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# Return stroke peak current observations of negative natural and triggered lightning in Brazil

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## Abstract

Observations of return stroke peak currents of negative natural and triggered lightning flashes in the Southeast region of Brazil are reviewed based on recent direct measurements. The natural flashes, both downward and upward, were captured in a 60 m tower in the Morro do Cachimbo Station. The triggered flashes were induced by the rocket-and-wire technique in the International Center for Triggered and Natural Lightning Studies, located in Cachoeira Paulista, Brazil, using both the classical and the altitude methods. Large variations in the peak current values were observed. The two data sets are compared to each other and to similar measurements done in other regions of the world, in an attempt to construct a general comprehensive picture of the peak current of different return strokes. © 2005 Elsevier B.V. All rights reserved.

*Keywords:* Natural lightning; Triggered lightning; Lightning peak current; Return stroke

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## 1. Introduction

Return strokes are one of the three mechanisms of charge transfer to ground during ground lightning flashes (Rakov et al., 2001). Their characteristics can be used to infer the thunderstorm electrical structure at different locations, as well as to improve lightning protection methods. First return strokes of natural downward negative flashes are known as typically more intense than other return strokes. About the relative intensity of the other

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types of natural (subsequent strokes of downward flashes and strokes of upward or object-initiated flashes—here considered as natural flashes) and triggered return strokes of negative flashes, Rakov (2001) found a similarity of the statistical peak current distributions, from measurements at objects with heights ranging from 4.5 to 540 m.

In Brazil, lightning observations in instrumented towers began in 1985 in the Morro do Cachimbo Station (MCS), located in the Southeast region of the country (Pinto et al., 1997, 2003). Since then, almost a hundred flashes were captured. By turn, triggering lightning observations began very recently (in 2000) in the International Center for Triggered and Natural Lightning Studies (ICTNLS), also in the Southeast region (Saba et al., 2002, submitted for publication). Up to the present, 13 flashes were triggered.

In this paper, a summary of the results obtained by these observations in terms of the return stroke peak currents of negative flashes is presented. In the last decades, this parameter has received more attention than the others lightning waveform parameters because it is the only one that is measured with a reasonable accuracy by lightning location systems. For this reason, in this paper we concentrate on it. Data on other lightning waveform parameters in Brazil can be found elsewhere (Triginelli et al., 1995; Schroeder et al., 1999, 2002) and are outside of the scope of this article. Also, no attempts were done to consider any dependence of the results on the period of the year and on the structure of the clouds which generate the flashes for the following reasons: 1) the results for upward natural and triggered flashes are based on data from a relatively small number of events; 2) the analysis done for downward natural flashes (Lacerda, 1999) did not indicate any significant dependence of the peak current on these parameters. Finally, the results are compared to each other and to similar observations done in other regions of the world, in order to investigate possible differences in the peak current of different types of strokes. Differently of Rakov (2001), only observations at short towers are considered.

## 2. Lightning facilities in Brazil

### 2.1. Morro do Cachimbo Station (MCS)

Morro do Cachimbo Station (MCS) was acquired by Companhia Energética de Minas Gerais (CEMIG) from the National Electric Engineering Research Institute (NEERI) located in South Africa. It was installed under the orientation of Dr. A.J. Eriksson. The station is very similar to the one operated in South Africa (Eriksson, 1979). Located near the city of Belo Horizonte (20°00'S and 43°58'W), MCS initiated its operations in 1985. It records the nearby cloud-to-ground lightning activity, the atmospheric electric field, and the direct current measurements. In addition, it provides photograph records and video images of the flashes striking the 60-m metallic tower. The tower is located on the top of a mountain about 1430 m above the sea level and 200 m above any other mountain in the region. The current is measured by two current transducers (CT) or magnetic coils that induce proportional voltage pulses, with a bandwidth of DC–1 MHz. In a lightning event in the tower, the discharge crosses a gap before the main CT. Current values up to 200 kA can be measured. One shunt of 0.5  $\Omega$  is prepared in a parallel path with other CT to allow the measurement of small (lower than 20 kA) current values with higher accuracy. The MCS



