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Features of the first and the subsequent return strokes in positive ground flashes based on electric field measurements

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ABSTRACT

This paper presents the characteristics of the electric fields produced by the first and the subsequent return strokes observed in positive ground flashes in Sweden. Fifty one positive ground flashes containing 60 return strokes recorded during 2014 summer thunderstorms were analyzed. In our analysis, only 12% of the cases were multiple-stroke while 88% were single-stroke. On average, the number of strokes per flash was 1.20 and the highest number of strokes per flash recorded was four. The geometric mean (GM) value of the interstroke interval was 60 ms while the distance between the first and the subsequent strokes ranged between 4.9 and 46.4 km. We found that the average duration of the subsequent strokes parameters were smaller than that of the first strokes. For the first strokes, the GM values of the slow front duration, the fast transition 10-to-90% risetime, the zero crossing time, the zero-to-peak risetime and the 10-to-90% risetime were 8.7 μs, 1.4 μs, 29 μs, 11 μs and 5.7 μs, respectively while for the subsequent strokes, the values were 4.0 μs, 0.91 μs, 11 μs, 5.8 μs and 3.2 μs, respectively. Possible reasons for the shorter duration of the subsequent return strokes parameters were discussed.

1. Introduction

1.1. Positive ground flash

Positive ground flashes can be defined as ground flashes that transport positive charges from cloud to ground. Though they are less dominant than their negative counterparts, positive ground flashes have attracted considerable attention because they produce strokes with higher peak currents and larger charge transfers. According to [1], the highest directly measured lightning currents and the largest charge transfers to the ground are thought to be associated with positive lightning, with peak current values reaching up to 300 kA and charges close to 1000 C. Since this could potentially cause severe damage to various objects and systems, knowledge on positive ground flashes parameters is important particularly in the field of lightning protection.

Among the characteristics that are thought to be associated with positive ground flashes is the single-stroke composition of the flash [1]. In contrast, majority of the negative ground flashes contain two or more strokes [2]. According to [3], the reason for the single-stroke nature of the positive ground flashes could be that the cloud-end of the bidirectional leader of the flash is negative and since negative leaders are not hindered by current cut-off, current continues to flow along the channel until the charges in the positive charge centre are depleted. For negative ground flashes, however, the cloud-end of the bidirectional leader of the flash is positive, and as positive leaders continue to propagate, they will be subjected to current cut-off when the channel behind the leader tip decays, leading to recoil leaders. These recoil leaders travel along the positive leader channel towards the flash origin and upon making contact with the cloud-end of the return stroke channel, results in subsequent return strokes.

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1.2. Review on previous studies

Even though positive ground flashes are usually single stroke, multiple-stroke flashes do occur. However, they are relatively rare compared to negative ground flashes. Based on the information found in the literature, past observations made on multiple-stroke positive ground flashes can be briefly summarized as follows:

1.2.1. Flash multiplicity

Flash multiplicity is often used to denote the number of strokes in a single flash [4]. Among the researchers that have reported the average flash multiplicity in positive ground flashes were Nag and Rakov [5], who found that majority (81%) of the 52 positive ground flashes recorded in Florida, U.S. were single stroke while only 19% were multiple-stroke flashes. In Germany, Heidler and Hopf [6] found that 75% of the 44 positive ground flashes recorded contained only one positive return stroke while the remaining 25% were multiple-stroke flashes. With 103 positive ground flashes combined from Brazil, U.S. and Austria, Saba et al. [7] too found that most of the positive ground flashes were single stroke and only 19% were multiple-stroke. Fleenor et al. [8] also found that majority of the 204 positive flashes recorded in the U.S. Central Great Plains were single stroke and only 4% produced multiple strokes. Baharudin et al. [9] reported a rather high percentage of multiple-stroke positive ground flashes in Sweden with 37% from the 107 flashes recorded. Lyons et al. [10] reported that out of the 2.7 million positive flashes recorded by the NLDN (U.S. National Lightning Detection Network) data for 14 selected summer months, 1002 were composed of more than 10 strokes. However, according to Rakov and Uman [4], it is likely that at least some of these multiple-stroke events were misidentified cloud discharges. Findings by Sonnadara et al. [11] supported Rakov and Uman [4] views since the results showed that lightning location system has the tendency to identify isolated cloud pulses as positive return strokes causing a substantially higher number of positive return strokes to be reported.

