Striking distance determined from videos of high-speed camera and simultaneous records of current of lightning strikes to a grounded structure

Silverio Visacro Miguel Guimaraes Maria Helena M. Vale

LRC – Lightning Research Center - Federal University of Minas Gerais
Belo Horizonte, MG, Brazil
Lrc@cpdee.ufmg.br

***Abstract* — Striking distances were determined from high-speed camera video records of recent flashes striking the instrumented tower of Morro do Cachimbo Station. Aspects related to the estimation of such distance in real conditions are discussed in light of the simultaneous records of lightning currents.**

Keywords - Video-records of lightning strikes to a tower, Striking Distance, Parameters of lightning strikes to a tower, Expressions to estimate Striking Distance.

I. INTRODUCTION

Although technical literature presents different meanings for *striking distance*, such as those presented in [1], the one that really matters for lightning protection is that defined originally in [2,3], as the distance of the extremity of the grounded structure to the downward leader tip, when an upward connecting leader is initiated from this structure. The striking distance is the key element to define the areas exposed to direct lightning strikes, which allows analyzing the competition among potential upward leaders initiated in the surroundings of the structure to define the one responsible for the attachment.

A large number of works in literature address the modeling of the final processes of lightning events to provide estimates of the striking distance, based on different approaches. In the past, several expressions derived from analytical and empirical developments were proposed to calculate this parameter from the lightning peak current, such as those suggested by a IEEE Working Group [4] and Erikson [5].

Recently, some elaborate models, such as that presented in [6], explore the correlation between the peak current and the charge transferred to the ground by the return stroke current during a given interval (for instance, in the first 100 μs) and assume a given distribution of this charge in the stepped leader to estimate the striking distance. In [7], the striking distance is modeled as a function of the leader potential instead of the leader charge. Any model developed for estimating the striking distance adopts simplifications in their formulation due to the complexity of the involved physical problem.

Notably the downward leader is represented by a single charged line, responsible for inducing the initiation of the upward leader from the structure. Depending on the model, the linear charge density is allowed to vary along this line. This simplification is adopted in well-known models employed to support the definition of protective practices, such as the Electrogeometric Model (EGM) and Leader Progression Models.

This work does not discuss such models. What it addresses is the determination of the striking distance from videos of a high-speed camera and a discussion of the impact of real conditions of the downward leader in this distance. This discussion is based on some recent videos of lightning strikes to an instrumented tower and corresponding simultaneous records of current in the time interval of a few hundreds of microseconds just preceding the return stroke.

II. MEASURING FACILITIES AND INSTRUMENTATION

All the data considered in this work were acquired at Morro do Cachimbo Station (MCS), in Brazilian southeast, where the vast majority of measured events corresponds to cloud-to-ground (CG) negative lightning [8,9,10]. Fig. 1 shows a view of this station with its 60-m-high instrumented tower, installed at an altitude of 1453 m, along with a view of the secondary shelter, where the camera is installed.

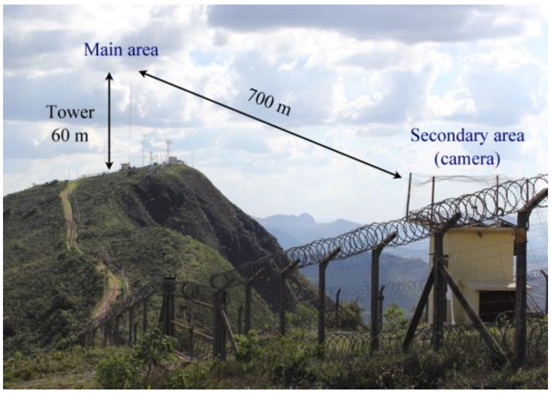

Figure 1. View of Morro do Cachimbo Station and of the shelter where the camera is installed.

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The configuration of the measuring systems in MCS at the time of the events reported in this paper is commented below.

