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Analysis of the Intra-Cloud lightning activity detected with Low Frequency Lightning Locating Systems

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Abstract*—Météorage detected nearly 4.3 million lightning discharges in 2017 in France out of which 86% are intra-cloud (IC) pulses. Benefiting from a new flash grouping algorithm that combines both IC pulses and Cloud-to-Ground (CG) return strokes, we observed that 95% of the flashes exhibit in-cloud activity breaking down in 76% of IC flashes and 19% of CG flashes we termed hybrid (HY) flashes as they are made of both IC and CG Météorage records. Météorage network manages to detect as many as 2.1 IC pulses per flash in -IC flashes, 3.0 for +IC flashes, 3.6 IC pulses for -HY flashes and up to 5.0 IC pulses for +HY flashes. IC pulses recorded during HY flashes are often of the same polarity as the paired return strokes. A detailed analysis showed that these IC pulses occur mostly before the first return stroke, in average 72% of all HY flashes. They are also observed between subsequent strokes and after the last return stroke in respectively 48% and 57% of the flashes. We computed a median inter-pulse delay of 7 ms and of 14 ms for +HY and -HY flashes respectively, and a median separation time between IC pulses and first return stroke of 54 ms and 82 ms respectively. The comparison of these statistics with results found in literature on Preliminary Breakdown Pulses (PBP) and K-changes revealed that they are in good agreement despite a limitation on the IC pulse detection efficiency. We conclude that the IC pulses detected by Météorage are related to such in-cloud processes. The second part of this analysis used a total lightning dataset consisting of LF and VHF data collected respectively by Météorage and SAETTA, a LMA network deployed in Corsica. The analysis permitted to assess the IC pulses location accuracy by Météorage is around 3 km in average with 1.64 km median value with a mean DE of 56%. We found the DE in Corsica is depending on the vertical extent of the flashes that must exceed 2.6 km (median value) to be detected by Météorage. Surprisingly, despite the median vertical extend of CG flashes is 2.7 km, they are perfectly detected by Météorage (97 % CG flash DE against high speed video records).

***Keywords*—Lightning Locating Systems; Intra-Cloud flashes; Preliminary Breakdown Pulses; K-changes; Detection Efficiency; Location Accuracy**

I. INTRODUCTION

Early Lightning Locating Systems (LLSs) operating in Low Frequency (LF) were designed to only locate the return strokes, these large vertical Cloud-to-Ground (CG) discharges, because they represent the real electrical threat for outdoor activity and property. Nowadays, the same systems have evolved to also detect and locate a fraction of intra-cloud (IC) flashes not only thanks to the improvements in electronics and signal processing techniques but also under the pressure of new applications. This new capability gives the opportunity to constitute a total lightning dataset combining both IC pulses and CG strokes at a continental scale. The IC pulses being detected in LF are related to charge transfers occurring in several processes at different stages of the lightning flash lifecycle.

On the contrary of the return strokes produced between the thundercloud and the ground, the IC discharges cannot be directly visually observed because most of them remain inside the cloud. Nevertheless, it is necessary to characterize this new total lightning feature by evaluating the real performances of a LLS operating in LF in terms of IC detection efficiency and IC location accuracy.

The first objective of this work is to analyze the IC pulses collected by the French National LF LLS, so called Météorage, and to compute statistics on a large dataset of observations to evaluate its capability to correctly detect the electrical processes generating IC pulses. It is well known that the Preliminary Breakdown (PB) phase in CG or Initial Breakdown in Cloud-to-Cloud (CC) lightning flashes occurring at the very beginning of a lightning flash tend to produce a train of bipolar pulses. Some of them can exhibit a peak current as intense as or larger than the first return stroke peak current which generates a strong electromagnetic signal detected by remote sensors operating in low frequency [Nag and Rakov, 2008]. However, many IC pulses can also be observed latter in the lifecycle of a flash, between subsequent strokes or at the end of a flash, that may correspond to K-change processes.

