ELECTRIC FIELDS CHANGES PRODUCED BY POSITIVE CLOUD-TO-GROUND LIGHTNING FLASHES

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Abstract - Abstract: Positive flashes correspond to approximately only 10% of the total number of flashes produced by a thunderstorm. However, strokes with high peak currents and long continuing currents are usually present in positive flashes. Therefore, positive flashes are responsible for more intense damage than the negative ones. Positive flashes often are preceded by significant and long duration intracloud (IC) discharge activity. We observe in detail the electric field variations produced by 80 cloud-to-ground lightning flashes in 9 different storms in S. Paulo, Brazil during the summers of 2009 to 2011. Preliminary breakdown pulses (PBP) preceding positive cloud-to-ground flashes and some characteristics of the electric field changes produced by the return stroke that occurred at ranges of 3 km to 80 km from the site of the electric field sensor were analyzed. All flashes presented PBP prior to the return stroke. The mean time interval between the PBP and return stroke was 157 ms. The pulse train duration have a mean value of 3.1ms. Only 6 out of 80 cases analyzed did not present pulse trains but only one single bipolar breakdown pulse before the return stroke. In 95% of cases the initial breakdown pulse presented the same initial polarity of the succeeding return stroke. Time interval between pulses in a pulse train had a mean value of 280 µs. The mean values of pulse width is 25.2 µs. The mean values of zero-to-peak risetimes and of the 10-90% risetimes for 72 return strokes electric field waveforms are 9.5 and 5.7 µs respectively. The arithmetic mean value of peak amplitudes of the positive return strokes fields normalized to 100 km is 17.0 V/m.

1 - INTRODUCTION

Although positive cloud-to-ground (+CG) lightning flashes are usually not as frequent as negative flashes, the special characteristics of positive CG lightning flashes make understanding the physical processes, by analyzing the measurements of their parameters, an important issue. The largest directly measured peak currents and charge transfers to ground are produced by +CG flashes [1]. Positive flashes are also a major concern for the designers of lightning locating systems because their electromagnetic waveforms are frequently very large and often have a complex structure [2].

Electric field change records have shown that positive lightning flashes to ground are often preceded by significant in cloud (IC) discharge activity lasting, on average, more than 100 ms [3-5]. In fact, optical measurements also show that positive discharges to ground often involve long, horizontal channels, up to tens of kilometers in length (e.g.,3;6-9). Kawasaki and Mazur [10] presented data clearly showing the existence of preliminary breakdown pulses just prior to the stepped leader of a positive ground flash and postulated that the origin of the preliminary breakdown pulses is a bidirectional leader process (e.g., 11,12).

Our study is primarily concerned with the electric field changes of prestroke processes in positive cloud-to-ground lightning flashes. Some characteristics of electric field signature of the return stroke pulse are also analyzed. Our results are compared with results from the few existing past studies in the literature.

In this paper we add to the existing statistics on the measured characteristics of prestroke processes and return stroke waveshapes hoping that it may help to improve the discrimination of in cloud discharges from positive cloud-to-ground discharges by lightning location systems. Evidences from Brazil and Austria show that breakdown pulses are sometimes misidentified as cloud-to-ground flashes by Lightning Location Systems. It may also help to understand the incloud processes that precede and initiate positive ground flashes better.

2 - INSTRUMENTATION AND DATA

80 electric field waveforms of positive flashes located by the Brazilian lightning location system were selected for the analysis of the preliminary breakdown pulses and the return stroke waveshapes. The recordings occurred during summer seasons from 2009 and 2011 in a geographical region that is covered by BrasilDat a lightning location system based on Vaisala technology. Further information about BrasilDat performance can be found in Naccarato and Pinto Jr. [13]. Data from the lightning location systems (LLS) were used to obtain the locations of the ground strike points and estimates of the peak current (Ip). The observing site used during the data acquisition was located at São Paulo state (23.212º S; 45.867º W, altitude: 635 m).

