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Two propagation scenarios of isolated breakdown lightning processes in failed negative cloud-to-ground flashes

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Key points

- Preliminary breakdown radiowave pulses typical for negative cloud-to-ground flashes are exceptionally observed without return strokes.
- Data show evidence of two possible propagation scenarios: the discharge leader either extends horizontally inside the cloud or fades out.
- The first analysis of a large number of events shows that waveform characteristics of pulse trains are very similar for both scenarios.

Plain language summary

Visible lightning return stroke represents a well-known manifestation of atmospheric electricity. However, it is only the last stage of a complex sequence of phenomena that starts inside an electrically charged thundercloud by a preliminary breakdown process, continues by a stepped leader that moves electrical charges into the lightning channel, neutralized eventually by a large return stroke current and followed in most cases by processes leading to subsequent strokes. All these phenomena occurring inside or below the thundercloud involve impulsive electrical currents and hence emit radio waves. Analysis of our observations of isolated breakdown radiowave pulses, which are not followed by a return stroke shows that the underlying processes are similar to a usual preliminary breakdown preceding negative cloud-to ground discharges. Nevertheless, a strong positive charge layer at the bottom of the thundercloud can force the breakdown current pulses to keep flowing inside the cloud or die out, and thus prevents them from evolving into a return stroke that would move the negative charge from the cloud to the ground.

Abstract

Isolated breakdown process (also known as attempted leader or inverted intra-cloud discharge) is a lightning phenomenon characterized by radiowave pulses similar to signatures of preliminary breakdown before negative cloud-to-ground flashes, but in this case no cloud-to-ground return strokes occur. We identified 128 isolated breakdown pulse trains in measurements collected in the Mediterranean by a broadband receiver (0.005 – 37 MHz) in 2015 and 2018. By combining these records with concurrent Lightning Mapping Array measurements of very high frequency radiation (60 – 66 MHz) emitted by in-cloud discharges we investigate the development of each discharge. We identify two scenarios: either the discharges continue to propagate almost horizontally for more than 150 ms (73%), or they quickly fade out (27%). The geo-localized sources of the observed isolated breakdown pulse trains, together with their waveform characteristics (duration, inter-pulse intervals, regularity, bipolar shapes) show that both scenarios are similar to initiation processes preceding negative cloud-to-ground flashes.

Index terms: 3304 Atmospheric electricity

3324 Lightning

3394 Instruments and techniques

1. Introduction

Both cloud-to-ground (CG) and intra-cloud (IC) lightning flashes usually start with a preliminary breakdown (PB) process (sometimes referred to as initial breakdown) which is characterized by a presence of trains of bipolar pulses in electromagnetic recordings (Marshall et al., 2014a and references herein). These pulse trains are emitted by in-cloud currents and can be detected hundreds of kilometers from their source (Kolmasova et al., 2016, Kotovsky et al., 2016). Measurements conducted several kilometers from lightning recently showed that the first PB pulse is preceded by an ionizing initiation event followed by an initial electric field change (Marshall et al., 2014b, 2019). The PB stage of negative CG lightning flashes usually converts into a stepped leader followed by the first return stroke (RS) (Rakov & Uman, 2003 and references herein).

However, sometimes the pre-stroke activity does not lead to a regular RS pulse. Norinder and Knudsen (1956) reported for the first time an observation of “pre-discharges lacking the main discharge”. Nag and Rakov (2008) described observation of trains of electric field pulses, which were not followed by RS pulses. These isolated trains possessed characteristics of PB sequences preceding negative CG discharges. They named them “first attempted cloud-to-ground leaders”. Sharma et al. (2008) introduced a term “isolated breakdown” for PB sequences which did not lead to any subsequent activity and compared properties of isolated breakdown pulse trains with those leading to RSs. They found that durations of pulse trains and inter-pulse time intervals were comparable for isolated breakdown and PB pulse trains. Kolmasova et al. (2018) showed that an intense radiation in a frequency band 60-66 MHz abruptly started with the first pulse and was present during the entire pulse train of both regular PB and isolated breakdown processes. Ma (2017) used the term PB-type flashes for PB pulses not followed by negative CG and found them to occur at the early stage of isolated thunderstorms. Zhang et al. (2002) reported

