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# Temporal and Wavelet Characteristics of Initial Breakdown and Narrow Bipolar Pulses of Lightning Flashes

MONA RIZA MOHD ESA



ACTA  
UNIVERSITATIS  
UPSALIENSIS  
UPPSALA  
2014

ISSN 1651-6214  
ISBN 978-91-554-9070-6  
urn:nbn:se:uu:diva-233671

Dissertation presented at Uppsala University to be publicly examined in Polhemsalen, Ångströmlaboratoriet, Lägerhyddsvägen 1, Uppsala, Monday, 1 December 2014 at 09:00 for the degree of Doctor of Philosophy. The examination will be conducted in English. Faculty examiner: Professor Farhad Rachidi ( Swiss Federal Institute of Technology (EPFL)).

### **Abstract**

Esa, M. R. M. 2014. Temporal and Wavelet Characteristics of Initial Breakdown and Narrow Bipolar Pulses of Lightning Flashes. *Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology* 1190. 51 pp. Uppsala: Acta Universitatis Upsaliensis. ISBN 978-91-554-9070-6.

Temporal and wavelet characteristics of initial breakdown pulses are meticulously studied especially during the earliest moment of lightning events. Any possible features during the earliest moment that may exist which lead to either negative cloud-to-ground (CG), positive cloud-to-ground, cloud or isolated breakdown flashes in Sweden are investigated. Moreover, the occurrence of narrow bipolar pulses (NBPs) as part of a CG event that has been recorded from tropical thunderstorms are also included in the investigation. Electric field signatures selected from a collection of waveforms recorded using fast electric field broadband antenna system installed in Uppsala, Sweden and Skudai, South Malaysia are then carefully analyzed in order to observe any similarities or/and differences of their features.

Temporal analysis reveals that there are significant distinctions within the first 1 ms among different types of lightning flashes. It is found that a negative CG flash tends to radiate pulses more frequently than other flashes and a cloud flash tends to radiate shorter pulses than other flashes but less frequently when compared to negative CG and isolated breakdown flashes. Perhaps, the ionization process during the earliest moment of negative CG flashes is more rapid than other discharges. Using a wavelet transformation, it can be suggested that the first electric field pulse of both negative CG and cloud flashes experiences a more rapid and extensive ionization process compared to positive CG and isolated breakdown flashes.

Further temporal analysis on NBPs found to occur as part of CG flashes show the disparity of the normalized electric field amplitude between the NBPs prior to and after the first return stroke. This indicates that the NBPs intensities were influenced by the return stroke events and they occurred in the same thundercloud. The similarity between the temporal characteristics of NBPs as part of CG flashes and isolated NBPs suggests that their breakdown mechanisms might be similar.

*Keywords:* Initial breakdown; Lightning flash; Narrow bipolar pulse; Temporal-Wavelet characterization

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ISSN 1651-6214

ISBN 978-91-554-9070-6

urn:nbn:se:uu:diva-233671 (<http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-233671>)

*To the loves of my life:  
My other half, Riduan  
My best supporter, Mawar Merah  
My sweet little candies, Fatihah, Huzaiyah & Ilham Linnaeus Ayra*



# Acknowledgements



In the name of ALLAH, the most Gracious, the most Merciful

First and above all, I praise Allah, the Almighty for providing me this opportunity and granting me the capability to stay strong and finally finish my PhD study.

This thesis will not be completed without help and support from these special persons. **Professor Vernon Cooray**, my mentor, my idol and my guru. Thank you Prof, for your warm encouragement, patience and knowledgeable advices. Your guidance has made this a thoughtful and rewarding journey.

I have been blessed with friendly and supportive lightning group members. My second supervisor, Dr. Mahbubur, many thanks for your courage and constructive critics. To Pasan, Oscar, Muzafar, Dalina, Dr. Azlinda, Dr. Zikri, Dr. Sharma and Dr. Liliana, thank you for all valuable ideas, reviews and comments. I am looking forward to continue doing the research together. I would also like to thank the English and Swedish proof read teams whom willingly read through this humble thesis; Prof. Eryk Dutkiewicz, Muzafar, Dalina, Riduan, Dr. Saman Majdi and Dr. Mahbubur. My special thanks also dedicated to Mr. Thomas and Mr. Ulf for the technical supports. To Gunnel, Maria, Ingrid and Anna for helping me concerning the administration issues. To all my friends in the Division of Electricity, thank you for the friendship and memories.

My partner cum office mate, Mohd Riduan Ahmad, thank you for being you. Your sceptical thinking, critical yet fruitful comments are helping me a lot (with tears come and go of course, but worth it!). Please never stop being a supportive husband for me and a loving Papa for our kids. Thank you Abang for this wonderful and memorable journey.

For the angels of my heart, Fatiha, Huzaifah and Ilham Linnaeus Ayra, thank you for being the best companions and patience with Mama's highs and lows. Ingat pesan Mama, "Kejayaan tidak akan datang dengan sendiri andai tiada usaha, tapi berusahalah dengan ikhlas, bersungguh-sungguh dan jangan cepat jemu, hasilnya pasti tiba dengan izin-Nya". Mama sayang anak-anak Mama.

Buat mak, Hajah Rosminah Mahmod, ayah, Mohd. Esa Ali dan atuk, Hajah Sadariah Abdullah, serta keluarga mertua yang disayangi, terima kasih atas doa, nasihat dan kasih sayang yang tak pernah putus untuk kami sekeluarga. Buat adik-adik, Iwan, Siti, Ijat dan Apit, jangan pernah berhenti doakan akakmu ini.

Buat sahabat-sahabat Malaysia di Sweden dan semua kakitangan Kedutaan Besar Malaysia di Stockholm, serta rakan karib di Malaysia, terima kasih atas dorongan dan sokongan sepanjang kami berada di bumi Viking ini. Ada jodoh dan umur kita bertemu lagi di Malaysia, bumi bertuah.

I would also like thank the World Wide Lightning Location Network (<http://wwlln.net>), collaboration among over 50 universities and institutions, for providing the lightning location data used in this thesis.

Last but not least, my appreciation goes to the Ministry of Education Malaysia (KPM) and Universiti Teknologi Malaysia (UTM) as well as Institute of High Voltage and High Current (IVAT) for giving me the opportunity to pursue my PhD study at Uppsala University and for the financial support for the past five years here in Sweden.

# List of Papers

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

- I        **Esa, M. R. M.**, Ahmad, M. R., Rahman, M., Cooray, V., (2014). Distinctive features of radiation pulses in the very first moment of lightning events. *Journal of Atmospheric and Solar-Terrestrial Physics*, (109): 22–28
- II        **Esa, M. R. M.**, Ahmad, M. R., Cooray, V., (2014). Wavelet analysis of the first electric field pulse of lightning flashes in Sweden. *Journal of Atmospheric Research*, (138): 253–267
- III        \***Esa, M. R. M.**, Ahmad, M. R., Cooray, V., Signature of narrow bipolar pulses in negative cloud-to-ground flashes of tropical thunderstorms. *Submitted to Journal of Atmospheric and Solar-Terrestrial Physics*, September 2014.
- IV        **Esa, M. R. M.**, Ahmad, M. R., Cooray, V., (2014). Wavelet profile of initial breakdown process accompanied by narrow bipolar pulse. *Submitted to Journal of Atmospheric and Solar-Terrestrial Physics*, October 2014.

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\*Equal contribution between first author and second author.

Other contributions of the author, not included in the thesis.

- V        **Esa, M. R. M.**, Ahmad, M. R., Cooray, V., (2014). Occurrence of narrow bipolar pulses between negative return strokes in tropical thunderstorms. *In: Proceeding of the 32<sup>nd</sup> International Conference on Lightning Protection (ICLP)*, Shanghai, China.

- VI **Esa, M. R. M.**, Ahmad, M. R., Cooray, V., (2014). Time-frequency profile of discharge processes prior to the first return stroke. *In: Proceeding of the 32<sup>nd</sup> International Conference on Lightning Protection (ICLP)*, Shanghai, China.
- VII Ahmad, M. R., **Esa, M. R. M.**, Johari, D., Ismail, M. M., Cooray, V., (2014). Chaotic pulse train in cloud-to-ground and cloud flashes of tropical thunderstorms. *In: Proceeding of the 32<sup>nd</sup> International Conference on Lightning Protection (ICLP)*, Shanghai, China.
- VIII Ahmad, M. R., **Esa, M. R. M.**, Cooray, V., (2014). Similarity between the initial breakdown pulses of negative ground flash and narrow bipolar pulses. *In: Proceeding of the 32<sup>nd</sup> International Conference on Lightning Protection (ICLP)*, Shanghai, China.
- IX Ahmad, M. R., **Esa, M. R. M.**, Cooray, V. Signatures of ordinary and sub microsecond narrow bipolar pulses observed in Sweden. *Submitted to Journal of Atmospheric Research*, September 2014.
- X Ahmad, M. R., **Esa, M. R. M.**, Cooray, V., Baharudin, Z. A., Hettiarachchi, P., Latitude dependence of narrow bipolar pulses occurrences. *Submitted to Journal of Atmospheric and Solar-Terrestrial Physics*, September 2014.
- XI Ahmad, M.R., **Esa, M. R. M.**, Cooray, V., Dutkiewicz, E., (2014). Interference from cloud-to-ground and cloud flashes in wireless communication system. *Journal of Electric Power System Research*, (113): 237–246.
- XII Ahmad, M.R., **Esa, M. R. M.**, Cooray, V., (2014). Occurrence of narrow bipolar event as part of cloud-to-ground flash activity in tropical thunderstorms. *In: Preprint of the 15<sup>th</sup> International Conference in Atmospheric Electricity (ICAE)*, Oklahoma, USA.
- XIII **Esa, M. R. M.**, Ahmad, M. R., Cooray, V., (2013). Wavelet analysis of the first pulse of initial breakdown process in lightning discharges. *Progress in Electromagnetics Research Symposium*, pp. 1377–1380.