The electric field measuring system used in this study consisted of a flat plate antenna with an integrator/amplifier, a GPS receiver, and a PC with two PCI-cards (a GPS card Meinberg GPS170PCI and a data acquisition card NI PCI-6110), and a data acquisition box (DAQ BOX NI BNC-2110). The waveform recording system was configured to operate at a sampling rate of 5 MS/s on each channel and the resolution of the A/D converter is 12 bits. The same type of measuring system has been used previously in lightning experiments in Austria and Sweden and is described in more detail by Schulz et al. [14]. The RC decay-time constant of the system was about 0.5 ms.

A slow electric field sensor was developed to measure lightning processes with long duration and low amplitude. The sensor is capable of measuring the field change produced by the leader, the continuing current and other similar processes in nearby lightning flashes. The system decay-time is approximately 1.5 s. The GPS receiver and acquisition system were the same for both systems.

Examples of recorded waveforms from both electric field sensors are shown in Figure 1. The electric field change due to positive return stroke is positive according to the physics sign convention. All 80 positive cloud-to-ground flashes were single stroke flashes and occurred at ranges of 3 km to 80 km from the electric field sensors site (Figure 2).

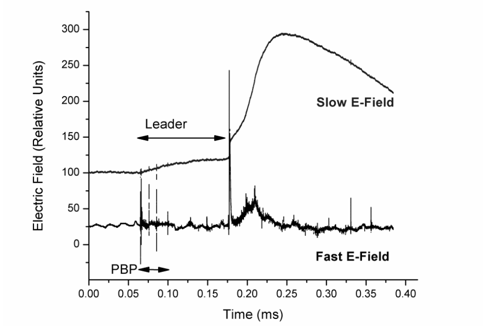

Figure 1: waveform example from electric field changes of the sensors: fast e-field - short decay time and slow e-field – long decay time

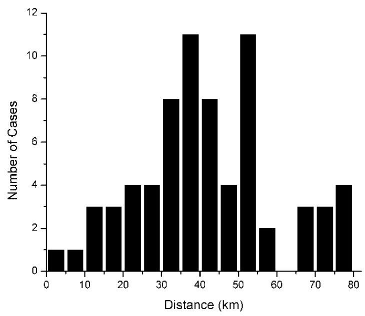

Figure 2: Distribution of the distances to the electric field sensor of the positive flashes.

3 - RESULTS

The electric field changes produced by the positive cloud-to-ground flashes showed similar waveforms. In this work we divide these changes in two regions that will be analyzed in detail (Figure 3). Region I is comprised by preliminary breakdown pulses (PBP) produced by lightning processes inside the cloud. Region II consists of the return stroke waveform (RS).

3.1 - REGION I - ELECTRIC FIELD VARIATIONS PRODUCED DURING THE PRELIMINARY BREAKDOWN

Electric field variation measurements of Rust et al. (1981) and Fuquay (1982) indicate that positive return strokes are preceded by significant in-cloud discharge activity lasting, on average, in excess of 100 or 200 ms. As shown in Figure 1 the electric field variation due to the preliminary breakdown and the leader were simultaneously visualized by the fast and the slow electric field sensors. The smooth electric field change between preliminary breakdown process and return stroke shown by the slow electric field measurement assures that both processes belong to the same flash.

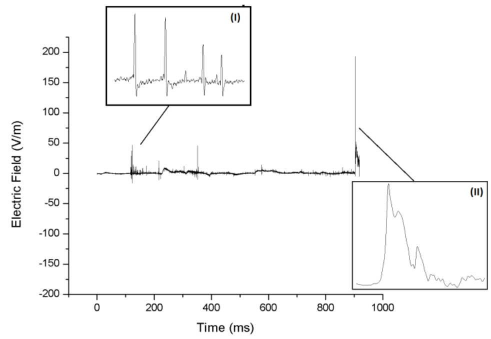

Figure 3: Electric field variations produced during the preliminary breakdown (Region I) and the return stroke (Region II).

