Features and Origin of Electromagnetic Fields Generated by Lightning Flashes

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Negative cloud-to-ground (CG) lightning flashes transport negative charge from cloud to ground. Negative ground flashes typically involve various processes identified as preliminary breakdown, stepped leader, return stroke, dart leader, dart-stepped leader, subsequent return stroke, and cloud activity between strokes, such as regular pulse trains and chaotic pulse trains. These processes can be identified through their electromagnetic field signatures. The main focus of this thesis is to document the features and understand the origin of electromagnetic fields, especially the chaotic pulse trains, generated by lightning flashes.

Electric field measurements have been used to study lightning flashes in Sweden. The equipment was a parallel flat plate antenna with an analog filter buffer circuit, connected to a digital high speed oscilloscope. Four simultaneous measurements were made: wideband measurement of the E-field (the vertical component) and its time derivative \( \frac{dE}{dt} \), and two narrowband measurements of the E-field, centred around 3 MHz and 30 MHz. Fourier and wavelet transforms were used in the analysis of the measured data.

The results show that preliminary breakdown pulses are stronger radiators at 3 MHz and 30 MHz than are the return strokes. A comparison of our results with those of previous studies obtained in different geographical regions clearly shows that the strength of preliminary breakdown pulses decreases with decreasing latitude. It is higher in the temperate regions (Sweden, for instance) and lower in the tropical regions.

A comparison of the time derivatives of preliminary breakdown pulses and of the narrow bipolar pulses shows that the physical origin of these two types of pulse is different, even though they may have similar appearances in the broadband fields.

This thesis introduces a new procedure to estimate the zero-crossing time of the lightning-generated radiation fields. The procedure is based on the fact that the time integral of the radiation fields generated by a discharge event whose duration is finite is equal to zero, and the zero-crossing time corresponds to the time when the peak of the integral is reached.

In addition to tabulating the various statistical parameters and features of Chaotic Pulse Trains (CPTs), it is shown that these pulse trains are created by the simultaneous propagation of several dart-stepped leader type discharges in the cloud. Each dart-stepped leader type discharge generates a Regular Pulse Train (RPT), and these pulse trains combine randomly in time to generate CPTs. This conclusion is based on the results obtained by numerical simulations and by analysing the signatures of these pulse trains using Fourier and wavelet transformations.

The results presented in this thesis show that electromagnetic fields, even those measured from a single station, can be used to extract information concerning the physical processes that gave rise to these fields.

**Keywords:** negative cloud-to-ground lightning flashes, HF and VHF radiation, chaotic pulse trains, lightning initiation, zero-crossing time, electromagnetic fields

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Dedication

To everyone
List of Papers

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


II  **Ismail, M. M.** and Cooray, V. (2017) On a comparison between initial breakdown pulses and narrow bipolar pulses in lightning discharges with special attention to the signature of electric field time derivative. *Manuscript.*

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Other contributions of this author not included in this thesis:


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Abbreviations and nomenclature

A.M. Arithmetic Mean  
BIL. Breakdown, Intermediate, stepped Leader  
CC. Cloud-to-Cloud lightning  
CG. Cloud-to-Ground flash  
CPT. Chaotic Pulse Train  
DL. Dart Leader  
DSL. Dart-Stepped Leader  
G.M. Geometric Mean  
GPS. Global Positioning System  
HF. High-Frequency  
IBP. Initial Breakdown Pulse  
IC. Intra-Cloud lightning  
IPD. Inter-Pulse Duration  
LPCR. Lower Positive Charge Region  
NBP. Narrow Bipolar Pulse  
NNBP. Negative Narrow Bipolar Pulse  
NPBP. Positive Narrow Bipolar Pulse  
PB. Preliminary Breakdown  
PBP. Preliminary Breakdown Pulse  
PD. Pulse Duration  
RF. Radio Frequency  
RPT. Regular Pulse Train  
RS. Return Stroke  
SL. Stepped Leader  
SRS. Subsequent Return Stroke  
TD. Time Duration  
VHF. Very High-Frequency  
ZCT. Zero-Crossing Time

Nomenclature: The terms initial breakdown pulse (IBP) and preliminary breakdown pulse (PBP) are used interchangeably throughout this thesis. They refer to the electromagnetic fields generated during the initiation of lightning flashes inside the cloud.
1 Introduction

1.1 General Description

*What is lightning?*
Lightning is a sudden electrostatic discharge that occurs during a thunderstorm. This discharge can occur between a cloud and the ground (CG lightning), between electrically charged regions of a cloud (called intra-cloud lightning or IC) or between two clouds (CC lightning). The main events in a lightning ground flash are the preliminary breakdown, stepped leader, return stroke, subsequent return stroke, dart and dart-stepped leader, and narrow bipolar pulses. The main events of a cloud flash are the leaders, recoil leaders, continuing currents, and K-changes. There are also discharge processes in cloud discharges that generate chaotic pulse trains (CPTs) and narrow bipolar pulses (NBPs).

*Why do we study the electromagnetic fields generated by lightning?*
The electromagnetic fields of lightning flashes are of interest both in lightning protection studies and in understanding the physics of lightning flashes. In lightning protection, knowledge of the characteristics of electromagnetic fields generated by lightning flashes is necessary in estimating the voltages and currents induced in structures by lightning flashes. The features of lightning-generated electromagnetic fields are of interest in lightning physics because they can be used as a vehicle to probe the physical mechanism behind lightning flashes. They can also be used to estimate the signature of currents in lightning flashes.

*How do we record and analyse the electromagnetic fields of lightning flashes?*
Usually, electromagnetic fields from lightning flashes are measured using a broadband antenna system with a long decay time constant, so that the long duration fields of a lightning flash can be recorded faithfully. By decreasing the decay time constants, the same antenna system can be used to record the derivative of the electromagnetic fields. Besides that, one can also use narrow-band systems working in the HF and VHF frequency bands to record these electromagnetic fields. The records can be studied either in the time domain or by converting them into the frequency domain using techniques such as Fourier transformations or wavelet transformations. The electromagnetic
fields can also be combined with the data obtained from high-speed video, VHF-mapping, and VHF interferometers to pinpoint their origins.

What are the different types of lightning flashes?