Two Pearson coils installed at the tower base are responsible for measuring lightning currents flowing through the mast, with a resolution of around 5 A in a 9-kA scale (noise level of ±10 A) and of 72 A in the 200-kA scale. The trigger level is 60 A. The data acquisition board allows storing 1-s records of current, with a time resolution of 33 ns and a 30 ms pre-trigger period (details in Visacro [10,11]).

In a secondary shelter, approximately 700 m distant from the main shelter, a high-speed camera is installed to record videos of lightning strikes to the tower. After detecting the flow of any current higher than 200 A along the tower, the redundant current measuring system sends a signal to the computer connected to the camera via wireless network to start to store a video record. At the time of measurements, the camera was set to record 2.5 seconds of video at a rate of 20,000 FPS with a pre-trigger, which allowed recording the whole flash acquiring successive frames at 50-μs intervals from about 0.5 s prior to the detection of the current threshold. To improve the visualization of the leader in the figures of this paper, a photo editing software was employed to apply some corrections on the original frames, such as the calibration of brightness and contrast, inversion of color and modification of the level of exposure, of offset and of gamma correction.

Two electric-field measuring systems, consisting of Whip antennas installed in a horizontal position 45 m and 700 m away from the tower, are able to detect the variation of the field yielded by lightning events striking the tower. The measured signals are acquired at a sampling rate of 100 kS/s. Field mills installed in the main and secondary areas are employed to calibrate the electric-field-change measuring systems.

All the measuring systems are synchronized by GPS.

III. Measured Events and Estimated Striking Distances

A. Measured flashes

The discussions of this paper are based on the results of simultaneous measurements of quantities of a set of lightning events striking the tower of MCS. These events consists of a single and two multiple-stroke flashes (2 and 4 strokes), for which we also obtained videos captured with a high-speed camera. The main parameters of these flashes of interest for this discussion are presented in Table 1.

TABLE I. Parameters of the Strokes of Interest

Stroke	***I_P* (kA)**	***Q* (C)**
Single stroke May 8, 2014	18,49	0,92
1st stroke Feb.25 2015 – 1st flash	20,24	5,88
1st stroke Feb.25 2015 –Second flash	33,60	9,14
3rd stroke Feb.25 2015 – Second flash	26,26	4,95

B. Estimated striking distances

The striking distances of the four events were determined based on the video records. Basically, their values were estimated considering the two-dimensional distance between the tower top and the tip of the downward negative leader approaching the ground at the video frame in which the upward leader was noticed for the first time, as indicated in Fig. 2. The identification of the unipolar pulse of current assumed to be responsible for launching the initiation of the upward leader also contributed to a better definition of the frame in which such initiation took place. See an example of such pulses in Fig. 3 and a discussion about them in [11].

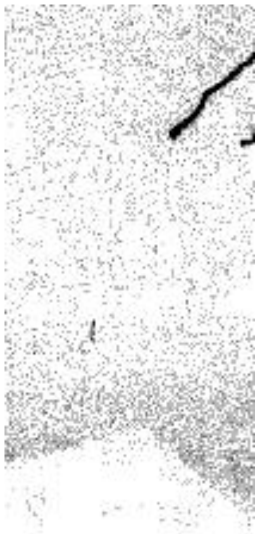

Figure 2. Example of the frame in which the upward leader was first detected.

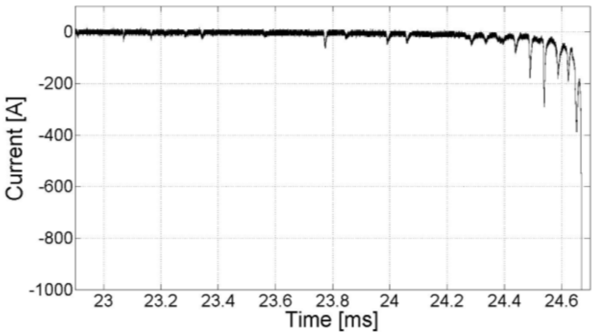

Figure 3. Unipolar pulses of current developed in response to the steps of the downward leader approaching the ground – Adapted from [11]

Anyway, the estimates comprises a certain level of error, associated to the “two-dimensional” nature of the measured distance, which tends to provide shorter striking distances. Also the time interval of 50 μs between frames, still considering the full exposure time during this interval, consist of a source of error. In this case, the error can result in shorter or longer distance. Nevertheless, the adopted method of estimation is considered reasonable in comparison with others methods reported in literature.

