Broadband and HF Radiation from Cloud Flashes and Narrow Bipolar Pulses

NOOR AZLINDA AHMAD
Dissertation presented at Uppsala University to be publicly examined in Å2001, Ångström Laboratory, Lägerhyddsvägen 1, Uppsala, Wednesday, May 25, 2011 at 14:15 for the degree of Doctor of Philosophy. The examination will be conducted in English.

Abstract

Remote measurement of electric field generated by lightning has played a major role in understanding the lightning phenomenon. Even though other measurements such as photographic and channel base current have contributed to this research field, due to practical reasons remote measurements of electric field is considered as the most useful tool in lightning research.

This thesis discusses the remotely measured radiation field component of electric field generated by cloud flashes (ICs) and narrow bipolar pulses (NBPs). The associated HF radiation of these events at 3 MHz and 30 MHz are also discussed. To understand the initiation process of these discharges, a comparative study of the initial pulse of cloud flashes against the initial pulse of cloud to ground flashes was conducted. The result suggests that both discharges might have been initiated by similar physical processes inside the thunderclouds. Comparing the features of initial pulse of cloud and ground flashes with that of pulses that appeared in the later stages of cloud flashes suggests that the initiation process involved in both flashes are not very much different from the initiation of cloud flashes at the later stage. The average spectral amplitudes of electric field of full duration cloud flashes (180 ms) showed $f^{-i}$ frequency dependence within the interval of 10 kHz to approximately 10 MHz. This is in contrast to the standard $f^{-2}$ decrement (or even steeper) at high frequency region for other lightning processes such as return strokes. It was suggested that small pulses which repeatedly appeared at the later stage of cloud flashes might have contributed to enhance the spectral amplitude at higher frequencies.

Electric fields generated by Narrow Bipolar Pulses (NBPs), which are considered as one of the strongest sources of HF radiation, were measured in the tropics of Malaysia and Sri Lanka. Their features were also studied and show a good agreement with previously published observations of NBPs from other geographical regions. Thorough analyses and observations of these pulses found previously unreported sharp, fine peaks embedded in the rising and decaying edge of the electric field change of NBPs. Therefore it was suggested that these fine peaks are mostly responsible for the intense HF radiation at 30 MHz.

Keywords: Lightning, Cloud Flashes, Narrow Bipolar Pulses, HF radiation

Noor Azlinda Ahmad, Disciplinary Domain of Science and Technology, Box 256, Uppsala University, SE-75105 Uppsala, Sweden.

© Noor Azlinda Ahmad 2011

ISSN 1651-6214
ISBN 978-91-554-8067-7
urn:nbn:se:uu:diva-150956 (http://urn.kb.se/resolve?urn=nbn:se:uu:diva-150956)
Till min älsklingar
Abdul Rahim, Sarah och Nurin
List of Papers

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


IV  **N. Azlinda Ahmad**, Z.A.Baharudin, M. Fernando, V.Cooray, Some Features of Electric Field Waveform of Narrow Bipolar Pulses. Submitted to Special Issue, Journal of Atmospheric Discharge, January 2011. Part of this work has been presented in the International Conference of Lightning Protection (ICLP), Cagliary, Italy, 2010.

Reprints were made with permission from the respective publishers.
Other contributions of the author, not included in this thesis


VI  Z.A. Baharudin, **N. Azlinda Ahmad**, M. Fernando, V. Cooray, J.S. Mäkelä, Comparative study on preliminary breakdown pulse trains observe in Malaysia and Florida. Submitted to Special Issue, Journal of Atmospheric Discharge, January 2011.


VIII Z.A. Baharudin, **N. Azlinda Ahmad**, M. Rahman, V. Cooray, M. Fernando, J.S. Mäkelä, H. Ahmad, Z.A. Malek. Negative cloud to ground lightning flashes in Malaysia. In manuscript.


X Z.A. Baharudin, M. Fernando, **N. Azlinda Ahmad**, M. Rahman, V. Cooray, J.S. Mäkelä, Slow field changes features prior the first return stroke observed in Malaysia. Submitted to Journal of Atmospheric and Solar Terrestrial Physics.

Contents

Outline of the thesis .............................................................................................................. 10

1. Introduction ..................................................................................................................... 11
   1.1 Types of lightning .................................................................................................. 13
   1.2 Objectives of the thesis ......................................................................................... 14

2. Data and measurement .................................................................................................. 16
   2.1 Parallel flat plate antenna .................................................................................. 16
   2.2 Electronic circuit .................................................................................................... 18
   2.3 High Frequency antenna ..................................................................................... 20
      2.3.1 3 MHz tuned circuit .................................................................................... 20
      2.3.2 30 MHz tuned circuit .................................................................................. 22
   2.4 Measuring sites ....................................................................................................... 25
      2.4.1 Vero Beach, Florida ....................................................................................... 25
      2.4.2 Universiti Teknologi Malaysia, Johor, Malaysia ........................................... 26
      2.4.3 Uppsala, Sweden ........................................................................................... 28
      2.4.4 Colombo, Sri Lanka ...................................................................................... 31

3. Types of cloud processes ............................................................................................. 32
   3.1 Cloud flashes (ICs) ............................................................................................... 32
   3.2 Narrow Bipolar Pulses (NBPs) ............................................................................. 34

4. High frequency radiation from lightning ...................................................................... 37
   4.1 Overview ................................................................................................................ 37
   4.2 Frequency spectrum of lightning electromagnetic fields ...................................... 41
   4.3 Possible causes of HF radiation from lightning .................................................... 43

5. Results and discussions ............................................................................................... 44
   Paper I .......................................................................................................................... 44
   Paper II ........................................................................................................................ 45
   Paper III ......................................................................................................................... 47
   Paper IV ........................................................................................................................ 49

6. Concluding Remarks ...................................................................................................... 51

Svensk sammanfattning ....................................................................................................... 53

Acknowledgements ............................................................................................................. 55
## Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CGs</td>
<td>Cloud to ground flashes</td>
</tr>
<tr>
<td>FWHM</td>
<td>Full Width at Half Maximums</td>
</tr>
<tr>
<td>dE / dt</td>
<td>Electric field time derivatives</td>
</tr>
<tr>
<td>HF</td>
<td>High frequency</td>
</tr>
<tr>
<td>ICs</td>
<td>Cloud flashes</td>
</tr>
<tr>
<td>kHz</td>
<td>Kilo Hertz</td>
</tr>
<tr>
<td>MHz</td>
<td>Mega Hertz</td>
</tr>
<tr>
<td>NBPs</td>
<td>Narrow Bipolar Pulses</td>
</tr>
<tr>
<td>NNBPs</td>
<td>Narrow Negative Bipolar Pulses</td>
</tr>
<tr>
<td>NPBPs</td>
<td>Narrow Positive Bipolar Pulses</td>
</tr>
<tr>
<td>RF</td>
<td>Radio frequency</td>
</tr>
<tr>
<td>RS</td>
<td>Return strokes</td>
</tr>
<tr>
<td>RT</td>
<td>Rise time</td>
</tr>
<tr>
<td>UHF</td>
<td>Ultra high frequency</td>
</tr>
<tr>
<td>UTM</td>
<td>Universiti Teknologi Malaysia</td>
</tr>
<tr>
<td>VHF</td>
<td>Very high frequency</td>
</tr>
<tr>
<td>ZCT</td>
<td>Zero crossing time</td>
</tr>
</tbody>
</table>
Outline of the thesis

The thesis is based on four papers and divided into six chapters. The first chapter (Chapter 1) gives an overview of the lightning process, the objectives and outline of the thesis.

Chapter 2 deals with the data and measurement set up.

Chapter 3 provides some theoretical background of cloud flashes. A general overview of the NBPs is discussed under different subsections in Chapter 3.

Chapter 4 deals with the high frequency radiation from lightning. The main objective in Chapter 4 is to provide some ideas of how lightning radiates at high frequency (HF) and what could be the possible HF sources.

Chapter 5 summarizes the papers which this thesis is based on. The conclusion of this thesis work is addressed in Chapter 6.

Nomenclature: In this thesis and in Papers I and II, the positive electric field change at ground level is defined in terms of the displacement of negative charges downward and positive charges being raised upward, similar to the electric field change of negative return strokes. For Papers III and IV, the definition is the opposite. Further the word ‘discharges’ and ‘flashes’ will be used interchangeably to address the lightning process.
1. Introduction

Lightning is perhaps the most powerful display of electrostatics in nature and is inescapable from humankind's attention. They are never invited, never been planned for and have never gone unnoticed. The rage of a lightning strike will wake a person in the middle of the night. The fury of a lightning strike is capable of interrupting midday conversations and activities. People will crowd around windows to watch the lightning displays in the sky, standing in awe with the power of static discharges.

