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Features of the Initial Breakdown Pulses in Negative Ground Flashes Observed in Colombia

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***Abstract*—In this work, the electric field signatures of the initial preliminary breakdown pulses (PBP) identified in 69 negative cloud-to-ground (CG) flashes recorded in Colombia are characterized. The measuring system was in the Bogotá savannah, which is a mountainous region located in the southwestern part of the Altiplano Cundiboyacense in the center of Colombia (altitude of 2550 m). The measurements were conducted using a broadband system (up to 50 MHz), with a full observation window of 500 ms and a 250 ms pre-trigger time. For the analysis of the most relevant features of the PBP waveforms several parameters were selected: pulse train duration (T_{PBP}), time interval between the largest peak of the PBP train and the FRS (PBP-FRS), ratio of higher peak amplitude of PBP to the first return stroke (PBP_{MAX}/FRS_M), interpulse time (IPT), number of individual pulses in each PBP train and individual pulse duration (T_{PULSE}). The results obtained show that PBP-FRS and PBP_{MAX}/FRS_M has an arithmetic mean (AM) of 5.4 ms and 0.47, respectively. The PBP-FRS presented values between 0.7 ms and 298.6 ms. On the other hand, the temporal parameter T_{PULSE} has a geometric mean (GM) of 1.46 ms, with a maximum value of 5.2 ms and a minimum of 0.5 ms. With respect to the IPT, it presents an AM of 125.68 μs and GM of 74.28 μs. In addition, other statistical results are shown.**

Keywords*— *Preliminary breakdown pulses, First return stroke, Lightning flashes.

I. INTRODUCTION (*Heading 1*)

Lightning flashes are created habitually in the clouds during the Cumulonimbus formation, they are also generated by other natural phenomena such as volcanic eruptions. These electric discharges are related with a transference of positive or negative charge between cloud-to-cloud (CC), cloud-to-ground (CG), cloud-to-air or cloud-to-ionosphere [1]. According to the direction in which the charges move and their polarity, the CG lightning flashes are divided into four types: negative downward (-CG), negative upward (-GC), positive downward (+CG) and positive upward (+GC) [2]. The lightning discharge process can be studied by the electric field change observation. These studies have shown that the negative CG lightning flashes represent more than 90% of global discharges, while 10% or less are positives. The positive discharges are responsible for more damage than negative ones, causing death and injuries in humans and animals, forest fires, blackouts, contingencies in transmission power systems, etc. [3].

From research conducted in different regions of the world, scientists agree on the following six stages (or events) related with the formation of CG lightning flashes: train pulses of preliminary discharges (PBP), stepped leader (SL), attachment process (AP), first return stroke (FRS), dart leader (DL) and subsequent return stroke (SRS), although these last two can be repeated several times in the same flash. From the stages presented above the most studied have been the return stroke discharges, while the least researched are the preliminary discharges [4], [5].

The electric field changes related with FRS and SRS in CG lightning flashes have been analyzed and reported by many researchers [5]. However, in several works it has been noticed that the FRS is sometimes preceded by a train of bipolar pulses lasting on the order of 1 ms (generally) [6]. In addition, some researchers have observed PBP train durations greater than 30 ms [7]. These trains habitually are identified as preliminary breakdown pulses (PBP) or initial breakdown pulses, and they may provide valuable information concerning the first event that led the electrical breakdown inside the clouds [8], [9].

After to study many PBP electric field signatures, Clarence and Malan proposed the “BIL” model in order to characterize the waveform before the FRS [6]. This model includes a preliminary breakdown stage (B), an intermediate stage (I) and the stepped leader stage (L). Clarence and Malan also suggested that the B stage is the result of the vertical discharge between the main negative charge center and the lower positive charge region inside the thundercloud. In their research, they found that the total duration of the preliminary breakdown process can be between 2 ms and 10 ms [6], [7].

