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Recent lightning measurements and results at Morro do Cachimbo Station

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***Abstract*— Results of recent lightning measurements at Morro do Cachimbo Station are presented and discussed. Two sets of interesting and rare results consisting of first-return-stroke M-components and upward lightning currents measured in tropical regions are addressed. Simultaneous records of currents, electric-field change, relative luminosity and video, available for some of such events, are considered to provide two main findings. First, a very large frequency of occurrence of M-components was found during first return strokes (and not only superimposed on continuing currents), different from the usual assumption of a few percent of first return strokes followed by M-components. Also, the parameters of the upward lightning measured in MCS show specific features compared with the counterparts in temperate regions, notably a very small charge (typically of 6 C), shorter duration and higher average current in the initial stage. All events were induced by intra-cloud lightning.**

Keywords—Lightning measurements in tropical region; Lightning Currents; M-components of first return strokes; Upward lightning; Upward unconnected leaders.

I. Introduction

Morro do Cachimbo Station MCS is presently the only facility operating in tropical regions to measure lightning currents and associated quantities. It was built in 1985 at a hill, 1,430 m high above sea level and includes an instrumented tower, consisting of a 60-m-high mast standing on insulators and supported by insulating wires. It is located in the outskirts of Belo Horizonte (43°580´W, 20°000´S), in the Brazilian Southeast. A view of this station, with its 60 m high tower, is presented in Figure 1.

The data obtained in the first period of MCS operation, comprising the lightning-current records of 157 strokes is summarized in a JGR publication [Visacro et al., 2004]. Those data refers basically to cloud-to-ground negative lightning, since only one positive lightning current was measured there and upward lightning were not detected. The most relevant results were the median values of the measured peak currents, 45 kA for first and 16 kA for subsequent return strokes, about 50% and 30% higher than corresponding traditional references in literature [Berger et al., 1975; Anderson and Eriksson, 1980].

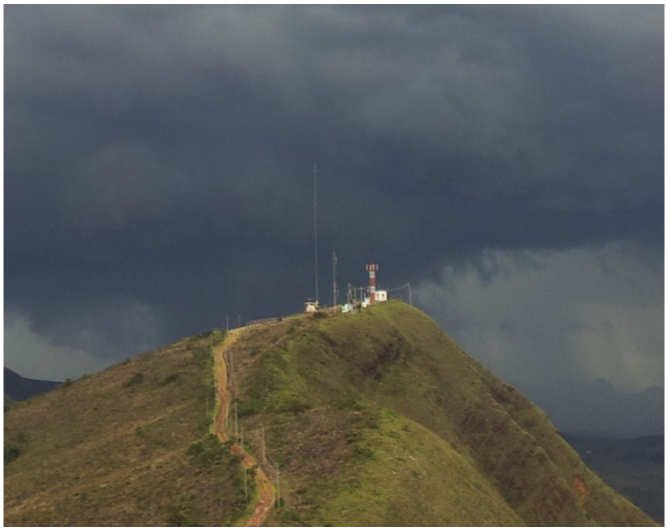

Fig. 1. A view of Morro do Cachimbo Station (MCS) - Brazil

This paper addresses some interesting results obtained at MCS recently, after the station measuring system was updated and had its recording capability vastly improved. Most of the results were obtained after 2010.

II. Measuring facilities

The core of MCS consists of the lightning-current measuring system. Currents of strikes to the instrumented tower are measured at the mast base. Presently, 1-s continuous records are stored for each current exceeding 60 A flowing along the tower, with a 33-ns time resolution and a 30-ms pre-trigger period (or alternatively 0.5-s-long records with a 17-ns resolution and 15-ms pre-trigger period). Two Pearson coils are used to measure the currents, within a range from 20 A to 200 kA, with a resolution of around 5 A in the 9-kA scale for noise level of ±10 A and of 72 A in the 200-kA scale. The current transducers feed an 8-channel data acquisition board with a sampling rate of 60 MS/s. In addition, a similar redundant system is used to ensure reliability of the measurements. Details of this measuring system are found in Visacro et al. [2010].

A high speed digital camera is installed in a shelter about 600 m away from the tower. It is triggered by the detection of a 200-A threshold current flowing along the tower and is synchronized by GPS to the current measuring system. An optical sensor installed on the roof of the main shelter, 20 meters away from the tower, is pointed to the tower top to record the changes of luminosity during the period of lightning current flow. An electric-field measuring system, consisting of Whip antennas horizontally installed 45 m away from the tower, is used to detect the variation of the field yielded by nearby return strokes (up to 10 km distant). A field mill is used to measure the ambient electric field and calibrate this electric-field-change measuring system. A single A/D data acquisition board installed in the shielded shelter is used for recording on a personal computer the synchronized data from the whip antennas, field mill and optical sensor along with GPS information, at a sampling rate of 100 kS/s.