Fig. 1. Detail of the base of the tower in the Morro do Cachimbo station.

uses a fiber optic link installed into an open duct with a copper plate ground system to transmit the information from the sensor to equipment room. The accuracy of the current and sampling time of the data analyzed in this work were initially limited to  $760 \text{ A}-1 \mu\text{s}$  and  $116 \text{ A}-0.2 \mu\text{s}$  for the main CT and the parallel CT, respectively. The sampling time of the main CT was changed to  $0.5 \mu\text{s}$  in 1992 and to  $0.2 \mu\text{s}$  in 1993, remaining unchanged up to the present. All events in the tower with peak current above  $116 \text{ A}$  are recorded. Figs. 1 and 2 show details of the base of the tower and of the current sensors, respectively.



Fig. 2. Detail of the current sensors in MCS.

## 2.2. International Center for Triggered and Natural Lightning Studies (ICTNLS)

The International Center for Triggered and Natural Lightning Studies (ICTNLS) is located inside the National Institute for Space Research (INPE) campus at Cachoeira Paulista (22°41'S and 44°59'W; altitude of 625 m), a small city located halfway between São Paulo and Rio de Janeiro. The ICTNLS is a result of a collaboration of several institutions in Brazil and France. The triggering site is located on a flat 120 m × 70 m area of a hilltop (Fig. 3). The control room is located 45 m away from the rocket launcher and has a capability of launching up to 12 rockets during the same event. The ambient electric field is monitored by a field mill connected to the control room via fiber optic link. The plastic maiden rockets are 0.85 m long and carry a wire spool with them. Around the launcher several instruments were mounted: standard video cameras, a high-speed digital camera, current sensors (a magnetic coil, a resistive shunt and magnetic cards), fast E-field sensors and optical sensors. The current measurements presented in this paper were done by a 1-m $\Omega$  coaxial shunt placed inside a metallic box located under the rocket launcher (Fig. 4). The accuracy of the current measurements is considered to be better than 1 kA for currents below approximately 50 kA.

## 3. Results

In the MCS, from 1985 to 2000, 29 downward and 6 upward flashes, with a total of 88 and 12 return strokes, respectively, were captured. In the ICTNLS, since 2000, peak currents of 2 classical and one altitude flashes, with a total of 9 and 7 return strokes,



Fig. 3. The launching system and the control room behind it in the triggering site.



Fig. 4. Detail of the current sensors in CPC.

respectively, were recorded. All strokes had peak currents above 2 kA. The altitude flash was triggered using a 60-m Kevlar insulator cable under the copper wire.

Table 1 shows a summary of all results obtained in Brazil. The downward and upward natural flashes were distinguished based on two criteria: the direction of branches in photographs (if it is discernible—about 60% of the cases) and on the steepness of the return stroke waveform, for the other cases. This second criterion was also applied for the cases in which the direction of the branches was available showing a very good agreement.

Table 1  
Summary of the statistics on return stroke peak current of negative flashes in Brazil

Type of return stroke		Sample size (strokes)	Peak current (geometric mean in kA)
Natural	Downward (first)	29	45
	Downward (subsequent)	59	18
	Upward	12	10
Triggered <sup>a</sup>	Classical	9	17
	Altitude	7	33

<sup>a</sup> No dependence of the peak current on the atmospheric electric field on ground and on the length of the copper wire was found (Solorzano, 2003).

One can see that first-strokes in downward natural flashes are the most intense, followed by the strokes in the altitude triggered flash. No distinction between first and subsequent strokes was made in the case of the altitude flash in Table 1, since in this flash the first stroke was not more intense than the other strokes (Saba et al., submitted for publication). Peak currents of subsequent strokes of downward natural flashes and strokes of classical triggered flashes were of the same order. Upward strokes of natural flashes were less intense than the other strokes.

