Analysis of the initiation phase in negative lightning flashes exhibiting an intense return stroke peak current

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ABSTRACT: We examined the initial conditions leading to negative cloud-to-ground (-CG) flashes with a return stroke larger than 100 kA (absolute value), so called -CG$_{<-100kA}$ flashes. The dataset is made of 88 flashes observed during summer 2017 over Corsica in France by a Lightning Locating System (Météorage), a Lightning Mapping Array (SAETTA) and BLESKA, a broadband HF magnetic field analyzer. We found that -CG$_{<-100kA}$ flashes exhibited in average a vertical extent of 2730m and initiated at an altitude of 3720m, these values being far below those we recorded for -CG$_{>-100kA}$ flashes, respectively 3600m and 5350m. In addition, -CG$_{<-100kA}$ flashes presented a short delay of about 2ms between the first preliminary breakdown pulse and the return stroke. We concluded that -CG$_{<-100kA}$ flashes are mainly related to low base and top thunderclouds which combined with the elevated terrain in Corsica might enhance the vertical electric field and the electrical charges motion resulting in large return strokes. Finally, we noted that all the analyzed strokes were followed by a period ranging from 7ms to 98ms during which no VHF activity was detected by SAETTA, likely to be related to the continuing current phase.

INTRODUCTION

Any downward CG flash usually starts with an initial breakdown which gives birth to a leader propagating toward the ground. The return stroke is the current wave that is produced when the leader and one of the resulting upward connecting leaders manage to connect creating a conductive path between the cloud and the ground. The return stroke then propagates upward from the ground as a current wave draining all the electrical charges deposited in the ionized channel to the charged regions in the thundercloud. Because the electrification process leads to the production of both positive and negative charges in the thundercloud, the current flowing in the return stroke can be of both polarities. Then, depending on the type of flash this sequence of leader/return stroke can occur several times during the same flash like for -CG flashes with multiple connections to the ground either along the same ionized channel or/and along new channels, whereas it generally happens only once in +CG flashes.

All the electrical processes involved in leaders and return strokes produce electromagnetic signals with a specific signature in magnitude and frequency. Depending on their propagation mode and their frequency range, those signals can travel over large distances either as ground waves or ionospherically reflected waves. Thus, with an appropriate sensor design it is possible to detect and measure the characteristics of such radio signals like the time and the direction of arrival and the magnitude of the electromagnetic signal at the sensor. When these data are collected by several sensors at different locations it is then possible to geo-locate a source event in 2D or 3D, timestamp it and compute some electrical properties of this source event. This is the principle of a Lightning Locating System that can collect large sets of lightning data based on a network of sensors and out of which operational applications and services can be derived and provided to end-users.

The objective of this work is to determine the initial conditions necessary to produce -CG lightning flashes with return strokes exceeding -100 kA in absolute value, so called -$CG_{<-100kA}$ flashes. We focused our study on Corsica because several instruments are deployed in this region for the EXAEDRE and SOLID projects consisting of studying thunderstorms and lightning activity in this complex Mediterranean area [See Defer et al., this conference for a description of both projects]. These instruments are Météorage [Pedeboy, 2015], SAETTA [Coquillat et al., 2017] and BLESKA [Kolmasova et al., 2018], the French national LLS, a Lightning Mapping Array (LMA) and a broadband magnetic field sensor respectively. They all provide complementary lightning records giving a unique opportunity to analyze in detail -$CG_{<100kA}$ flashes through their synergetic use. Furthermore, Corsica and more generally the Mediterranean Sea exhibit in average a rate of intense first return strokes higher than over the continent as it can be seen in the analysis of global lightning distribution from Said et al. [2013] and Pédeboy et al. [2017].

DATA AND METHOD

The period of this study ranges from the 1st of June to the 30th of September 2017. Unfortunately, a lack of thunderstorms in autumn 2017 shortened the stormy season earlier than usually. The study period limited to summer time prevented from full evaluating the potential seasonal effect on the occurrence of -$CG_{<-100kA}$ flashes and on their characteristics.