Figure 1 Benjamin Franklin’s kite experiment proved the electrical nature of lightning (Adapted from a)

---
a http://knowledgelost.org/culture/benjamin-franklin-the-perfectionism
More than 250 years ago, Benjamin Franklin’s idea that lightning is an electrical discharge in nature has opened a pioneering research field in lightning. Since then, our knowledge of the lightning phenomena has advanced greatly. Among the remarkable breakthroughs of lightning research are the electrostatic field measurements from lightning, which has confirmed the appearance of positive electric dipole inside the thunderclouds and the use of cathode–ray oscillographs to record and investigate lightning discharges. Furthermore, the invention of the streak camera which was used extensively in the lightning study by B.J.F Scholand, D.J Malan and their colleagues in South Africa in 1930s, has contributed significantly to our understanding of lightning. It is often believed that the revolution of lightning research began in the early nineteenth century although some significant work has been carried out in the latter half of the nineteenth century. Modern measurements of lightning research can be divided into five categories:

i) spectroscopic measurement
ii) electric current measurement
iii) photographic
iv) electric and magnetic field measurement
v) acoustic measurement

Tremendous advancements in instruments and measuring techniques have helped in comprehending the characteristics of lightning. Lightning can be detected either from the ground or space. Examples of lightning detection from the ground are Time of Arrival (TOA), magnetic direction finding and interferometry. The interferometry technique introduced by Proctor is preferably used to achieve higher resolution observations and has been widely employed in lightning observations and detections. From space, lightning can be detected by using satellites or imaging sensors (LIS). However, no differences between the lightning types (cloud or ground discharges) can be distinguished.

Even though lightning measurement spans a wide range of studies, the main objective of this thesis work is to focus only on remotely measured electric field from lightning. This is mainly due to the practical limitations of other techniques and the random nature of lightning. A great deal of useful information can be obtained by analyzing the broad band and narrow band radiation fields generated by lightning. In this thesis, features of broad band electric field radiation of cloud flashes and narrow bipolar events together with the associated HF radiation at 3 MHz and 30 MHz are studied. The data were recorded in the temperate, tropical and subtropical regions.
1.1 Types of lightning

Lightning can be divided mainly into two types namely, cloud to ground discharges (CGs) and cloud flashes (ICs). Rare forms of lightning such as blue jets, red sprites and elves have been also documented. When lightning strikes the ground or a grounded object, it is called a ground discharges (CGs). There are four types of CGs:

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

The downward negative lightning transports negative charges from the main negative charge center to ground and account for 90 % of ground discharges\textsuperscript{51}. The other 10 % of ground discharges are downward positive lightning which transport positive charges to ground from the main positive charge center. Even though positive CGs constitute only 10 % of the discharges, they are always associated with the highest peak current (~300 kA) and largest charge transfers to ground (hundreds of Coulombs)\textsuperscript{53}. Upward lightning, as opposed to the downward lightning typically occur due to the presence of tall objects or structures (more than 150 m) and hence can be considered to be initiated by the object itself. According to Berger, (1978, in Rakov and Uman\textsuperscript{53}) this type of flashes has been observed to transport more often negative charges than positive charges to ground.

\textbf{Figure 2} Electric charges distribution inside a thundercloud and the location of where lightning can occur (Adapted from Brittanica online\textsuperscript{b}).

\textsuperscript{b} http://www.britannica.com/EBchecked/topic/340767/lightning
If the discharges happen inside a thundercloud or between thunderclouds, the terms intracloud flashes or cloud flashes (ICs) are typically used. Cloud discharge is the most common of all types of lightnings. Further explanation of cloud discharge is given in Chapter 3 and is also discussed in Paper I and Paper II. Despite ordinary cloud flashes, there is another type of cloud discharge known as Narrow Bipolar Pulses (NBPs). Narrow bipolar pulses (NBPs) are intracloud events with higher peak amplitude and strong high frequency emission compared to the first return strokes and other intracloud discharges. Among their main features are:-

a) High altitude discharges ~ Their main location is at 15 km to 20 km altitude for NNBPs and at 7 km to 14 km altitude for NPBPs\textsuperscript{38,47,80}

b) Shorter pulse duration typically within 10 µs to 30 µs\textsuperscript{34, 44, 57}

c) Accompanied by powerful radio frequency (RF) emission\textsuperscript{27,38,47, 62}

d) Emit weak or almost no optical emission\textsuperscript{27}

Even though some studies attempted to explain the NBPs discharge using the runaway breakdown mechanism\textsuperscript{24, 25} the knowledge on the physical mechanism of NBPs is still limited and remains unsolved to the lightning community. Details of these pulses are given in Chapter 3 and also discussed in Paper III and Paper IV.

1.2 Objectives of the thesis

Lightning is known as the most fascinating natural discharge on earth. Great advances in our modern communication systems (for instance wireless, satellite, antenna, radio transmission), avionics and electronics industries, has raised a demand for progressive lightning research work. While some parts of this discharge processes have been successfully understood, scientists are still struggling to find the answer to the question, ‘What initiates lightning?’ This is an interesting question as the mechanism and initiation processes themselves remain popular subjects of debate. It is thus essential to have a good knowledge regarding the initiation process of the lightning.

The main objectives of this thesis work are:

1) To study the initiation process of cloud flashes (ICs), ground flashes (CGs) and narrow bipolar pulses (NBPs) by analyzing the broadband electric field radiations. Understanding the initiation mechanism of the in-cloud process is vital considering that this is the part which has been a subject of debate for years. In addition to this, the study
of the initiation process is essential in order to understand the physics behind in-cloud discharges.

2) To study the radiated high frequency (HF) emission at 3 MHz and 30 MHz associated with ICs and NBPs. Having both, the knowledge and the understanding, of how ICs and NBPs radiate at HF and how this HF radiation coupled with the electronics systems are important. This is because our communications, radio and TV broadcasting, satellites, avionics systems and some microelectronics integrated component systems are working in this HF range. Using the information from the HF radiation from lightning discharges, better lightning protection for the above systems can be developed.
2. Data and measurement

This chapter describes the experimental setup, devices, location and measuring techniques. For this thesis work, data was based on the measurements carried out at four different locations: Vero Beach in Florida, Uppsala in Sweden, Colombo in Sri Lanka and Johor in Malaysia.

2.1 Parallel flat plate antenna

Electric field intensity at the ground can be measured as a function of time by measuring the voltage between the upper plate of the antenna and the ground. In the case of parallel flat plate antenna systems, as shown in Figure 3, the wavelength of the electric field is much larger than the dimension of the antenna. This condition is necessary otherwise the current induced in different parts of the antenna will reach the electronic circuitry at different times. By considering that there are no other metallic objects that might
influence the electric field to be measured, the voltage that drives the antenna is given by:

\[ V(t) = h_{\text{eff}} E(t) \]  

where \( h_{\text{eff}} \) is the effective height of the antenna and \( E(t) \) is the electric field to be measured. The effective height depends on the antenna geometry and its physical height. The effective height of the antenna is approximately 0.25 m and the physical height is 1.5 m.

![Figure 4](image_url) Flat plate antenna with associated electronic circuits used for the electric field measurement (Adapted from Uman64).

When the measuring circuit is attached to the antenna, the output voltage, \( v \) as depicted in Figure 4 will depend on the decay time constant, \( RC \) of the circuit. If \( RC = \infty \) then the output voltage corresponds exactly with the driving voltage. In this case the output voltage has the same temporal development as the background electric field. The antenna circuitry used is similar to those described and used previously by Cooray and Lundquist\textsuperscript{16, 17}, Cooray and Pérez\textsuperscript{15}, Arthuro and Fernando\textsuperscript{3}, Sharma et al.\textsuperscript{56} and Sonnadara et al.\textsuperscript{64}. 

17
2.2 Electronic circuit

The electric circuit attached to the antenna system consists of an MSK 0033 buffer amplifier, capacitors and resistors. The purpose of using a buffer amplifier is to isolate the high input impedance of the antenna and offer enough power to drive the signal from antenna to the oscilloscope through the coaxial cable. The input impedance of MSK0033 is $10^{12} \, \Omega$.

Figure 5 Circuit diagram of buffer amplifier (Adapted from Cooray\textsuperscript{12})

Figure 6 Electronic circuit of the buffer amplifier.
The components used in the electronic circuit of Figure 6 above are the following:

\[ R_1 = 50 \, \Omega, \, C = 15 \text{ pF} - 10 \text{ nF} \text{ (depends on the fast or slow field requirement)}, \, R_2 = 100 \, \text{M}\Omega, \, C_b = 0.1 \text{ pF}, \, C_v = 10 \text{ pF} - 60 \text{ pF} \text{ and } R_o = 43 \, \Omega. \text{ The output resistance of the buffer amplifier is } 7 \, \Omega, \text{ therefore the total output resistance, } R_{OT} \text{ is } 50 \, \Omega \text{ (} R_o + 7 \, \Omega). \]

The antenna capacitance, \( C_g \), was in the range of 58 pF to 60 pF. However, a value of 59 pF has been used as the standard value of the antenna capacitance and in decay time calculation. \( C_c \) is the capacitance of the RG 58 coaxial cable (100 pF for 1 meter length coaxial cable). The value of \( C_c \) may vary according to the length of the coaxial cable used to connect the lower plate of the antenna to the input of the electronic circuit. Also, \( C_c \) is one of the parameters responsible for controlling the magnitude of the measured voltage. The high resistance, \( R_2 \) is used to control the decay time constant of the circuit, \( \tau_d \) according to the equation below:

\[ \tau_d = R_2 \cdot \left( C_g + C_c + C \right) \]  

The value of \( R_2 \) was selected such that the decay time constant of the measuring system was large enough to record the impulse signal generated by cloud and ground discharges. Typically the value of \( \tau_d \) is 10 ms for the radiation field measurement and 1 s or more for the static (slow) field measurement.