- XIV Ahmad, M.R., **Esa, M. R. M.**, Cooray, V., (2013). Narrow bipolar pulses and associated microwave radiation. *Progress in Electromagnetics Research Symposium*, pp. 1087–1090.
- XV **Esa, M. R. M.**, Ahmad, M. R., Cooray, V. Rahman, M., (2012). Distinctive features of initial breakdown process between ground and cloud discharges. *In: Proceeding of Asian Conference of Electrical Discharges (ACED)*, Johor Bahru, Malaysia.
- XVI Ahmad, M.R., **Esa, M. R. M.**, Cooray, V., Dutkiewicz, E., (2012). Performance analysis of audio streaming over lightning-interfered MIMO channels. *In: Proceeding of International Symposium on Communications and Information Technologies (ISCIT)*, Gold Coast, Australia, pp. 513–518.
- XVII Ahmad, M.R., **Esa, M. R. M.**, Hettiarachchi, P., Cooray, V., (2012). Preliminary observations of lightning signature at 2400 MHz in Sweden thunderstorm. *In: Proceeding of IEEE Asia-Pacific Conference of Applied Electromagnetics (APACE)*, Malacca, Malaysia, pp. 88–91.
- XVIII Ahmad, M.R., **Esa, M. R. M.**, Rahman, M., Cooray, V., (2012). Measurement of bit error rate at 2.4 GHz due to lightning interference. *In: Proceeding of the 31st International Conference on Lightning Protection, ICLP*, pp. 1–4.
- XIX Ahmad, M.R., **Esa, M. R. M.**, Cooray, V., Rahman, M., Dutkiewicz, E., (2012). Lightning interference in multiple antennas wireless communication systems. *Journal of Lightning Research*, (4): 155–165.
- XX Ahmad, M.R., Rashid, M., Aziz, M. H. A. **Esa, M. R. M.**, Cooray, V., Rahman, M., Dutkiewicz, E., (2011). Analysis of Lightning-induced Transient in 2.4 GHz Wireless Communication System. *In: proceeding of IEEE International Conference on Space Science and Communication (IconSpace)*, Sydney Australia, pp. 225 – 230.



The Scientific Committee of the  
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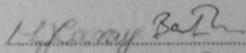
*Time-Frequency Profile of Discharge Processes Prior to the Fast Return Stroke*

at the International Conference on Lightning Protection and  
has made notable contributions in the field of lightning research  
and lightning protection

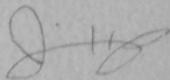
32<sup>nd</sup> International Conference on Lightning  
Protection  
ICLP 2014  
Shanghai, CHINA  
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# Abbreviations

–CG	negative cloud-to-ground flash
+CG	positive cloud-to-ground flash
+NBP	positive narrow bipolar pulse
–NBP	negative narrow bipolar pulse
BW	bandwidth
CID	compact intracloud discharge
DAQ	data acquisition
DOG	Derivative of Gaussian
DSO	digital storage oscilloscope
E	electric field
FWHM	full width half maximum
FT	Fourier transform
GPS	global positioning system
IB	isolated breakdown
IC	cloud flash
kHz	kilo Hertz
km	kilometre
ms	milliseconds
ms <sup>-1</sup>	meter per second
μs	microsecond
MHz	Mega Hertz
MM	Multiple-peaks Multiple-spreads
MS	Multiple-peaks Single-spread
<i>N</i> region	negative main charge centre region
<i>p</i> region	lower positive charge region
<i>P</i> region	positive main charge centre region
PBP	preliminary breakdown process
PD	pulse duration
RG58	type of coaxial cable
RS	rise time
RS1	first return stroke
s	second
SL	stepped leader
SM	Single-peak Multiple-spreads
SS	Single-peak Single-spread
VLF	very low frequency

V/m	volt per meter
WWLLN	World Wide Lightning Location Network
ZCT	zero crossing time
$\pi$	pi
$\tau_r$	rise-time constant
$\tau_d$	decay-time constant
$\sim$	approximation

# Thesis Outline

This thesis is based on four journal papers (**Papers I, II, III, and IV**) and divided into four main chapters. Each chapter will be described in the sequence order as follows:

Chapter 1 introduces important concepts about initiation of lightning discharges and narrow bipolar pulses. The objectives and the contributions of this thesis are summarized at the end of the chapter.

Chapter 2 explains about measurements conducted in Uppsala, Sweden and South Malaysia as well as the methods used throughout the analysis process.

Chapters 3 and 4 deal with the overview of thesis works and the findings are discussed as part of the summary of each paper.

Chapter 5 concludes the thesis works.

*Nomenclature:* The term ‘flash’, ‘discharge’ and ‘lightning’ are used interchangeably in this thesis to describe either cloud lightning or cloud-to-ground lightning. The term isolated breakdown pulses (IBP) and isolated breakdown (IB) are also used interchangeably throughout this thesis especially in chapter 3 to describe the initial breakdown pulses that does not lead to any subsequent activities such as return stroke or cloud flashes.



# 1. Introduction

Lightning is one of natural phenomena that is believed to be the most remarkable electric charge flow from an ambiguous origin. Its occurrence is usually accompanied by a very bright light and loudest thunder sound. Globally, lightning has been recorded to appear about few tens of flashes every second, 9 million flashes per day and more than a billion discharges annually [Dwyer and Uman, 2014; Oliver, 2005].

Historically, the study of lightning began more than a couple of centuries ago when the world famous scientist, Sir Benjamin Franklin started his first in-lab electricity experiment in 1746 and 6 years later he flew his legendary ‘kite-and-key’ during an outdoor experiment. Since then, the quest of lightning research continues with lots of impressive techniques and approaches since our knowledge and detailed physical understanding are still very limited.

## 1.1 Lightning Initiation

The hypothesis about lightning initiation in the cloud has been proposed to be explained using these famous postulations known as conventional breakdown theory and runaway breakdown theory [Gurevich and Zybin, 2005]. Indeed, these hypotheses are actually interrelated in a few possible ways or scenarios which occur in the thundercloud that initiate a lightning [Dwyer and Uman, 2014].

In theory, lightning initiation can be defined as the process that occurs in a thundercloud that involves the formation of hot leader channels in random directions (either vertically or horizontally) by bridging two charge regions, e.g., (1) vertical channel bridging between the main negative charge center ( $N$  region) and lower positive charge pocket ( $p$  region) [Clarence and Malan, 1957], (2) vertical channel bridging between the  $N$  region and main positive charge center ( $P$  region) [Proctor, 1997], (3) Norinder and Knudsen (1956) and Krehbiel et al. (1979) suggested that a horizontal channel extended from the main negative charge source giving rise to electrical discharges.

In classical studies, the initial breakdown process in a negative cloud-to-ground flash (–CG) was denoted using BIL where the breakdown ( $B$ ) stage followed by the intermediate ( $I$ ) stage and then the stepped leader ( $L$ ) stage [Schonland, 1956; Clarence and Malan, 1957]. However, even though their studies show that the starting point of the  $B$  stage is somewhere between the

$N$  region and  $p$  region, these researchers had different opinions regarding the discharge mechanism of these processes specifically whether the preliminary breakdown process (PBP) and stepped leader (SL) is a continuous process or completely two different discharge mechanisms.

Sharma et al. (2008) suggested that the discharge process ( $B$  stage) during lightning initiation could be grouped into three categories as follows:

- a. Initial breakdown process leading to CG and commonly known as preliminary breakdown process (PBP).
- b. Initial breakdown process associated with cloud discharge (IC).
- c. Initial breakdown process that does not lead to any subsequent activities known as isolated breakdown pulses (IBP). Nag and Rakov (2009) used ‘attempted first cloud-to-ground leaders’ and ‘inverted IC flash’ in describing IBP flash.

Despite so many theories to explain the process, this particular lightning physics problem still remains unsettled.

## 1.2 Narrow Bipolar Pulse (NBP)

The study regarding narrow bipolar pulses (NBPs) has become a popular subject in lightning research. This in-cloud lightning event was earlier called Le Vine pulses also known as compact intracloud discharge (CID) and narrow bipolar event (NBE). Firstly reported by Le Vine about 3 decades ago, this unique electric field signature displays such temporal characteristics as a typical pulse duration (PD) of about 10–20  $\mu\text{s}$  [Sharma et al., 2008; Zhu et al., 2010], with typically a much narrower rise time (1–2  $\mu\text{s}$ ) [Medelius et al., 1991; Azlinda Ahmad et al., 2010], a very high frequency component [Light and Jacobson, 2002; Nag et al., 2010], a very weak optical emission [Jacobson, 2003] and a significantly large amplitude relative to return strokes and cloud flash pulses [Smith et al., 1999].

Previously, NBP was commonly reported to exist in isolation [Le Vine, 1980; Cooray and Lundquist, 1985; Willett et al., 1989; Medelius et al., 1991; Smith et al., 1999; Hamlin et al. (2009)] and sometimes initiated IC flashes [Rison et al., 1999; Smith et al., 2004]. However, it was recently reported that NBP was also detected as part of CG flashes [Nag et al., 2010; Azlinda Ahmad et al., 2010; Wu et al., 2011]. In addition, more recent works showed that NBPs radiate an intense microwave frequency component and are the source of a disturbance to the wireless communication channel at 2.4 GHz and these works also reported that such a microwave radiation burst preceded about few microsecond the starting point of NBP [Ahmad et al., 2012; Ahmad et al., 2013; Ahmad et al., 2014].

Narrow bipolar pulses have been observed with both positive and negative polarities where +NBPs are found to be more common than –NBPs and the source height of –NBP is believed to be higher than +NBP. The occurrence of NBP is reported to exist inside the cloud either between the main positive and main negative charge centres (*P-N* regions) for +NBP and between the screening layer (cloud top) and main positive charge centre (*P* region) for –NBP [Zhu et al., 2010; Nag et al., 2010].

Nag et al. (2010) reported about 6 % of the total examined +NBPs have occurred as part of a CG flash in Florida thunderstorms. Azlinda Ahmad et al., (2010) reported that about 2.8 % of the total recorded NBPs have occurred as part of a CG flash in Malaysian thunderstorms during the southwestern monsoon season. Wu et al. (2011) reported that about 0.2 % of the total examined NBPs have occurred as part of a CG flash in South China thunderstorms. Nag et al. (2010) have observed the occurrence of NBPs events in between return strokes where the subsequent return stroke has created a new termination on ground, which created the possibility that a particular subsequent return stroke was initiated by the +NBP. However, such an event was detected only once.

### 1.3 Objectives and Contributions

The whole idea of this thesis work is to understand the behaviour and characteristics of the initial part of a lightning flash from its electromagnetic field and how its unique progresses in the initiation breakdown process lead to different types of lightning flashes.

