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# Features of the Electric Fields Generated by Lightning with Special Attention to Positive Ground Flashes

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### **Abstract**

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This thesis focuses on the main processes in positive ground flashes and the distant lightning environment for both positive and negative ground flashes. It presents the characteristics of the preliminary breakdown pulses (PBPs), the characteristics of the electric field pulses observed during leader propagation, and the characteristics of the electric fields produced by the first and the subsequent return strokes. It also features the observations of distant positive and negative ground flashes at distances up to 1000 km. The results were based on electric field measurements conducted remotely during summer thunderstorms in Sweden in 2014.

We found that the majority of the positive ground flashes were preceded by PBPs. Some were preceded by more than one PBP train, and the parameter values for the subsequent PBP trains were found to be smaller than the values for the first PBP train. Three types of PBPs were also identified. The results suggest that the PBPs in positive ground flashes during summer thunderstorms in Sweden are weak, and the inverted dipole charge cloud configuration is consistent with our observation.

A small percentage of these positive ground flashes were observed to be preceded by pronounced leader pulses. The presence of these pulses suggests that the leaders propagate in a stepped manner. We inferred that these pulses were due to the upward-connecting negative leader since their characteristics were similar to those of a negative stepped leader. On the basis of the leader pulses' time of initiation and the average speed of the leader, we estimated the distance travelled by the leader. One case of positive return stroke preceded by negative leader pulses was also observed, and the occurrence of these pulses was the first in positive ground flashes to be reported.

The majority of these positive ground flashes were found to be single-stroke. Comparison between the first and the subsequent return strokes showed that the average durations of the subsequent stroke parameters were smaller than that of the first strokes. The distances reported by the lightning location system suggest that the subsequent strokes probably created new terminations to ground. Two possible reasons were given to explain the reason for the shorter duration of the subsequent return strokes parameters compared to the first strokes.

Finally, observations of distant positive and negative ground flashes showed that the electric field waveforms have a typical shape, like a distorted 'W' (or distorted 'M' for negative ground flashes) followed by small oscillations. These small oscillations were more pronounced in negative ground flashes, especially at a greater distance. The heights of the ionospheric reflections estimated for both ground flashes were found to likely correspond to a D-layer of the ionosphere. Two possible reasons were suggested for the small oscillations observed in the waveforms.

*Keywords:* positive ground flashes, preliminary breakdown pulses, multiple-trains PBPs, positive leader, bidirectional leader, negative leader branch, subsequent return strokes, distant lightning

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*To Family*



# List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

- I **Johari, D.**, Cooray, V., Rahman, M., Hettiarachchi, P., and Ismail, M. M. (2016) Characteristics of preliminary breakdown pulses in positive ground flashes during summer thunderstorms in Sweden. *Atmosphere (Basel)*, 7(3), 39.

Part of this work was presented at the 4<sup>th</sup> International Symposium on Winter Lightning (ISWL) in Joetsu, Japan, 2017.

- II **Johari, D.**, Cooray, V., Rahman, M., Hettiarachchi, P. and Ismail, M. M. (2017) Characteristics of leader pulses in positive ground flashes in Sweden. *Electric Power Systems Research*, 153:3-9.

Part of this work was presented at the XIII International Symposium on Lightning Protection (SIPDA) in Balneário Camboriú, Brazil, 2015.

- III **Johari, D.**, Cooray, V., Rahman, M., Hettiarachchi, P. and Ismail, M. M. (2017) Features of the first and the subsequent return strokes in positive ground flashes based on electric field measurements. *Electric Power Systems Research*, 150: 55-62.

Part of this work was presented at the 33<sup>rd</sup> International Conference on Lightning Protection (ICLP) in Estoril, Portugal, 2016.

- IV **Johari, D.** and Cooray, V. (2017) Oscillations observed in bipolar electric field from distant cloud-to-ground lightning flashes. *Manuscript*.

Other contributions of the author, not included in this thesis:

- V **Johari, D.**, Cooray, V., Hettiarachchi, P., Rahman, M. and Ismail, M. M., Some characteristics of leader pulses in positive

cloud-to-ground flashes. *Proceedings of the XIII International Symposium on Lightning Protection (SIPDA)*, Balneário Camboriú, Brazil, 2015.

- VI **Johari, D.**, Cooray, V., Rahman, M., Hettiarachchi, P. and Ismail, M. M., Some characteristics of subsequent return strokes in positive ground flash in Sweden. *Proceedings of the 33<sup>rd</sup> International Conference on Lightning Protection (ICLP)*, Estoril, Portugal, 2016.
- VII **Johari, D.**, Cooray, V., Rahman, M., Hettiarachch, P. and Ismail, M. M., Some features of preliminary breakdown pulses in positive ground flashes in Sweden. *Proceedings of the 4<sup>th</sup> International Symposium on Winter Lightning (ISWL)*, Joetsu, Japan, 2017.
- VIII Ismail, M.M., Rahman, M., Cooray, V., Sharma, S. R., Hettiarachchi, P. and **Johari, D.** (2015) Electric field signatures in wide-band, 3 MHz and 30 MHz of negative ground flashes pertinent to Swedish thunderstorms. *Atmosphere*, 6(12): 1904-1925.
- IX Ismail, M.M., Cooray, V. and **Johari, D.** (2017) On the zero-crossing time of radiation fields generated by return strokes in lightning flashes. Submitted to *Atmosphere*.
- X Ismail, M.M., Rahman, M., Cooray, V., Fernando, M., Hettiarachchi, P. and **Johari, D.** (2017) On the possible origin of chaotic pulse trains in lightning flashes. *Atmosphere*, 8(2), 29.
- XI Ismail, M.M., Sharma, S.R., Cooray, V., Rahman, M., Hettiarachchi, P. and **Johari, D.**, HF and VHF electric field radiation produced by preliminary breakdown process pertinent to Swedish thunderstorms, *Proceedings of the 9<sup>th</sup> Asia-Pacific International Conference on Lightning (APL)*, Nagoya, Japan, 2015.
- XII Ismail, M.M., Cooray, V., Rahman, M., Fernando, M., Hettiarachchi, P. and **Johari, D.**, On the possible origin of chaotic pulse train in lightning flashes, *Proceedings of the XIII International Symposium on Lightning Protection (SIPDA)*, Balneário Camboriú, Brazil, 2015.
- XIII Ismail, M.M., Cooray, V., Rahman, M., Hettiarachchi, P. and **Johari, D.**, On comparison between initial breakdown pulses and

narrow bipolar pulses in lightning discharges with special attention to electric field derivative characteristics, *Proceedings of the 33<sup>rd</sup> International Conference on Lightning Protection (ICLP)*, Estoril, Portugal, 2016.

- XIV Ismail, M.M., Cooray, V., Rahman, M., Hettiarachchi, P. and **Jo-hari, D.**, Wavelet transform reveals the origin of chaotic pulse train in lightning flashes, *Proceedings of the 4<sup>th</sup> International Symposium on Winter Lightning (ISWL)*, Joetsu, Japan, 2017.
- XV Ismail, M.M., Rahman, M., Cooray, V., Hettiarachchi, P. and **Jo-hari, D.**, Characteristics of chaotic pulse trains associated with dart and dart-stepped leader in lightning flashes in Sweden, *Proceedings of the 4<sup>th</sup> International Symposium on Winter Lightning (ISWL)*, Joetsu, Japan, 2017.

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# Abbreviations

AM	Arithmetic Mean
GM	Geometric Mean
GPS	Global Positioning System
GW	Ground Wave
IC	Intra Cloud
kHz	kilo Hertz
LLS	Lightning Location System
MeV	Mega electron Volt
MHz	Mega Hertz
MS/s	Mega Sample per Second
MSC	Mesoscale Convective System
N	Sample size
PB	Preliminary Breakdown
PBP	Preliminary Breakdown Pulse
RLC	Resistor (R), Inductor (L) and Capacitor (C)
RS	Return Stroke
SMHI	Swedish Meteorological and Hydrological Institute
SRS	Subsequent Return Stroke

*Nomenclature:* The term ‘flash’, ‘discharge’ and ‘lightning’ are used interchangeably in this thesis to describe either cloud lightning or cloud-to-ground lightning.



# 1. Introduction

## 1.1. Lightning

Lightning is an electrical discharge that occurs in the Earth's atmosphere. At any moment, there are about 100 discharges per second worldwide [1]. Lightning is commonly associated with thunderclouds but it can also occur in snowstorms and sandstorms and around plumes of erupting volcanoes [2]. During a thunderstorm, as the thunderclouds become charged, large voltages can develop between the cloud and the ground or between different parts of the cloud. As the electric field associated with these voltage differences exceeds the critical value necessary for breakdown, electrical discharges take place in the air, leading to a lightning flash. Air is a good insulator in general, but at this critical electric field (i.e.  $1.5 \times 10^6$  V/m at 5 km above sea level or  $3.0 \times 10^6$  V/m at sea level [3]), it is converted into a conductor by the cumulative action of avalanches, streamers and leaders, making it capable of conducting electrical currents [4]. The rapid heating of the air to 25,000 to 30,000 K during a lightning flash causes a rapid increase in the atmospheric pressure, leading to a rapid expansion of the air, creating a shock wave before it transforms into a sound wave known as thunder [5].