Météorage is the French national operational Low Frequency LLS based on the latest Vaisala's technology (LS7002 sensors and Total Lightning Processer) that detects return strokes and deliver polarity and stroke peak current amplitude. The detection efficiency for flashes and strokes is 97% and 93%, respectively. SAETTA, is a Lightning Mapping Array (LMA) made of 12 VHF stations deployed across Corsica and operated by the Laboratoire d'Aérologie (France). It provides high-resolution 3D VHF sources locations allowing the mapping in details the different leader paths. Such a system is usually considered as a ground truth reference because its detection efficiency of the negative leaders is almost 100%. To rely on high quality data, we restricted our study to Corsica only where the performances of SAETTA are optimal. Finally, BLESKA is a broadband HF analyzer (5 kHz - 37 MHz) that is a clone of the IME-HF analyzer for TARANIS, the French space mission dedicated to TLE observation. It is connected to the SLAVIA sensor (Shielded Loop Antenna with a Versatile Integrated Amplifier) to detect the E-W horizontal component of the magnetic field fluctuations. This instrument which is installed in Ersa in the Cap Corse (North of the Corsica Island) provides two kind of high resolution waveforms records, a so called long duration record (208 ms) and on the contrary a short duration record of 300µs that encompasses preliminary breakdown, stepped leader and return stroke signals.

The lightning flash dataset used in the present study results from flash grouping algorithms combining for Météorage both IC pulses and CG strokes on spatial-temporal basis, and for SAETTA, the VHF sources based on a leader propagation speed of 3 10^5 $m.s^{-1}$ criteria. This means that all pairs of subsequent VHF sources producing a leader step whose speed is equal or lower to this limit are considered to belong to the same leader. The leaders are then associated to a given flash on a temporal basis [Pédeboy et al., 2018]. Both Météorage and SAETTA datasets were time and space correlated to combine LF and VHF data in a real total lightning dataset. We define a -CG$_{<-100kA}$ flash as a -CG flash that contains at least one return stroke equal or greater than 100 kA in absolute value. This study focused on the analysis of -CG flashes that contain only negative return strokes.

RESULTS

Météorage recorded 87 -CG$_{<-100kA}$ flashes containing 386 return strokes leading to an averaged multiplicity of 3.4 strokes per flash (Figure 1). This subset represents about 2.7% of the total amount of -CG flashes detected by Météorage during the studied period and over the area of study that is slightly in excess compared to the 1% observed in France during the same period, confirming the enhancement of intense -CG strokes in this area. The monthly distribution of -CG$_{<-100kA}$ flashes shows that 35 flashes were observed during 3 thunderstorms in June, another 5 flashes during 2 thunderstorms in July, none in August and the remaining 47 flashes during 6 thunderstorms in September. It is interesting to note that -CG$_{<-100kA}$ flashes tend to not occur during the core summer time, namely July and August. The number of -CG$_{<-100kA}$ flashes per thunderstorm is 7.8 with a maximum value of 22 -CG$_{<-100kA}$ flashes for a single thunderstorm occurring on the 2nd of June. The mean delay between two successive -CG$_{<-100kA}$ flashes is 8.9 minutes and the median value is 4.6 minutes. A total of 110 return strokes with a peak current higher than 100 kA in absolute value was observed by Météorage. Surprisingly, 21 -CG$_{<-100kA}$ flashes contain two of such intense strokes and 1 -CG$_{<-100kA}$ flashes contain three of them. The peak current distribution of the return strokes exceeding 100 kA in absolute value ranges from -330 kA to -100 kA with an arithmetic and geometric means of -142 kA and -128 kA, respectively.

