2018 25th International Lightning Detection Conference &
7th International Lightning Meteorology Conference
March 12 - 15 | Ft. Lauderdale, Florida, USA

Striking Distance determined from a new criterion for initiation of the upward positive leader

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***Abstract*— Experimental results of negative downward lightning obtained at Morro do Cachimbo Station, Brazil, were used for determining striking distances according to four different approaches: using solely high-speed video frames; video-frames and records of current; video-frames, records of current and a reverse propagation procedure; current and a composite average propagation speed. A new criterion for positive upward connecting leader initiation was presented and discussed. The results showed that estimated first-return-stroke striking distances exhibit very high dispersion and are very different from striking distances estimated for natural subsequent return strokes and triggered-lightning strokes.**

Keywords—striking distance; negative downward lightning; positive upward connecting leader initiation.

I. INTRODUCTION

Striking distance (SD) is a parameter of great interest for lightning protection design and a controversial topic in lightning physics. The controversy concerns the existence of different concepts for it. According to the traditional concept, it consists of the distance between the tips of the negative leader and the grounded structure upon the upward connecting leader (UCL) initiation [Golde, 1945]. Other authors define it as the distance between the negative leader tip and grounded structure upon the break-through phase [Rakov and Lutz, 1990].

As far as lightning protection is concerned, the traditional definition is the relevant one. In this respect, many researchers have addressed the challenge of estimating the striking distance from parameters of the return stroke (RS), notably the peak current I_P, by means of very simple expressions of the type $SD = A \times I_P^B$. For instance, Love [1973] proposed values of 10 and 0.65 for the pair of constants A and B and this expression corresponds to the IEC-2010 curve [IEC standard 62305-1; 2010]. Elaborate theoretical models of the attachment process have also been used to determine this parameter, for instance those by Dellera and Garbagnati [1990a; 1990b], Rizk [1990], Mazur and Ruhnke [2003], Becerra and Cooray [2006]. On the other hand, recent experimental results of SD have been obtained from triggered lightning and negative downward lightning, for instance those by Wang et al., [2013; 2014; 2015], Tran and Rakov [2015], Visacro et al. [2016], Saba et al. [2017].

This work presents a discussion that explores the contents of a recent authors' paper [Visacro et al., 2017b], which considers conceptual aspects related to striking distance and quantitative results of this parameter. In this respect, the work presents a new criterion for assessing the UCL initiation, which is fundamental for determining SD (traditional definition), based on a threshold value of the continuous current preceding the return stroke (4-A threshold). This criterion is supported by experimental results of currents measured at Morro do Cachimbo Station (MCS) and by inferences from the process involved in the formation of positive leaders [Visacro et al., 2016a]. Detailed information about MCS instrumentation can be found in [Guimaraes et al., 2017; Visacro et al., 2017a; 2017b].

II. UPWARD CONNECTING LEADER INITIATION

As discussed in [Visacro et al., 2016a], under the effect of an intense electric field resulting from the superimposed effect of the cloud charges, the corona layer above the ground and the charges of the negative leader approaching the ground, streamers are developed from the grounded structure tip, and eventually, a positive leader is formed at the streamers root. The simple elongation of the conductive body (UCL), under the increasing local electric field, results in a very fast increase of the continuous current measured at the structure base. This behavior is clearly observed in the pre-return-stroke current of the first stroke in all negative CG lightning measured at MCS in the recent years.

It was amazing identifying a 4-A continuous current threshold as a common condition for launching this fast continuous-current increase in all records of measured currents. This led to the conclusion that this condition corresponds to the initiation of the positive sustained UCL from tower top.

Figure 1 illustrates this condition for the first stroke of a negative downward lightning flash measured at MCS on 25 February 2015, at 20:16:49 (UT). The typical profile of pre-return-stroke currents measured at MCS have been extensively discussed in [Guimaraes et al., 2017, 2018; Visacro et al., 2010, 2017a, 2017b].

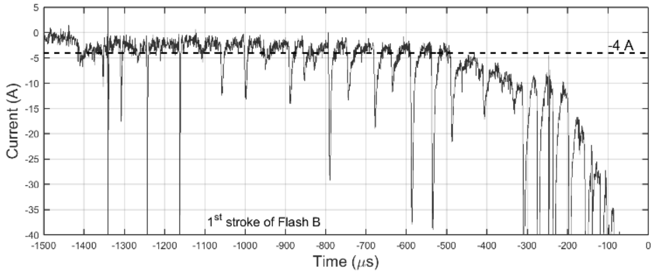

Fig. 1. The 4-A threshold for a pre-return stroke current of the first stroke of a flash measured at MCS on 25 February 2015, at 20:16:49 (UT). Adapted from [Visacro et al., 2017b].

