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Analysis of Forked Strokes Characteristics over Southeastern Brasil During the Summer Season of 2013

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***Abstract*— The objective of this work is the analysis of overall characteristics of 35 cloud-to-ground (CG) strokes that presented two or more contact points to the ground in a millisecond scale. This dataset includes both the "classical" forked strokes (first observed in streak camera records) and the new class of this type of phenomenon, called "upward illumination" strokes, introduced in more recent works. The genesis of the latter is very similar to the classical forked strokes, i. e., one branch from the main trunk of a stepped leader produces a second stroke after the first return stroke occurs. The main difference from the classical forked stroke events are: a) UI stroke channels appear to completely disconnect from the main trunk during its development, b) the time between strokes is longer than in the case of classical forked strokes and c) the peak currents of the UI strokes are, usually, very small. From the visual inspection of the 35 selected events, 22 were classified as forked strokes and 13 UI strokes. A new name was given to the broad class of strokes that present two or more contact points in a millisecond and sub-millisecond scale, "multi ground contact strokes" (MGCS). Subclasses received the names "forked strokes" and "UI strokes", related to the previous findings from the literature. All MGCS flashes were recorded during the summer season of 2013 in Southeastern Brazil as part of a five-day campaign employing a network of high-speed camera sensors known as the RAMMER network. The high-speed video records were obtained by three identical cameras installed in São José dos Campos and a fourth mobile camera (whose only difference from the other three is its capability to record colored images). All four cameras were set up for recording at 1200 x 500 pixels spatial resolution, 2500 frames per second, and 400-µs time interval between frames. A total of 357 negative CG flashes were recorded. The physical processes that generate either forked strokes and UI strokes are discussed in details. RAW data from BrasilDAT network was used to identify and give more information about the MGCS, such as: peak current estimates and precise interstroke intervals in the microsecond range. Plots of time intervals between strokes versus peak current added new information on the physical characteristics and distinctive features of UI and forked strokes..**

Keywords—forked strokes; UI strokes; high-speed cameras; lightning location systems; physical properties of lightning

I. INTRODUCTION

During the development of a negative lightning channel to ground, several branches are usually formed and, sometimes, concurrent branches reach the ground virtually at the same time. Those events receive many names in literature, such as twin strokes [Schonland et al., 1935], double-ground strokes [Rakov and Uman, 1994], forked strokes [Ballarotti et al., 2005], multiple ground contact strokes (MGC) [Guo and Krider, 1982, Kong et al., 2009], upward illumination (UI) [Stolzenburg et al., 2012, 2013], etc. One of the first reports of this type of event was given by Scholand et al. [1935], when the authors used a streak-camera to register two ground attachments within a time interval of 73 microseconds. The authors pointed out that those two flashes probably shared one single trunk higher up in the cloud, and then that were probably twin strokes instead of different flashes. Later, Guo and Krider [1982], during a field campaign of lightning observations with a set of optical and E-field detectors, discovered in their data evidence of double-grounded strokes from different branches of the same downward leader. They also verified that the time interval between those strokes were in the order of tens of microseconds. Rakov and Uman [1994] studied 13 double-ground stroke cases (standard video records), among which nine had simultaneous E-field measurements. It was also verified that the occurrence of double-grounded strokes generally happen during the first stroke sequence, but they also observed strokes of order 2 and 3 presenting the same behavior. Ballarotti et al. [2005] were the first researchers to

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analyze forked strokes with digital high-speed cameras. Their results are based on six flashes observed in Brazil during the summer seasons between 2003 and 2005 that presented forked strokes. Some of the events were also observed by an E-field measuring system as well and stroke orders up to four were reported to present forked strokes.

Most of the forked stroke intervals reported in the literature range from tens to few hundreds of microseconds. This is probably due to the removal of charge from the first ground strike location, producing a ground potential wave propagating from the attachment point of the return stroke upwards, impeding further development of the remnant branches. In some cases, one or more branches are so close to ground after the first return stroke that the ground potential does not reach the distant portion of that branch and they end up connecting the ground too [Guo and Krider, 1982, Rakov and Uman, 1994, Kong et al., 2009]. However, Rakov and Uman [1994] and Ballarotti et al. [2005], among others, observed intervals greater than 1 ms in some cases, contradicting the Guo and Krider [1982] theory for forked strokes. A possible explanation came recently from Stolzenburg et al. [2012, 2013]; they observed several cases of forked strokes with multiple high-speed cameras and several E-field detectors. Their analysis showed that, in some cases, the branch that generate the second return stroke in a forked stroke sequence is completely disconnected from the main leader during its development, and certain conditions allow this leader segment to continue its propagation and connect to ground. So, these cases of second strokes are in fact an upward illumination (UI, as they termed them), not a complete return stroke, since it does not connect back to the main channel. Later, Stolzenburg et al. [2012, 2013] analyzed more cases and after some further deliberation decided to call them "UI strokes".

TABLE I. COMPARISON TABLE OF MGCS OBSERVED ON DIFFERENT LOCATIONS.

Study	Location	Sample size	% of MGCS flashes	Averaged Interval (ms)
Rakov and Uman [1994]	Florida, USA	190 flashes	7.9%	0.015 – 3.335
Ballarotti et al. [2005]	Vale do Paraíba, Brazil	455 flashes	1.3%	< 2
Kong et al. [2009]	4 Chinese cities, China	59 flashes	15.3%	0.004 – 0.486
Stolzenburg et al. [2013]	Florida, USA	18 flashes	10.58%	1.25 (UI only)
Present work	Vale do Paraíba, Brazil	357 flashes	9.8%	0.126 (Forked) 1.39 (UI)

The occurrence rate of forked strokes is also a matter of debate. Table I show the percentage of forked stroke observations during several field campaigns for different locations. The values range from 1.3% [Ballarotti et al., 2005] to 15.3% [Kong et al., 2009]. Kong et al. [2009], however, pointed out that the differences found in their work might be related to the analyzed samples.

There are inconsistencies on the naming convention of this type of event. Prior to the works of Stolzenburg [2012, 2013], all names used to classify return strokes with two or more ground terminations did not consider the recently found UI strokes. The need for a name that would enclose both forked and UI strokes motivated the creation of the term "multiple ground contact strokes" (MGCS), a broader class of events with two subclasses: a) "forked strokes" and b) "UI strokes", to differentiate "classic" events and the upward illumination phenomenon, respectively. This terminology explicitly separates out MGC flashes, which are flashes with sequential different ground terminations. In this work we analyze 35 cases of MGCS flashes within the millisecond range (26 "forked strokes" and 9 "UI strokes") in five thunderstorm days, during the 2012/2013 RAMMER campaign. The E-field data came from BrasilDAT sensors, which records fragments of waveforms and stores the RAW data in plain text files. Beside that information, both Brazilian lightning location systems (BrasilDAT and RINDAT) provided estimated peak currents and locations for most of MGCS flashes. In the following sections we will discuss the general characteristics of forked strokes and UI strokes observed in Vale do Paraíba region in addition to presenting statistics of their daily and overall occurrence.

TABLE II. NUMBER OF RECORDED LIGHTNING PER DAY AND PER RAMMER STATION.

Day	R1	R2	R3	RM	Sub-Total	MGCS	% of MGCS
02/18	0	25	23	19	67	5	7.5%
02/19	11	17	19	27	74	11	14.9%
02/22	6	14	13	22	55	4	7.3%
03/06	14	31	33	38	116	11	9.5%
03/08	18	8	1	18	45	4	8.9%
TOTAL					357	35	9.8%

II. INSTRUMENTATION AND DATA DESCRIPTION

The dataset of this work is comprised of high-speed camera records from the RAMMER Network [Saraiva et al., 2011] and Brazilian Lightning Location System data from RINDAT [Pinto Jr. et al. 2007] and BrasilDAT networks [Naccarato et al., 2012]. During the summer season of 2012/2013, the RAMMER network was composed by of sensors installed within and in the vicinity of São José dos Campos, São Paulo, Brazil. Each sensor has the following equipment: a) A Phantom model V9.1 high-speed camera, set to operate with a 1200 x 504 pixels spatial resolution at 2500 frames per second; b) A GPS system to time stamp the videos with a precision of 1 ns, also allowing the correlation of lightning recorded by the camera with the LLS data; c) A lightning transient sensor, sensitive to fast ambient light variations, which triggered the cameras automatically during part of the recordings; d) Personal computer with 2 TB of hard disk space, which executes programs for system control and data storage. Each sensor is capable of automatic operation. During the aforementioned summer season, the sensors were operated either manually and/or automatically. Five days had significant amount of lightning recorded and, for that reason, were used in the present work. Table II shows the number of flashes filmed by each station, being the names R1 through R3 referring to the RAMMER stations at fixed locations and RM to the mobile station. RAMMER mobile was an adapted car ready to operate as a fully functional RAMMER station anywhere. It was used uniquely during this campaign and the videos obtained were from a color camera (instead of monochromatic, as the other stations) with the same spatial resolution but with a higher frame rate (3000 frames per second, instead of 2500). The last row in Table II is the information about the number of multi ground contact stroke (MGCS) flashes recorded on each day. In the following sections these numbers will be discussed in details.

