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Characterizations of ground flashes from tropic to northern region

ZIKRI ABADI BAHARUDIN

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Abstract

Baharudin, Z. A. 2014. Characterizations of ground flashes from tropic to northern region. *Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology* 1145. 78 pp. Uppsala: Acta Universitatis Upsaliensis. ISBN 978-91-554-8946-5.

This thesis portrays new information concerning the cloud-to-ground (CG) lightning flashes or ground flashes produced by thunderclouds. It emphasizes the importance of characterizing lightning studies as the relationship between lightning mechanisms, and of incorporating the influence of geographical location, latitude and storm type. Sweden, Malaysia and USA were chosen as the main locations for field experiments in 2009 to 2011 to gather a significant number of negative and positive CG flashes. This work provided data on a total of 1792 CG lightning flashes (1685 negative and 107 positive ones) from a total of 53 thunderstorms by monitoring both the slow and the fast electric field and the narrowband radiation field at 3 and 30 MHz signals simultaneously. This thesis is comprised of: (i) the relationship of the Low Positive Charge Region (LPCR) and Preliminary Breakdown Pulse (PBP) trains to the occurrence of negative CG, (ii) slow field changes generated by preliminary breakdown processes in positive and negative ground flashes, and (iii) the occurrence of positive and negative ground flashes. It was revealed that the PBP train appeared have a higher strength in the in Sweden. The strength of the PBP train was caused by the LPCR; in contrast, weak PBP trains were characteristic in tropical countries constituting insignificant LPCR and needing little energy to break the “blocking” agent to allow the flash to propagate downward to the ground. The second contribution concerns the characteristics of the PBP train mentioned; this includes novel information for Malaysia. Further, it is stated that there are some different characteristics in the PBP trains in Johor, Malaysia and Florida, USA. The studies of slow field changes generated by preliminary breakdown processes clarifies unclear features concerning the starting position of slow field changes generated by preliminary breakdown processes in positive and negative ground flashes. It was found that the slow field changes did not occur before the initial process of the commencement of preliminary breakdown. Single-station electric field measurements incorporating narrowband radiation field measurement and high resolution transient recording (12 bits) with an accuracy of several nanoseconds, allows one to distinguish between the intracloud activities and the preceding processes of ground flashes. The results for the interstroke intervals, amplitude distribution of subsequent return-stroke (SRS) and the number of strokes per flash in the tropics, subtropics and northern regions were similar. Finally, a significant number of positive return-stroke (RS) electric fields provided statistically significant information on the characteristics of these strokes.

Keywords: Positive/negative cloud-to-ground lightning flashes, Initiation position, slow field changes, close ground flashes, preliminary breakdown process

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Dedication to:
Professor Vernon Cooray,
Dr. Mahbubur Rahman,
Dr. Fernando Mahendra,
my wife Sazillah,
our children Adeeb, Asheef,
and Ahmad Saidnursi,
and my beloved mother, Zinun.

List of Papers

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

I **Z. A. Baharudin**, N. Azlinda Ahmad, M. Fernando, V. Cooray, J. S. Mäkelä, (2012). Comparative study on preliminary breakdown pulse trains observed in Johor, Malaysia and Florida, USA. *Atmospheric research*, 117, 111 – 121.

II **Z. A. Baharudin**, M. Fernando, N. Azlinda Ahmad, J. S. Mäkelä, M. Rahman, V. Cooray, (2012). Electric field changes generated by the preliminary breakdown for the negative cloud-to-ground lightning flashes in Malaysia and Sweden. *Journal of Atmospheric and Solar Terrestrial Physics*, 84 – 85, 15 – 24.

III **Z. A. Baharudin**, V. Cooray, M. Rahman, P. Hettiarachchi, N. Azlinda Ahmad. Electric field changes generated by the preliminary breakdown for the positive cloud-to-ground lightning flashes in Sweden. *Submitted to Journal of Atmospheric and Solar-Terrestrial Physics*, April 2014.

IV **Z. A. Baharudin**, N. Azlinda Ahmad, J. S. Mäkelä, M. Fernando, V. Cooray, (2014). Negative cloud-to-ground lightning flashes in Malaysia. *Journal of Atmospheric and Solar-Terrestrial Physics*, 108, 61 – 67.

V **Z. A. Baharudin**, V. Cooray, M. Rahman, P. Hettiarachchi, N. Azlinda Ahmad. On the characteristics of positive lightning ground flashes in Sweden. *Submitted to Journal of Atmospheric and Solar-Terrestrial Physics*, August 2013.

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Other contributions of the author, not includes in this thesis

VI **Z. A. Baharudin**, M. Fernando, N. Azlinda Ahmad, V. Cooray, J. S. Mäkelä, (2010). Comparative study on preliminary breakdown pulse trains observed in Malaysia and Florida. *In: Proc. International Conference of Lightning Protection (ICLP), Cagliari, Italy, 2010.*

VII N. Azlinda Ahmad, M. Fernando**, Z. A. Baharudin**, M. Rahman, V. Cooray, Ziad Saleh, Joseph R. Dwyer, Hamid K. Rassoul, (2010). The first electric field pulse of cloud and cloud-to-ground lightning discharges. *Journal of Atmospheric and Solar Terrestrial Physics*, 72, 143 – 150.

VIII N. Azlinda Ahmad, **Z. A. Baharudin**, M. Fernando, V. Cooray. Radiation field spectra of long-duration cloud flashes. *Submitted to Journal of Atmospheric Science Letter*, December 2013.

IX N. Azlinda Ahmad, Fernando, **Z. A. Baharudin**, M. V. Cooray, Ahmad. H., Abdul Malek, Z., (2010). *The characteristics of narrowbipolar pulses in Malaysia*. Submitted to Journal of Atmospheric Science Letter, December 2013.

X N. Azlinda Ahmad, Z. A. **Baharudin**, M. Fernando, V. Cooray. Some features of electric field waveform of narrow bipolar pulses. *In: Proc. International Conference of Lightning Protection (ICLP), Cagliari, Italy, 2010.*

Contents

Abbreviations

BIL	initial breakdown, intermediate, stepped leader
CG	cloud-to-ground flash
CC	cloud-to-cloud
HF	high frequency
IC	Intracloud
kHz	kilo hertz
LPCR	Low Positive Charge Region
MHz	mega hertz
N	negative charge region
N_+	positive field changes
N_-	negative field changes
P	positive charge uppermost region
p	LPCR
PBP	preliminary breakdown pulse
RF	radio frequency
RS	return-stroke
SRS	subsequent return-stroke
ΔT	pre-starting time

1 Introduction

1.1 Motivation

The phenomenon of lightning has been the subject of intensive studies by electrical engineers and researchers. Its behavior is fairly predictable in general terms, although the exact description of the physical processes for specific instances is not predictable. The interpretation, and sometimes speculation, is often complicated which owing to the complexity and variability of lightning generation mechanisms. Furthermore, as there is no conclusive evidence that lightning could be prevented, one has to recognize the possibility of a lightning strike and take appropriate measures to make each strike harmless. Lightning protection is, then, the implementation of appropriate actions for the characteristics of the lightning anticipated.

Many of the characteristics of lightning flashes, such as the characteristics of storms (individual or systems), occurrence statistics, pulse structure, number of strokes per flash and the polarity of the charge lowered to the ground, apparently depend on the season, geographical region, latitude and storm type. Year after year, investigators have reported novel findings where lightning characteristics are concerned; these parallel the progress in the development of technology available for lightning electromagnetic field measurements. Characterization of electric fields from electromagnetic field measurements is still considered an important tool for electrical engineers and researchers. This is because the knowledge obtained significantly improves the investigators' understanding of the potential effect of deleterious coupling of lightning fields with various objects especially to sensitive electronic devices.