Despite being the most observed natural phenomenon in the world, lightning is still not well understood. Many questions about lightning remain unanswered in spite of recent progress in the area. For example, the most basic question of how lightning is initiated inside the thunderclouds is still being researched, and the physical mechanisms that govern the propagation of different types of lightning leaders (e.g. negative stepped, first positive) between the cloud and the ground are still not known [6]. In addition, knowledge of the physics of positive lightning remains poorer than that of negative lightning [7]. These gaps in the knowledge, together with the dangerous threat that lightning poses, serve as guides and motivation for lightning researchers around the world to continue studying this phenomenon.

## 1.2. Main objectives

The electromagnetic fields generated by the lightning flashes are of importance in lightning studies [8]. Features of the electromagnetic fields (e.g. the temporal and spatial variation) can be used to understand the physical

mechanism behind the lightning processes while in lightning protection studies, the electromagnetic fields can be used to estimate the voltages and currents induced in structures due to lightning strikes.

The main objectives of the thesis are based on the electric fields generated by the lightning flashes. They are as follows:

**i) To characterize the preliminary breakdown pulses of the positive ground flash**

The physical mechanism that initiates lightning in the thundercloud is still not well understood. For positive ground flashes, many suggestions have been presented (e.g. [9–15]) but agreement on the initiating mechanisms has not been reached [14]. In addition, information about preliminary breakdown pulses (PBPs) in positive ground flashes is still insufficient compared to information about those in negative ground flashes [16]. Some of these studies did not include statistics on how many positive ground flashes begin with the initial breakdown pulses (e.g. [9],[10]). The study of the preliminary breakdown process before positive return strokes is therefore important as it helps to resolve the understanding of the in-cloud process that initiates positive ground flashes. The findings from this study would also add to existing statistics of PBP characteristics in positive ground flashes and help to improve our overall understanding of positive ground flashes.

**ii) To characterize the leader pulses in positive ground flashes**

This study is motivated by the fact that very little is known about the downward positive leaders in positive ground flashes [17]. Although plenty of information about negative leaders has been discovered [18], positive leaders are much less studied [6]. Their characteristics are still not well understood [19], and their mode of propagation is still a topic of much interest. The study is therefore essential as the outcome would help to improve our understanding of positive leaders and add to the existing knowledge on positive ground flashes.

**iii) To determine the features of the subsequent return strokes in positive ground flashes**

Not much knowledge is available in the literature concerning the subsequent return strokes in positive ground flashes. Information about their characteristics, such as the risetime and the zero crossing time, is still lacking, mainly due to the lack of the occurrence of multiple-stroke positive ground flashes. The study is therefore important as it helps to characterize positive subsequent return strokes and provide information for many engineering applications.

**iv) To determine the source of oscillations observed in bipolar electric field from distant cloud-to-ground lightning flashes**

This study involved both the positive and negative ground flashes. It was conducted to understand the reason for the appearance of oscillating field change in distant lightning. Compared to close lightning, characteristics of lightning-produced electric fields for distant lightning are influenced by the propagation path of the fields. The possibility that the small oscillations observed in the waveforms come from the low-frequency component of the return stroke current that oscillates in the lightning channel was investigated. The analysis would be useful to understand the physics behind distant lightning and the interaction of the lightning electromagnetic fields with the ionosphere.

## 2. Background and theory

This chapter gives an overview of the important aspects of positive ground flashes and distant lightning related to the study.

### 2.1. General description

#### 2.1.1. Definition and types of lightning

Lightning can be defined as a transient, high-current electrical discharge of atmospheric origin, whose path length is measured in kilometres [2]. They can be categorized into ground flashes and cloud flashes [20]. Ground flashes make contact with the ground while cloud flashes do not. Depending on the charges being transported to the ground and its point of initiation, a ground flash can further be subdivided into downward and upward ground flashes [20]. Downward ground flash is initiated from the cloud, while upward ground flash is initiated from a tall structure under the influence of the background electric field of the cloud. The polarity of the charges being transported from the cloud to the ground will determine the polarity of the flash, and the point of initiation will determine the direction of the flash. Cloud flashes, on the other hand, occur within a thundercloud, between the thunderclouds and between a thundercloud and clear air. They account for the majority of all lightning discharges [6],[21]. The term *IC* (intracloud flash) is often used to refer to all cloud flashes [22].

#### 2.1.2. Thundercloud configurations

A typical thundercloud consists of three charged regions [21]. The main positive charge centre is located at the top while the main negative charge centre is located in the middle in a region of  $-15$  to  $-10$  °C isotherm. A smaller positive charge pocket is located below the main negative charge centre. This tripolar structure usually supports the occurrence of intracloud discharges, negative ground flashes and air discharges [23] but not favourable for positive ground flashes [15]. The cloud charge configurations that are found to be more conducive for positive ground flashes are the tilted dipole, the positive monopole, the inverted dipole and the unusually large lower positive charge region [15].

In a tilted dipole, the upper positive charge region is displaced horizontally from the negative charge region by wind shear. The positive monopolar charge structure is found during the dissipating stage of Japanese winter thunderclouds, when the negative charge and positive charge carried by the graupel particles fall out of the cloud relatively quickly, leaving behind the positive charge carried by the ice crystals at the main positive charge centre. The inverted dipole has charge centres with polarity opposite to that found in typical positive dipole thunderclouds, while the unusually large lower positive charge region has a larger-than-usual lower positive charge region.

Two scenarios have also been found to be conducive for positive ground flashes. They are the negative in-cloud leader channel cut-off and the branching of the in-cloud discharge channel [15]. The negative in-cloud leader channel cut-off scenario is found in mesoscale convective systems (MSCs). Negative leaders in IC discharges in MSCs move horizontally for several kilometres, and when a negative leader gets cut off, the rear end of the leader channel gets positively charged (i.e. recoil leader is formed) and a positive leader is launched from this rear end of the leader channel, resulting in positive ground flash. Positive ground discharges can also be produced by the branching of the in-cloud discharge channels, most probably when these channels occur near or below the cloud base.

### 2.1.3. Mechanism of lightning flash

#### i) Lightning initiation

Two mechanisms can explain the initiation of lightning in the thunderclouds [18],[24]. One is the classical mechanism, which assumed that the electrical field required to initiate the discharge is caused by the collisions of several charged particles, which increases the electric field briefly to cause the breakdown. The other mechanism is the electron runaway breakdown, which proposed that the initiation of lightning is due to the acceleration of cosmic-ray-generated high energetic electrons in the thunderstorm's electric fields to produce an avalanche of MeV electrons.

In the classical mechanism, the initiation of a lightning flash starts with an electrical breakdown in a small region. It requires the electric field in the air to increase beyond the critical electric field ( $1.5 \times 10^6$  V/m at 5 km above sea level). During a thunderstorm, large electric fields are generated within the thundercloud because of the separation of charges in the thundercloud. This electric field is enhanced by the roughly spherical shape of the cloud droplets. During collisions, this field enhancement is increased because several charged particles can act as a single object with an elongated shape [24]. When the electric field exceeds the critical electric field necessary for breakdown, electrical breakdown will be initiated in a small region (in the form of a spark).

This electrical discharge gives rise to streamer discharges, and when the electric field exceeds 250 kV/m over a region, these streamer discharges propagate and initiate a leader discharge. Once a leader is created, it starts to propagate when the background electric field is about 100 kV/m, leading to either a cloud or a ground flash [24].

### **ii) Bidirectional propagation of a leader**

The initiation of a leader in the cloud produces two leader branches. One branch is negatively charged while the other is positively charged. This leads to the leader propagating in two opposite directions. The bidirectional propagation of a leader can be explained as follows [24].

In general, the electrical breakdown in the thundercloud leads to the formation of a conducting channel. When the conducting channel is exposed to the electric field, opposite charges accumulate at the channel tips. The concentration of charges increases the electric field at the tips and gives rise to streamer discharges of opposite polarity from the two ends of the conducting channel. This adds length to the leader channel, and the leader channel grows in both directions [24]. The leader then propagates, and this mode of propagation is called a bidirectional propagation.

### **iii) Recoil leaders**

As the tip of the positive leader branch moves forward, the conductivity of the channel behind the tip may decrease and result in the cut-off of the current to the tip. As the positive leader branch continues to move forward, negative charges will accumulate at the cut-off point. When the electric field exceeds the critical value for breakdown, a negative leader is initiated at the tip and moves through the cut-off gap, reconnecting the conducting path. According to [24], this negative leader is known as the recoil leader. Even though the mechanism is not fully understood, recoil leaders have been observed during the propagation of some downward positive leaders to ground, in which they were seen to retrace the channel segments that were previously ionized by the positive leader (e.g. [19]).

According to Mazur et al. [25], however, even though the literature defines recoil leaders as negative leaders, recoil leaders should be defined as bipolar and bidirectional leaders. This is because their observations showed that a recoil leader develops from a small region along a path of the decayed channels of a previous positive leader and propagates initially as a bidirectional and bipolar leader along the now invisible path of that leader. According to them, they were able to observe the positively charged part of one particular recoil leader despite the fact that only the propagation of the negatively charged parts of leaders was highly visible in the majority of their records.