The position of the cameras is presented in Figure 1. Red markers are the stationary sensors (R1 through R3) and the blue marker corresponds to the mobile sensor (RM), which always operated in the same location during the campaign. Blue dots are all MGCS recorded by the high-speed cameras and also located by the LLS (26 cases).

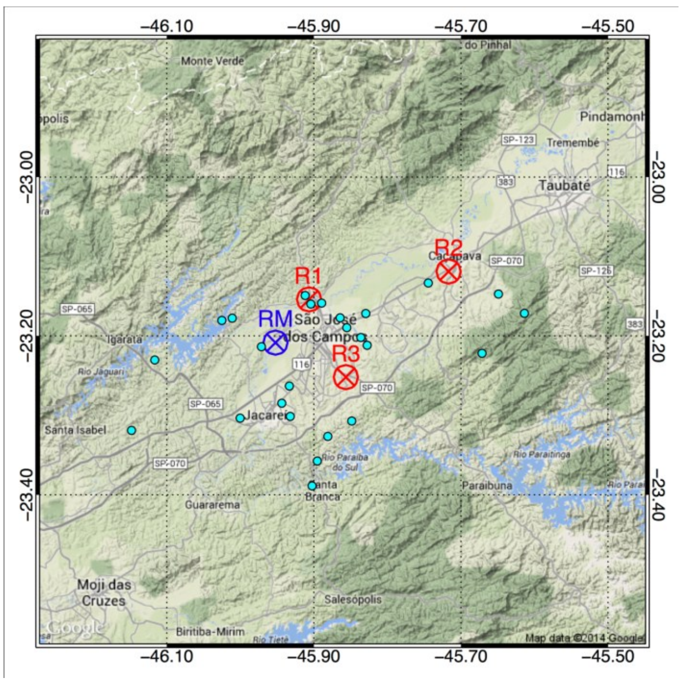


Fig. 1. Map of RAMMER sensors. Red markers are for still sensors (R1 through R3) and the blue marker is the mobile station (RM). Light blue dots are the MGCS recorded during five days.

In order to facilitate the visual inspection of the digital high-speed video records of all the analyzed events, computational resources have been used. A multi-purpose Python library called PyRAW, developed by some of the authors and colleagues (previously used by Campos et al. [2013] and Saraiva et al. [2014]), allows the manipulation and enhanced visualization of RAW image files. Data from any high-speed camera whose manufacturer software allows the user to convert individual frames into RAW files (either ASCII or binary) can be analyzed with the help of PyRAW. Some of its functionalities range from background removal to the creation of luminosity versus time graphs and time integrations. For the present work, however, it was used to create false color versions of the frames of interest for MGCS case studies. Figure 2 shows an example of a downward leader very close to the camera which was recorded by the R1 sensor. Figure 2a is the original frame and 2b is a false color version of the same frame; note that the channel is more evidenced, making easy to remove background, study the relative intensity of different channel parts, etc. For monochromatic cameras this function allows the visualization of the greyscale in a colored palette, with the blue pixels representing the lower values (closer to zero) while the red pixels show pixels that got close to saturation. For colored cameras (which is the case used in the mobile RAMMER station) the user is allowed to choose which color channel (red, green or blue) or combination of channels (e.g., the sum of two or three channels) should be considered in the creation of the false color visualization. Full documentation of the PyRAW library will be presented in a future paper.

At the time of the observations, the LLS networks available were BrasilDAT (comprised of EarthNetwork sensors) and RINDAT (comprised of Vaisala sensors). A combined analysis of data from both networks allowed the identification of most of forked stroke cases. Although the main strokes were observed, the second strokes on the forked stroke sequence were not observed by any LLS. The only sequence of strokes that was completely reported was the UI event with one of the longest time interval between strokes in our database (2.8 ms). In order to further investigate E-field data, RAW data of BrasilDAT sensors were made available by the staff of EarthNetworks. RAW data are ASCII files containing E-field information, GPS time stamped up to tens of nanoseconds. Upon the occurrence of identifiable return strokes the sensors save an E-field waveform lasting approximately 700 µs. Some noise level is automatically removed from the RAW data and return strokes often saturate close sensors. For that reason we used a combined analysis of RAW data from as many sensors as possible to minimize errors.

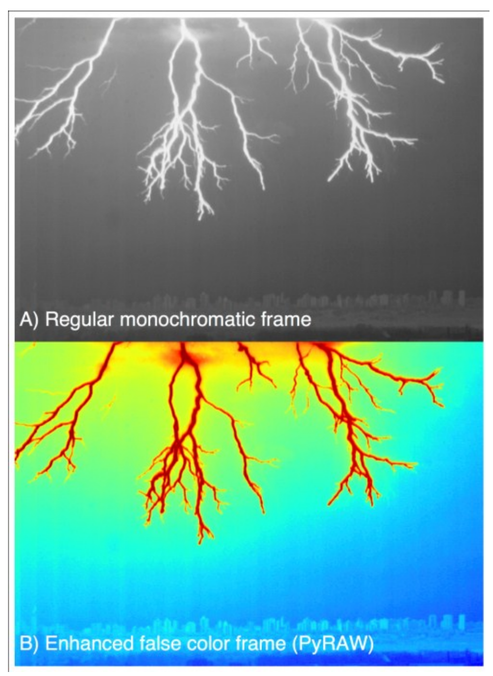


Fig. 2. A) One frame screenshot from a high-speed video taken by the Phantom V9.1 Monochromatic camera. B) Same frame enhanced by the PyRAW program, using a rainbow color palette.

III. Data Analysis

During February and March of 2013, five days of lightning recordings with multiple high-speed cameras of the RAMMER network generated a database of 357 lightning flashes. A full report on the number of flashes recorded in each RAMMER station is provided in Table II. In every recording day (February 18th, 19th and 22nd, and March 6th and 8th) several multiple ground contact strokes (MGCS) were observed. A total 35 lightning flashes were chosen as possible candidates of MGCS.

In section III.A the overall statistics of all events are presented, either all together as multiple ground contact strokes, or divided in forked strokes and upward illumination strokes. The main differences between the two types of MGCS are discussed in section III.B. More detailed analyses of all events are presented in section III.C, while in section III.D five case studies (two forked and three UI strokes) are presented.

A. Summary of the Observations

One of the first reports of multiple ground contact strokes (MGCS) came from Scholand et al. [1935] and reasonable explanations about their mechanism were proposed several years later by Guo and Krider [1982] and Rakov and Uman [1994]. The main theory says that upon the connection to the ground, the main stroke carries an upward wave at ground potential, at speeds of the order of $1x10^8$ m s^{-1}, , which is responsible for transferring the remaining charges from the main trunk and its branches to ground. So, if at least one branch is close enough to ground, the return stroke wave might not arrive in time to stop its development, allowing it to connect to ground and form a MGCS. Ideally, the interval between strokes on a MGCS should not exceed 200 µs, considering a constant return stroke speed through the whole channel and in its branches. However, several works observed intervals much higher than the limit proposed in the literature and they are summarized in Table I.

Recently, Stolzenburg at al. [2012, 2013] proposed a mechanism for MGCS that happen to present intervals greater than the 200 µs limit, the UI strokes. In our database of 35 MGCS we were able to identify 22 forked stroke flashes and 13 UI stroke flashes, classified accordingly to the classes described above.

The time intervals between ground contacts were calculated based on the waveforms of BrasilDAT sensors; usually using three or more waveforms superposed to make sure the return strokes were correctly identified. A total of 16 time intervals of forked stroke flashes and all UI stroke intervals were obtained. Finding intervals below 30 µs range was difficult due to the limited sample rate of the sensors. The forked strokes time intervals ranged from below 30 µs to 555 µs. Only two cases presented intervals above the 200 µs range and neither of their forking points were observed below cloud base. The UI intervals, on the other hand, ranged from 240 – 2650 µs. All values found here are similar to those available in literature and listed in Table I. The difference appears when forked stroke flashes are separated from UI stroke flashes. This way, the forked stroke flashes presented here are more related to the classical theory than if the whole dataset is considered. On the other hand, UI stroke flashes seem to have minimum and maximum intervals to happen. Only two cases of UI observed here presented intervals below 500 µs, so it is reasonable to assume that UI requires more time to develop than regular forked strokes, but less time than a complete leader-return stroke sequence (maximum of 2650 µs, much shorter than the 8-42 ms median durations of stepped leaders found in the literature review of chapter 4 and table 4.2 of Rakov and Uman [2003]).

Rakov and Uman [1994] and Ballarotti et al. [2005] reported that forked strokes tend to happen up to the 4th stroke order of the flash. Intriguingly, Kong et al. [2009] observed the highest percentage of forked stroke flashes in the literature (15% of 59 flashes), but all forked strokes happened on the first stroke of the flashes. In our dataset, 13 flashes (59%) presented forked strokes in the first stroke and the remaining nine events occurred in strokes of orders 2 – 6 (adding up to the remaining 41% of the dataset). 46% (6) of the UI stroke flashes happened during the first stroke sequence. No UI presented more than two terminations to the ground, but two forked stroke flashes presented more than two. The first had five simultaneous connections to the ground within one frame exposure interval (390 µs), the second presented one stroke outside the field of view and on the next frame of the camera two strike points were registered within the field of view. No BrasilDAT sensor was able to geo-locate any of these two cases, probably due to an irregular waveform. It is worth noting that only channels forming new paths to the ground presented any type of MGCS, including those that were not the first of their flashes.