the polarity-inverted IC discharges, which originated from the middle negative charge region and propagated downward to the lower positive charge region (LPCR), where they developed horizontally. Qie et al. (2008) found a majority of IC discharges to originate in the lower dipole during a major stage of a hailstorm at Tibetan Plateau. They called them lower level IC flashes and speculated that hails in the lower part of the cloud substantially contribute to the unusual strength of the LPCR. Zhang et al. (2015) hypothesized that the initiation processes of the inverted IC discharges, normal negative CG discharges and hybrid IC-CG discharges did not differ and that their later differentiation was controlled by the strength of the LPCR. Chilingarian et al. (2020) observed a termination of terrestrial gamma-ray enhancements by inverted IC discharges. This means that electric field between the main negative charge region and the LCPR was strong enough to accelerate electrons.

The role of LPCR in an evolution of discharges was also intensively modeled (Nag and Rakov, 2009; Tan et al., 2005; Iudin et al., 2017). Tan et al. (2014) found that the types and polarities of lightning discharges might depend on locations and magnitudes of oppositely charged layers near initiation points. For negative CG flashes, the magnitude of the LPCR near the lightning initiation needed to be strong enough for initiation breakdown, however an exceptionally strong LPCR could obstruct further propagation of the discharge down to the ground. Iudin et al. (2017) similarly concluded that a strong LPCR could block further vertical extension of the discharge.

This overview shows that lightning events characterized by PB pulses, which fail to evolve into negative stepped leaders and subsequent return strokes, were given different labels in the literature: “attempted CG leaders” (Nag and Rakov, 2008,2009), “isolated breakdown ” (Sharma et al, 2008; Esa et al., 2013a,b; Kolmasova et al., 2018), “inverted IC discharges”

(Zhang et al., 2002, 2015; Nag and Rakov, (2009); Chilingarian et al., 2020), “low-level IC flashes” (Qie et al., 2008), or “PB-type flashes” (Ma, 2017). All these expressions probably describe the same phenomenon. Out of these possibilities, we think that “isolated breakdown” is the best term to characterize what actually happens in the cloud, because properties of these events are far from normal IC discharges, but close to the breakdown processes preceding normal negative CG discharges.

In the present letter, we report results of our new investigation of properties of the isolated breakdown processes including their pulse train characteristics and propagation schemes. Our analysis is based on a combination of broadband magnetic-field measurements, narrowband electric-field Lightning Mapping Array (LMA) records, and Low Frequency detections of the French operational Météorage network. For the first time, we discuss this phenomenon based on larger number of cases compared to previous studies dealing only with several cases (Zhang et al. 2002; Coleman et al. 2008). Our analysis of more than 100 isolated breakdown events allows us to draw new conclusions about their propagation schemes. The observations were collected in Mediterranean during two observational campaigns in September - November 2015 and September - November 2018 in the frame of the SOLID (Space-based Optical Lightning Detection) and the EXAEDRE (EXploiting new Atmospheric Electricity Data for Research and the Environment) projects, respectively. Our results show that the duration of isolated breakdown pulse trains, the inter-pulse intervals, and the regularity of their temporal distribution in the analyzed events are similar to PB processes preceding regular CG discharges but are very different from typical initial breakdown processes of normal IC discharges. We present for the first time two typical scenarios of the isolated breakdown processes: (i) negative leaders keep propagating horizontally for more than 150 ms (73%) or (ii) discharges

substantially weaken within the same time interval (27%). In sections 2 and 3 we describe both instrumental setup and dataset. In section 4, we present results of our analysis of the measurements. In section 6, we discuss and summarize our results.

2. Instrumentation

To detect fluctuations of the E-W horizontal component of magnetic field we use the broadband analyzer BLESKA (Broadband Lightning Electromagnetic Signal Keeper Analyzer) (Kolmasova et al., 2018), a clone of the IME-HF analyzer (Instrument de Mesure du champ Electrique Haute Fréquence) developed for the TARANIS (Tool for the Analysis of Radiation from lightning and Sprites) spacecraft (Blanc et al., 2007) and adapted for ground-based measurements. The analyzer is connected to the magnetic sensor SLAVIA (Shielded Loop Antenna with a Versatile Integrated Amplifier) and detects signals in the frequency range from 5 kHz to 37 MHz, sampled at 80 MHz. The absolute time is obtained from a GPS receiver with an accuracy of 1 μ s. The duration of triggered waveform snapshots is 208 ms. The receiver was installed close to Ersu, France (550 m, 42.97°N, 9.38°E), at the northernmost point of the Corsica island, in 2015. It was moved by a few kilometers in 2018 (100 m, 43.00°N, 9.36°E). BLESKA detects broadband pulses exhibiting peak-to-peak amplitudes larger than 0.4 nT which is well above the level of environmental interferences.