In the last decade, several studies about the characteristics of PBP have been conducted in Europe, Asia, USA and Brazil [7], [10], [11]. However, in Colombia this type of studies has not been carried out yet. In this way, this paper presents a statistical characterization of the PBP prior to the FRS observed in electric field signatures recorded in Bogota, Colombia located in the central region of the country at 2550 meters above sea level (masl). This characterization will be carried out using several parameters (temporal and magnitude) such as: pulse train duration (T_{PBP}), time interval between the largest peak of the PBP train and the FRS ($PBP - FRS$), ratio between the peak value of the PBP and its FRS (PBP_{MAX}/FRS_M), interpulse time (IPT), number of individual pulses and individual pulse duration (T_{PULSE}).

II. Instrumentation

During more than three decades, the measuring systems used around the world to capture lightning-generated electric field signatures have been composed by the same stages and they have similar technical characteristics [7], [12]. The basic scheme to measure lightning electric fields consists of an electric field sensor, an electronic circuit based on an operational amplifier and a recording equipment. Under these conditions, the measuring system used in this work is shown in Fig. 1 [13].

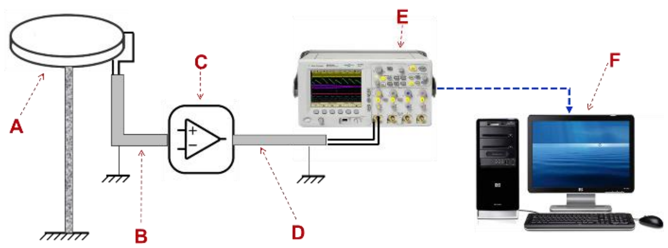


Fig. 1. *Scheme of the electric field measuring system. (A) parallel-plate antenna; (B) short coaxial cable RG58U; (C) electronic circuit; (D) long coaxial cable RG58U; (E) digital oscilloscope.*

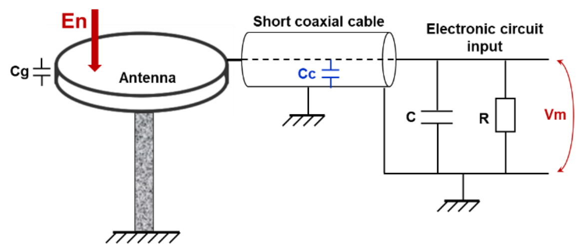
The measuring system presented in Fig. 1 consists of a circular antenna with parallel plates, an electronic circuit implemented with the buffer-amplifier BUF602 and the recording device is an Agilent DSO6104A digital oscilloscope. For the connection of the elements (B) and (D), coaxial cables RG-58/U were used [13]. The cable connected between the circuit and the oscilloscope was properly terminated to avoid reflections. It is important to mention that the BUF602 is a new replacement for the typical amplifier LH0033 because its manufacture was stopped since 2008. A summary of the features of the measuring system is presented in Table 1.

The diagrams of the parallel plate antenna and its equivalent circuit are shown in Fig. 2(a) and Fig. 2(b), respectively. In these figures En is the vertical component of the electric field, Vg is the voltage of the antenna, Cg is the capacitance of the antenna, Cc is the capacitance of the short coaxial cable, R_1 is the input resistance (coupling) between the cable and the electronic circuit, C is the coupling capacitance of the electronic circuit, R is the input resistance that controls the decay-time of the circuit ($\tau_d = 38\ ms$) and Vm is the input measured voltage (before the buffer-amplifier). A complete description of the electronic circuit and the measuring system can be reviewed in [14].

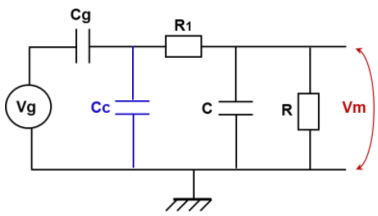
For the acquisition process, the oscilloscope was set to operate at a sampling rate of 100 ns, using a fixed window of 500 ms (observation window). In addition, the trigger was adjusted to capture transient signals with positive or negative polarity whose magnitude exceeded 6 V/m (or 150 mV) and the pre-trigger time was set to 250 ms. The parallel-plate antenna and the electronic circuit were located on the roof of block B5 of the Camilo Torres Unit at the Universidad Nacional de Colombia Campus. The approximate height between the ground plane and the roof of building is 15 meters. The recording equipment was located in an office belonging to the EMC-UNC research group (5th floor of the building).

