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Characteristics of leader pulses in positive ground flashes in Sweden

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ABSTRACT

This paper presents the characteristics of the electric field pulses observed during leader propagation in positive ground flashes. We analysed in detail the electric field changes occurring just before the first return stroke in 51 positive ground flashes during 2014 summer thunderstorms in Uppsala, Sweden. Pronounced leader pulses (having the same polarity as the return stroke) were observed in 22% of the cases. They were observed to occur within 1.4 ms before the first return stroke. Interpulse duration ranged from 13.3 to 50.3 μs with a mean value of 24.7 μs. The peak amplitude of the leader pulses relative to the return stroke peak ranged from 2.7 to 17.8%. The presence of these pulses shows that the leaders propagate in a stepped manner. Based on the leader pulses' time of initiation and average speed of the leader, the distance travelled by the leader was also estimated. One case of positive ground flash preceded by opposite polarity leader pulses just before the return stroke is also reported. To the best of our knowledge, this is the first time that such a case in positive ground flashes is reported. We suggest that these opposite polarity leader pulses are due to the negatively-charged leader branch of a bi-directional leader inside the cloud that propagates towards observation point.

1. Introduction

1.1. Positive ground flash

Cloud-to-ground lightning can be defined as a transient, high-current discharge that transports charges from thunderclouds to the ground. The overall discharge, termed a flash, is composed of a number of processes such as preliminary breakdown, stepped leaders, connecting leaders, return strokes, dart leaders and subsequent return strokes [1]. Depending on the charges being transported to ground, a ground flash can be categorized into positive and negative. Positive ground flash is therefore a ground flash that brings positive charges down to earth. Of the two, positive ground flashes are less dominant and account for about 10% of global cloud-to-ground lightning [2].

According to [2], among the five observed properties that are thought to be associated with positive ground flashes is the propagation of the leaders that appears to move either continuously or in a stepped manner. In contrast, negative leaders always propagate in a stepped manner when they travel towards the ground. This means that during negative leader formation, the leader steps appear bright while the leader channel remains dark in between steps formation [1]. Positive leaders, on the other hand, exhibit a continuously luminous channel image either without such steps or with superimposed steps in the forms of luminosity enhancements [2].

1.2. Review on previous studies

As part of the process in cloud-to-ground lightning flashes (CG), many studies have been conducted to characterize the leader process in both positive (e.g. [3–7]) and negative ground flashes (e.g. [8–11]). Plenty of information have been discovered for negative leaders [1] but the same cannot be said about positive leaders. Characteristics of leaders in positive ground flashes are still not well understood [7] and very little is known about the downward positive leaders in positive ground flashes compared to leaders in

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negative ground flashes [12]. Based on the information found in the literature, past observations made on leader process in positive ground flashes, particularly on the stepping behaviour of the pulses, can be briefly summarized as follows:

1.2.1. Electric field measurements

Using electric field measurements, several researchers have observed the pulses preceding the first return stroke in their electric field waveforms (essentially radiation). Cooray and Lundquist [13], for example, observed that some positive waveforms were preceded by small amplitudes pulses which they attributed to the leader process. Hojo et al. [14] observed that 26–30% of the waveforms had discernable pulses preceding the positive return stroke. Schumann et al. [5] reported a rather large percentage where they observed leader pulses in 74% of the cases. Nag and Rakov [15] reported that 27% of the first return stroke waveforms were preceded by pronounced step pulses.

According to Cooray and Lundquist [13], their electric field observations indicated that in some cases, positive leader behaves in a stepped manner during the last few hundred microseconds of its journey towards the earth. On the other hand, they said that the pulses they observed could also be due to the negative connecting leader that may develop upward from the ground under the influence of the downward positive leader. Based on their results and observations by Berger [16] and Les Renardières Group [17], Hojo et al. [14] inferred that most positive return strokes are preceded by leaders that propagate downwards either continuously or in a stepped manner. Berger [16] had previously obtained a streak-camera image of a positive leader propagating continuously downward. The observations showed that positively charged leaders display a very weak luminosity and less clear, or no stepping as compared to negative leaders that exhibit a very distinct and bright stepping. In contrast, Les Renardières Group [17] observed that a positive leader in a long laboratory spark exhibits stepping depending on the humidity, with higher humidity conducive for stepping. As for Schumann et al. [5], they said that it is difficult to say whether the pulses are due to downward leader or not since both downward positive leader and upward connecting negative leader would produce the same polarity pulses in the waveforms. Nag and Rakov [15] stated that the reason for the occurrence of the field pulses indicative of stepping prior to the return stroke pulse in some positive cloud-to-ground discharges is not known. According to them, the pulses could be associated with a descending positive leader, an upward connecting negative leader, which may be launched in response to the non-stepped positive downward leader, or both.