As shown in Figure 3, Region I consisted of a train of bipolar pulses occurring tens or hundreds of milliseconds prior to the return stroke. Electric field signatures of the initial process presenting a train of bipolar wave shape pulses were also observed by Ushio et al.[15] and Gomes and Cooray [16].

In the dataset presented here, all 80 (100%) positive cloud-to-ground flashes analyzed (distances of 3 to 80 km) presented breakdown pulses prior to the return stroke. Qie et al. [17] analyzed positive flashes en China with distance range of up to 25 km and they also detected preliminary breakdown pulse trains in their 18 cases (100%).

Gomes and Cooray [16] found that approximately 9% of the initial breakdown processes had more than one breakdown pulse train preceding the return stroke. In this work, all return strokes were preceded by only one pulse train. In the following sections the features of the preliminary breakdown process will be discussed.

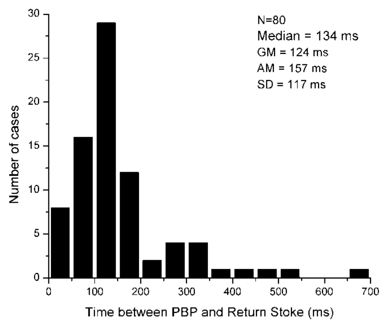

Figure 4: Distribution of time intervals between the PBP and return stroke.

3.1.1 - TIME INTERVAL BETWEEN PBP AND RETURN STROKE

The separation between PBP and return stroke is the time duration between the highly active region of the pulse train and the return stoke. The time interval between the preliminary breakdown pulse train and return stroke ranged from 9.3 to 653.5 ms, and their distribution is shown in Figure 4. The mean value of 157 ms is similar to the mean found by Qie et al. [17] in China, but much larger than the mean values found by Ushio et al. [15] in Japan and by Gomes and Cooray [16] in Sweden (Table 1). The lowest average value (12 ms) was obtained in Japan, where winter storms are known to have low cloud bases and cloud tops. In such storms, a positive leader would probably reach ground in a lower time interval.

3.1.2 - PULSE TRAIN DURATION

The duration of the pulse trains was defined as the time between the regions of pulse activity at the beginning and at the end of the pulse train that have amplitudes of 10% of the maximum amplitude [16]. Ushio et al. [15] did not use a specific criterion to define the pulse train duration and therefore only an estimate of the duration is given (1 ms). In this study we used the definition given by Gomes and Cooray [16] and there is a good agreement between their and our mean values. Comparisons with past studies are shown in Table 1. Figure 5 shows the distribution of the pulse train duration. Only 6 out of 80 cases analyzed did not present pulse trains but only one single bipolar breakdown pulse before the return stroke.

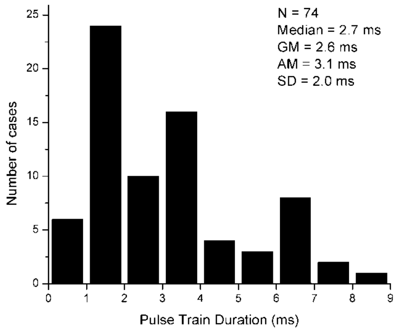

Figure 5: Histogram of pulse train durations preceding +CG strokes.

3.1.3. TIME BETWEEN PULSES IN PULSE TRAIN

The mean time between pulses was obtained by measuring the time interval between three to five consecutive bipolar pulses belonging to the same pulse train in 74 different positives cloud to ground flashes. Time between pulses is shown in Figure 6. Some comparison with past studies is shown in Table 1. The time interval between pulses in pulse trains found in our analysis was nearly two times larger than the one found by Qie et al.[17].

