Multi-Stroke Positive Cloud-To-Ground Lightning Sharing the Same Channel Observed With a VHF Broadband Interferometer

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Abstract This work presents the first observation of a multi-stroke positive cloud-to-ground lightning flash sharing the same channel to ground mapped with a very high frequency broadband interferometer and a Lightning Mapping Array. This type of lightning flash is very rarely observed, and it is currently unclear how frequent it is and even under what conditions it occurs. Our observations indicate a scenario where the first downward positive leader initiates from a decayed negative channel. After the first return stroke, some of the main negative channel branches stop propagating and are likely cut off. A fast recoil leader and/or a fast breakdown play a crucial role in reconnecting these previously decayed leader channels and initiating the subsequent positive stroke. The mechanism we propose to describe the phenomenon allows us to explain its rarity and the discrete positive charge transfer to the ground.

Plain Language Summary In the same lightning flash, whose usual duration is less than a second, there can be multiple negative cloud-to-ground strokes with different terminations or following a preexisting channel to the ground. In contrast, it is not common to have multiple positive cloud-to-ground (+CG) strokes, and especially multi-stroke +CG flashes sharing the same channel to ground are very rarely observed. This polarity asymmetry is not well understood and many aspects are debated. In this letter, we present for the first time a very high frequency (VHF) radio band observation of a multi-stroke +CG flash along the same channel, observed simultaneously by a VHF broadband interferometer and a Lightning Mapping Array in north-central Colombia. These combined observations have unprecedented temporal and spatial resolution and allowed us to observe in detail the development of the flash and especially to understand the initiation mechanism of the subsequent positive stroke.

1. Introduction

Positive cloud-to-ground (+CG) lightning flashes are less frequent than the negative counterpart, about 10% of the global cloud-to-ground lightning, but in general, their charge transfer is an order of magnitude greater (Rakov & Uman, 2003). For this reason, they usually can cause more damage, especially to tall structures like wind turbines (e.g., Becerra et al., 2018; Montanyá et al., 2014) or cause wildfire ignition (e.g., Blouin et al., 2016; Fuquay et al., 1972). Furthermore, +CG flashes are mainly associated with the production of transient luminous events like sprites (e.g., Boccippio et al., 1995; Williams et al., 2010). Therefore, +CG flashes have attracted significant research interest in recent years and some aspects are still debated or require a better understanding.

One of these aspects concerns the origin and the development of multi-stroke +CG lightning. Positive flashes usually have a single stroke (Rakov & Uman, 2003). However, several cases of multi-stroke positive flashes were recently observed and reported in the literature. The first study reporting optical observations of multi-stroke +CG flashes was conducted by Fleenor et al. (2009). They documented for the first time subsequent positive strokes sharing the same channel to ground, and observed nine multi-stroke +CG flashes of which five cases involve a preexisting channel. Saba et al. (2010) reported high-speed video observations of 19 multi-stroke +CG flashes and only one case of subsequent positive stroke along the same channel. These optical observations highlighted the occurrence and rarity of the phenomenon, but present limitations in describing the flash development within the cloud and the mechanisms that make subsequent positive strokes possible.

Thanks to improved lightning detection systems, new observations and findings on multi-stroke +CG flashes are emerging. Wu et al. (2020) reported 47 new observations during the winter season in Japan. They observe that downward positive leaders (DPLs) in multi-stroke flashes are mostly originated from in-cloud negative leader
channels. They did not observe any subsequent stroke along the same channel. Yuan et al. (2020) investigated the origin of an uncommon three-stroke event with different terminations to ground and proposed a mechanism involving an advancing negative leader.

Recently, Zhu et al. (2021) observed 84 multi-stroke +CG flashes during a supercell storm in Argentina. They observed 54 (64%) +CG flashes with a subsequent leader likely following a preexisting channel to ground (within 100 m between the striking points) and they suggested that the behavior of subsequent leaders in positive lightning can be very similar to subsequent leaders in negative lightning. These new observations raise interest and new questions about the conditions necessary for these phenomena to occur and what mechanisms may explain the discrete charge transfer along the same channel in +CG flashes.

2. Instrumentation and Methodology

The data presented in this work were recorded during an observational campaign at the Universidad Industrial de Santander campus of Barrancabermeja (Colombia) in autumn 2019. Instruments, processing techniques, and the deployment of the instrumentation are further described in Urbani et al. (2021) and in the Supporting Information S1.