Table II shows the estimated striking distances for the strokes of Table I, along with their peak current. It also presents estimates of this distance obtained from the application of traditional expressions provided by the technical literature.

TABLE II. ESTIMATED STRIKING DISTANCES (SD)

Flash and stroke	***Peak Current (kA)***	***"Measured" SD* (m)**	***Estimated* SD (m)**	
			r_s^a	R_a^b
Single stroke May 8, 2014	18,5	132	53	85
1st stroke Feb.25 2015 1st Flash	20,2	106	56	90,6
1st stroke Feb.25 2015 Second flash	33,6	148	79	132
3rd stroke Feb.25 2015 Second flash	26,3	60	67	110

a IEEE WG [4]: $rs=8\,(kA)^{0.65}$ (m)

b Erikson [5]: $Ra=0.84H^{0.6}\,(kA)^{0.74}$ (m)

Apparently, the results of Table II suggest fragility of the estimates of the striking distance given by expressions that correlate this parameter with the peak current.

In most cases, the estimates given by the expression of IEEE WG developed under the assumption of flat ground exhibit larger error. The errors seem less pronounced for estimates of the expression by Erikson, which takes the height of the structure into account.

Following, conditions of each specific event, presumably responsible for the deviation in the estimated striking distances from those determined from the video records, are discussed.

IV. DISCUSSIONS

Figure 4 shows the last frame before the one that detected the attachment of the upward and downward leaders for each of the strokes mentioned in Tables 1 and 2. The exception is the first flash. In this case, the frame containing the attachment is presented, once the luminosity resulting from a lightning discharge during the previous frame prevented the possibility to distinguish the leaders at that frame.

As commented below, only two of these events can be considered ordinary first return strokes, the ones in the lines shown in yellow in Table II, corresponding to frames (b) and (c) in Fig. 4. For such events, though the estimates of striking distance given by the IEEE WG expression show errors of about 100%, the estimates given by Eriksson expression exhibit errors in the range of 10 to 15%, which is considered a quite reasonable result. The errors in the estimates of SD for the two other events are very large.

