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On the features of a dart-stepped leader based on simultaneous measurements of current, e-field and high-speed video

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***Abstract*—This work discusses features of a dart-stepped leader in comparison to those of regular dart leaders that initiated subsequent return strokes measured at Morro do Cachimbo Station. The discussions are based on simultaneous measurement of lightning currents, electric fields and videos acquired with a high-speed camera. The video and simultaneous records are expected to be presented during the Conference.**

***Keywords*—Lightning; Subsequent return stroke; Dart-stepped leader; High-speed camera; Simultaneous measurement of lightning currents, electric fields and high-speed-camera videos;**

I. INTRODUCTION

About 80% of negative cloud to ground lightning flashes exhibit subsequent return strokes [Rakov and Uman, 2003]. A regular subsequent return stroke is formed by a dart leader that recharge the dissipating lightning channel a few tens of milliseconds after the flow of current of a first return stroke (or of a previous subsequent return stroke) ceases.

In some events, a long length of the lightning channel close to the ground termination is entirely dissipated before the start of the dart leader. In these cases, after recharging the remaining length of the channel, a dart-stepped leader is responsible for forging a new path to the ground in the virgin air, following a process similar to that of first stroke stepped leaders. In such events, the new termination is typically distant from the termination of the previous return strokes, being the average distance about 2.4 km, though distances around 10 km has already been reported [Rakov and Uman, 2003].

In this work, we address the features of a dart-stepped leader of a subsequent return stroke, which fortunately terminated to the tower of Morro do Cachimbo Station, where the preceding strokes had also terminated. The presented analysis is based on the simultaneous records of current, electric field, luminosity and on video records acquired with a high-speed camera, available for all strokes in the measured flash.

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II. THE MEASURING SYSTEM OF MCS

Morro do Cachimbo Station (MCS) is presently one of the few operating facilities in the world dedicated to the measurement of lightning current and other quantities. The station became operational in 1985, when a 60 m high instrumented tower was installed at a mountaintop located in the surroundings of Belo Horizonte, Brazil.

The MCS complex comprises two different areas: the main one, where lightning currents, ambient vertical electric field and relative luminosity are measured; and the secondary area, where lightning videos are recorded with high-speed cameras and vertical electric field data are acquired as well. These areas are distant 700 m from each other, as illustrated in Figure 1.

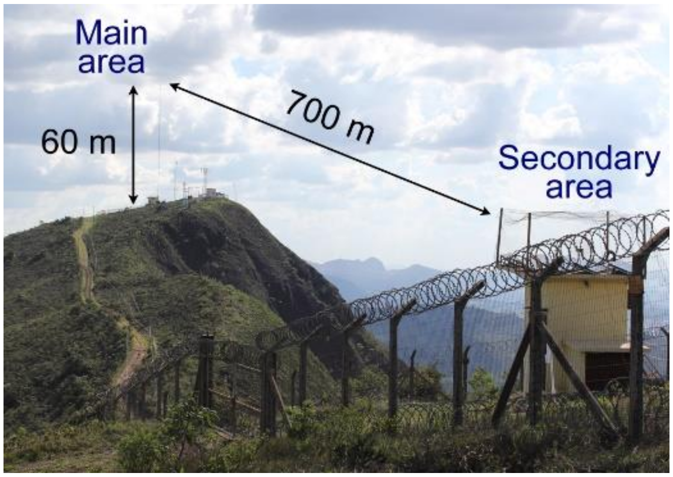

Fig. 1. View of Morro do Cachimbo Station (MCS)

A. *The measuring system of the main area*

Lightning currents are measured at the main area by two systems that work redundantly. Each system is composed by two

Pearson coils installed at the tower base and connected to attenuators and surge arresters. Such devices adequate the voltage level to the digitizer NI PCI-5105 installed in a personal computer and set to acquire data at a sampling rate of 60 MS/s.

The sensors and the digitizer cover a range from 5 A to 200 kA, presenting a very low noise level, around 10 A. The trigger level of the main current computer is 60 A. The second current computer is configured to send a communication signal to the camera whenever a current measurement is performed; hence, its trigger level is 200 A, higher than the first computer so that the probability of recording events not associated to strikes to the tower is low.

Four whip antennas, one plate antenna and one field mill are installed 50 meters far from the tower to measure ambient vertical electric field. These sensors feed an acquisition system that records data at a sampling rate of 100 kS/s.

An optical sensor pointing to the tower top is installed on the roof of the shelter and provides information about the ambient luminosity variation due to lightning occurring nearby. Such data is also acquired with a sampling rate of 100 kS/s.