The magnetic field records are combined with the measurements of 12-LMA-station SAETTA (Suivi de l'Activité Electrique Tridimensionnelle Totale de l'Atmosphère) network operated in Corsica since June 2014 (Rison et al., 1999; Coquillat et al., 2019). Each station is equipped with an electric-field antenna and detects very high frequency (VHF) radiation emitted by lightning discharges in the 60-66 MHz band and sampled at 25 MHz. In each 80- μ s time interval, the individual stations identify the times of arrival of the strongest VHF peak exceeding

a predefined threshold. The arrival times of the radiation peaks coming from the same source and detected by at least six individual LMA stations are used to calculate the 3D-location of a VHF radiation source. SAETTA also estimates power of individual geo-located VHF sources. GPS receivers are connected to each LMA station and provide a time assignment with an accuracy of 1 μ s (Thomas et al., 2004).

Locations, polarities, and peak currents for discharges used in our study were provided by the French lightning locating system Météorage. To achieve an optimum coverage of the South-East France and Corsica regions it combines sensors installed across France, and sensors operated by Italian national service SIRF. The detection efficiency is 94%, the median location accuracy 120 meters (Pedeboy and Toullec, 2016) and the accuracy of estimation of peak current amplitudes is about 18% (Schulz et al., 2016). Characteristics of both CG and IC discharges were available for both 2015 and 2018 datasets with an improved IC discharge detection efficiency for 2018.

3. Dataset

We visually inspected all triggered 208-ms long magnetic-field waveform captures recorded by BLESKA during autumn 2015 and autumn 2018 in order to identify sequences of bipolar pulses. We have chosen only the magnetic-field records containing pulse trains during which SAETTA was able to geo-locate at least one VHF source. To distinguish isolated breakdown events from usual PB pulses preceding -CG lightning and from PB preceding normal IC discharges, we used the following criteria:

- i) RS pulses were absent after the initial pulse sequence within the 208-ms long magnetic-field waveform snapshots.

- 198 ii) The list of Météorage records did not contain any CG detection within 1s after the time of
199 the strongest isolated breakdown pulse in magnetic field records.
- 200 iii) Knowing that the usual PB pulses have the same initial polarity as the corresponding RS
201 pulses (Rakov and Uman, 2003), we selected only trains of pulses that exhibited the same
202 polarity as negative RS pulses. This criterion together with a visual inspection of the pulse
203 train waveforms leads to the exclusion of PB pulse trains preceding normal polarity IC
204 discharges. We were able to check the pulse polarity without any ambiguity by combining
205 the magnetic loop antenna orientation with the locations of the IC pulses detected by
206 Météorage. By applying this polarity criterion, we reduced our dataset by 20 %. We verified
207 that the arrival azimuth of all analyzed events was further than 2 degrees from the eastward
208 and westward directions (perpendicular to our magnetic loop) to avoid any misclassification
209 of the polarity. A visual inspection of excluded trains showed that all excluded events
210 lacked at least one typical signature of PB pulse trains preceding -CGs: i.e., duration of
211 about 1-2 ms, inter-pulse intervals of about 100 μ s, and a regular temporal distribution of
212 pulses (Nag and Rakov, 2008). We also noted that the peak amplitude of pulses randomly
213 varied within the trains for all excluded events.