This thesis work is based on two main objectives. The first one is to investigate and differentiate the earliest moment of the lightning initiation process among different types of lightning discharges by looking at it from two different perspectives; temporal and wavelet domains. This objective covers the studies conducted in **Papers I** and **II** for four types of lightning flashes namely negative CG flash, positive CG flash, IC flash, and IBP flash.

The second objective aims to investigate temporal and wavelet characteristics of initial breakdown processes that have been accompanied by NBP prior to the first return stroke of negative CG flashes. In **Paper III**, an observation of NBPs occurrence as part of CG flashes is reported. Temporal analysis has been conducted to understand whether these NBPs are different from isolated NBPs as well as how they are related to the return stroke event. In **Paper IV**, wavelet characteristics of initial breakdown pulses, NBPs, and stepped leaders, all occurring prior to the first return stroke, are investigated.

These two subjects (lightning initiation and NBPs) are among the top ten questions in lightning research listed by Dwyer and Uman, (2014). The contributions of each paper are summarized as follow:

### **Paper I – Distinctive Features of Radiation Pulses in the Very First Moment of Lightning Events**

Instead of analysing the whole duration of the initial breakdown process, we choose to analyse and study the first millisecond of the initial breakdown process for 4 types of lightning events. The earliest moments from 110 lightning events are chosen which include negative and positive CG flashes, IC flash and IBP flash which were recorded during the summer in Uppsala, Sweden between May and August 2010.

Significantly, the temporal comparative features show that in average –CG pulses appeared more frequently than other lightning discharges, the ratio of pulse amplitudes relative to the largest pulse of +CG pulses is distinctively higher than others and IC pulses tend to have the shortest duration compared to the other lightning discharges.

### **Paper II – Wavelet Analysis of the First Electric Field Pulse of Lightning Flashes in Sweden**

As an alternative to the time domain approach, the first electric field pulse of 4 type of lightning events is analysed through the wavelet domain. The first electric field pulse from the same 110 waveforms recorded from a fast field broadband measurement system that have been previously used in **Paper I** are wavelet-transformed and their features in both temporal and spectral perspectives are described and compared according to their categories.

In general, it is discovered that both single peak and multiple peaks pulses of –CG and IC flashes radiated energy at higher frequencies and gain a larger bandwidth when compared to +CG and IBP flashes. Based on the temporal and spectral analysis, it is suggested that the first electric field pulses of the IC flash radiated energy at a higher frequency in both single spread categories and radiated energy at lower frequency in both multiple spread categories when compared to the –CG flash. The analysis also suggests that the breakdown mechanism of IBP is a unique event and distinctive from +CG.

### **Paper III – Signature of Narrow Bipolar Pulses in Negative Cloud-to-Ground Flashes of Tropical Thunderstorms**

The occurrence context of NBP in Malaysia is studied and the appearance of NBP as part of a CG flash is also observed and reported. The intention is to understand how the appearance of NBP at different stages either prior to or after the return stroke has a connection to the return stroke event particularly to the –CG flash.

Apparently, a strong negative background electric field magnitude will produce –NBP with a higher electric field intensity particularly preceding the return stroke activities. The reduction of the background electric field magnitude after the first return stroke also significantly decreased the electric field magnitude of –NBP at least by half. The considerable deviation of the normalized

electric field amplitudes of both +NBP and –NBP from isolated NBPs is a strong suggestion that they have occurred inside the same thunderstorm that initiated the return stroke event and not from isolated thunderstorms.

#### **Paper IV – Wavelet Profile of Initial Breakdown Process Accompanied by Narrow Bipolar Pulse**

The aim of this paper is to investigate the time-frequency profile for sets of lightning events particularly focusing on the initial breakdown process that occurred prior to the first return stroke of negative CG flashes. Such processes include PBPs and stepped leaders which were accompanied by NBP. By selecting only 6 located NBPs prior to the first return stroke from **Paper III**, each pulse in each event is wavelet-transformed and plotted accordingly.

Obviously, the maximum power spectrum magnitude of NBPs is extremely high compared to the PBP and SL pulses. The pattern of the power spectrum magnitude of the PBP pulse trains show that it is higher at the earlier stage and decreases toward the end. On the other hand, an opposite pattern is observed for SL pulse trains.



## 2. Methodology

In this chapter, the lightning measurement campaigns that providing the data for the analysis will be described. In a later section, the approach on how the data is analysed is summarized.

### 2.1 Experimentation

The data analysed in this thesis were recorded in two different regions which are in Uppsala, Sweden and South Malaysia. Data used in **Paper I** and **II** were recorded during summer 2010 at the temperate region, whereas for **Paper III** and **IV**, the lightning electric field signatures were captured during the north-eastern monsoon season at the tropical region in 2012.

Basically, there are 3 parts that are very important in the measurement of fast electric field intensities from lightning discharges. These 3 parts involved; (1) the Antenna system, (2) the Buffer circuit and (3) the Recording system. In general, the whole measurement system used in both measurement sites is shown in Figure 1. Particularly, the only difference in both measurement campaigns is the usage of the type of oscilloscope in the recording systems which will be explained briefly in section 2.1.1 and 2.1.2, for the measurement campaign in Uppsala, Sweden and Skudai, South Malaysia, respectively.

In the antenna system, 2 circular and flat shape aluminium plates are designed in parallel to act as a capacitor that will capture the electric field from lightning electromagnetic radiation which the signal will then pass through the buffer circuit. The buffer circuit is connected directly to the plate top via coaxial cable (RG58) and the lower plate is connected to the ground.

The buffer circuit unit is designed to drive the signal coming from the antenna system to the recording system. There is no amplification of the incoming signal since the gain of the operational amplifier used in the buffer circuit is unity. The buffer is battery-powered in order to minimize its sensitivity to the interference caused by other electronic devices and recording equipment. The upper and lower frequency limits are determined by the rise-time and decay-time constants,  $\tau_r$  and  $\tau_d$ , respectively. Theoretically, the higher 3dB frequency limit of bandwidth of the antenna output is given by  $1/2\pi\tau_r$ , while for lower frequency limit of bandwidth is given by  $1/2\pi\tau_d$  [Cooray; 2003].

The last part of the measurement system consist of the transient recorder or digital storage oscilloscope (DSO) that connected to a large memory space

external hard disk. The DSO is set such that it is able to capture the desired lightning electric field signatures without losing any important features. The detail of each measurement campaigns is described later in the next section.

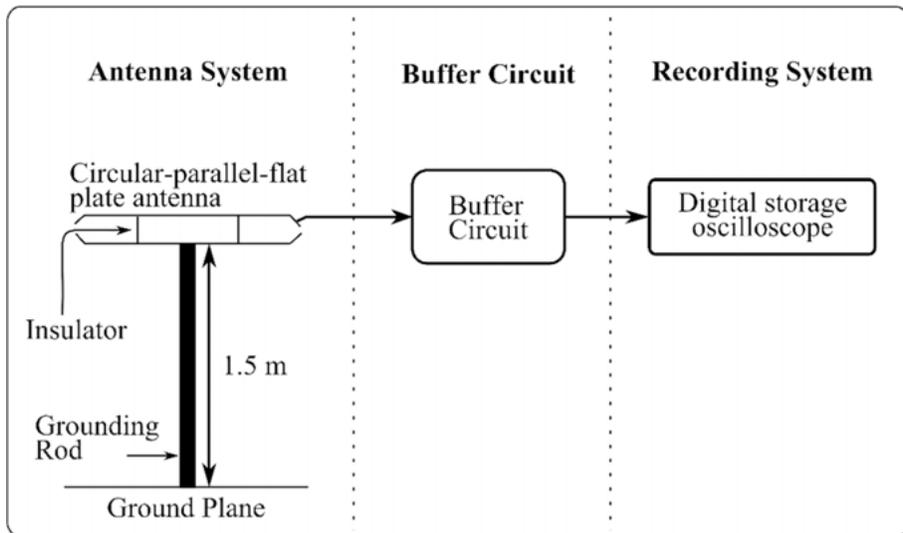


Figure 1. Broadband electric field change recording system.

### 2.1.1 Experimentation in Uppsala, Sweden

The circular-parallel-flat plate antenna used in capturing the electric field intensity was installed near to the premise of Angstrom Laboratory, Uppsala University (59.8°N, 17.6°E) about 100 km to the west of Baltic Sea. The measurement campaign was carried out during summer thunderstorms between mid of May to the end of August 2010. In this measurement, the rise- and decay-time constants used in the buffer circuit is 10 ns and 15 ms, respectively. Therefore, the antenna output is digitized at rates between 10.6 Hz and 16 MHz.

The transient recorder used in this measurement is an independent, isolated 4-channel 12-bit Yokogawa SL1000 and equipped with data acquisition (DAQ) modules 720210. The whole recording unit was placed inside a fully grounded wagon about 10 meters away from the antenna and buffer circuit units. The recorder's sampling rate was set to 20 Mega samples per second with 50 ns time resolution and pre-triggered delay was set to 200 or 300 ms with the total of 1 second full window frame. A total of 885 waveforms were recorded during this measurement campaign. This measurement setup was previously used and explained in great details by Baharudin (2014) and Ahmad (2011).

### 2.1.2 Experimentation in Johor, Malaysia

The whole wideband electric field change recording system was located near the premise of Observatory Station in the Universiti Teknologi Malaysia (UTM), Skudai, South Malaysia. This particular station is situated at the southern region of Malaysia (1.5°N, 103.6°E) which is on top of the hill about 132 m above sea level and about 30 km from Tebrau strait. The rise- and decay-time constants used in the buffer circuit for this measurement site is 10 ns and 15 ms, respectively, which are similar to the buffer circuit used in measurement in Uppsala, Sweden.

The buffer circuit was connected to a LeCroy Wave Runner 44Xi-A DSO, placed inside the building, via 10 meters long shielded RG58. The DSO digitized the output of the buffer circuit at 25 Mega Samples per second (20 ns time resolution with 500 ms full window size and 150 ms pre-triggered delay) and 8-bit vertical resolution with a 100 MHz bandwidth (10 ns impulse width resolution). The DSO was triggered by either a positive edge or a negative edge of the incoming signal with the trigger level varied between 0.5 V and 1.0 V. A total of 1262 lightning electric field signatures managed to be recorded during this measurement campaign. Additional details of this instrumentation and location techniques in South Malaysia are given by Ahmad et al. (2013) and Ahmad et al. (2014).