In each of all five days of recordings, a statistically significant number of flashes were observed by the RAMMER network and a daily number of occurrences of MGCS was calculated. Table III summarizes the daily percentages of forked and UI stroke flashes. In general, 7 – 14% of CG flashes were MCGS per day, similar to the results presented by Kong et al. [2009] (~15%), and Rakov and Uman [1994] (~8%), but substantially different from Ballarotti et al. [2005] (1.3%). Although the work of Ballarotti et al. [2005] had lightning recorded on the same region than the present work, the instruments are different. The camera used at that time, however, had lower spatial and temporal resolutions; this combination tends to enhance the blooming effect on the moment of the return stroke, impeding the proper visualization of the double ended strokes in some cases. In general it seems that the ratio of forked/UI strokes is evenly distributed per day, unless on February 22nd, when no UI was observed.

TABLE III. Percentages of forked and UI strokes over the total amount of MGCS observed per day.

Day	% of Forked stroke flashes	% of UI stroke flashes
02/18	80,00%	20,00%
02/19	63,64%	36,36%
02/22	100,00%	0,00%
03/06	45,45%	54,55%
03/08	50,00%	50,00%

B. Differentiation Between Forked Strokes and UI strokes

The overall dataset of MGCS was sorted between forked strokes and UI strokes through careful visual inspection of each high-speed video record. The events that were classified as forked strokes were those that followed three conditions: (i) presented two or more ground terminations that occurred temporally close in the high-speed video record (either in the same frame or in separated by no more than two frames); (ii) both ground terminations appeared actively luminous at the same time on at least one frame; (iii) all the grounded branches were fully and uniformly illuminated after ground contact has been made. Conditions (ii) and (iii) are assumed to indicate that both terminations were responsible for injecting electrical currents into the same channel trunk, shared by both branches above their forking point. One example of a high-speed video frame of a forked event is shown on Figure 3.

Fig. 3. Cropped high-speed video frame of a MGCS event classified as a forked stroke. The forking point is visible below cloud base and both ground contact branches are uniformly illuminated.

UI strokes were identified following the visual similarities compared to the events previously studied by Stolzenburg et al. [2012, 2013] and the digital imagery presented in their works. For these processes the conditions (i) and (ii) of the forked strokes also needed to be met, with the relevant difference being its third characteristic: (iii) the upward-propagating luminosity enhancement in one of the branching channels needs to be non-uniform, i.e., it should not illuminate the entire channel branch where it occurred (never reaching its forking point, for those events in which it was distinguishable and visible). An example of these events is presented in Figure 4. As the classification presented in the beginning of section III suggests, the elapsed time after the "main" return stroke until the UI event was not considered when sorting the dataset. This parameter will be analyzed in detail in a later section of the present work.

C. *Overall Statistics of the Events*

1) Interstroke intervals: The high-speed cameras had exposure times ranging from 330 to 390 μs (depending on the frame rate), which means that any intervals between strokes within this time range would be impossible to estimate without the assistance of additional instruments, as described below. Also, any measures done with more than one frame interval would still have an uncertainty of 390 μs.

Southeastern Brazil is covered by two LLS networks, one comprised by EarthNetworks (EN) sensors and other by Vaisala sensors. Both types of sensors try to match known characteristics of return strokes with the waveform data and send that information to a central processing station. The recorded waveform time range is always greater than most of forked strokes time interval, so it is almost impossible for any network to properly detect both strokes. In the case of UI strokes, the time interval is usually of the order of a few milliseconds, so it is feasible that two locations are provided. However, in our database only one UI stroke had both of its strokes detected, and probably not coincidently the detection occurred on the UI with the longest time interval (2.65 ms).

Fig. 4. Cropped high-speed video frame of a MGCS event classified as an UI event. The left-hand side branch corresponds to the UI process, as the non-uniform brightening indicates. Although there is still visible (although dim) luminosity in the upper part of the channel, its lower region is considerably brighter.

Using RAW data from the BrasilDAT sensors, we were able to evaluate intervals between strokes with a resolution within tens of nanoseconds. The EN sensors record 700 microseconds of information from each stroke. From those 700 μs of data, all noise is eliminated and the remaining data is sent to the central. Even though the network is unable to geolocate both strokes, the RAW E-field data provided that information, thus allowing us to estimate the interstroke times. This analysis required E-field information from several EN sensors for each flash. The E-field timings were normalized by the peak field of the first stroke on the closest sensor to the flashes. After normalization, the data from all sensors were put side by side and the two peak fields presented in all waveforms were chosen. The calculated time differences between peaks are compatible with those presented in the literature for each class of event [Schonland, 1935, Guo and Krider, 1982, Rakov and Uman, 1994, Ballarotti et al., 2005, Kong et al., 2009, Stolzenburg et al., 2012, 2013]. An example of RAW data analysis is presented in Figure 5 for a forked stroke case. Figures 6 and 7 present plots of the interstroke interval versus parameters associated with the peak currents of the return strokes, giving an idea of how the intervals are distributed. More information can be found in section III.C.3.

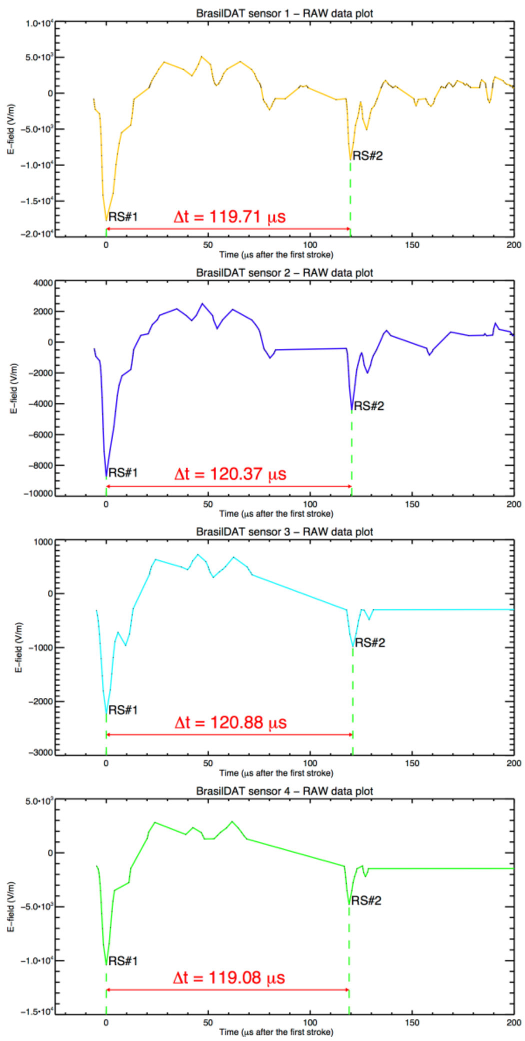


Fig. 5. Example of RAW data from 4 different BrasilDAT sensors for the same forked stroke flash.

2) One-dimensional Distance Between Ground Contacts: For 25 of the MGCS events analyzed it was possible to calculate the horizontal separation between their ground strike points through photogrammetric analysis of their high-speed video records. A limitation of the estimate obtained through this technique, however, is the fact that only the component that is parallel to the camera sensor can be taken into account.

Table IV provides a statistical summary of the values that were obtained from the camera records. Forked strokes (16 events) and UI (9 events) were considered separately (one column for each) and then grouped into a single sample (on the right-hand column). A simple comparison of each group of data suggests that they do not present statistically significant differences. The average separations for both type of phenomenon were close to 1200 m, with very similar maximum values as well (3350 to 3800 m for UI and forked, respectively). Although the relative difference between their minimum values is large (120 to 280 m), this value should be considered with caution due to the underestimation that is inherent to this one-dimensional technique applied to estimate a two-dimensional parameter. Overall, the authors believe that these results suggest that forked strokes and upward illumination events are produced by leader branches that do not have any significant differences between them, i.e., neither type of MGCS events are associated with branches that are exceptionally distant from or close to the main channel of the return stroke.

TABLE IV. STATISTICAL PARAMETERS OF THE HORIZONTAL DISTANCE ESTIMATES BETWEEN EACH GROUND CONTACT OF THE ANALYZED MGCS EVENTS FOR WHICH THERE WAS AN AVAILABLE LLS SOLUTION. THESE VALUES SHOULD BE CONSIDERED AS LOWER BOUNDS FOR THIS PARAMETER DUE TO THE FACT THAT IT WAS MEASURED IN THE PLANE PARALLEL TO THE CAMERA SENSOR.