214 The resulting dataset consists of 128 isolated breakdown events (33 events in 2015; 95
215 events in 2018).

217 **4. Data Analysis**

218 The sequences of the isolated breakdown pulses identified in the magnetic-field records
219 were usually a few milliseconds long. They were preceded by an electromagnetically quiet
220 period lasting several tens of milliseconds in all cases. The inter-pulse intervals lasted from
221 several tens of microseconds to a few hundred of microseconds. The strongest pulses in

individual sequences usually occur during the first millisecond after the first recognizable pulse. The pulse activity following the sequences of the isolated breakdown pulses was weak or completely absent. Two examples of magnetic-field waveforms containing the isolated breakdown events recorded by BLESKA are shown in Figs. 1a and 2a, displaying a detail of 3 ms, while Figs. 1b, 1c, 2b, and 2c present the whole 208-ms long waveforms. Waveforms in Fig. 1 and Fig. 2 were respectively captured on October 2, 2018 and October 13, 2015. Red arrows point at the time of Météorage IC detections. Their peak currents were estimated to 16.2 kA and 9.4 kA, respectively.

Correspondence of the isolated breakdown pulses measured by BLESKA and the VHF sources geo-located by SAETTA is shown in Fig. 1a, 1b, 2a, and 2b: each dot corresponds to one reconstructed source of VHF radiation color-coded by its power. It is evident from Figs. 1a and 2a that almost none of the observed isolated breakdown pulses have a counterpart within the geo-located VHF radiation sources during the displayed three milliseconds. This effect was already reported by Kolmasova et al., 2018, and explained by a decreased ability of the LMA system to geo-locate VHF sources if the counts of samples above the threshold reached a maximum of 2000 (40-ns) detections within an 80- μ s LMA window at individual stations. This maximum of 2000 detections was regularly reached at the LMA stations located close to developing discharges suggesting that continuous VHF radiation was received during the initial phase of the isolated breakdown events. During the 208 ms-long records in Figs. 1b and 2b, SAETTA was able to geo-locate 444 and 159 VHF sources, respectively. The number of geo-locations during all 128 events varies from 1 (our condition for including an event in the analysis) to 843 VHF sources. The first geo-located VHF source occurred within the ± 1 ms window around the first detectable isolated breakdown pulse in 75 % of cases. In more than 85 % of events, the geo-

located VHF source occurring close to the first detectable magnetic-field pulse was also the most powerful one, with power varying from 8 to 36 dBW (24 dBW on average). Geo-located VHF sources occurring later in time were weaker in amplitude, and, similarly as in Figs. 1b and 2b, their power did not exceed 20 dBW. VHF sources were predominantly reconstructed at an altitude between 2 and 6 km, even if some sources appeared also below and above this altitude range (for an overview, see animations S1 and S2 in the Supporting Information). We also noted localized VHF sources, which did not have their counterparts in the broadband waveforms. These VHF sources occurred especially in the later part of the records, well behind the train of the isolated breakdown pulses. This effect can be explained by a lower sensitivity of the broadband analyzer to signals generated by horizontal currents. We also speculate that during the horizontal propagation of the discharges, the in-cloud channels might become shorter, and as a result, the frequency of emitted radiation might have shifted above the upper frequency limit of the broadband receiver (37 MHz) but still stay detectable by SAETTA at 66 MHz. Kolmasova et al. (2018) reported that individual peaks of strong VHF radiation recorded at individual stations (raw LMA data) still corresponded well to the broadband pulses during lightning initiation, even in the situation when the LMA was unable to reconstruct geo-located VHF sources. Examples of VHF radiation detected by SAETTA station B are illustrated in Figs. 1c (29 km away) and 2c (108 km away). VHF radiation in Fig. 1c remained very intense up to the end of the record, while in Fig. 2c it was generally weaker and the counts and strengths of VHF sources dropped after 120 ms to very low values, suggesting a different discharge development. We inspected the time evolution of both strength and count of raw LMA station data for the 128 events and found that for three quarters of them the intense VHF radiation continued to occur at least for the closest LMA station up to the end of the 208-ms long magnetic-field record, similarly to Fig. 1c. For the

remaining quarter of cases, the VHF radiation substantially dropped at all LMA stations before the end of the magnetic-field record, similarly to Fig. 2c.