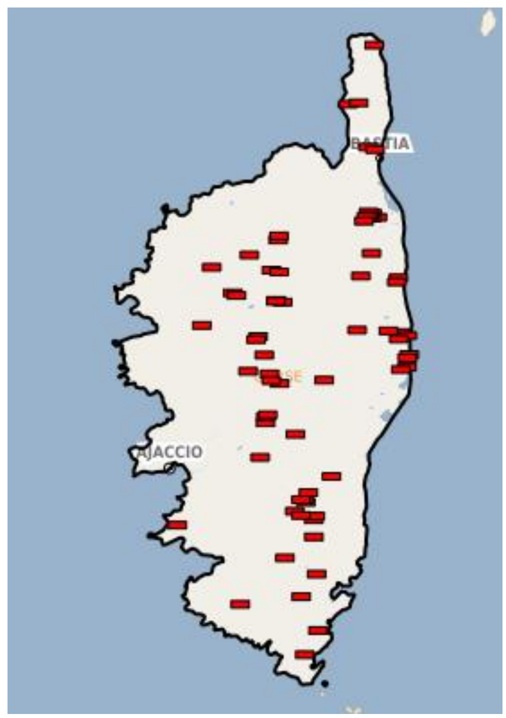

Figure 1- Locations of the -CG$_{<-100kA}$ flashes

Based on SAETTA data, the vertical extent of every -CG$_{<-100kA}$ flash was computed as the difference between the 5th and 95th percentile of the vertical distribution of the VHF source altitude. We remind that the CG flashes studied here are located within the nominal range of the SAETTA network. In addition to this parameter, we assumed the altitude of the first VHF source in -CG$_{<-100kA}$ flashes characterizes the altitude of the main negative charges region in the cloud. Table 1 provides some statistics on these parameters for $-CG_{<-100kA}$ flashes and for -CG return strokes between -100 kA and 0 kA detected over Corsica on the 1st of June 2017. The result obtained from the complete $-CG_{<-100kA}$ flashes dataset is presented in parenthesis.

Table 1 Statistics on vertical flash extent and first VHF source altitude

	Flash Vertical Extent		1st VHF src altitude	
	$-CG_{<-100kA}$	$-CG_{>-100kA}$	$-CG_{<-100kA}$	$-CG_{>-100kA}$
Arithmetic mean (m)	2727 *(3266)*	3723	3588 *(3774)*	5355
Geometric mean (m)	2422 *(2675)*	3696	3507 *(3670)*	5296
Maximum (m)	5147 *(7610)*	8481	6419 *(9628)*	11197
Std Dev. (m)	1101 *(1711)*	1282	1024 *(1154)*	1711

The distribution of the power of the first VHF source in $-CG_{<-100kA}$ flashes has a median value of 18 dbW to be compared to the 7 dbW for the $-CG_{>-100kA}$ flashes which tends to demonstrate the $-CG_{<-100kA}$ flashes are initiated by strong negative leaders. Despite this study focused on the initial conditions of $-CG_{<-100kA}$ flashes, we observed in 59 cases a silent period during which none VHF source was located after the return stroke occurred. These periods lasting from 7 ms to more than 98 ms are in general starting about 270 µs (median value) after the intense return stroke, even though in 3 cases the silent period started about 3 ms before the return stroke occurred.