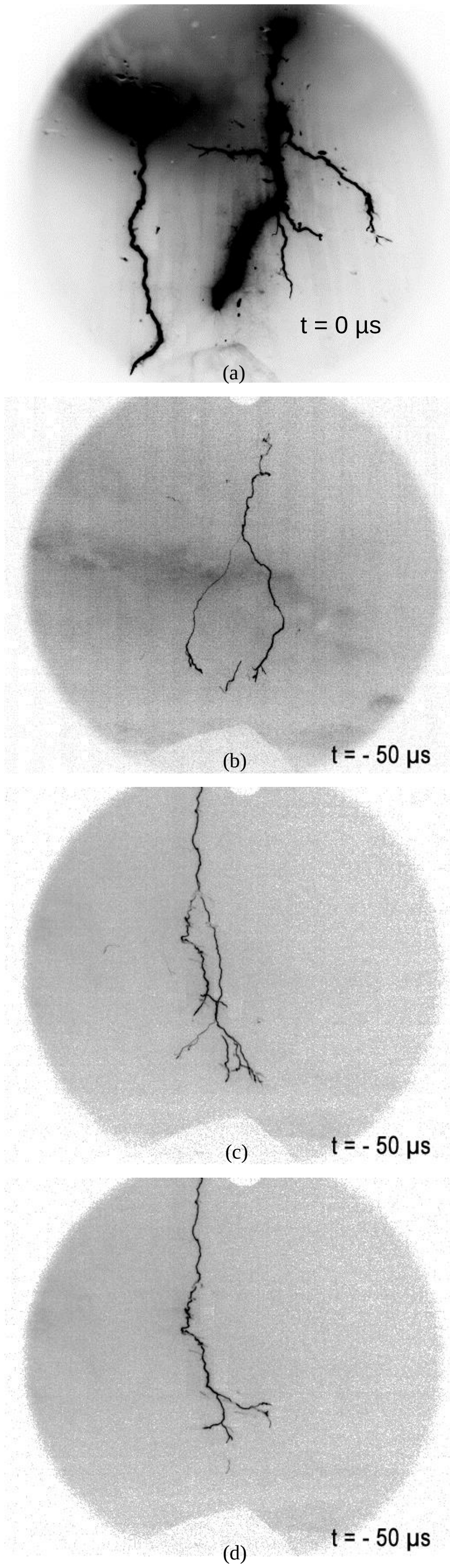

Figure 4. Frames of the downward and upward leaders of the four strikes to the tower of Morro do Cachimbo Station in their final stage to indicate specific conditions, except for (a). Same order of Table II.

Figure 4(a) shows that the initiation of the upward leader was developed under the influence of another previous leader (in addition to the influence of the leader that later connected to the tower). This previous leader resulted in an independent lightning event that terminated to the ground nearby the station a few hundred of microseconds before the current of the return stroke began to flow along the tower. The contribution to the electric field at the tower tip of the charge deposited in this previous leader explains the very large striking distance (132 m) for a peak current of 18.5 kA.

On the other hand, Figure 4(d) refers to a subsequent return stroke initiated by a dart-stepped leader. A very low value of the striking distance (60 m) is observed for a relatively large peak current (26.3 kA). However, is spite of the existence of some branching in the negative downward leader in the last 200 m above the tower due to the reconstruction of stepped leader, the waveform of the return stroke current is quite different from that of ordinary first stroke. It does not comprise a second peak and the decay is too fast. The time-to-half value has the same order of magnitude of the rise time, about 5 µs. Though branching of the downward leader is observed from a given height, indeed the current path was practically the same of that of the previous return stroke.

V. CONCLUDING REMARKS

Naturally, the number of samples of striking distance is too low to lead to any consistent conclusion. Nevertheless, the authors would like to share their results with the scientific community, once such kind of data is extremely rare.

It is worth mentioning some recent reports of a striking distance quite lower than the values estimated from the peak current using traditional expressions. The results of such reports are quite different from those observed in this work for regular first strokes.

Considering the samples of this work, there are some suggestions that the expression given by Eriksson based on peak currents and height of grounded structure is able to provide relatively consistent estimates of this parameter for regular first return strokes, with errors below 15%. The deviation in relation to the observed values of SD is conservative, in terms of lightning protection, meaning that it provides values of SD a little lower than those observed with the video camera. The results would become more conservative if one considers three-dimensional distances.

The results also denote that, in real phenomena, conditions may occur that affect strongly the striking distance and this may significantly deviate its value from that derived from expressions based on simplified models of the structures of the downward leader. In this work, the occurrence of a nearby independent return stroke a little before the one that terminated to the tower was responsible to increase substantially the striking distance value in relation to that calculated from the peak of the current flowing through the tower.

Also, it is worth commenting that the estimate obtained for a subsequent return stroke resulting from a dart stepped leader with clear branching process had a very strong error. Due to the branching process, this stroke could terminate to a distant point instead of the tower, for instance to the conductors of a transmission line. And, probably, in incidence analysis, it would be considered a first stroke, since it has a significant peak current compared with the median peak current of subsequent return strokes and no information would be available to identify it as a third stroke of a multiple-stroke flash.

To conclude, it is important to mention the need of prudency in relation to the comments above. Additional data is required to achieve any generalized conclusion about the striking distance.

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