2.1. VHF Broadband Interferometer

A VHF broadband interferometer (INTF) is an instrument capable of mapping lightning discharges with a high temporal resolution. We designed and built our version, which consists of three VHF antennas (20–80 MHz bandwidth) deployed along two orthogonal baselines of 22 m. The digitizer used for the acquisition system is a GaGe Razor Express 1,604 with four channels, 16-bit resolution, and 200 MS per second sampling rate. The interferometric processing technique is a window-based cross-correlation method (Stock et al., 2014) improved by a clustering algorithm to average overlapping solutions and perform noise reduction (Urbani et al., 2021). The time window length used is 512 samples (2.56 ns), timing uncertainty, and angular resolution are reported in the Supporting Information S1.

2.2. Colombia Lightning Mapping Array

The Colombia LMA was installed by the Universitat Politècnica de Catalunya lightning research group (López et al., 2019). It consisted of eight VHF antennas (60–66 MHz bandwidth) deployed with baselines from ∼6 to ∼36 km around the city of Barrancabermeja. The processing technique based on the time-of-arrival is provided by New Mexico Tech (Rison et al., 1999; Thomas et al., 2004).

2.3. Quasi-3D Conversion

Simultaneous detections of a lightning flash with the INTF and the LMA allow us to use a postprocessing technique, which has the great advantage of combining the high temporal resolution of the INTF with the spatial accuracy of the LMA. This interpolation technique called “Quasi-3D conversion” was introduced and described by Stock (2014). This technique is approximated and imperfect because, in some cases, there simply are not enough LMA sources to reconstruct the correct development of all leader branches (or fast lightning processes) and sometimes, it may introduce artifacts. Noise reduction and supervised processing are needed to get reliable results. Despite that, Quasi-3D reconstruction adds substantial information to understand the overall structure of the flash, removing the typical ambiguity in the 2D data of the interferometer (Figures 1e and 1f).

3. Observations and Analysis

We observed two multi-stroke +CG flashes with a double stroke along the same channel to ground, named with the timestamp in UTC of the first return stroke (RS1): (a) 2019-10-27 11:05:10 and (b) 2019-10-27 11:15:06. We present in detail only the second flash for the sake of brevity, but where some differences are relevant, or some important results are consistent, we mention the other case.
Figure 1. Multi-stroke Positive cloud-to-ground flash along the same channel, event: 2019-10-27 11:15:06 (UTC). (a) Electric field waveform recorded by a flat plate antenna, LINET detections (Betz et al., 2009) and Geostationary Lightning Mapper energy (Goodman et al., 2013). (b) Flash evolution in altitude, Quasi-3D data. (c) Time-distance plot from the flash initiation, Quasi-3D data. (d) Time-elevation plot, interferometer (INTF) data compared with LMA data. (e) Spatial development of the flash, Quasi-3D data. (f) Elevation-azimuth plot, INTF data. It is possible to observe (see letter A) the subsequent positive stroke (red) along the same preexisting cloud-to-ground channel (green). The correspondence between panels (e) and (f) is highlighted through the letters A-F. An animation of the entire flash is available in the Supporting Information.
3.1. Multi-Stroke +CG Flash: 2019-10-27 11:15:06

In this section, we describe the development of the multi-stroke +CG flash (b), which can be best appreciated from the Quasi-3D data animation provided in the Supporting Information S1. A frame of this animation and the evolution of the main physical quantities and dimensions are shown in Figure 1. Additionally, a schematic representation of the flash development is provided in Figure 2.

The origin of the flash (b) was located by the LMA at an altitude of around 6 km and a horizontal distance from the INTF of about 4.5 km.

After an initiation phase, of which the duration is around 1.5 ms propagating upward, several negative leader branches start growing with an average speed of $1.2 \times 10^5$ m/s in two main directions, upward and horizontal (Animation S1, Figure 2a). The strong VHF emission of the negative leaders masks the positive leader development, and only a faint emission belonging to the positive leaders can be clearly located at a height of around 5.5 km after 31 ms from the initiation. The upward negative leader subsequently forks again and both branches stop propagating about ~40 ms before the first positive stroke, reaching an altitude of around 10 km. The main horizontal negative leader branch grows westward, generating multiple secondary branches.