III. Striking Distance of Events Observed At MCS

The discussions of this work are supported by the data of 17 negative CG lightning measured at MCS from 2008 to 2017. Complete simultaneous records of current, electric field, luminosity and high-speed video are available for 3 events. Their striking distance was determined using four different methodologies: from high-speed video only; from current and high-speed video; from current, high-speed video and a reverse propagation procedure. The fourth methodology, based only on the record of current and on an average composite propagation speed, was proposed and applied to 17 measured events.

A. *Striking Distance determined solely from high-speed video*

Figure 2 shows high-speed video frames of events A, B and C, in which the positive upward connecting leaders were visually detected for the first time (UCLs debut frame). As indicated in the figure, the corresponding SD were directly determined as the distance between the DNL and the tower top.

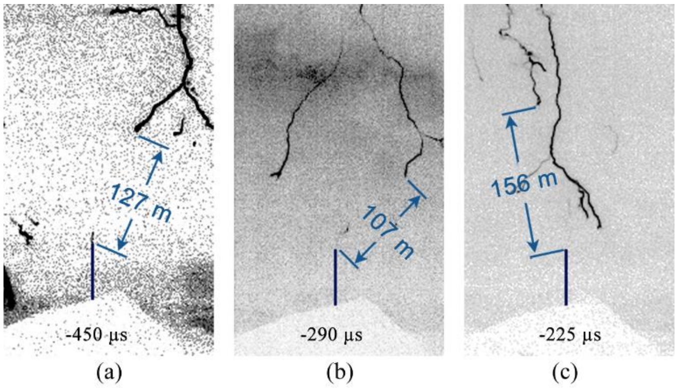

Fig. 2. Striking distance determiend solely from video frames of events: (a) A (8 May 2014 – 19:29:34 UT), (b) B (25 February 2015 - 20:16:49 UT), and (c) C (25 February 2015 - 20:29:43 UT). Adapted from [Visacro et al., 2017b].

B. *Striking Distance determined from current and video*

From the proposed criterion for UCL initiation, an improved methodology was developed: the striking distance was determined as the distance between the DNL and tower top in the frame recorded during the occurrence of the 4-A threshold. Figure 3 shows such frames with the corresponding calculated SDs. Note that, in most cases, the SD determined using this approach is longer than those estimated solely from UCLs debut frame, from 17% to 36% longer for events A, B, and C.

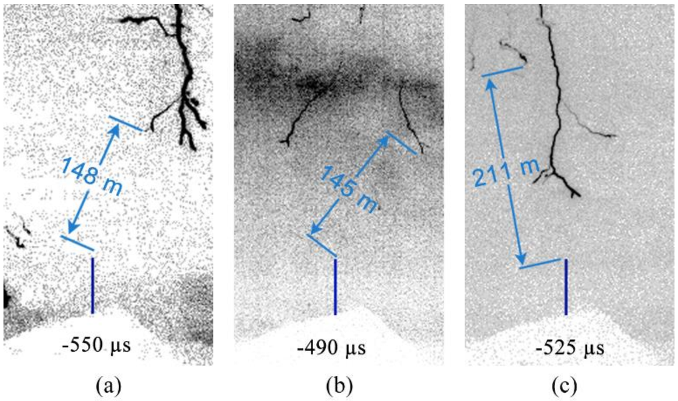

Fig. 2. Striking distance determiend from current and video. Adapted from [Visacro et al., 2017b].

C. *Striking Distance determined from current, video and reverse propagation*

A further improvement in the SD estimate can be achieved by means of a “reverse-propagation” procedure. The first step in this procedure consists of determining the position of the negative leader tip at the time the upward leader was first detected t_{ULd} in the video and the time elapsed between the UCL initiation t_{ULi} (4-A criterion) and t_{ULd}. Then, the distance propagated by the negative leader over this time interval (t_{ULd} - t_{ULi}) is determined from the corresponding leader propagation speed, as determined from the high-speed videos. Considering this distance along the negative leader path in the frame containing t_{ULd} (reverse propagation) allows determining the position of the negative leader tip upon UCL initiation and, therefore, the striking distance.

The SDs of events A, B and C calculated under this approach were, respectively, 152 m, 154 m and 225 m. This approach is considered the most accurate procedure among the four ones.