Through the characterization of field data, one can extract information such as the time dependence of the voltage or current, which can be used for modeling and as an input for the computation of lightning electromagnetic fields. Any lightning model is actually necessarily an approximate mathematical construct designed to reproduce certain aspects of the physical processes involved in the lightning discharge. The basic assumptions of the model should be consistent with both the expected outputs of the model and the availability of quantities required as an input to it.

1.2 Objective and summary of contribution of the thesis

The main objective in writing this thesis was to characterize the availability of physical information in the processes underlying cloud-to-ground (CG) lightning flashes (that is, negative and positive CG flashes) by using remote measurements of lightning-generated electric fields. As mentioned in Section 1.1, the occurrences of CG flashes depend on the geographical region, as well as other related factors such as the latitude and type of storm. Hence, this thesis has considered those factors when acquiring data from three different locations: Sweden, Malaysia and USA. In general, research has been carried out with the intention of generating valuable data to address the lack of information in previous studies on CG flashes. The contributions are summarized in five publications as follows:

Paper 1: Comparative study on preliminary breakdown pulse trains observed in Johor, Malaysia and Florida, USA

The objective of this paper was to investigate the relationship between the preliminary breakdown pulse and the first return-stroke (RS) electric fields using high resolution data recorded from thunderstorms in Malaysia and USA (both data were recorded in 2009). These data were compared with other available results from Sweden, Finland, Sri Lanka and USA (recorded by Nag and co-workers in 2008 and 2009). This study revealed that the strength of the ground-flash-initiation breakdown process in the cloud, measured against on a comparison with the peak radiation field of the resulting RS, is larger in the northern region (Sweden and Finland) compared to that of the tropical regions (Malaysia and Sri lanka). Besides, it is known that the initial preliminary breakdown processes in negative CG flashes in Malaysia are different from those in USA. These are described.

Paper 2: Electric field changes generated by the preliminary breakdown for the negative cloud-to-ground lightning flashes in Malaysia and Sweden

In this paper, the objective was to clarify the unknown features of the electric field changes preceding negative first return flashes, and especially in determining the position of slow field (electrostatic field) changes that associated in the preliminary breakdown process. This study shows that the position of slow field changes are always found occur after the first preliminary breakdown pulse (PBP) or does not start before the PBP.

Paper 3: Electric field changes generated by the preliminary breakdown pulse for positive lightning ground flashes in Sweden

This paper had a similar aim that outlined for Paper 2, but the main consideration is the positive CG flash in this instance. This is the first time a study on the electric field changes, generated by the preliminary breakdown for positive CG flashes, is found to be associated with the slow field changes in the preliminary breakdown process. This result is consistent with that in Paper 2, where the slow field changes do not start before the preliminary breakdown process.

Paper 4: Negative Cloud-To-Ground Lightning Flashes in Malaysia

The main objective of this paper was to provide statistical information on negative CG flashes in Malaysia since there was no available information previously in Malaysia on this. The study has found that the results for CG flashes in Malaysia, USA, Sweden, Sri Lanka and Brazil are similar where all characteristics are concerned (that is, time intervals, the ratio of the subsequent return-stroke (SRS) to the first RS, and the number of strokes per flash).

Paper 5: The characteristics of positive cloud-to-ground flashes in Uppsala, Sweden

Insufficient positive ground flashes have caused difficulty in collecting a large sample of electric fields generated by positive ground flashes. The purpose of this paper is to present a significant number of positive RS electric fields so that statistically significant information on stroke characteristics could be gathered. From these electric field records, we have reported the number of strokes per flash, inter-stroke intervals and the amplitude distribution of subsequent return strokes (SRS).

2 Cloud-To-Ground Lightning Flashes From Lightning–Producing Cumulonimbus

2.1 Terminology of cloud-to-ground lightning flashes

Lightning and lightning discharges within a cloud are usually termed “lightning flashes” or simply called “flashes”. They can be intracloud (IC)), cloud-to-cloud (CC), cloud-to-ground (CG), or surrounding air discharges, the latter also being known as air discharges. Lightning flashes are massive electrostatic discharges caused by unbalanced electric charges in the atmosphere, resulting in a strike, from IC, CC or CG discharges and accompanied by the loud sound of thunder. The lightning flash can be defined as a transient, high-current electric discharge whose path length is generally measured in kilometers. Lightning occurs when some region of the atmosphere attains a sufficiently large electric charge, and therefore electric fields, to instigate the electrical breakdown of the air.

The most common sources of lightning is the thundercloud, usually formed by cumulonimbus, where the lightning is associated with the convective mechanism in the cloud systems, ranging from 3 to 20 km in vertical extent, while the horizontal dimension of active air-mass thunderstorms varies from 3 km to 50 km or more[81,100]. Basically, the structure of the thundercloud was found to be a tripolar electrostatic. A tripolar electrostatic cloud structure is one where the body of cloud is essentially divided into the positive charge uppermost region (net positive charge), followed by the negative charge region (net negative charge) below it or at its midlevel, and an additional small pocket of positive charge, also known as Low Positive Charge Region (LPCR) at the bottom of the cloud. Figure 1 shows an example of the probable distribution of cloud charges adapted from the measurements obtained by Malan[53].

Thunderclouds are large atmospheric heat engines, with input energy from the sun and water vapor as their primary heat-transfer agent. Hence, they may underlie the mechanical workings of the winds (vertical or horizontal) generated by a storm, causing an outflow of condensation (in the form of rain and hail) from the bottom of the cloud and small ice crystals from the top of it, along with electrical discharges (IC,CC,CG), including corona, lightning, sprites, elves, and blue jets. However, the processes that operate in a thundercloud to produce the actions mentioned above are poorly understood owing to the fact that they are a large, complex and short-lived phenomena[48,81]. Interestingly, lightning also occurs during snow storms (thundersnow)[9,92,93,94], volcanic eruptions[2,10,55], and nuclear explosion[16,101].

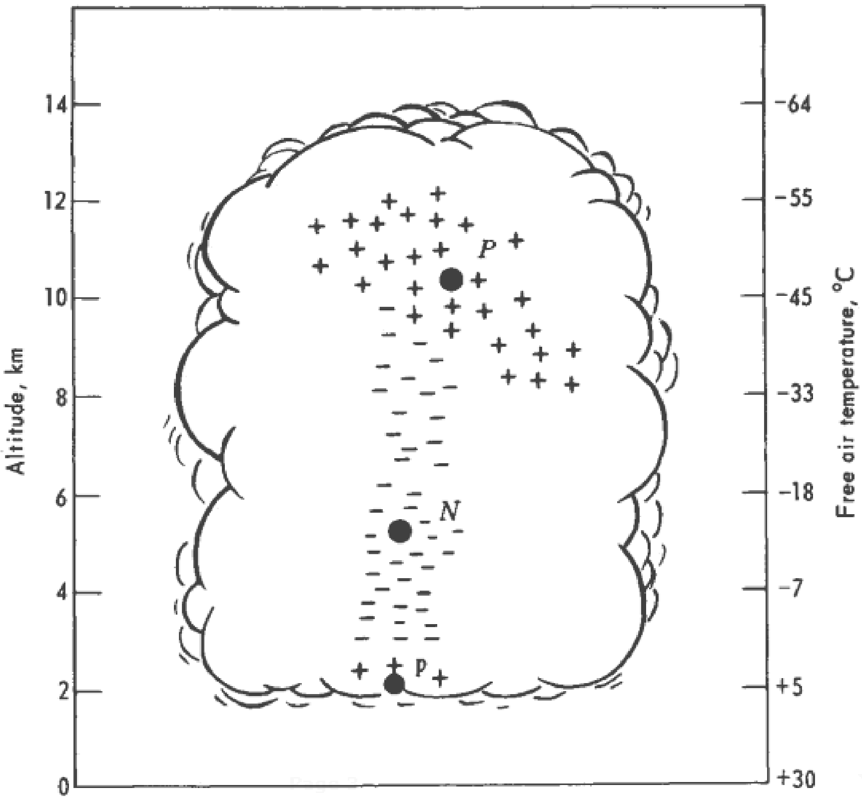


Figure 1. The probable distribution of thundercloud charges, *P* – positive charge uppermost region, *N* – negative charge region and *p* – Low Positive Charge Region (LPCR) for a South African thundercloud according to Malan (1952, 1963). Adapted from [100]

Ground flashes or CG are the best known of all the different types of lightning since they strike the ground, thereby posing the greatest threat to life and property. CG are lightning discharges between a cumulonimbus cloud and the ground; they can generate four types of possible flashes as defined comprehensively by K. Berger [12,13] and discussed in detail by Rakov and Uman[81], and as illustrated in Figure 2. The various types of ground flashes can be viewed in terms of: (i) the polarity of the charges in the cloud from where the leader is initiated or to the place where it propagates, or (ii) the direction of the leader. It is also noticed that the portion of polarity (downward or upward) denotes the polarity of the resultant current to the ground.

