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Upward leader development observed with high-speed camera at Morro do Cachimbo Station and simultaneous records of current and electric field

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***Abstract*—Features of a specific lightning event registered at Morro do Cachimbo station are discussed, mainly with regard to the upward connecting leader development in the instrumented tower. Waveforms of current, electric field and relative luminosity provide useful and important information for the discussion, as well as videos acquired at a sampling rate of 20,000 FPS, to be presented during the conference.**

Keywords – negative CG lightning; upward connecting leaders; unconnected upward leaders; lightning attachment; lightning measurements;

I. INTRODUCTION

Negative downward cloud-to-ground (CG) lightning involves the propagation of a negative downward leader and the correspondent development of positive upward leaders in nearby grounded structures due to charge induction [1]. The lightning channel is established when the connection between these two leaders that propagates in opposite directions occurs. The conditions of the attachment process and of the upward leader initiation have been intriguing researchers for a long time.

In particular, the formation of upward leaders comprises, initially, the occurrence of negative unipolar pulses of current on the grounded structure, developed in response to the stepped propagation of the downward leader that approaches the ground. A few hundreds of microseconds just prior to the attachment, such pulses become superimposed to an uprising continuous current, which could be an indication of the upward leader inception in the structure [2,3].

This paper addresses the features of this pre-return-stroke phase, mainly with respect to the development of upward leaders in the instrumented tower of Morro do Cachimbo Station (MCS). The discussion is based on simultaneous measurements of lightning current, vertical ambient electric field, relative luminosity and videos obtained with high-speed cameras of a specific event registered at the station on February 25th, 2015.

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II. THE MEASURING SYSTEM OF MCS

Lightning measurements have been performed at Morro do Cachimbo Station (MCS) since 1985 [4-6], when an instrumented tower, consisting of a 60-meter high mast standing on insulators and supported by insulating wires, was installed at a mountaintop located in the surroundings of Belo Horizonte, Brazil.

The station comprises two different areas: the main one, where lightning currents, ambient electric field and luminosity are measured, and the secondary area, where videos of strikes to the tower are recorded by a high-speed camera, along with the associated vertical electric field. As illustrated in Figure 1, the secondary area is located approximately 700 meters far from the main one.

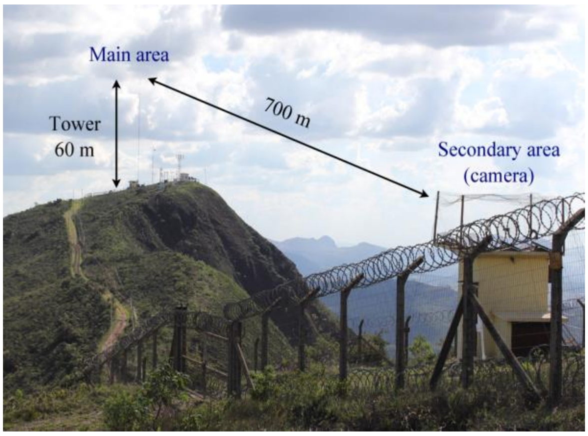

Figure 1. View of Morro do Cachimbo Station (MCS)

A. Main Area

The measuring system of lightning currents is the core of the station. Two NI PCI 6105 installed in different computers perform redundant data acquisition of currents flowing along the tower with sampling rates as high as 60 MS/s. Each system comprises two Person coils installed at the tower base and covers a range from 5 A to 200 kA, presenting a very low noise level, around 10 A. One digitizer is set to acquire data when current amplitudes higher than 60 A are detected. Since the other one is responsible for sending a communication signal to start the video recording, its current trigger level is 200 A.

Approximately 50 meters distant from the tower, there are six sensors installed to measure the vertical electric field during thunderstorms. Signals from five antennas (four whip and one plate) and one field mill are acquired at a sampling rate of 100 kS/s.

Additionally, an optical sensor pointing to the tower top is installed on the roof of the shelter. It provides information about the variation of ambient luminosity due to lightning occurring nearby the station. Such data is also acquired at 100 kS/s.

B. Secondary Area

On the secondary area, there is a video recording system that comprises a high-speed camera and a dedicated computer to store the videos acquired during lightning incidence to the tower. Presently, this camera is configured to record videos at a sampling rate of 40,000 FPS, which means that frames are acquired at every 25 μs, with an exposure time of 25 μs. At any moment a current higher than 200 A is detected flowing along the tower, a video is recorded by this system.