3.1.4. BREAKDOWN PULSE

A typical bipolar initial breakdown wave shape pulse is shown in Figure 7a. Usually there are two or three smaller pulses superimposed on the rising portion of theinitial breakdown pulse, while the falling portion and the opposite polarity overshoot are smooth. This waveshape is similar to the ones observed in negative CG flashes [18]. In contrast with negative discharges, Gomes and Cooray [16] found that the initial polarity of PBP in some of positive discharges can be opposite to that of the following return stroke pulse (see, also Ushio et al.[15]).

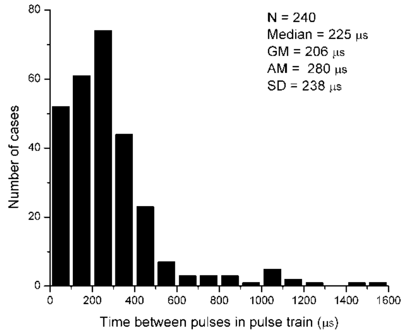

Figure 6: Distribution of time interval between pulses in pulse trains.

In 64 cases the first breakdown pulse exhibited two or more smaller pulses which were superimposed on the rising portion of the initial breakdown pulse (as in Figure 7a). The other 16 cases that did not exhibit two smaller pulses in the first breakdown pulse, presented them in their strongest breakdown pulse.

In agreement to what was found by Gomes and Cooray [16] and by Ushio et al. [15], in the majority of the analyzed cases (76 out of 80) the initial breakdown exhibited the same initial polarity of the succeeding return stroke (Figure 3-I and 3-II). In only 4 cases the initial polarity differed from the succeeding return stroke. Since sequences of in cloud pulses tend to preserve the initial polarity of individual waveforms, these fields would appear to be radiated by currents which effectively transfers charge of one polarity in one direction in an intermittent but systematic way (Weidman and Krider 1979). In this study, following a previous study of Gomes and Cooray [16], T1 and T2 are defined as the aproximate duration of the first half cycle and the second half cycle (Figure 7a), respectively, of an individual bipolar pulse. Thus, T1+T2 is aproximately equal to the total pulse width. For comparison Table 1 shows our results and other of authors. T1, T2 and T1+T2 distributions are shown in Figures 7b, 7c and 7d.

Table 1: Comparison with other past studies

Arithmetic mean values	This study	Ushio et al. [15]	Qie et al. [17]	Gomes and Cooray [16]
Time interval between PBP and RS (ms)	157 (80)	12 (19)	165.1(18)	56(57)
Pulse train duration (ms)	3.1 (74)	1 (19)	-	3.0 (57)
Time between pulses in pulse train (µs)	280 (240)	54.2 (219)	165(50)	96 (57)
First half of cycle with same polarity of RS	95%(80)	89% (19)	-	80% (71)
First half of cycle - T_1 (µs)	9.1 (315)	-	-	19 (57) *
Second half cycle - T_2 (µs)	16.4 (315)	-	-	19 (57) *
T_1 + T_2 (µs)	25.2 (315)	18.8 (132)	27 (50)	38 (57) *

*Mean values obtained for pulses having the initial polarity similar to the subsequent return stroke.