D. *Striking Distance determined from current records and a composite average propagation speed*

Once simultaneous measurements of current and high-speed videos are extremely rare, a new approach for estimating the SD based solely on records of current was developed. According to this approach, the distance between the negative leader tip and tower top upon UCL initiation is determined from a composite two-dimensional propagation speed of the upward and downward leaders ($v_{DL+UL} = v_{DL} + v_{UL}$) and the time elapsed between the occurrence of the 4-A threshold and the return-stroke initiation, Δt_{Ct-RSi}, equation (1).

$$SD = v_{DL+UL} \times \Delta t_{Ct-RSi} \quad (1)$$

Taking into account that the propagation speed of negative downward leaders observed at MCS with high-speed videos remains practically constant in the last hundreds of microseconds prior to the return stroke [Visacro et al., 2017b], a speed of 0.34 × 10^6 m/s was assumed for the representative composite propagation speed. Note that the impact of the dispersion of upward positive leaders' speed on the composite speed is relatively low due to the larger values of the negative leaders' speed, which exhibits extremely low dispersion. Although equation (1) tends to overestimate the SD, as it does not consider the leader path but a straight line, the three-dimensional nature of the striking distance tends to diminish this overestimation.

This approach was tested for event A, B and C, yielding the first-return-stroke SD estimates shown in the sixth column of Table I (Current and composite DNL speed), exhibiting errors lower than 18% in relation to those determined using the most accurate approach (current, video and reverse propagation). Then, it was used for determining the SD of all 17 records of first-return-stroke currents measured at MCS.

TABLE I. FIRST STROKE SDS OF MCS DATA
DETERMINED UNDER FOUR DIFFERENT APPROACHES

Event	I_P (kA)	Striking distance (m)			
		Debut frame	*Current and video*	*Current, video and reverse propagation (X)*	*Current and composite DNL speed (Y)*
A	-18.5	127	148	152	180
B	-20.2	107	145	154	167
C	-33.6	156	211	225	184

IV. DISCUSSION

Figure 3 depicts the SDs determined from MCS data using the two last approaches: X (fifth column of Table I - 3 events only); current and composite speed - 17 events. The figure also presents experimental SD results presently available in literature [Wang et al., 2013, 2014, 2015; Tran and Rakov, 2015; Saba et al., 2017], for first and subsequent strokes.

It is worth recognizing that the assumptions of all approaches contain errors, notably those related to the leaders' speed, uncertainties in ground termination position and peak current estimates. For instance, underestimations of about 20% and above can occur for individual peak currents estimated by LLS (Lightning Location Systems) for natural first and subsequent return strokes [de Mesquita et al., 2012]. Except for the results of this work and those of triggered lightning by Wang et al. [2013], all peak currents presented in Figure 3 were estimated by LLS. Moreover, the exact position of ground termination was not known in the results by Tran and Rakov [2015] and Wang et al. [2015].

As mentioned, the reverse propagation is considered the most accurate approach to estimate the SD. The differences between the propagation speeds of the positive and negative leaders calculated in this work and by Saba et al. [2017] suggest that assuming a same speed for both leaders, as done by Tran and Rakov [2015] and Wang et al. [2014, 2013], leads to underestimation of the SD. On the other hand, adopting a general composite propagation speed in the last 300 m propagated distance, as used in this work for estimating the SD of 17 first return strokes from records of current, is expected to yield moderate errors, as demonstrated by the SD calculated for events A, B, and C, which exhibit a maximum error of 18%.