III. Summary of Events Measured at MCS Recently

Table I summarizes the total number of events, whose currents were measured at Morro do Cachimbo Station from the end of 2008 to Dec. 2013, all of which of negative polarity. Most of the records were measured after 2010. Operational failures were frequent in 2008 and 2009, leading to the loss of records. In the last two years, no record of lightning events has been lost, increasing the number of measured flashes (7 flashes measured during the campaign of October 2012 to April 2013).

TABLE I. Summary of Records Of Currents Measured Recently at MCS (Negative Polarity)

Event	*Number*	*Percentage*
Total number of records	57	100 %
Associated with Downward Lightning.	48	84%
Connected Leaders (flashes since 2008)	16	28%
Unconnected Upward Leaders (since 2011)	32	56%
Upward Lightning (since 2010)	9	16%

In light of the previous results of measurements at MCS, it is worth remarking a few aspects. First, the median peak currents of negative cloud-to-ground lightning still remains significantly higher than those by Berger, about 50% and more than 30% for first and subsequent return strokes. Secondly, the frequency of upward lightning has increased significantly. Furthermore, the currents of a large number of unconnected upward leaders have been measured after the measuring system´s trigger was set to 60 A.

The present work focus on two differential aspects related to the recent measurements at MCS, the occurrence of first-stroke M-events and specific features of the current of local upward lightning. Apparently, these are the only currents of natural upward lightning measured in tropical regions. Some results about upward unconnected leaders are also considered. This work discusses and summarizes the results and findings of 3 recent works by Visacro e al. (2013), Guimarães et al. (2014) and Visacro et al. (2013b)

IV. Measured M-components of First Strokes

A. First simultaneous current- and video-record of M-events in natural lightning.

On October 19th, 2012, we measured for the first time the current of a natural first-return stroke exhibiting M-components in negative cloud-to-ground lightning. This measurement was considered special because, in addition to the record of currents, we also got the correlated video-, the electric-field-change- and relative-luminosity-records. Fig. 2 shows the simultaneous records of the measured current and video of this first return stroke, which depicts the 250-µs spaced video frames along with the 17-ns spaced records of current in a 3.5 ms time scale.

The flow of two M-component currents clearly matches the increase of luminosity of the faint channel detected by the fast video-camera. The details of such M-components in amplified scales of current shown in Fig. 3 and Fig. 4 denote that their parameters are all compatible with those of triggered lightning.

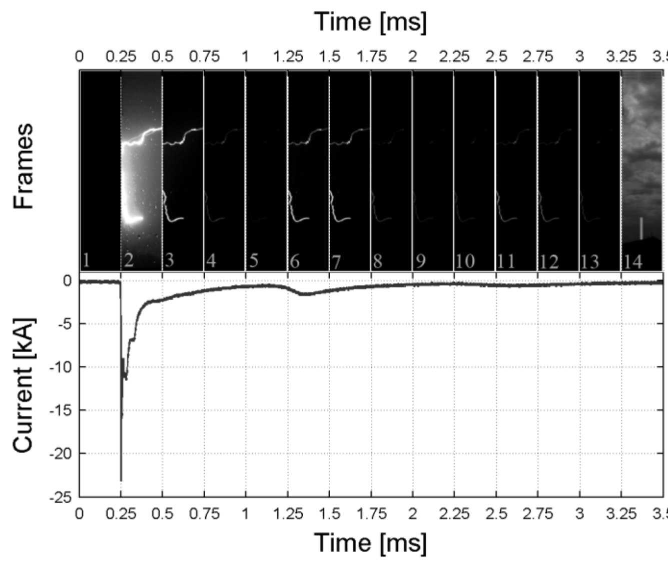

Fig. 2. Simultaneous records of current and video of a first return stroke exhibiting two M-components. Adapted from [Visacro et al., 2013].