	Forked strokes	**UI strokes**	**Overall**
Number of measurements	16	9	25
Arithmetic Mean (m)	1200	1250	1220
Minimum (m)	280	120	120
Maximum (m)	3800	3350	3800
Geometric Mean (m)	920	910	920

3) Peak current estimates: As commented in subsection III.C.1, the inability of the network in properly identify cases of forked strokes and even UI strokes only allowed the observation of one event. Flash 65 of Feb. 19th had the longest time interval of the whole set, 2.65 ms, and peak currents for both strokes were provided by BrasilDAT. As expected, the value of the second stroke was lower than the first one by a factor of 4 (-33 kA in the first stroke and -8 kA in the second). To estimate the peak currents of other forked and UI strokes, the RAW data of BrasilDAT was used once again in order to measure the peak fields of all second strokes. Firstly, the ratio between peak fields of the second and first strokes was calculated. Second, since the distance between strokes is relatively small (if compared to their distance to any of the sensors), it is reasonable to assume that multiplying the ratios by the peak current estimates of the first strokes would provide reasonable values of peak currents for the second strokes. The only test possible to verify this calculation was using Flash 65 data and compare with the LLS value. The ratio calculated for this flash was 0.3, and multiplying this value by the first stroke peak current of -33 kA gives a peak current of -10 kA for the second stroke. The difference between the LLS and the calculated peak currents was only 2 kA (25%). So, these calculated values may not be used as absolute values, but are reasonable estimates of the relative magnitude of all second peak currents.

In Figure 6, calculated ratios are plotted against time intervals between strokes. Blue circles correspond to the UI stroke flashes and orange circles are classical forked stroke flashes. The plot shows that UI strokes tend to have larger intervals compared to forked strokes and, generally, peak fields lower than 40% of the corresponding first strokes. On the other hand, forked strokes barely crossed the barrier of 400 μs of time interval and their peak fields are usually closer to matching the peak field of their related first strokes. One UI stroke flash deviates from the general behavior, with a ratio of 0.8, but that case presented a peculiar development that might be responsible for this value. This flash is analyzed in more details in section III.D. Regarding forked stroke flashes with small ratios, every one of them also shared a very small interstroke interval. These intervals are difficult to verify for some waveforms and may lead to errors, either for the interval estimates or for the peak estimates.

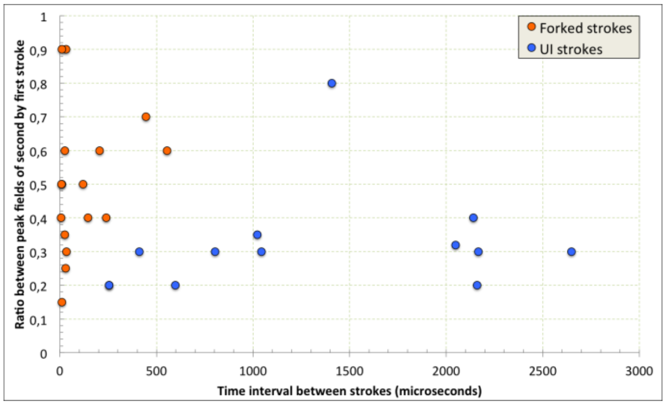


Fig. 6. Plot of interstroke intervals versus ratio between second and first Photogrammetric study of UI strokes: For all UI strokes for which LLS solutions were available and the downward leader development was visible, it was possible to conduct detailed analyses of two-dimensional leader speed evolution by means of photogrammetry techniques. Also, for these events, it was possible to obtain estimates of the total channel length that was brightened by the occurrence of the UIs. Both results are discussed in the present section.

Figure 7 is the equivalent plot of Figure 6, but this time the interstroke intervals are plotted against calculated peak currents of the first and second strokes. All peak currents are in absolute values, but all MGCS flashes are of negative polarity. The bars represent each MGCS flash, the upper limit of each bar represent the first stroke peak current and the lower limit is the second stroke peak current. The only noticeable trend is that UI strokes presented peak currents always below 10 kA, independent of their parent return stroke.

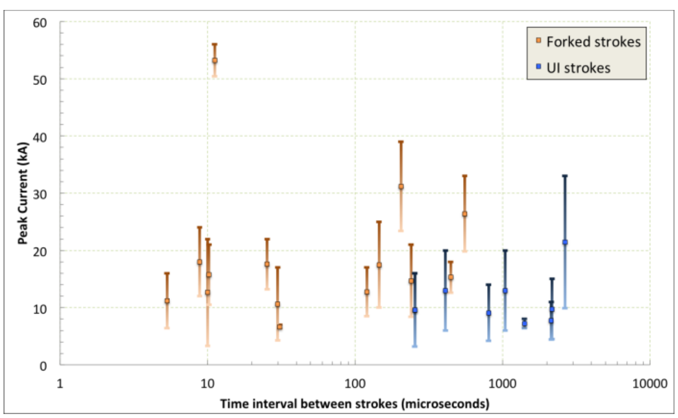


Fig. 7. Plot of interstroke intervals versus peak currents. The bars represent the first and second strokes in each MGCS. Orange bars represent forked strokes and blue bars represent UI strokes. The upper limit on the bars is always the peak current of the first stroke and the lower limit is the peak current of the second stroke. The x-axis is in log scale to better visualize the results.

Rakov and Uman [1994] and Stolzenburg et al. [2013] measured peak fields of E-field detectors and also presented the same kind of analysis. Rakov and Uman [1994] calculated the ratio Rs/Rp (second stroke peak field/first stroke peak field) for 9 double field signatures. At the time, no differentiation between forked and UI strokes were possible. Stolzenburg et al. [2013] measured E-field data from several sensors; they triangulate subsequent stroke positions and estimated peak currents for their UI cases. The results are not shown in their paper individually, but in the form of average, minimum and maximum values. Their results matched our observations of UI strokes.

a) Leader speeds: Five UI strokes had the downward stepped leader speeds calculated for both the main channel, which produced the return stroke, and the channel which lead to the occurrence of the UI. As discussed in the case studies presented below in section III.D, it was shown that the UI branch develops most of its extension with speeds compatible with the main stroke channel, usually diverging from it in the latest moments of its development. Additionally, if one takes all the speed measurements obtained for all analyzed UI events, it can be shown that they are statistically very similar. The five different UI strokes allowed 114 and 87 individual measurements of downward stepped leader speeds for the main and UI branches, respectively. The statistical summary of these measurements are presented in Table V.

TABLE V. STATISTICAL PARAMETERS OF THE LEADER SPEED ESTIMATES OBTAINED FOR THE MAIN BRANCH (WHICH PRODUCES THE RETURN STROKE) AND THE UI BRANCH FOR THE ANALYZED UI EVENTS.

	Main (stroke) branch	**Upward illumination branch**
Number of measurements	114	87
Arithmetic Mean (x 10^5 m s^{-1})	3.1	3.1
Minimum (x 10^5 m s^{-1})	0.91	0.87
Maximum (x 10^5 m s^{-1})	6.5	5.6
Geometric Mean (x 10^5 m s^{-1})	3.0	2.9

Simple comparison of each parameter strongly suggests that both branches propagate with the same range and typical values of speeds. The higher maximum found for the main branches is probably related to the final acceleration of the leader that could not be seen on the UI branches. Additionally, although not shown in the present work, histograms of speeds for both branches are also very similar, endorsing the idea that there is no statistically significant difference between them.

b) UI channel total brightening length: As discussed in section III.B, the UI processes usually do not illuminate its branch uniformly over the whole length. As demonstrated in greater detail in the case studies of section III.D, the lower part is usually brighter than the upper region, which connects to the main stroke branch. This behavior is illustrated on Figure 8. Due to this non-uniformity, we present estimates of the length of both the complete brightened channels and the section that were most intensely illuminated. This was done for six events (the same five that had their leader speeds calculated along with a sixth event whose leader development could not be tracked) and the resulting values are shown in

Table VI. On average, the brightest segment corresponded to about 70% of the total length illuminated by the UI process.

TABLE VI. TABLE VI – STATISTICAL PARAMETERS OF THE LENGTH OF THE TOTAL AND BRIGHTEST CHANNEL SEGMENTS ILLUMINATED BY UI STROKES.

	Total brightened channel length	**Length of the brightest channel segment**
Number of measurements	6	5[a]
Arithmetic Mean (m)	2300	1600
Minimum (m)	1400	1100
Maximum (m)	3100	2200
Geometric Mean (m)	2200	1500

[a] For one of the analyzed events there was no distinguishable brightest segment during the UI.

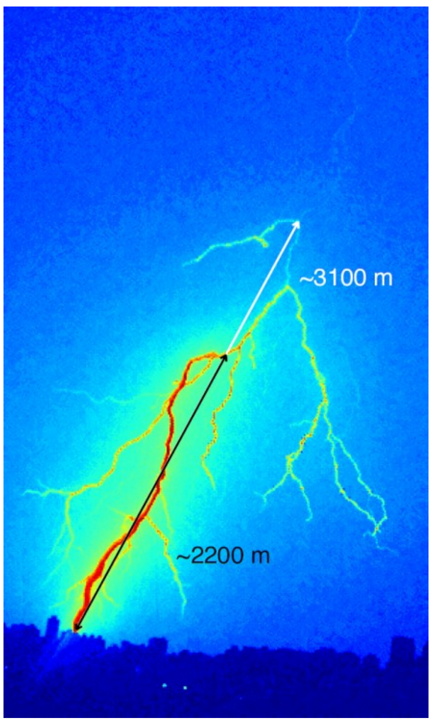


Fig. 8. Examples of the most intense (black line) and the total brightened segments (white + black lines) of one case UI channels. The false color version of the frame makes it easier to identify the boundaries of each region.