We illustrate the propagation of discharges starting with the isolated breakdown pulses in Figs. 1d-f and 2d-f. Each dot represents one geo-located VHF source color-coded by its time of occurrence. The discharge in Fig. 1 started at an altitude of about 2 km, moved up by about two kilometers in 30 ms, and kept propagating with nearly horizontal branches in a limited interval of altitudes for 100 ms (Fig. 1b). Finally, one branch moved down back to the initiation altitude and the other one propagated horizontally. This discharge was recorded during a weak lightning activity (7 discharges over 20 min). It was the first discharge of a 3-discharge sequence of 150-second duration with a similar vertical distribution of geo-located VHF sources. The discharge in Fig. 2 shortly propagated almost at a constant altitude (Fig. 2b). This discharge was also recorded during a rather weak lightning activity (7 discharges in 12 minutes). After combining all 3D propagation maps with the information about the presence/absence of VHF sources detected at individual LMA stations for all isolated breakdown events, we identify two different propagation scenarios: the discharges continue to propagate horizontally for more than 150 ms (Type A, as in Fig. 1 – 73 %), or they fade out sooner than 150ms (Type B, as in Fig. 2 – 27 %).

We inspected the magnetic field waveforms of individual pulse trains in order to compare their characteristics with typical signature of PB pulse trains prior -CGs: duration of about 1-2 ms, inter-pulse intervals of about 100 μ s, and a regular distribution of bipolar pulses (Nag and Rakov, 2008). We have found that the majority of the pulse sequences lasted about two milliseconds or less for both scenarios (91% of type A events, 94% of type B events); the pulses within the trains were bipolar in all cases and regularly distributed in more than one half of cases (57% of type A events, 66 % of type B events). Inter-pulse intervals were typically about 100 μ s

long (82% of type A events, 60 % of type B events). The intervals between pulses within individual trains were sometimes also shorter, about 50 μ s (9% of type A events, 20 % of type B events) or longer up to 150-200 μ s (9 % of type A events, 20 % of type A events).

In 86 % of cases for both scenarios, the pulse peak amplitudes within the entire duration of trains were monotonically increasing and then decreasing or only decreasing (examples in Fig. 3). In the remaining 14% of cases for both scenarios, the pulse peak amplitudes were distributed randomly within the pulse sequences.

Fig. 3e shows that the two scenarios do not imply any clear differences in terms of spatial distributions of the locations of the first geo-located VHF source in each event, time-stamped close to the first recognizable isolated breakdown pulse. Fig. 3f presents the distribution of peak currents reported by Météorage, always corresponding to a pulse with the largest amplitude in each individual sequence. Median values of the peak current are 20 kA and 17 kA for types A and B, respectively. Note that these distributions are similar in both cases, and that the currents might be underestimated for both categories, as shown by Kaspar et al. (2016). The distribution of initiation heights for types A and B is again similar (Fig. 3g) with median values of 3.5 km and 3.8 km, respectively.

5. Discussion and summary

We have analyzed 128 sequences of the isolated breakdown pulses observed simultaneously by a broadband receiver, a LMA network, and Météorage in West Mediterranean for two periods, in 2015 and in 2018. We verified findings of Kolmasova et al. (2018) that intense VHF radiation in raw LMA data coincides with the first isolated breakdown pulse in the broadband magnetic-field measurements and that the most intense VHF radiation are often correlated with

the broadband pulses. The number of geo-located VHF sources within the 208 ms-long magnetic-field records, varied from units to hundreds. There were only a few geo-located VHF sources occurring simultaneously with the magnetic-field isolated breakdown pulse trains. In the majority of cases (85 %), the VHF sources occurring within 1 ms around the first detectable isolated breakdown pulse in each event were also the most powerful ones detected during each pulse train. Their power ranged from 8 to 36 dBW (~ 6 W to 4 kW), about two orders of magnitude weaker than the typical VHF power accompanying Narrow Bipolar Events as reported by Bandara et al. (2020), but by two orders of magnitude stronger than the typical VHF radiation detected around the initiation event of -CG flashes or normal IC discharges (Marshall et al., 2019).

We have identified two scenarios of the isolated breakdown process based on the 128 sequences: the discharge continues to propagate horizontally for more than 150 ms (Type A - 73 %) or dies out sooner (Type B - 27 %). Typical in-cloud currents, which generated the strongest isolated breakdown pulses are similar for both types. These currents are reported by Météorage around 20 kA and they do not differ from peak currents, which emitted the most intense PB pulses preceding -CG discharges in Florida, US (Karunarathne et al., 2019). Typical initiation altitudes (3.5 km, similar for both types) correspond to the region between the main negative and lower positive charge centers, where -CG discharges are initiated (Stolzenburg and Marshall, 2008). Geo-located VHF sources occurring close to the first detectable magnetic-field pulses in both types of trains also exhibited similarly strong power (on average 24 dBW). Our analysis of pulse train wave shapes shows that isolated breakdown pulse trains of both types cannot be distinguished from the reported pulse sequences preceding -CG discharges (e.g., Kolmasova et al., 2014, 2018, 2019; Zhang et al, 2015; Smith et al, 2018) and exhibit different properties