1.2.2. Criteria to determine subsequent return strokes from the same flash

Previous researchers have used certain criteria to determine whether a subsequent return stroke (for both positive and negative flashes) belongs to the same flash [8,12–15]. Rakov and Uman [12] considered a sequence of strokes came from a single flash if each stroke occurred within 500 ms of the previous one. Thottappillil et al. [13] also used the same criteria as [12] to identify subsequent strokes that belong to a flash. According to Cummins et al. [14], the NLDN groups additional strokes into a flash if they are within 10 km of the first stroke and the time interval from previous stroke is less than 500 ms. Fleenor et al. [8] used the NLDN method to group their video images of the return strokes into a flash. For some researchers, they have defined a flash as the group of all ground strokes that strike within 10 km of each other within a 1 s interval [15]. Saba et al. [7], however, suggested that the method used to group strokes that are co-located in space and time should be reconsidered for positive flashes to ground, since their results showed that positive strokes have very low interdependence on each other. Their findings led them to conclude that the criteria normally used in lightning location systems to group negative strokes into flashes may not be valid for positive ground flashes.

1.2.3. Ground termination strike points of subsequent return strokes

Another important observation that have been made by previous researchers was the termination point made by the subsequent return strokes. Subsequent stroke can follow either the previously formed channel of the return stroke or create a new termination on ground. Different approaches have been used to determine the termination points made by the subsequent strokes [5,7,8,16]. Saba et al. [7] and Fleenor et al. [8] used high-speed video recordings, Ishii et al. [16] used wideband electric field records and time-of-arrival method, while Nag and Rakov [5] inferred the ground termination based on NLDN locations and detailed examination of electric field waveform features. Saba et al. [7] found that all except one subsequent stroke of the 20 multiple-stroke positive flashes created new ground terminations. Fleenor et al. [8] found four of the nine positive subsequent strokes produced new ground contact while the remaining five remained in pre-existing channel. Ishii et al. [16] found that all 17 return strokes in multiple-stroke positive flashes had different terminations. Nag and Rakov [5] inferred that three of the eight strokes followed the pre-existing channel of the first stroke while five strokes created new terminations on ground.

1.3. Significance of study

Besides flash multiplicity and subsequent strokes ground termination, several researchers have also reported the interstroke intervals in positive ground flashes [5–9,16–18] and the peak amplitude of the subsequent stroke relative to the first stroke peak [9]. However, characteristics of the subsequent strokes in positive ground flashes such as risetime and zero crossing time are still lacking. Since not much knowledge is available in the literature concerning subsequent strokes in positive ground flashes, the study would be important as the information would be useful for many engineering applications.

1.4. Objectives

This paper presents the characteristics of the electric fields produced by the first and the subsequent return strokes observed in positive ground flashes during 2014 summer thunderstorms in Uppsala, Sweden (59.837°N, 17.646°E). Based on the electric field measurements, we obtained the average number of strokes per flash, the interstroke intervals between successive strokes, the slow front and fast transition parameters, the zero crossing time, the zero-to-peak risetime and the 10-to-90% risetime. We also determined the distance between the first and the subsequent strokes based on lightning location system data. Comparative studies were made between the first and the subsequent strokes parameters, and results for the subsequent return strokes were compared with findings from a previous study.

2. Methodology

2.1. Measurement setup

Electric fields generated by the cloud-to-ground lightning flashes were measured at a station in Uppsala, Sweden (59.837°N, 17.646°E) during 2014 summer season. The measurement setup consisted of a parallel plate and a vertical whip antennas (complete with buffer electronic circuits), a DL850 Yokogawa transient recorder and a Meinberg M400 GPS antenna system. The decay time constants of the buffer circuits were 15 ms and 1 s for the fast field and slow field, respectively. The sampling rate for the measurement was 100 Msample/s with 10 ns interval and the transient recorder was set to work in a pre-trigger mode at 20% of the 1 s recording length. Detailed description on the antenna systems, the buffer electronic circuits and the measuring system calibration can be found in [19]. Further readings can also be found in [20–22] since the measurement setups used were identical. The electric field records were GPS time-stamped with 1 μs accuracy. In order to obtain the locations of the ground flashes, data from the Swedish