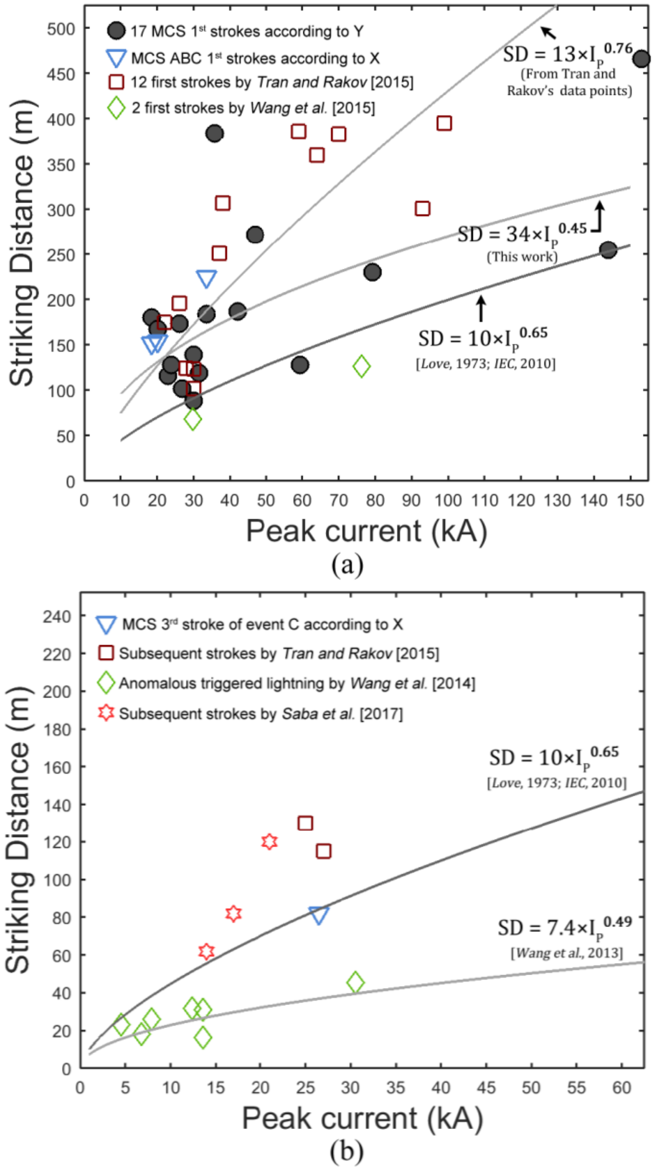

Fig. 3. Striking distances determined under different approaches. Adapted from [Visacro et al., 2017b].

Figure 3 reveals some general features, as the well-known trend toward the SD increase with increasing peak current.

It also denotes a very high dispersion of SD for natural lightning within any peak current range. This is an important observation, which should be expected, due to the very complex and specific geometry of negative leaders. Negative leaders exhibit multiple branches forged according to an unpredictable geometrical distribution. Though the initiation of the upward leader occurs at a defined threshold electric field value, the distance of the negative leader tip to the grounded structure upon this initiation can vary significantly, depending on the geometry of the negative leader's branches. Thus, *assuming a sole SD value for a given return stroke peak current is not realistic.* It would be physically sound only under the ideal condition of a single non-branched negative leader approaching the structure, as usually assumed in theoretical models.

Figure 3a presents samples of first return stroke peak currents varying from 18 to153 kA. Almost all estimated SD are longer than those given by IEC-2010 curve [IEC standard 62305-1, 2010]. The two samples by Wang et al. [2015] are exceptions, though it is worth mentioning that the corresponding SDs are probably underestimated due to the adopted assumption of equal propagation speeds for the negative and positive leaders. The data by Tran and Rakov [2015] show the largest discrepancy in relation to IEC-2010 curve, exhibiting significantly longer SD values. This can be, in part, attributed to the expected underestimation of the peak currents determined by LLS, though their assumption of a same speed for the positive and negative leaders tends to underestimate the striking distance.

The effect of the MCS tower's height and location at a mountain top is expected to increase the SD in relation to those found in flat ground. Nevertheless, the minimum estimated SD values for MCS data are very close to the IEC-2010 curve. Note that, probably, the SD results of the other works were developed for tall structures/objects as well, as the upward leader had to be long enough to be visually detectable by distant cameras.

Figure 3b presents SDs determined for natural subsequent strokes preceded by stepped leaders (peak currents within a narrow range from 14 to 28 kA). These results are relatively close to the IEC-2010 curve. Underestimation of peak currents determined by LLS would approach the data by Tran and Rakov [2015] and Saba et al. [2017] toward this curve, as well. The SDs estimated for the anomalous triggered lightning, including that of the first stroke, are all close to the curve obtained by Wang et al. [2013] for triggered lightning, which presents shorter values than those of subsequent strokes preceded by stepped leaders.

V. FINAL REMARKS

Figure 3 presented general features of the striking distance, such as the trend of increase with increasing peak currents, and a very significant dispersion. As commented, this dispersion indicates that the idea of a sole SD for a given peak current is not consistent. It would be possible only in the ideal condition of a single negative downward leader, with no branch, propagating towards the grounded structure.

The differences between SDs of first and subsequent strokes of comparable peak currents are expected, due to their distinct pre-return stroke profile, which only reflects the electric field above the grounded structures prior to the initiation of UCLs.

In Figure 3, the minimum striking distance values for first return strokes and new ground terminations strokes preceded by stepped leaders are all close to or longer than the values given by the IEC-2010 curve, which reinforces the use of this curve for a conservative estimate of the attractive radius in lightning protection design. Using shorter attractive radius in lightning-protection design provides better protection for grounded structures, meaning that the chances for shielding failure are decreased.

On the other hand, when it comes to the lightning performance of electric systems, for instance, of transmission lines, the frequency of strikes to the system is the most relevant parameter. In this respect, using the average curves of SD would be recommended, for instance, that determined for first return strokes in this work: SD = 34 × $I_P^{0.45}$.

ACKNOWLEDGMENT

This work has been supported by the Brazilian agency CAPES. Miguel Guimaraes would like to acknowledge the financial support provided by the Brazilian National Council of Technological and Scientific Development (CNPq) for his participation in this work, process number 151209/2017-0.

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