1.2.2. High-speed video recordings

From high-speed video recordings, previous studies showed that downward-moving positive leaders could produce step-like pulses. Wang and Takagi [4] recorded a downward positive leader that radiated optical pulses like a negative stepped leader over the height from 299 m to 21 m above the ground but with a much larger rise time. Kong et al. [6] observed a downward-moving positive leader whose optical images showed a stepped-like development characteristics with a high intensity in the leader tip, and the pulses in the fast electric field 0.5 ms prior to the return stroke also suggested a stepped-like development. Saba et al. [7], however, did not observe any discrete steps that might indicate stepping. Instead, they observed that all downward positive leaders showed continuous progression towards the ground. An interesting finding from a recent study by Saba et al. [3] also showed that the pulses observed just before the return stroke were solely due to the upward connecting leader. Based on this, they suggested that if positive leaders step, their steps do not produce any significant electromagnetic radiation and are much weaker than those produced by the stepping of the connecting negative leader.

1.3. Objectives

This paper presents the characteristics of the leader pulses occurring just before the first return stroke in positive ground flashes during 2014 summer thunderstorms in Uppsala, Sweden (59.837°N, 17.646°E). The study is motivated by the fact that lightning processes in positive ground flashes are less well investigated than those in negative ground flashes [12]. Since there is still much discussion about the characteristics of positive leaders in positive ground flashes, the findings would add to existing knowledge. We present a comprehensive study of the leader pulses based on electric field measurements. We determined: (1) the percentage of detection of pronounced leader pulses, (2) the time of initiation of pronounced leader pulses before the first return stroke, (3) the peak amplitude of pronounced leader pulses relative to the return stroke peak and (4) the interpulse duration between successive pulses just before the first return stroke. One case of positive ground flashes preceded by opposite polarity leader pulses just before the return stroke is also reported.

1.4. Sign convention

The atmospheric sign convention is used throughout the paper according to which a downward directed electric field is considered to be positive. According to this notation, a negative charge in a cloud produces a negative field at ground level and a negative return stroke will produce a positive field change [18]. A positive charge in a cloud will then produce a positive field at ground level and a positive return stroke will produce a negative field change.

2. Methodology

2.1. Measurement setup

Electric field measurements were carried out in Uppsala, Sweden (59.837°N, 17.646°E) from June to August 2014 during summer season. The measurements were conducted using broadband antenna system (up to 100 MHz) consisting of a parallel plate antenna and a vertical whip antenna, a 12-bit Yokogawa transient recorder and a Meinberg M400 GPS system. The parallel plate antenna was used to detect the fast variation of the electric field (i.e. fast field) while the vertical whip antenna was used to detect the slow variation (i.e. slow field). Each antenna has a buffer amplifier circuit with decay time constants of 15 ms for fast field and 1 s for slow field. The sampling rate for the measurement system was 100 Msample/s with 10 ns interval and the measurements were conducted for a record length of 1 s with 200 ms pre-trigger time. The transient recorder was triggered automatically based on the voltage amplitude of the incoming signal from the parallel plate antenna and the trigger level was set above noise level at 50 mV. Detailed description on the antenna system and the buffer electronic circuits can be found in [19]. Further readings can also be found in [20–23] since the measurement setups used were identical.

2.2. Swedish Lightning Location System

Information obtained from the Swedish Lightning Location System (LLS) were used to estimate the location and peak currents of the positive return strokes. The overall lightning flash detection efficiency of the Swedish LLS is about 85% and varies from point to point within Sweden [24]. Around the measuring site, the flash detection efficiency of the LLS is approximately 90% [25]. The