#### iv) Mechanism of negative ground flash

The overall lightning discharge is termed a *flash*, and it involves many physical processes. In general, a downward ground flash is composed of processes such as the preliminary breakdown, stepped leaders, connecting leaders, return strokes, dart leaders, subsequent return strokes, continuing currents and M-components [18].

The most common downward ground flash is the one that lowers negative charges from the thundercloud to the ground. It is called a *negative ground flash* and is initiated by an electrical breakdown event in the thundercloud called the *preliminary breakdown*. This breakdown event, which consists of multitudes of discharges, leads to the development of a leader that propagates in a stepped fashion towards the ground. As it propagates, the *stepped leader* creates branches. When it approaches the ground, the stepped leader induces opposite polarity charges on objects projecting above the earth surface. Since opposite charges attract, these charges attempt to join the downward-moving stepped leader by forming an upward-moving *connecting leader*. When one of the connecting leaders successfully meets the stepped leader, the charges stored in the thundercloud are released, and the flow of charges towards the ground generates large current in the channel, making the channel glow. A complete conducting path is formed, and a wave of ground potential called the *return stroke* travels towards the cloud.

The lightning flash may end after the first return current stops flowing, in which case the discharge is called a single-stroke flash. Subsequent return strokes are initiated if additional negative charges are available at the upper portion of the previous stroke channel [6]. When these additional charges are available, a continuously propagating leader known as a *dart leader* moves down the defunct return stroke channel, depositing negative charges along the channel from the negative charge centre to the ground [6].

The reason that the first return stroke current ceases to flow even though negative charges are still available at the upper portion of the previous stroke channel is probably because of the bidirectional nature of the stepped leader [24]. For negative ground flashes, the cloud-end of the bidirectional leader of the flash is positive, and as the positive leader branch continues to propagate, it will be subjected to current cut-off when the channel behind the leader tip decays. Current will stop flowing but the formation of the recoil leader may reconnect the conducting path, resulting in subsequent return strokes [24].

## 2.2. Downward positive ground flash

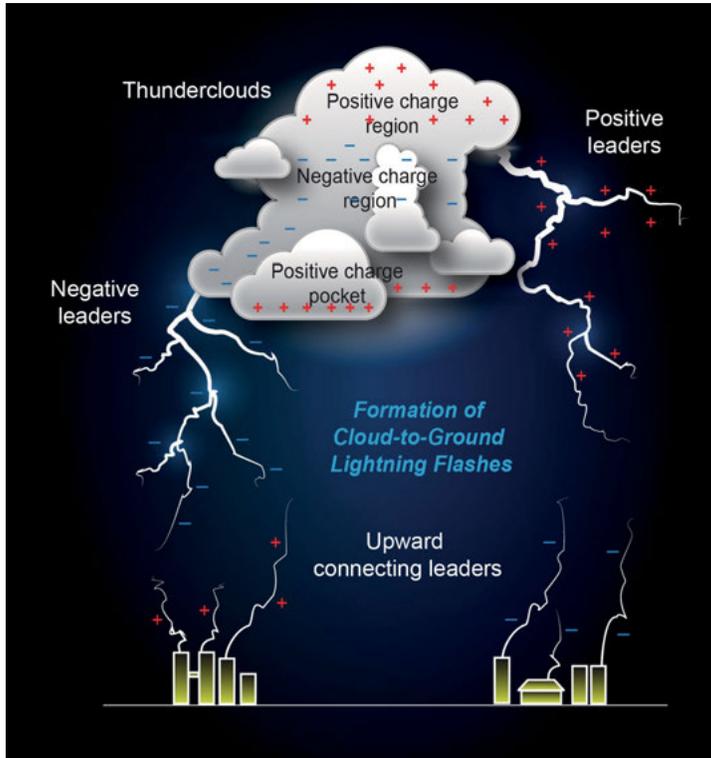
A downward positive ground flash is a ground flash that transports positive charges down to earth. Its mechanism is similar to the negative, but positive ground flashes are different in certain aspects [18]. For example, negative

ground flashes lower negative charges from the negative main charge centre while positive ground flashes lower positive charges either from the main upper positive charge region of the cloud or from the small lower positive charge region. *Figure 1* shows the formation of cloud-to-ground lightning flashes in typical tripolar thunderclouds configuration. Compared to downward negative ground flashes, downward positive ground flashes are less dominant and account for only about 10% of global cloud-to-ground lightning [26]. Even though they are less dominant than their negative counterparts, positive ground flashes have attracted attention for several reasons [26].

First, they can produce return strokes with higher peak currents and larger charge transfers, with peak current values reaching up to 300 kA and charges reaching hundreds of coulombs or more. This could potentially cause severe damage to various objects and systems. Second, positive lightning is also the dominant type of cloud-to-ground lightning in certain conditions such as during the cold season and the dissipating stage of any thunderstorm. Besides winter thunderstorms and the dissipating stage of a thunderstorm, other conditions that favour the occurrence of positive ground flashes are the shallow clouds, such as the trailing stratiform regions (i.e. the flat or sheet-like clouds region as opposed to the more vertically developed cumulonimbus cloud region) of an MSC (i.e. thunderstorm clusters); some severe storms; and thunderclouds formed over forest fires or contaminated by smoke. Third, positive lightning has been found to be related to luminous phenomena in the middle atmosphere known as sprites. Fourth, reliable identification of positive discharges by lightning location systems (LLSs) has important consequences for various studies since misidentification of positive return strokes as cloud discharges can cause a substantially higher number of positive return strokes to be reported [27].

### 2.2.1. Characterization of positive ground flash

Positive ground flashes have been characterized as having a single stroke in a flash, and the return stroke tends to be followed by a period of continuing currents. Multiple-stroke positive ground flashes, though they do occur, are not as common as multiple-stroke negative ground flashes. According to [24], 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; since negative leaders are not hindered by current cut-off, current continues to flow along the channel (and hence, the continuing current) until the charges in the positive charge centre are depleted. Positive ground flashes are also normally observed to be preceded by significant in-cloud discharge activity, often involve long horizontal channels up to tens of kilometres, and have leaders that appear to move either continuously or in a stepped fashion [6],[26].



*Figure 1.* Illustration showing formation of cloud-to-ground lightning flashes in typical tripolar thunderclouds configuration

### 2.2.2. Discrimination between positive return strokes and cloud flashes

Positive flashes can be separated from negative flashes based on the polarity of the electric field waveform. The differentiation is easy because positive and negative return strokes have polarity opposite to each other in the electric field waveforms. Comparison between positive flashes and cloud flashes, on the other hand, can be quite difficult because a positive return stroke and a cloud pulse can have the same polarity in the waveforms. On a smaller scale, however, the temporal behaviour and fine structure of the radiation fields from ground and cloud flashes are different [28], and positive flashes can be separated from cloud flashes based on detailed examination of the electric fields in the microsecond and millisecond time scale. The standard procedure to differentiate between positive ground flashes and cloud flashes can be found in existing literature (e.g. [18]).

### 2.3. Distant lightning

The electric fields produced by lightning vary depending upon the distance of the lightning channel from the measuring station. For relatively close electric fields, the characteristics are determined mainly by the characteristics of the currents in the lightning flash. At these ranges (less than a few hundred km), the fields propagate from the lightning source to the observation point either by means of a ground wave in the atmosphere along the finitely conducting Earth boundary or by line of sight directly through the atmosphere. On the other hand, characteristics of distant electric fields at distances ranging from a few hundreds to thousands of kilometres are influenced by the propagation path of the fields [29],[30].

In general, propagation effect is the attenuation of the electromagnetic wave due to the absorption of energy from the electromagnetic field by the finitely conducting ground [31]. The amount of energy absorbed by the ground will be higher if the frequency of the electromagnetic field is higher. For perfectly (i.e. infinitely) conducting ground, the amplitude of the electric field decreases inversely with distance. However, if the ground is finitely conducting, the amplitude of the field decreases much more rapidly than does the inverse distance. Since the rate of decrease of the wave is higher if the ground is finitely conducting, the effect will be much more pronounced for electric fields at greater distance. Hence, the electric fields from distant lightning are much more influenced by the propagation effect than lightning at closer distances.

One of the observed signals from distant lightning flashes are called atmospherics or sferics [30]. They propagate in a waveguide mode in the spherical Earth-ionosphere cavity by means of multiple reflections, and at a given range, consist of a ground wave and a sequence of sky waves. Typical frequency of sferics ranges between 3 kHz – 30 kHz and their waveforms show different characteristics during night and day time due to the different properties of the ionosphere during the two periods of time [30].

## 3. Methodology

This chapter provides an overview of the measurement setup and techniques used in the study. For further description regarding the antenna systems, buffer electronic circuits and system calibration, see Ref [32]. Refs [33,34] are also recommended for further reading because the measurement setups used in those studies were identical to those used in our study.