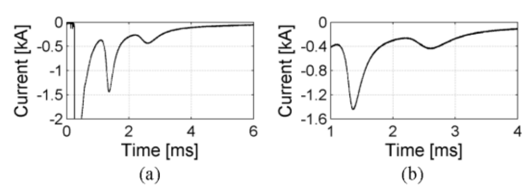

Fig. 3. Details of the 2 first-return-stroke M-component currents. Adapted from [Visacro et al., 2013]

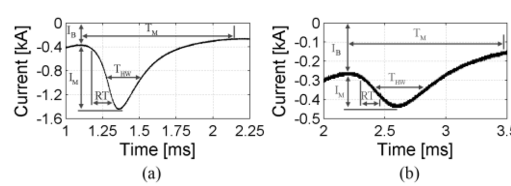

Fig. 4. Details of the 2 first-return-stroke M-component currents. Adapted from [Visacro et al., 2013]

Also, the records of the optical sensor and of the electric-field changes were all consistent with triggered lightning M-components, including the time-shift of the peak of the M-component electric field in relation to the current peak at the close range [Mazur and Ruhnke, 2011].

Inspecting the records of current of the recent first-return strokes measured at MCS, one intriguing aspect was observed. Apparently a lot of records seem to exhibit features of M-components, different from the expectations by Thottappillil et al. [1990] of a rare occurrence of first-return-stroke M-components, based on the expectation of a very low number of first return strokes followed by continuing currents (a few percent), though apparently consistent with the frequency of such events in the records by Malan and Schonland [1947]. This apparent contradiction motivated speculating on the frequency of first-return-stroke M-components, as discussed next.

B. M-events observed in recently measured first return-stroke currents

We examined all the recent first-return-stroke currents measured at MCS. Around 50% of the examined records exhibited M-components. In Table II, the parameters of such events are compared with those of triggered lightning reported by Thotappillil et al. [1995].

TABLE II. COMPARISON OF THE STATISTICAL PARAMETERS OF M-COMPONENT CURRENTS OF THE FIRST RETURN STROKES MEASURED AT MCS (ONLY 7 SAMPLES CONSIDERED WITH ELLAPSED TIME > 90 μS) AND OF TRIGGERED LIGHTNING [THOTTAPPILLIL ET AL., 1995].

Parameter	1st return strokes Geometric Mean (min-max values)	Triggered lightning Median (95% - 5%)
Magnitude I_M (kA)	1.65 (0.19 - 4.54)	0.12 (0.02 - 0.76)
Risetime R_T (ms)	0.06 (0.019 - 0.22)	0.42 (0.1- 1,8)
Duration T_M (ms)	0.41 (0.12 - 1.11)	2 (0.6 - 7.6)
Half-peak width T_{HW} (ms)	0.16 (0.049 - 0.38)	0.8 (0.19 - 3.6)
Base current (A) / CC level I_{CC} (A)	2,491 (260 -12,700)	183 (34 - 991)
Charge Q (C)	0.32 (0.09 - 0.79)	0.13 (0.03 - 0.38)
Elapsed time ΔT_{MR} (ms)	0.33 (0.09 - 2.00)	7.7 (0.7 - 156)

Compared with the triggered-lightning counterparts, the measured first-return-stroke M-component currents are relatively more intense, lasts shorter time and transfer a magnitude of charge to the ground about 3 times higher than those observed in triggered lightning.

Typically, the elapsed-time of the first M-components in different events were very short, from 0.2 to 0.85 ms, shorter than the return-stroke duration. This is consistent with the results obtained from first-return-stroke E-field change by Malan and Schonland [1947]. This means that the first M-components occurred during the return stroke process rather than superimposed on continuing currents following the return stroke. This explains the discrepancy in the finding of around 50% of first-return-stroke records of current exhibiting such components in relation to the expectations in Thottappillil et al. [1990].

C. M-events observed in recently measured electric-field changes of lightning strokes nearby MCS

To enlarge the analyses, we also examined the E-field change records of first return strokes measured in 3 recent storms nearby MCS. M-component changes were observed in more than 10% of the records, though this number is expected to be significantly higher due to the low resolution of the analyzed records that limits the capacity to distinguish low-amplitude M-components.

D. Conclusions

The results commented above show that M-events are a common feature of first return strokes. The percentage of first return stroke exhibiting M-components is definitely expected to be in the range of tens and not of a few percent.

The first M-component frequently occurs during the return stroke process rather than only superimposed on the continuing current following the return stroke. Apparently, this also holds true for subsequent return strokes.

Thus, we suggest improving the concept of M-component [Rakov and Uman, 2003] to include the finding above. It could be expressed as the process of charge transfer from ground upward while the lightning channel is still active. This process causes an enhancement of the channel luminosity due to the surge of current traversing the channel during the return stroke current of first and subsequent return strokes, superimposed on continuing currents or during the initial continuous-current stage of object-initiated and rocket-triggered lightning.