D. *Case Studies*

In the present section a few selected MGCS events are discussed in greater detail. This is intended not only to discuss some of their peculiarities but also to serve as a reference to how the parameters and characteristics discussed elsewhere in the paper were determined. Two "classical" forked stroke events are described in 3.4.1, each one representing an extreme in the spectrum of interstroke intervals (one had them separated by about 30 µs while the other had a delay of more than 200 µs before the second ground contact was established). UI events are the subject of 3.4.1, where three cases are discussed. The first and second cases had about 2 and 1 milliseconds between ground contacts, respectively, while the third is the most unique event. The latter UI stroke was preceded by an attempted leader that might be related to its unusually large E-field peak ratio when compared to its preceding main return stroke (about 0.8, the highest observed for UI events).

1) *Forked Strokes:*

a) Flash #1, February 18th, 2013: The first selected forked stroke event was flash #1, observed at 20:16:39 (UT). The very first stroke of this flash was forked, producing two ground terminations that could be observed in the same video frame. The left-hand termination becomes inactive in the following frame while the luminosity of the right-hand termination lasted for about 12.6 milliseconds. Both are shown in Figure 9a,b,c.The time interval between these ground contacts was determined to be 30.9 µs from the analysis of the waveforms provided by six different BrasilDAT sensors (one of which is presented on the lower part of Figure 9). About 88 milliseconds after the first (forked) stroke of Case 1 another return stroke occurs, following the path to ground that was formed by its right-hand branch. We note, however, that about half the leftmost branch was re-illuminated by its preceding dart leader (not shown in the frames included in the paper). A fourth return stroke follows the third after 36 milliseconds, but this time its dart leader did not penetrate the channel of left-hand termination.

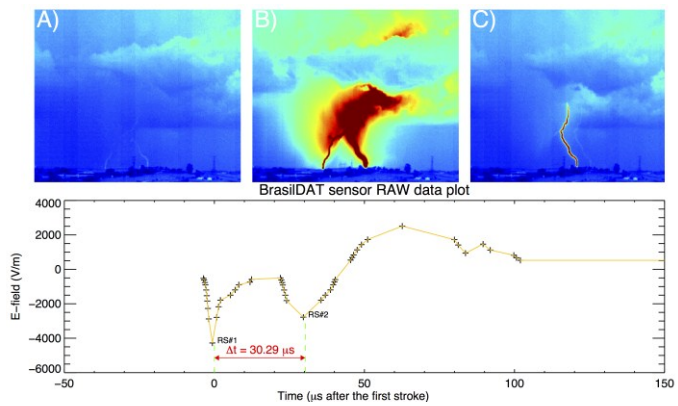


Fig. 9. A, B and C: Selected video frames (false color from monochromatic data) and BrasilDAT waveform of the forked stroke of flash #1 (on the plot below).

Although visually the brightness of the left-hand channel of the forked stroke is considerably less intense than the right-hand channel (Figure 9), the multiple E-field waveform analysis has shown that their peak values were very similar, with a ratio of 0.9. The stroke for which a solution was provided by the BrasilDAT (right-hand) presented an estimated peak current of –7 kA, so from the ratio it is reasonable to assume that the left-hand ground termination had a peak of –6 kA. The solution also provided a distance from the camera of approximately 29 km, allowing the photogrammetric analysis of the video frames. It was possible to estimate the two-dimensional distance between each ground termination and the forking point, visible below cloud base. The distances found were: 1320 m for the right-hand channel and 1530 m for the left-hand channel, with the forking point estimated to be about 1280 m above ground. Their horizontal separation in the plane parallel to the camera sensor is about 1420 m, but this should be taken as a lower bound estimate (as discussed on section III.C.2).

Considering the photogrammetric results for this event, it is possible to estimate the upper bound value for the return stroke speed if one assumes that its wave did not reach the extremity of the left-hand channel before it made ground contact. The return stroke wave would need to travel about 2850 m (the sum of the lengths of both branches up to the forking point) in no more than 30.9 μs (their temporal separation provided by the E-field analysis). This leads to a return stroke speed of 9.22 x 10^7 m s^{-1}, which is close to the range of maximum values (1.2-2.8 x 10^8 m s^{-1}) usually found in literature for natural lightning (see, for a summary, Table 4.5 of Rakov and Uman [2003]). From this result one may argue that the hypothesis usually found in literature (e.g., Guo and Krider [1982], Rakov and Uman [1994]) is reasonable under the light of the available information for this event.

b) Flash #54, February 19th, 2013: The second forked stroke event is flash #54, observed at 19:10:13 (UT). Two return strokes preceded the MGCS, following different paths to ground and with no apparent channel segments shared with the forked stroke of interest (which was observed 52 milliseconds after the second stroke). Two other strokes were recorded after the MGCS (after 56 and 166 ms) and both followed the same path to ground (although different from all previous four strokes).

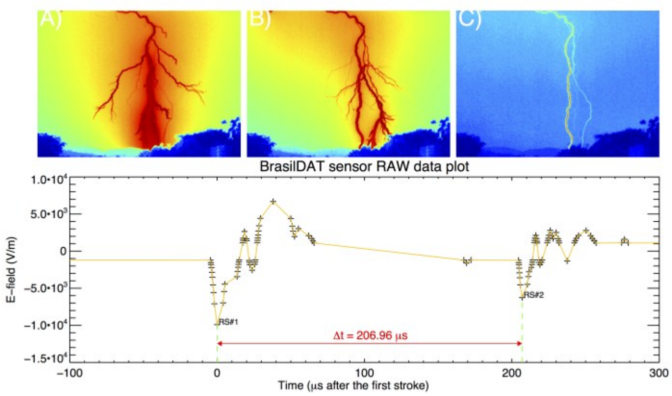


Fig. 10. A, B and C: Selected video frames (false color from the blue channel data) and BrasilDAT waveform of the forked stroke of flash #54 (on the plot below).

In this MGCS event the ground contacts were observed in two consecutive video frames, as shown in Figure 10a,b. Through the waveform analysis of data provided by five different BrasilDAT sensors (one of them is shown in the bottom of Figure 10) it was found that the temporal separation from the left-hand (first) channel to the right-hand (second) channel was about 205 μs and the ratio between the first and second E-field peaks was found to be 0.6. As the solution provided for the first ground contact had a peak current estimate of –39 kA, it is reasonable to assume that the second (right-hand) ground termination had a peak of –23 kA. BrasilDAT data also allowed the calculation of the distance from the camera to the flash, which resulted in 18.4 km. From this information it was possible to estimate the approximate two-dimensional length between each ground contact and the forking point, which is more visible in Figure 10c (upper, central region of the frame). The left-hand and right-hand channels had their distances estimated to be 5060 and 5100 m, respectively. As done for the previous analyzed event, if one considers the time between each ground contact (205 μs) and the distance between the ground contact points of the left-hand to the right-hand channels (totaling a distance of about 10160 m) it is possible to estimate the upper bound for the return stroke traveling wave. The value found is 5.0 x 10^7 m s^{-1}, also in good agreement with the speeds found in literature (as discussed in the previous case study) and the current theory to explain the occurrence of forked strokes.

2) Upward Illumination Events:

a) Flash #17, February 19th, 2013: The first selected UI event was flash #17, observed at 18:19:43 (UT), about 40 minutes before the occurrence of flash #54 (discussed on section III..D.1.b). This flash produced one return stroke and, 70 milliseconds later, a second return stroke that was an UI stroke. There are no visible common branches between them, although they leave the opaque region of the thundercloud in the same region of the high-speed video imagery. About 35 milliseconds prior to the occurrence of the main return stroke of the UI event its stepped leader became visible below cloud base. As shown in the selected frames of Figure 11a and b, there were two main leader branches, but the right-hand one touched ground first, producing the main return stroke. However, five frames after the stroke (1950 ms), the left-hand branch made ground contact, producing an upward illumination that can be seen in the two consecutive frames of Figure 11c,d. From the analysis of the E-field waveforms of five BrasilDAT sensors (one of them shown on the bottom of Figure 11), a more precise interval between the ground contacts was determined to be 2170 μs. The ratio between the E-field peaks was 0.3, so as the main stroke had its peak current estimated to be –15 kA, it is reasonable to assume that the UI had a peak current of approximately –5 kA. It importante to notice that the false color enhancing techinique used in the sequence of figures is different from all others with the objective to show the weak conection between the UI and the main branch.

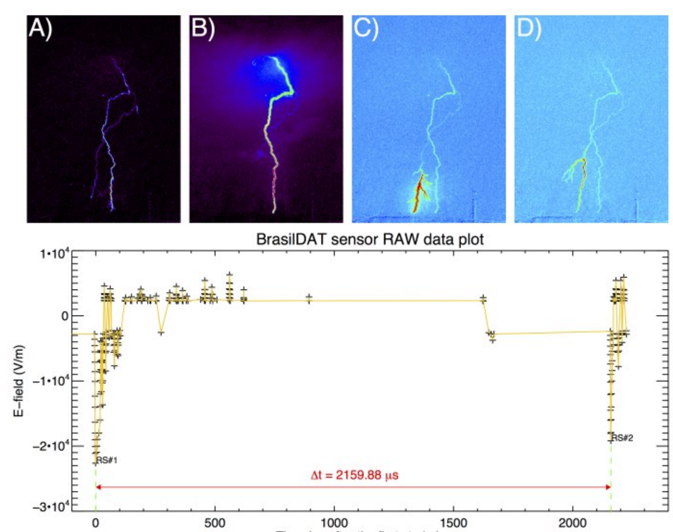


Fig. 11. A, B and C: Selected video frames (false color from monochromatic data) and BrasilDAT waveform of the UI stroke of flash #17 (on the plot below).