According to our best interpretation of the data (Figure S3 in Supporting Information S1, Figure 2c), it seems that the DPL does not originate from the typical bidirectional leader development after the flash initiation (e.g., Li et al., 2020; Mazur, 2002; van der Velde et al., 2014), but from the negative horizontal channel in its lowest altitude location (~5.7 km). A similar scenario is widely reported in the literature (e.g., Krehbiel, 1981; Nag & Rakov, 2012; Saba et al., 2009; Wu et al., 2020). In our data, it is possible to observe a recoil leader along a decayed secondary branch of the horizontal negative channel simultaneously with the DPL initiation, 4.8 ms before RS1. This could be an evidence of a disconnected channel and it might create the conditions to initiate the first DPL (Figure 2b, Figure S3 in Supporting Information S1). Further details on the initiation and propagation of the first DPL are discussed in Section 3.3 and reported in the Supporting Information S1.

RS1 brings ground potential to the channel, inserting negative charge along the in-cloud leader channels. The majority of the negative leader channels are involved, but there is more VHF activity in the horizontal channel compared with the vertical ones. After RS1, another main leader branch initiates and propagates northward with
a similar speed (negative branch F, Figures 1e and Figure 2d). All the leader branches to the east stop propagating after 40 ms from RS1 (Figures 2e) and 18 ms later, even the northward branch (F) stops propagating, while the main horizontal branch continues to propagate, reaching a length of about 25 km (Figure 2f). Approximately 2 ms before the second return stroke (RS2), a fast recoil discharge can be observed, which appears to involve or possibly trigger the subsequent DPL (Figure 2g). More details on this fast process and the initiation of the second DPL are discussed in Section 3.2. The interstroke interval between the RS1 and RS2 is about 74.5 ms, whereas in flash (a) it is about 25.5 ms.

Similarly, after the RS2, it is possible to observe a burst of VHF activity that can be associated with the continuing current phase (e.g., Lapierre et al., 2017). The continuing current can also be seen from the Geostationary Lightning Mapper data and the electric field measurements (Figure 1a). Figure 1e shows the increase in VHF activity, especially in the westward horizontal branches (C,D,E) and in the previously stopped northward branch (F), where the fast processes (red color) correspond to the re-ionization of the leader tips, an effect of the continuing current. The negative leader branch (F) restarts to propagate again after RS2 (Figure 2i). A new leader branch (B) is initiated after 15 ms from RS2, giving rise to a particularly extended and branched negative leader with a higher speed of $2.4 \times 10^5$ m/s, probably developing in a previously highly ionized area.

3.2. Initiation of the Subsequent Positive Leader Along the Previous Channel

One of the main questions regarding multi-stroke +CG flashes is how the subsequent DPL could initiate and propagate along the same channel of the first DPL, and why this is not as common as in -CG flashes. To investigate this aspect, we analyze what happens in the last milliseconds before the RS2. In this section, we describe the observations and the analysis for flash (b); the other case is reported in the Supporting Information S1.

Figure 3a is an overview of the data collected in the last 4 ms before RS2. It can be seen that a fast recoil leader [A] starts to propagate at about 2.4 ms before RS2. After 0.5 ms, it initiates a new breakdown phase [B] and then it continues to propagate, likely retracing a previous channel [C] until about 1.5 ms before RS2. We observed that the recoil leader initiates from the far end of a secondary decayed branch belonging to the main horizontal negative leader branch. This secondary branch is the one likely involved in triggering the first DPL (Figure S3 in Supporting Information S1) and subsequently extended by RS1 (Animation S1). The recoil leader retraces the channel propagating backward (Figure 3b). Although we are not able to precisely localize the three-dimensional development of this branch, the fact that it proceeds from a lower to a higher elevation suggests that the recoil leader is approaching, in the INTF reference system. This assumption is also supported by the increase of the VHF intensity and the monotonic enhancement of the electric field detected by the flat plate antenna in time correspondence with the recoil leader stage [A], as indicated by a black arrow (EF1) in Figure 3a. The combined observations of the leader's spatial development and the electric field enhancement allow us to infer the leader polarity, which is consistent with an approaching negative leader. The recoil leader speed was estimated to be between $1.0–1.5 \times 10^7$ m/s by comparison with the speed of the previous negative leader ($1.2 \times 10^6$ m/s) along the same channel.

