less than 6% of difference in relation to the charge of the real event). Furthermore, in the analyses, we considered two conditions for the altitude of the flat ground: (a) 1-km average altitude in the 500 m to 5 km radius around the tower of MCS Station, as considered in Sections B to D, and (b) the sea-level altitude (0 m), as considered in Section E.

B. *Effective height of MCS tower*

To determine the effective height of MCS tower placed over a flat ground at a 1-km altitude, using the same model described in Section 2, the same SD of 150 m was adopted as the variation of the altitude in 400 m affected slightly the transferred charge (5.45 C). The intensity of the electric field 1.5 m above the top of towers of different heights was determined to find the one corresponding to the threshold field of 573 kV/m, 1.5 m above the tower. The continuous curve in Fig. 2 shows the variation of this field as a function of the tower height. An effective height $H_{E1\text{-}km}$ of 102 m was determined for MCS tower. The dashed line indicates the effective height that would be found assuming the cloud charge as the sole source of electric field: 225.4 m.

Two main conclusions stem from the results of Fig. 2. First, the estimated effective height of MCS tower is significantly different from the value of 145 m determined in [2] (difference of about 50%). Secondly, the effective height of 102 m determined for the conditions of a negative CG lightning is less than the half value of the height of about 225 m determined solely from the background field, yielded only by the cloud charges in the same conditions.

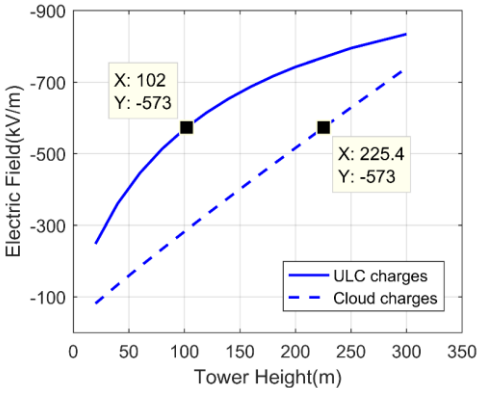

Fig. 2. Electric field produced 1.5 m above the tower placed over a flat ground (1000-m altitude) by the negative leader whose tip is 150 m distant from the tower tip (continuous line) and by the background field (dashed line).

In sections C and D, the results of a rehearsal intended to prospect the influence of the tower and mountain heights in the effective tower height are presented, considering a 1-km altitude flat ground.

C. *The influence of the tower height in the electric-field intensity above the tower*

As mentioned before, the electric field ahead the tower top governs the initiation of the propagation of the upward connecting leader. Fig. 3 exhibits the electric field calculated 1.5 m above the top of a tower with varying height, placed 400 m above flat ground at a 1-km altitude, resembling a condition somewhat similar to that of MCS ground. The height of the tower is varied from 10 m to 100 m. Note that the intensity of the electric field is very sensitive to the variation of the tower height.

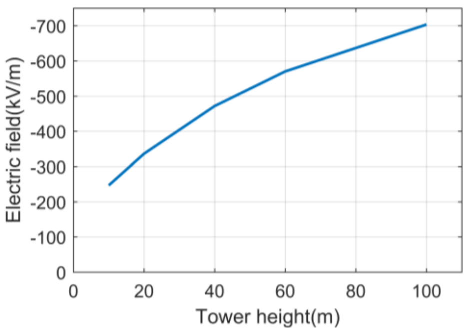

Fig. 3. Electric field produced 1.5 m above the tower, placed over a 400-m high hill over a flat ground (1000-m altitude), as a function of tower height, by the negative leader whose tip is 150 m distant from the tower top.

D. *The influence of mountain height on the effective tower height*

We also prospected how the variation of the mountain height affect this field, by varying this height whereas the tower height was preserved (60 m). The 400-m high mountain, whose shape was assumed a half-ellipsoid with a 400-m radius at the flat ground surface, had its height varied between 0 to 600 m, Fig. 4 exhibits how the intensity of the electric field 1.5 m above the tower is affected. Note that the field is not so sensitive to the mountain height variation.

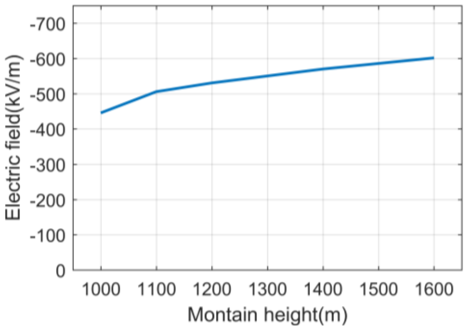

Fig. 4. Electric field produced 1.5 m above a 60-m high tower, placed over a mountain, whose height was varied from 0 to 600 m above a flat ground (1000-m altitude), as a function of mountain height by the negative leader whose tip is 150 m distant from the tower top.