V. MEASURED UPWARD LIGHTNING

A. Introduction

Upward lightning currents are rarely measured in tropical regions. Recently we measured 9 upward-lightning currents at the short instrumented tower of MCS in addition to the currents of 32 positive unconnected upward leaders. Simultaneous records of current, electric-field change, relative luminosity and video were obtained for some of these upward events.

Figure 5 shows the records of current of an upward lightning event measured recently at MCS, comprising a typical initial stage IS (Diendorfer et al., 2009), followed by a single 6.5-kA-peak return stroke about 250 μs later (a). It shows the initial low intensity and long duration continuous current I_{CC}, whose average and maximum values are about 150 A and 560 A, respectively. No I_{CC} pulses were observed.

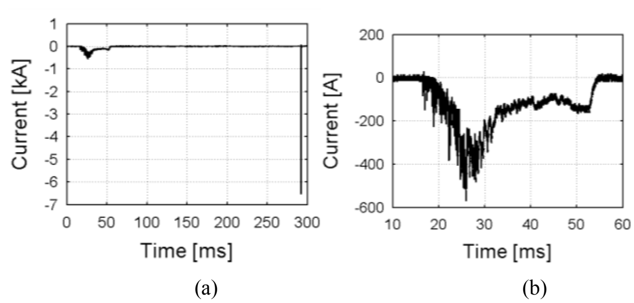

Fig. 5. Record of current of an upward lightning measured at MCS on Nov. 16, 2012: (a) the whole record, including the initial stage IS followed by a single return stroke, (b) detail of the initial continuous current stage. Adapted from [Guimarães et al., 2014].

The simultaneous records of the measured current and electric field change (measured 45m distant from the tower) of the negative upward event in Figure 5 are shown in Figure 6.

Presumably, Fig. 6 shows a negative electric field change produced by an intracloud negative leader approaching and passing by the tower, and the slow positive electric field change of an upward leader starting from the tower [Mazur and Ruhnke, 2011]. Note that the current starts at the beginning of the upward electric-field excursion. The abrupt negative electric-field change just before the upward leader initiation could be attributed to a change in the direction of the negative leader toward the tower. Also note that the lightning location system LLS indicated no return stroke at the time this event occurred. Quoting Visacro [2013], "Since positive leaders usually do not show regular steps, the presence of the positive unipolar pulses of current prior to the upward-leader initiation and superimposed on the current in the initial stage reinforces the interpretation that such pulses are displacement currents developed in response to the steps of a negative leader of an intracloud flash approaching and passing by the tower".

B. Features of the upward lightning

The analyses of the measured data revealed that all the upward events were negative (meaning that the upward leaders were all positive). The correlated electric-field changes, available for 8 events (and luminosity in the video just before the events, in some records) show they were all triggered by nearby lightning [Wang et al., 2008]. The finding of 100% of upward events triggered by nearby lightning is consistent with the results by Warner (2011), also developed in warm periods.

Only two upward lightning events exhibited return strokes following the initial continuous current. The first one had a single return stroke with a 6.5-kA peak current (charge transfered of 0.35 C) and the second had 4 return strokes with peak currents varying from 3.1 to 10.4 kA (charges varying from 0.08 to 0.16 C). Only 4 events of 9 presented pulses superimposed on the continuous current in the initial stage, not one of these pulses exceeding 2 kA.

The average current of the upward lightning events at MCS has a larger geometric mean (197 A), almost twice that of currents measured in temperate regions, but the geometric mean of their duration (26 ms) is about 10 times shorter. Their specific energy (geometric mean of $1.6 \cdot 10^3$ A^2s) is comparable to that of events measured in temperate regions, though about 2 to 3 times lower. All events show positive unipolar pulses of current in the phase preceding the initial stage - very similar to those of the early phase of first-strokes and of unconnected upward leaders. These pulses are interpreted as displacement currents induced by a negative intracloud leader approaching the tower.

The most impressive finding is a typical value of around 6 C for the charge transferred in the initial stage by 8 of 9 measured upward lightning currents. This value is about 5 times lower than the geometric mean of the charge of upward lightning measured in temperate regions but coincides with the geometric mean of the charge of first strokes measured at MCS. The implication in terms of physical interpretation of this result is still under analysis.