### 3.1. Measurement setup

The measurement setup consisted of a broadband antenna system, a DL850 Yokogawa transient recorder and a Meinberg M400 GPS antenna system. The block diagram for the setup is shown in *Figure 2*.

The broadband antenna system consisted of a parallel plate antenna and a vertical whip antenna, each with its corresponding buffer amplifier circuits. The parallel plate antenna was used to detect the fast variation of the vertical electric field (i.e. fast antenna), while the vertical whip antenna was used to detect the slow variation (i.e. slow antenna).

Each antenna was connected to a buffer amplifier circuit via a 60 cm RG58 coaxial cable. The buffer amplifier circuit was used to transfer the signal from the antenna to the transient recorder. The decay time constants for the buffer amplifier circuits were 15 ms for the fast antenna and 1 s for the slow antenna. The decay time constant of 15 ms for the fast antenna was large enough to record the transient signals generated by the lightning flashes [32] (i.e. well above the decay time of the measured signal), while the decay time constant of 1 s for the slow antenna was long enough to reproduce the slowly increasing electric field faithfully (i.e. the static component).

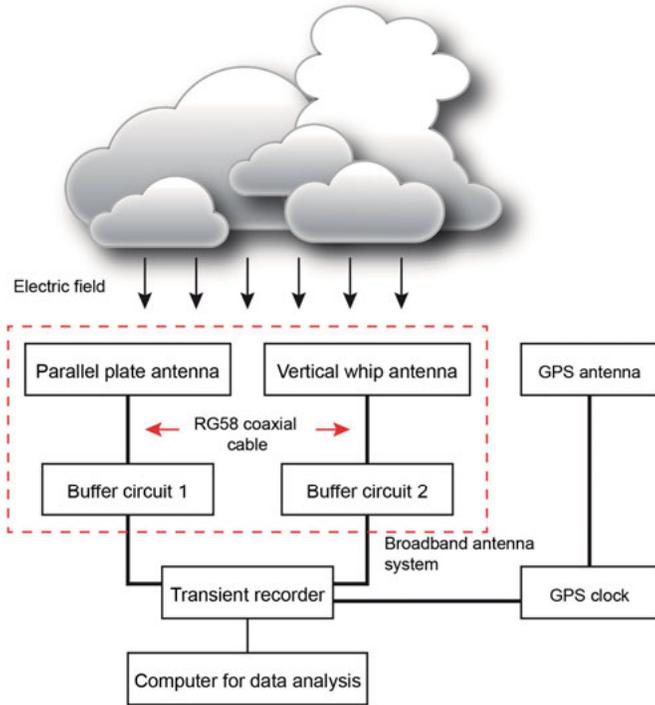


Figure 2. Block diagram for the measurement setup

The equivalent circuit of the buffer electronic circuit is given in Figure 3.

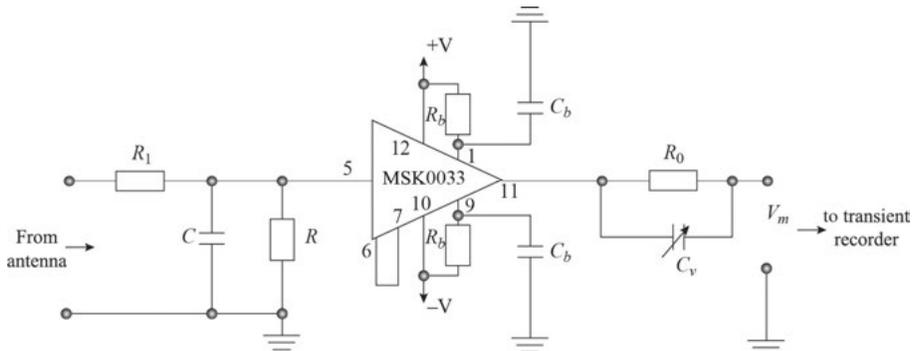


Figure 3. Equivalent circuit of the buffer electronic circuit (adapted from [35])

The electronic circuit consisted of an MSK 0033 buffer amplifier, capacitors and resistors. MSK 0033 is a high-speed, wide-bandwidth operational amplifier with a very high input impedance of  $10^{12} \Omega$  [36]. The purpose of using a buffer amplifier is to isolate the antenna system from the recording system (For this reason, a buffer amplifier is also known as isolation buffer). By doing so, we can control the decay time constants of the antenna system without

affecting the recording part of the system, and we can terminate the RG58 cable connected to the transient recorder with a 50 Ω resistor (to avoid reflection) without affecting the decay time constants of the antenna system. The buffer amplifier can also be used to provide amplification of the signal generated by the antenna but in our case, the amplification was set to unity.

The values of the components used are as follows:

$R_1 = 50 \Omega$ ,  $C = 15 \text{ pF}$  for the fast antenna,  $10 \text{ nF}$  for the slow antenna,  $R = 100 \text{ M}\Omega$ ,  $R_b = 100 \Omega$ ,  $C_b = 0.1 \text{ pF}$ ,  $R_0 = 43 \Omega$ ,  $C_v = 10 - 60 \text{ pF}$

The  $R_1$  value was selected to match the RG58 cable’s characteristic impedance of 50 Ω. The R and C values determine the cut-off frequency of the filter and the decay time constant of the whole system.  $R_b$  and  $C_b$  are components for the operational amplifier power-supply-bypassing to avoid power-supply-induced oscillation. The  $R_0$  and  $C_v$  are components for impedance matching with the cable connected to the transient recorder. Since the output impedance of the buffer is about 7 Ω (i.e. buffer is connected in series with  $R_0$ ), the  $R_0$  value was selected to be 43 Ω to match the 50 Ω cable’s characteristic impedance.

On the basis of the calibration work done previously by Galvan and Fernando [32], the relationship between the background electric field  $E_n$  and the measured voltage  $V_m$  for physical height of 1.5 m and corresponding effective height of 0.27 m for the parallel-plate antenna is given by:

$$E_n = 20.6V_m \dots\dots\dots(1)$$

Signals from the buffer amplifier circuits were fed into the transient recorder by using RG58 coaxial cables. Since RG58 has a 50 Ω characteristic impedance, each cable was terminated with a 50 Ω resistor to avoid reflections. To avoid any distortion to the electric field, the antennae were located far from the recording instrument. For this purpose, long coaxial cables of about 10 to 15 m were used.

The transient recorder was used to record the electric fields generated by the lightning flashes. It is a high-speed, high-resolution recorder, with a sampling rate of 100 MS/s at 10 ns interval and 12-bit resolution. The high-speed and high-resolution features of the transient recorder ensure that the fast features of the electric field waveforms can be recorded faithfully [18]. The GPS antenna system provided timing information for each of the recorded electric fields. The whole system had a bandwidth from a few Hz to about 100 MHz.

## 3.2. Measuring techniques

Measurements of the electric fields generated by the cloud-to-ground lightning flashes were carried out in Uppsala, Sweden (59.837°N, 17.646°E) from June to August of 2014 during the summer. They were conducted at a station close to the Ångström Laboratory, Division of Electricity, Uppsala University.

The recording length was set to 1 s to ensure that the whole activity pertinent to a lightning flash would be captured. The transient recorder was set to work in a pretrigger mode at 20% of the 1 s recording length. The transient recorder was triggered automatically based on the voltage amplitude of the incoming signal from the parallel plate antenna. The electric field records were GPS time-stamped with 1  $\mu$ s accuracy.

For close lightning measurement, the trigger level was set above noise level at a 50 mV minimum. During the measurement period, the trigger level was changed depending on how close the thunderstorm was, monitored through the Swedish Meteorological and Hydrological Institute (SMHI) website and observations at the site. When the thunderstorms were close to the station, a higher trigger level was set in an attempt to ensure close flashes would be recorded. For distant lightning measurements, the trigger level was set slightly above the noise level to capture very distant lightning.

The atmospheric sign convention was used, according to which a downward-directed electric field is considered to be positive. For details regarding the sample size and selection criteria used in each study, see Papers I to IV.

## 4. Results and discussions

This chapter gives a summary of the research work. It covers the main processes in positive ground flashes such as the preliminary breakdown, the leader propagation and the first and subsequent return strokes. The work also covers the distant lightning environment of both positive and negative ground flashes.

### 4.1. Characteristics of preliminary breakdown pulses in positive ground flashes during summer thunderstorms in Sweden (Paper I)

Positive ground flash is normally preceded by a significant in-cloud discharge activity that lasts more than 100 ms [26]. This initial breakdown, often referred to as preliminary breakdown, is an important in-cloud process that leads, in the case of negative ground flashes, to the initiation of the downward-moving stepped leaders [37]. In the case of negative ground flashes, it is usually assumed to be a result of electrical breakdown between the negative charge centre and the lower positive charge pocket. In the case of positive ground flashes, the physical process that leads to the preliminary breakdown is still not well understood and information on the features of PBPs in positive ground flashes is still insufficient [16]. With these goals in mind, we analysed 51 positive ground flashes obtained from remote electric field measurement.

#### 4.1.1. Summary of results

The 51 positive ground flashes analysed were located at distances 6 to 130 km from the measurement station.