The second objective is to assess the performances of Météorage in terms of IC flash Detection Efficiency (DE) and Location Accuracy (LA) similarly to the work done by Murphy et al [2014].

II. DATA AND METHOD

The first part of this work consists in characterizing in terms of statistics the IC activity as detected by Météorage. This system is using the most recent lightning detection technology from Vaisala, namely LS7002 sensors and TLP V.1.2.2 capable to locate individual IC pulses and CG return strokes. Since the 1rst of January 2017, Météorage operates a flash grouping algorithm which combines both IC pulses and CG strokes in a single flash if the delay between subsequent events is smaller than 500 ms and the separation distance is less than 10 km for two subsequent CG strokes. This maximum distance is extended to 20 km when a IC pulse is being grouped with either another IC pulse or a return stroke to take into account the horizontal extent of a lightning flash. concerned. The total duration of a flash cannot exceed 1 second. As a result, the new algorithm produces three different types of flashes as IC, CG or Hybrid flashes (HY). The two first types are respectively made of IC pulses or CG strokes only, whereas the latter consists of a combination of IC pulses or CG strokes. All flashes produced by the algorithm are assigned with a polarity which is based on the general rule in use among LLS operators stating that a flash gets the characteristics (polarity, amplitude, position, timing…) of its first event. Thus, IC and CG flashes are respectively represented by the first IC pulse and CG stroke. In case of HY flashes, this is the first return stroke that is used to define the flash. When CG or HY flashes exhibit return strokes of different polarities they are termed as bipolar flashes. This distinction is not made for IC flashes that can be either only positive or negative. Prior this date, the flash grouping algorithm was based on CG strokes only and individual IC pulses were leading to single pulse IC flashes. As a result, the number of IC flashes computed by the system was dramatically outnumbered in respect with the real occurrence of IC flashes in nature. It is expected that the new algorithm delivers more reliable and consistent flash data.

The performances of Météorage in terms of CG stroke and CG flash DE and strokes relative LA, namely the distance between computed locations of strokes using the same channel, were determined based on high speed video records gathered across France between 2013 and 2015. As a result, the stroke and flash DE are respectively 93% and 97% and the median LA is about 110m [Schulz et al., 2014, 2015; Pedeboy et al., 2016].

The lightning dataset collected by Météorage during 2017 in France, was analyzed to characterize the IC activity. Several general statistics on parameters of IC pulses and flashes like the seasonal evolution, polarity, peak current was investigated. Further detailed analyses were carried out to evaluate the type of IC processes detected by Météorage in the HY flashes. We mainly focused on the study of IC pulses occurring prior the first located return stroke, between two subsequent strokes and after the last located return stroke. The idea was to evaluate the capability of LF LLS to detected physical processes like preliminary breakdown pulse trains, J and K processes or recoil leaders terminating the flash.

The second part of this work aims at determining the IC pulses and flashes detection LA and flash DE performances of Météorage. It is based on a comparison between the LF lightning and SAETTA (Suivi de l'Activité Electrique Tridimensionnelle Totale de l'Atmosphère) datasets taking the latter as a ground truth reference. SAETTA is a Lightning Mapping Array (LMA) system developed by the New Mexico Tech (USA). The network is made of 12 VHF stations installed across Corsica since 2014. It detects the signals generated by the leaders in the VHF (60-66 MHz) domain at high temporal (80 µs) and spatial resolutions which allow a highly detailed 3D mapping of lightning flashes. The theoretical performance projections for SAETTA are estimated to be 20 m for the radial error, 5 m for the azimuthal error 50 m for the elevation. As the performances of a LMA system generally outperform those of LLSs in LF, it is possible to consider LMA flash data as ground truth. However, similarly to the grouping of return strokes in flashes for Météorage it is necessary to build up the SAETTA flash dataset by grouping the VHF sources related to the leaders and sometimes K-changes in flashes based on spatial-temporal criteria. The flash grouping algorithm used in this work firstly group sources based on a maximum interval of 100 ms considering that the continuity of a flash is broken when the delay between to subsequent sources exceed this limit. Then, the consistency of the sources in every group is check based on a maximum propagation speed of the leaders of 300 km/s. When subsequent sources distance/delay ratio exceed the speed limit, the algorithm considers the sources do not belong to the same leader, and a new one is created and so on. This method allows discriminating between different flashes occurring in the same timeframe but in different lightning cells. The same algorithm was used to identify the world's longest duration lightning flash observed in August 2012 in South-East France and published in the official WMO Archive of Weather and Climate Extremes [Lang et al., 2016].