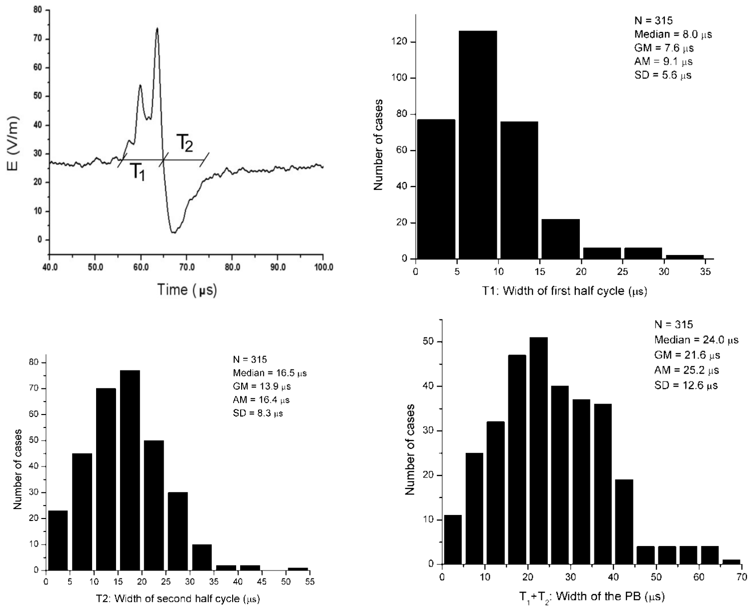

Figure 7: (a) Typical preliminary breakdown pulse (b) T1: width of initial half cycle of pulses (c) T2: width of second half cycle of pulses (d) T1+T2 width of pulses

The 10-90 percent risetime values for PBP ranged from 0.6 to 22 µs. The distribution of risetime PBP is shown in Figure 8 and it is not very different from the usual risetime values found for return strokes.

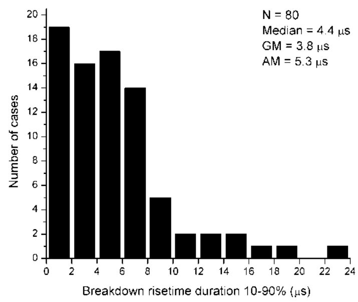

Figure 8: Histogram of preliminary breakdown pulse risetime duration.

3.2. REGION II - ELECTRIC FIELD VARIATIONS PRODUCED BY THE RETURN STROKE

A typical return stroke pulse is shown in Figure 9(a). Only the magnitude of the electric field change is considered here. The measured initial electric field peak normalized to 100 km for 72 positive return strokes located at distances of 3 to 80 km ranged from 3.1 to 80.9 V/m. The histogram of initial electric field peak normalized is shown in Figure 9(b). The median, geometric mean (GM) and arithmetic mean (AM) equal to 12.6 V/m, 13.4 V/m and 17.3 V/m respectively and are about 2 to 3 times larger than the usual values of initial electric field peak found for negative cloud-to-ground return strokes [19].

The distributions of zero-to-peak risetimes and of the 10-90% risetimes for 72 return strokes electric field waveforms are shown in Figure 10. Table 2 summarizes the statistics of these parameters for this study and other studies.

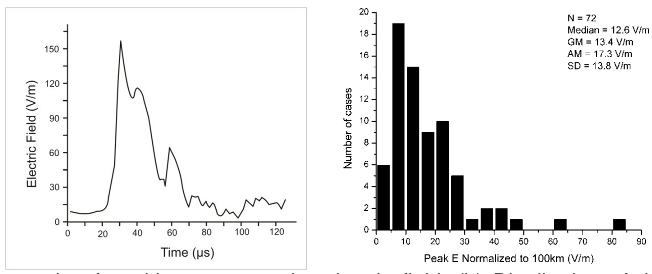

Figure 9: (a): Waveform for example of positive return-stroke electric field. (b) Distribution of the peak electric field normalized to 100km.

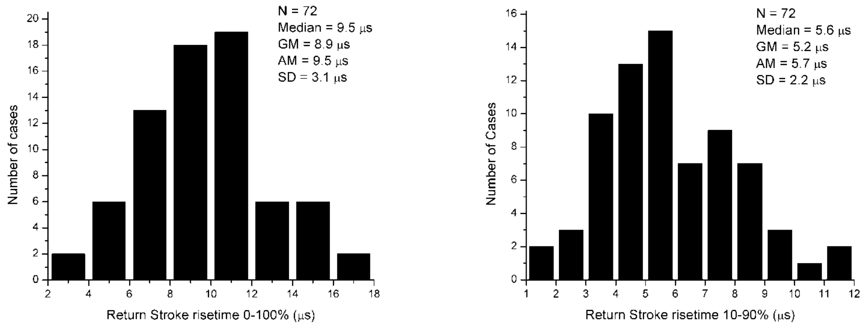

Figure 10: (a) Histogram of the return stroke zero-to-peak risetime (b) Histogram of the return stroke 10-90% risetime.