##### **i) Detection and classification of the PBP**

It was found that the majority (86%) of the positive ground flashes were preceded by PBP trains. Depending on the number of trains preceding the first return stroke, the PBP trains could be classified into single (84%) and multiple (16%). *Figure 4* shows for the sample waveforms for the different types of the PBPs.

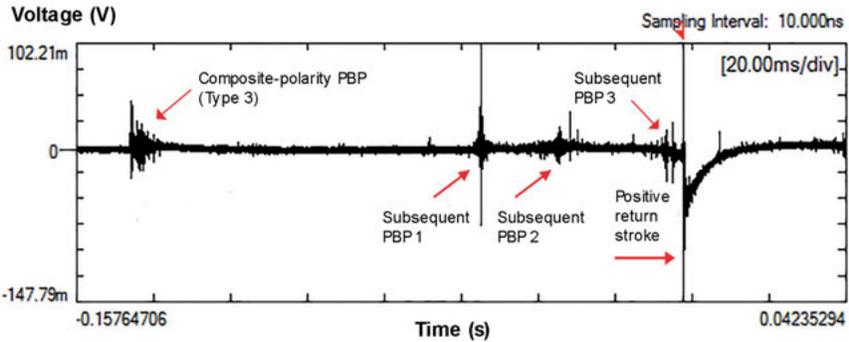
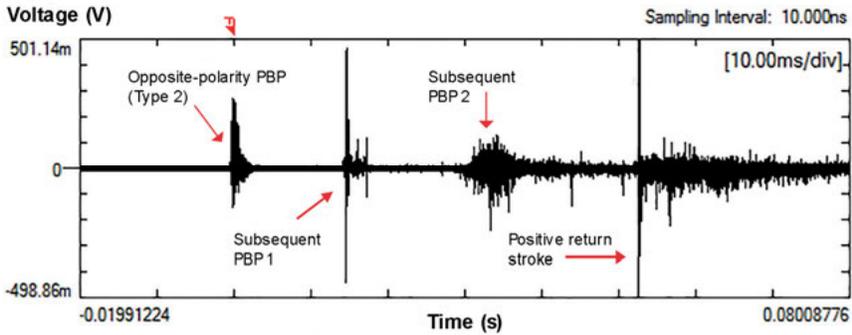
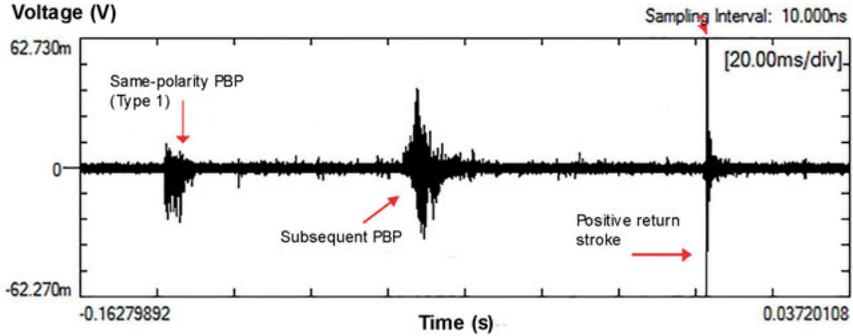


Figure 4. Type 1 PBP – same-polarity PBP (top); Type 2 PBP – opposite-polarity PBP (middle) and Type 3 PBP – composite-polarity PBP (bottom) (after the recategorization of the PBP trains) (from fast antenna)

## ii) Characteristics of the first PBP train

The first PBP train could be categorized into three types. Type 1 PBPs (48%) have the same polarity as the first return stroke, Type 2 PBPs (34%) have opposite polarity, and Type 3 PBPs (18%) have composite polarity. The average ratio of the PBP peak to the first return stroke ranged only between 0.21 and 0.26.

For each type, the temporal characteristics of the PBP, such as the time interval between the largest PBP and the first return stroke, the pulse train duration, the interpulse duration, the individual pulse duration and the total pulse duration, were obtained. For Type 1, Type 2 and Type 3, the PBP–return stroke separations were 75.1 ms, 114.6 ms and 59.2 ms; the pulse train durations were 5.9 ms, 2.6 ms and 24.8 ms; and the interpulse durations were 115.1  $\mu$ s, 93.7  $\mu$ s and 57.2  $\mu$ s, respectively. For individual pulse duration, the average values for the first half-cycle for Type 1, Type 2 and Type 3 were 8.2  $\mu$ s, 3.8  $\mu$ s and 4.9  $\mu$ s; for the second half-cycle the values were 10.0  $\mu$ s, 7.3  $\mu$ s and 8.3  $\mu$ s; and the total pulse durations were 16.9  $\mu$ s, 10.0  $\mu$ s and 12.8  $\mu$ s, respectively.

### iii) Characteristics of the subsequent PBP trains

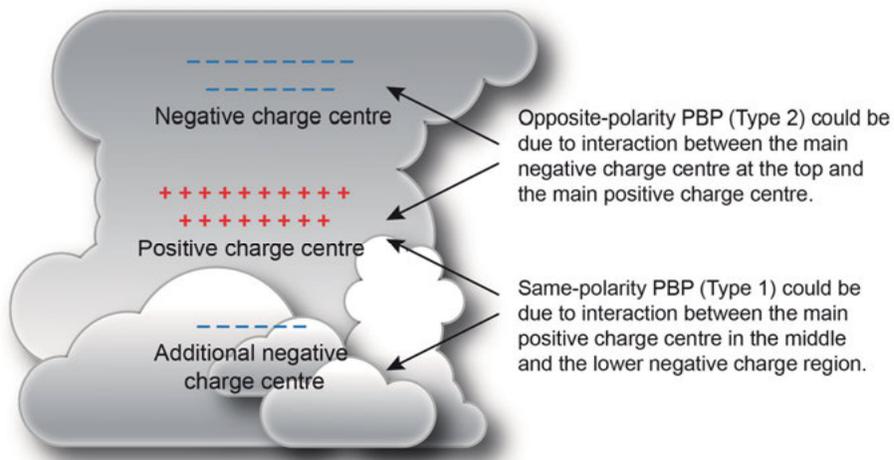
Compared to the first PBP train (overall), the parameter values for the subsequent PBP trains were smaller. The PBP peak amplitude relative to the return stroke peak was only 0.14. The time intervals between the largest PBP and the first return stroke, pulse train duration, individual pulse duration and interpulse duration for the subsequent PBP trains were 73.23 ms, 3.63 ms, 11.05  $\mu$ s and 43.78  $\mu$ s, respectively.

## 4.1.2. Discussion

Initially, we considered pulse bursts that have a duration of the order of a millisecond as the PBP train, while other pulse bursts with longer train duration were categorized as IC discharges. This gave us 84% single-train PBPs and 16% multiple-trains PBPs. However, the categorization may not be accurate considering that all of these discharges probably occurred in the cloud and were observed to precede the first return stroke in the electric field waveforms. On this basis, we recategorized the PBP trains, which gave us only 39% single-train PBPs and 61% multiple-trains PBPs (see Paper VII). For the single-train PBP category, only one PBP train was observed preceding the first return stroke. For the case of multiple-trains PBPs, up to four PBP trains were observed to precede the first return stroke. We assumed that the multiple-trains PBPs belonged to the same positive ground flash since no other ground flashes were present in the electric field waveform. In cases where multiple-trains PBPs were observed, the last PBP train was probably the one that led to the return stroke.

The average ratio of the PBP peak to the first return stroke indicates the strength of the PBP. Since the mean values for all three types are less than half, PBPs in Sweden can be considered weak. PBPs with amplitudes smaller than these might not be detected by the measurement system. This could be the reason for the nondetection of PBPs in some of the positive ground flashes. In addition, if the PBP trains occurred outside the pretrigger setting of the transient recorder, they would also have been missed.

It can be seen that the same-polarity PBP (Type 1) has a higher percentage of occurrence while the PBP–return stroke separation for opposite-polarity PBP (Type 2) is larger than that for the same-polarity PBP (Type 1). Based on these, our results are consistent with the inverted dipole charge configuration. The inverted dipole (shown in *Figure 5*) has been suggested as the dominant charge structure during the dissipating stage of ordinary thunderstorms [38], and the presence of smaller negatively charged region at the lower level has been found to assist in the initiation of positive ground flashes (as discussed in [15] and references therein). This explains why we obtained a higher percentage of same-polarity PBPs (Type 1). Since the main negative centre is now located above the main positive centre for inverted dipole charge configuration, this would also explain why our PBP–return stroke separation for opposite-polarity PBPs (Type 2) is larger than that for same-polarity PBPs (Type 1).



*Figure 5.* Illustration showing the inverted dipole charge configuration with additional negative charge region at the lower level

According to the inverted dipole charge configuration, same-polarity PBP (Type 1) could be due to breakdown between the main positive charge centre in the middle and the lower negative charge region while opposite-polarity PBP (Type 2) could be due to breakdown between the main negative charge centre at the top and the main positive charge centre.

The composite-polarity PBP (Type 3) could be due to a nonvertical bidirectional leader process. When the breakdown channel is vertical, electric field changes recorded during this bidirectional movement of the charges would result in same-polarity pulses. However, when the channel is curved and not straight (as discussed by [10] and references therein), pulses in the waveform could have mixed polarity.