TABLE I. Specifications of Electric Field Measuring System

ID	Elements	Technical characteristics
A	***Electric field antenna***	• Circular parallel plates • Diameter of the plates: 0.45 m • Separation between plates: 0.03 m • Antenna bandwidth: 30 MHz • Metallic support mast: 1.5 m
B	***Short coaxial cable (antenna-electronic circuit)***	• Reference: RG 58 / U • Characteristic impedance: 50 Ω • Length: 50 cm • Simple shielding
C	***Electronic circuit***	• BUF602 buffer amplifier • Bandwidth: 1000 MHz • Growth rate: 8 kV / µs
D	***Long coaxial cable (electronic circuit-oscilloscope)***	• Reference: RG 58 / U • Characteristic impedance: 50 Ω • Length: 12 m • Simple shielding plus metal shell
E	***Oscilloscope***	• Agilent DSO6104A • Bandwidth: 1 GHz • Maximum sampling: 4GSa / s
F	***Desktop computer***	• 4-core processor at 2.3 MHz • 4 GB RAM memory • 320 GB Hard Drive • LAN and WI-FI connection



(a)



(b)

Fig. 2. *Antenna of parallel plates. (a) Scheme including the electronic circuit; (b) equivalent circuit*

III. Methodology

The electric field waveforms generated by PBP trains preceding the FRS were recorded from three winter thunderstorms in Bogota, Colombia during 2017 (15^{th} and 16^{th} November and 1^{st} December). All pulse trains were produced by negative CG flashes measured in the central region of Colombia (4.641° N, 74.091° W and 2550 meters above sea level). From a data set composed by 363 recorded flashes the PBP trains were detected in 69 signatures (19%).

The methodology applied to characterize the PBP trains it was chosen after an extensive bibliographic review (articles, case studies, books, etc.). The criteria selected to carry out characterization are similar to those used by different studies, such as Baharudin *et al.* [7], Wu *et al.* [10], Zhang *et al.* [12], Johar *et al.* [15], Makkela *et al.* [16], among others. In this way, the criteria employed for analyze the waveforms of the PBP trains are defined as follows:

A. Only are characterized pulses whose peak-to-peak value exceeds twice the average noise level of the electric field.
B. The pulses belong to the same PBP train if the separation between them is less than 2 ms.
C. Only PBP trains with at least three pulses are characterized.

Fig. 3(a) shows an electric field signature produced by a negative CG flash recorded in Colombia on November 16, 2017 at 18:01:57. In Fig. 3(b) it is possible to identify the PBP train and the FRS. In order to describe the characteristics of each PBP train six parameters were selected: pulse train duration (T_{PBP}), time between the largest peak of the PBP train and the FRS ($PBP - FRS$), ratio between the peak value of the PBP and its FRS (PBP_{MAX}/FRS_M), interpulse time (IPT), number of individual pulses and individual pulse duration (T_{PULSE}) and the full width of the pulse [7], [10].

The graphical identification of the parameters (temporal and magnitude) mentioned above and the methodology used for their characterization are shown in Fig. 4. In addition, Table II and Table III present the mathematical expressions used to calculate some of these parameters. Analyzing the signature observed in Fig. 3(c) the following points were obtained: $E_{pm} = 22.6\ V/m$, $E_{FRS} = 32.8\ V/m$, $E_{REF} = 0.26\ V/m$, $t_{FRS} = 0\ ms$ and $t_{pm} = -4.1\ ms$. In Fig. 3(c), the variable E_{REF} is the background electric field in the signature. This reference value is different in each signature due to the DC level presents in this type of signals. Therefore, using the equations presented in Table II, the parameters $PBP_{\max}/FRS_M$ and $PBP - FRS$ (see Fig. 3(c)) are 0.7 and 4.1 ms, respectively. In addition, the PBP train duration is 1.1 ms.