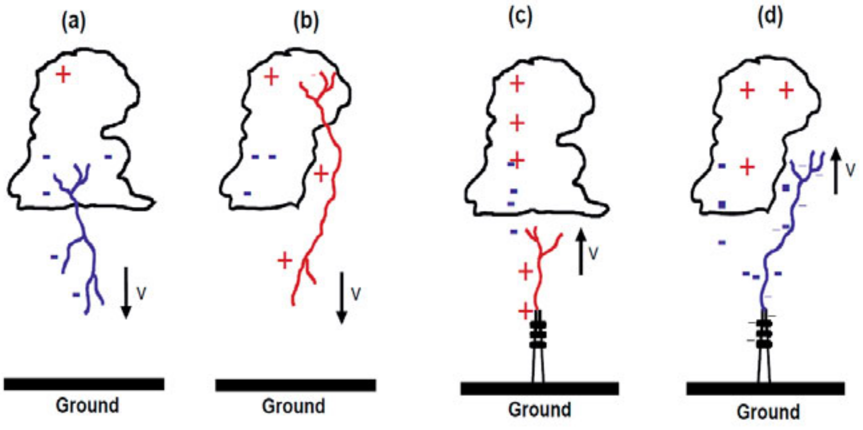


Figure 2. Types of cloud-to-ground lightning flashes: comprising (a) downward negative lightning, (b) downward positive lightning, (c) upward negative lightning, and (d) upward positive lightning.

The first type of ground flash denoted in Figure 2(a) shows downward negative lightning. This predominates in structures with heights of less than about 100 m. It is believed that 90 % of global ground flashes are the transport of negative charges to the ground. The peak current (first RS) is about 30 kA. Typically, the range of average of negative ground flash may be comprised of three to five strokes within a flash [82], however they have been observed to occur as many as 26 times in one flash[46]. According to the classification of Berger et al[13] as depicted in Figure 2(b), downward positive lightning accounts for about 10 % or less of global CG lightning flashes. Positive ground flashes, however, give rise to larger currents and larger positive charge transfer than their more numerous counterparts, negative ground flashes[13,48]. Upward negative lightning, illustrate in Figure 2(c) was first observed at the Empire State Building in New York City,[35] and was thought to be associated with high structures. For example, according to Berger,[13] who conducted lightning observations at Mt. San Salvatore in Switzerland with measurement equipment (in the form of 70 and 80-meter masts) located at 650 m, at the top of the mountain, his equipment was stuck by 1196 flashes in 11 years. Of these, 75 % were determined to be negative upward flashes ,only about 11 % were negative downward ones, and the remaining 14 % were identified as positive upward flashes, illustrated in (d).

2.1.1 Downward-moving process

The earlier studies by Clarence and Malan[15] in 1957 suggested that the ground flashes usually began with three successive discharge processes (see Figure 3) which are known as the initial breakdown and also sometimes referred to as the preliminary breakdown; these are followed by a predischarge, which comes prior to the first return-stroke in a flash, the so-called stepped leader[81,100]. Sometimes, stepped leaders occur immediately after the preliminary breakdown process but that can also appear after the so-called intermediate stage, which may last up to 400 ms.

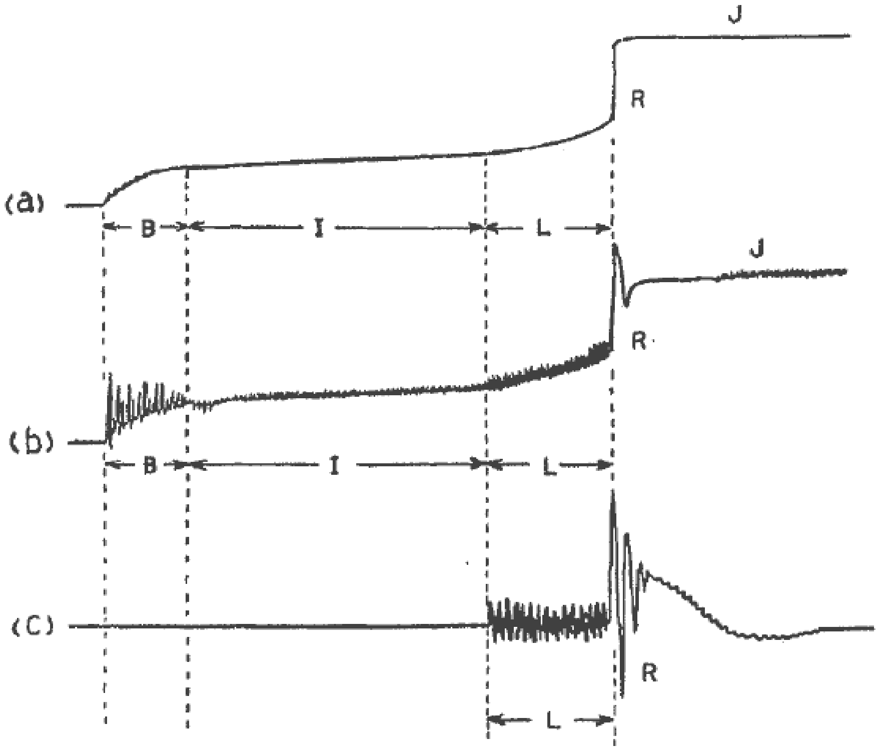


Figure 3. Example of the characteristic signatures of the signals for ground flash used by Clarence and Malan (1957) to introduce the so called BIL structure of the electric field prior to the first return-stroke: (a) The electrostatic field at 5 km. (b) The electrostatic field at 50 km. The relative amplitude of the signature for R has been reduced. (c) The radiation field at 500 km. The time is nonlinear, with the duration of B, I, and L being 2 – 10, 0 – 400, and 4 – 30 ms, respectively. This illustration is adapted from Clarence and Malan [15].

For convenience, the negative CG mechanism is used to describe the terminology related to CG. Preliminary breakdown is widely believed to commence with a local electrical breakdown between the negative charge center and the Low Positive Charge Region (LPCR) at the base of the thundercloud that may last from a few milliseconds to some tens of milliseconds[81,101]. This initial breakdown would serve to mobilize the electric charges that, previously, were attached to ice and water particles. The strong concentration of negative charge at the bottom of the negative charge region would produce electric fields and these could then cause a negatively charged column to be propelled down towards the earth.

The formation of a negatively charged column is called the stepped leader progression, because the column appears to move downwards in luminous steps. By means of high-speed time-resolved photographs[26,81], the typical average speed in a series of discrete luminous steps is 2×10^5 ms^{-1} and the length of successive steps is some tens of meters, with the duration of each step being 1 μs. The time interval between the steps was found to be about 20 to 50 μs. The peak current for a pulse associated with an individual step was found to be 1 kA or greater. The stepped leader serves to form a conducting path or channel between a cloud charge source and the ground.