Lightning flashes can be divided into two main types: cloud-to-ground discharges (CGs) and cloud discharges (ICs). When lightning flashes strike the ground or grounded objects, they are called ground discharges. There are four types of CG:

i) Downward negative lightning
ii) Downward positive lightning
iii) Upward negative lightning
iv) Upward positive lightning

Downward negative lightning flashes are the main focus of this thesis.

1.2 Negative Cloud-to-Ground flashes

1.2.1 Lightning Initiation

The exact mechanism of lightning initiation is still unknown. However, research shows that the initiation of lightning ground flashes inside the cloud is accompanied by electric field pulses known as preliminary breakdown pulses. Thus, the first preliminary breakdown pulse should contain some information on the origin of the lightning flash. Sometimes, lightning flashes are initiated immediately after the emission of a narrow bipolar pulse. Unfortunately, at present we do not understand how these events are physically related to the initiation of lightning flashes inside the cloud. If both narrow bipolar pulses and preliminary breakdown pulses are generated at the time of initiation of lightning flashes, one should find some relationship between these two types of pulses. Our study actually shows that their broadband signatures have many similar characteristics, but the signatures of their derivatives indicate that they are probably produced by different physical processes.

1.2.2 Preliminary Breakdown Pulses (PBPs)

A ground flash occurs between the charged centres of the cloud and the ground. When a ground flash brings positive charge down to earth, it is called a positive ground flash, and when it brings negative charge, it is called a negative ground flash [1]. Electromagnetic field measurements show that a ground flash is initiated by an electrical breakdown process that takes place inside the cloud. This process is called preliminary breakdown or initial breakdown. The electric field pulses generated by this process are called PBPs or
IBPs. The strength of electric field produced by the PBPs can indicate the strength or the magnitude of the lower positive charge region (LPCR) [2, 3].

1.2.3 Stepped Leader (SL) and Connecting Leader

A stepped leader is a column of charge that proceeds from a cloud to the ground. On its way toward the ground, a stepped leader may give rise to several branches. As the stepped leader approaches the ground, the electric field at ground level increases steadily. When the stepped leader is a few hundred meters above the ground, the electric field at the tip of the grounded structures increases to such a level that electrical discharges are initiated from them. These discharges, called connecting leaders, travel toward the descending stepped leader. One of the connecting leaders may successfully bridge the gap between the ground and the stepped leader.

1.2.4 Return Stroke (RS)

Once a connection is made between the stepped leader and the ground, a luminous wave of near-ground potential travels along the channel toward the cloud with a speed close to that of light. This event is called a return stroke. The strength of the electric field produced by the return stroke is related to the magnitude of the current in the channel and to its speed of propagation.

1.2.5 Dart-Stepped Leader (DSL) and Dart Leader (DL)

After a return stroke, if the return stroke channel happens to be in a partially conducting stage with no current flow, the electrical activity in the cloud may initiate a dart leader that travels towards the ground. Depending on the channel’s conductivity, the dart leader may propagate continuously or in a stepped manner towards the ground. When the latter happens, it is called a dart-stepped leader. Sometimes, the lower part of the channel may decay to such an extent that the dart leader stops before actually reaching the ground. Such an event is called an “attempted leader” [1].

1.2.6 Subsequent Return Strokes (SRS)

When a dart or dart-stepped leader approaches the ground, another attachment and neutralization process called a subsequent return stroke takes place. A lightning ground flash may involve several of these subsequent return strokes. It is usually assumed that the successive strokes belong to the same flash if the time separation between strokes is shorter than about 500 ms [4]. A detailed discussion on inter-stroke intervals and the ratio of the radiation field peaks of SRS to RS is given in subsection 3.1.4.
1.2.7 Regular Pulse Trains (RPTs)

Regular pulse trains consist of a train of pulses, with each pulse having a signature similar to those of the electric field pulses generated by dart-stepped leaders. According to Krider et al. [5], RPTs are generated by a dart-stepped leader or K-change type discharges propagating inside the cloud. The observations made by Rakov et al. [6] show that RPTs occur both in cloud flashes and in cloud activity taking place between return strokes. Krider et al. [5] showed that the maximum amplitude of the Fourier spectrum of the individual pulses of regular pulse bursts is located close to 200 kHz. The detailed characteristics of RPTs in the time domain and in the frequency domain are given in subsections 3.4, 3.5, and 3.6.

1.2.8 Chaotic Pulse Trains (CPTs)

Chaotic pulse trains were first observed by Weidman [7]. Since the CPTs that Weidman observed occurred during the leader stage of the subsequent return strokes, he coined the term “chaotic subsequent return stroke” to represent subsequent return strokes preceded by chaotic pulse bursts. Subsequent studies have demonstrated that CPTs can also occur in the electric fields of cloud flashes without any return strokes [8–10]. Gomes et al. [10] observed the occurrence of CPTs in ground flashes either just before the subsequent return strokes or without any association with subsequent return strokes. The detailed characteristics of CPTs in the time and frequency domains are given in subsections 3.4, 3.5, and 3.6.

1.3 Main Contributions of the Thesis

This thesis deals with the features of electromagnetic fields generated by lightning flashes and their possible origin in the lightning flash. The main focus of the thesis work is on lightning initiation, negative cloud-to-ground flashes, and cloud activity between return strokes. The main contributions made within this thesis work are the following:

1) **Paper I:** Measurement of wideband electromagnetic fields from CG lightning flashes in Sweden was conducted simultaneously with that of narrowband electromagnetic radiation fields at 3 and 30 MHz. To the best of our knowledge, this is the first time that the electric field records of whole lightning flashes in Sweden were analysed simultaneously with narrowband signals. In addition to presenting new data, a comparative
analysis of the literature on negative ground flashes with wide- and narrowband data on electric field radiation from PB, SL, RS, and SRS was carried out.

2) **Paper II**: The physical mechanism of IBPs and NBPs in lightning discharges is not well understood. However, there are similarities in the wideband signals of the electromagnetic fields generated by these two processes, which may lead to a conclusion that they are produced by a similar process. In this study, we have compared the electric fields and the time derivatives of the electric fields (dE/dt) of these two types of pulses (IBPs and NBPs) and showed that they are produced by different processes.

3) **Paper III**: A new technique is proposed to evaluate the zero-crossing time of the radiation fields based on the signature of the integral of the radiation field. We have also compared the results obtained using this new procedure with the ones obtained using traditional techniques.

4) **Paper IV**: After categorizing the electric field signatures of CPTs and RPTs associated with downward dart or dart-stepped leaders into different types, their temporal characteristics were analysed.

