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Some characteristics of subsequent return strokes in positive ground flash in Sweden

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***Abstract*—This paper presents the characteristics of the first and subsequent strokes observed in positive ground flashes during 2014 summer thunderstorms in Uppsala, Sweden. We obtained the average number of strokes in the positive ground flashes and the relative amplitude of the subsequent stroke peak to the first stroke peak. We also determined the characteristics of the first and subsequent strokes, and compared the values between them. In our analysis, only 12% of the cases were multiple-stroke flashes while majority (88%) were single-stroke flashes. On average, the number of strokes per flash was 1.20 and the highest number of strokes per flash recorded was 4. The relative peak amplitude of the subsequent stroke to the first stroke peak was 0.83 with values ranging between 0.09 and 2.33. As for the stroke characteristics, we found that the average values for all parameters for the subsequent stroke were smaller than that of the first stroke. The average values for the slow front duration, fast transition 10-to-90% risetime, zero crossing time, zero-to-peak risetime and 10-to-90% risetime for the subsequent strokes were 4.9µs, 1.1µs, 14µs, 6.6µs and 3.8µs, respectively.**

Keywords-positive ground flash; subsequent return stroke; multiplicity; return stroke characteristics

I. Introduction

A. Positive Ground Flash

Positive ground flashes can be defined as ground flashes that transport positive charges from cloud to ground [1]. Though they are less dominant than their negative counterparts, positive ground flashes have attracted considerable attention since 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 ground are thought to be associated with positive lightning, with peak current values reaching up to 300kA and charges of more than hundreds of coulombs. This could potentially cause more damage to various objects and systems, making understanding their physical parameters an important issue particularly in the field of lightning protection.

B. Review on Previous Studies

According to [1], among the five observed properties that are thought to be associated with positive ground flashes are the single-stroke composition of the flash. In contrast, majority of the negative ground flashes contain two or more strokes [2]. Even though positive ground flashes are usually single stroke, multiple-stroke flashes do occur. However, they are relatively rare compared to negative ground flashes.

Among the researchers that have reported the average number of strokes in positive ground flashes were Nag and Rakov [3], 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 [4] found that 75% of 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. [5] too found that most of the positive ground flashes were single stroke and only 19% were multiple-stroke. Fleenor et al. [6] 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. In Sweden, Baharudin et al. [7] found that 37% of the 107 positive ground flashes recorded were multiple-stroke. In another study, Lyons et al. [8] reported that out of 2.7 million positive flashes recorded by the NLDN data for 14 selected summer months, 1002 were composed of more than 10 strokes. However, according to Rakov and Uman [1], it is likely that at least some of these multiple-stroke events were misidentified cloud discharges. Findings by [9] supported [1] views since the results showed that lightning locating system (LLS) has the tendency to identify isolated cloud pulses as positive return strokes causing a substantially higher number of positive return strokes to be reported.

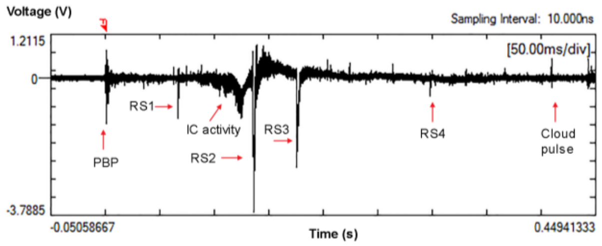

Figure 1. A four-stroke positive ground flash recorded in Sweden (Flash no.55 recorded on 7th August 2014 at 07:41:23378875)

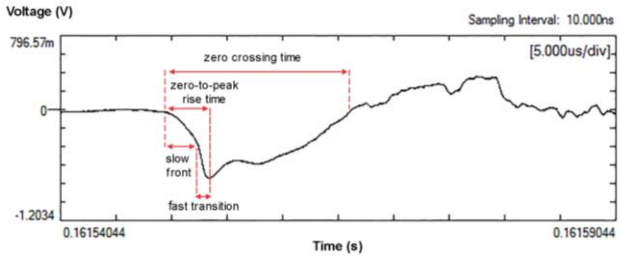

Figure 2. Definitions for the slow front duration, fast transition time, zero-to-peak rise time and zero crossing time

C. Objective

This paper presents the characteristics of the first and subsequent strokes observed in positive ground flashes during 2014 summer thunderstorms in Uppsala, Sweden (59.837°N, 17.646°E). Electric field changes based on electric field measurements were analyzed. We obtained the average number of strokes in the positive ground flashes and the relative amplitude of the subsequent return stroke peak to the first return stroke peak. We also determined the stroke characteristics such as the slow front duration, the fast transition 10-90% risetime, the slow front amplitude relative to peak, zero crossing time, zero-to-peak rise time and 10-90% risetime of the return stroke, and compared the values between them.