2.1.2 Upward-moving process

When the stepped leader moving downwards is carrying negative charge near the ground, the electric field at ground level increases steadily. Further, the moment when the stepped leader reaches a height of a few hundred or less meters from the ground, the electric field, particularly at the tip of grounded structures, increases until it exceeds the critical value for the initiation of one or more upward-moving discharges, which are launched from the ground towards the leader tip. These upward-moving discharges are called upward-connecting leaders. One of the upward-connecting leaders may successfully bridge the gap between the ground and the downward leader. When the contact is made between the downward and upward-moving leaders, the first return-stroke (RS) begins and its wave (wavefront) travels upwards, carrying ground potential up towards the cloud along the channel created previously by the stepped leader. Concurrently, the occurrence of a transient enhancement of the channel luminosity below the branch point is often observed; this is referred to as the branch component. The average speed of an upward-moving RS wavefront is typically between one-third and one-half the speed of light over the visible channel. The current measured at the ground rises approximately 10 to 30 kA in a few microseconds and decays to the half-peak value in some tens of microseconds while profiling a number of subsidiary peaks (see Figure 4 showing the subsidiary peaks) which were thought to be associated with the branches.

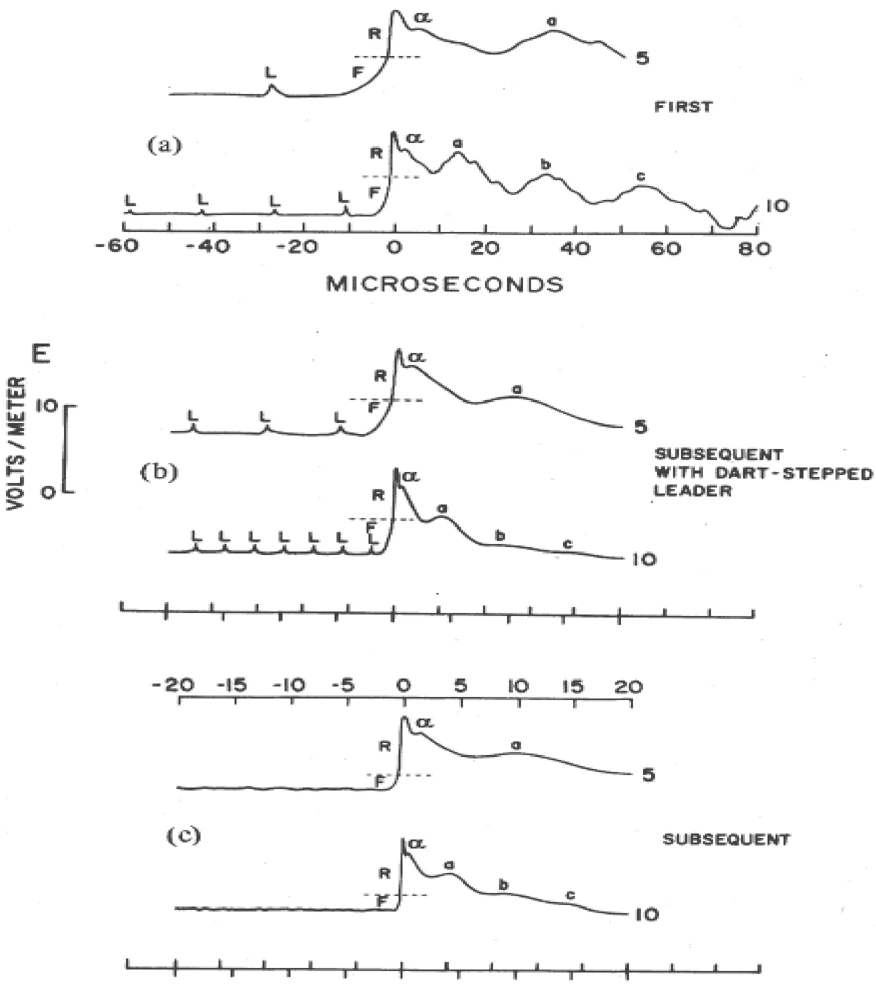


Figure 4. The radiation fields produced by (a) the first RS, (b) a subsequent return-stroke (SRS) preceded by a dart–stepped leader, and (c) a SRS preceded by a dart stepped leader in a lightning discharge to ground. The field amplitude is normalized to a distance of 100 km. The small pulses attributed to the stepped leader (L) are followed by a slow front (F) and an abrupt, fast transition to peak R. Following the fast transition, there is a small secondary peak or shoulder α and large subsidiary peaks, a, b, and c. Adapted from Weidman and Krider[104].

2.2 Modes of Charge Transfer for CG

There are three possible modes of charge transfer to ground in negative lightning SRS. The three modes of charge transfer for negative ground flashes are: (a) dart-leader – RS sequence, (b) continuing currents and (c) M-components (see Figure 5).

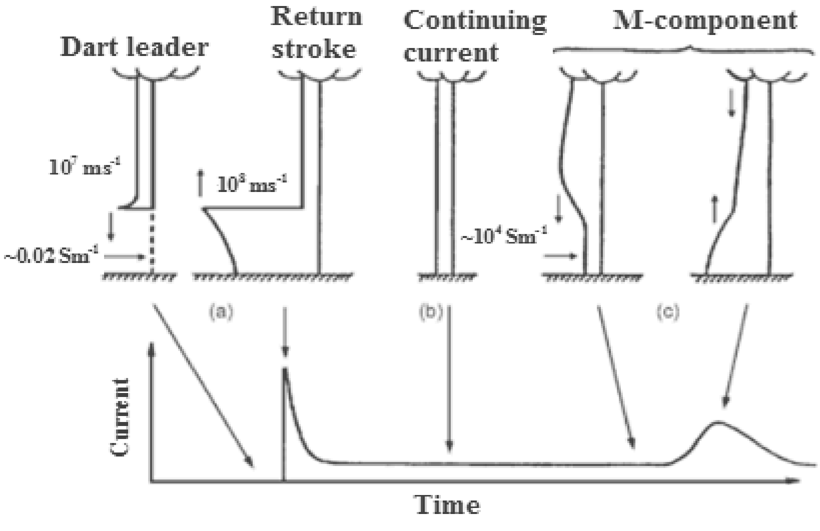


Figure 5. Schematic of physical mechanism and current versus time waveform for three modes of charge transfer to ground for negative CG lightning flashes during lightning SRS: (a) dart-leader/RS sequence, (b) continuing current, and (c) M component. Adapted from [80].

2.2.1 Dart-leader – return-stroke sequence

The stepped leader deposits negative charge along the conducting path between the cloud and ground, while the RS traverses that path, it can either neutralize some negative charges on the stepped leader or deposit some positive charge on the stepped leader channel and in the cloud charge source region. After the first RS has ceased to flow, the ground flash might end, in this case, it is called a single-stroke flash. On the other hand, if additional charge is made available to the top of the channel, the first RS of the ground flash could be followed by a few or more additional RS (SRS); in this instance, the flash is said to be a multiple-stroke flash. In multiple-stroke flashes, each preceding stroke appears to drain charge from higher areas in the negative region of the cloud, carrying the cloud potential earthward once more by the action of the dart-leader. This charge is made available during the time interval between the previous RS (eg., the end of the first RS) and a higher region of negative charge (eg., the initiation of dart leader) due to the action of the so called J-process and K-process. J-processes are thought to be a relatively slow positive leader extending from the place where the flash originates into the negative charge region[8,45], which consists of a small number of K-process steps. K-processes are relatively fast streamers (recoil streamer) that begin at the tip of the positive leader and propagate towards the origin of the flash in the cloud. In other words, J-processes and K-processes play a role in transporting additional negative charge into and along existing channels in the cloud for the ground flashes. The dart-leader deflects from the previous RS path and forms a new termination on the ground with similar action relating to the attachment process that has been described in the first return stroke process. When the dart-leader contacts with upward-moving leaders from the ground, the SRS may occur and again serves to neutralize the charge leader.