The analysis of the false color visualization of the video frames clearly show that the UI channel remains luminous even after the main return stroke occurred, suggesting that there is no channel current cutoff as in the cases analyzed by Stolzenburg et al. [2012, 2013]. This characteristic can be seen in greater detail in Figure 12, which shows the evolution of the UI process in two consecutive frames. It is possible to see that many secondary branches are illuminated as the UI process advances. In the second frame (Figure 12b) it is possible to see that these branches continue to have their luminosity intensified as the UI return stroke moves further up, so that upper branches are brightened as well. The arrows allow a comparison of the advancement between the two frames and show how in Figure 12b no branching below the lower arrow is visible. One can also notice that portions of the UI channel located even further up are also intensified, although no other secondary branches are re-illuminated. Through a photogrammetric analysis it was possible to estimate that each pixel is equivalent to about 20 meters, so the total length of the intensified channel up to the lower arrow could be estimated to be about 2000 m, and the segment between the two arrows is about 500 m long. The distances between each ground contact and the forking point that lead to each one of the two main branches could also be estimated: 5600 m for the left-hand channel (UI) and 5900 m for the right-hand channel (main stroke). This adds to a total distance of approximately 11500 m. If one considers the classical model for regular forked strokes and the time interval between ground contacts (2170 μs), the upper bound of the return stroke propagation speed for this event is 5.3 x 10^6 m s^{-1}, considerably lower than the values usually found in literature. For the UI to occur either its branch should be completely cut off from the main return stroke channel or some other mechanism restricted the penetration of the return stroke wave into its lower part (possibly by a reduction on its propagation speed). A complete discussion on this issue is will be presented in a future paper.

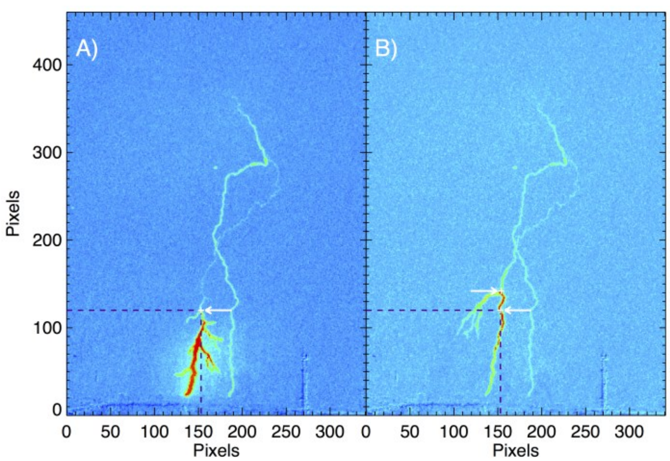


Fig. 12. The evolution of the UI process of flash #17 over two consecutive video frames. Each pixel (vertical or horizontal) is equivalent to 20 meters.

The photogrammetric analysis of flash 17 also allowed the tracking of its preceding stepped leader. Plots of leader tip height and leader two-dimensional speed versus time are presented in Figure 13, in which time t = 0 corresponds to the time of occurrence of the main return stroke. Due to the fact that the leader exited the cloud opaque region above its cloud base, a considerably long portion of its channel was visible (about 6000 m). The UI branch was formed around 5500 m above ground (30 ms prior to the main return stroke) and presented a two-dimensional speed that was initially higher than the one calculated for the main stroke branch. Both leader branches developed almost synchronously up to the final 2000 m (5 ms) before ground contact, presenting an oscillation in their speed profiles (similar to what was reported by Campos et al. [2014] for natural stepped leaders). After that the leader tip height versus time plot (Figure 13a) shows that the UI branch is progressively left behind, presenting lower speeds when compared to the main return stroke branch (as confirmed by speed versus time graph as well). There is acceleration in the final part of the development of both leader branches, but the main channel makes ground contact first. The UI branch becomes more tenuous after the stroke, reaching ground about 2.2 ms later. As its final development is not visible to the camera, its last speed measurement (2.6 x 10^5 m s^{-1}) actually consists of a lower bound.

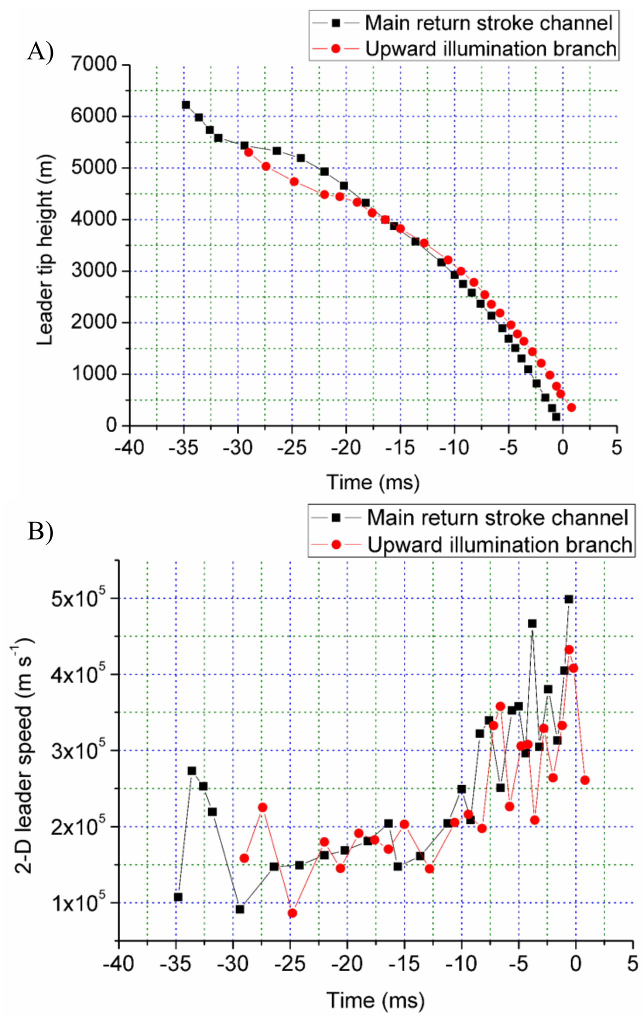


Fig. 13. (a) Stepped leader tip height and (b) 2-D leader speed of the UI stroke of flash #17.

b) Flash #85, March 6th, 2013: The second selected UI event was flash #85, observed at 22:41:01 (UT). Unlike flash

#17, presented in the previous section, the very first return stroke of flash #85 was the one that produced the UI event. A subsequent stroke occurred 171 ms after the main stroke of the UI event and followed its path to ground. During that interstroke interval, however, an attempted leader occurred in the UI branch, and will be discussed later in this section.

The forking point of this UI event was located outside the camera field of view, but the non-uniformity of the brightness of the UI branch was clear enough to allow its identification. Figure 14a shows the channel of the main return stroke, two frames after it occurred. On the following frame (i.e., three frames after the stroke) the UI occurred, as shown in Figure 14b. E-field waveforms of five BrasilDAT sensors provided an estimate of the interval between the ground connections of the main stroke and the UI, and the obtained value was about 1040 µs. In the analyzed waveforms the ratio between the E-field peaks was 0.3 (similarly to flash #17, discussed in the previous section). As the main stroke had its peak current estimated to be –20 kA, by assuming that the same ratio applies here the peak current of the UI was approximately –6 kA.

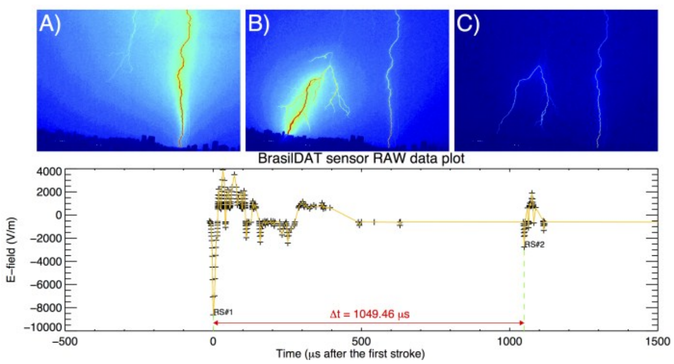


Fig. 14. (a) Selected video frames (false color from the blue channel data) and (b) BrasilDAT waveform of the UI stroke of flash #85.

Careful inspection of the UI frames, shown in greater detail in Figure 15 (generated from the data associated with the blue channel of the colored high-speed camera), indicate a relationship between the branches illuminated by the return stroke and those illuminated by the UI development. Each pixel is equivalent to approximately 9.3 m at the estimated distance from the camera to the ground strike point. Figure 15a shows one of the branches that was illuminated by the return stroke. By comparing the positions of the mid and upper arrows of Figure 15a and 15b it is apparent that the UI did not penetrate the segments illuminated by the return stroke, even though it is not possible to confirm that with the available imagery. Although this may indicate that there is complete current cutoff between the main stroke channel and the UI branch, the high-speed video data shows that the upper region of the UI channel remains luminous (similar to what was observed for flash #17 in the previous section).