The dataset used for the performance analysis is based on the lightning data collected during 19 thunderstorm days ranging from June to October 2017 by both Météorage and SAETTA. To guarantee a very good LMA sources accuracy, the study is limited to the data observed in the core region of SAETTA (latitude between 41.3N and 43N and longitude between 8.5E and 9.6E). Each Météorage IC pulse or Météorage CG return stroke occurring in the time window and the area of a LMA flash is combined with the LMA flash in an object we can consider as a single lightning flash. The area of a LMA flash is determined by the rectangle encompassing the limits of the horizontal extent of the flash plus 0.2 degrees in all directions to consider the apparent poor Météorage location accuracy of IC pulses. According to the different possible combinations, such objects exhibit either only Météorage IC pulses or Météorage CG strokes, both or no LF data. This result in several types of total lightning flashes that can be labelled as "pure" IC flashes, "pure" CG flashes, HY flashes and flashes free of any located LF IC pulse and CG stroke (FICG).

III. RESULTS

A. General statistics

In this section we present some general statistics on the occurrence, polarity, peak current and seasonality of IC pulses, IC and HY flashes.

1) Intra-Cloud pulse : Météorage observed in 2017 over France more than 3.6 million IC pulses, where about 94% occurred during the lightning season in summer between May and August. With less than 0.6 million CG strokes detected, the IC pulses represent 86% of the total discharges observed in average during the year. The -IC pulses exhibit a mean peak current of -5.6 kA and a median value of -4.1 kA. The mean and the median peak current values for the +IC pulses are respectively 5.3 kA and 4.3 kA. The peak current distribution is larger for -IC pulses, reaching extreme values up to -99 kA, than for +IC pulses where the maximum is +35 kA. However, it is interesting to note the absolute mean and median values are quite comparable whatever the polarity whereas they strongly differ between +CG and -CG strokes.

Based on this IC pulse and CG stroke data the new flash grouping algorithm produced more than 1.0 million of IC flashes, 0.26 million of hybrid flashes and 0.07 million of CG flashes. As a result, 94% of all the flashes detected in France in 2017 contain at least one IC pulse.

2) Intra-Cloud flashes : The IC flashes represent in average 76% of the total flashes observed in 2017 in France. The mean number of IC pulses per IC flashes, referred as IC Pulse Multiplicity (ICPM) here, is 2.6 regardless the pulse polarities. However, +IC flashes exhibit a higher ICPM than for -IC flashes, respectively 3.0 and 2.1. The ratio of +IC flashes in respect to the total IC flashes is 53%. The mean and median values of the separation delay between subsequent IC pulses, computed on more than 1.0 million IC flashes, are 75 ms and 23 ms respectively. The separation delay is computed as the time difference between subsequent pulses of the same flash.

3) Hybrid flashes : The HY flashes represent in average about 19% of the total flashes detected in 2017. The mean ICPM for HY flashes is 3.9 but like for IC flashes this result is dependent on the polarity of the flashes. Thus, +HY flashes exhibit a mean ICPM of 5.0 against 3.6 for negative flashes. A more detailed analysis of the in-cloud lightning activity in HY flashes is presented in the next section.