2.2.2 Continuing Current

The lightning continuing current is thought to be a flow of impulsive current in the SRS at low levels of tens to hundreds milliseconds. The long duration of the continuing current that exceeds 40 ms is termed as a long continuing current. The continuing current typically exhibits a number of superimposed surges that rise to a peak and fall off to the background current level in some hundreds of microseconds, the peak being generally in the hundreds of ampere range, but occasionally in the kilo-amperes range. These current surges are associated with the enhancements in the relatively faint luminosity of the continuing current channel and are called M-components.

2.2.3 Lightning M-component

The term 'M-component' refers to a rapid electric field variation in the continuing current carried by the RS that increases the channel luminosity temporarily [46,102]. According to Figure 5, the M-component appears to be a superposition of two waves propagating in opposite directions. The spatial front length is approximately a kilometer from the cloud height.

2.3 Background of remote measurements of lightning generated electric fields

Scientists have proven that the use of simultaneous measurement of the electrostatic and radiation field allows the determination of electric field data over the time of a complete lightning flash with suitable time resolution of the rapidly occurring field variation. Previously, Wilson[105,106], Appleton et al.[1], and Schonland and Craib[85] were among the pioneers who conducted the measurements of electrostatic field (also known as the slow field) and radiation field (also known as electrostatic field changes or the fast field) from thunderclouds. Their independently conducted results were consistent. Among the conclusions from their studies are the following: (i) The thundercloud is essentially an electric dipole, with a net positive charge located above a net negative charge. Its magnitude can be deduced from measurement of the slow field or fast field change of the thundercloud as a function of horizontal distance, i.e. between the location of the discharge and the measurement station. (ii) Usually a CG lightning flash lowers the negative charge from cloud to ground with an average electric moment (M), the destruction of charge takes place at a level of about 100 Coul-km.

The work of Wilson and of Schonland and Craib was conducted using an antenna connected to a capillary electrometer (a mercury-sulfuric-acid capillary electrometer). The capillary electrometer measures the electric field intensity with a resolution of about 0.1 s. The charge induced on the antenna caused the motion of a drop of sulfuric acid within a capillary tube filled with mercury. The displacement of the acid drop was proportional to the field. On the other hand, Appleton, Watson-Watt, and Herd used an antenna attached to an oscilloscope, in addition to using similar equipment to that of Wilson. By the early 1930s, the combination of slow and fast field measurements of thunderclouds obtained by Wormell[107], Jensen[40,41,42,43], and Haliday[33] strengthened and supported the facts determined by previous works, and in particular, the transportation of negative charge was predominant for ground flashes. For example, Schonland and Allibone[87] reported at least 95 % of the 404 flashes from 50 South African thunderstorms were caused by negative charge. Similarly, Haliday[33] reported that 267 of the flashes measured were found to be negative ground flashes.

The other features determined by the measurement techniques mentioned above concerned the importance of charge amount, flash distance and the polarity of field changes. To this effect, extensive investigations using these methods were performed in the 1950s[15,51,52,67,68,108]. The investigators revealed that the majority of lightning flashes associated with slow field changes occurred comparatively slowly, and had the duration of slow sections either between initial sections and RS or latter sections of return-stroke.

Pierce[68] had summarized his observation using a capillary electrometer during the summers of 1939 and 1946, then the data obtained in 1947 and 1949 were recorded using an oscilloscope. He also included the data of Wilson (recorded from 1920 to 1924) and Wormell (recorded in 1926 to 1936). He did not, however, specify if the field changes (N_+—positive field changes or N_-—negative field changes) were attributable to cloud or ground flashes, or any specific section preceding the first RS. He concluded that the ratios of N_+/N_- were consistent for the magnitudes of electric field less than 100 V/m since there is no significant change in the magnitude between 0.1 and 100 V/m. However, the positive field changes became increasingly strong for 100 V/m and above.

In 1930s, considerable advancements had been made in lightning measurement techniques, such as the simultaneous electrostatic field and the use of photographic records. Schonland[86,87] was the first researcher to make a combination of visual observation and photographic record with an electric field measurement. From correlated data of the field change measurement and photographic measurement, Jensen[40,41,42,43] recorded 185 flashes at close distance and reported that most of the ground flashes exhibited positive field change or lowering of negative charge. Clarence and Malan[15] were the first investigators to introduce the BIL terminology (discussed in Papers 1 and 2) utilizing a combination of photographic observation with electric field measurements obtained using a field mill[50] for slow fields and oscillographic methods (similar to the method of Appleton, Watson-Watt and Herd) to monitor changes in the radiation field.

The excellent observations performed by Kitagawa and his co-workers[46] of various electrostatic field changes and lightning properties based on their simultaneous photographic and high time-resolution electric field records that clarified some of the properties of lightning. During that period of time, the most obvious features in their records (see Figure 6) were the abrupt field change caused by the return-stroke (or the known R changes). Furthermore, in Figure 6, C-change arising from continuous current, the M-change from the M-component, the K-change which occurred in the interstroke intervals, and the J-change which was attributed to the so-called junction process occurring in the cloud between strokes, were revealed with success.

Since the 1970s until recently, the concept of remote measurement of electromagnetic field generated by lightning[39,70,71] has been used to determine how much lightning occurs within a given region and to find the statistics of discharge parameters that were important in research and in the design of lightning protection. Furthermore, this measurement had become tools with which to provide lightning detection and mapping lightning location in order to minimize the harmful effects of lightning by providing early warnings of such hazards.

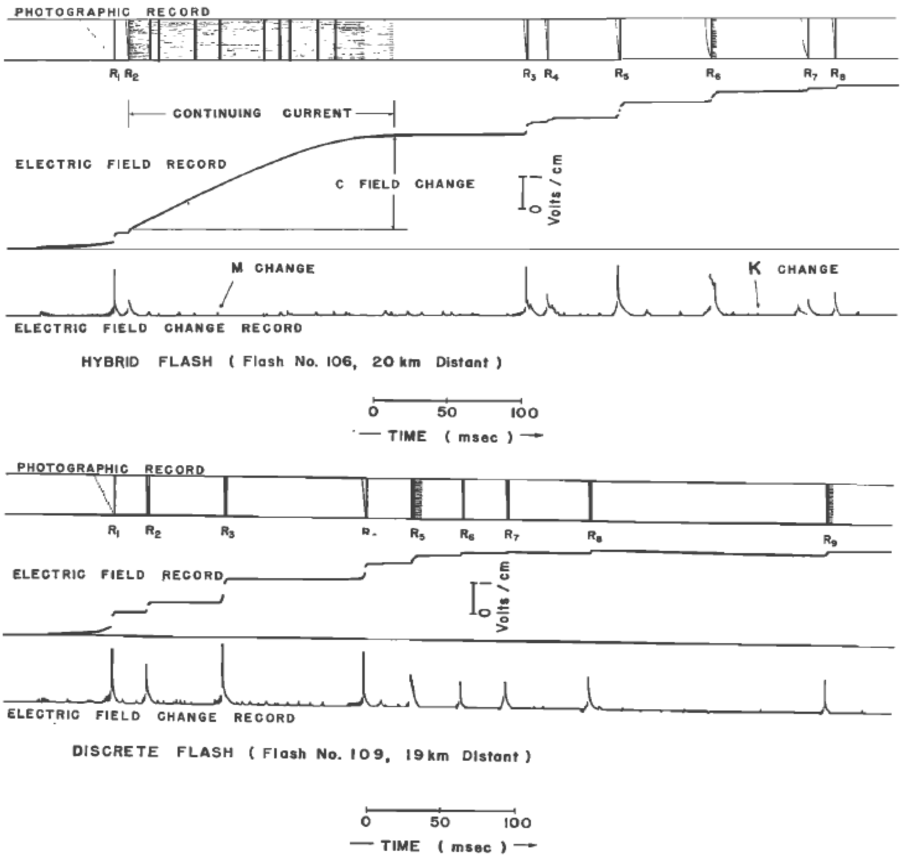


Figure 6. Simultaneous photographic, slow electric field, and fast electric field from negative CG in New Mexico, adapted from Kitagawa et al[46].