After 0.5 ms, we observed a strong increase of the VHF intensity and a variation in the electric field consistent with a fast negative breakdown [B], which likely reconnects previously disconnected leader channels. According to what we can see with the INTF, it is interesting to note that it does not seem to retrace a previous channel, but it traces a new path connecting itself with the origin of the flash (Figures 3b and 3c). After the connection with the origin of the flash, another recoil leader [C] can be observed, likely the continuation of [A] and [B], in a decayed leader branch clearly not belonging to the main horizontal leader channel. When the recoil leader [C] stops propagating, it can be observed in the electric field waveform by the indication (EF2) of an accumulation of positive charge, which gives rise to the second DPL in the following 0.3 ms.

Finally, we show in Figure 3e the first 300 microseconds after the second DPL connection to the ground. It is interesting to note that the whole in-cloud VHF activity during this time interval is located around the recoil leader A-C. Especially, as indicated by the arrows, along the recoil channel [A], then in [C] and in the junction point between [A] and [B] from where it originates a new fast negative leader. These observations seem to support the hypothesis that the recoil leader A-C is not an uncorrelated lightning process happening before RS2 but probably the trigger mechanism of the subsequent DPL.
Figure 3. Initiation of the second downward positive leader (DPL) along a previous channel to ground, multi-stroke Positive cloud-to-ground flash 2019-10-27 11:15:06 (UTC). (a) Overview of the last 4 ms before second return stroke. Time-elevation plot of the very high frequency (VHF) sources mapped by the interferometer and LMA. Electric field waveform (red line) recorded by the flat plate antenna and VHF waveform (gray line). Black arrows indicate the electric field variations in correspondence, respectively, with the approaching recoil leader (EF1), and the DPL (EF2). (b) and (c) Recoil leader and new breakdown connecting a previous channel end to the flash origin, respectively colored by time and VHF power. (d) Elevation-azimuth plot of the leader channels A-C. (e) VHF sources in the subsequent 300 microseconds after the DPL connection to the ground. It is relevant to note VHF activity near the previous leader channels A-C.
3.3. Comparison Between the First Positive Stroke and the Subsequent Stroke

The striking point of +CG flash (b) is about 1.2 km away from our INTF location. The accuracy of this location is good because LINET detected both positive strokes and provides compatible values (same longitude: −73.8412 and latitude: 7.0674 and 7.0670). Furthermore, the INTF mapping confirms that they have the same channel and same striking point. According to LINET, the peak current of RS1 is 52.2 kA and the subsequent 20.7 kA and the time elapsed between them is about 75 ms.

In Figure 4, we provide an unprecedented high-resolution comparison between the first positive stroke and the subsequent stroke. It is particularly interesting to note the different VHF signatures of the two DPLs. The first DPL is propagating in virgin air with a quite constant 2D speed of $1.5 \times 10^6$ m/s in the last 750 $\mu$s before RS1. The VHF waveform presents an intermittent pattern of bursts of VHF pulses with an evident periodicity, every 10–20 $\mu$s, located on the positive leader tip (Figure 4a). A similar observation of this intermittent pattern was
recently shown by Pu et al. (2021). Further analysis of the VHF bursts and the DPL propagation is reported in the Supporting Information S1.

The subsequent DPL is faster, following a pre-ionized channel, its average 2D speed is quite constant at $1.3 \times 10^7$ m/s and slightly accelerating in the last 20 $\mu$s to $2.0 \times 10^7$ m/s. This speed range is very similar to the speed of dart leaders following negative CG strokes (e.g., Urbani et al., 2021) and the recent measurements of Zhu et al. (2021). In the subsequent DPL, it is not possible to clearly distinguish any intermittent pattern. This could be due to the higher speed or different propagation conditions along the preexisting channel.

Another remarkable observation is regarding the VHF waveform of the return strokes (Figures 4a and 4c). RS1 has a more intense VHF signal and a 2D speed of $5.1 \times 10^7$ m/s while in RS2 the signal amplitude is much weaker and the 2D speed is higher, about $1.23 \times 10^8$ m/s. It is interesting to note that despite the higher speed and the weaker signal, the INTF was able to better map RS2 than RS1, which suggests that in RS1 more sources were simultaneously emitting (along the channel or in different branches) while in RS2 what has been mapped is the wavefront of the return stroke (Figure 3e). We suggest that the different VHF signatures between the first and the subsequent return stroke could be due to the different conductivity of the channel, higher in RS2 than RS1.