5) **Paper V**: The discharge mechanism by which CPTs are generated in lightning flashes is currently unknown. In this paper, an attempt is made to understand the origin of CPTs in lightning flashes. Based on the results of this study, it was concluded that CPTs are produced by a random addition of RPTs generated by several dart-stepped like leaders propagating simultaneously in the cloud.

6) **Paper VI**: The wavelet transformation technique was used to test the hypothesis made in Paper V, that chaotic pulse trains are created by the superposition of several RPTs. The results confirmed the hypothesis.
2 Methodology

2.1 General Overview

The measurements of electric field signatures generated by negative CG flashes in Swedish thunderstorms were recorded in Uppsala (59.837°N, 17.646°E) from May to August in 2014 and 2015. The site is 70 km inland of the Baltic Sea and 38 m above sea level. The vertical component of the electric field pertinent to negative CG lightning flashes was sensed by parallel plate antennas. The distances to the negative CG flashes from the measurement site were estimated using the Swedish Lightning Location Network (LLN). The flashes analysed here ranged from 10 to 100 km from the measuring station. The timing for each event was provided by global positioning system (GPS). In the 2014 measurement campaign, three parallel plate antennas were employed to sense the wideband electric field and the radiation at 3 and 30 MHz, respectively. Meanwhile, in the 2015 measurement campaign, three parallel plate antennas were employed to sense the wideband electric field, 3 MHz radiation, and time derivative of electric field (dE/dt), respectively.

In this thesis, the polarity of electric field pulses is defined according to the atmospheric electricity sign convention. According to this convention, a negative charge in a cloud produces a negative field at ground level, and a negative return stroke produces a positive field change.

2.2 Electric Field Measurement and Analysis

2.2.1 Wideband

The antenna system used to record the wideband electric fields consists of a calibrated parallel flat plate antenna and an electronic buffer circuit suitable for fast electric field measurements. The flat plate antenna was 1.5 m above the ground plane. The system is identical to the ones used previously in the studies reported in references [11–13]. A 60 cm-long coaxial cable (RG58) was used to connect the antenna to the electronic buffer circuit. The zero-to-peak rise time of the output was shorter than 30 ns when a step input pulse was applied to the fast electric field antenna system. The decay time constant of the fast electric field antenna, which is determined by the RC constant of
the electronics, was 15 ms. This decay time constant was found to be sufficient for the faithful reproduction of microsecond-scale electric field changes. Signals from the antenna system were fed into a 12-bit digital transient recorder (Yokogawa SL 1000 equipped with DAQ modules 720210) by a properly terminated (50 Ω resistor) 10 m-long coaxial cable (RG-58). The total sampling time was set to 250 ms, with a sampling rate of 10 ns per point. A pre-trigger time of 30% of the total time window (250 ms) was used in these measurements. The trigger setting of the oscilloscope was set in such a way that the signals of both polarities could trigger the system.

2.2.2 3 MHz (HF radiation)

The high frequency (HF) radiation at 3 MHz was detected by a tuned antenna system whose electric field sensing flat plate was on the roof of a 3 m-high van in the vicinity of the wideband antenna. The field enhancement caused by placing the antenna over the roof of the van was obtained by connecting the antenna on the roof of the van to a wideband system and comparing the amplitudes of wideband signals measured simultaneously by two antennas (i.e., one located above ground and the other located on the roof of the van). The tuned circuit at 3 MHz is a combination of passive elements in which the inductance (47 µH) is connected in series with the antenna (58 pF) and 50 Ω termination, forming a simple RCL circuit. The bandwidth of the tuned circuits at 3 MHz is 264 kHz. The 3 MHz signal was fed by a 3 m-long, properly terminated (50 Ω resistor) cable into a digital transient recorder (Yokogawa SL 1000). The sampling time, pre-trigger time setting, sampling rate, and trigger settings were identical to those used in the wideband measurement.

2.2.3 30 MHz (VHF radiation)

The circuit tuned at 30 MHz was constructed using an active band pass topology consisting of LMH6559 (high speed buffer) and LMH6609 (voltage feedback operational amplifier). The cable length and oscilloscope settings are identical to those used in the 3 MHz measuring system.

2.2.4 Time Derivatives of Electric Fields (dE/dt)

One can select the value of the RC product of the antenna system in such a way that the output of the antenna is proportional to either the electric field or the electric field’s derivative. Electric field measurements require a long RC constant, and the measurement of an electric field’s derivative requires a very short RC constant. In order to make the RC constant short enough to record the electric field’s derivative, the 3m-long cable from the antenna was fed directly to the oscilloscope. The cable was terminated with its characteristic impedance of 50 Ω. The 50 Ω resistance, together with antennal capacitance,
produced an RC constant of $2.5 \times 10^{-9}$ seconds. This time constant is much shorter than the duration ($\Delta t$) of the electric fields that are of interest to the present study (i.e., $RC \ll \Delta t$). Thus, the output voltage is proportional to the time derivative of the electric fields of interest. In order to test the measuring system, the measured $dE/dt$ was compared with the derivative of the broadband electric field (obtained from another antenna system). The comparison showed that the antenna system was measuring the $dE/dt$ signal faithfully (see Figure 1).

![Figure 1: Comparison of the measured dE/dt with the derivative of the broadband signal.](image-url)
3 Main results and discussion

3.1 Electric Field Signatures of Wideband, 3MHz, and 30 MHz of Negative Ground Flashes Pertinent to Swedish Thunderstorms (Paper I)

3.1.1 General Overview of CG Flashes

The average total duration of the ground flashes is about 102 ms, with a geometric mean of about 83 ms. It should be mentioned that the recording length (250 ms, with 30% pre-trigger) might be insufficient to cover the whole flash in some cases. Similarly, the average duration of the activity before the inception of RS (i.e., the duration of the so-called BIL phase) was found to be about 13 ms, with a geometric mean of about 7 ms. Furthermore, the average time interval between the highest peak of PB pulse trains and the following RS was found to be about 11 ms, with a geometric mean of about 7 ms. According to Gomes et al. [14], the time separation between the most active part of the breakdown pulse train (usually the centre of the pulse train) and the succeeding return stroke in Swedish lightning flashes had an arithmetic mean and a geometric mean of 13.8 ms and 8.7 ms, respectively. These numbers are not far away from the ones obtained in the present thesis.