Recently, scientists have proven that the use of high resolution recording techniques based on either electromagnetic field measurements or photographic measurements provided an advantage when investigating as they had a tendency to produce new information on the microstructure-lightning-processes, including the whole process of flashes.

3 Electric Field Measurement

3.1 Antenna systems for determining an electrostatic and broadband radiation field

The measurement systems and experimental set-up that were used in the work performed in connection with this thesis were described in detail in this chapter. The measurements were conducted at Vero Beach (Florida), Uppsala and Johor, located in USA, Sweden and Malaysia, respectively. The measurement system used to obtain the electric field from lightning consisted of a metallic antenna, electronic circuitry and a transient recorder. In this thesis, the frequency operation in the measurement systems was limited to 33 MHz for the broadband radiation field. The data were downloaded to a PC-computer for storage and analyzed using Matlab or viewer-software provided by Yokogawa.

In principle, the operation of both whip and flat-plate antenna in this measurement was similar, with the exception of the dimension of the antennas, the association of circuitry characteristic (decay time constant) and mode of transient recorder (see Figures 7 and 8). The operations of the antennas for slow and fast electric field were identical to the descriptions found in the literatures, as reported by Uman[100], Cooray[26] and Galvan and Fernando[30]. A whip antenna and a flat-plate antenna, the workings of which are illustrated in Figures 7 and 8, are associated with the electronic circuitry as depicted in Figure 9 for measuring the electrostatic field (also known as the slow electric field), and the radiation field (also known as fast electric field) signal, respectively. The electric field intensity was induced by the charge from the background electric field was measured between the upper metallic part of the antenna (i.e., the long rod of the whip antenna or the flat-plate antenna) and the ground.

The plates of the antennas were oriented perpendicular to the electric field vector or parallel to the ground to avoid any effect from the horizontal electric field. Three parallel flat plate antennas were used to detect the fast electric field, radiation fields at 3 and 30 MHz signals, while a whip antenna was used to detect the slow electric field signal (see Figure 9). The whip antenna consisted of a lower metallic rod, an upper metallic rod (3.3 m) and an insulator. The lower metallic rod was buried about 0.5 m in the ground while the other end was about 1.5 m above the ground level. The upper and lower metallic rods were insulated from each other by an insulator of 0.05 m thickness with a capacitance of 58 pF.

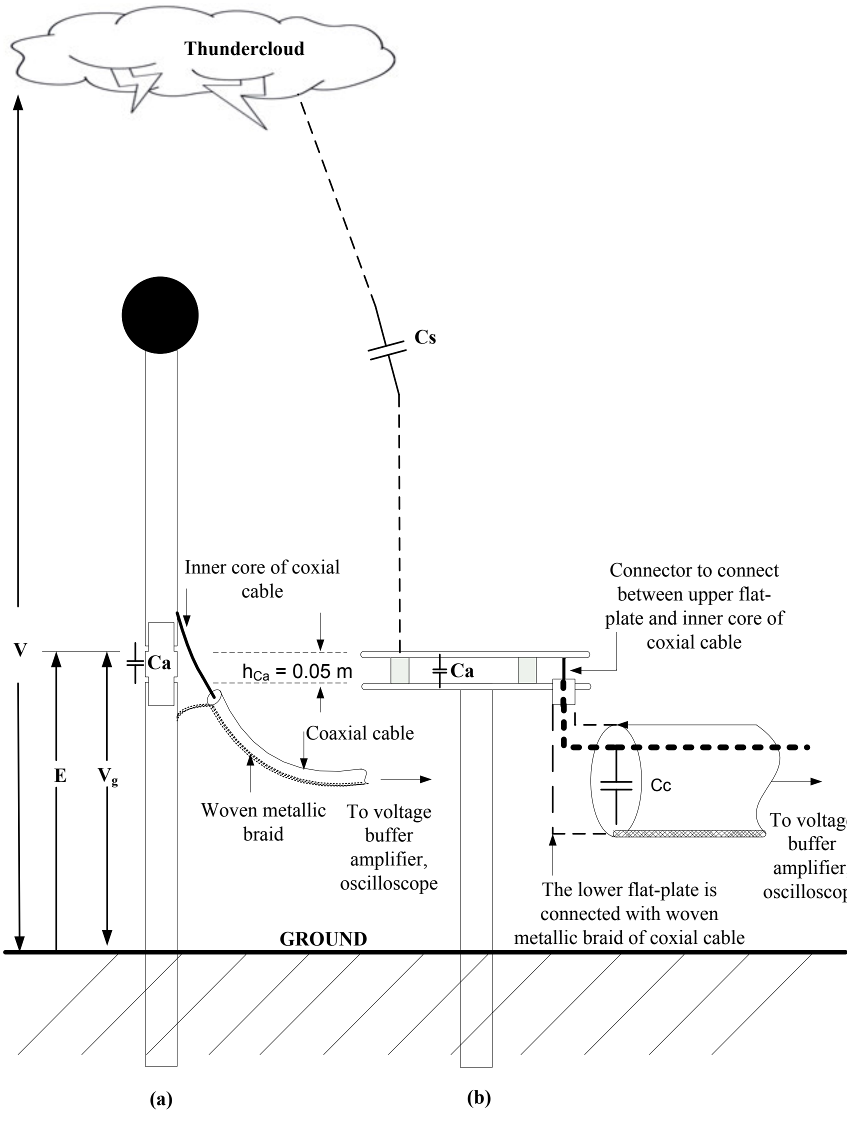


Figure 7. Whip antenna (a) for slow field and flat-plate antenna and (b) for the fast field measurement