In order to determine the measured voltage of the antenna system, some factors of the electronic circuit from the capacitive divider and the resistive divider has to be considered. Therefore equation [1] is modified like so:

\[ V_m = h_{eff} E(t) \left( \frac{C_g}{C_g + C + C_c} \right) \left( \frac{R_{OT}}{R_{OT} + R_m} \right) \]  

\[ V_m = h_{eff} E(t) \left( \frac{59 \text{ pF}}{59 \text{ pF} + 60 \text{ pF} + 15 \text{ pF}} \right) \left( \frac{50}{50 + 50} \right) = h_{eff} E(t)(0.22) \]

where:

\( R_m \) (matching resistor for coaxial cable connection) = 50\( \Omega \)

\( V_m \) = measured voltage

(Nomenclature: The antenna has been calibrated by applying a known vertical electric field to the antenna. Then, the output voltage between parallel
plates and the effective height of the antenna were measured taking into account the electronic circuit attached to the antenna.)

2.3 High Frequency antenna

2.3.1 3 MHz tuned circuit
An inductance of 47 µH connected in series with the antenna capacitor and 50 ohm termination formed a simple RLC circuit. The resonance frequency is 3 MHz with the experimental bandwidth of 264 kHz. An equivalent circuit of the 30 MHz resonator is shown in Figure 7, while the experimental results of the circuit’s response are shown in Figure 8 and Figure 9, respectively. See Appendix A for details of series RLC circuit.

Figure 7 The equivalent circuit of 3 MHz tuned circuit
**Figure 8** Output response of 3 MHz resonator circuit when 5 V_{pp} input pulse voltage (from signal generator) was applied.

**Figure 9** The output response of 3 MHz tuned circuit as a function of frequency
2.3.2 30 MHz tuned circuit

The electronic circuit of 30 MHz circuit, the diagram and the circuit’s response are shown in Figure 10, 11, 12 and 13 respectively. The components used in the circuit are: high speed buffer LHM6609, operational amplifier LHM6599, \( R_1 = 1 \, \text{k}\Omega \), \( R_2 = 18 \, \text{\Omega} \), \( R_3 = 27 \, \text{k}\Omega \), \( C_1 - C_4 = 6 \, \text{pF} \), \( C_5 \) and \( C_6 = 10 \, \text{pF} \).

Similar to the antenna system, the high speed buffer LHM6559 is used in this circuit to isolate the high input impedance of the antenna and to deliver a stable signal to the filter circuit. The input resistance is 200 k\( \Omega \) while the output resistance is only 1.2 \( \Omega \). The output of the high speed buffer is connected to the input of voltage feedback operational amplifier. The purpose of operational amplifier (op-amp) used in the 30 MHz circuit is to amplify (increase) the weak input signal. LHM6609 is a type of operational amplifier used in this 30 MHz band pass filter circuit. See Appendix B for circuit’s detail.

![Figure 10](image)

**Figure 10** Electronic circuit of 30 MHz tuned circuit
Figure 11 An equivalent band-pass filter circuit for 30 MHz resonator

Figure 12 Output response of 30 MHz resonator circuit when 5 V_{p-p} pulse voltage (from signal generator) was applied.
In order to check the output response from the resonator circuit (for both 3 MHz and 30 MHz), a 5 Vp-p input voltage from the signal generator was applied. The antenna capacitance was replaced by a 59 pF capacitor. The theoretical, experimental and simulation values of 3 MHz and 30 MHz are tabulated in Table 1.

**Table 1** Theoretical and experimental values for the oscillator circuit at 3 MHz and 30 MHz

<table>
<thead>
<tr>
<th>Tuned Frequency (MHz)</th>
<th>Bandwidth (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Theory</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>30</td>
<td>31</td>
</tr>
</tbody>
</table>
2.4 Measuring sites

![Measuring sites](image)

*Figure 14* Measuring sites located in Malaysia (Johor), Sri Lanka (Colombo), Florida (Vero Beach) and Sweden (Uppsala).

2.4.1 Vero Beach, Florida

The measurement was done at the premises of Vero Beach Marine Laboratory, Florida (27°N, 80°W), owned by the Florida Institute of Technology. The measuring site is located close to the sea and antennas were placed about 200 m from the sea wall. Data obtained in Florida were presented in Paper I.
A flat plate antenna was used to sense the signal from the vertical electric field. The output signal was fed into four channel digital transient recorders (Yokogawa DL1640L) operating at 12-bit using 25 m long coaxial cable (RG 58) and properly terminated to avoid reflections. Antenna and measuring systems were distanced from each other to avoid disturbances. Additionally, all measuring equipment was kept in a control room. The decay time constant of the fast field antenna system was adjusted to 10 ms. Data captured was 160 ms in length with 40 ms pre-triggered mode and the distance of events was estimated based on time to thunder.

2.4.2 Universiti Teknologi Malaysia, Johor, Malaysia

Data published in Papers III and IV were obtained during a lightning measurement campaign from April to June 2009 in Johor, Malaysia. The state of Johor is located at the southern tip of Peninsular Malaysia (1°N, 103°E), close to the equator. The measuring site was situated on top of a hill, in the vicinity of the observatory building, a premise belonging to Universiti Teknologi Malaysia (UTM). The site is 132 m above sea level and approximately 30 km away from the Tebrau Straits. Since the measuring site is located rather close (2 km) to the wireless communication tower, there were significant disturbances between the range of 500 kHz to 1500 kHz, corresponding to AM broadcasting in the medium wave radio band. Moreover,
disturbances may also arise from multiple stations transmitting in Malaysia, Singapore and Indonesia, since they are in proximity to each other. In order to minimize the effect of background noise, all data were first passed through the third order high pass filter using a MATLAB® computer simulation before conducting any further analysis. No additional filter circuit was connected to the antenna system. Three flat plate antennas were used to sense the vertical electric field, 3 MHz and 30 MHz signal. All antennas were placed side by side to each other, with the distance between antenna being 1 m each, and were set 8 m from the control room where the recording systems were kept. The decay time constant of the fast field antenna system was adjusted to 500 µs. The data were captured with 10 ns sampling time with a total record length of 250 ms. Moreover, each record contained a 100 ms pre trigger delay.

Infra-red images (IR) from the multifunction transport satellite (MTSAT), together with the accumulated rainfall data from radar observations provided by the Malaysian Meteorological Department (MMD), were used in Papers III and IV to estimate a rough distance to the flashes. Even though information on the location of lightning could not be obtained from the IR images, they could at least provide the study with a clue to the location of the thundercloud. For measurement in Malaysia, only flashes recorded on the 19th and 28th of April 2009 were selected for analysis as they were emitted by a very isolated thundercloud located 50 km (inland) from the measuring site. Therefore it was assumed that flashes on these days came from a range of 50 km.
2.4.3 Uppsala, Sweden

In Sweden, the measurements were performed during the summer from June to August, 2010 in the vicinity of the Ångström Laboratory, Uppsala University, Sweden (59° N, 17°E). The measuring base station was located about 100 km inland from the Baltic Sea. All the measuring equipment was placed inside a stationary van, ten meters away from the High Voltage Laboratory. The inner body of the van was half-covered with an aluminum metal plate and was fully grounded. Two parallel plate antennas used to measure the 3 and 30 MHz radiation were symmetrically installed on the roof of the van while another parallel flat plate antenna used to sense the vertical electric field radiation (far field) was placed approximately 2 meters away from the van. Disturbances from the electronic devices and recording apparatus placed inside the van were minimized since all the measuring equipments were battery-powered. A long vertical antenna was used to measure the slow field signal and placed equally about 2 meters away from both the van and the radiation field antenna. Signals from flat plate antennas were fed into a four-channel, 12-bit resolution digital transient recorder (Yokogawa SL1000 equipped with DAQ modules 720210). The transient recorder was operating at either a 50 ms or 100 ms pre-trigger delay with a 100 MHz or 50 MHz sampling rate. The measuring window was adjusted to record signals at either 250 ms or 500 ms, depending on the sampling rate chosen.
The distance for data collected in Uppsala was estimated based on time to thunder. Based on this estimation, it was found that the distance to flashes in Paper II was in the range of less than 20 km where the shortest distance was approximately 1.4 km while the maximum distance was 16.4 km.