Two whip antennas and one field mill installed at the secondary area are connected to a digitizer NI PCI-6133 that acquires electric field data at a sampling rate of 1 MS/s.

III. TYPICAL CURRENT PROFILES OF PRE-RETURN-STROKE PHASE

Most of the analysis of negative downward lightning current in the literature focuses on the return stroke phase, mainly with respect to the parameters of the impulsive interval, such as amplitude, front time and maximum time derivative. The stage just before the attachment, sometimes referred to as early phase [2], comprises important aspects regarding the understanding of lightning attachment.

Figure 2 presents current waveforms of a negative downward lightning registered at MCS on April 13th, 2014 [6]. In Figure 2a, a time window of 3 ms shows the current recorded during the return stroke, while Figure 2b presents the early phase of this current.

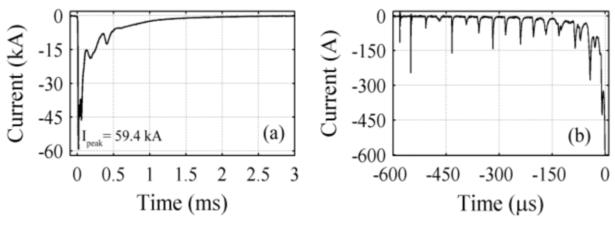

Figure 2. Current of a negative downward lightning recorded at MCS on April 13th, 2014, during (a) the return stroke process and (b) the early phase. Adapted from [6]

In this detailed portion of the initial stage, one can note the presence of the negative unipolar pulses, developed in the tower in response to a downward leader approaching the ground, and the uprising continuous current, initiated around -340 μs.

These two features can also be observed in the pre-return stroke phase of subsequent strokes initiated by dart-stepped leaders, but they are not expected to be noted in currents of regular dart leaders.

Current profiles of unconnected upward leaders also show these unipolar pulses and the uprising continuous current. Such leaders have the same nature of upward connecting leaders, since both are originated in grounded structures due to the approach of a downward leader. However, in the case of unconnected upward leaders, the connection with the downward leader fails and the charge stored in the upward one flows back to the ground.

Figure 3 presents a waveform of an unconnected upward leader measured at MCS on April 13th, 2014 [6], a minute after the event presented in Figure 2. The same unipolar pulses can be observed from -500 μs to 0 μs, as well as the uprising continuous current. Nevertheless, since this leader failed to connect the downward one, the current experiences a collapse: the positive charge deposited at the tower extremity and along the upward leader flows back to ground, resulting in a relatively intense current [2,3] of opposite polarity.

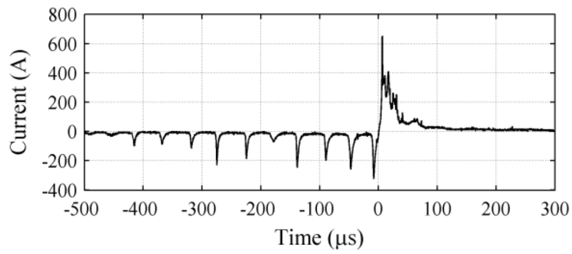

Figure 3. Waveform of an unconnected upward leader recorded at MCS on April 13th, 2014. Adapted from [6]

IV. THE UPWARD LEADER DEVELOPMENT IN A SPECIFIC FLASH MEASURED AT MCS

On February 25th, 2015, a negative downward lightning with two return strokes was registered at MCS. For this event, named as Flash 17, data from all MCS measuring system are available: current, electric field registered at 50 m and 700 m, relative luminosity and video record acquired with a sampling rate of 20,000 FPS.

A. Brief description of the event

In Figure 4, records of current, electric field (measured 700 meters far from the tower) and luminosity variation detected during the occurrence of Flash 17 are shown.

The time axis origin in Figure 4 is centered at the beginning of the first return stroke. The second return stroke was registered 36 ms later. The frames obtained just prior to the second stroke and the current waveform confirmed that this subsequent stroke was initiated by a regular dart leader.

According to Figure 4b, some tens of milliseconds before the attachment, electric field variations, presumably associated to disruptions occurring inside the thunderclouds, could be already observed. At -1.5 ms, a very intense disruption, which was also detected by the optical sensor, led to a stronger variation in electric field. The frames obtained by the camera showed that this strong disruption illuminated all the branches of the downward leader in the field of view of the camera.