B. Analysis of Intra-Cloud pulses in flashes

In this section we analyze the located IC pulses occurring in HY flashes to determine if the data collected by Météorage is related to preliminary breakdown pulses (PBP) which are known to produces prior the first return stroke in most of the negative and positive CG flashes. Similarly, the K-changes generate IC pulses either between two subsequent return strokes or after the last one in CG flashes and in IC flashes as well. In addition, to general statistics we compute statistics on several parameters that characterize such IC processes in the objective to compare with statistics found in the literature. Out of these parameters, the most relevant are the delay between subsequent IC pulses (inter pulses delay), between the last IC pulse and the following return stroke (separation delay between IC and return stroke), the rate of first IC pulse exhibiting a peak current higher than its corresponding stroke and the consistency of the IC pulses polarity with the flash polarity. The results will be discussed in the next chapter.

1) Intra-Cloud pulses prior the first return stroke : We observed in average that 72% of the total of HY flashes exhibit at least one IC pulse prior the occurrence of the first return stroke breaking down in that 72% for +HY, 73% for -HY and 59% for bipolar flashes. If we consider that in about 6% of the CG flashes no IC pulse was located and that all flashes exhibit a PBP, Météorage is capable to detect and locate about 55% of the total. About 66% of the +HY and 70% of -HY flashes are starting with an IC pulse of the same polarity as for the first return stroke. For 28% of the -HY flashes, the first IC pulse exhibit a peak current greater or equal to the one of the first return stroke. Out of these cases, 78% of the IC pulses are of negative polarity. Regarding the +HY flashes, we observed only 7% of the total flashes presenting an IC pulse with a peak current higher than the return stroke. This result is sensible as the +CG strokes generally exhibit strong peak current.

TABLE I. STATICTICS ON IC PULSES DETECTED AT THE BEGINNING OF HY FLASHES

	+HY flashes	-HY flashes
Inter IC pulses delay (ms)		
Number of data	60541	214583
Mean/Stdev	45/180	59/192
Median	7	14
Separation delay (ms)		
Number of data	9565	69583
Mean/Stdev	99/116	122/124
Median	54	82
Duration (ms)		
Number of data	4709	38005
Mean/Stdev	157/164	194/177
Median	102	147

Table I gives additional statistics on the separation delay as it was defined previously and the duration of the IC activity occurring before the first CG stroke that is computed as the time difference between the last and the first IC pulse when several such events are detected by the system.

In average, 2.9 IC pulses per positive flash, 2.4 per negative flash and 2.5 for bipolar HY flashes are detected prior the first return stroke occurrence.

2) Intra-Cloud pulses between return strokes : We observed in average that 48% of the total HY present at least one IC pulse between subsequent return strokes. However, this result is mainly driven by the bipolar flashes as 65% are found to fulfil this condition, against 20% for -HY and only 4% of the small fraction of multi-strokes +HY flashes. Most of the IC pulses exhibit the same polarity as the flash with 65% for -HY and 77% for +HY flashes. The different separation delays are summarized in Table II. We found that 2.1 IC pulses are detected in average, between subsequent return strokes in negative flashes. We also observed that 4.3% of +HY flashes exhibit more than one return stroke which is consistent with the multiplicity of 1.04 found by Saba et al [2010] from high-speed video records. In these cases, 77% of the IC pulses occurring in between both return strokes are positive, and the mean total number is 2.7.

TABLE II. STATICTICS ON IC PULSES DETECTED BETWEEN SUBSEQUENT STROKES IN HY FLASHES

	+HY flashes	-HY flashes
Inter IC pulses delay (ms)		
Number of data	2727	31955
Mean/Stdev	20/43	38/60
Median	5	13
Separation delay (ms) with next stroke		
Number of data	1519	24560
Mean/Stdev	38/62	77/91
Median	13	43
Separation delay (ms) with previous stroke		
Number of data	5700	88633
Mean/Stdev	32/66	55/80
Median	6	23

3) *Intra-Cloud pulses after the last return stroke :* We observed in average that 57% of the total HY flashes exhibit at least one IC pulse after the occurrence of the last located return stroke breaking down in 77% for +HY, 54% for -HY and 59% for bipolar flashes. Like IC pulses occurring prior the first stroke and between subsequent strokes, the IC pulses producing at the end of a flash are mostly of the same polarity as the last return stroke. The rates are 65% for -HY and 77% for +HY flashes.