Table 2 shows a summary of return stroke peak currents of negative flashes obtained in other countries. Only direct current measurements are included in this table. The minimum peak current thresholds are not the same in all observations in this table, but, for most of them, they were around 2 kA, as in Table 1. In the case of natural flashes, only data for short towers (less than 70 m) are presented, in order to avoid any possible influence of the tower height.

From the comparison of Tables 1 and 2, several points merit to be addressed. The geometric mean of the first-stroke peak current of downward natural flashes in MCS (45 kA) and in South Africa (44 kA) are much higher than the values reported in Switzerland (30 kA) and Italy (33 kA). The difference (~50%) is much higher than that it would be expected considering the difference in the location of the current sensors (at base in MCS and South Africa, and at top in Switzerland and Italy) in the tower (Guedes et al.,

Table 2  
Summary of the statistics on return stroke peak of negative flashes in other countries

Type of return stroke		Location	Sample size (strokes)	Peak current (geometric mean in kA)	Reference
Natural <sup>a</sup>	Downward (first-stroke)	Switzerland	101	30	Berger et al. (1975)
		South Africa	12	44	Eriksson (1979)
		Italy	42	33	Garbagnati and Lo Pipero (1982)
	Downward (subsequent strokes)	Switzerland	135	12 <sup>b</sup>	Berger et al. (1975)
		South Africa	8	18	Eriksson (1979)
		Italy	33	18	Garbagnati and Lo Pipero (1982)
	Upward	Switzerland	176	10	Berger (1978)
		South Africa	1	10	Eriksson (1979)
		Italy	142	8	Garbagnati and Lo Pipero (1982)
Triggered	Classical <sup>c</sup>	Alabama, US	37	11	Fisher et al. (1993)
		Florida, US	305	12	Depasse (1994)
		France	54	10	Depasse (1994)
		Altitude	Florida, US	2	21

Data from magnetic links are not considered due to their large inaccuracy.

<sup>a</sup> Only short towers are considered, since for tall towers the current peaks are significantly influenced by the presence of the object (Rakov, 2001).

<sup>b</sup> Same value was reported by Anderson and Eriksson (1980) for a smaller sample size.

<sup>c</sup> Other values reported in the literature can be found in Rakov et al. (1998) and Rakov (1999). There are no significant variations with respect to the values shown in this table.

submitted for publication). Guedes et al. (submitted for publication) used a return stroke current model derived from Guerrieri et al. (1996, 1998), but modified (following the suggestion of Rachidi et al., 2002) to consider a current divisor in the tower top, in order to have a self-consistent model. They estimated that the differences in the peak current observed at different locations for short towers are less than 15% for all type of strokes. With respect to subsequent strokes in downward flashes, the value in MCS (18 kA) is the same that in South Africa and Italy, and higher than that reported in Switzerland (12 kA). Again, the difference (50%) can not be explained by considering the difference in the location of the current sensors. Note that, in this case, a same value was obtained in MCS and Italy for different locations of the sensors. Upward return strokes, in turn, show lower peak current values than subsequent return strokes of downward natural flashes in all locations. The difference is significant in MCS and Italy, and only marginal in Switzerland. In South Africa, the number of events is not statistically significant.

Return stroke peak currents of classical triggered flashes are very similar to strokes of upward natural flashes in all locations. The higher value in ICTNLS is probably a result of the small data sample. For instance, a similar value (15 kA) was obtained in KSC in Florida in 1990 for a similar small data sample of 8 strokes (Fisher et al., 1993).