## 4.2. Characteristics of leader pulses in positive ground flashes in Sweden (Paper II)

Another observed property associated with positive ground flashes is the propagation of the leaders that appear to move either continuously or in a stepped manner [26]. Stepping means the leader channel appears bright during leader formation but remains dark in between step formation [18]. Positive leaders exhibit a continuously bright channel image, either without such steps or with superimposed steps in the form of luminosity enhancements [26]. This mode of propagation of the leaders is still a topic of much interest and since their characteristics are still not well understood [19], it has motivated us to undertake the study.

### 4.2.1. Summary of results

The study involved 51 positive ground flashes located at distances 6 to 130 km from the measurement station.

#### **i) Percentage of detection**

In our study, pronounced leader pulses were observed in 22% of the cases.

#### **ii) Characteristics of pronounced leader pulses**

We found that the leader pulses appeared 0.26 to 1.40 ms before the following first return stroke with an average of 0.95 ms. The peak amplitude of the leader pulses relative to the return stroke peak ranged between 2.7 and 17.8% of the return stroke peak with an average of 6.4%. The interpulse duration between successive pulses just before the first return stroke ranged between 13.3 and 50.3  $\mu\text{s}$  with a mean of 24.7  $\mu\text{s}$ . *Figure 6* shows typical pronounced leader pulses observed just before a positive return stroke.

#### **iii) Opposite-polarity leader pulses**

One case of positive ground flash preceded by opposite-polarity leader pulses just before the return stroke was also observed (shown in *Figure 7*). They were observed to start 0.02 ms before the following return stroke; the interpulse duration was 1.78  $\mu\text{s}$ , and the peak amplitude was 3.77% of the return stroke peak.

### 4.2.2. Discussion

The presence of these leader pulses suggests that the leaders propagate in a stepped manner. Since their characteristics were similar to those of a negative stepped leader [39–42], we inferred that these pulses could be due to the up-

ward-connecting negative leader. However, we could not rule out the possibility that they might also come from the downward-moving positive leaders since we have observations only from the electric field measurements.

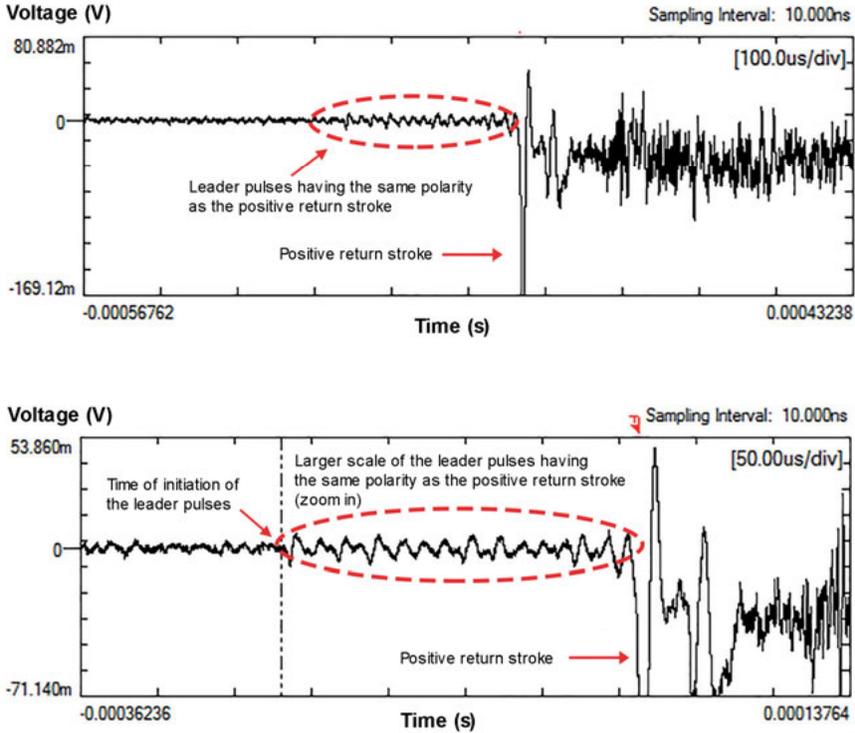


Figure 6. Typical pronounced leader pulses observed just before a positive return stroke (top) and a larger scale (zoom in) of the waveform (bottom) (from fast antenna)

On the basis of the leader pulses' time of initiation and average speed of the leader, we calculated the distance travelled by the leader.

If the pulses were due to the downward positive leader, the time of initiation obtained from the electric field records could be used to estimate the height of the positive leader from ground level when it started propagating in a stepped manner. With an average 2-D speed of  $2.7 \times 10^5 \text{ ms}^{-1}$  for the downward leader [19] and the average time of initiation of 0.95 ms, the minimum height of the leader tip when it started its stepping process was approximately 256.5 m. Of course, the length of any connecting leader present during the encounter had to be added to the above to get the actual height. If the pulses were due to the upward-connecting negative leader instead, the distance the connecting leader travelled would be an estimate of the striking distance of the ground flash. Using the average 2-D speed of  $3.0 \times 10^5 \text{ ms}^{-1}$  calculated by [39], we estimated

that the connecting leader travelled a distance of approximately 285 m from the ground before attachment to the downward positive leader.

For the one case in which a positive return stroke was preceded by negative polarity pulses, the leader pulses could be due to the negative leader branch of a bidirectional leader propagating inside the cloud. This is the first time that such a case has been reported for positive ground flashes.

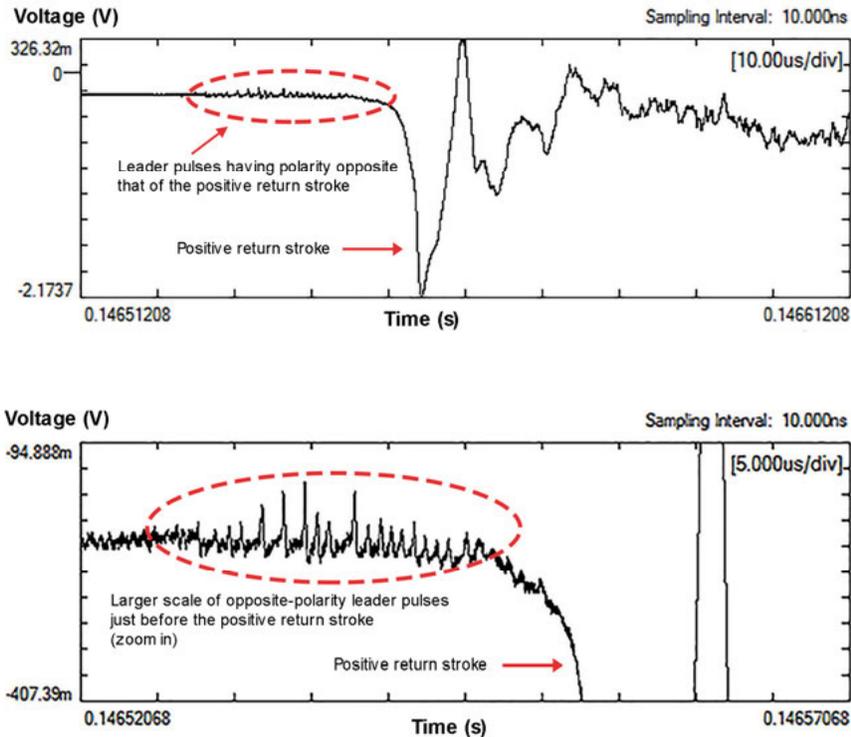


Figure 7. A positive ground flash preceded by opposite-polarity leader pulses (i.e. opposite that of the positive return stroke) (top) and a larger scale (zoom in) of the waveform (bottom) (from fast antenna)

#### 4.3. Features of the first and the subsequent return strokes in positive ground flashes based on electric field measurements (Paper III)

Positive ground flashes are usually composed of a single stroke. Multiple-stroke positive flashes, though they do occur, are rare [26]. Due to this rarity, not much knowledge is available in the literature concerning positive subsequent strokes. This brings us to the next important study for positive ground flashes involving multiple-stroke flashes.

### 4.3.1. Summary of results

In our study, 51 positive ground flashes containing 51 first strokes and nine subsequent strokes were analysed. They were located at distances 6 to 150 km from the measurement station.

#### i) Flash multiplicity, interstroke intervals and distance between strokes

We found that the majority of the positive ground flashes were single-stroke and only 12% were multiple-stroke. Flash multiplicity was 1.20, and the highest number of strokes per flash recorded was four. *Figure 8* shows a four-stroke positive ground flash recorded during the measurement. For the nine subsequent strokes, the geometric mean (GM) value of the interstroke interval was 60 ms while the LLS-reported distance between the first and the subsequent strokes ranged between 4.9 and 46.4 km. Since we did not have any video recordings, we were not able to determine whether the subsequent stroke followed the previously formed channel of the return stroke or created a new termination on ground. However, the LLS-reported distances suggest that the subsequent strokes created new terminations to ground.