**Figure 17** Measurement set up in Uppsala, Sweden showing a stationary van with two parallel plate antennas mounted on it. The recording apparatus are placed inside the van
Figure 18  Parallel plate antenna with buffer amplifier circuit attached to record vertical radiation field

Figure 19  The recording unit – Yokogawa SL1000, Data Acquisition Unit.
2.4.4 Colombo, Sri Lanka

In Sri Lanka, the measurement was performed during the monsoon period in April, 2010 in the campus of Colombo University (6°54’N 79°54’E). The vertical electric field and dE / dt of lightning were measured using two parallel flat plate antennas. All antennas were placed side by side, with a distance of 1 meter, and approximately 20 meters from the control room where the recording systems were kept. A 60 cm long coaxial cable (RG 58) was used to connect the antenna and electronic buffer circuit. The rise time of the fast antenna system for step input pulses was less than 30 ns while the decaying time constant was 13 ms. Signals from flat-plate antennas were fed into two four channel digital transient recorders (12-bit Yokogawa DL1640L) using 25 m long RG 58 coaxial cable and properly terminated to avoid reflections. The oscilloscope operated at a sampling rate of 100 MS/s has been set to work at either 50 or 125 ms pre-trigger with window triggering mode, so that flashes with both polarities will be captured. Unfortunately no reliable information of the distance was available. Data recorded in Sri Lanka is presented in Paper IV.

In all measuring sites, the wide-band electric field recording system was operated at a -3 dB bandwidth of 33 MHz, while the oscillators tuned to 3 MHz and 30 MHz were operating at a -3 dB bandwidth of 264 kHz and 2020 kHz, respectively.
3. Types of cloud processes

In this chapter, an overview of cloud flashes (ICs) and Narrow Bipolar Pulses (NBPs) with the possible mechanism are discussed.

_Nomenclature:_ The ‘physics’ sign convention is used in this chapter where the electric field change at ground level due to downward displacement of negative charges is considered positive. It has to be noted that the sign convention used in this chapter is not the same as the sign convention used in Papers III and IV.

3.1 Cloud flashes (ICs)

Almost three quarters of lightning flashes do not involve ground strikes\(^5\). They merely redistribute charges between charge centers within the cloud. In general, this type of lightning flashes is known as cloud flashes (ICs) and they can be divided into three categories:

(a) Intracloud discharges - occurs within the confines of thunderclouds;
(b) Intercloud discharges – occurs between one thundercloud and another; and
(c) Air discharges – occurs between thundercloud and air.

However, the characteristics of these three types of lightning flashes cannot be distinguished. As a result, the above three types are commonly recognized as cloud flashes. Unlike CGs, they were considered to be of no direct harm to the human beings and animals on ground or to other structures\(^5\). Nevertheless, even though they are of minimal danger to ground based objects and systems, ICs are of much concern for the avionic industries. The interference of HF and VHF radiation with ICs and other sophisticated solid state devices are also of great concern in lightning protection.

The breakdown process in ICs has been studied since the early 1930s in order to understand the lightning initiation mechanism. Even though over 90% of lightning account for ICs, they are not well-studied like their counterpart,
CGs. Difficulty of visual observations, inability to measure the ground based current and difficulty in locating the flashes are several reasons as to why ICs are less studied. Considering this, remote measurements of electric field radiation serve as a good tool for studying ICs.

ICs are most likely to be initiated near the upper and lower boundary of the main negative charge center and often in the former case bridge the main negative and main positive charge regions in the thundercloud. A classical work pertaining to cloud flashes was carried out by Kitagawa and Brook\textsuperscript{31}. By analyzing electric field variations from ICs, they concluded that ICs consist of three stages: initial, very active and junction. Later, studies conducted by numerous authors \textsuperscript{5, 16, 17, 34, 59, 67, 70} showed that ICs consist of only two stages: an early (active) stage and a later stage. The early stage takes place during the first 40-ms of the flash\textsuperscript{67}, while the remainder of the flash constitutes the later stage. As has been reported by Cooray\textsuperscript{12}, the typical duration of ICs may range from 200 ms to 500 ms. Examples of radiation fields from ICs are shown in Figures 20 and 21. Further discussions on ICs can be found in Paper I and Paper II.

**Figure 20** The electric field radiation from negative polarity cloud flashes
Narrow Bipolar Pulses (NBPs) or also known as compact intracloud discharges (CIDs) can be singled out from other lightning processes due to their association with strong radio frequency (RF) radiation. They have also attracted considerable attention because they are a primary candidate for proposed satellite-based VHF global lightning monitors. They have been reported with positive and negative polarity, namely, Narrow Positive Bipolar Pulses (NPBPs) and Narrow Negative Bipolar Pulses (NNBPs).
NBPs were first reported by Le Vine\textsuperscript{34} and later, various studies of these distinct pulses were conducted either by using broadband electric field \textsuperscript{43, 44, 57, 74} or satellite based measuring systems \textsuperscript{18, 27, 28, 62, 69}. In most cases, they were reported as isolated events without being preceded or followed by other known lightning activity within a time frame of tens of milliseconds\textsuperscript{57, 62}. However, some studies found that NBPs are associated with the initiation of other intracloud discharges\textsuperscript{27, 28, 44, 54}. As reported by Jacobson\textsuperscript{27}, other activities may occur before, during or after NBPs within a fraction of the time interval. Electric field waveforms similar to those of Le Vine\textsuperscript{34} have also been observed by Weidman and Krider\textsuperscript{70}, Cooray and Lundquist\textsuperscript{17}, Bils et al.\textsuperscript{5} and Villanueva et al.\textsuperscript{67}. However, their findings showed wider duration bipolar pulses than that observed by Le Vine\textsuperscript{34}. LeVine\textsuperscript{34} in his measurement used RF radiation at 3 MHz and 300 MHz as a triggering source with the bandwidth set to 300 kHz. Bils et al.\textsuperscript{5} reported a bandwidth from 3 Hz to 4 MHz with a recorded distance of 10 km while Cooray and Lundquist\textsuperscript{17} reported a bandwidth between 10 kHz to 600 kHz. It is possible that the difference observed is due to the different nature of the experiment and methods of observations used in different studies. In addition, the result reported by Cooray and Lundquist\textsuperscript{17} might have been attenuated since the signals were propagating at a distance between 100 km to 200 km.

\textbf{Figure 22} Example of a typical electric field of narrow positive bipolar pulses (NPBP – according to physics sign convention) observed in this thesis work.
NBPs were commonly observed in the tropical region compared to the temperate region. Sharma et al.\textsuperscript{57} failed to record any narrow bipolar activities in Sweden whereas the same experimental set up carried out in Sri Lanka, a tropical region, recorded numerous records of positive bipolar events. Similarly, as reported in Paper III of this thesis work, NBPs were frequent during our measurement in Johor, Malaysia. Even though it was speculated that meteorological conditions\textsuperscript{57} might influence the presence of NBPs in temperate regions, one has to carry out further investigations to confirm their existences. This is because it is not known with certainty whether the absence is due to the atmospheric condition or the properties of thunderclouds analyzed in earlier studies. Therefore, until a specific measurement for NBPs is executed, we are not in the position to comment on the absence of NBPs in the temperate region.

In addition to this, positive NBPs were reported to occur at an altitude of 6 km – 15 km and at a higher altitude which is 15 km – 21 km for negative NBPs\textsuperscript{38, 47, 80}. In most cases NBPs were reported to occur singly, without being preceded or succeeded by any other known lightning activity within a time frame of tens of milliseconds\textsuperscript{57, 62}. However, in present study they were observed to be associated with the initiation of intra-cloud discharges. Unlike other lightning processes, they were also reported to occur without the formation of leaders\textsuperscript{18}.

Further results and discussions on NBPs are presented in Paper III and Paper IV. It should be noted that even though NBPs were suggested as probably being initiated by a runaway breakdown mechanism\textsuperscript{23} and it has been speculated as a bouncing wave phenomenon\textsuperscript{45}, at present the mechanism of these events remain mysterious and poorly understood.
4. High frequency radiation from lightning

This chapter covers some previously published works on HF and VHF from ICs. It is composed into 3 main sub sections: general overview of HF radiation from lightning discussed in 4.1, frequency spectrum of lightning electromagnetic fields discussed in 4.2 and possible causes of HF radiation from lightning discussed in 4.3.

4.1 Overview

Electromagnetic radiation from lightning is characterized by a broadband frequency in the range of kHz to GHz. It is essential to study the high frequency radiation from lightning due to its adverse interference with advanced electronics devices during thunderstorms. Recently, there has been a lot of interest in the strong emissions produced by lightning at UHF and VHF frequencies. This is because lightning emission is impulsive and the large amplitude represents a potential hazard to any system which is sensitive to a transient field\(^7\).