## 2.2 Data Analysis

The methodologies used in analysing the data are divided into two different approaches. Mainly, the analyses that have been done involved both time and wavelet domains. In the time domain analysis, the signal is characterized directly which has been done for the data in **Paper I** and **III**. Several temporal characteristics that have been selected will be described in the following section 2.2.1 below.

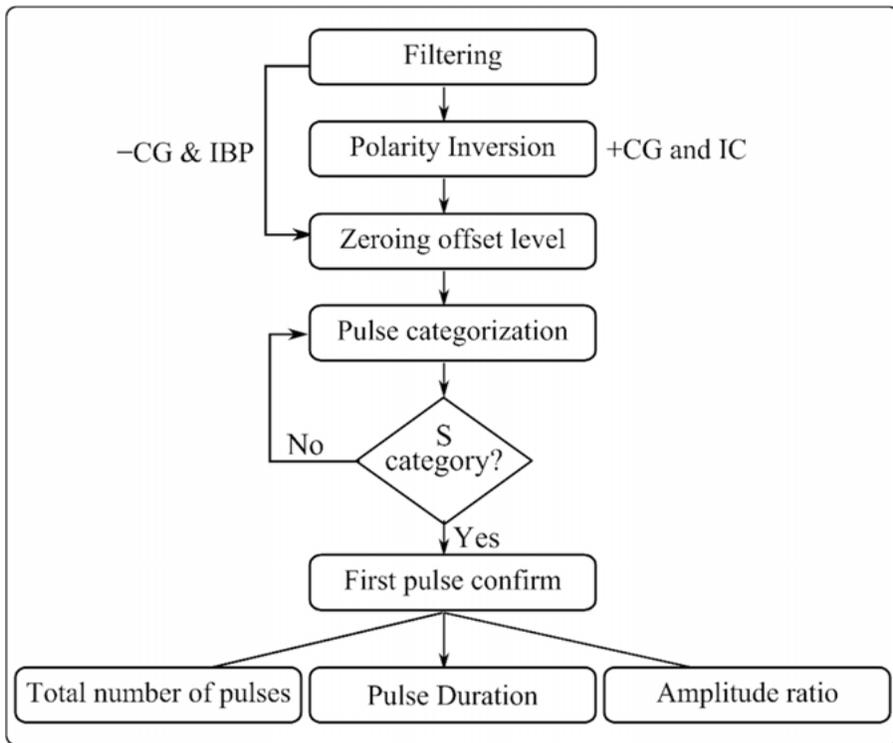
On the other hand, for the analysis that is done in the wavelet (so-called time-frequency) domain, the signals are required to be wavelet-transformed. The transformed signal will then analysed using wavelet properties or parameters which has been done in **Paper II** and **IV** and explained in section 2.2.2 below.

### 2.2.1 Time Domain Characterization

Basically, time domain analysis is usually used by the lightning researchers to characterize the lightning electromagnetic pulses. Essentially, using the time domain characterization, the result shall be reported in terms of pulses' rise time (RT), zero crossing time (ZCT), full width half maximum (FWHM), interpulse duration (IPD) and pulse duration (PD). As has been done in **Paper**

**I**, the parameters are utilized to describe the pulses in order to differentiate 4 types of lightning flashes which are total number of pulses, the average of the normalized amplitude and PD. Partly in **Paper II** also utilize PD and ZCT in characterizing the first electric pulse. Also in **Paper III**, we selected RT, ZCT, FWHM and PD to describe the temporal characteristics of our located narrow bipolar pulses.

Particularly done in **Paper I** and **II**, the selection of the very first pulse is the most crucial part. The selection process mainly consists of several steps. The detail of each step is explained discretely in **Paper I** (Data section) and simplified as illustrated in Figure 2 below.



*Figure 2.* The step-by-step process of selected waveforms to define the first pulse. CG, cloud-to-ground flashes; IBP, Isolated breakdown pulses; IC, cloud flashes.

Figure 2 shows the step-by-step process in order to identify the first pulse of initial breakdown process. All waveforms shall undergo several steps before the temporal analysis can be done. Positive CG and IC have extra steps in order to have the same polarity with  $-CG$  and IBP. Therefore, direct comparison can be performed.

## 2.2.2 Wavelet Domain Characterization

This method is recently used to portray the lightning electromagnetic pulses in a different perspective. The approach to analyze the electric field signal radiated from lightning has been carried out extensively since it has been introduced by Miranda (2008) to differentiate between far and close cloud-to-ground (CG) flashes and then continued by Sharma et al. (2011) and Li et al. (2012) for various type of electric field signatures.

In the previous years, Fourier Transform (FT) is the most popular method to transform the signal into frequency domain, mainly just focusing on the signal's spectral characterization. However, using the FT method one will not be able to preserve the time information which is very crucial in lightning research. Therefore, by using the wavelet transformation it may help the researcher to keep both temporal as well as spectral information.

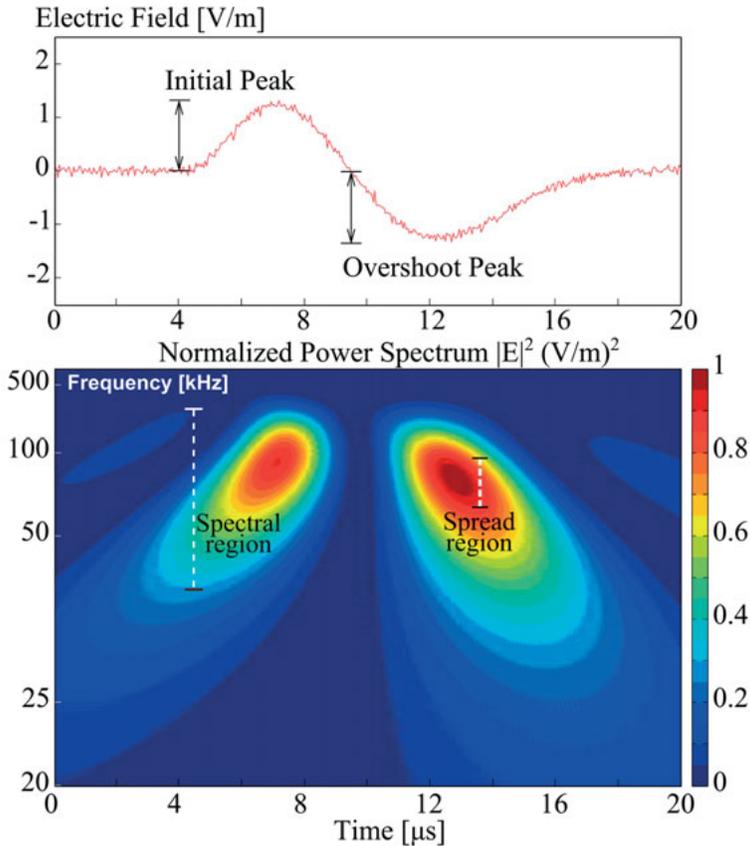
During the process, the pulse undergoes the wavelet transformation and the result is plotted in the frequency versus time axes as illustrated in Figure 3. The pulses were wavelet-transformed using a selected algorithm and the normalized power spectrum was estimated. Particularly for **Paper II** and **IV**, the selected algorithm for the wavelet transformation was Derivative of Gaussian (DOG). This algorithm was believed to be the most stable as the results will be less diverged [Sharma et al., 2011]. The power spectrum was normalized to the maximum value because the information of the distance between the source of radiation and the point of observation was absent.

Figure 3 shows an example of the first electric field pulse in initial breakdown process of isolated breakdown pulse (IBP) flash pulse in the time domain (top) and its corresponding normalized power spectrum in the wavelet or time-frequency domain (bottom) for both initial and overshoot stages of the electric field pulse. The intensity level of the normalized power spectrum is plotted according to the colour coding contour. The vertical colour bar on the right hand side of the bottom figure shows the scale for intensity level from 0 to 1. The dark-red colour contour represents the highest intensity level while the dark blue colour represents the background noise.

This method is mainly used in both **Paper II** and **IV** as we are motivated to characterize the initial part of lightning initiation in a spectral perspective. Particularly, in **Paper II**, we described every first pulse based on these parameters; spectral region, spread region, bandwidth, and ratio of power peak of initial to overshoot stages. However in **Paper IV**, we chose to characterize the pulses using 3 parameters, which are the first two parameters that used in **Paper II** and maximum power spectrum magnitude are applied.

By referring to Figure 3, the spectral region is bounded by the light-blue colour contour while the spread region is bounded by the dark-red colour contour. The maximum frequency of the spectral region in Figure 3 is about 200 kHz during initial stage and slightly lower during overshoot stage at about 150 kHz. On the other hand, the minimum frequency of the spectral region is about

40 kHz during initial stage and 30 kHz during overshoot stage. Therefore, the bandwidth (BW) of the spectral region in Figure 3 is estimated about 160 kHz and 120 kHz for initial and overshoot stages, respectively. The definitions and detailed explanations of all parameters are given in Table 1.



*Figure 3.* Wavelet power spectrum of the first pulse for isolated breakdown flashes (IB) which in Single-peak Single-spread (SS) category (**Paper II**).

In order to describe the distinctive feature, 4 categories have been introduced which are Single-peak Single-spread (SS), Single-peak Multiple-Peaks (SM), Multiple-peaks Single-spread (MS) and Multiple-peaks Multiple-spreads (MM). The example of the SS category is shown in Figure 3. The example of the other 3 categories can be referred in **Paper II** (Figures 3, 4, 5) which are explained in Table 1 below.

In **Paper IV**, every single pulse of PBP, SL, NBP and the first RS have been wavelet-transformed and analysed in terms of frequency components and power spectrum characterization. The value of the power spectrum is not normalized to the maximum value since the distance information for NBPs and RS were available.

Table 1. Definitions of important wavelet parameters used in **Paper II** and some in **Paper IV**.