D. Sign Convention

The atmospheric electricity sign convention is used throughout the paper according to which a downward directed electric field is considered to be positive.

II. METHODOLOGY

Electric field measurements were conducted at a measuring 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, a DL850 Yokogawa transient recorder and a Meinberg M400 GPS antenna system. Detailed description on the antenna systems and the buffer electronic circuits can be found in [10]. Further readings can also be found in [11],[12],[13] since the antenna systems used were identical. The sampling rate for the measurement was 100Msample/sec with 10ns interval and the transient recorder was set to work in pre-trigger mode at 200ms with a recording length of 1s. The electric field records were GPS time-stamped with 1µs accuracy. To obtain the locations of the ground flashes, data from the Swedish lightning locating system (LLS) were used. Electric field records from the field measurements were correlated with data from the LLS with time of occurrence of the first return stroke as the matching criteria. The LLS data were also used to double-check the stroke polarity of the recorded waveforms

III. RESULTS AND DISCUSSION

Presented here are the analyses for 51 positive ground flashes containing 60 return strokes. Of the 60 return strokes, 52 were detected by the LLS at distances 6 to 150km from the measuring station while three strokes were estimated using time-to-thunder method (7 to 14km). The locations for the remaining five stokes could not be estimated since they were not detected by the LLS and no thunder was heard during the event.

A. Flash Multiplicity

Flash multiplicity is often used to represent the number of strokes in a single flash [1]. We considered return strokes that

TABLE I. DISTRIBUTION OF POSITIVE GROUND FLASHES WITH DIFFERENT NUMBER OF STROKES

Researcher	Location	Measurement Period	Sample Size, N	Occurrence of Flashes with Number of Strokes				Average Multiplicity
				Single Stroke	*Two Strokes*	*Three Strokes*	*Four Strokes*	
Present study	Uppsala, Sweden	Summer 2014	51	45 (88%)	4 (8%)	1 (2%)	1 (2%)	1.2
Baharudin et al. (2016)	Uppsala, Sweden	Summers of 2010 & 2011	107	67 (63%)	30 (28%)	7 (6%)	3 (3%)	1.5
Nag & Rakov (2012)	Florida, US	Apr-Oct & Nov-Feb, 2007-2008	52	42 (81%)	9 (17%)	1 (2%)	-	1.2
Saba et al.(2010)	Brazil, U.S. & Austria	Feb 2003-Sep 2009	103	83 (81%)	19 (18%)	1 (1%)	-	1.2
Fleenor et al. (2009)	U.S. Central Great Plains	July 2005	204	195 (96%)	9 (4%)	-	-	1.04
Heidler et al. (1998)	Munich, Germany	1995-1997	32	28 (87.5%)	4 (12.5%)	-	-	1.13
Heidler & Hopf (1998)	Munich, Germany	1984-1993	44	33 (75%)	8 (18%)	2 (5%)	1 (2%)	1.3

occurred within the 500ms duration of the previous stroke to belong to the same ground flash [14]. However, we did not have any means to determine the termination point for each subsequent stroke. Of the 51 positive ground flashes selected, 45 flashes composed of single-stroke (88%) while six were multiple-stroke (12%). From these six flashes, four flashes were two-stroke flashes, one flash had three-stroke and another flash had four strokes. On average, the number of strokes per flash was 1.20. The distribution of strokes per flash and comparison with previous studies are given in Table I. As can be seen, majority of the flashes composed of a single-stroke flash with mean multiplicity ranging between 1.04 and 1.5 across the locations. Among the studies compared, the occurrence of a four-stroke positive ground flash is very few with only 4 cases reported [4],[7]. For our case, the four-stroke positive flash waveform is shown in Figure 1.

There was a significance difference between the results obtained by Baharudin et al. [7] and our study, considering the measurements were conducted at the same geographical location and climate. Baharudin et al. [7] found 37% of the positive ground flashes were multiple-stroke while we only found 12%. Our value, however, was consistent with that found by Nag and Rakov [3] (19%), Saba et al. [5] (19%) and Heidler et al. [15] (12.5%). Percentage obtained by [7] was also the largest among the studies. Possible reasons for this could be due to the sample size used where [7] had twice the sample size obtained from two different summer periods while we only had data from one measurement campaign. Similar observation can also be seen between the results obtained by Heidler and Hopf [4] and Heidler et al. [15], who found multiple-stroke positive flashes were 25% and 12.5%, respectively. Both studies were also conducted at the same geographical location and climate but there was quite a large difference between the percentages of the multiple-stroke positive flashes obtained, which indicated that higher sample size from different measurement periods can affect the percentage.