TABLE II. MATHEMATICAL EQUATIONS OF THE PARAMETERS PBP_{MAX}/FRS_M AND $PBP - FRS$

Type	**Parameter**	**Equation**
Temporal	$PBP_{\max}/FRS_M$	$\frac{(E_{pm} - E_{REF})}{(E_{FRS} - E_{REF})}$
Magnitude	$PBP - FRS$	$t_{FRS} - t_{pm}$

TABLE III. MATHEMATICAL EQUATIONS OF THE PARAMETER T_{PULSE}

Type	**Parameter**	**Equation**	
		Bipolar	**Unipolar**
Temporal	$T1$	$t_{ZC} - t_o$	---- o ----
	$T2$	$t_F - t_{ZC}$	
	T_{PULSE}	$T1 + T2$	$t_{ZC} - t_F$

Fig. 4(a) shows that the PBP train has 14 pulses and 13 IPT. In addition, it can be seen the electric field level used to classify the pulses that will be characterized in each signature (7.5 V/m), this level of electric field corresponds to twice the average electric field level of the noise level in the characterized waveforms (criterion A). Fig. 4(b) and Fig. 4(c) show the method used to characterize the temporal parameter T_{PULSE} in bipolar and unipolar pulses, respectively. In Fig. 4(b), T_{PULSE} is obtained from the addition of T1 and T2, while in Fig. 4(c) this parameter is achieved from the difference between t_0 and t_f.

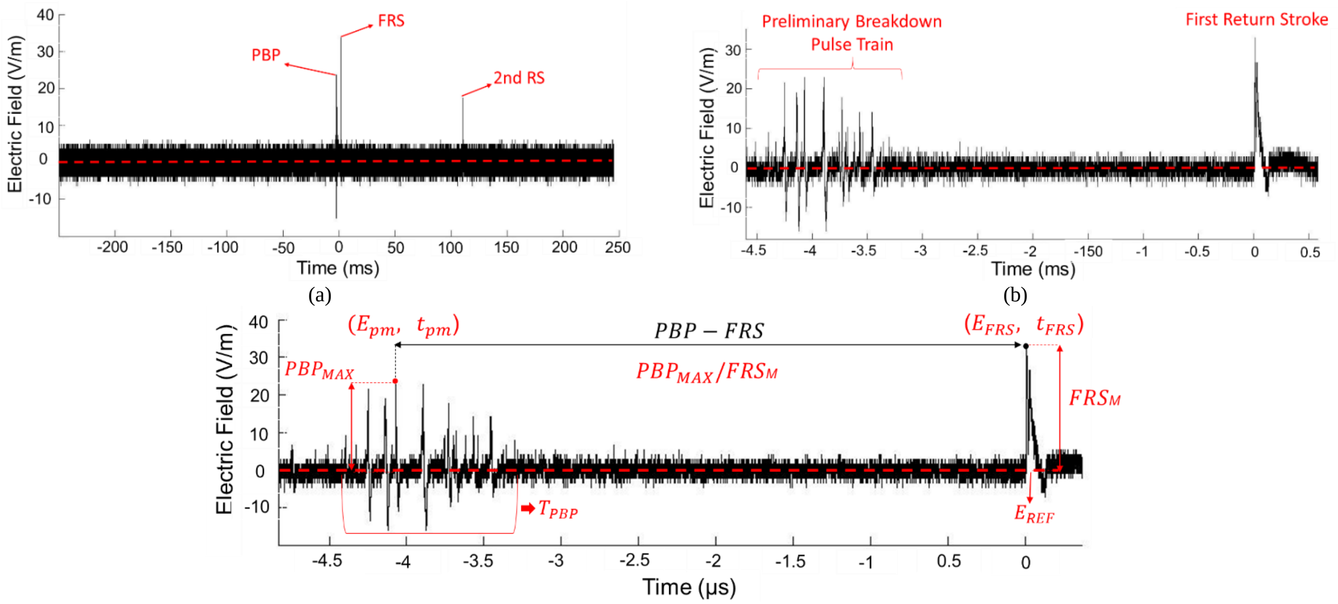


Fig. 3. Electric field signature produced by a negative CG flash. (a) Complete signature including PBP, FRS and second RS; (b) zoom on PBP train and the FRS; (c) identification of $PBP - FRS$, PBP_{MAX}/FRS_M and T_{PBP} --- Note: data obtained in November 16th 2017 at 18:01:57.