Parameters/Categories	Definitions
Spectral region	Region where predominant energy radiate.
Spread region	Part of spectral region, which is the most intense energy radiation.
Power spectrum	Energy radiated by each pulse after undergoing the wavelet transformation.
Power spectrum peak frequency	The frequency where the maximum power spectrum is located
Bandwidth	Difference between average maximum frequency and average minimum frequency.
Ratio of power peak	Ratio of power peak of initial stage corresponds to overshoot stage power peak.
*Single-peak single-spread (SS)	Pulse with single peak (in time domain) with single spread region (in wavelet domain). (Illustrated in Figure 3)
*Single-peak multiple-spreads (SM)	Pulse with single peak (in time domain) with multiple spread regions (in wavelet domain). (Refer Fig. 3 in <b>Paper II</b> )
*Multiple-peaks single-spread (MS)	Pulse with multiple peaks (in time domain) with single spread region (in wavelet domain). (Refer Fig. 4 in <b>Paper II</b> )
*Multiple-peaks multiple-spreads (MM)	Pulse with multiple peaks (in time domain) multiple spread regions (wavelet domain). (Refer Fig. 5 in <b>Paper II</b> )

**Note:** The asterisk (\*) indicates SS, MS, SM and MM are correspond to wavelet categories



### 3. Temporal and Wavelet Characteristics of the Earliest Moment of Lightning Flash Event (**Papers I & II**)

In this chapter, the results of temporal and wavelet analysis of the earlier moment of the lightning initiation process for different type of lightning flashes are summarized.

#### 3.1 Overview

In general, comparative studies on lightning initiation in thundercloud have been done by earlier researchers for many years before. Their approach was more to analyse the whole duration of the initial breakdown process. On the other hand, **Papers I** and **II** are focusing only on the earliest part of lightning initiation for 4 types of lightning flashes namely; negative cloud-to-ground (-CG), positive cloud-to-ground (+CG), cloud flash (IC) and isolated breakdown pulse (IBP). Our investigation involved both the time and wavelet (or time-frequency) domains in order to investigate any possibilities of distinctive features that may exist leading to one of the lightning events mentioned above.

#### 3.2 Temporal Characteristics (Paper I)

Out of 885 waveform that have been gone through a critical selection process, 110 fine structure waveforms that involved 44 -CG, 16 +CG, 39 IC, and 11 IBP were chosen to be analysed in the time domain parameters; total number of pulses, average ratio of amplitude relative to the largest amplitude and pulse duration (PD). In addition, the first electric pulses from the same 110 waveforms then undergo the wavelet transformation for further investigation in the wavelet domain.

It is found that the -CG flash tends to radiate more pulses than other flashes with an average of 45 pulses in the first millisecond. A cloud flash tends to radiate pulses with the shortest duration but less frequently than -CG and IBP flashes. It is also discovered that +CG flashes gained a distinctively highest ratio of the amplitude relative to the largest pulses in the first millisecond

when compared to the other 3 lightning flashes. Table 2 shows the mean and standard deviation of each parameter pertinent to the lightning discharge types.

Table 2. *Mean and standard deviation.*

Lightning Discharge Type	Total number of pulses	Average ratio of pulse amplitudes	Pulsed duration ( $\mu$ s)
Negative CG (–CG)	<b>44.61 <math>\pm</math> 15.82</b>	0.30 $\pm$ 0.06	11.08 $\pm$ 5.62
Positive CG (+CG)	16.81 $\pm$ 6.75	<b>0.48 <math>\pm</math> 0.15</b>	13.19 $\pm$ 6.41
Cloud Flash (IC)	18.69 $\pm$ 7.32	0.33 $\pm$ 0.10	<b>5.76 <math>\pm</math> 4.79</b>
Isolated Breakdown Pulses (IBP)	26.55 $\pm$ 8.78	0.32 $\pm$ 0.08	15.07 $\pm$ 4.70

A significantly higher number of pulses in the –CG flash category within the first 1 ms is most probably because the speed of the leader extension is much faster at the initial stage of the initial breakdown process at about  $1.2 \times 10^6 \text{ ms}^{-1}$  and dropping to  $6 \times 10^5 \text{ ms}^{-1}$  at the later stage as reported by Campos and Saba (2013). A report by Stolzenburg et al. (2013) has shown that the average velocity of the first leader channel is much more rapid compared to the subsequent channel extension with  $1.09 \times 10^6 \text{ ms}^{-1}$  and  $7.8 \times 10^5 \text{ ms}^{-1}$ , respectively. Based on this evidence, it can be suggested that the ionization process is more rapid in the earlier stage of the initial breakdown process of the –CG flash when compared to +CG, IC, and IBP flashes. On the other hand, a higher number of pulses in the –CG flash category could be due to the space leaders and rules out the possibility of a more rapid ionization process in the earlier stage of the initial breakdown process.

### 3.3 Wavelet Characteristics (Paper II)

Figure 4 shows the categorical composition of each flash group. Clearly from the figure, only –CG and IC flashes are composed of all the 4 categories while the multiple peaks multiple spreads (MM) category is absent from the +CG flash and all the multiple spread categories are absent from the IBP flash. This categorization method provides a clear distinction between the group of IBP and +CG flashes and the group of –CG and IC flashes as the latter group has all the 4 categories. Also, a clear distinction could be made between IBP and +CG. On the other hand, no clear distinction could be made between –CG and IC in the wavelet domain as both flashes have a comparable amount of the single spread category (84 percent in –CG and 82 percent in IC) and almost the same amount of the multiple spreads category (16 percent in –CG and 18 percent in IC). However, in the time domain, a single peak could be differentiated from multiple peaks, just for the single spread category only. The IC flash consist of a higher number of Single-peak Single-spread (SS) category

at 72 percent compared to the –CG flash at 52 percent while the –CG flash consists of a higher number of Multiple-peaks Single-spread (MS) category at 32 percent compared to the IC flash at 10 percent.

The single spread category of both single peak (SS) and multiple peaks (MS) is dominant among all lightning flashes where the smallest amount recorded from the IC flash is at 82 percent and the largest amount recorded from the IBP flash is at 100 percent. Isolated breakdown pulses flash have the largest amount of the SS category at 82 percent and the –CG flash has the smallest amount of the SS category at 52 percent. In contrast, the –CG flash has the largest amount of the MS category with 32 percent compared to IC, IBP and +CG with 10, 18 and 19 percent, respectively. On the other hand, the multiple spreads category of both single peak (SM) and multiple peaks (MM) have the largest amount recorded from the IC flash at 18 percent, a small percentage when compared to their counterpart of the single spread category (SS and MS).

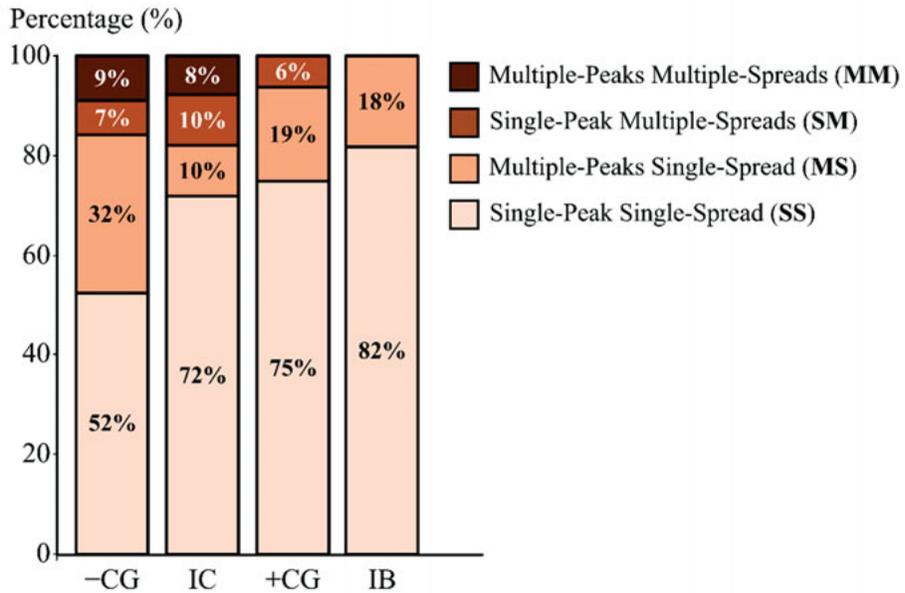


Figure 4. The fraction in percentage of categories for different type of lightning flashes. CG, cloud-to-ground; IC, cloud flash; IB, isolated breakdown.

The analysis of the spectral and spread regions (see Figures 7 and 8 in **Paper II**) reveals a high degree of distinction between the group of +CG and IB flashes and the group of IC and –CG flashes as we have observed from the temporal-wavelet categorization study. In general, IC and –CG flashes were observed to radiate energy predominantly at higher frequencies and have a larger bandwidth compared to the +CG and IB flashes in all temporal-wavelet categories. Moreover, IC and –CG flashes were observed to have a higher

bandwidth ratios compared to the +CG and IB flashes in all categories. It can be suggested that the initial leader development of both IC and –CG flashes underwent a more rapid and extensive ionization process when compared to the +CG and IB flashes.

In a specific comparison between –CG and IC flashes, both temporal (see Figures 9 and 10 in **Paper II**) and wavelet analyses suggest that the first electric field pulses of the IC flash radiated energy at a higher frequency in both single spread categories (SS and MS) and radiated energy at lower frequency in both multiple spread categories (SM and MM) when compared to the –CG flash. This finding may explain the observation of a much slower and less bright type  $\alpha$  leader (ionization process not so extensive) compared to fast and very bright type  $\beta$  leader (ionization process more rapid and extensive).

## 4. Wavelet Profile of Initial Breakdown Process Accompanied by Narrow Bipolar Pulses (**Papers III & IV**)

In this chapter, the results of the observation of narrow bipolar pulse (NBP) occurrence as part of the cloud-to-ground (CG) flash and wavelet analysis of the initial breakdown process accompanied by NBP are summarized.

### 4.1 Occurrence of NBPs as Part of CG Flash (Paper III)

More than three quarter (84.4 %) of NBPs that have been examined appeared to occur in isolation; that is, no other lightning flashes occurring prior to or following the NBPs within the record length (500 ms with a 150 ms pretrigger). Narrow bipolar pulses mostly appeared in a single pulse but sometimes in pairs. Similarly, Nag et al. (2010), Azlinda Ahmad et al. (2010) and Wu et al. (2011) found that the majority of NBPs they examined to occur in isolation within the record length of 500 ms (100 ms pretrigger delay), 250 ms (100 ms pretrigger delay) and ~20 ms, respectively. Moreover, about 14.5 % of the examined NBPs were found to occur as part of CG flashes where all of them were detected as a single event. All the located NBPs (horizontal distance information from the origin of NBP to the observation point) were recorded from thunderstorms in a distance range from 20 km to 100 km as illustrated in Figure 5.