It is also possible to notice three distinct levels of intensity in the UI development. The bottom arrow shows where the most intense pixels (i.e., red) ended in the upward propagation of the UI (Figure 15b). Photogrammetric analysis indicates that this channel segment was about 2200 m long. The second level of intensity is shown by the middle arrow, where the green/yellow pixels are located. This point is about 2700 m away from the ground strike point of the UI and it is possible to notice that the illuminated right-hand branch presented similar intensity values, which persisted and moved farther down in the consecutive frame (Figure 15c). Finally, the top arrow shows the upper level of illumination, mostly made of light blue pixels. This third section was about 3100 m from the ground contact point and was not illuminated in the following frame. This false color imagery suggests that the UI attenuates as it moves towards its forking point, and that the illumination of its branches may continue if conditions allow (as Figure 3.4.7b indicates). It is not possible, however, to estimate if this non-uniformity could be caused by the three-dimensional channel morphology of this event, but the analysis of earlier frames (associated with the development of the stepped leader) did not support the idea of this behavior to be caused by geometry factors.

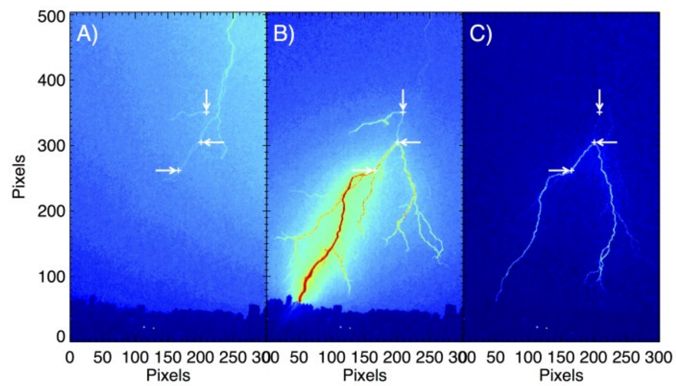


Fig. 15. Details of the region of the UI branch of flash #85 (false color from the blue channel data). (a) Corresponds to the main stroke frame, while (b) and (c) correspond to the first and second frames of the UI process, respectively (taken three and four frames after the main stroke). Each pixel (vertical or horizontal) is equivalent to 9.3 meters.

About 125 ms after the main stroke of the UI event occurred, an attempted leader was observed. As shown in Figure 16c, it retraced the UI branch while propagating towards ground, but its development was interrupted about 1600 m above ground. The comparison of the selected frames, however, shows that the attempted leader followed the leftmost branch of the UI channel and would not have reached the same ground strike point if it had persisted. It is also worth noting that the attempted leader moves beyond the point where the UI interrupted its development, supporting the idea that it is very unlikey that a complete current cutoff happened in that branch. This observation added to the fact that the upper region of the UI branch remains luminous suggests that there is a transition in the channel conductivity régime between the UI-intensified branches and those that were illuminated by the return stroke (Figure 15a). Further support to this idea is given by flash #115, occurred on the same day but not presented in detail in this work, which had three subsequent return strokes following the same channel of the UI to ground.

The photogrammetric technique also allowed a detailed analysis of the stepped leader development in the bottom 4500 m of the UI and main stroke channels. Figure 17a and 17b show the leader tip height and leader two-dimensional speed versus time plots. It is possible to notice that the leader speeds oscillate up to the final 2 ms (1000-1250 m) prior to the main return stroke. Both branches propagated almost synchronously up to the final 5 ms (2000-2250 m), but after that moment the UI branch began to develop more slowly and did not present the final acceleration that can be seen on Figure 17b for the main stroke channel. Figure 17c shows the region of the leader tip height versus time graph in which the UI branch began to be left behind. In this event the slower development of the UI branch at later times seem to be more prominent than what was observed for flash #17 (Figure 13). It is important to note, however, that this speed reduction does not coincide with the upper region of UI development: as mentioned previously, the speed reduction took place in the 2000-2250 m range of heights, while the UI propagated almost up to 3000 m above ground.

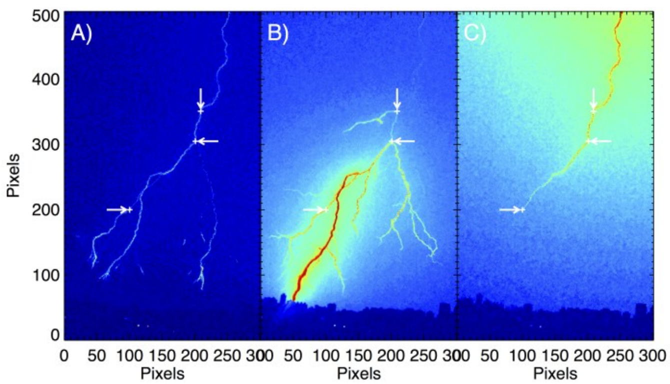
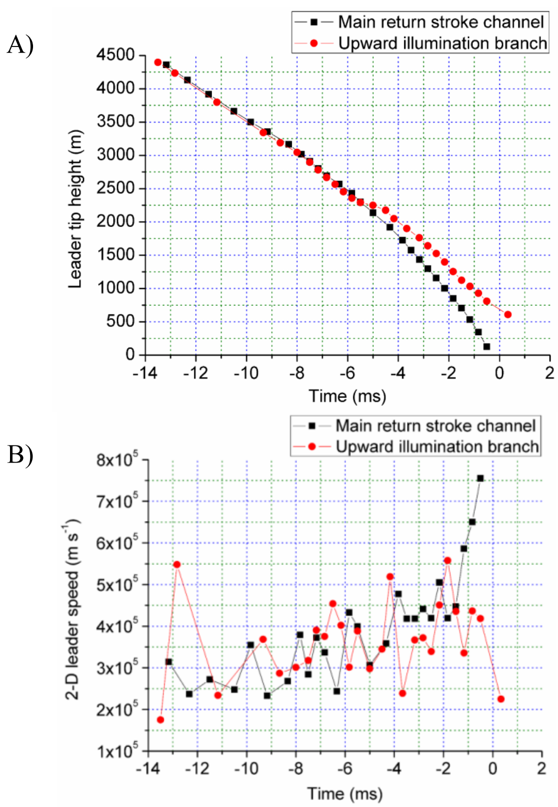


Fig. 16. Details of (a) the stepped leader, (b) the UI process and (c) the subsequent attempted leader that occurs after the UI of flash #85. All frames are false color from the blue channel data. Each pixel (vertical or horizontal) is equivalent to 9.3 meters.



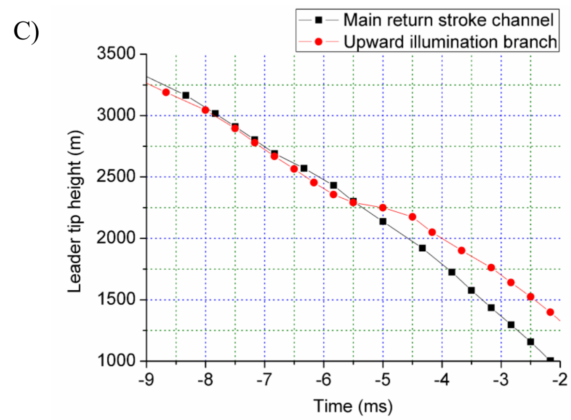


Fig. 17. (a) Stepped leader tip height and (b) 2-D leader speed of the UI stroke of flash #85; (c) is equivalent to (a) but zoomed into the instant the leader tips diverged.

c) Flash #22, March 8th, 2013: The third selected UI event was flash #22, observed at 19:12:31 (UT) on March 8th, 2013. Differently from what was observed in the previous case studies, it was not possible to visually confirm the non-uniformity in the UI brightness, so this event was classified as an UI due to the long time interval between its ground contacts, but not so long to be considered a new complete return stroke. Flash #22 presented 10 return strokes that followed four different channels to ground. The stepped leader that gave rise to the first stroke presented a large number of branches, and about 24 milliseconds later an attempted leader retraced its leftmost branch. The second stroke occurred 45 milliseconds after the first, retracing the rightmost branch of the initial stepped leader. All branches were re-illuminated by the leader process (Figure 18a) prior to the stroke (shown in Figure 18b, with its contact point outside the field of view), and the leftmost (through which the attempted leader developed 21 milliseconds earlier) continued its propagation and ultimately produced the UI event four frames later (shown in Figure 18c). Data from five different BrasilDAT sensors allowed the determination of the time interval between the ground contacts, which was 1408 µs long. The UI channel lasted about 6 frames (2.4 ms) while the channel of the main return stroke remained active for 23 frames (9.2 ms). Two return strokes followed the UI channel to ground, occurring 19 and 75 milliseconds after the UI made ground contact. Finally, six return strokes were observed in a fourth ground termination. The first stroke of this sequence occurred 143 milliseconds after the second stroke that followed the UI channel and was initiated was a dart-stepped leader that diverged from the channel of the main stroke of the UI event.