Many studies have been performed to understand the temporal HF radiation from lightning. Le Vine and Krider\(^{36}\) reported the temporal variation of HF from the first and subsequent return strokes at several selected frequencies which are 3, 30, 129 and 295 MHz. Krider et al.\(^{32}\) show the temporal variation of HF radiation at 3, 69, 139 and 295 MHz for large amplitude intra-cloud pulses. Clegg and Thomson\(^{10}\) reported the HF radiation at 10 MHz that is associated with cloud and ground flashes in Suva Fiji. Similar HF radiation at 10 MHz was also documented by Hayenga\(^{26}\) using interferometric technique and the data were recorded within a distance of 3 km to 10 km. Cooray\(^{11}\) reported the temporal variation of HF radiation at 3 MHz, near the time of the first return strokes. Data were recorded within a 50 km to 100 km distance and propagating over sea water. The HF radiation at 3 MHz during the leader and return strokes process has been studied by Jayaratne and Cooray\(^{30}\). Data were collected in Sri Lanka at a distance of approximately 40 km over sea water. The stepping process preceding the first return strokes was observed to be responsible for the strong HF emission at 3 MHz while similar HF radiation was absent during the subsequent return strokes process. Cooray and Perez\(^{15}\) observed longer duration of 3
MHz radiation associated with positive return strokes than that of negative return strokes. Shao et al.\textsuperscript{61} have further investigated the HF radiation from the positive return strokes. Their study which was extended up to the UHF region showed that the positive ground flash emits less or no radiation particularly at the VHF region. Direct measurement by using narrow band techniques was reported by Mäkelä et al.\textsuperscript{40}. The narrow band receiver tuned to 10 MHz to capture radiation from chaotic pulses associated with subsequent return strokes. Leaders preceding first return strokes emit substantially less HF radiation than during the first return strokes (return strokes are however the most prominent HF emitter) while the leader preceding subsequent return strokes emit weak or no HF radiation at all. Also, it was observed that the radiation intensity will increase with the presence of chaotic pulses that are typically observed preceding the subsequent return strokes.

There are only few observations and studies of HF radiation from NBPs compared to cloud discharges and return strokes. According to Smith et al.\textsuperscript{62} the mean duration of HF emission (3 MHz to 30 MHz) associated with NBPs is 2.8 µs and the amplitudes 10 times larger than emissions from ordinary cloud flashes or return strokes. Furthermore, observations by Rison\textsuperscript{52} have confirmed that the strong emission produced by NBPs was 30 dB stronger than that of other lightning processes such as ICs and CGs within the same storm. Examples of broadband radiation field of cloud flashes with corresponding 30 MHz and 3 MHz radiation measured in this study are shown in Figures 23, 24 and 25, respectively. Meanwhile examples of broadband radiation field of NBPs with corresponding 30 MHz and 3 MHz radiation are shown in Figures 26 and 27.

![Electrical field waveform of ICs](image)

**Figure 23** Typical electric field waveform of ICs obtained from broadband electric field measured simultaneously with 3 and 30 MHz for the first 40 ms interval.
Figure 24 Typical electric field waveform of ICs obtained from broadband electric field measured simultaneously with 3 MHz and 30 MHz within 40 to 80 ms interval.

Figure 25 Typical electric field waveform of ICs obtained from broadband electric field measured simultaneously with 3 MHz and 30 MHz within 80 to 120 ms interval.
Figure 26 An NPBP with the corresponding 30 MHz radiation shown in (a) and (b), respectively. Similarly, an additional NNBP with its corresponding 30 MHz radiation is shown in (c) and (d), respectively.

Figure 27 An NPBP and its associated HF radiation at 3 MHz is shown in (a) and (b), respectively, while an additional NNBP and its associated HF radiation at 3 MHz is shown in (c) and (d), respectively.
4.2 Frequency spectrum of lightning electromagnetic fields

In order to analyze the effects of lightning on modern avionic and communication systems, it is necessary to know the properties of the various individual processes during the flash in order to determine how these signals couple with digital circuits. For that reason, investigation on frequency spectrum of lightning electromagnetic fields has been carried out. Le Vine defines “spectrum” as “the magnitude of the Fourier transform of the electric field $E(t)$ radiated during the discharge”. Traditionally, there are two methods used to study the frequency spectrum of lightning flashes. Narrowband oscillators tuned to any interested frequency can be used to directly measure the energy radiated by lightning in that frequency. To obtain the average frequency variation over a large range, one needs a large number of such oscillators tuned to different frequencies. The second method is to obtain the frequency spectrum by Fourier transforming the broadband electric field waveform. This technique was used in Paper II to obtain the frequency spectrum of ICs within the interested frequency range.

![Graph](image)

**Figure 28** Examples of spectral amplitude of the first return strokes using Fourier transformation technique adapted from Le Vine.

The broadband frequency spectrum of the first and subsequent return strokes from frequency interval of 1 kHz to 1 MHz was shown by Serhan et al. Their data which were based on electrostatic and radiation fields fall off as $f^{-1}$.
within 10 kHz to 100 kHz. Above 100 kHz, the amplitude spectra of the strokes degrade rapidly with increasing frequency due to the propagation effect. Weidman et al.\textsuperscript{72} have studied the radiation spectra of return strokes, stepped leaders and intra-cloud discharges in the frequency range of 100 kHz to 20 MHz. Similar to Serhan et al.\textsuperscript{55}, their result shows that the amplitude spectra falls off as $f^{-1}$ for frequency up to 2 MHz and decrease as $f^{-2}$ up to 10 MHz. At beyond 10 MHz, the frequency falls off rapidly as $f^{-5}$. The frequency spectrum of cloud flashes which is closely related to the one described in Paper II was charted by Sonnadara et al.\textsuperscript{64}. Sonnadara et al.\textsuperscript{64} analyzed the spectrum of the first 10 ms of ICs, which is the most active stage of cloud flashes\textsuperscript{67}. Their results showed that for frequencies up to 2 MHz, the spectra follows $f^{-1}$ frequency dependence and continues with $f^{-2}$ or higher for frequencies above 2 MHz.

![Figure 29](image)

**Figure 29** The amplitude spectra of lightning obtained from direct measurement (narrow band systems) adapted from Le Vine\textsuperscript{35}.

In addition to the spectral amplitude of lightning, some studies have calculated the energy spectral density (ESD) of lightning. ESD is basically the square of the spectra amplitude. Energy spectral density from Narrow Bipolar Pulses was reported by Willet et al.\textsuperscript{74}. Being known as the possible source of the strongest HF radiation from lightning, sources of these pulses radiate much stronger than the first-return strokes at frequencies from 10 MHz to at
least 50 MHz. Also, Willet et al.\textsuperscript{75} reported the ESD for first, subsequent, step and dart stepped leaders, chaotic process and characteristic cloud pulses.

4.3 Possible causes of HF radiation from lightning

There are many possible causes of HF radiation from lightning. In an earlier study, Brook and Kitagawa\textsuperscript{9} suggested that the radiation from lightning is associated with the formation of streamers. This suggestion was due to their observation of a 60 µs to 100 µs delay between the beginning of the return strokes and the appearance of the strong HF radiation, which are roughly the times required for the current pulses to propagate from ground to cloud. Measurements made by Le Vine and Krider\textsuperscript{36} confirmed the delay as observed previously by Brook and Kitagawa\textsuperscript{9}. However, they found that the delay was too short, typically 20 µs, which led them to suggest that branches in the main channel were the primary sources of HF radiation. Later, Cooray\textsuperscript{11} reported that there was actually no such delay and what had been observed previously was due to the propagation effect when electric fields propagate over finitely conducting ground. This report was based on data obtained from measurements close to the sea (200 m from the sea) where the propagation path was entirely over the sea water thus eliminating the possible propagation effect.

On the other hand, calculations done by Le Vine and Meneghini\textsuperscript{37} inferred that the channel tortuosity of lightning has a significant effect on the high frequency domain compared to the equivalent straight conducting channel and this was later supported by Le Vine\textsuperscript{33}. Cooray and Pérez\textsuperscript{15} suggested the ionization of virgin air or the re-ionization of an old channel as a possible significant source of HF radiation. Further, as shown by Cooray and Fernando\textsuperscript{14}, charge irregularities and micro scale branches are probably the source of HF radiation while the channel tortuosity can lead to HF emissions but confined only to the first few microseconds of the return strokes.
5. Results and discussions

The research work presented in the following papers cover different areas of the physics of cloud discharges. The study of the initiation of ICs and NBPs is presented, and the HF radiation associated with them is also discussed.

Paper I

The first electric field pulse of cloud and cloud-to-ground lightning discharges

Despite the advancement in lightning research field, there is still little understanding of the in-cloud process by which lightning is initiated. In general, the initiation of lightning evolves three stages\(^{63}\): (1) the build-up of in-cloud electric fields on large spatial scales, (2) local enhancement of the electric field to produce regions in which ionizing collisions between accelerated electrons and air molecules result in propagating corona streamers and (3) propagation of sufficient electric current through and beyond the region of very high local fields to form the hot, completely ionized lightning channel (leader stage). There are two possible candidates for which lightning is initiated; conventional and runaway breakdown mechanisms. In both hypotheses, the process begins with accelerated electrons which lead to electron avalanched through the ionization process.