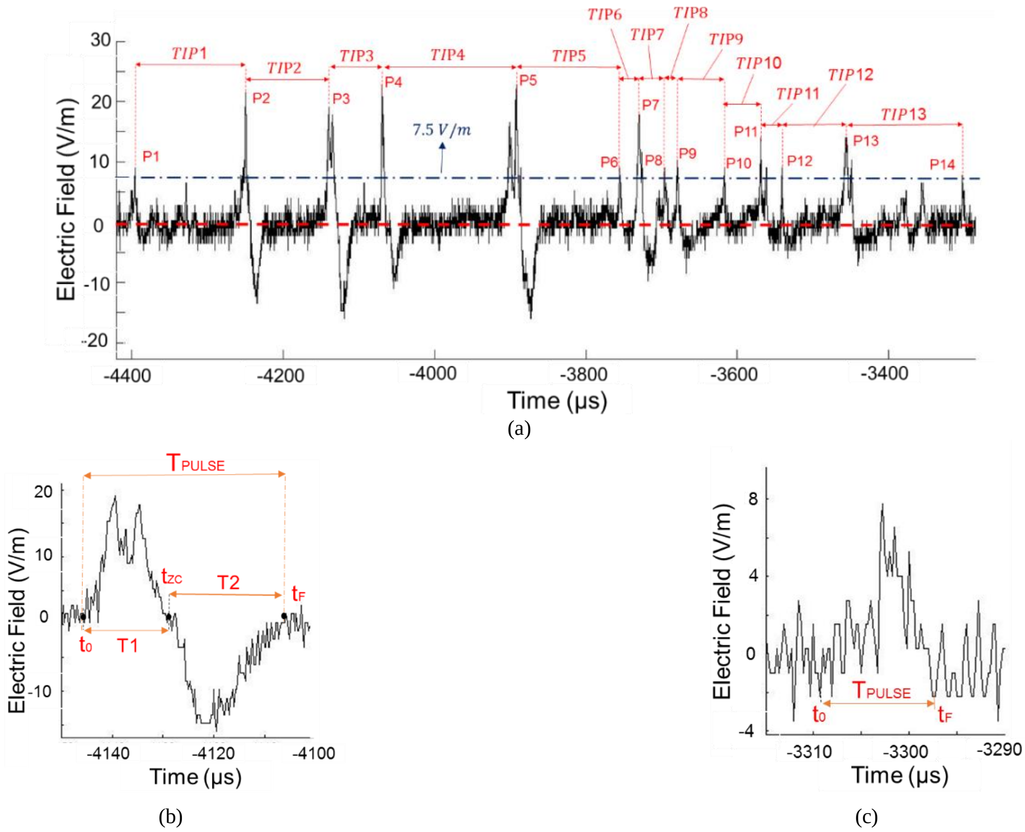


Fig. 4. Parameters identified in the PBP signature showed in Fig. 3. (a) number of individual pulses per train and IPT; (b) T_{PULSE} for bipolar pulse; (c) T_{PULSE} for unipolar pulse.

IV. Results and Discussion

The PBP trains were characterized employing statistical measurements, such as: geometric mean (GM), arithmetic mean (AM), minimum value (Min) and maximum value (Max). Table IV presents the statistical results for each parameter of the PBP signatures defined in this work. In addition, between Fig. 5 and Fig. 10 the statistical results for each parameter are presented using histograms.

TABLE IV. Statistical results obtained from the characterization of PBP trains.

Parameter	N°	Min	Max	AM	GM
TPBP (ms)	69	0.5	5.2	1.74	1.46
PBP-FRS (ms)	69	0.7	298.6	35.67	10.24
PBPmax/FRS	69	0.2	3.5	0.70	0.56
Pulses per train	1019	3	44	14.77	11.85
IPT (μs)	950	2.3	1950	125.68	74.26
T_{PULSE} (μs)	1019	1	83.8	17.19	11.86

Fig. 5 and Fig. 6 show the histograms for the train pulse duration and for the PBP–FRS time, respectively. The distribution presented in Fig. 5 shows that 32 of 69 signatures (46.4%) have a PBP train duration less or equal to 1.4 ms, while the remaining waveforms (37) exhibited a duration between 1.4 and 4.2 ms approximately. On the other hand, it can be seen in Fig. 6 that the parameter PBP–FRS presents a GM and AM of 10.24 ms and 35.87 ms, respectively, with individual values from 0.7 up to 298.6 ms (Min and Max values). Additionally, the histogram in Fig. 6 shows that 39 flashes (56.5%) present a PBP–FRS separation less than 10 ms, while 16 signatures (23.2%) are greater than 30 ms.