4. Discussion

The recent observations by Zhu et al. (2021) by means of the low/high frequency with the Córdoba Argentina Marx Meter Array suggest that the processes in positive flashes with multiple strokes to ground sharing the same channel appear very similar to the mechanism in -CG flashes but with opposite polarity. Their observations belong to a supercell storm anomalously charged with the main negative charge region located above the main positive charge region. They observed that the positive subsequent strokes were initiated from the decayed in-cloud negative branches near their far ends by recoil leaders. In the three-stroke +CG flash presented by Zhu et al. (2021), they were able to map the positive recoil leader propagating backward, with a duration of more than 10 ms.

Similarly to Zhu et al. (2021), we observed that subsequent strokes occur after some negative leader branches stop propagating. Therefore, the presence of decayed negative channels seems to be a key aspect in multiple positive strokes. We also observed a recoil leader initiated from the far end of a decayed leader channel, but in our case, it is a much faster process (speed $10^7$ m/s and duration of 1.8 ms) and according to our analysis, the recoil leader polarity seems to be negative. In both flashes that we recorded, we observed a fast negative breakdown a few hundred microseconds before the second DPL initiation, at 200 microseconds for flash (a) and 1.8 milliseconds for (b), respectively. The observation of this fast breakdown along a new channel path, described in Section 3.2, has never been reported before. Our interferometer and LMA data do not show a slow positive recoil leader of several milliseconds before the subsequent return stroke as observed by Zhu et al. (2021), but this is not necessarily in contradiction with their observations. Our instrumentation operates at a higher frequency radio band, and it is more suited to detect breakdown and streamer activity near the head of propagating leaders instead of in-cloud current pulses. Therefore, we do not exclude that a slow positive recoil process like the one described by Zhu et al. (2021) could occur along with one of the cutoff negative leaders during stage (f) in Figure 2, while their instrument does not resolve the very fast process we observed during stage (g).

We propose an alternative interpretation of our data, which does not require a slow positive recoil leader, but still involves the presence of decayed channels that cut off after the RS1 (Figures 2e and 2f). The evidence of this disconnection is found in the fast breakdown observed at 2 milliseconds before the DPL (Figure 3). We assume an accumulation of positive charge at the root of one of the previous negative leaders, during stage (f), to explain the negative recoil leader we observed in the opposite direction of a propagating negative leader branch. The fast breakdown acts as a switch that reconnects the decayed leader channel branches and allows the positive charge to propagate downward in the preexisting return stroke channel to ground (Figures 2g and 2h). In this scenario, the positive leader occurs after the trigger mechanism and is much faster in time (two orders of magnitude) than what was observed by Zhu et al. (2021). Actually, our observations have similarities to the two-stroke +CG flash shown by Zhu et al. (2021) in their Figure 4, where a slow positive recoil leader is not evident and it might be an indication of a fast breakdown before RS2, as it can be seen in the electric field waveform.
This mechanism might explain why the multi-stroke +CG flashes along the same channel are rare. The reason could be that usually in single stroke +CG flashes the DPL originates from the bi-directional flash initiation (e.g., van der Velde et al., 2014), whereas in multi-stroke +CG flashes, the DPLs mostly originate from in-cloud negative leader channels (Wu et al., 2020; Yuan et al., 2020). Furthermore, the condition of sharing the same channel to ground instead of initiating a new DPL may be subordinated to the possibility of a reconnection with a decayed channel through a fast recoil leader and/or a breakdown.

The available cases suggest that this type of +CG flash requires more than one main negative leader branch near the flash origin and first stroke location. In addition, the cutoff must occur within tens of milliseconds after the RS1 in order to maintain the conductivity of the channel to ground for it to be reused. These conditions may not be facilitated in all storms.

Due to the scarcity of similar observations, the data presented are particularly valuable in describing the multi-stroke +CG flashes along the same channel. A single mechanism is unlikely to explain each occurrence. Further studies and observations will lead to a more complete understanding of this phenomenon.

Data Availability Statement

Measurements and data file supporting the conclusions are available at: https://doi.org/10.7910/DVN/YUWYRD.
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