338 compared to the ones of initiation pulses preceding normal IC discharges (Nag and Rakov, 2008;
339 Nag et al., 2009). These results therefore indicate that isolated breakdown processes of both
340 types correspond to usual -CG discharges, which failed to propagate to ground. Several modeling
341 investigations (Nag and Rakov et al., 2009; Tan et al., 2014; and Iudin et al., 2017) show that an
342 excessive LPCR can play a crucial role in blocking the propagation of the CG discharges through
343 a potential well. Figs 1S and 2S in the Supporting Information show how this potential well
344 changes as a function of LPCR properties. Both a larger strength and/or a lower altitude of the
345 LPCR can lead to the development of a positive potential well below it. Our results are
346 consistent with the outcomes from Iudin et al. (2017) even though they used a different LPCR
347 charge distribution, position, radius, and thickness. Our results also agree with observation from
348 Coleman et al. (2008) who combined balloon measurements of vertical electric field and LMA
349 VHF sources and found that horizontal extensions of lightning channels correlated with
350 potential extrema.

351 In conclusion, we find that the isolated breakdown events (also known as attempted -CG
352 leaders, inverted IC discharges, low-level IC flashes, or PB-type flashes) can show two different
353 discharge propagation scenarios: the discharge either continues to propagate horizontally or
354 quickly fades out. Based on the observed duration of the isolated breakdown pulse trains, on the
355 inter-pulse intervals, on their regularity, and on the bipolar shapes of the pulses, as well as on the
356 geo-localization of their sources, we find that both scenarios described in this study are similar to
357 PB processes preceding -CG flashes. More studies are needed to detail the geographical or
358 seasonal variation of these two types of the isolated breakdown processes and their relation to the
359 microphysical and electrical structure of the parent thunderstorms.

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Fig. 1

Fig.1 Example of an isolated breakdown event (type A) occurring on 2 Oct 2018 at 13:55:19.236 UT: (a) 3-ms long detail of the BLESKA waveform showing a sequence of isolated breakdown pulses overlaid on altitude of geo-located SAETTA VHF radiation sources color-coded by their power; (b) the whole 208 ms-long BLESKA record with geo-located VHF radiation sources; (c) the BLESKA record with peaks of radiated VHF power recorded at the SAETTA station B (color-coded by their counts within individual 80 μ s LMA windows); (d–f) 3D location of VHF radiation sources color-coded by time (7 SAETTA stations minimum, $\chi^2 < 1$).

Fig. 2 Same as Fig. 1 but for an isolated breakdown event (type B) occurring on 13 Oct 2015 at 22:09:30.073 UT.

Fig. 2

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Fig.3 a-d) 1.5-ms long details of the BLESKA waveform showing sequences of isolated breakdown pulses overlaid on altitude of geo-located SAETTA VHF radiation sources: (a) isolated breakdown event (type A) occurring on 20 Sep 2015 at 10:32:45.013 UT, (b) isolated breakdown event (type A) occurring on 01 Oct 2018 at 15:45:41.593 UT, (c) isolated breakdown event (type B) occurring on 27 Nov 2018 at 10:34:33.387, (d) isolated breakdown event (type B) occurring on 20 Sep 2015 at 09:36:11.775 UT, (e) Map showing the 2D location of the geo-located VHF sources occurring within 1ms from the first recognizable magnetic-field pulse (blue: type A, red: type B). Green diamonds show the locations of SAETTA stations. The light blue star locates the BLESKA receiver. The blue and red arrows point to the events shown in Figs. 1, 2, and 3a-d, respectively. (f) Histograms of the Météorage peak current corresponding to largest pulses identified within magnetic-field pulse sequences; (g) Histograms of initiation heights obtained as altitudes of the LMA geo-located sources occurring within 1ms from the first recognizable isolated breakdown pulse (altitude uncertainty: ~20 m above Corsica and up ~500 m at 200 km from the coast).