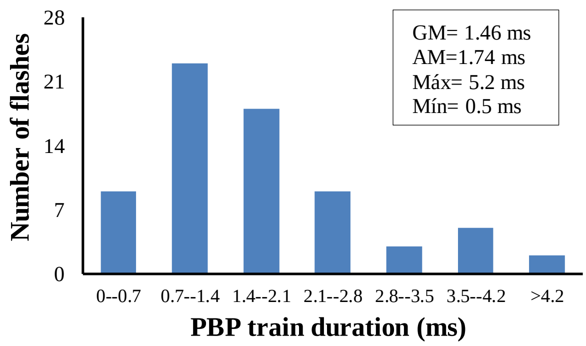


Fig. 5. *Distribution of the PBP train duration*

The distributions for the parameter PBP_{MAX}/FRS_M and the number of pulses per train are shown in Fig. 7 and Fig. 8, respectively. It can be seen in Fig. 7 that the minimum and maximum values for PBP_{MAX}/FRS_M are 0.2 and 3.5 respectively, with a GM of 0.56 and AM of 0.7. In this way, the histogram reveals that 55 signatures (79.7 %) present a PBP_{MAX}/FRS_M in a range less than 1.0, while 21 flashes (30.4 %) show magnitude ratios between 1.0 and 3.5. It means that most part of PBP trains have pulses whose magnitude is equal to or less than that of the FRS.

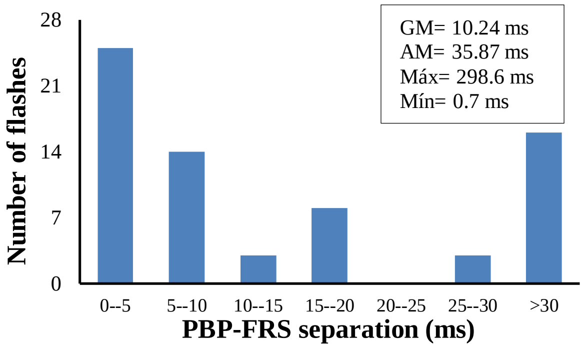


Fig. 6. *Distribution of the PBP–FRS separation.*

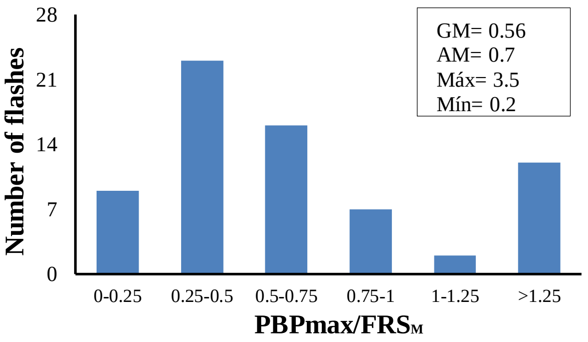


Fig. 7. *Distribution of the PBP/FRS ratio*

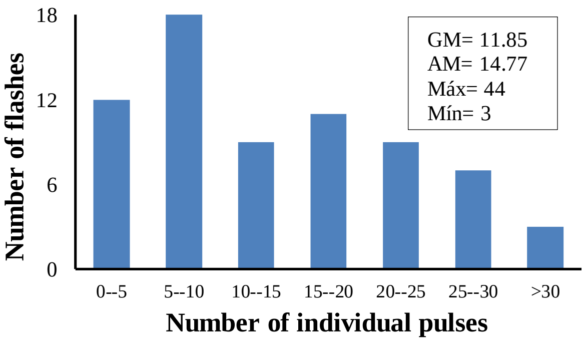


Fig. 8. *Distribution of individual pulses per train.*

With respect to Fig. 8, it is possible to observe that the quantity of individual pulses per train presents a GM and AM of 11.85 and 14.71, respectively. For this case, the analysis revealed PBPs with a minimum of 3 and a maximum of 44 pulses per train. The distribution shows that 39 (56.5%) CG flashes have between 3 and 15 pulses. In addition, it can be seen that 3 signatures (4.3%) present more of 30 pulses.