B. Peak Amplitude of Subsequent Stroke relative to First Stroke Peak

The ratio between the subsequent stroke amplitude and the first stroke peak was also analyzed and the values are given in Table II. On average, the ratio of the subsequent stroke peak to the first return stroke peak was 0.83 with values ranging between 0.08 and 2.3. Our mean value was slightly higher than that observed by Baharudin et al. [7] who found the mean ratio to be 0.48, possibly due to the difference in sample size used.

TABLE II. RATIO OF SUBSEQUENT STROKE PEAK AMPLITUDE TO FIRST STROKE PEAK

Researcher	**Period**	**Sample Size, N**	**Ratio of subsequent stroke peak to first stroke peak**		
			Max	***Min***	***AM***
Present study	Summer 2014	9	2.3	0.08	0.83
Baharudin et al. (2016)	Summers of 2010 & 2011	53	3.7	0.05	0.48

AM = Arithmetic Mean

C. Return Stroke Characteristics

In order to analyze the characteristics of the subsequent stroke, we determined the slow front duration, the fast transition 10-90% risetime, the slow front amplitude relative to peak, zero crossing time, zero-to-peak rise time and 10-90% risetime of the return stroke. We then compared the values of the subsequent return strokes with the first return stroke. The statistics are given in Table III. Of the 60 return strokes, 51 were first strokes while nine were subsequent strokes.

The definitions for the parameters are given in Figure 2. According to [16], the initial rising part of a return stroke consists of a slow rising portion called the slow front and a relatively fast rise to the peak called the fast transition. The breakpoints between the slow front and fast transition is about 50% of the total peak in first return strokes and 20% in the subsequent strokes.

In our analysis, the average slow front duration for the first return strokes was found to be 9.2µs while the value for subsequent stroke was 4.9µs. For fast transition 10-90% risetime, the average value for the first return strokes was 1.7µs while the value for subsequent stroke was 1.1µs. The slow front amplitude relative to peak for the first return strokes was found to be 40% while the value for subsequent stroke was 37%. For zero crossing time, the average value for the first return strokes was 32µs while the value for subsequent stroke was 14µs. The average zero-to-peak rise time for the first return stroke was 12µs while for the subsequent stroke, the value was found to be 6.6µs. For 10-90% risetime, the average value for the first return strokes was 6.3µs while the value for subsequent stroke was 3.8µs. It can be seen that in comparison, the average values for the subsequent return stroke were smaller than the first return stroke for all parameters.

TABLE III. COMPARISON ON RETURN STROKE CHARACTERISTICS BETWEEN FIRST AND SUBSEQUENT STROKES

Parameters	**First Return Stroke**					**Subsequent Return Strokes**				
	Sample size, N	***Max***	***Min***	***AM***	***GM***	***Sample size, N***	***Max***	***Min***	***AM***	***GM***
Slow front duration (µs)	51	18	4.1	9.2	8.7	*9*	7.9	0.65	4.9	4.0
Fast transition 10-to-90% risetime (µs)	51	5.1	0.27	1.7	1.4	*9*	2.2	0.37	1.1	0.91
Slow front amplitude relative to peak (%)	51	75	8.1	40	35	*9*	61	11	37	33
Zero crossing time (µs)	31	100	12	32	29	*5*	27	2.7	14	11
Zero-to-peak rise time (µs)	51	23	5.7	12	11	*9*	9.6	1.4	6.6	5.8
10-to-90% risetime *(µs)*	51	13	2.4	6.3	5.7	*9*	5.4	0.85	3.8	3.2

AM = Arithmetic Mean, GM = Geometric Mean

IV. Conclusion

From the 51 positive ground flashes selected for the analysis, only 12% of the cases were multiple-stroke flashes while majority (88%) were single-stroke flash. On average, the mean number of strokes per flash was 1.20 and the highest number of strokes per flash recorded was 4. It was not possible to determine whether the subsequent stroke follow the previously formed channel of the return stroke or create a new termination on ground since we did not have any video recordings.

The ratio between the subsequent return stroke peak amplitude and the first return stroke peak was 0.83 with values ranging between 0.08 and 2.3. This is slightly higher than that observed by [7] who found the mean ratio to be 0.48.

In comparison, the average values for the subsequent return strokes were smaller than the first return strokes for all parameters. The average slow front duration for the first and subsequent return strokes were 9.2µs and 4.9µs respectively. For fast transition 10-90% risetime, the average value for the first and subsequent return strokes were 1.7µs and 1.1µs respectively. The slow front amplitude relative to peak for the first and subsequent return strokes were 40% and 37% respectively. For zero crossing time, the average value for the first and subsequent return strokes were 32µs and 14µs respectively. The average zero-to-peak rise time for the first and subsequent return strokes were 12µs and 6.6µs respectively. For 10-90% risetime, the average value for the first and subsequent return strokes were 6.3µs and 3.8µs respectively.

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