Finally, there is not much information for return stroke peak current of altitude flashes in the literature. As far as we know, only two direct current measurements in 1989 (Laroche et al., 1991) and in 1995 (Lalande et al., 1998; Rakov et al., 1998) has been reported, both in Florida. While in ICTNLS the altitude strokes are very intense (see Table 1), in Florida they were intense (36 kA) in one case—only peak current of the first stroke of a 12 stroke flash was reported (Laroche et al., 1991) and weak (12 kA) in the other case—only peak current of the first stroke of a 4 stroke flash was reported (Lalande et al., 1998; Rakov et al., 1998). Also, the first stroke in ICTNLS was not more intense than the subsequent strokes, a fact verified in Florida in 1995 comparing close related magnetic field data. Based on this, we are lead to conclude that there is no statistically significant information available to conclude that first and subsequent strokes of altitude flashes are different. Also, the triggering setups were not exactly the same in the two locations (Florida and Brazil). In Florida, differently of the case in ICTNLS described before, the altitude flashes were triggered using a 400-m Kevlar insulator cable between two copper wires, with a 50-m grounded copper wire under the Kevlar cable.

Due to the small number of peak current measurements of altitude strokes, it is worth mentioning that peak currents for other altitude strokes can be estimated indirectly from magnetic field observations at close range (Rakov et al., 1998), using the Ampere's law. At least three altitude strokes have close magnetic field data reported in the literature: the second stroke of a 4 stroke altitude flash identified as 9516 in Rakov et al. (1998) and the first two strokes of another 4 stroke altitude flash identified as 9514 also in Rakov et al. (1998). An increase by 25% in the values obtained by the Ampere's law was adopted following the suggestion of Rakov (1999) to take into account the contribution of the displacement current related to the time derivative of the vertical electric field. No corrections, however, were considered in association with the angle between the plane of antenna and the direction to the lightning channel, which in principle could influence the peak current estimates from these measurements. If the values estimated from the magnetic field data were considered in Table 2, the geometric mean of the peak current of altitude strokes would be 13 kA.

#### 4. Discussion and conclusions

From a comparative analysis of return stroke peak currents of natural (as observed at short towers) and triggered negative flashes, we are lead to conclude that:

1. Peak currents of first-stroke of downward natural flashes are higher than all other strokes. The reason for that is probably related to the physical difference in the attachment process for this type of stroke. Assuming that the peak current can be estimated multiplying the linear charge density at the downward moving leader tip, at the time of the attachment with the upward moving leader, by the speed of the return stroke, we can infer that the peak current of first stroke of downward natural flashes are higher since both quantities are higher (Rakov and Uman, 2003). The available results also indicate significant variations in the peak current values at different locations. The variations are apparently not related to instrumental aspects or grounding conditions (see Rakov, 1999 for a detailed discussion about this topic), being probably related to different thunderstorm electrical structures at these locations.
2. Peak currents of subsequent strokes of downward natural flashes seem to be the same in all locations. The only exception is the value in Switzerland. One possible explanation for this fact is that this value is contaminated by lower peak current values of upward return strokes of natural flashes due to the difficulties to identify the direction of flashes in which no branches are discernible in photographs (in general, a significant fraction). As far as we know, there is no clear information regarding how Berger has identified the direction of the flashes for these cases. However, it is not possible to rule out a local effect.
3. Peak currents of strokes of upward natural flashes are lower than subsequent strokes of downward natural flashes in all locations, although they are initiated in a similar manner, that is, by downward dart leaders. A possible reason for this is that upward natural flashes start more frequently in the first stages of a thundercloud, in response to the electric field at the top of the tower produced by an intracloud flash. At these stages, the charge inside a storm is believed to be lower.
4. Peak currents of strokes of classical triggered flashes seem to be the same in all locations. The variations reported in the literature can be explained by differences in the number of events in the data sets and/or by different time intervals chosen to launch a rocket. Seasonal effects can not be disregarded as well. Also, the peak current values of the strokes of classical triggered flashes are similar to those of strokes of upward natural flashes, being less intense than subsequent strokes of downward natural flashes. A possible reason to explain why strokes of classical triggered flashes are less intense than subsequent strokes of downward natural flashes is that they are induced at times when no conditions to produce a subsequent stroke of a natural flash are reached.
5. Peak currents of strokes of altitude triggered flashes are not well known yet. Only nine direct measurements and three indirect estimates exist. The peak current values in these measurements, however, are quite different. The difference may be related to differences in the triggering setup and/or, merely, to the small number of reported events.

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