3.1.2 Preliminary Breakdown Pulses (PBP)

3.1.2.1 Pulse Duration and Inter-pulse Interval

Of the 98 flashes with detectable PB pulse trains, 56 (57%) were found to be consistent with the BIL form. Of the flashes showing the BIL form, 33 out of 56 (58%) showed regular pulses in the PB pulse train. Another 23 (41%) flashes having the BIL form had irregular pulses with complicated shapes in the PB pulse train. The remaining 42 flashes (43% of total) were identified as having only a BL form. These flashes did not have the intermediate stage, and the leader stage directly followed the breakdown stage. From the present study conducted in Sweden (a temperate region), the average individual pulse duration of the PB pulses was found to be 19 μs, which is slightly higher than that in Florida (a subtropical region, with 17 μs) and significantly higher than that observed in Malaysia (a wet, tropical region, with 11 μs).
Furthermore, the PB inter-pulse interval in lightning flashes in Sweden (54 µs) is slightly lower than that in Florida (73 µs) and significantly lower than that in Malaysia (152 µs). From the range of inter-pulse intervals observed in the three regions, there seems to be a significant difference between the pulse intervals in a temperate region (Sweden) and those in the wet tropics (Malaysia). The inter-pulse interval seems to be a function of the latitude, but more data from the same regions and other geographical locations are needed before making a conclusion.

The total duration of the PB pulse train in a temperate region (this study, 2.6 ms, Sweden) is comparable to that in the subtropics (Nag and Rakov [15], 2.7 ms, Florida) but significantly shorter than that in the tropics (Baharudin et al. [16], 12.30 ms, Malaysia). Again, as before, there is a tendency for the duration of PB pulse trains to increase as one moves from temperate to tropical regions. Such variation in the duration of the PB pulse trains is probably caused by the differences in the heights of the charge centres in the different regions, which in turn is caused by the differences in the meteorological conditions, the altitude of clouds, and the vertical temperature profile.

3.1.2.2 PB to RS Ratio

The amplitude ratio of the peak electric fields of the highest PB pulse to that of the following RS has been analysed. Similar studies have been conducted by Gomes et al. [14], Nag and Rakov [15], Baharudin et al. [16], Mäkelä et al. [17], and Cooray and Jayaratne [18]. However, in the present study, electric field strengths from the PBP and the following RS at 3 and 30 MHz have also been analysed. The arithmetic mean, the geometric mean, and the standard deviation of the PB to RS ratio of the wideband signals obtained in the present study are 0.7, 0.5 and 0.8, respectively. The minimum and the maximum values of the ratios observed are 0.03 and 6. As mentioned earlier, the present analysis also includes the PB to RS ratio at narrowband frequencies. From 98 flashes, the PB/RS ratio at 3 MHz had an arithmetic mean, a geometric mean, and a standard deviation of about 1.9, 1.6, and 1.5, respectively, and had minimum and maximum values of 0.06 and 11. Meanwhile, from eight flashes, the PB/RS ratio at 30 MHz had an arithmetic mean, a geometric mean, and a standard deviation of 1.4, 1.3, and 0.65, respectively, and had minimum and maximum values of 0.56 and 2.4, respectively.

A comparison of the results obtained in this thesis with the results presented previously by other researchers in references 14–17 shows that the mean of the PB to RS ratio is relatively high in temperate regions, such as Sweden and Finland, compared to that of tropical regions, such as Malaysia and Sri Lanka. This indicates that the peak amplitude of the PB pulses is higher in the temperate regions than in the tropical regions. Results obtained in Florida, a mid-
latitude region, show mixed values comparable to either tropical or temperate values [15].

Data on the ratio of the 3 MHz and 30 MHz signals associated with PB and RS in the tropics are not available in the literature but, as can be seen, the PB to RS ratio for 3 MHz and 30 MHz signals is higher than the corresponding ratio of the wideband signals in Sweden (see Figure 2 (a, b)). This shows that the PB pulses are strong radiators of 3 and 30 MHz.

The results presented above are in agreement with the argument made in references 2, 18, and 19, that at higher latitudes, the detection of stronger PB pulse trains in lightning flashes could be due to the stronger lower positive charge region (LPCR) below the main negative charge centre. A larger LPCR enhances the electric field between the negative charge centre and itself, leading to an intense breakdown process. The height of the cloud can also influence the amplitude of the broadband and narrowband signal amplitudes of PB pulses. At a given distance from the strike point, the distance to the LPCR increases with increasing cloud height.
3.1.3 Stepped Leader (SL)

The inception of PB activity in the cloud may subsequently lead to descending stepped leaders that culminate in return strokes. The stepped leader may immediately follow the PB pulse train, or there may be a pause in between. The pause is referred to in the literature as the “Intermediate stage” in the BIL structure, even though some researchers [20] have interpreted the BIL structure as the start and the continuation of the stepped leader, without any “pause”. Researchers such as Gomes et al. [14], Beasley et al. [21], and Thomson [22] have used different techniques to identify the beginning of the stepped leader. However, according to Cooray [23], a major problem in evaluating the duration of a stepped leader field is caused by the difficulty of pinpointing its exact beginning. In our study, we have used 3MHz radiation to identify the initiation of the stepped leader. In the data, one can notice that the intensity of the 3MHz radiation increases after the intermediate stage. At the same time, one can observe the appearance of pulses in the broadband electric field, indicating the movement of a stepped leader. We have also observed that, in the case of BL structure, the 3 MHz signal shows a “transition phase” with no significant variations in amplitude between the “B” and “L” phases. The corresponding part of the wideband signal shows slow field changes between “B” and “L”, as shown in Figure 3. To identify the beginning of the stepped leader in the case of BL structure, a comparison between the wideband and the 3 MHz signals was used. We can consider the start of a leader as being
when the 3 MHz signal shows a “transition phase” with no significant amplitude variations after the breakdown (“B”) region in the corresponding wideband signal.

The arithmetic and geometric means of SL/RS are 0.14 and 0.11, respectively, for the wideband signals. However, for 3 MHz signals, the ratio (SL/RS) is much larger (the arithmetic and the geometric means are 0.42 and 0.38, respectively) than that of the wideband signals, as depicted in Figure 4 (a, b). This also indicates that 3 MHz radiation is a good measure to identify the initiation of a stepped leader after the preliminary breakdown.