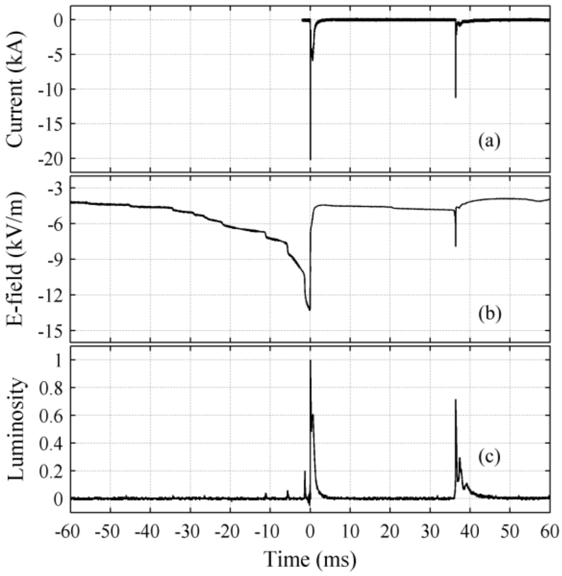

Figure 4. Recorded waveforms of (a) Current, (b) electric field measured at the secondary area (700 m) and (c) luminosity variation in relative units of Flash 17 (February 25th, 2015)

Figure 5 shows the current waveforms of each stroke of Flash 17, along with the amplitudes and the total transferred charge values. The peak current of the first stroke (20.24 kA) is 51% shorter than the geometric mean (GM) of 39.65 kA, calculated for the first stroke currents measured at MCS since 2008. However, the total transferred charge of 5.88 C is close to the GM of 6.17 C, also obtained for the same recent events.

In the case of the second stroke, its amplitude (11.24 kA) is also considerably shorter than the geometric mean calculated for subsequent strokes measured at MCS since 2008 (GM = 19.86 kA). Nevertheless, the total transferred charge during this stroke is 85% of the geometric mean of 2.79 C.

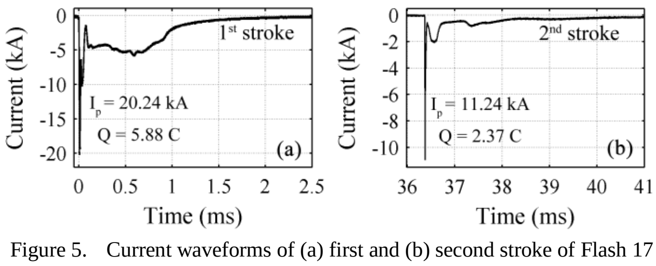

Figure 5. Current waveforms of (a) first and (b) second stroke of Flash 17

B. *Initial stage of the first stroke*

Adopting the same time reference of Figures 4 and 5, a detailed portion of the current waveform just prior to beginning of the first stroke of Flash 17 is illustrated in Figure 6.

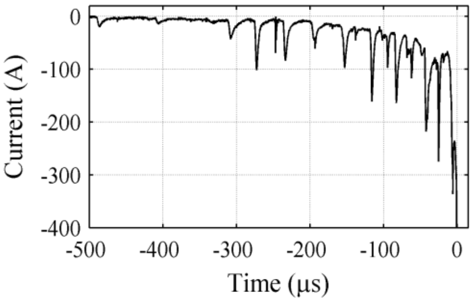

Figure 6. Initial stage of the current of the first stroke of Flash 17

The typical negative unipolar current pulses of early phases of first strokes can be observed and, apart from a few pulses, the interval between them is very regular, around 40 μs. The last pulse before the return stroke, observed in -6 μs, presented a peak value around 330 A, though in previous early phases current measurements registered at MCS, some pulses reached the kiloamperes range.

The uprising continuous current became more evident (average value around 10 A) in -400 μs, some tens of microseconds before the visual detection of the upward leader in the recorded frames. From -100 μs to 0, this continuous current reached values of the order of 100 A.

Figure 7 shows two frames acquired in different intervals of the event, using a 50 μs exposure time. In order to ease the visualization of the leaders, a photo editing software was used to apply some corrections on the original frame. First, the colors of the frame were inverted, so that the leader traces became more evident. Since the video was recorded during daylight, it is difficult to view the leader without such procedure. Then, the levels of brightness/contrast and of exposure/offset/gamma were adjusted to highlight the channel in relation to the ambient luminosity. These adjustments were carefully performed in order to preserve the original shape of the leader and the result is the clear view of the event in the frames of Figure 7.

The frame in Figure 7a precedes the one where the attachment was first observed, which means it was obtained at most 50 μs before the attachment. Figure 7b shows the frame recorded approximately 200 μs after the connection between the downward leader and the upward leader.