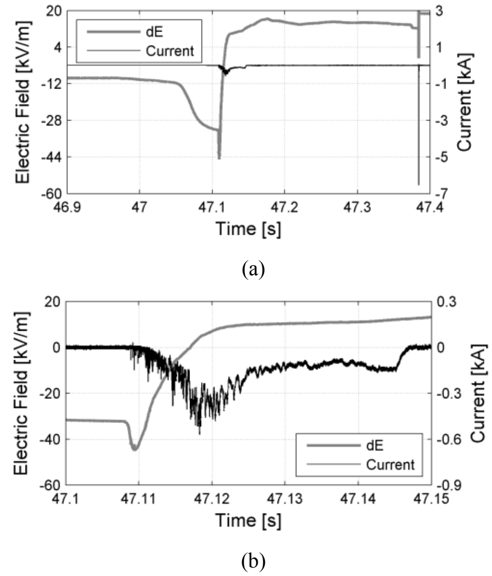

Fig. 6. Simultaneous records of current and electric field change measured 45m distant from the tower (electric-field change calibrated using a field mill). Adapted from [Guimarães et al., 2014].

VI. MEASURED UNCONNECTED UPWARD LEADERS

The most frequent event measured at MCS consists of unconnected upward leaders. The current of such events shows a very specific profile, including a polarity change, as illustrated in Fig. 7.

This profile consists basically of unipolar pulses of current that corresponds to the displacement of electrons downwards the tower in response to the stepped leader approaching the ground (or positive pulses of conventional current flowing upwards). Such pulses are quite similar to those of first-return strokes in the pre-return stroke phase [Visacro et al., 2010]. They are seen in the 3-to-1-ms period prior to the collapse of current, typically with a few-microseconds front-time and average duration around 10 μs and an inter-peak interval around 50 μs. After a sequence of low-amplitude unipolar pulses of current (from 20 to 200 A) in a few millisecond interval, an uprising continuous current becomes evident around 300 μs prior to the collapse of current. Stronger pulses of current are superimposed to such uprising current.

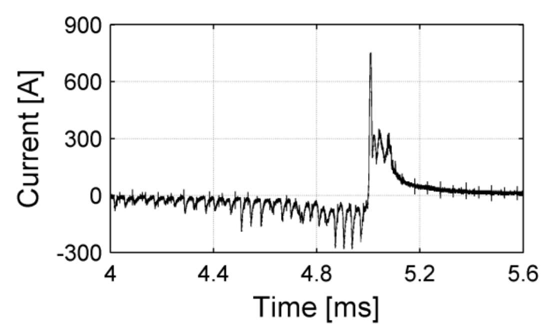

Fig. 7. Typical profile of current of upward unconnected leaders measured at MCS. Adapted from [Visacro et al, 2013b].

Quoting Visacro (2013b), “The difference on the current profiles of connected and unconnected leaders corresponds to the final phase preceding the return stroke or the collapse of currents (last around 300- µs prior to both events). While in the connected leaders the current experiences a continuous and consistent increase from a few hundreds of microseconds before the return stroke, in the upward unconnected leaders the current rises but retains a certain value, without evolving, until the process collapses. The positive charge deposited at the structure extremity and along the upward leader is then discharged to the ground, causing the flow of a relatively intense current”. In the presented case, after a short time (less than 10 µs) the discharge current reached a peak of hundreds of Amperes.

The charge displaced upward the tower before the collapse of current is very reduced (from a few to around 100 mC) and is basically equal to that of the discharge. Fig. 8 denotes this aspect for a specific event measured at MCS. The charge is determined from the integration of the current (pulses plus uprising current within an interval of 2ms before the collapse) and is about 3 mC. The peak current of the discharge is 134 A.

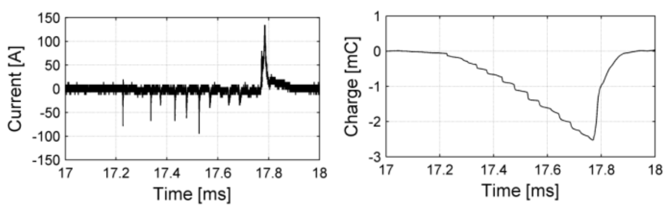

Fig. 8. Charge transferred by the current of an unconnected upward leader. Adapted from [Visacro et al. 2013b].

Table 3 shows the geometric mean of some parameters of current of 11 unconnected upward leaders measured at MCS, which presented very clear records.

TABLE III. PARAMETERS OF UNCONNECTED-LEADER CURRENTS

Parameter	*Discharge current peak (A)*	*Charge* (mC)*	*Number of pulses > 20 A***	*Pulse peak (A)*	*Interpeak interval GM (µs)*
Geometric Mean	**274**	**7.9**	**9.5**	**-72**	**48**

* Charge accumulated by the unipolar pulses or discharged

** within the interval of 500 µs prior to the charge collapse

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