There is one characteristics of the UI event of flash #22 that makes it unique compared to the rest of the dataset of the present paper: the ratio between E-field peaks was unusually high, 0.8 (only observed for classical forked strokes), even though the main return stroke was not particularly intense (–8 kA). There are two immediate possible reasons for this: (i) the attempted leader that occurred 22 ms before the UI made ground contact increased its channel conductivity, making it possible for its peak current to become higher than usually observed (relative to the main stroke); or (ii) it was not an UI event, as the high-speed video data is not conclusive about this (except for the time interval after the main stroke). It is impossible to say if (i) might explain the two return strokes that used the UI channel, as the UI of flash #115 (mentioned in the previous section) also had subsequent return strokes despite the fact that its E-field peak ratio was low (0.2). If (ii) is the truth about this event, it is unlikely that these temporally close ground contacts were created by means of the physical model for the classical forked strokes due to the fact that the longest time interval observed in the dataset of forked strokes of the present work was 554 μs, almost 3 times shorter. The combination of these characteristics (large interval and E-field peak ratio) apparently makes flash #22 to lie between the physical models of forked and UI strokes. This is particularly relevant under the light of Figure 6, where the point associated with the UI of flash #22 did not fall in either region.

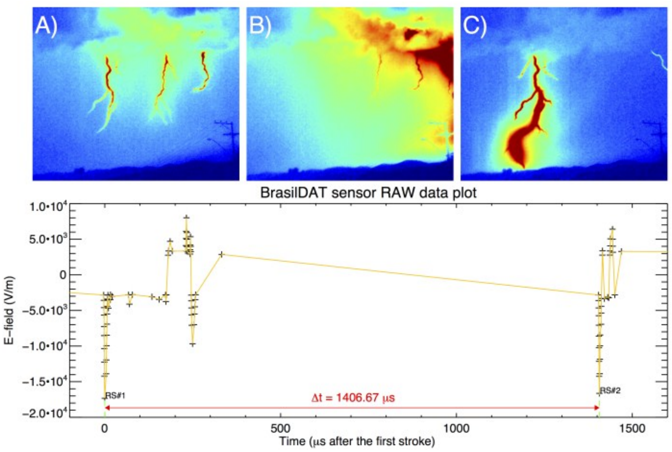


Fig. 18. A, B and C: Selected video frames (false color from the red channel data) and BrasilDAT waveform of the UI stroke of flash #22 (on the plot below).

Due to the limited visibility of the leader processes that preceded the UI event of flash #22, no detailed plots are presented.

IV. Discussion

During the course of this work, two names were given to very similar classes of events. Forked strokes refer to that classic theory, since Schonland [1935], of strokes that hit the ground two or more times in intervals of the order of microseconds. Upward illumination strokes were studied for the first time by Stolzenburg et al. [2012, 2013] and seem to be a subclass of forked strokes with little or no connection to the main branch. The general term used here, "multi ground contact strokes" (MGCS), reflects the similarity between those events. In typical return/subsequent stroke process, a series of steps must be completed in order to produce the stroke, such as, breakdown, leader processes (stepped/dart), K and J discharges, recoil leaders, etc. In a MGCS, independent of how the development goes into a forked or a UI stroke, one branch of one of the strokes is the cause for additional ground contacts without the need of a new occurrence of the aforementioned processes. So, in principle, forked and UI strokes belong to the same family of events.

In Table I, the percentage of flashes with MGCS is presented for this work, 9.8%. This value seems consistent for individual days, with values of percentage ranging from 7.3 – 14.9%. This is also consistent with the works of Rakov and Uman [1994] and Kong et al. [2009], and even with Stolzenburg et al. [2013], who had only considered UI stroke flashes on their analysis. Another result presented here is that these events are not generally reported by LLS networks, even though all four UI events analyzed by Stolzenburg et al. [2012] were reported by LINET only (among other LLS whose datasets were also analyzed) as negative strokes with low peak currents. In conclusion, near 10% of all flashes have one or more ground contact points that are like "ghosts" to the LLS. In our database, 35 MGCS flashes presented a total of 109 contact points, 40 due to MGCS, corresponding to ~40% of all contact points in these flashes. This means that about 4% of all ground contact points from the complete database are MGCS. This percentage is enough to be taken into account on the design of newer lightning locating systems.

In Section III, some of the main parameters of MGCS were discussed divided in the subclasses of forked strokes and UI strokes. The identification between those 2 events was made primarily from video analysis and the fine detailing regarding timing and peak current was made with RAW data from BrasilDAT network. The main findings presented in Section III are discussed below:

A. *Forked Strokes*

- The time intervals of forked strokes ranged from 5 – 554 μs, in agreement with those found in the literature. However, Figure 6 shows only two values in the 500 μs range, with all others being below 300 μs. In datasets without discrimination between forked and UI strokes it is probable that higher values of intervals belong to UI strokes. If one considers that the conductivity on the channel is not uniform and, thus, the speed of the propagating return stroke wave could be slower, higher values of intervals up to 500 μs are reasonable. That way, these results are compatible with the theory of Guo and Krider [1982].

- Separation between strokes was estimated on the video frames and they seem to be very small, even considering errors due to perspective. Mean values are around 1200 m. It is worth noting that those distances, even with the rough 1D estimation, did not show separations higher than 4 km between strokes and mean values that are also lower than typical mean values of flashes with return strokes that hit the ground at different locations. The lower distances are a response to lower altitude forking points, compared to regular subsequent strokes that hit ground at different places.

- Another parameter measured is the ratio between the E-field of the second stroke by the first stroke in the forked sequence. Those ratios were also calculated by Rakov and Uman [1994] and the results are remarkably similar. Figure 6 shows the plot of interstroke interval versus E-field peak ratio and it seems that the second strokes can share almost as much current as their parent stroke. A plausible explanation is that the second strokes connect so fast to the ground so that the charges presented on the main channel can be divided between both connection points almost equally. If, however, the branch that produced the second stroke has a lower conductivity, it is feasible that the ratio of charge flowing through that branch will be smaller compared to the parent stroke.

B. *UI strokes*

- The visual inspection is the first and best way so far to identify an UI stroke. In a typical forked stroke case, the luminosity of the second channel is uniformly distributed up to the forking point (when visible). On the UI strokes the luminosity is not always visible up to the forking point. Instead, a very thin channel between the brightest point and the forking point was observed in most of our observations (e.g., Figures 4 and 12). Stolzenburg et al. [2012, 2013] observed gaps between the brightest point and the forking point, inferring that a cutoff might have occurred. Their observations were made at much higher frame rate than RAMMER network with a lower spatial resolution (320 x 240 pixels). That frame rate (which implies in a small exposure time), combined with low spatial resolution could be responsible to produce a false impression of disappearance of the channel at some point when it, in fact, still existed. Our spatial resolution was higher (1200 x 504) and the frame rate slower (330 - 390 μs) and that allowed us to observe thinner channel connections between the brightest point and the forking point, as presented in the case studies of Section III.D.
- The occurrence of not of cutoff on UI branches are not competing theories. Both effects might happen in different cases at different conductivity régimes. The leader speed analysis of selected cases showed that UI branches slow down on the final moments, close to ground. Those speeds could happen due to a change in the conductivity of the branch so that the channel either: (a) can cutoff from the main branch and continue to propagate down to the ground due to the external E-field; or (b) the low conductivity is not sufficiently low to cutoff the channel, but inhibits the return stroke wave to penetrate the UI branch in time to stop its further propagation.
- Interstroke intervals for UI events are much higher than those for forked flashes. Lower values are also different from forked strokes, since the lowest time interval measured for a UI event was ~250 μs and the maximum value of ~2600 μs. Intriguingly no one has ever observed an UI interval greater than 4000 μs. Would this time be the limit for the return stroke wave to propagate down to the lower conductivity channel and stop its propagation? More observations are needed to evaluate this hypothesis.

V. CONCLUDING REMARKS

In the summer season of 2012/2013, the RAMMER network registered 5 days of lightning flashes with sufficient data so each day could be studied individually. Each day presented a significant proportion of CG flashes multiple ground contact strokes (MGCS), of the order of 10% per day. Based on recent literature, those MGCS were divided in two classes, classical forked stroke flashes and upward illumination (UI) flashes. Several broad and detailed analyses of their characteristics were performed. The general features revealed that the percentage of the MGCS flashes (~10%) should be considered in future development of lightning location systems.

The visual inspection of both classes of events suggested that forked and UI strokes have both common and different characteristics. The visual evaluation shows that forked strokes have two (or more) clear connections to the ground from a common forking point, but UI strokes looked like gigantic connecting leaders, since they seem to not visually illuminate back to the forking point. While forked strokes have small interstroke intervals (~ 120 μs), UI strokes have longer intervals, but seem to be limited to remain below 3 – 4 ms. The minimum value found for a UI stroke was 254 μs, which was comparable to some of the largest values found for forked strokes. Other remarkable characteristic is the ratio between the second stroke and first stroke on the MGCS sequence. Second strokes on forked stroke sequences seem to be able to almost match the peak fields of their parent stroke, while the UI strokes usually have a lower peak fields on their second strokes. As for the separation between ground contacts, both events shared the same average of ~1200 m.

After separating forked strokes from UI strokes, Guo and Krider [1982] theory seems very reasonable and match most of our observations of forked strokes.

During our analysis we were able to identify cases of UI strokes with optically active channels connected to their forking points, contrary to all observations by Stolzenburg et al. [2012, 2013]. Our observations do not deny the existence of cutoff in UI strokes, but open room for more speculation on the processes leading to the UI strokes. We suggested that distinct channel conductivity régimes could play an important role in the long interstroke intervals, still maintaining some form of connection to the main channel.

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