The location data was obtained by using the timestamp of the global positioning system (GPS) and matched with the data collected by the World Wide Lightning Location Network (WWLLN). At the moment, WWLLN consists of 70 very low frequency (VLF) stations worldwide with the location accuracy and time accuracy of  $\pm 5$  km and  $\pm 15$   $\mu$ s respectively, as reported by Hutchins et al. (2013). The World Wide Lightning Location Network is capable of detecting NBPs with detection efficiency that varies between 10 and 30% [Lay, 2008]. Out of 173 NBPs, 45 NBPs (18 isolated NBPs, 25 NBPs as part of a CG flash, and 2 NBPs as part of a cloud flash) were successfully detected by the WWLLN system.

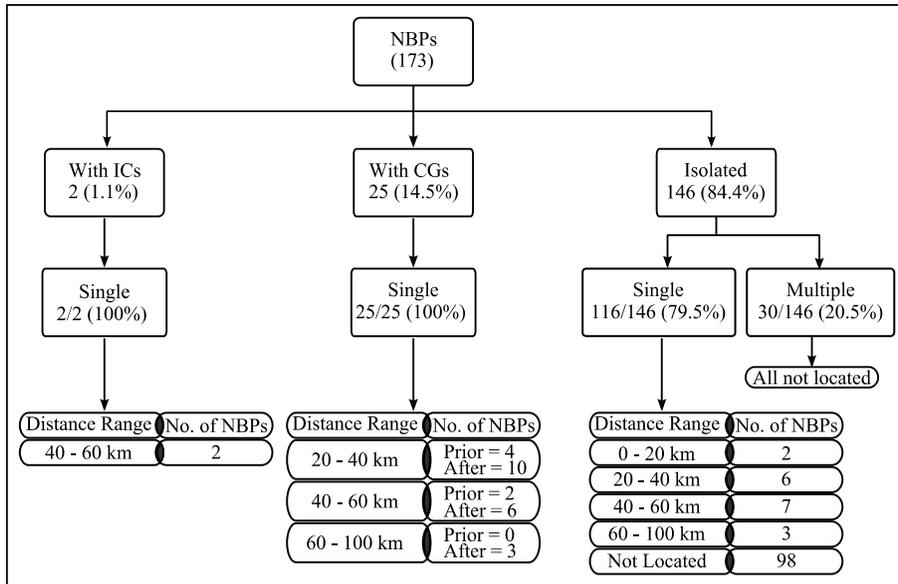


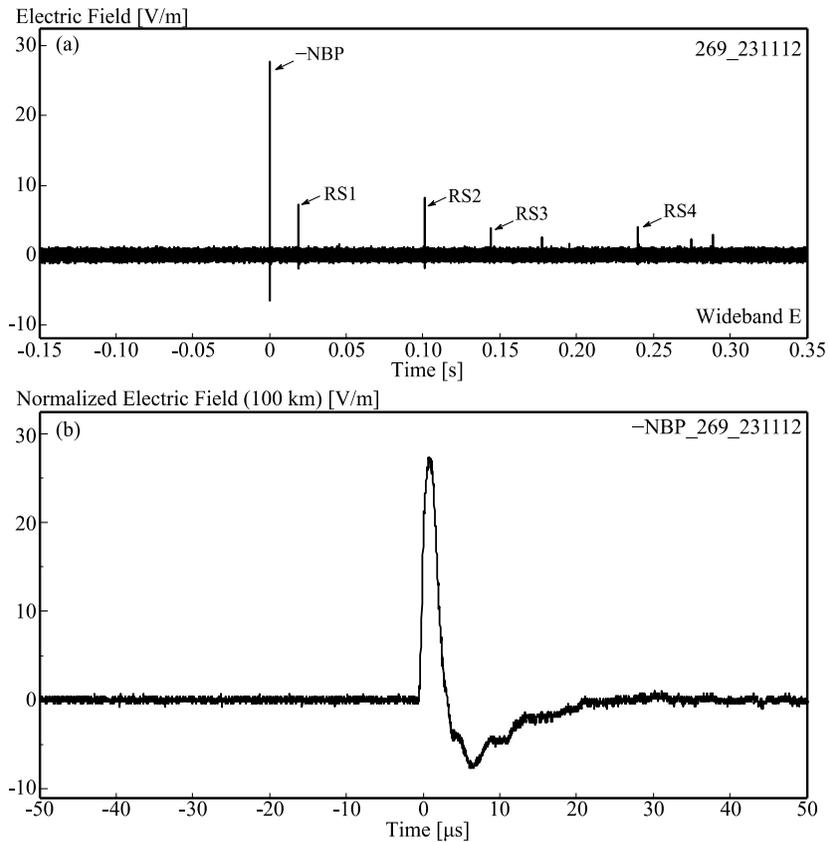
Figure 5. Categorization of NBP occurrence recorded during the Northeastern Monsoon season in the tropical region, Malaysia. NBPs, narrow bipolar pulses; CGs, cloud-to-ground flashes; ICs, cloud flashes.

6 out of 25 NBPs were found to occur prior to the first return stroke (RS1) which was located around 20 to 60 km from the observation point. The rest were found to occur after the first return stroke. Examples of two –NBPs that occurred prior to RS1 and after the fourth return stroke (RS4) are shown in Figures 6 and 7. The horizontal distance between the –NBP to the RS1 is 5 km, whereas the horizontal distance between RS4 and –NBP is 19 km, respectively. Overall, it is found that the range of time intervals between the examined NBPs and the RS1 is between 19 and 158 ms, much shorter than the time range observed by Nag et al. (2010), which was between 72 and 233 ms.

The normalized electric field intensity of –NBPs is found to be significantly larger, by about a factor 3, than +NBPs. This is an indication that the total negative background electric field was much stronger than the positive background electric field. Interestingly, we also discovered that in the mean amplitudes of the –NBPs that occurred prior to the RS1 are about twice larger than the –NBPs that occurred after the RS1. On the other hand, the normalized electric field intensity of +NBPs has slightly increased by a factor of 1.3. It is suggested that the total negative background electric field became relatively weak. This is the result if one assumes that the –NBPs were created by the electrical activity taking place below the negative charge center.

In general, the electric field in the vicinity of the negative charge center is higher before the first return stroke than after the return stroke. Thus, the discharge events that produce –NBP before the return stroke have a larger electric field in which to develop than the discharge events taking place after the first

return stroke. If the sources of  $-$ NBPs are located below the negative charge center this very well could be the reason for the disparity in the amplitudes of these pulses that occur before and after the first return stroke



*Figure 6.* (a) Wideband electric field waveform of  $-$ NBP captured prior to the first return stroke from a 4-stroke negative CG flash within 500 ms window size with 150 ms pretrigger delay and (b) the expansion of  $-$ NBP that prior to the first return stroke.

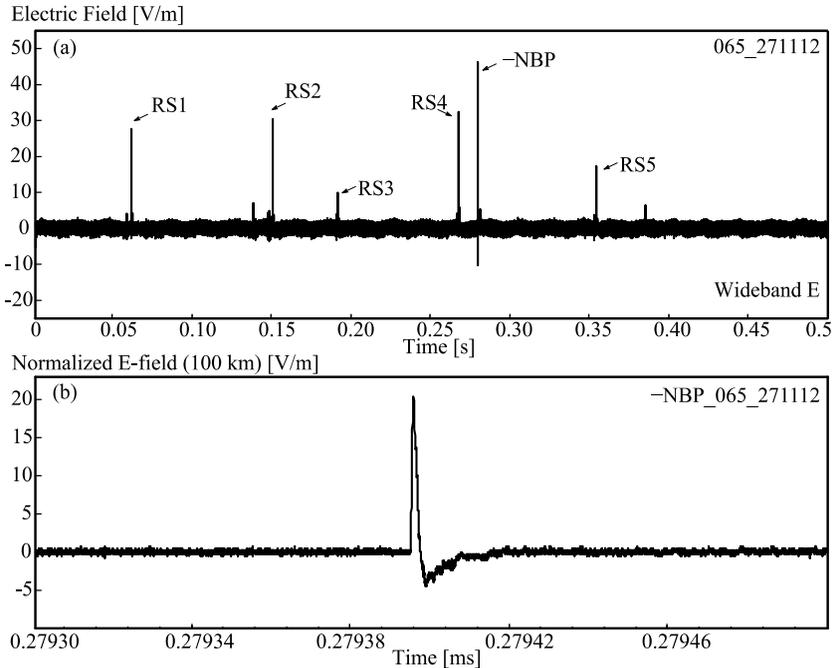


Figure 7. Wideband electric field waveform of  $-NBP$  captured in between return strokes from a 5-stroke negative CG flash within 500 ms window size with 150 ms pretrigger delay and (b) the expansion of  $-NBP$  in Figure 7(a).

## 4.2 Wavelet Profile of Lightning Events Prior to the First Return Stroke (Paper IV)

In order to illustrate a complete profile of the initial breakdown process prior to the first return stroke using wavelet transformation, 6 negative CG flashes were chosen which compose the preliminary breakdown process (PBP) and stepped leader (SL) accompanied by the NBP event before the first return stroke. An example of the wavelet profile of the initial breakdown process accompanied by a  $+NBP$  is shown in Figure 8. Another example shows a  $-NBP$  accompanied by initial breakdown process pulses can be seen in Figure 6 in **Paper IV**.

The most obvious thing that can be observed is that the magnitudes of the maximum power spectrums of both NBPs are significantly larger than PBP and SL pulses. It is found that a similar pattern of the maximum power spectrum magnitude is revealed from PBP trains where the maximum power spectrum magnitudes in the initial stage are significantly higher and decreased towards the end of PBP trains (refer Figure 7 in **Paper IV**). On the other hand,

the opposite pattern is observed for stepped leader (SL) pulses where the magnitudes of the maximum power spectrum are increasing towards the end of SL process before RS1 (refer Figures 9 a(i) & a(ii) in **Paper IV**).