#### ii) Return stroke parameters

We also found that, in comparison, the average durations of the subsequent return strokes parameters were shorter than that of the first strokes. The results are summarized in Table 1.

Table 1. Summary of the electric field parameters produced by the first and subsequent return strokes in positive ground flashes in Sweden

Return Stroke Parameters	All			First RS			SRS		
	N	AM	GM	N	AM	GM	N	AM	GM
Slow front duration ( $\mu\text{s}$ )	60	8.5	7.8	51	9.2	8.7	9	4.9	4.0
Fast transition 10-to-90% rise time ( $\mu\text{s}$ )	60	1.6	1.3	51	1.7	1.4	9	1.1	0.91
Slow front amplitude relative to peak (%)	60	40	35	51	40	35	9	37	33
Zero crossing time ( $\mu\text{s}$ )	36	30	25	31	32	29	5	14	11
Zero-to-peak rise time ( $\mu\text{s}$ )	60	11	10	51	12	11	9	6.6	5.8
10-to-90% rise time ( $\mu\text{s}$ )	60	5.9	5.2	51	6.3	5.7	9	3.8	3.2
Initial electric field normalized to 100 km (V/m)	55	14	12	49	15	13	6	8.5	6.1
LLS-reported peak current (kA)	52	56	42	46	59	46	6	27	23

N = Sample size

For the duration of the slow front, the arithmetic mean (AM) and GM values were 8.5 and 7.8  $\mu\text{s}$  for the 60 return strokes, 9.2 and 8.7  $\mu\text{s}$  for the 51 first strokes and 4.9 and 4.0  $\mu\text{s}$  for the nine subsequent strokes, respectively. For the fast transition 10-to-90% risetime, the AM and GM values were 1.6 and

1.3  $\mu\text{s}$  for the 60 return strokes, 1.7 and 1.4  $\mu\text{s}$  for the 51 first strokes and 1.1 and 0.91  $\mu\text{s}$  for the nine subsequent strokes, respectively. For the slow front amplitude relative to the peak, the AM and GM values were 40 and 35% for the 60 return strokes, 40 and 35% for the 51 first strokes and 37 and 33% for the nine subsequent strokes, respectively. For the zero-crossing time, the AM and GM values were 30 and 25  $\mu\text{s}$  for 36 return strokes, 32 and 29  $\mu\text{s}$  for the 31 first strokes and 14 and 11  $\mu\text{s}$  for the five subsequent strokes, respectively. For the zero-to-peak risetime, the AM and GM values were 11 and 10  $\mu\text{s}$  for the 60 return strokes, 12 and 11  $\mu\text{s}$  for the 51 first strokes and 6.6 and 5.8  $\mu\text{s}$  for the nine subsequent strokes, respectively. For the 10-to-90% risetime, the AM and GM values were 5.9 and 5.2  $\mu\text{s}$  for the 60 return strokes, 6.3 and 5.7  $\mu\text{s}$  for the 51 first strokes and 3.8 and 3.2  $\mu\text{s}$  for the nine subsequent strokes, respectively. For the initial electric field peak normalized to 100 km, the AM and GM values were 14 and 12 V/m for the 55 return strokes, 15 and 13 V/m for the 49 first strokes and 8.5 and 6.1 V/m for the six subsequent strokes, respectively. For the LLS-reported peak current, the AM and GM values were 56 and 42 kA for the 52 return strokes, 59 and 46 kA for the 46 first strokes and 27 and 23 kA for the six subsequent strokes, respectively.

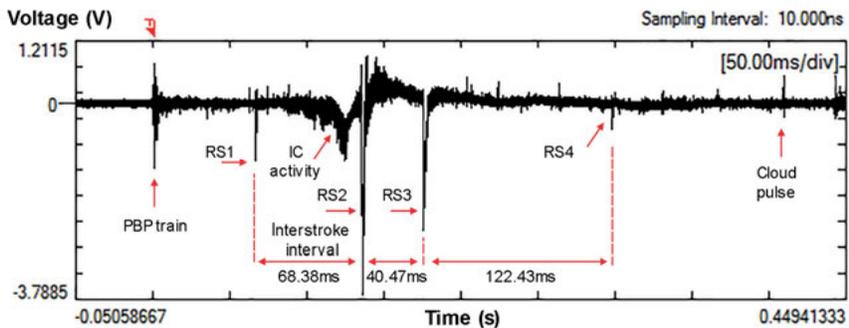


Figure 8. A four-stroke positive ground flash recorded in Sweden (from fast antenna)

#### 4.3.2. Discussion

There are two possible reasons for the shorter duration of the subsequent return stroke parameters compared to that of the first strokes. It could be due to the higher speed of propagation of the return stroke or it could be due to the rapid decay of the current generated by the neutralization process along the channel [18]. In general, the radiation field generated by a ground flash decays rapidly when the return stroke front reaches the end of the return stroke channel section. Higher propagation speed causes the return stroke to reach the end of the channel faster compared to when the speed is lower. This results in shorter duration of the electric field. The return stroke current amplitude also

decays as it propagates along the channel, in general. A rapid decay of this current makes the duration of the return stroke electric field shorter. This could be the second reason for the shorter duration of the subsequent return stroke parameters in the electric field waveforms.

#### 4.4. Oscillations observed in bipolar electric field from distant cloud-to-ground lightning flashes (Paper IV)

Characteristics of lightning-generated electric fields vary depending upon the distance of the lightning channel from the measuring station. For close lightning, the characteristics are determined by the characteristics of the lightning current but for distant lightning, the characteristics are significantly influenced by the propagation path of the fields [29],[30]. In order to investigate the reason for the appearance of oscillating field change in distant lightning, we considered both the positive and negative ground flashes at distances up to 1000 km.

##### 4.4.1. Summary of results

The analysis involved 34 positive ground flashes located at distances 117 to 411 km and 34 negative ground flashes located at distances 366 to 971 km from the measurement station.

##### **i) General observations**

The electric field waveforms were observed to have a typical shape like a distorted ‘W’ (or a distorted ‘M’ for negative ground flashes) followed by small oscillations. Sample waveforms are shown in *Figure 9*. The oscillations started after the second peak and were more pronounced in negative ground flashes, especially at greater distances. For negative ground flashes, 74% had SRS and they showed wave shapes similar to those of the first return strokes. None of the positive ground flashes analysed, however, had any SRS. In both the positive and negative ground flashes, PBP trains were observed in 71% of the cases. For positive ground flashes, the average time separations between the largest PBP and the ground wave were much larger (17.8 ms for same-polarity PBP and 36.7 ms for opposite-polarity PBP) compared to that of the negative ground flashes (2.6 ms).

##### **ii) Ionospheric reflections**

On the basis of the difference in time of arrivals of the ground wave and the first sky wave, we estimated the ionospheric reflections heights for both flashes. The average time interval between the ground wave and the first sky

wave for positive ground flashes was found to be  $129 \mu\text{s}$ , with the corresponding ionospheric reflection height of  $71 \text{ km}$ . For negative ground flashes, the average time interval between the ground wave and the first sky wave was  $64 \mu\text{s}$  with the corresponding ionospheric reflection height of  $67 \text{ km}$ . The estimated reflection height values were found to correspond probably to a D-layer of the ionosphere.

### iii) Features of the small oscillations

For the small oscillations, the average amplitudes of the oscillations relative to the return stroke peak, the period of the oscillations and their corresponding frequencies for positive ground flashes ranged from  $0.02$  to  $0.11$ ,  $212$  to  $359 \mu\text{s}$  and  $3.0$  to  $4.7 \text{ kHz}$ , respectively. For negative ground flashes, the corresponding values ranged from  $0.03$  to  $0.28$ ,  $183$  to  $237 \mu\text{s}$  and  $4.3$  to  $5.5 \text{ kHz}$ .

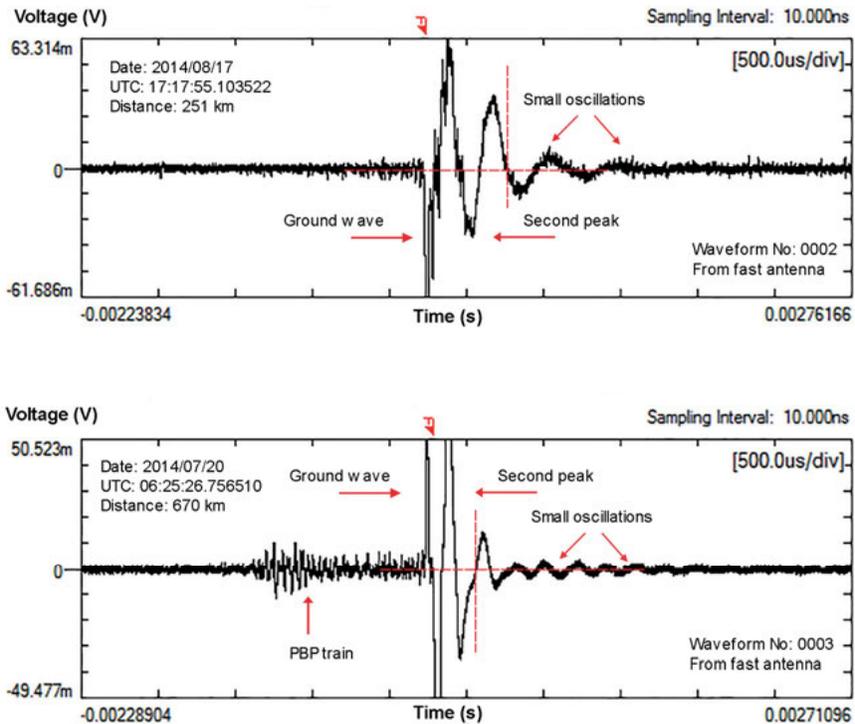


Figure 9. Sample waveforms for distant positive (top) and negative (bottom) ground flashes recorded during summer thunderstorms in Sweden