Table 2**:** Statistics of different parameters of positive return stroke fields obtained in different studies.

	Number	Median	GM	AM	SD
Zero-to-peak risetime (µs)					
This work	72	9.5	8.9	9.5	3.1
Hojo et al [20]	32	--	--	22.3	--
Cooray [21]	20	--	--	8.9	1.7
Ushio et al. [15]	19	--	--	18	--
10-90% risetime (µs)					
This work	72	5.6	5.2	5.7	2.2
Hojo et al [20]	32	--	--	6.7	--
Cooray [21]	15	--	--	6.2	1.4
Peak Amplitude Normalized to 100km (V/m)					
This work	66	12.6	13.4	17.0	12.3
Cooray et al. [22]	46	--	--	15.7	6.7

4. DISCUSSION AND SUMMARY

The electric field changes produced by all positive cloud-to-ground flashes showed similar waveforms. In this work we divided these changes in two regions that present high frequency oscillations: the first is a train of bipolar pulses occurring tens or hundreds of milliseconds prior to the return stroke and the second is return stroke waveform. The slow electric field sensor was helpful to provide the link between the first and the second regions. The mean time interval between the preliminary breakdown pulse train and return stroke (157 ms) found was similar to the ones found in China and much larger than those found in Japan and in Sweden.

The criteria used to define the duration of the pulse trains was the same used by Gomes and Cooray [16] and there is a good agreement between their and our mean values of pulse train duration.

Ushio et al. [15] analyzed the PBP of positive CG flashes in Japan thunderstorms, and found that the mean time interval between successive preliminary breakdown pulses is 54.2 µs, which is shorter than all other values shown in Table 1. Also, the duration of the breakdown pulses (T1+T2) in Japan is shorter than what was measured in Brazil, China and Sweden. According to Ushio et al. (1998), if the source location of PBP is between the main negatively charged region and the minor positively charged region below in the usual convective thunderstorms in summer, in winter storms in Japan it would be between the positively charged region and a screening layer. As this distance is lower, shorter pulse duration and shorter pulse interval would be expected. The results presented in Table 1 corroborate this interpretation.

Breakdown pulses with the same polarity of the return stroke were observed in 76 (95%) of the 80 analyzed cases. This percentage is similar to the ones found in the other studies (Japan, 89% and Sweden, 80%).

The average value of the 0-100% risetimes of field change caused by positive cloud-to-ground flashes was 9.5 µs which is similar to the risetime of the breakdown pulses. This value found was much less than Hojo et al.[20] and Ushio et al. [15], however was similar to Cooray [21]. The reason of this variation of values could be the difference of environment noise of the measurement sites. The value of 10-90% rise time of positive return stroke was about 5.7 µs and was similar to the literature.

The mean value of peak amplitudes of the positive return strokes fields, when normalized is 13.4 V/m. Cooray et al. (2004) found mean value lower by about 50%.
All results presented here were obtained from summer air mass thunderstorms in Brazil. The mean values from

Qie et al.[17] were observed during summer thunderstorms in the Chinese inland plateau area which, according to the authors, present some special characteristics if compared with the typical summer thunderstorms. The measurements performed by Gomes and Cooray [16] were conducted in Sweden, during frontal thunderstorms which have different charge distributions than the usual convective thunderstorms in Brazil. Finally, the results obtained by Ushio et al. [15] in Japan were for positive flashes produced by winter thunderstorms, which according to the authors, may have a source location of PBP quite different from the one expected in usual summer thunderstorms.

To understand the physics behind the PBP preceding positive cloud-to-ground flashes, a lot more investigations are needed. A combination of VHF mapping and other types of observations (e.g., multiple-station electric field change, radar, and optical observations) would be desirable to interpret the physics of the processes that are responsible for the PBP.

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