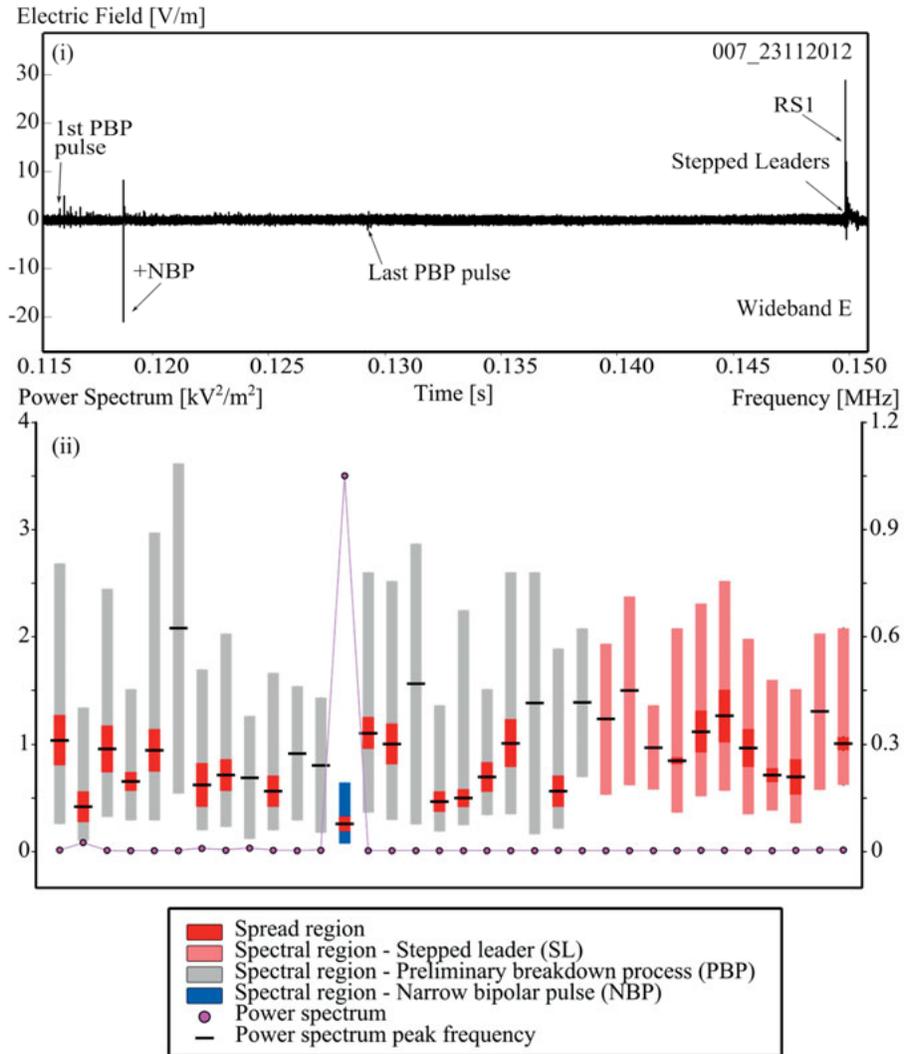


Figure 8. Wavelet profile of positive NBP and initial breakdown process that occurred prior to the first return stroke.



## 5. Thesis Conclusion

In this chapter, the conclusions are made based on the two main objectives mentioned earlier in section 1.3. The conclusions in numericals 1 to 2 are meant for **Papers I** and **II**, where the rest of the conclusions (3–7) are portrayed specifically for **Papers III** and **IV**. The conclusions that can be drawn from the present works are as follows:

1. There is a significant distinction between the negative cloud-to-ground (–CG) flash, positive cloud-to ground (+CG) flash, cloud flash (IC) and isolated breakdown pulses (IBP) flash at the earliest moment of initial breakdown process. At that particular moment, it is found that in both the temporal and wavelet domains:
  - a. Within the first 1 ms, the –CG flash radiates pulses more frequently than other discharges, the +CG flashes gained distinctively higher ratio of amplitude relative to the largest pulses and the IC flash tends to radiate shorter pulses but less frequently than the –CG and IBP flashes.
  - b. The first electric field pulse of the IC and –CG flashes radiate energy predominantly at higher frequencies and having a larger bandwidth compared to the +CG and IBP flashes.
  - c. The first electric field pulse of the IC flash radiates energy at a much higher frequency in both single spread categories (SS and MS) and radiates energy at a much lower frequency in both multiple spread categories (SM and MM) when compared to the –CG flash.
  - d. The first electric field pulse of the +CG flash radiates energy at a much higher frequency in single peak categories (SS and SM) and radiates energy at a much lower frequency in both multiple peaks categories (MS and MM) when compared to the IBP flash.
2. The initial leader development of both the IC and –CG flashes are more rapid than the +CG and IBP flashes.
3. About 3.5% of the total narrow bipolar pulses (NBPs) recorded in tropical thunderstorms in Malaysia were found to occur prior to the first return stroke (RS1).
4. A large amplitude of –NBP that occur before RS1 and a low amplitude after RS1 indicate that the total electric field becomes weaker after the return stroke and it is also an indication that the –NBP and return stroke occurred in the same thunderstorm.

5. Temporal characteristics of NBPs that occurred as part of CG flashes are similar to isolated NBPs.
6. The power spectrums of both +NBP and -NBP are significantly higher than PBP and SL pulses.
7. From the wavelet profile, it is observed that the power spectrum for PBP is higher at the initial stage and decreased at the later stage. The opposite trend is observed for the SL power spectrum profile.

## 6. Summary in Swedish

### 6.1 Temporal- och waveletkaraktäristik av det förberedande sammanbrottet och de smala bipolära pulserna i blixurladdningar

Det förberedande sammanbrottpulser som äger rum i molnen har noggrant studerats i tidsdomän och med hjälp av Wavelet-analys. Varje möjligt särdrag som uppstår under det inledande skedet av ett blixtnedslag har studerats på blixtar i Sverige. Dessa särdrag kan föregås av och leda till antingen negativa moln-till-jord (CG) blixtar, positiva moln-till-jord blixtar, molnblixtar eller isolerade sammanbrottsblixtar. Även förekomsten av smala bipolära pulser (NBPs) som en del av CG händelser i tropiska åskväder har inkluderats i denna studie. Det elektriska fältet från blixtar har registrerats med hjälp av ett snabbt bredbandsantennsystem installerade i Uppsala, Sweden och i Skudai, södra Malaysia. Valda elektriska fältsignaturer från denna samling av data har där- efter noggrant analyserats för att observera eventuella likheter eller/och skillnader i deras särdrag.

Temporalanalys visar att det finns signifikanta skillnader inom den första mil-lisekunden mellan olika typer av blixtar. Man har funnit att negativa CG-blix- tar tenderar att utstråla pulser oftare än andra blixtar och molnblixtar tenderar att utstråla kortare pulser än andra blixtar, samt mindre frekvent jämfört med negativa CG-blixtar och isolerade sammanbrottsblixtar. Eventuellt, är jonise- ringsprocessen under det inledande skedet för negativa CG-blixtar snabbare än andra urladdningar. Genom Wavelet transformation har man funnit att pul- ser med en topp i alla blixtar tenderar att stråla energi med högre frekvenser jämfört med pulser som har multipla toppar. Efter ytterligare Wavelet trans- formation, kan det föreslås att den första pulsen av elektriskt fält, både för negativa CG-blixtar och molnblixtar upplever en snabbare och mer omfat- tande joniseringsprocess jämfört med positiva CG-blixtar och isolerade sam- manbrottsblixtar.

Vidare temporalanalys på NBPs som en del av CG-blixtar, visar skillnaden i amplitud i normaliserade elektriskt fält hos NBPs, före och efter den första

huvudurladdningen. Detta tyder på att intensiteten i NBPs påverkades av huvudurladdningen och de ägde rum i en och samma åskmoln. Likheten mellan de temporala egenskaper som återfinns i NBPs som en del av CG-blixtar och isolerade NBPs, tyder på att deras sammanbrottsmekanismer kan vara likartade. De temporala egenskaperna för NBPs som ägde rum med CG-blixtar och isolerade NBPs visar att det ligger inom de medelvärden som tidigare beräknats av andra forskare för olika delar av världen.

Wavelet-analys för det förberedande sammanbrottsprocesser, visar att det maximala effektspektrumet, både för positiva och negativa NBPs är extremt höga jämfört med förberedande sammanbrottspulser och stegurladdningspulser. Liknande mönster hittas i de flesta fall att effektspektrumets magnitud för det förberedande sammanbrottsprocesser är högre i början och minskar mot slutet. Dock, har ett motsatt mönster observerats för stegurladdningspulser.

# Bibliography

- Ahmad, M. R., Esa, M. R. M., Cooray, V., Rahman, M. and Dutkiewicz, E., 2012. Lightning interference in multiple antennas wireless communication systems. *Journal of Lightning Research*, vol. 4, 155–165.
- Ahmad, M. R., Esa, M. R. M., and Cooray, V., 2013. Narrow bipolar pulses and associated microwave radiation, in: *Proceedings of PIERS 2013 Stockholm*, The Electromagnetics Academy, Cambridge, 1087–1090.
- Ahmad, M. R., Esa, M. R. M., Cooray, V., and Dutkiewicz, E., 2014. Interference from cloud-to-ground and cloud flashes in wireless communication system. *Electric Power System Research*, vol. 113, 237–246.
- Ahmad, N. A., 2011. *Broadband and HF radiation from cloud flashes and narrow bipolar pulses*. PhD Thesis, Uppsala University, Division of Electricity.
- Azlinda Ahmad, N. A., Fernando, M., Baharudin, Z. A., Rahman, M., Cooray, V., Saleh, Z., Dwyer, J. R., Rassoul, H. K., 2010. The first electric field pulse of cloud and cloud-to-ground lightning discharges. *Journal of Atmospheric and Solar-Terrestrial Physics*, vol. 72, 143–150.
- Azlinda Ahmad, N., Fernando, M., Baharudin, Z. A., Cooray, V., Ahmad, H., and Abdul Malek, Z., 2010. Characteristics of narrow bipolar pulses observed in Malaysia. *Journal of Atmospheric and Solar-Terrestrial Physics*, vol. 72, 534–540.
- Baharudin, Z. A., 2014. *Characterization of ground flashes from tropic to northern region*. PhD Thesis, Uppsala University, Division of Electricity.
- Campos, L. Z. S., Saba, M. M. F., 2013. Visible channel development during the initial breakdown of a natural negative cloud-to-ground flash. *Geophysical Research Letter*, vol. 40, 1–6.
- Clarence, N. D. and Malan, D. J., 1957. Preliminary discharge processes in lightning flashes to ground. *Quarterly Journal of the Royal Meteorological Society*, vol. 83, 161–172.
- Cooray, V. and Lundquist, S., 1985. Characteristics of the radiation fields from lightning in Sri Lanka in the tropics. *Journal of Geophysical Research*, vol. 90, 6099–6109.
- Cooray, V., 2003. The mechanism of lightning flash. In: *The Lightning Flash*, Ed. Vernon Cooray. The Institutions of Electrical Engineers (IEE), London, p. 215.