The electric field intensity needed for the breakdown to occur between parallel plate electrodes is approximately 3 MV/m, measured in dry air (760 Torr, 273 \(k\) or 0\(°\)C). However, this critical electric field intensity will decrease with decreasing pressure (increasing cloud altitude) and also with the presence of hydrometeors. \textit{In situ} measurement of electric field sounding inside the thundercloud using aircrafts\(^{21}\), balloons\(^{41, 68, 79}\) and rocket\(^{78}\) showed that the maximum electric field inside the thundercloud is always less than the required electric field breakdown in the air. In the runaway breakdown mechanism, the thunderstorm electric fields accelerate the relativistic electrons generated by cosmic ray showers to generate relativistic avalanches causing runaway breakdown. It was suggested that the runaway breakdown are responsible for triggering the lightning\(^{22}\). According to Solomon\(^{63}\), the
conventional breakdown mechanism alone cannot trigger the initiation process, while the runaway breakdown appears to be a likely candidate.

The purpose of this study is to understand the initiation mechanism of cloud and ground flashes. Since the visual observation of cloud flashes is difficult, remote sensing of electric fields provides some valuable information on the initiation of the in-cloud process. A few analyses have been reported by numerous authors\textsuperscript{5, 16, 17, 67, 70} on lightning cloud discharges. From their analyses, it was found that large microsecond scale pulses were typically present at the beginning of the cloud flashes that could be related to the initiation of the breakdown process. Detail analyses of microsecond scale pulses in the first 10 ms of cloud flashes were done by Sharma et al.\textsuperscript{56} and Bodhika et al.\textsuperscript{6}. A study by Nag et al.\textsuperscript{46} on microsecond and sub microsecond scale pulses of ground flashes found that over 70 % of the flashes have pulse durations of less than 4 µs, with 87 % of them being bipolar. Another 22 % have pulse durations less of than 1 µs. Beasley et al.\textsuperscript{4} showed a significant VHF radiation at the preliminary variations of electric field records of ground discharges. In all of the above studies no detailed analyses of the initial electric field pulse of cloud and ground flashes were discussed.

On the basis of the broadband electric field measurements, the characteristics of initial pulses from 38 cloud flashes and 101 ground flashes have been analyzed. Our results show that the characteristics of field parameters such as pulse duration, rise time, zero crossing time and full width at half maximum (FWHMs) of the first pulse of cloud and ground flashes are similar. These results were also compared to the microsecond and sub-microsecond scale pulses observed at the later stage of the cloud flashes. It was found that the field characteristics of microsecond scale and sub-microsecond scale pulses were similar to those of the initial pulse of cloud and ground flashes. Hence, it is suggested that a) the mechanism process of the first pulse of cloud flashes is similar to those of at the later stage of the flash and b) cloud and ground flashes are probably initiated by the same mechanism.

\section*{Paper II}

\textbf{Radiation Field Spectra of long-duration cloud flashes}

Even though cloud flashes pose no threat to human, animals and other structures on the ground, the understanding of HF emission produced by cloud flashes is essential, both for scientific investigation and for engineering assessment. Since the intensities of HF radiation from lightning vary considerably with frequency, the magnitudes are conveniently decided upon by consulting their spectral amplitude\textsuperscript{51}. However, the study of frequency spec-
trum obtained from cloud flashes is scarcely found in the literature. To date, only a few series of studies on lightning cloud flash spectrum have been published. Weidman et al. reported the amplitude spectra of individual intra-cloud pulses in the range of 100 kHz to 20 MHz. Weidman and Krider calculated the spectral amplitude of individual intra-cloud pulses from derived electric field time derivatives (dE / dt) of the ground-based electric field measurements while Sonnadara et al. have analyzed the spectrum of electric fields of the initial 10 ms of cloud flashes. Apparently, no study has been conducted to investigate the frequency spectrum of the electromagnetic field produce by a one complete cloud flash and thus, the objective of this study.

For this study, the average spectral amplitudes of cloud flashes have been evaluated using long records of broadband radiation fields. A sample of 22 electric field variations of 180 ms of cloud flashes has been Fourier analyzed to determine their spectrum in the frequency range of 1 kHz to 10 MHz. The result shows that the spectrum decreases with a dependence within the entire frequency interval. It was found that at a high frequency band, particularly above 2 MHz, the decrement observed in this study is less steep than the decrement of other lightning processes such as return strokes, stepped leaders, subsequent return strokes and individual intra-cloud pulses. In fact, our spectrum is inconsistent with the frequency spectrum of the 10 ms active stage of cloud flashes.

According to Nanevics et al. and Le Vine, large pulses such as return strokes and pulses with abrupt changes such as K changes are dominant at low frequencies. At a high frequency band, probing discharges are dominant. It seems that the result of this study is in line with their suggestions since long duration cloud flashes are characterized by many microseconds scale pulses embedded intermittently on the electric field waveform. In addition, the dependence matches the decrease in spectral amplitude using direct measurement (narrow band) systems, particularly at high frequency. In the narrow band system, the resonator circuit is tuned to the interested frequency and the frequency response is measured directly. However, with this technique it is difficult to determine which lightning event corresponds to the interested frequency. This is because depending on the bandwidth of the oscillator system, the oscillations corresponding to an event may continue for some time, resulting in an overlap with oscillations that correspond to another event.

It is essential to consider how the signal propagation could affect the amplitude of the lightning frequency spectrum. Signal attenuation depends on several factors such as the frequency content (high frequency attenuate more than lower frequency), channel height, ground conductivity, earth terrain,
roughness and curvature of the propagation path. Waves from the signals propagation path that follows the earth curvature are called ground waves. If the signals propagate through the ionospheric reflection, those signals are known as skywaves. At low frequencies (30 kHz – 300 kHz), the attenuation of ground wave is low. Absorption of the skywave is high especially in daylight, particularly in the summer, but low absorption during the night. At medium frequencies (300 kHz – 3 MHz), the ground wave will be affected significantly by poor ground conductivity. The skywave is completely absorbed by the ionospheric layer during the daytime. At high frequencies (3 MHz – 30 MHz), ground wave is severely attenuated over short distance. As reported by Lin et al.39, the normalized field peaks suffer 10 % attenuation when propagated at a distance of 50 km. Since all signals in this study were recorded within a distance of 20 km, it is expected that the propagation effect (especially from the ground wave) is lesser and can be neglected. Moreover, it has been shown by Cooray13 that the propagation effects on the electric field generated by cloud flashes are less severe than that of return strokes since significant portion of its total radiation field is contributed mostly by the sky wave.

Paper III

Characteristics of Narrow Bipolar Pulses observed in Malaysia

Narrow Bipolar Pulses (NBPs) is a type of discharge that occurs inside thunderclouds. Because of this, they are considered as intra-cloud discharges. In some studies, they are also known as Narrow Bipolar Events (NBEs) 18, 69, 80 or Compact Intra-cloud Discharges (CIDs) 62. Owing to their origin at altitude between 6 km to 21 km, (where most commercial planes fly) and accompanied by strong HF – VHF radiation emission, the understanding of the physical process of these events is thus vital especially from an engineering point of view. They have been reported to occur in the tropic and subtropical regions but none have been observed in the temperate region. During our three months’ measurement campaign in Sweden (June to August 2010), no NBPs was ever recorded. It is possible that the difference in thunderstorm types is responsible for the absence of NBPs in the temperate region. Due to the absence of NBPs in Sweden, we have chosen to study the characteristics of NBPs recorded in the tropical region.

Data analyzed in this study were obtained from our measurement in the vicinity of the Universiti Teknologi Malaysia (UTM) campus, Johor, Malaysia. In Malaysia, NBPs were observed to occur very frequently; most of the time during the pre-thunderstorm stage. However, some of the NBPs were also recorded during the active stage of thunderstorm, and relatively less NBPs were recorded during the later stage of thunderstorm. Both polarities
of NBPs, namely Narrow Negative Bipolar Pulses (NNBPs) and Narrow Positive Bipolar Pulses (NPBPs) have been recorded. It should be noted that in this study, the sign convention used to describe the electric field change at ground level corresponds to the atmospheric electricity. According to the sign convention, the positive field change at ground level is produced by a movement of negative charge downwards, which is similar to the process taking place in a negative ground flash. Thus an initially negative peak followed by a positive overshoot is termed as Narrow Positive Bipolar Pulses (NPBPs), whereas the opposite is termed as Narrow Negative Bipolar Pulses (NNBPs). The characteristics of NBPs from other tropical region have also been reported by Sharma et al.\textsuperscript{57} and Cooray and Lundquist\textsuperscript{17}. However, only positive bipolar pulses were recorded in their study. Furthermore, it was observed from their study that NBPs occurred separately, without being accompanied by other lightning processes i.e., cloud flash or ground flash activities.

In this study, the radiation field parameter of NBPs such as the pulse durations, peaks amplitude and full width at half maximum (FWHM) were studied. The information is essential especially for those working with the mathematical modeling of NBPs. It was found that the mean peak amplitude of narrow positive bipolar pulses (NPBPs) normalized to 100 km was 22.7 V/m, a factor of 1.3 higher than that of narrow negative bipolar pulses (NNBPs) which is 17.6 V/m. It was observed that the pulse duration in our study is approximately two times longer than the one recorded by Sharma et al.\textsuperscript{57} but three times shorter than Cooray and Lundquist\textsuperscript{17}. We suggest that the difference between the pulse duration measured in Malaysia and Sri Lanka could be attributed to the propagation effect. This is because our data were recorded from a distance of 50 km inland, while in Cooray and Lundquist’s work the data were recorded at a distance of 100 km to 200 km.