![Figure 3](image.png)

*Figure 3:* The pulse structure, together with the 3 MHz signal, around the transition from “B” to “L” in the case of “BL” type structure.
Figure 4: A section of a ground flash containing the stepped leader field with (a) wideband and (b) 3 MHz radiation. Recorded on 19 July 2014 at 18:25:47.489798 from a flash whose strike point (60.1850°N, 17.87690°E) was 40.76 km from the measuring station.
3.1.4 Return Stroke and Subsequent Return Stroke
3.1.4.1 Inter-stroke Interval

From the data, we have analysed the distribution of inter-stroke intervals and how the inter-stroke interval varies as a function of stroke order. The arithmetic and geometric means of inter-stroke interval (i.e., the time separation between strokes) were 40 ms and 37 ms, respectively, with a range of 2 ms to 142 ms, based on 98 flashes and a total of 206 subsequent return strokes. Our data, together with the data available in the literature, indicate that there is a tendency for the inter-stroke interval to depend on the geographical region. The arithmetic mean values of the inter-stroke interval for tropical regions (Sri Lanka [24], Malaysia [25], Papua New Guinea [26], and Brazil [27]) lie between 83 and 90, whereas they lie between 64 and 65 for temperate regions (Sweden [28] and China [29]). The variation of the inter-stroke interval with the stroke order is shown in Figure 5. Note that there is a tendency for the inter-stroke interval to decrease as the stroke order increases. The interval between the first RS and the first SRS shows higher arithmetic and geometric means (46 ms and 43 ms, respectively) than other intervals, as depicted in Figure 5.

![Inter-stroke Interval](image)

*Figure 5: Inter-stroke interval as a function of stroke order*
3.1.4.2 The Relative Peak Amplitudes of the First and Subsequent Return Strokes

In general, the subsequent return stroke peak amplitude is less than that of the first return stroke. According to our data, the average value of the ratio of the broadband subsequent return stroke peak to the first return stroke peak is 0.46. At 3 MHz, the arithmetic mean value of this ratio is 1.05, and the geometric mean is 0.77. This indicates that, in general, the strength of the 3 MHz radiation is more or less the same in the first and subsequent return strokes.

A plot of the SRS to RS ratio of the successive return strokes as a function of stroke order is shown for both wideband and 3 MHz in Figure 6. Observe that the ratio decreases in general, with some scatter. The same tendency is shown in the case of the ratio obtained for the 3 MHz radiation.

![Figure 6: The ratio of the peak amplitudes of SRS and RS (both for wideband and for 3 MHz signals) as a function of stroke order. WB = wideband.](image)

3.1.5 Some Aspects of the 30 MHz Radiation

In our study, we could observe 30 MHz radiation only from PB. Even though the mechanisms pertinent to the generation of radiation in the frequency range above 3 MHz are not well understood, it is thought that this radiation is caused by the electrical breakdown of virgin air rather than by the high current pulses propagating in pre-existing channels. The data presented in sections 3.1.2.2 and 3.1.4.2 also show that more 3 MHz radiation is generated during preliminary breakdown processes taking place inside clouds (probably associated...
with the breakdown of virgin air) than during the subsequent return strokes that propagate along conducting channels.

3.1.6 Number of Strokes

The maximum number of strokes (multiplicity) observed in our study was 11. An example is shown in Figure 7 together with the 3 MHz signal. Since our recording window was 250ms, it is very likely that we might have missed some subsequent strokes that occurred outside our time window. Nonetheless, within the given time window, the average number of return strokes observed was three, which is in reasonable agreement with those observed in different geographical locations [30, 31].

![Figure 7: A flash with the maximum stroke multiplicity observed in Sweden during the 2014 measurement campaign, with wideband and 3 MHz radiation. The flash was recorded on 21 July 2014 at 15:34:54.829297. The distance from the measuring station to the first strike location (59.7350°N, 17.74230°E) was 13.5 km.](image)
3.2 Comparison between Initial Breakdown Pulses and Narrow Bipolar Pulses in Lightning Discharges, with Special Attention to Time Derivative of Electric Field Characteristics (Paper II)

The physical mechanisms of initial breakdown pulses and narrow bipolar pulses in lightning discharges are not well understood, and there are different opinions about the origins of these pulses. The question is whether these two types of pulses are produced by the same (or a similar) mechanism active inside the cloud. In this study, we made an attempt to answer this question by comparing and contrasting the electric field and electric field derivative of these two pulses.

In Figure 8, a typical wideband electric field pulse identified as an initial breakdown pulse is shown together with the corresponding measured electric field derivative. Unfortunately, NBPs are very rare in Swedish thunderstorms [32], so we have used the NBP data of Willet et al. (1989) [33] in our comparison between the electric fields and electric field derivatives of initial breakdown pulses and NBPs. Figures 8 and 9 show a preliminary breakdown pulse and a NBP together with their time derivatives. Observe the similarity in the signatures of the broadband electric fields. Of course, not all preliminary breakdown pulses had signatures similar to NBPs. While NBPs have a smooth rise to peak, many preliminary breakdown pulses had multiple pulses on their rising part. This comparison shows that, while the broadband signatures of many preliminary breakdown pulses may resemble those of NBPs, the electric field derivatives of the two types of pulses differ significantly. One major difference is the highly oscillating nature of the derivatives of NBPs in comparison to those of initial breakdown pulses.

To study this further, we have analysed the electric field data from Malaysia, which contain both IBPs and NBPs. An example of these pulses is shown in Figure 10. As pointed out earlier, observe that the broadband signatures of the two pulse types are similar. In Figures 11 and 12, the derivatives of both types of pulses, obtained numerically from the broadband records, are shown. Note again that the derivative for NBPs oscillates more than that of the initial breakdown pulses.

The comparison shows that there is a significant difference between the electric field derivatives of IBP and NBP. This makes a strong case for the argument that they are produced by two different physical mechanisms.
Figure 8: An example of a typical initial breakdown pulse (IBP) measured from a Swedish thunderstorm within 20 km from the measuring station. (a) Electric field. (b) Electric field derivative.