B. The measuring system of the secondary area

On the secondary area, there is also a measuring system that record data related to the vertical ambient electric field during the occurrence of thunderstorms. This system comprises two whip antennas, one field mill and a digitizer that acquires data at a sampling rate of 1 MS/s. The trigger level of this system is ± 4 kV/m.

The video-recording system of MCS is installed at the secondary area and comprises a high-speed camera connected to a dedicated computer configured to store the videos acquired during lightning incidence to the tower. Presently, this camera is set to record videos at a sampling rate of 40,000 FPS, with an exposure time of 25 µs. When the measuring system of the main area detects a current higher than 200 A flowing along the tower, a video is recorded and stored by this system automatically.

III. THE RECORDED EVENT: FLASH 18

On February 25th, 2015, a negative downward lightning flash presenting four return strokes, named as Flash 18, was recorded at MCS. For this event, data from all the measuring systems of the station were acquired: current, electric field measured at distances of 50 m and 700 m, luminosity and videos recorded at a sampling rate of 20,000 FPS.

A. A brief description of the flash

Figure 2 depicts the simultaneous records of current, electric field measured at 700 m and relative luminosity during Flash 18. The time axis origin is centered at the instant believed to be that of the attachment of the first stroke. The interval between the strokes are: 63.7 ms (1st and 2nd), 85.8 ms (2nd and 3rd) and 85.1 (3rd and 4th).

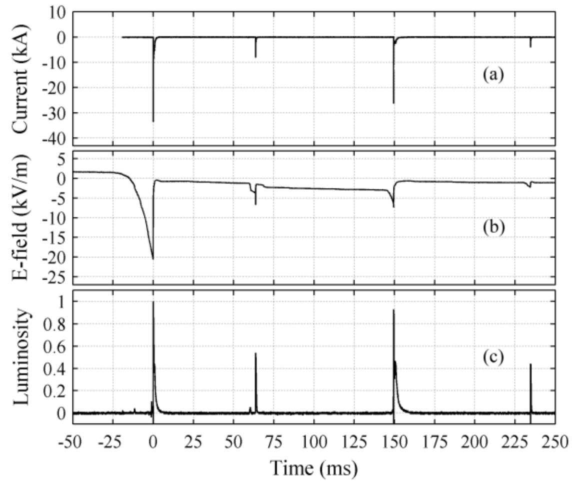

Fig. 2. Simultaneous measurements of (a) current, (b) electric field (700 m) and (c) relative luminosity of Flash 18 (February 25th, 2015)

The peak value of the first return stroke current (I_p) was about 34 kA and the total transferred charge (Q) was 9 C. The peak current of the subsequent return strokes are indicated in Figure 3, along with the waveform of their currents and total transferred charge per stroke.

Figures 3a, 3b and 3c shows, respectively, the current waveforms of second, third and fourth strokes. Considering all the subsequent stroke currents measured at MCS since 2008, the geometric mean (GM) of I_p and Q were calculated and their values are, respectively, 19.86 kA and 2.79 C.

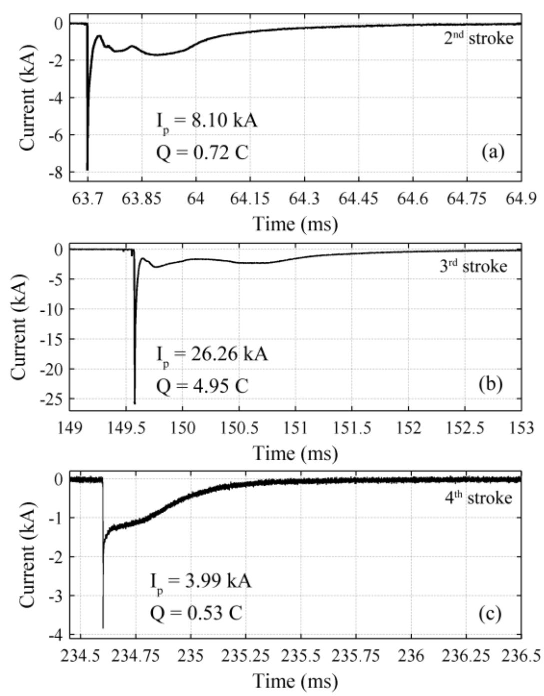

Fig. 3. Current waveforms of (a) second, (b) third and (c) fourth stroke of Flash 18

In the case of the second and fourth strokes, the computed parameters (I_p and Q) presented values much lower than the respective geometric means of subsequent strokes measured at Morro do Cachimbo Station.