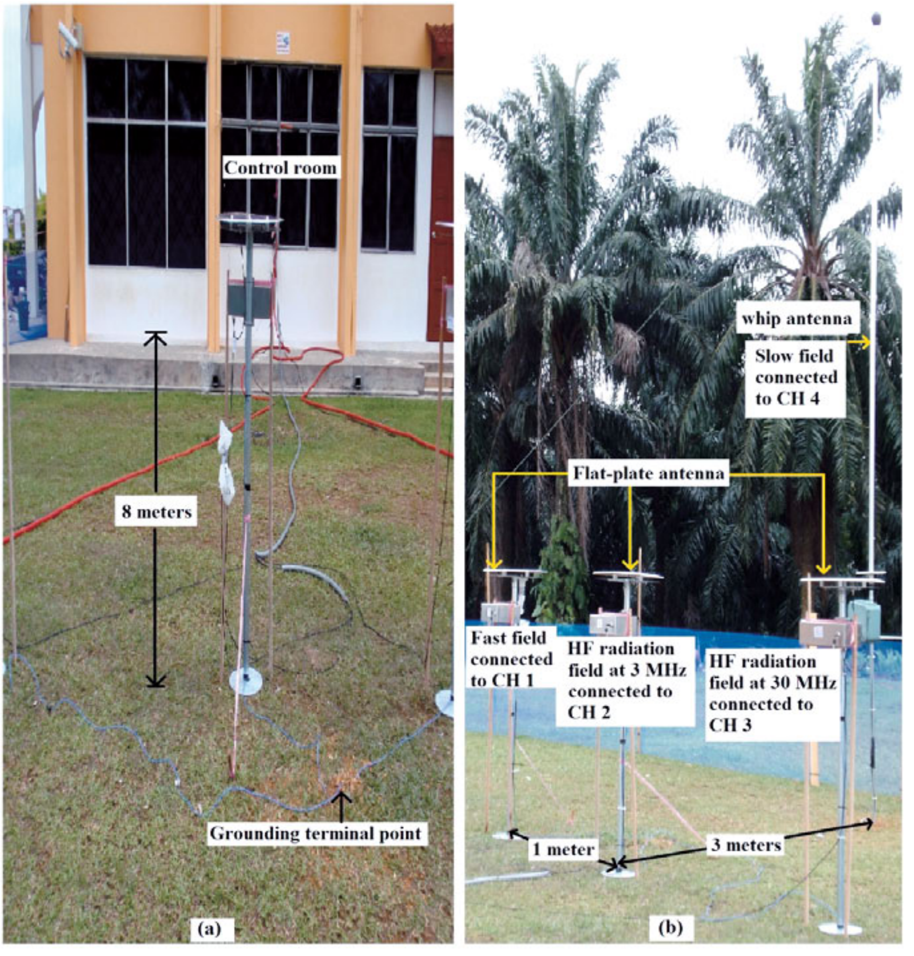


Figure 8. Measuring site located in Johor, Malaysia. (a) Front view from antenna to control room. (b) Side view for flat-plate and whip antennas.

The physical height, insulator thickness and diameter of each of the parallel flat plate antennas were about 1.5, 0.05 and 0.45 m, respectively. All three of these antennas were placed side by side at a distance of 1 to 1.5 meters apart. The whip antenna was placed 3 meters away from the flat plate antenna system. As shown in Figure 8, the antennas were located 8 meters from the control room where the recording system was set up. This condition makes it necessary to use long coaxial cables; therefore a matching resistor was used and connected at the input of the oscilloscope to avoid unwanted reflected signals.

3.1.1 Electronic circuitry for the measurement of slow and fast electric fields

The electronic circuit is illustrated in Figure 9, in the form of (a) a circuit diagram and (b) with a photograph of the operational circuit in situ. The latter is comprised of a combination of *RC*-circuit and voltage follower or high-speed buffer—MSK0033, which acted as a drive circuit to control the signal between the antenna and transient recorder through the coaxial cables. In other words, the high-speed buffer was used to match the impedance of the coaxial cable.

Moreover, MSK0033 offered a very high input impedance ($10^{12}\ \Omega$) and low output impedance ($6\ \Omega$), which made it possible to reduce power consumption at the source, distortion from overloading, crosstalk and other electromagnetic interference[58]. In order to obtain an accurate measurement of the slow electric field (which exists predominantly for close distance of the lightning flash) and the fast electric field (which requires measurement of fields far in the distance), the electronic circuitry should have reasonable precision to ensure that meaningful values for the amplitude and rise time can be attained[26,100]. This can be done by maintaining a reasonable decay time constant for the *RC*-circuit. For example, the *RC*-circuit of the fast electric field was modified in such a way that the value of R becomes higher while keeping the value of C as low as possible.

By considering the wavelength of an electric field to be much larger than the dimension of the antenna, the antenna may operate as a capacitive voltage source with a voltage proportional to the background electric field, $e\ (t)$. This means that an adaptation can be made to the equipment and circuit shown in Figures 7 and 9 in the form of a simplified lump circuit, as displayed in Figure 10. As the background electric field varies over time, the charge induced on the antenna will also vary, generating a current in the electrical circuitry.

The equivalent circuit displayed in the electric field measuring system in Figure 10 showed a combination of the capacitance of antenna C_a, the capacitance of the coaxial cable C_c (the link between the antenna and the electronic circuit), and the capacitor for controlling the decay time constant – C (which was performed by adjusting the operating frequency of the antenna system).

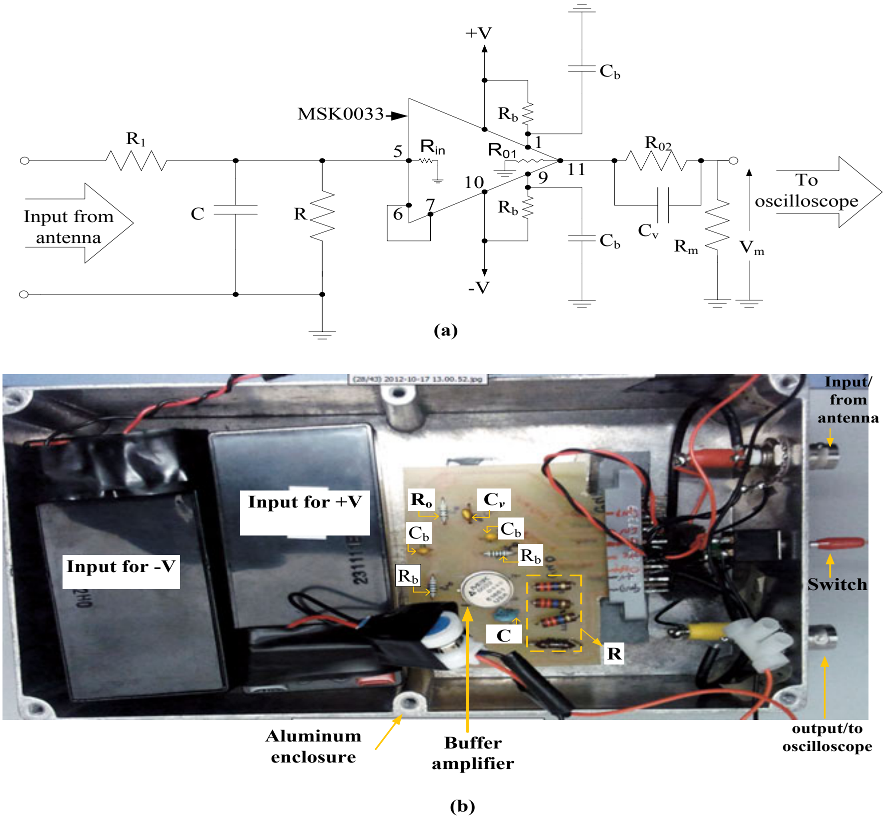


Figure 9. Coaxial cable driver used to control the signal between the antenna and the transient recorder. (a) The electronic circuitry of slow or fast electric field measurement. (b) The circuit board of the coaxial cable driver supplied with a lead acid battery; these components are fixed inside an aluminum container, the edges of which are just visible.

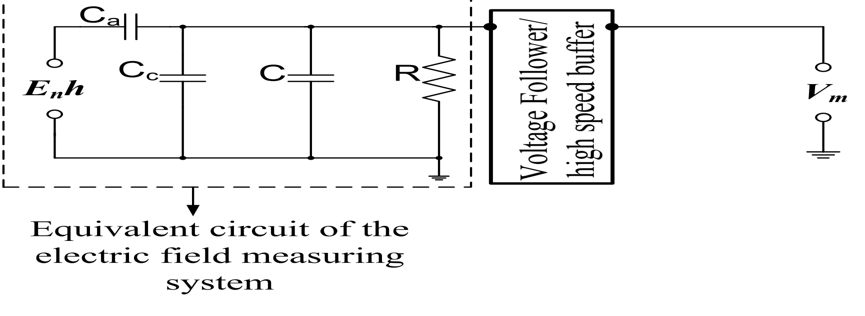


Figure 10. Equivalent circuit for the antenna connected to the high speed buffer.