Figure 9: A positive NBP measured from a thunderstorm over the sea, 45 km from the measuring station. (a) Electric field; (b) Electric field derivative. Adapted from Willett et al. [33]. Note that these authors have used a physics sign convention that is opposite to the one adopted in this thesis.
Figure 10: A comparison between IBP (black line), NPBP (red line), and NNBP (blue line) recorded in Malaysia. The upper set of diagrams shows the electric field, and the lower set shows the derivative of the electric field. Observe the similarity of the electric fields of IBP and NNBP and the differences in the corresponding derivatives.
Figure 11: A Comparison between IBP (blue line) in Sweden and NPBP (red line) in Malaysia. (a) Electric field. (b) Electric field derivative.
3.3 On the Zero-Crossing Time of Radiation Fields Generated by Return Strokes in Lightning Flashes (Paper III)

The distant radiation field of a return stroke can be expressed in terms of the derivative of a current moment, $M(t)$, defined as [34]

$$M(t) = \int_{0}^{h(t)} I(z, t) \, dz \quad (1)$$

In the above equation $I(z, t)$ is the return stroke current at height $z$, and $h(t)$ is the instantaneous height of the return stroke front. The height is measured from ground level. The distant radiation field at ground level at a distance $d$ from the strike point, $E(t, d)$, is given by [34]

$$E(t, d) = \frac{1}{2\pi\varepsilon_0 c^2 d} \frac{dM(t - d / c)}{dt} \quad (2)$$
Equation 2 shows that the zero-crossing time of the radiation field gives the time at which the current moment of the discharge process reaches its peak value. Observe first that, since the current moment will reach zero when the current in the channel ceases, the time integral of the radiation field of a return stroke is equal to zero. This makes the radiation field bipolar.

It is important to point out that the equations given above are valid only for the distant radiation field. However, close to the channel, the electric field may have contributions both from induction and from electrostatic terms. The time integral of these terms does not go to zero. Thus, it is important that only the distant radiation fields are used in the analysis of the zero-crossing time. Of course, one can immediately see whether the fields are contaminated by static fields by observing the behaviour of the integral of the field. If the integral continues to increase as time increases, it is a sure indication that the field contains a static component. It is also possible that the initial part of the field is mainly radiation, while the tail of the field is contaminated by static fields. In this case, the integral of the radiation field may reach a peak and then start to decay, but after continuing this decay for some time, it may start to increase again. However, even in this case, one can make a reasonable judgement concerning the time at which the current moment reached its peak value and hence the zero-crossing time of the radiation field. One also has to be careful to make sure that the distance to the lightning flash is such that the initial portion of the field is not contaminated by ionospheric reflections. If the distance to the lightning flash is within about 200 km, the ionospheric reflections are usually delayed by about 100 µs and therefore do not disturb the zero crossing times [35].

Figure 13 shows an example of a radiation field generated by a negative return stroke together with its integral. The point where the integral of the radiation field reaches its peak value is marked, and it is this time that is selected as the zero-crossing time of the radiation field. Note that in the example shown in Figure 13, the traditional method of defining the zero-crossing time (i.e., defining the first crossing of the zero line by the electric field as the zero-crossing time) would have generated a zero-crossing time significantly smaller than the one estimated based on the method of integration. That is, the conventional approach gives a smaller zero-crossing time than the new approach presented here. The zero-crossing times obtained from the new approach can be considered a better barometer to represent the physical phenomenon taking place in the return stroke channel.
Figure 13: The zero-crossing time (ZCT) of the radiation field generated by a negative return stroke, estimated using the traditional and time integral methods. The traditional method gives a value of 42 µs for the zero-crossing time, while the new method gives 66 µs. Note that “X” represents the ZCT as defined using the traditional method, while “O” represents ZCT as defined using time integral method.
3.4 Characteristics of Chaotic Pulse Trains and their Connection to RPTs Associated with Dart and Dart-Stepped Leaders in Lightning Flashes in Sweden (Paper IV)

In this study, electromagnetic field radiation bursts known as chaotic pulse trains (CPTs) associated with dart and dart-stepped leaders in Sweden were analysed. There were 206 subsequent return strokes in 98 flashes, and 50% of these subsequent return strokes were preceded by CPT. In our data, 73 dart-stepped leaders and 30 dart leaders were associated with CPT; different types of CPT were analysed based on their occurrence with respect to the regular pulse trains (RPTs) associated with dart and dart-stepped leaders. We categorized the CPTs associated with dart and dart-stepped leaders as follows:

- Type A: RPT preceding CPT and separated in time (18 cases).
- Type B: RPT following CPT and separated in time (17 cases).
- Type C: RPT without CPT (12 cases).
- Type D: CPT without RPT (8 cases).
- Type E: CPT superimposed on the dart leader and dart-stepped leader fields (6 cases).
- Type F: RPT superimposed on the dart and dart-stepped leader fields (6 cases).
- Type G: mixed train, with CPT preceding RPT without being separated in time (10 cases).
- Type H: mixed train, with CPT following RPT without being separated in time (16 cases).
- Type I: mixed train, with CPT appearing in the middle of RPT without any time separation (6 cases).
- Type J: mixed train, with RPT appearing in the middle of CPT without any time separation (4 cases).

In the study, 103 CPTs (types A–J) associated with dart and dart-stepped leaders were detected in 64 flashes. Out of these, 64 trains were detected between the first and second return strokes (RS), 27 trains were detected between the second and third RS, and 12 trains were detected between the third and fourth RS. The average time separation from the end of the preceding RS to the beginning of CPT and RPT (types A, B, C, D, G, H, I, and J) was about 24 ms (arithmetic mean, or A.M) or 23 ms (geometric mean, or G.M). The average time separation from the end of the preceding RS to the beginning of CPT or RPT (types E and F) was about 34 ms (A.M) or 32 ms (G.M). The average time separation from the end of the CPT-RPT sequence (types A, B, C, D, G, H, I, and J) to the following RS was found to be about 4 ms (A.M) or 3.6 ms (G.M). The average time separation from the end of CPT or RPT (types E and F) to the following RS was about 82 µs (A.M) or 79 µs (G.M). Finally, the
average time separation from the beginning of dart and dart-stepped leaders to the following RS was about 78 µs (A.M) or 72 µs (G.M).

The statistical information provided here on the occurrence of CPT-RPT associated with dart and dart-stepped leaders (type A–J) in Swedish thunderstorms may help us to understand the chaotic pulse characteristics and their possible origin in lightning flashes.