## 4.4.2. Discussion

There are two possible causes for the small oscillations observed in the waveforms. They could be due to the low-frequency component of the return stroke current that oscillates in the lightning channel, or they could be due to the

filtering of the frequencies by the Earth-ionosphere waveguide. Using a transmission line model to represent the return stroke and a simple RLC circuit analysis to calculate the frequency, we estimated the frequency of oscillations as around 2.5 to 5 kHz, which suggests that the oscillations observed in the waveform may come from the low-frequency component of the current that oscillates in the return stroke channel. The gradual decrease of the amplitude seen in the waveform is probably due to channel resistance and mismatching. Another possible cause for the small oscillations is the filtering of the frequencies by the waveguide. Since sferics propagate in a waveguide mode, they cannot contain frequency components below 1 to 3 kHz as this is the cut-off frequency of the Earth-ionosphere waveguide [30].

## 5. Conclusions

Conclusions based on our findings are as follows:

### **i) Paper I**

We concluded that the nondetection of PBPs in some of the positive ground flashes could be due to the relatively small PBP amplitude below noise level and their occurrence outside the pretrigger setting of the transient recorder. Second, the PBPs in positive ground flashes in summer thunderstorms in Sweden are weak on average since the ratio of the PBP peak to the first return stroke peak lies only between 0.21 and 0.26. Third, the inverted dipole cloud configuration is consistent with our observation. Same-polarity PBP (Type 1) could be due to the interaction between the main positive charge centre in the middle and the lower negative charge region while opposite-polarity PBP (Type 2) could be due to the interaction between the main negative charge centre at the top and the main positive charge centre. The composite-polarity PBP (Type 3) could be due to the bidirectional leader process in a nonvertical channel.

### **ii) Paper II**

The presence of the leader pulses before the positive return strokes suggests that the leaders propagate in a stepped manner. Since their characteristics were found to be similar to those of a negative stepped leader [39],[40],[41],[42], we inferred that these pulses result from the upward-connecting negative leader. However, we could not rule out the possibility that the pulses could also be due to the stepping of downward positive leaders since we only have electric field measurements. Based on the leader pulses' time of initiation and average speed of the leader, the distance travelled by the leader could be estimated. If the pulses were due to the downward positive leader, the time of initiation of the pulses obtained from the electric field records could be used to estimate the height of the leader when the pulsation began. If, however, the pulses were due to the upward-connecting negative leader, the distance the connecting leader travelled would be an estimate of the striking distance of the ground flash. One case of positive ground flash preceded by negative leader pulses just before the return stroke was also observed. Interestingly, this is the first time that such a case in positive ground flashes has been reported. These pulses could be due to the negative leader branch of a bidirectional leader inside the cloud that propagates towards the observation point.

### **iii) Paper III**

Next, we found that indeed the majority of the positive ground flashes were single-stroke. Only 12% of the positive ground flashes were multiple-stroke, and flash multiplicity was 1.20. For the nine subsequent strokes, the GM value of the interstroke interval was 60 ms while the LLS-reported distance between the first and the subsequent strokes ranged between 4.9 and 46.4 km. The LLS-reported distances suggest that the subsequent strokes created new terminations to ground. The shorter duration of the subsequent return strokes parameters compared to the first strokes could be due to two reasons. It could be due to the higher speed of propagation of the return stroke or it could be due to the rapid decay of the current generated by the neutralization process along the channel [18].

### **iv) Paper IV**

Besides the lightning processes, our study also involved the distant lightning environment. Our observations of distant positive and negative ground flashes showed that the electric field waveforms from ground flashes at distances up to 1000 km have a typical shape like a ‘W’ (or an ‘M’ for negative ground flashes) followed by small oscillations. Compared to positive ground flashes, the oscillations were more pronounced in negative ground flashes. We suggest that the small oscillations observed in the waveforms come from the low-frequency component of the return stroke current that oscillates in the lightning channel. We used a transmission line model to represent the return stroke and a simple RLC circuit analysis to calculate the frequency, and the frequency values estimated suggest that the oscillations seen in the waveform may come from the low-frequency component of the current that oscillates in the return stroke channel, with the gradual decrease of the current amplitude due to channel resistance and mismatching. Another possible cause of oscillations is the filtering of the signal frequencies by the propagation through the Earth-ionosphere waveguide.

## 6. Recommendations

Recommendations based on each paper are as follows:

### **i) Paper I**

For future study, it is recommended that the pretrigger setting of the transient recorder be increased to a value greater than 200 ms to improve the possibility of capturing all PBPs. To support the inverted dipole cloud configuration hypothesis, further investigation is required.

### **ii) Papers II and III**

The use of high-speed video cameras would be essential to provide additional support to the electric field measurements. The data can be used to trace and observe the paths followed by the leaders and can also be used to determine the termination points on the ground made by each subsequent return stroke.

### **iii) Paper IV**

More observations and in-depth analysis are required to support the hypothesis that the oscillating field change observed in the distant lightning is due to the low-frequency component of the return stroke current that oscillates in the lightning channel.

# Svensk sammanfattning

Avhandlingen lägger sin fokus på huvudprocesserna som sker i en positiv jordblixtn och det avlägsna elektromagnetiska fältmiljön genererat av både positiv och negativ jordblixtn. Den presenterar egenskaperna hos *i)* förberedande sammanbrottpulserna (PBPs), *ii)* elektriska fältpulserna observerade under uppbyggnaden av blixtkanalen, och *iii)* elektriska fälten som produceras av de första och de efterföljande huvudurladdningarna. Den karakteriserar också observationer av avlägsna positiva och negativa jordblixtnar vid avstånd upp till 1000 km. Resultaten har baserats på elektriska fältmätningar som utfördes på avstånd under sommar åskväder i Sverige år 2014.

Från studien fann vi att majoriteten av de positiva jordblixtnar föregicks av PBPs. Några föregicks av mer än en PBP-kedja, och parametervärdena för de efterföljande PBP-kedjorna visade sig vara mindre än det för det första PBP-kedja. Tre typer av PBPs kunde identifieras, baserat på pulsens polaritet i förhållande till huvudurladdningen. Resultaten tyder på att PBPs i de positiva jordblixtnarna som inträffade under sommar åskvädet i Sverige är svaga, och den inverterade dipol-formade laddningskonfigurationen av molnet överensstämmer med våra observationer.

Likafullt, en liten andel av dessa positiva jordblixtnar som observerades föregicks av tydliga förurladdningspulser. Förekomsten av dessa pulser tyder på att förurladdningarna propagerar i steg. Deras egenskaper visade sig likna dem hos negativa stegurladdningar, så att vi kunde dra slutsatsen att dessa pulser berodde på den uppåtriktade negativa fångurladdningen. Baserat på förurladdningspulsers starttid och dess genomsnittliga hastighet uppskattades även det avstånd som förurladdningen kunde färdas. Ett fall av positiv huvudurladdning som föregicks av negativa förurladdningspulser kunde också observeras. Förekomsten av dessa pulser, den första i positiva jordblixtn som rapporteras, beror förmodligen på den negativa förurladdningsförgrening av en dubbelriktad förurladdning inuti molnet som propagerar mot observationspunkten.

Flertalet av dessa positiva jordblixtnar innehöll endast en urladdning. Jämförelse mellan de första och efterföljande huvudurladdningarna visade att den genomsnittliga varaktigheten av de efterföljande huvudurladdningar parametrarna var mindre jämför med motsvarande parametrar av den första urladdningen. Avstånden rapporterade av blixtnlokaliseringsystem tyder på att de efterföljande huvudurladdningarna troligen slog ned på olika ställen i marken. Två möjliga orsaker angavs som förklaring till den kortare varaktigheten av

de efterföljande huvudurladdningar parametrarna jämför med motsvarande parametrar av den första urladdningen.

Vidare observationer av avlägsna positiva och negativa jordblixtrar vid avstånd upp till 1000 km visade att elektriska fältkurvorna har en utpräglad, förvrängd "W" form (eller förvrängd "M" för negativa jordblixtrar) följt av små svängningar. Dessa små oscillationer var mer utpräglade i negativa jordblixtrar jämfört med de positiva, särskilt vid större avstånd. Jonosfärskiktets reflektionshöjd uppskattade för positiva och negativa jordblixtrar visade sig ungefärligt motsvara ett D-skikt i jonosfären. Två tänkbara orsaker föreslogs för de små oscillationer som observerades i vågformerna.

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