TABLE III. STATICTICS ON IC PULSES DETECTED AFTER THE LAST STROKE IHY FLASHES

	+HY flashes	-HY flashes
Inter IC pulses delay (ms)		
Number of data	11844	45962
Mean/Stdev	46/80	60/91
Median	11	17

Table III presents the statistics on IC pulses separation delays only. Note that the delay between IC pulses and the last stroke is included in the results of Table II.

In average, 3.5 IC pulses per positive HY flash and 2.4 per negative HY flash are detected after the last return stroke occurrence.

4) *Intra-Cloud pulses in bipolar flashes :* Finally, a rate of 5% of the total amount of the HY flashes were found to be bipolar, meaning they exhibit at least two return strokes that are of opposite polarity. About 59% of these events start and terminate with an IC pulse that are slightly mainly -IC pulses (59%) at the beginning and practically balanced (51%) at the end. However, 70% of the bipolar HY flashes exhibit at least one IC pulse between the subsequent return strokes which in comparison to the +HY and -HY flashes is incredibly high. This might be due to a discrimination issue where weak CG strokes are classified as IC pulses.

In average, the number of IC pulses detected prior the first stroke is 2.5, 3.2 between return strokes and 3.0 after the last stroke.

5) *Seasonality of flash rates :* It is interesting to note that some parameters are affected by seasonal effect. Some strong monthly variations are found like on the IC pulse and flash rates which are minimum in winter and maximum in summer with more than 79% of IC flashes in July (see figure 1). +IC pulses are also predominant in summer where they represent up to 64% of the monthly amount of IC flashes in August. Because of this increase, the ICPM of +HY flashes is reaching a maximum of 6.1 IC pulses per flash in August against 4.1 for -HY flashes. This result is mainly driven by the increase of the rate of +IC pulses detected at the end of the flash. The -HY flashes are less affected by this seasonal effect as they exhibit a majority of -IC pulses.

Surprisingly, the monthly variations on the rate of -HY flashes exhibiting a first IC pulse peak current stronger than the maximum peak current of the first return stroke in winter, about 40% against 24% in summer. This effect is not visible for +HY flashes. Similarly, the rates of -HY and +HY flashes starting, ending or exhibiting an IC pulse between subsequent strokes are stable in the year.

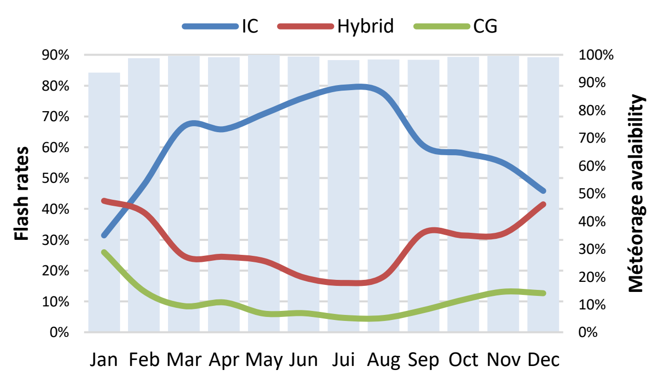

Figure 1- Monthly distributions of the percentages of IC, CG and Hybrid flashes in respect to the total amount of flashes detected by Météorage in France in 2017. The blue bars show the monthly Météorage availability (right vertical axis).

C. *Performances of Météorage for IC detection*

In this section we determine the performances of Météorage in terms of IC pulse LA and DE based on the total lightning dataset which combines LF and VHF records from the French LLS and SAETTA. The area of study is Corsica.

1) *IC pulses location accuracy :* We compare the position of IC pulses as computed by Météorage against the position of preceding VHF sources located by SAETTA. When the delay between a LMA source and an IC pulse is comprised between 0 and -2 ms both events are assumed to be time consistent. To note, all LMA source exhibiting a timestamp more recent than the IC pulse cannot be correlated. Then, among all the potential

LMA sources that are time correlated, the distance to the closest one is considered as the IC pulse location error. Pairs of data exhibiting a distance greater than 15 km are considered in the analysis as time correlation issues and are rejected.