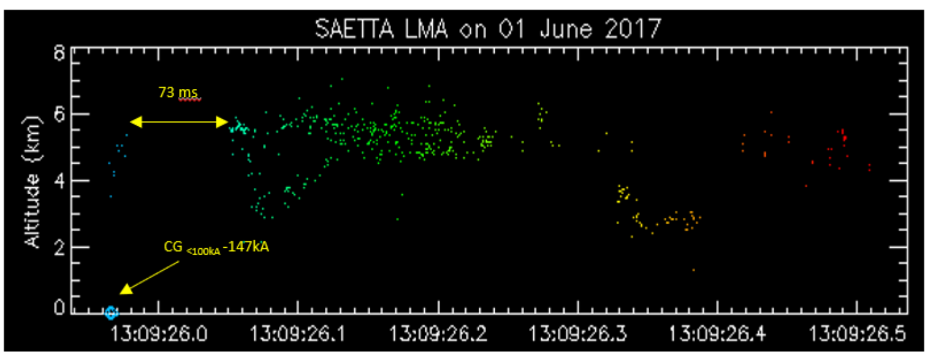

Figure 2 – Example of a $-CG_{<-100kA}$ flash exhibiting a return stroke of -147 kA observed by both Météorage (blue diamond on X axis) and SAETTA (altitude vs time). One can note the weak VHF activity prior and the silent period (73 ms) after the return stroke.

BLESKA recorded 26 long duration waveforms (208 ms) associated to $-CG_{<-100kA}$ flashes from which it was possible to compute the separation delay between the first pulse in the preliminary breakdown pulses sequence and the return stroke (PB-RS delay). The distribution ranges from 0.69 ms to 7.3 ms with an arithmetic mean of 2.5 ms and a geometric mean of 2.21 ms. These values are about one order of magnitude lower than those reported by Baharudin et al. [2012] and Zhu et al. [2014] for -CG flashes considering all the peak current distribution. The PB-RS delay could be roughly estimated based on the Météorage dataset for 10 $-CG_{<-100kA}$ flashes where the return stroke was preceded by an IC pulse assuming that the IC pulse occurred at the beginning of the flash. The results show a distribution ranging from 1.4 ms and 7.3 ms with an arithmetic and geometric means of 2.8 ms and 1.9 ms respectively. Interestingly, the comparison with the delays derived from BLESKA reveals that the values are very consistent even though some timing errors in Météorage due to location errors are expected. It must be also noted that it was not possible to discriminate the preliminary breakdown phase from the stepped leader in the BLESKA records as shown in Figures A and B.

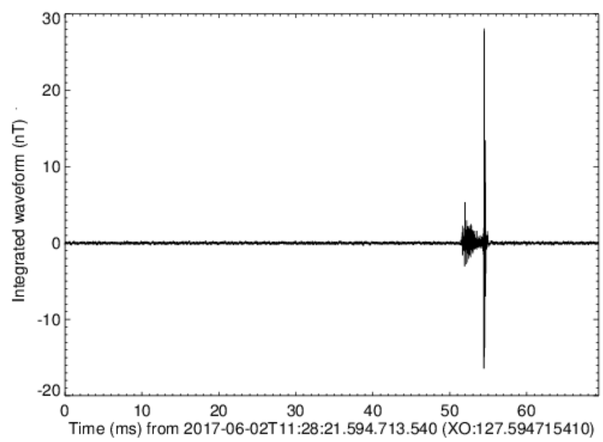

Figure A – Part of the long duration record showing the magnetic field waveform related to the preliminary breakdown, the stepped-leader and the return stroke recorded by BLESKA.

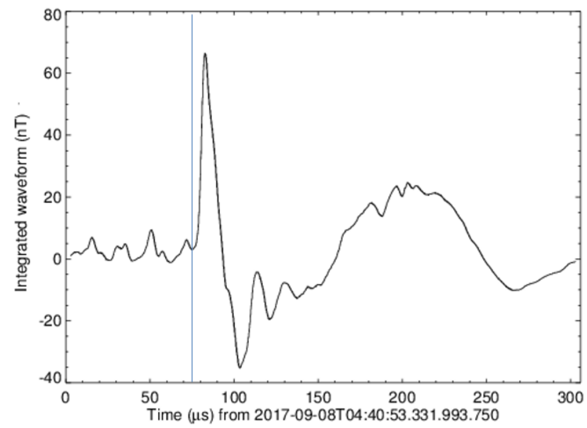

Figure B –Magnetic field signal generated by a return stroke located at 46 km from BLESKA. The blue vertical line shows the Météorage's stroke timestamp corrected for the propagation delay.