On the other hand, the parameters calculated from the current waveform of the third stroke, indicated in Figure 3b, are significantly higher than the GM of MCS subsequent stroke current parameters. The peak current of 26.26 kA is 32% greater than the GM of 19.86 kA and the total transferred charge during the third stroke is almost 1.8 times higher than the GM of 2.79 C.

The current waveform of the third stroke differs significantly from the currents observed during second and fourth stroke. The wavefront of the third stroke current is slower, reaches higher values and lasts more, which leads to the observation that such current is, on average, more similar to a first stroke than to a regular subsequent. This difference is attributed to the fact that the third stroke of Flash 18 was initiated by a dart-stepped leader, while the other two subsequent strokes were initiated by regular dart leaders.

B. *The features of the third stroke*

Figure 4 shows a frame recorded 150 µs prior to the third return stroke. About 85 ms after the current of the second return stroke had ceased, the dissipating channel began to be recharged by an apparent regular dart leader. Approximately 500 µs before the third return stroke, a branching process was initiated at the tip of the former dissipating channel. The branching of the leader is a clear evidence that the third return stroke was preceded by a dart-stepped leader. This evidence indicates that the channel of the third stroke could have terminated to another point, distant from the tower. However, as observed on the acquired data, the dart-stepped leader did terminate at the tower.

In order to improve the visualization of the leader in Figure 4, a photo editing software was used to apply some corrections on the original frame, such as brightness/contrast calibration, colour inversion and level modifications of exposure/offset/gamma correction.

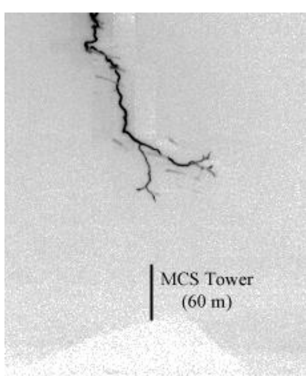

Fig. 4. Frame recorded with a high-speed camera 150 µs before the third return stroke of Flash 18 (exposure time = 50 µs, 20,000 FPS)

An interesting aspect, which is not exhibited in Figure 4, is the formation of an upward leader at the tower top just before the third return stroke.

The early phase of the current waveform of the third stroke also indicates some features of the stepped propagation of the leader, consisting of negative unipolar pulses of current, similar to the propagation of stepped leaders in first return strokes [Visacro et al, 2010]. Figure 5 illustrates the current recorded some hundreds of microseconds prior to the third (Fig 5a) and to the fourth (Fig 5b) return stroke. Note the smooth profile of the current initiated by a regular dart leader.

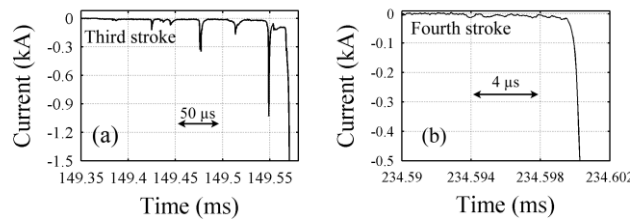

Fig. 5. Pre-return stroke phase of
(a) third stroke and (b) fourth stroke of Flash 18

The unipolar pulses of current in Fig 5a correspond to the measured response at the tower base to the stepped propagation of the downward leader that approaches the structure. Thus, they are not expected to be observed in subsequent strokes initiated by regular dart leaders.

Compared to the typical profile of currents of first return strokes [Visacro et al, 2010], a smaller number of the negative unipolar pulses was detected just before the third stroke. This is consistent with the fact that only the lower parcel of the lightning channel is formed by steps in the case of a dart-stepped leader.

Still regarding Figure 5a, similar to the profile of first return stroke currents, one can observe the negative pulses become superimposed on an uprising continuous current, a few hundred of microseconds before the return strokes. This uprising current is usually more intense in first strokes.

The video recorded during the occurrence of Flash 18 allowed calculating the average two-dimensional propagation speed of the downward leader. This propagation speed was determined for the first, second and third strokes, since the propagating downward leader could not be detected in the case of the fourth stroke.

For the last 16 steps prior to each return stroke, the two-dimensional length variation at the downward leader tip was accounted and the average propagation speed was computed during this 800 µs interval. The average propagation speed of the downward leader of the second and third stroke are, respectively, 0.36×10^6 m/s and 0.23×10^6 m/s.