- Cooray, V., 2007. Propagation effects on the radiation field pulses generated by cloud flashes. *Journal of Atmospheric and Solar-Terrestrial Physics*, vol. 69, 1397–1406.
- Cooray, V. and Cooray, G., 2012. Electromagnetic radiation field of an electron avalanche. *Journal of Atmospheric Research*, vol. 117, 18–27, doi: 10.1016/j.atmosres.2011.06.004.
- Cooray, V., Cooray, G., Marshall, T., Arabshahi, S., Dwyer, J., and Rassoul, H., 2014. Electromagnetic fields of a relativistic electron avalanche with special attention to the origin of lightning signatures known as narrow bipolar pulses. *Journal of Atmospheric Research*, vol. 149, 346–358.
- Dwyer, J. R. and Uman, M. A., 2014. The physics of lightning. *Journal of Physics Reports*, vol. 534, 147–241.
- Esa, M. R. M., Ahmad, M. R., Cooray, V., 2014. Wavelet analysis of the first electric field pulse of lightning flashes in Sweden. *Journal of Atmospheric Research*, vol. 138, 253–267, doi: 10.1016/j.atmosres.2013.11.019.
- Gomes, C. and Cooray, V., 2004. Radiation field pulses associated with the initiation of positive cloud to ground lightning flashes. *Journal of Atmospheric and Solar-Terrestrial Physics*, vol. 66, 1047–1055.
- Gravetter, Frederick J., Wallnau, Larry B., 2007. Introduction to analysis of variance, *Statistics for the Behavioural Sciences*. Thomson Wadsworth, Belmont, pp. 392–397.
- Guo, C. and Krider, E.P., 1982. The optical radiation field signatures produced by lightning return strokes. *Journal of Geophysical Research*, vol. 87, 8913–8922.
- Gurevich, A. V. and Zybin, K. P., 2005. Runaway breakdown and the mysteries of lightning, *Physics Today* 58 (5), 37.
- Gurevich, A. V., Karashtin, A. N., 2013. Runaway breakdown and hydrometeors in lightning initiation. *Physical Review Letter*, vol. 110, 185005, doi: 10.1103/PhysRevLett.110.185005.
- Hamlin, T., Wiens, K.C., Jacobson, A.R., Light, T.E.L., and Eack, K.B., 2009. Space- and ground-based studies of lightning signatures, in: Betz, H.D., Schumann, U., and Laroche, P. (Eds.), *Lightning: Principles, Instruments and Application*. Springer Science+Business Media B.V., 287–307.
- Jacobson, A. R., 2003. How do the strongest radio pulse from the thunderstorms relate to lightning flash? *Journal of Geophysical Research*, vol. 108 (D24), 4778.
- Krehbiel, P. R., Brook, M. and McCrory, R., 1979. An analysis of the charge structure of lightning discharges to the ground. *Journal of Geophysical Research*, vol. 84, 2432–2456.
- Horner, F. and Bradley, P. A., 1964. Spectra of atmospheric from near lightning. *Journal of Atmospheric and Solar-Terrestrial Physics*, vol. 26, 1155 – 1166.

- Hutchins, M. L., Holzworth, R. H., Virts, K. S., Wallace, J. M., and Heckman, S., 2013. Radiated VLF energy differences of land and oceanic lightning, *Geophysical Research Letter*, vol. 40, 1–5.
- Lay, E. H., 2008. Investigating Lightning-to-Ionosphere Energy Coupling Based on VLF Lightning Propagation Characterization, PhD thesis, University of Washington, Washington, USA.
- Le Vine, D. M., 1980. Source of the strongest RF radiation from lightning. *Journal of Geophysical Research*, vol. 85, 4091–4095.
- Li, Q., Li, K., Chen, X., 2013. Research on lightning electromagnetic fields associated with first and subsequent return strokes based on Laplace wavelet. *Journal of Atmospheric and Solar-Terrestrial Physics*, vol. 93, 1–10.
- Light, T. E. L., and Jacobson, A. R., 2002. Characteristics of impulsive VHF lightning signals observed by the FORTE satellite. *Journal of Geophysical Research*, vol. 107 (D24), 4756.
- Medelius, P.J., Thomson, E.M., and Pierce, J.S., 1991. E and dE/dt waveshapes for narrow bipolar pulses in intracloud lightning, in: *Proceedings of the International Aerospace and Ground Conference on Lightning and Static Electricity*, NASA Conference Publication, vol. 3106, 12-1–12-10.
- Miranda, F. J., 2008. Wavelet analysis of lightning return stroke. *Journal of Atmospheric and Solar-Terrestrial Physics*, vol. 70, 140–1407.
- Nag, A. and Rakov, V. A., 2009. Electric field pulse trains occurring prior to the first stroke in negative cloud-to-ground lightning. *IEEE Transaction of Electromagnetic Compatibility*, 51(1), 147–150.
- Nag, A., DeCarlo, B. A., Rakov, V. A., 2009. Analysis of microsecond- and submicrosecond-scale electric field pulses produced by cloud and ground lightning discharges. *Journal of Atmospheric Research*, vol. 91, 316–325.
- Nag, A., Rakov, V.A., Tsalikis, D., and Cramer, J.A., 2010. On phenomenology of compact intracloud discharges. *Journal of Geophysical Research*, vol. 115, D14115, doi: 10.1029/2009JD012957
- Norinder, H. and Knudsen, E., 1956. Pre discharges in relation to subsequent lightning strokes. *Arkiv foer Geofysik*. 2 (27), 551–571.
- Oliver, John E. 2005. *Encyclopedia of World Climatology*. National Oceanic and Atmospheric Administration. ISBN 978-1-4020-3264-6. Retrieved February 8, 2009.
- Proctor, D. E., 1997. Lightning flashes with high origin. *Journal of Geophysical Research*, vol. 102, 1624–1693.
- Rakov, V. A. and Uman, M. A., 2003. *Lightning: Physics and Effects*, Cambridge University Press, pp. 121–122.

- Rison, W., Thomas, R. J., Krehbiel, P. R., Hamlin, T., and Harlin, J., 1999. A GPS-based three-dimensional lightning mapping system: Initial observation in Central New Mexico. *Geophysical Research Letter*, vol. 26, 3573–3576.
- Schonland, B. F. J., 1956. The lightning discharge, in: Flügge/Marburg, S., *Handbuch der Physik*. 22, Springer-Verlag, New York, pp. 576–625.
- Sharma, S. R., Cooray, V. and Fernando, M., 2008. Isolated breakdown activity in Swedish lightning. *Journal of Atmospheric and Solar-Terrestrial Physics*, vol. 70, 1213–1221.
- Sharma, S. R., Fernando, and M Cooray, V., 2008. Narrow positive bipolar pulses. *Journal of Atmospheric and Solar-Terrestrial Physics*, vol. 70, 1251–1260.
- Sharma, S. R., Cooray, V., Fernando, M., Miranda, F. J., 2011. Temporal features of different lightning events revealed from wavelet transform. *Journal of Atmospheric and Solar Terrestrial Physics*, vol. 73, 507–515.
- Smith, D. A., Shao, X. M., Holden, D. N., Rhodes, C. T., Brook, M., Krehbiel, P. R., Stanley, M., Rison, W., and Thomas, R.J., 1999. A distinct class of isolated intracloud lightning discharges and their associated radio emissions. *Journal of Geophysical Research*, vol. 104, 4189–4212.
- Smith, D. A., Heavner, M. J., Jacobson, A. R., Shao, X. M., Massey, R. S., Sheldon, R. J., and Wiens, K. C., 2004. A method for determining intracloud lightning and ionospheric heights from VLF/LF electric field records. *Radio Science*, vol. 39, RS1010.
- Stolzenburg, M., Marshall, T. C., Karunarathne, S., Karunarathna, N., Vickers, L. E., Warner, T. A, Orville, R. E., Betz, H. D., 2013. Luminosity of initial breakdown in lightning. *Journal of Geophysical Research: Atmosphere*, vol. 118, 2918 – 2937, doi:10.1002/jgrd.50276.
- Ushio, T., Kawasaki, Z., Matsu-ura, K., Wang, D., 1998. Electric fields of initial breakdown in positive ground flash. *American Geophysical Research: Atmosphere*, vol. 103 (D12), 14135–14139.
- Willet J. C. and Bailey, J. C., 1989. A class of unusual lightning electric field waveforms with very strong high-frequency radiation. *Journal of Geophysical Research*, vol. 94, 16255–16267.
- Wu, T., Dong, W., Zhang, Y., and Wang, T., 2011. Comparison of positive and negative intracloud discharges. *Journal of Geophysical Research*, vol. 116, D03111, doi: 10.1029/2010JD015233.
- Wu, T., Dong, W., Zhang, Y., Funaki, T., Yoshida, S., Morimoto, T., Ushio, T., and Kawasaki, Z., 2012. Discharge height of lightning narrow bipolar events. *Journal of Geophysical Research*, vol. 117, D05119.
- Wu, T., Takayanagi, Y., Yoshida, S., Funaki, T., and Ushio, T., 2013. Spatial relationship between lightning narrow bipolar events and parent thunderstorms as revealed by phased array radar. *Geophysical Research Letter*, vol. 40, 618–623, doi:10.1002/grl.50112.

Zhu, B., Zhou, H., Ma, M., and Tao, S., 2010. Observations of narrow bipolar events in East China. *Journal of Atmospheric and Solar-Terrestrial Physics*, vol. 72, 271–278.

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