In addition to the previous results, the detailed analysis of our data revealed some surprising outcomes that are thought to be related to technical issues in the instruments. They are presented and commented here below.

LF flashes without VHF counterpart

A total of 5 -$CG_{<-100kA}$ flashes detected by Météorage in LF could not found their counterpart in the VHF data collected by SAETTA. Indeed, these events are correlated with one to three reconstructed VHF sources only which are difficult to be considered as LMA flashes. Analysis of raw data of the 12 LMA stations revealed unexpected VHF signal: for one these 5 -$CG_{<-100kA}$ flashes, the Météorage LF record occurred at the beginning of a 500 ms flash just at the end of a 3 ms continuous VHF burst. For the other four, the Météorage LF record occurred at the end of 1-to-3 ms continuous VHF burst, recorded by between 6 to 8 SAETTA stations, with almost other VHF radiation recorded within a 2-s time window.

No VHF activity prior LF discharges

Out of the total 81 remaining Météorage/SAETTA correlated flashes, 29 -$CG_{<-100kA}$ flashes (36%) do not exhibit any reconstructed VHF source prior the first discharge detected by Météorage. In 15 flashes the first discharge is an IC pulse, in 8 flashes it is a return stroke and in the last remaining 6 flashes it is a return stroke exceeding 100 kA in absolute value. However, it turned out that a strong VHF activity was detected at some individual VHF stations. Therefore, it is likely the LMA location algorithm failed to produce any consistent source locations leading to an apparent lack of VHF activity prior the return stroke [Kolmasova et al., 2018].

Abnormal intense return stroke multiplicity

Interesting also to note that in 19 (21%) -$CG_{<-100kA}$ flashes, Météorage detected two (even three in one flash) subsequent return strokes greater than 100 kA in absolute value. These subsequent discharges always exhibit a comparable peak current value, less than 10% of the first stroke peak current value in average. The corresponding inter-stroke delay ranges from 0.8 to 29.4 µs with an arithmetic and geometric mean of 11.8 and 8.8 µs. Such separation delay combined with a detailed analysis of the sensors detecting individuals subsequent stroke revealed that these multiple intense stroke flashes are not real but created by the system itself. The electromagnetic signal is so large and complex that the sensors triggered on different parts of the waveform resulting in several return strokes with the same polarity and similar magnitude.

DISCUSSION

Our study shows the -$CG_{<-100kA}$ flashes are produced by thunderstorms exhibiting a low altitude main negative charges region. This statement is derived from the statistics on the altitude of the first VHF source, considered here as the altitude of the main negative charges region, in Table 1. Indeed, one can note that -$CG_{<-100kA}$ flashes are initiated at a median altitude of 3507 m whereas the remaining -CG flashes are observed to be initiated at 5296 m. This result is consistent with Zhu et al [2016] who reported VHF source heights ranging from 4.8 to 6 km for five -CG flashes with return strokes higher than 50kA (absolute value) in Florida, USA. Another remarkable difference between -$CG_{<-100kA}$ and -$CG_{>-100kA}$ flashes is in the vertical flash extent. Indeed, the median vertical length is 2422 m for the first ones (see Table 1), as it is 3696 m for the latter. Radar observations are currently being processed to document the cloud environment associated with the -$CG_{<-100kA}$ flashes studied here.