E. The influence of the flat ground altitude

An aspect that deserves a discussion concerns the altitude of the flat ground to consider when comparing the effective height of instrumented towers installed in regions of different altitudes. Apparently, it should be the sea level (0 m).

This leads to a problem when determining the effective height for negative CG lightning using the approach of a bipolar bidirectional leader. The longer channel (for instance, that developed for a strike to a tower over 0-m altitude flat ground in relation to that of a higher altitude such as MCS: 1440 m) implies larger transferred charge for 0-m altitude case (6.13 C) and different distribution of charge along the channel. The overall effect is lowering the intensity of the electric field above the tower for the 0-m altitude. Thus, to reach the critical field 1.5 m above the tower, a shorter striking distance would be required. Furthermore, the effective height has to be determined considering lightning events exhibiting similar return-stroke characteristics (at least the same charge). To preserve the charge for a longer channel under the bipolar leader approach, one has to decrease the assumed corona radius of the leader (in relation to that of the event striking a tower placed at higher altitudes). Finally, considering the requirement of variation of the striking distance, it becomes clear that there are several solutions in terms of effective tower height. Several pairs SD and $H_{E\text{-}0m}$ are able to satisfy the threshold-field condition 1.5 m above the tower. In this scenario, we used the model described in Chapter 2 to determine the effective height of MCS tower over a 0-m altitude flat ground, adopting a reduced corona radius to ensure the same transferred charge (5.45 C). Note that this contributes to reduce further the electric field above the tower. Fig. 5 exhibits the variation of the electric field 1.5 m above towers of different heights placed over a 0-m altitude flat ground and allows determining the pairs of tower effective height and corresponding striking distance that satisfies the threshold condition (573 kV/m 1.5 above the tower). The corresponding values are presented in Table 1.

IV. Final Remarks

The preliminary results presented in this work for the conditions of MCS suggest that using more realistic approaches for determining the effective height of towers for negative CG lightning leads to values significantly different from those published in works adopting different approaches, when assuming a reference flat ground at the average altitude of the station surroundings (1000 m for MCS).

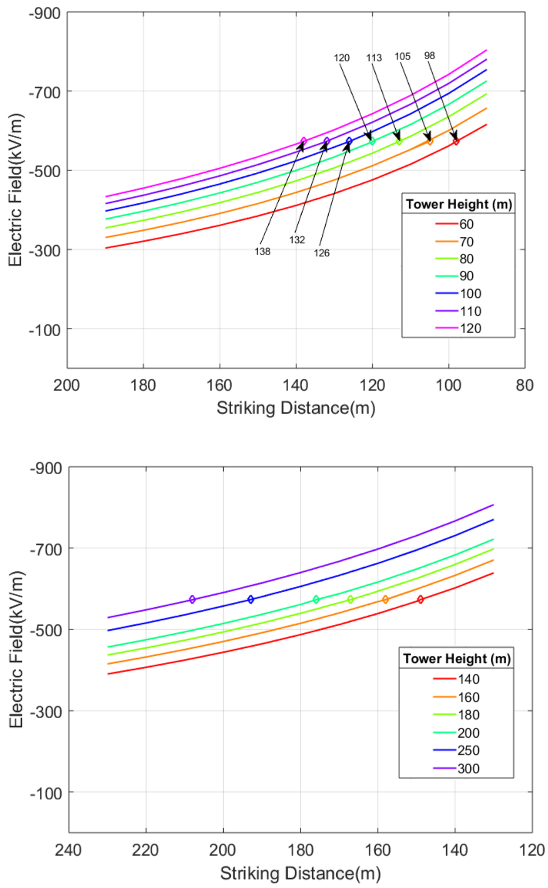

Fig. 5. Variation of the electric field produced 1.5 m above a tower placed placed over a 0-m altitude flat ground as a function of the striking distance by the negative leader approaching the tower. The tower height is varied from 60 m to 300 m.

Table I. Effective Towers Heights as a Function of the Striking Distance

$H_{E\text{-}0m}$ (m)	SD (m)	$H_{E\text{-}0m}$ (m)	SD (m)	$H_{E\text{-}0m}$ (m)	SD (m)
60	98	150	154	240	190
70	105	160	158	250	193
80	113	170	163	260	196
90	120	180	167	270	199
100	126	190	171	280	202
110	132	200	176	290	205
120	138	210	179	300	208
130	144	220	183		
140	149	230	187		

On the other hand, determining the effective tower height under the bipolar leader approach in reference to a universal 0-m altitude flat ground seems to be meaningless, as there is a large number of solutions, each one of them corresponding to a pair striking distance and effective tower height, shown in table I.

The results of this work are intended to be provocative, aiming to stimulate reflections on the concepts related to the application of effective heights presented in literature to problems involving negative CG lightning events.

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