3.5 On the Possible Origin of Chaotic Pulse Trains in Lightning Flashes (Paper V)

3.5.1 Characteristics of RPTs

Pulses in the RPT occur at quite regular time intervals. Each pulse in the RPT begins with a fast and large-amplitude portion, followed by a small and slowly varying overshoot. However, in some pulses, the opposite overshoot is not that pronounced. If we consider any pulse with an opposite overshoot to be bipolar, then almost all the pulses we observed in the present study can be categorized as bipolar. However, in a study conducted by Kolmasova and Santolik [36], each individual pulse is considered to be unipolar if the immediately following overshoot of the opposite polarity does not exceed one-half of the peak amplitude of the original’s pulse. If we use this criterion, then most of the individual pulses in the RPT should be categorized as unipolar. However, as indicated earlier, any radiation field pulse generated by a finite-duration event should have an opposite overshoot. In the present study, we have recorded a total of 42 distinct RPTs, and the total number of individual pulses in these RPTs was 800, so on average, each RPT had about 22 pulses. The individual pulse duration (PD) has an arithmetic mean of about 2 ± 1.0 µs. A sequence of pulses normally persists for 23–98 µs, with an arithmetic mean of inter-pulse duration (IPD) of about 5 ± 1.3 µs. The average electric field amplitude of pulses in the RPT was about one-fifth of the electric field peak of the return stroke; this ratio varied from 0.1 to 0.4.

3.5.2 Characteristics of CPTs

In the present study, we have recorded a total of 40 distinct CPTs. There were 1120 individual pulses in these CPTs, so each CPT had 28 pulses on average. Because of their chaotic behaviour, especially with regard to their amplitudes, pinpointing the exact beginning and end of each pulse in the CPT is difficult.

The total duration (TD) of the CPT is estimated using the criterion adopted by Gomes et al. [10]. According to this criterion, TD is the time duration between
the regions of pulse activity at the start and end of the pulse train where the pulse amplitude is equal to 10% of the maximum amplitude in the CPT. In several cases where the noise level was high, we had to increase this limiting value to 20%. In our study, the observed duration, TD, of the CPTs varied from 20 to 120 µs. We estimated the TD, PD, and IPD manually, with an estimated uncertainty of about ±0.5 µs. Pulse duration (PD) is the width of an individual pulse when the amplitude at the start and end of the individual pulse is equal to 10% of the maximum amplitude. The width of each pulse, or its duration (PD), varied within the range of 0.5 to 13 µs, with an arithmetic mean and standard deviation of about 4 and 3 µs, respectively. The inter-pulse duration (IPD) is the time duration between the maximum amplitude of two consecutive pulses in the train. The IPD varied within the range from 2 to 13 µs, with an arithmetic mean and standard deviation of about 8 and 5 µs, respectively. The arithmetic mean of the ratio of the maximum amplitude of the CPT to the following return stroke peak was 0.4 ± 0.3.

3.5.3 HF Radiation

In the current study, we recorded HF radiation at 3 MHz simultaneously with the CPT and the RPT. The HF radiation associated with CPTs was previously reported by Mäkelä et al. [37], but as far as we know, there were no reports on measurements of HF radiation associated with RPTs. Similar to a chaotic pulse burst, the amplitude of which is chaotic in nature, the 3 MHz signal associated with CPTs had a chaotic nature. In contrast, the 3 MHz signal associated with an RPT had a more or less regular variation in amplitude. This information was important because it could be utilized to find the transition of the electric field from one type of pulse train to another type (i.e., RPT to CPT or vice versa) using the 3 MHz signal. Indeed, this was used as a check to confirm the estimated transition times between pulse trains using the wide-band signal.

3.5.4 Numerical Analysis: Construction of a CPT through the Numerical Superposition of RPTs

The similarity in the widths of individual pulses in both regular pulse trains and chaotic pulse trains and the occurrence of regular pulse trains at the start, in the middle, or at the end of chaotic pulse trains suggested to us that the CPTs are probably created by the superposition of several RPTs at random times. This is a physically reasonable scenario because, during lightning flashes, there could be instances where several dart-stepped leaders, or similar discharge processes, are simultaneously active in a cloud. Each dart-stepped like leader produces an RPT, and the sum of the signals from all the dart-stepped like leaders may appear as a CPT. Indeed, by numerical superposition of several RPTs, we have shown that this could be the case.
In the numerical superposition, we tried superimposing either an RPT of the same polarity or RPTs with mixed polarities (i.e., adding both positive and negative RPTs to create CPTs). Both procedures gave rise to chaotic-type pulse bursts. The reason we tried constructing a CPT with mixed polarity was that our records showed that, occasionally, the polarity of pulses in RPTs changes. In other words, the RPT may start with pulses of one polarity but end with the other. This showed that, in some situations, it is possible for an RPT of one polarity to interact with an RPT of the opposite polarity in the creation of CPTs.

Interestingly, the pulse trains created by superimposing several RPTs at random times have characteristics very similar to those observed in chaotic pulse trains. An example is shown in Figure 14. The similarity of simulated CPTs to the ones measured strongly suggests that these pulse trains are created by a series of dart-stepped leader like discharges propagating simultaneously in the cloud.

As an additional check, we have analysed the Fourier spectrum of measured and constructed CPTs. The results show that the Fourier spectra of constructed and measured CPTs are almost identical, and, as shown in Figure 15, they both have a peak around 200 kHz. This similarity of the Fourier spectrums also suggests the common origin of RPTs and CPTs.
Figure 14: Chaotic pulse burst produced by the numerical superposition of RPTs. (a) the three RPTs used in the superposition. (b) The constructed CPT together with a measured example.

Figure 15: Comparison of the Fourier spectra of simulated (superposition of three RPTs) and measured CPTs.
3.6 Wavelet Transformation of CPTs and RPTs (Paper VI)

3.6.1 Characteristics of RPTs and CPTs in the Time-Frequency Domain

Pulses in RPTs occur at quite regular time intervals and have a consistent pattern. One observation of interest to this study is that RPTs occur in association with CPTs. In the present study, 42 RPTs, with a total of 800 pulses (22 pulses on average in each train, mostly following or preceding the CPT), were found. In this study, we have used the wavelet transformation to analyse these pulse trains.

This study uses the following definitions for wavelet parameters: The spectral region is the region where radiated energy is significant. In the diagrams, this region is bounded by a light blue colour contour. The spread region is the spectral region where radiation is most intense. In diagrams, this region is bounded by a dark red colour contour. Wavelet transformation shows that the spread region of RPT is in the range of 85 kHz to 300 kHz, and the spectral region is in the range of 80 kHz to 600 kHz.