A total of 5479 IC LF pulses, regardless their polarity, was correlated with VHF sources. The delay between VHF source and IC pulse ranges from 1 microsecond to 1 ms with a mean value of 0.3 ms. The mean number of sensors used in locating the IC pulse is 4.6 with a minimum of 2 sensors and a maximum of 34. The mean absolute value of peak current amplitude is 6.6 kA. As a result, the location accuracy shows a mean value of 3 km, a median value of 1.64 km, and a minimum of 2 m and a maximum distance of 14.9 km which corresponds to the upper limit used in the correlation process.

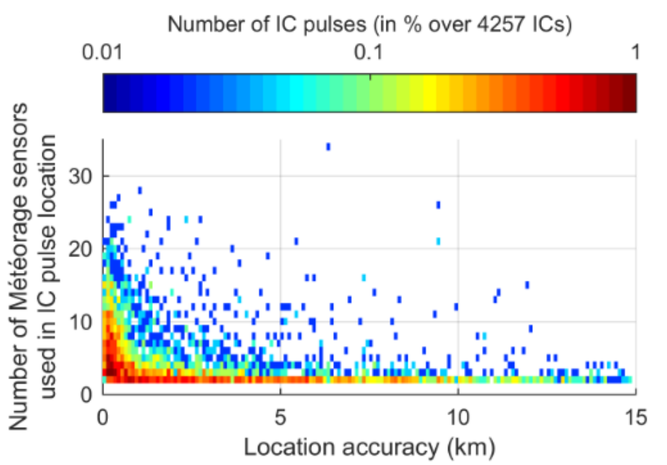

Figure 2- Distribution of the errors distances between IC pulses and their corresponding VHF sources as a function of the number of sensors used by Météorage to locate the IC pulse. The data are distributed per 100 m steps on the horizontal axis, and 1 sensor on the vertical axis. The color code varies from 0.02% à 1.22%.

The distribution of the location errors as a function of the number of sensors locating the IC pulse is shown in figure 2. It shows a positive correlation between the number of sensors used in a location and the LA, meaning that as expected the more sensors the smaller error. In general, the number of sensors in a solution depends on the strength of the peak current of the discharge. The more intense the current in the discharge, the stronger the signal at the discharge origin, the longer the signal propagation path. As a result, there is a higher probability that more sensors detect strongest discharges. However, it is interesting to note in some cases, despite a high number of sensors used in the IC pulse location, implying a very good accuracy, large errors are observed. This is more likely related to a correlation issue where the LMA source taken as a reference is not involved in the corresponding IC pulse. The number of such events are evaluated to be less than 100 so they should not influence the mean and median values of the location accuracy.

2) IC flashes detection efficiency : The IC pulses detection efficiency is estimated based on the assumption that the CG and HY flashes detection efficiency by Météorage is 100%. This is not exact as the validated CG flash DE is 97% [Schulz et al., 2015], but one can roughly consider FICG to represent the part of IC flashes not detected by Météorage. Thus, we can derive from this number the IC flash DE. Out of the 13967 LMA flashes analyzed, 5691 were classified as IC flashes, 2922 as HY flashes, 929 as CG flashes and 4425 as FICG. Based on the previous assumption, the mean IC flash DE is 56%. However, this result varies quite significantly from a thunderstorm to another as it can be seen in Figure 3.

A more detailed analysis showed that the DE depends on the vertical extent of the flash. This parameter is computed as the difference of altitude of the VHF sources representing the 95th and 5th percentiles of all sources in the LMA flash. Indeed, the FICG flashes show a median vertical extent of 2.6 km whereas it is 4.1 km for the IC flashes being detected. Interestingly, the median vertical extent for HY and CG flashes are quite small with respectively 3.4 km and 2.7 km which is very similar to FICG flashes. This latter result is consistent with the no detection of IC pulses in such flashes because of the small size of their vertical extent. The CG flash DE seems not to be affected by this parameter because the energy generated by the return stroke might compensate the smaller total length of the radiating channel.