One can note the presence of two branches of the downward leader, indicated as A and B in Figure 7a, approaching the tower region. In -50 μs, each one presented two-dimensional length (from the branching point to their respective tips) greater than 250 m. A careful analysis of this figure reveals the presence of two different upward leaders initiated at the tower tip. This was the first time that such feature was observed in the video recordings obtained at MCS.

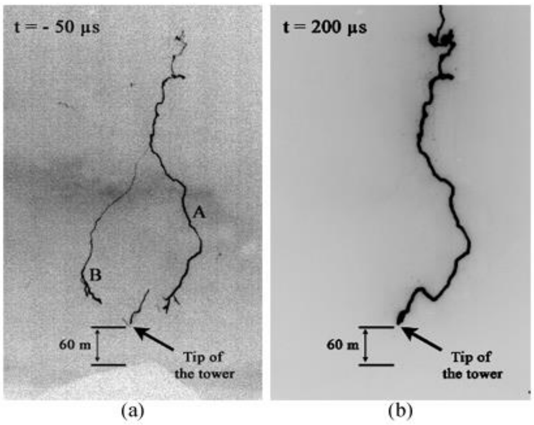

Figure 7. Frames acquired (a) just before and approximately (b) 200 μs after the attachment of the first stroke of Flash 17 (exposure time = 50 μs, 20,000 FPS)

The longest upward leader observed at -50 μs was induced by branch A, since the former propagated in the direction of the latter. Likewise, the shortest upward leader, which was observed only in the frame depicted by Figure 7a, developed towards branch B. The comparison between Figures 7a and 7b shows that the attachment occurred between the longest upward leader and branch A.

The simultaneous observation of the video recorded by the high-speed camera of this early phase, along with the correlated current and electric field waveforms, allows a better understanding of the upward leader development. Particularly, it is possible to observe a very interesting interaction between the downward leader branches and the tower.

In this respect, the regular interval between consecutive unipolar pulses in Figure 3 became disturbed by intermediary pulses since -150 μs. One can attribute the presence of these intermediary pulses to an increase on the propagation speed of the downward leader. However, as denoted by Figure 7a, a second upward connecting leader was developed from the tower during the last tens of microseconds before the initiation of the return stroke. Due to the direction of propagation, it is reasonable to conclude that branch B induced the formation of this new upward connecting leader.

Thus, the current waveform presented in Figure 3 comprises features of the development of both upward leaders. The intermediary pulses, which disturbed the regularity between pulses developed due to consecutive steps of branch A, are associated to the second upward leader. In the absence of branch B, such intermediary pulses would not be detected.

Since the subsequent stroke was initiated by a regular dart leader, in which steps and branching are not expected, one cannot observe the negative unipolar pulses indicated in Figures 2b, 3 and 6. The current of the pre return stroke phase of the second stroke, presented in Figure 8, shows no pulses. However, when it comes to subsequent strokes initiated by dart-stepped leaders, branches and pulses are likely to be observed.

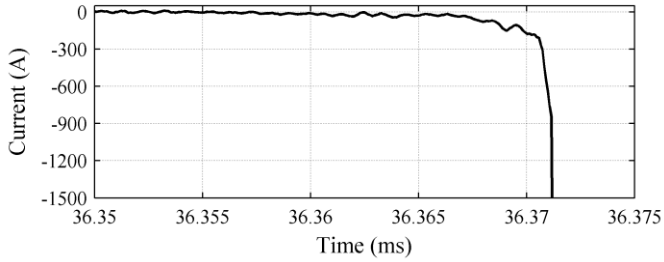

Figure 8. Initial stage of the current of the second stroke of Flash 17

V. CONCLUSIONS

The formation of two upward connecting leaders by concurrent branches, which had not been observed in previous videos acquired at MCS, was presented and this particular feature consists in a differential aspect of the data reported in this paper.

The features of the early phase of two consecutive strokes measured at MCS were discussed, based on current measurements and on videos recorded with a high-speed camera at a sampling rate of 20,000 FPS. The simultaneous analysis of such data allowed the observation of relevant features regarding the upward leader inception and development.

The frame recorded just before the first return stroke showed that two upward connecting leaders were developed from MCS tower. The unexpected intermediary current pulses observed prior to the initiation of the return stroke were attributed to the propagation of branch B. In the absence of such branch, no disturbances would be noted during the regular interval of about 40 μs between pulses induced by consecutive steps of branch A.

In the case of the subsequent stroke, no pulse was detected, since it was initiated by a regular dart leader.

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