As mentioned previously, in our study, we have recorded about 40 CPTs with 1120 pulses (each train had 28 pulses on average). According to the wavelet analysis, the spread region and the spectral region of CPTs are in the frequency ranges of 100 kHz to 400 kHz and 80 kHz to 3 MHz. Note that the spread region of the RPTs coincides closely with the spread region of the CPTs. This also indicates the common origin of these pulse trains.

3.6.2 Numerical Superposition: CPT Created by RPTs through Wavelet Transform Technique

In this section, we will show that the hypothesis that the CPTs are a superposition of several RPTs is supported by the wavelet analysis of the measured and constructed CPTs. We will also show that the wavelet transformation of constructed CPTs is similar to that of the measured CPTs.

Since, according to our hypothesis, the chaotic pulse burst is a superposition of several regular pulse bursts, the power radiation associated with the chaotic pulse burst can be treated as the sum of the power radiation associated with regular pulse bursts. Thus, when wavelet transformations of several RPTs overlap, depending on their relative shift and frequency range, the resulting wavelet transformation should show characteristics similar to that of a measured CPT.
Figure 16 shows the wavelet transformation of 3 RPTs that were used to construct a CPT. Figure 17 shows the sum of the time domain signals and the sum of the wavelet transformations. Figure 18 shows a measured CPT together with its wavelet transformation. Note the similarity of the two wavelet transformations, one constructed and the other obtained from measurements. They both have intense power radiation at about 200 kHz, as shown in Figures 17 and 18. This observation also supports the hypothesis that CPTs and RPTs have a common origin.

**Figure 16**: (a) The three RPTs used in constructing a CPT. (b) The wavelet transformations of the three RPTs.
Figure 17: (a) The simulated CPT obtained by addition of three RPTs. (b) The sum of wavelet transformations of the three CPTs. (c) An expanded view of the region where the power radiation is intense. The region of the highest power is marked by two dotted lines. Note that it occurs around 200 kHz.
Figure 18: (a) A measured CPT. (b) The wavelet transformation of the CPT. (c) An expanded view of the region where the power radiation is intense. The region of the highest power is marked by two dotted lines. Note that it occurs around 200 kHz.
4 Concluding remarks and future works

4.1 Concluding Remarks

The conclusions of the thesis are summarized as follows:

(a) **Paper 1:**
   - We find more intense but shorter-duration preliminary breakdown activity in temperate regions than in tropical regions.
   - When compared to return strokes, preliminary breakdown pulses generate stronger fields at 3 and 30 MHz.
   - The inter-stroke intervals of return strokes tend to decrease as the order of the subsequent return strokes increases. Inter-stroke interval seems to be shorter in temperate regions than in the tropics.

(b) **Paper II:**
   - The study showed that the physical mechanisms that lead to the NBP and the IBP are different. A similarity of the broadband signal may not be a guarantee that the processes are produced by the same mechanism.

(c) **Paper III:**
   - A new procedure was introduced to estimate the zero-crossing times of the radiation fields. The new procedure generates zero-crossing times which are significantly later than the ones obtained using the traditional method.

(d) **Paper IV and V:**
   - The electromagnetic field radiation bursts known as CPTs and RPTs which are generated by lightning flashes were analysed. Statistical data on the features of chaotic pulse trains (CPTs) and regular pulse trains (RPTs) were provided, and it was hypothesized that CPTs are created by the superposition of several RPTs.

(e) **Paper VI:**
   - Simulations based on Fourier and Wavelet transformations of CPTs and RPTs support the hypothesis made in Papers IV and V.
4.2 Future works

The results of this thesis are based on the electromagnetic fields from lightning flashes measured at a single recording station. In future, multiple station measurements, in combination with interferometric studies, are needed to push this field forward.
Svensk Sammanfattning

Negativa markblixtar (cloud-to-ground, CG) transporterar negativ laddning från moln till mark. Negativa markblixtar omfattar typiskt olika processer, vilka identifieras som förurladdning, stegurladdning, huvudurladdning, pilurladdning, stegvis pilurladdning, efterföljande huvudurladdning, regelbundet pulstág och kaotiskt pulstág. Dessa processer ger sig till känna genom sina Elektromagnetiska fältsignaturer. Denna avhandling fokuserar på att dokumentera dragen hos och förstå källorna till elektromagnetiska fält från blixturladdningar, i synnerhet de kaotiska pulstågen.


Resultaten visar att förurladdningspulser strålar starkare än huvudurladdningar vid 3 MHz och 30 MHz. En jämförelse av våra resultat med tidigare studier i olika geografiska områden visar tydligt att styrkan hos förurladdningspulser avtar med latituden. Styrkan är alltså högre i tempererade områden (t.ex. Sverige) och lägre i tropiska områden.

En jämförelse av tidsderivatorna hos förurladdningspulser och smala bipolära pulser visar att de har olika fysikaliska ursprång, fastän de kan ha liknande utseenden i bredbandsfälten.

Denna avhandling introducerar en ny procedur för att skatta tidpunkten för nollgenomgången hos strålningsfälten från blixtar. Proceduren bygger på att tidsintegralen av strålningsfältet från en urladdning med ändlig varaktighet är lika med noll, samt på att tidpunkten för fältets nollgenomgång svarar mot den tidpunkt då tidsintegralen når sitt maximala absolutbelopp.

Förutom att tabellera olika statistiska parametrar hos kaotiska pulståg (CPT), visas det att dessa pulståg skapas av flera samtidiga stegvisa pilurladdningar i molnet. Varje sådan stegvis pilurladdning alstrar ett regelbundet pulstág (RPT). Flera stegvisa pilurladdningar kombineras slumpmässigt i tiden så att
de alstrar kaotiska pulståg. Denna slutsats bygger på resultaten som erhållits ifrån numeriska simuleringar och genom att analysera signatureerna från dessa pulståg med hjälp av Fourier- och wavelettransformer.

Resultaten som presenteras i denna avhandling visar att elektromagnetiska fält, även om de mäts från en enda station, kan användas för att utvinna information om de bakomliggande fysikaliska processerna.
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With best regards,

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A doctoral dissertation from the Faculty of Science and Technology, Uppsala University, is usually a summary of a number of papers. A few copies of the complete dissertation are kept at major Swedish research libraries, while the summary alone is distributed internationally through the series Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology. (Prior to January, 2005, the series was published under the title “Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology”.)