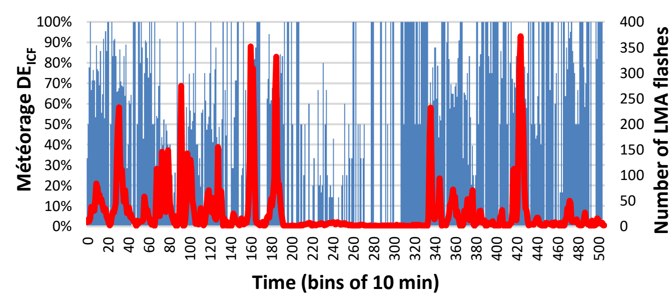

Figure 3- Evolution of the IC flashes DE for Météorage on the total period of SAETTA observations. The blue bars represent the IC DE per 10 minutes bins representing 19 thunderstorm days and refer to the left axis. The red curve shows the number of LMA flashes per 10 minutes bins and refer to the right axis.

IV. Discussion

We found that Météorage detects about 70% of HY flashes exhibiting at least one IC pulse prior the first return stroke. Wooi et al [2016] reported that 40% of the flashes they observed occurred without PBP which is consistent with our result. However, Schulz and Diendorfer [2006] measured a much higher rate of 89% in multi-strokes and 71% in single stroke negative flashes in Austria. Their results are based on records made on close flashes (50 to 100 km) only and with a standalone electric field recorder. On the contrary, the flashes in our dataset are located by several sensors located at much larger distances (Météorage' sensor baselines are 250 km in average) that of course affect the detection efficiency of the weakest PBP. It can be noted that the polarity and the seasonality of thunderstorms do not influence this result. However, in this analysis we do not consider the IC/CG event discrimination issues that exists mainly for discharges exhibiting weak peak currents. Classification Accuracy (CA), meaning the percentage of the case where the classification a given event is good, have been estimated in Kohlmann et al. [2017]. The authors claimed that the CA is 96% for IC pulses, 85% for -CG first strokes and 92% for +CG first strokes.

In addition, we found that most of the IC pulses starting a flash are of the same polarity as the first return strokes (66% of the +HY and 70% for -HY flashes). Similarly, several authors have reported comparable results, even though slightly higher, like Ushio et [1998] who found a rate of 89.5% (17/19), Nag and Rakov [2012] 87.5% (7/8), Schuman et al [2013] 95% out of 80 CG flashes, Gomes and Cooray [2004] 80% (57/71) and Zhang et al. [2013] claimed a percentage of 81%. Again, we explain the smaller rate we obtained by the limitations in terms of detection efficiency of the low peak current pulses despite the fact we compare our results with statistics based on small dataset of observations. This must affect not only the detection of flashes with weak PBP but also the duration and the separation delay between PBP and return strokes. To illustrate this latter comment, we can compare our statistics with those from Gomes and Cooray [2004] who reported a mean separation time between PBP and return strokes in +CG flashes of 56 ms. Johari et al [2016] reported a mean separation time between PBP and the return stroke in +CG flashes of 75.1 ms for PBP of the same polarity as the corresponding return stroke, and 114.6 ms for the PBP of opposite polarity. Interestingly, Zhang et al. [2013] reported a separation delay of 99.5 ms and 112.1 ms in Guangzhou (China). As expected, we obtain higher delays (mean values of 122 ms for -HY and 99 ms for +HY flashes) because with Météorage only the strongest IC pulses are detected.