It has to be noted that NBPs of both polarities were observed in Malaysia. Similarly, NBPs of both polarities were also observed from the measurements in New Mexico\textsuperscript{18,69} and Shanghai, China\textsuperscript{80}. However, from the electric field measurement in Colombo, Sri Lanka\textsuperscript{17,15} and Gainsville, Florida\textsuperscript{47} only NPBPs were recorded. Sri Lanka is a small island located in the warm tropical Indian Ocean, while Florida is surrounded by the Atlantic Ocean in the sub-tropical region. In fact both of the measuring stations in Sri Lanka and Florida were located at areas close to the open sea. It was reported that the sea breeze circulation is one of the most prominent mesoscale in Sri Lanka\textsuperscript{1} while in Florida the air mass due to the thermal instabilities and sea breeze convergence are the primary types of thunderstorm\textsuperscript{19}. According to Jayamaha\textsuperscript{29} the warm sea surface around the island will cause tropical air masses to spread over the country. According to Williams and Stanfill\textsuperscript{76} there was evidence of traditional thermal hypothesis for the difference in ocean and
land lightning activities. Since land is much hotter than sea, the updraft strength is stronger over the land than over the ocean. Meanwhile, the measuring site in Malaysia was located several tens of kilometers inland from the Tebrau and Malacca Straits and more than 100 km inland from the open South China Sea (in the east). During the southwest monsoon period, the thundercloud formation was greatly affected by the wind blowing from the Indian Ocean. However, since Peninsular Malaysia is bounded by Singapore in the south and Sumatra Island in the west, the geographical location of Peninsular Malaysia is that the frontal sea breeze circulation is not as strong as those in the open coastal area (such as Florida) or the open island (such as Sri Lanka) because it is been shielded mainly by the Sumatra Island. Therefore it is possible that the meteorological conditions may favor the production of both NPBPs and NNBPs.

Paper IV

Some features of electric field waveform of narrow bipolar pulses

In Paper IV, we observed that NBPs are characterized by many small peaks superimposed on the rising and decaying edge of radiation field waveform and the appearance has never been reported elsewhere. Since in previous studies\textsuperscript{16, 34, 74}, NBPs were reported to be characterized by smooth, fast rising pulses similar to those of return strokes, we are thus interested in further deepening our investigation on the small peaks occurrence in our present study. We have investigated data recorded from Malaysia and Sri Lanka, and the small peaks were observed in data from both locations. Overall, the peaks are narrow, with nanoseconds scale pulse duration and time separation between each successive pulse having the order of few tens of nanoseconds. All data were recorded using a 12 bit resolution recording unit and this has allowed us to observe the small peaks very clearly. It is possible that the absence of these peaks in previous studies was due to the limitation of the digitizer resolution. The appearance of small peaks on the electric field waveform of NBPs is in line with the noisy features of NBPs electric field time derivatives (dE /dt). We have performed several statistical analyses on the subsidiary peaks of dE / dt. It was found that the separation between these peaks (40 ns) is approximately equal to the time separation between small peaks found on the electric field waveform of NBPs. This observation led us to speculate that NBPs were produced as a result of frequent small scale discharges.

\textsuperscript{c} http://www.met.gov.my
Following this, the HF radiation at 30 MHz associated with NBPs has also been studied and discussed. There are few studies that have been published showing the temporal variation of HF radiation associated with NBPs\textsuperscript{45, 62}. However, none of the studies focus on the temporal HF radiation that accompanies NBPs. Our observation found that the burst of the HF noise begins simultaneously with the onset of the NBP electric field, but not preceding the electric field change. There are some records showing the HF radiation prior to NBPs. However in these cases, NBPs were observed as being accompanied by some in-cloud processes, which may be responsible for the HF emission prior to NBPs. Our observation thus confirms the absence of leader process during the formation of NBPs.

We also observed a slight delay of less than 1 µs between the onsets of NPBPs to the beginning of HF radiation. An even longer delay (approximately 3 µs) was observed from the onset of NNBP to the beginning of HF radiation. It is expected that the delays were a result of the propagation effect since data were recorded from a distance of 50 km. We could not find any possible explanation as to why there was a longer delay with the NNBP. It is suggested that the responsible process that emits the 30 MHz radiation from NBPs of both polarities could be the same since the duration of the 30 MHz radiations are similar. The mean duration of the 30 MHz radiation is about 10 µs which implies that the processes which produce long-lasting noise have no effect when the channel is formed.

On the basis of our analysis, we conclude that:
(a) No streamers or leader process took place before the initiation of NBPs.
(b) Some small scale discharges were involved during the formation of NBPs and these discharges could be responsible for the intense HF radiation from NBPs.
Electric fields generated by lightning can be used to understand the physics behind lightning initiation mechanisms. Even though 90% of lightning flashes are cloud flashes, due to various reasons work on cloud flashes are relatively scarce. Thus the objective of this work is to reveal new knowledge on cloud discharges. Compared to CG flashes, cloud flashes do not pose a direct threat to human life and properties. However, HF radiation associated with ICs may interfere with sophisticated electronic systems widely used in modern avionic and health systems. Therefore, the knowledge on HF radiation associated with ICs is of importance to evaluate the threat on electronic systems. In this study investigation was carried out on the HF radiation generated by ICs and NBPs. The results discussed in this work are based on the measurement performed in different geographical locations—subtropical, tropical and temperate regions. For example, data for Paper I was obtained from measurements done in Vero Beach, Florida in the subtropical region. Data for Paper II and Paper III were obtained from Sweden and Malaysia, respectively. Results discussed in Paper IV were based on data obtained from Malaysia and Sri Lanka, both in the tropical region.

Even though ICs and CGs are two different lightning activities, it is suggested that their initiation processes which takes place inside the thunder-cloud could be the same, depending upon the differences between the initial pulses of these discharges. Interestingly, it was found that small pulses which typically appear in the later stage of ICs also have similar characteristics to the initial pulse of CGs. Further investigation on cloud flashes revealed that their spectral amplitudes peak at approximately 20 kHz and continue to decrease as $f^{-1}$ to the high frequency at 10 MHz. The result was in contrast to the typical distribution of CGs frequency spectrum, stepped leaders and intra-cloud pulses, where the curve will decrease further as $f^{-2}$ or more at high frequency region (particularly above 2 MHz). Our result also produced some inconsistency with the $f^{-2}$ decrement in the first 10 ms spectrum of cloud flashes. It is expected that the increase in pulse rates of cloud flashes contributes significantly to the increment of spectral amplitudes at high frequency.

Since NBPs appeared to be associated with ICs we have conducted a study to further investigate this phenomenon. A measurement conducted during
the southwest monsoon period in Malaysia in the tropics observed numerous records of NBPs from both polarities. Apparently, NBPs appear similar to the characteristic pulses and large bipolar pulses typically observed in the preliminary breakdown and active stage of CGs and ICs, respectively. However distinct features of the narrow pulse duration (typically in the range of less than 30 µs), larger peak amplitude than ICs and CGs and its association with intense HF – VHF radiation are those that characterize NBPs from others. In general, it was observed that the characteristics of NBPs observed in Malaysia are similar to those recorded in other geographical regions such as in Sri Lanka and Florida. Being known to mostly occur singly, it is evident from our study that NBPs were not isolated phenomenon but occur simultaneously with ordinary lightning. Indeed, a majority of NBPs (63 %) recorded in this thesis work was observed to initiate cloud discharges or to be accompanied by other lightning activities such as return strokes, within few tens of milliseconds before and after the pulses. It is also shown from our studies that no stepped-leaders processes were involved during the formation of NBPs. A slight delay of less than 1 µs was observed between the onsets of NBPs to the beginning of HF radiation while a longer delay (approximately 3 µs) was observed from the onset of NNBP to the beginning of HF radiation. Further investigation on the electric field waveform of NBPs has led us to observe many small peaks embedded in the envelope of the electric field change of NBPs. This observation is indeed in line with the noisiness feature of the electric field time derivatives of (dE /dt) of NBPs. We have shown that the time separation between each successive small peaks is in the order of few tens of nanoseconds, similar to the time separation of subsidiary peaks embedded in dE / dt. On the basis of our observations, it is proposed that NBPs were produced as a result of many small scale discharges which were mostly responsible for the intense burst of 30 MHz emission.
Fjärrmätning av elektriska fält som genereras av blixten har spelat en viktig roll i förståelsen av blixtens fenomen. På grund av praktiska anledningar anses fjärrmätning av elektriska fält som den mest användbara metoden i blixtsforskning. Därtill har också andra mätningsmetoder som optisk, fotografisk, kanal basström och åska kännetecknas också bidragit till blixtsforskningsområdet. Denna avhandling diskuterar om den fjärrätning av det strålffälts komponent av elektriska fält som genereras av molnblixtar (ICs) och smala bipolär pulser (NBPs). Eftersom elektromagnetisk strålning från blixten kännetecknas av en bredbandsfrekvens (i intervallet mellan kHz till GHz), är det viktigt att undersöka den högfrekvensa strålningen från blixten på grund av dess negativa inflytande på avancerad elektroniska utrustningar som händer under åskvänder. Orsaken för denna händelse är därför att blixtutsläpplen är impulsiv och den stora omfattningen representerar en potentiell risk för alla system som är känslig för ett kortvarigt fält. Därför diskuterar avhandlingen också blixtens HF-strålning på 3 MHz och 30 MHz.