As denoted by such computed values, the propagation speed of the dart-stepped leader (0.23×10^6 m/s) is very close to the typical value for stepped leaders found in literature (0.20×10^6 m/s), mainly because only the last hundreds of microseconds were considered on the calculation. Moreover, as expected, both values are lower than the one found for the regular dart leader observed on the second stroke (0.36×10^6 m/s).

Regarding the observed shapes of the first and third stroke lightning channel at lower altitudes (close to the tower tip), there was a discrete difference between them, as it can be seen in Figure 6.

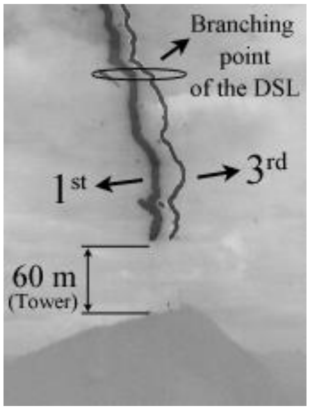

Fig. 6. Comparison between lightning channels observed during first and third stroke of Flash 18, with the indication of the branching point of the dart-stepped leader (DSL)

This image is the superposition of three different frames acquired with the high-speed camera: one recorded in a good weather condition; the other two recorded, respectively, during the first and the third return stroke phase of Flash 18. The colours of the lightning channel were inverted, the opacity of the three frames was adjusted to allow the simultaneous visualization of them and the frame containing the channel of the third stroke was horizontally displaced so that one can see the slight difference between them from the branching point to the tower.

Right below the indicated branching point of the dart-stepped leader in Figure 6, a visual inspection of both lightning channels allows one to note that they presented some minor differences in their geometries. This was expected, since at this altitude the leader started to propagate in a stepped fashion.

In the case of the second stroke, which was initiated by a regular dart leader, the lightning channel geometry is the same as the first stroke. Likewise, the lightning channel of the fourth return stroke, also initiated by a regular dart leader, preserved the shape of the channel observed in the third stroke.

IV. Final Remarks

The records of a flash measured recently at Morro do Cachimbo Station were discussed, with focus on the features of a dart-stepped leader observed in this event. Differences and similarities in the formation of strokes initiated by dart-stepped leaders, regular dart leaders and stepped leaders were addressed in the light of the measured data. Currents of each subsequent stroke were presented, as well as electric field data and relative luminosity of the entire event. Frames recorded with a high-speed camera during the flash occurrence, particularly during the third stroke, supported the discussion.

The video records clearly shows the branching of the leader after the initiation of the dart leader, about 500 µs before the third return stroke. This branching characterizes such leader in a dart-stepped one, that late connected to an upward leader initiated at the tower top, several tens of microseconds before the return stroke.

Since the dart leader began to step only 500 µs prior to the return stroke, the path forged in the virgin air that terminated to the tower is not very different from the path of the original channel crossed by the previous return stroke currents. The current waveform in the pre-return stroke phase shows a set of negative unipolar pulses developed in response to the dart-stepped leader approaching the ground.

It is noticeable the large charge transferred by the third return stroke and its peak current in comparison to those of the other regular subsequent return strokes. In addition, the average propagation speed of the dart-stepped leader (0.23×10^6 m/s) is lower than that of regular dart leaders and comparable to that of first return strokes.

References

Guimarães, M., Araujo, L., Pereira, C., Mesquita, C., Visacro, S., Assessing currents of upward lightning measured in tropical regions, Atmospheric Research, Volume 149, November 2014, Pages 324-332, http://dx.doi.org/10.1016/j.atmosres.2014.01.005.

Rakov, V. A., and M. A. Uman (2003), Lightning: Physics and Effects, Cambridge Univ. Press, New York.

Visacro, S., M. H. M. Vale, G. M. Correa; A. M. Teixeira, "The early phase of lightning currents measured in a short tower associated with direct and nearby lightning strikes", Journal of Geophysical Research, vol. 15, p. D16104, 2010.

Visacro S., Araujo L., Guimarães M., Arcanjo M. Lightning currents of upward leaders in negative downward events, In Proc. 8th Asia Pacific Int. Conference on Lightning, Seoul, Korea, 2013.

Visacro, S., A. Soares Jr. and M. A. O. Schroeder et al. (2004), Statistical analysis of lightning current parameters: Measurements at Morro do Cachimbo station, J. Geophys. Res. (109), D01105, doi:10.1029/ 2003JD003662.

Visacro, S., C. R. Mesquita, A. De Conti, F. H. Silveira. 2012. Updated statistics of lightning currents measured at Morro do Cachimbo station, Atmos. Res. 117, 55-63.