The statistical distribution for the interpulse time (IPT) is depicted in Fig. 9. It was found that 542 (57 %) intervals between pulses present a value less than 100 µs, while 39 intervals (4.1 %) have a duration great that 400 ms. Moreover, it can be seen in Fig. 9 that IPTs exhibited a GM and AM of 74.28 and 125.68 µs, respectively, whit values in the range of 2.3 to 1950 µs (Max and Min value). Finally, Fig. 10 shows the statistical results for the temporal parameter T_{PULSE}. This parameter presents a GM of 11.86 µs and AM of 17.19 µs. The minimum value of T_{PULSE} was 1 µs, while the maximum was 83.8 µs. The histogram reveals that major part of the individual pulses (690 signatures or 65.1%) have a duration in a range between 1 and 20 µs, while 8 pulses (0.7%) exhibited values greater than 60 µs.

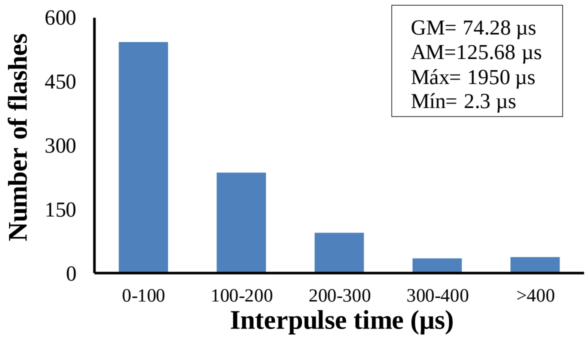


Fig. 9. *Distribution of time interpulse (IPT)*

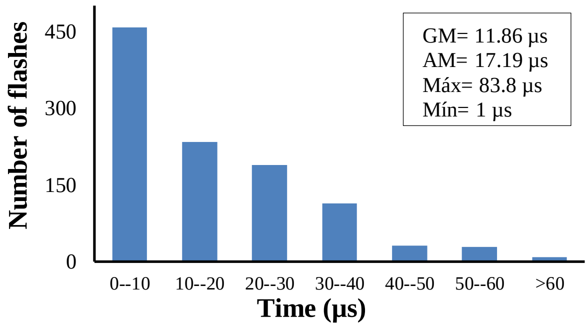


Fig. 10. *Distribution of individual pulse duration*

V. CONCLUSIONS

In this study, the analysis and characterization of 69 electric field signatures produced by PBP trains preceding the FRS in negative CG lightning flashes was performed. All the waveform analyzed present similar characteristics: (a) bipolar pulses at the beginning and in the middle of the train; (b) unipolar pulses at the end of the signatures; (c) the PBP train starts with small pulses, continues with pulses of greater amplitude, and ends with pulses of lower magnitude; (d) the initial polarity (bipolar pulses) of the pulses is similar than the FRS.

The statistics results obtained from the data set show that the duration of the pulse trains has an arithmetic mean (AM) of about 1.7 ms, with individual values from 0.5 up to 5.2 ms (maximum and minimum values). On the other hand, the temporal parameter PBP-FRS presents an AM of 35.87 ms, with maximum and minimum values of 0.7 and 298.6 ms, respectively. Other parameter temporal as the time interpulse and individual pulse duration, showed an AM of 125.68 µs and 17.19 µs, whit geometric mean (GM) of 74.3 µs and 11.9 µs, respectively. The magnitude ratio PBP_{MAX}/FRS_M has a GM of 0.56 and individual values from 0.2 up to 3.5. Finally, the number of pulse per train presents an AM and GM of 14.7 and

11.8 respectively, with maximum and minimum values of 3 to 44 pulses per PBP train. Future works should be oriented to compare these results with those obtained in other regions of the world (tropical, subtropical and temperate locations)

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