Även om molnblixtar (ICs) och jordblixtar (CGs) är två olika blixtaktiviteter, föreslås det att de har samma inledande processer (som äger rum inom åskmoln), beroende på skillnaderna mellan avskedens initialpulsare. För att förstå avskedens inledande processer, utförs en komparativ undersökning för att jämföra mellan molnblixtars och grund blixtars initialpulsare. Resultatet tyder på att både utsläpp kan ha initierats av liknande fysiska processer inne i åskmoln. Den genomsnittliga spektrala amplituden för elektriska fält i en fullvaraktighet molnblixtar (180 ms) visade en $f^{-1}$ frekvens beroende inom intervallet 10 kHz till ca. 10 MHz. Detta står i kontrast till den standard $f^{-2}$ minskning (eller ännu mer) vid hög frekvens av regionen för andra blixtprocesser såsom avkastning anslag. Det föreslogs att små pulser som gång på gång dök upp i senare skede av molnblixtar kan ha bidragit till att öka den spektrala amplituden vid högre frekvenser.

Elektriska fält som genereras av smala bipolär pulser (NBPs) betraktas som en av de starkaste källorna till HF-strålning som mätts dessutom i tropikerna i Malaysia. Deras egenskaper studerades också. Smala bipolär pulser (NBPs) eller också känt som kompakt intramoln utsläpp (CIDs) kan urskiljas från andra blixtprocesser på grund av sina koppling till starka radiofrekvensstrålning. De har också fått stor uppmärksamhet eftersom de är en huvudkandidat för rekommenderade satellitbaserade VHF globala blixtmonito-
Resultatet visar en god överensstämmelse med tidigare publicerade NBP-observationer från andra geografiska områden. Pulslängden av NBPs varierar mellan 20 is - 30 is med den normaliserade maximal amplitud är i storleksordningen 10 V / m, i genomsnitt 2 - 3 gånger större än maximal amplituden av vanliga avkastning anslag. De observerades att släppa intensiva HF strålning vid 30 MHz. Grundliga analyser och observationer av dessa pulser hittades tidigare orapporterade skarpa, fina toppar inbäddade i brynets uppgång och nedgång när NBPs elektriska fält förändras. Avslutningsvis visade vår analys att ingen stråle- eller ledarprocess ägde rum före NBPs inledande, och några småskaliga utsläpp var inblandade under bildning av NBPs som skulle kunna ansvara för den intensiva HF-strålningen från NBPs.
Acknowledgements

First of all, I would like to express my gratitude to the Ministry of Higher Education, Malaysia for providing me the scholarship under the Skim Latihan Bumiputra (SLAB) to pursue my study in Uppsala University, Sweden. I am also very grateful to the Universiti Teknologi Malaysia, Johor for giving me opportunity to do my PhD study in Sweden.

I am heartily thankful to my highly dedicated supervisor, Professor Vernon Cooray who has taught me a lot during my years; who with his patience, courage and spirits has lit up my way. Indeed, it is an honor to be given an opportunity to work in his group of lightning research.

Very special thanks to my colleague, Dr. Mahendra Fernando who has devoted himself reading, correcting my papers and guiding me throughout my thesis work. My sincere gratitude goes to other colleagues in the Lightning research group; our big brother – Mahbubur, my lovely roommate- Liliana, Prasan, Oscar, Mona and Riduan, thanks all for the friendship. To my research partner Zikri, thank you so much for helping me during our measurement campaign and also designing the electronic circuit. *Semoga Allah SWT membalas segala kebaikan dan tunjuk ajar yang diberikan.* Also, I would like to thank my fellow colleagues in Finland, Dr. Jäkke and Nikko, for all the moments we worked and been through together. Special thanks to Gunnel Ivarsson and Elin Tögenmark for taking care of the administration issues related to my studies, Thomas for keeping my computer working and Ulf Ring for the technical support. All the rest at the Division for Electricity, Ångström Laboratory is thanked and my sincere appreciation is given where appreciation is due.

Thanks to the Dean of Faculty of Electrical Engineering, Universiti Teknologi Malaysia (UTM), Johor, Prof. Ir. Dr. Abdul Halim bin Mohd Yatim, former dean, Dato’ Prof. Dr. Ahmad Darus, Prof. Dr. Hussein Ahmad and all staff members of Institute of High Voltage and High Current (IVAT), UTM, for their kind help and support throughout my studies.
Untuk semua keluarga Malaysia di Sweden - Kak Saz, Kak Ami, Amad dan Mimi (Happy parenting!), Shahrin dan Kak Yan, Ejant dan Rom, Ros dan Zalmi, Kak Farizah dan Shahril, Syee Ling, Kak Qory, Kak Nana (already back in Malaysia), Kak G, Kak Fizah & keluarga, Aunti Fauziah & keluarga, Kak Ailin& keluarga, Kak Azlina & keluarga, Kak Yati & keluarga, Dr Azian & keluarga, Wan & Pojie, Nor, Bibo, Nurul & keluarga serta Ja dan Ipen di Malaysia, terima kasih atas persahabatan yang telah dijalankan. Tak lupa juga kepada semua kakitangan Kedutaan Besar Malaysia di Stockholm, terima kasih atas layanan mesra dan kerjasama yang diberikan terutama kepada para pelajar yang sedang menuntut di bumi Viking ini. Semoga ukhuwah antara kita akan berkekalan ke akhir hayat.


Akhir kalam, untuk “dia” yang bergelar suami, teman, sahabat, guru dan pembimbingku, Ab Rahim Ab Rahman, - Tiada kata dapat diucapkan atas setiap pengorbanan, kesabaran, semangat, doa dan sokongan yang tidak terhingga selama ini. Semoga hidup kita sekeluarga sentiasa dalam keredhaan Allah Yang Maha Agung. It is said that behind every good man is a great woman but I believe that behind every good wife is a great husband!

Alhamdulillah...
(All praise to Allah Almighty)
He indeed has accepted my prayer.


Appendix A

Resonant circuits are used to respond selectively to signals of a given frequency while discriminating against signals of different frequencies. The 3 MHz resonant circuit used in this study was designed based on series RLC circuit.

For the above RLC circuit, according to Kirchoff’s Voltage Law

\[ v_D(t) = v_L + v_R + v_C \]  \[ \text{[A-1]} \]

\[ v_D(t) = L \frac{d^2i(t)}{dt^2} + R \frac{di(t)}{dt} + \frac{i(t)}{C} \]  \[ \text{[A-2]} \]

\[ \frac{v_D(t)}{L} = \frac{d^2i(t)}{dt^2} + R \frac{di(t)}{dt} + \frac{i(t)}{LC} \]  \[ \text{[A-3]} \]

where:
\[
\frac{R}{L} = 2\tau, \quad \tau = \frac{R}{2L}
\]  \hspace{2cm} [A-4]

\(\tau\) is the decay time constant of the circuit. It determines how fast the transient response of the circuit will die away.

The bandwidth of the circuit is given by:

\[
\text{BW} = \frac{1}{\tau}
\]  \hspace{2cm} [A-5]

The resonant frequency of the circuit is given by:

\[
\frac{1}{LC} = \omega^2_0
\]  \hspace{2cm} [A-6]

\[
\omega_0 = \frac{1}{\sqrt{LC}} \quad \text{in rad/s} \quad \text{or} \quad f_0 = \frac{1}{2\pi\sqrt{LC}} \quad \text{in Hz}
\]
Appendix B

The 30 MHz tuned circuit was designed based on the second order active band-pass filter. The transfer function of a band-pass filter with operational amplifier (in Laplace domain) is given by:

\[ H(s) = \frac{V_o}{V_i} = \frac{H_o \beta s}{s^2 + \beta s + \omega_o^2} \]  

[B-1]

The center frequency \( \omega_o \) is given by:

\[ \omega_o = \frac{1}{C_1 \sqrt{\left( \frac{R_1 R_2}{R_1 + R_2} \right) R_3}} \text{ in rad/s} \]  

[B-2]

\( \beta \) is the bandwidth and is given by:

\[ \beta = \frac{1}{\pi C_1 R_3} \text{ Hz} \]  

[B-3]

\( H_o \) is the maximum amplitude of the filter and is given by:

\[ H_o = -\frac{R_3}{2R_1} \]  

[B-4]
Acta Universitatis Upsaliensis

Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology 822

Editor: The Dean of the Faculty of Science and Technology

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”.)