Finally, the limited IC pulses DE also influence the statistics on the percentage of first IC pulses whose peak current is greater than its corresponding return stroke. We found a ratio of 28% for -HY flashes where Schulz and Diendorfer [2006] reported a result of 8% for negative CG flashes, and 19% for Nag and Rakov [2008]. As the system detects mostly the more intense pulses and miss the weakest the percentage of large IC peak currents tend to be higher. In addition, the observed CG flashes could also result from this limitation and might be HY flashes where no IC pulse could be detected by Météorage. The 5% rate of bipolar flashes found in this study is consistent with the 6.7% claimed by Gorin and Shkilev [1984]. Most, if not all, reported bipolar flashes are related to upward lightning flashes. Such events are known to exhibit a lot of recoil leaders draining charges downward in the preexisting channel. The polarities of IC pulses recorded in between return stroke are practically balanced with only 57% of IC pulses. Further analysis must be carried out to check whether these flashes are upward flashes, like the presence of a tall objects nearby the flash locations.

Miranda et al [2003] measured a mean value of 18.5 ms for the inter K-changes delay, and a median value of 12 ms. Thottappillil et al [1990] reported a geometric mean of 12.5 ms that is very similar to our result of 14 ms for negative flashes. However, the mean value of 38 ms we compute is twice the result from Miranda.

Regarding the results on the performances of Météorage, it must be noticed that the area of study is less well covered than the core center of the network. Indeed, the baselines of the closest sensors covering the island range from 150 to 350 km. It is expected that the French LLS might underperform in this region.

V. CONCLUSION

This study aimed at analyzing for the first time IC pulses data collected by Météorage, the French National LF LLS to first characterize the occurrence of IC pulses, then compute some statistics on IC pulses occurring in HY flashes, identify the in-cloud processes initiating such IC discharges detected in LF and finally assess the performances of Météorage in terms of IC pulses LA and DE.

We found the IC pulse represent about 86% of all the discharges detected in France in 2017 by Météorage, namely a total of nearly 4.3 million. Benefiting from a new flash grouping algorithm in operation since January 2017 that combines IC pulses with CG return strokes, we observed that 72% of HY flashes exhibit at least one IC pulse prior the first return stroke, 48% between subsequent strokes and 57% after the last stroke. Furthermore, an average of about 3 IC pulses are detected per flash ranging up to 6.1 in summer for +HY flashes and 4.1 for -HY flashes. Based on this dataset, we studied the characteristics of IC pulses depending on they occurred prior the first return stroke, between two subsequent strokes or after the last return strokes.

We focused on some important parameters like separation time between successive IC pulses, between the last IC pulses and its corresponding stroke, the rate of IC pulses exhibiting a peak current greater than the return strokes, IC pulse polarity reversal rate and the duration of the PBP train for both +HY and -HY flashes. We found that 70% of HY flashes exhibit PBP, 55% if we consider the CG flashes where no IC pulse was detected, 28% of -IC pulses presenting a peak current greater than its corresponding return stroke, a mean separation time between PBP and first return strokes of 122 ms for -HY and 99 ms for +HY flashes. Despite an IC pulse DE limitation, these results are very comparable to those of some other authors. As a result, we concluded the IC pulses as detected by a LF LLS are mainly related to both PBP and K-changes.

We think this work gives relevant statistics on PBP and K-changes that present the advantage to be computed on a large dataset and a one-year period. However, they might be overestimated because of a IC pulse DE limitation.

The second part of this analysis permitted to assess the IC pulses LA is around 3 km in average and 1.64 km median value. There is a strong correlation between LA and the number of sensors locating the IC pulse as more the sensors are smaller the location error is. However, for reason to be further investigated some IC pulses located with many sensors still exhibit significant location errors. In addition, the IC pulse DE is found to be 56% in average but with strong variations depending on the lifecycle of the thunderstorm. Indeed, the IC flashes exhibiting a rather small vertical extent (less or equal to 2.6 km median value) are most likely missed by Météorage. Such events tend to occur in very convective thunderstorms. Surprisingly, despite the median vertical extend of CG flashes is 2.7 km, they are perfectly detected by Météorage (93 % stroke DE against high speed video records). These results are very good, both on LA and DE, particularly considering the coverage of the LLS is not as good as in Corsica than in continental France.

Further works should be carried out to check the exact impact of the vertical extent on the detection efficiency of the IC pulses by operational LLS.

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