The question is to understand how small channel lengths associated to low main negative charges region can produce intense return strokes with short-duration downward stepped leaders and little preliminary breakdown. In this, we assume the vertical tilt of the channel is negligible so the vertical flash extent we have computed can reflect the channel vertical length. Based on rocket-triggered lightning observations, Schoene et al. [2010] inferred the return stroke peak current is mainly dependent on the charges deposited at the base of the channel, so the total length of the conductive channel cannot be neither positively nor negatively correlated to the magnitude of the peak current. However, we can infer the electric field is higher because of the short distance between the main negative charges region and the ground. This effect is likely to increase the speed motion of the electrical charges resulting in a larger return stroke. Indeed, Zhu et al [2016] concluded that a high-intensity negative lightning is characterized by shorter and, by inference, faster stepped leaders. They observed a higher delay of 8.8 ms (mean value) between preliminary breakdown and return stroke that might be related to the smaller peak amplitude they considered in their study (-50 kA). The small delay between preliminary breakdown and return stroke, in average about 2 ms, and the impossibility to discriminate the stepped leader phase from the preliminary breakdown would tend to demonstrate the ionization process is very fast, and the strong electric field resulting from the height of the main negative charge region could be the cause.

In addition, if the lack of VHF sources we observed prior intense return strokes is likely to be an artefact from the SAETTA instrument (see an example in Figure 3) that must be further investigated, the silent period of 33.6 ms in average that is noticeable after the return stroke is real. Indeed, the analysis of the raw data detected at all the LMA stations show that no VHF activity is detected just after the return stroke occurred. Sun et al [2014] who observed a -CG flash with a VHF short-baseline time-difference of arrival (TDOA) system reported a quiescent VHF activity period after the return stroke and before the first K change occurred during the continuing current phase. However, it is interesting to note from their results the continuing current lasted 3.5 ms against more than 70 ms for the silent VHF period.

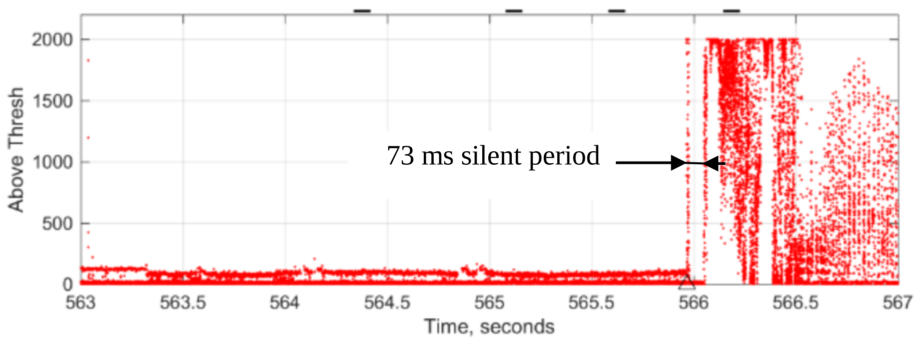

Figure 1 - Raw data from a SAETTA station that is just below the lightning flash. We can observe a 73 ms silent period just after the return stroke

CONCLUSIONS

We analyzed a total of 87 -CG$_{<-100kA}$ that were observed by different instruments in Corsica (France) during the summer period of 2017. The comparison of these events with other -CG flashes, namely flashes with return strokes of amplitude less than 100 kA (absolute value), revealed they are initiated at lower altitude, about 3600 m (mean value) whereas the other -CG started at a mean altitude higher than 5300 m. In addition, we found -CG$_{<-100kA}$ flashes present a smaller vertical extent, in average 2700 m to be compared to the 3700 m for the -CG flashes with return strokes less than 100 kA in absolute value. Such conditions are likely to happen during winter thunderstorms despite our study cannot confirm this trend because of the limited period of our dataset. Finally, we observed the delay between the first pulse of the preliminary breakdown and the return stroke is short, about 2 ms in average. From these results, we concluded the -CG$_{<-100kA}$ flashes are produced by low altitude thundercloud generating a higher electric field due to the reduced distance between the ground and the main negative charges region. This effect is likely to produce a faster motion of charges leading to an intense peak current. In addition, we observed a silent period in terms of VHF activity after the return stroke produce, with a mean value about 33.6 ms that is likely to be related to the continuing current flowing in the channel after the return stroke. Finally, we noticed some issues in the lightning data provided by Météorage and SAETTA that must be further investigated.

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