The determination of the measuring voltage V_m, actually only considered the effects of the total capacitance C_T since the value of the resistance was relatively high compared to C_T. If h_{phy} was the physical height of the upper metallic antenna above the ground, then, V_m in Figure 10 can be represented as:

$$V_m = V_g \cdot \frac{C_a}{C_a + C_c + C} \qquad [3.1]$$

Where, $V_g = E_n \cdot h_{phy}$ [3.2]

3.1.2 Calibration of antenna

The physical height of the antenna did not provide the real effective height – h_{eff} of the antenna system since the lower plate of the antenna is grounded. Hence, the h_{eff} of the antenna has to be defined in order to calibrate the system as a whole[30] for slow and fast fields. Equation [3.1] had to be written as:

$$V_m = E_n \cdot h_{eff} \cdot \frac{C_a}{C_a + C_c + C} \qquad [3.3]$$

The calibration of the parallel-plate antenna was achieved by applying a known electric field E_n using an impulse generator (Marx generator) to the antenna. The testing was repeated for different physical heights. The experimental set up for calibration of the antenna is illustrated in Figure 11.

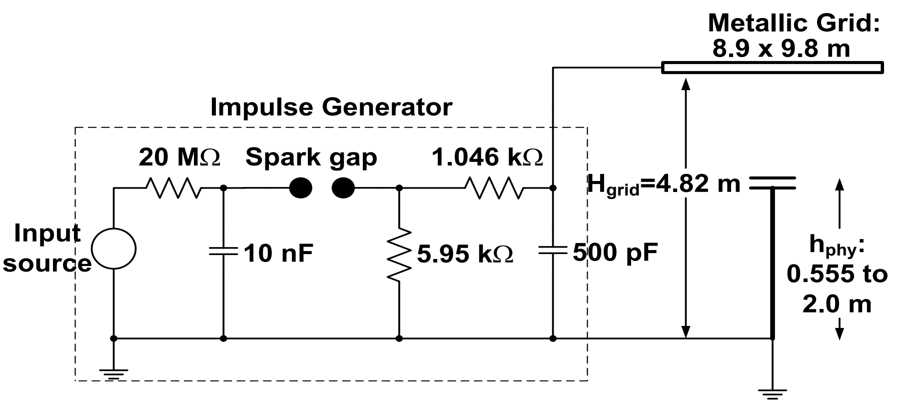


Figure 11. The set-up for calibrating the antenna.

The antenna was placed at the middle of a large metallic grid, which was expected to be adequate to ensure that a uniform electric field would be produced at the mid-point. Next, the antenna was tested at different heights under different levels of electric field as summarized in Tables 3.1 and 3.2. The ratio of E_n/V_m is called the measured factor – F_{meas}. The relationship of F_{meas} and h_{phy} (results displayed in Table 3.2) is plotted in Figure 14, and discussed on Page 36 (see Figure 14).

Table 3.1. The measured voltage V_m for different applied electric fields E_n, and the ratio of E_n/V_m. The physical height h_{phy} of the antenna is 0.555 m.

Applied electric field E_n(V/m)	**Measured voltage V_m (V)**	**Measured factor $F_{meas}=E_n/V_m$ (m^{-1})**
11.2033	0.231	48.4994
22.7593	0.486	46.8299
31.2863	0.699	46.7658
44.9585	0.961	46.7830
52.3443	1.119	46.7778
63.8381	1.364	46.8033
73.8589	1.597	46.2485
84.0249	1.815	46.2947
94.3983	2.061	45.7799
104.3568	2.257	46.2369
115.3527	2.523	45.7204
127.5933	2.700	47.2568
140.2489	2.960	47.3814

Table 3.2.The mean of F_{meas} for different h_{phy} of the antenna.

h_{phy} (m)	**E_n (V/m)**	**Max E_n (V/m)**	**Min E_n (V/m)**	**Max V_m (V)**	**Mean of Measured factor F_{meas}(m^{-1})**
0.555	11.2033	140.2489	0.231	2.96	46.7213
0.750	10.7884	114.3153	0.294	3.03	37.2634
1.000	11.4315	84.4398	0.394	2.92	28.8865
1.250	11.4730	70.7469	0.478	2.89	24.5224
1.500	11.3278	62.2407	0.546	2.94	20.6037
1.750	11.2863	60.9958	0.620	3.23	18.5675
2.000	11.7012	53.4025	0.705	3.19	16.6477

Next, the result for F_{meas} was validated with the calculated factor F_{calc}. This made it possible to determine the mathematical expression for the estimated factor (F_{calc}) by creating the relationship of E_n, V_m and the analytical factor, F. The analytical factor is comprised of the capacitance in the electric circuitry (C_a, C_c and C), the output resistance of the buffer ($R_{0T} = R_{01}+R_{02}$) and the matching resistor for the coaxial cable, which was responsible for controlling the magnitude and decay time constant of the measured voltage. From equation [3.3], one obtains:

$$V_m = E_n \cdot h_{eff} \cdot F \qquad [3.4]$$

$$\text{Where, } F = \frac{C_a}{C_a+C_c+C} \cdot \frac{R_{OT}}{R_{OT}+R_m}$$

The values of C_a, C_c, C, R_{0T} and R_m were obtained from the schematic diagram in Figure 9(a). This gave $F=0.22$. Then the equation [3.4] became:

$$V_m = 0.22 \cdot E_n \cdot h_{eff} \qquad [3.5]$$

The estimated factor of 0.22, however, was not really representative of the real behavior factor for the electric circuit for the antenna system. This is because the analytical factor F only considered the physical components of passive elements, without taking into account the high frequency effect. This mean that, to determine, the most representative value of F is necessary to have a real factor F_{cc}. This was obtained by observing the frequency response for the antenna system as a whole, using a network analyzer (Hewlett Packard Network Analyzer) and an s-parameter test set. This system is capable of testing any circuit within the frequency operation from 100 kHz to 500 MHz. The frequency response of the whole antenna system in this thesis is shown in Figure 12.

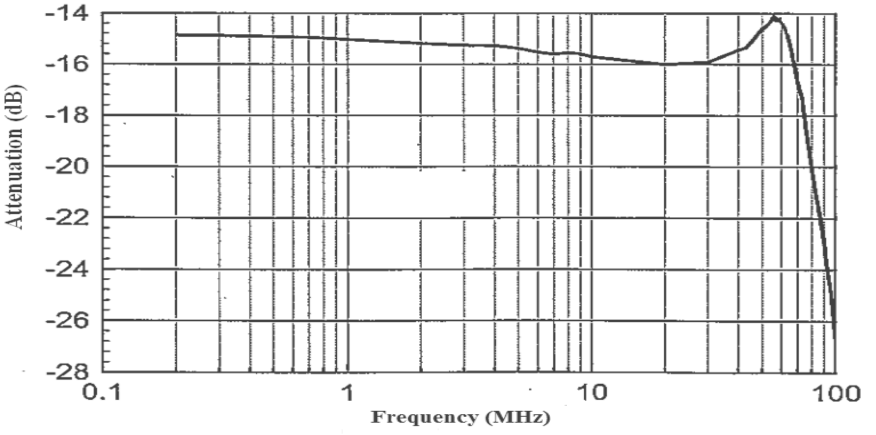


Figure 12. Gain variation of antenna system from 100 kHz to 100 MHz.

Note that the attenuation of the antenna system occurred at –14.9 dB. Thus, the *Fcc* of the antenna system is:

$$20log_{10}\left(\frac{V_m}{E_n \cdot h_{eff}}\right) = -14.9dB$$

$$F_{cc} = \frac{V_m}{E_n \cdot h_{eff}} = 10^{\frac{-14.9}{20}} \approx 0.18$$

Hence, the equation, [3.5], becomes:

$$V_m = 0.18 \cdot E_n \cdot h_{eff} \qquad [3.6]$$

The h_{eff} can now be determined by manipulating Equation [3.6]. Figure 13 shows the variation of the effective height with respect to the physical height for the flat-plate antenna that was used for this thesis work. Moreover, it appears that the h_{eff} increases linearly with h_{phy} and the linear regression relationship can be written as

$$h_{eff} = 0.148838 \cdot h_{phy} + 0.039155 \qquad [3.7]$$

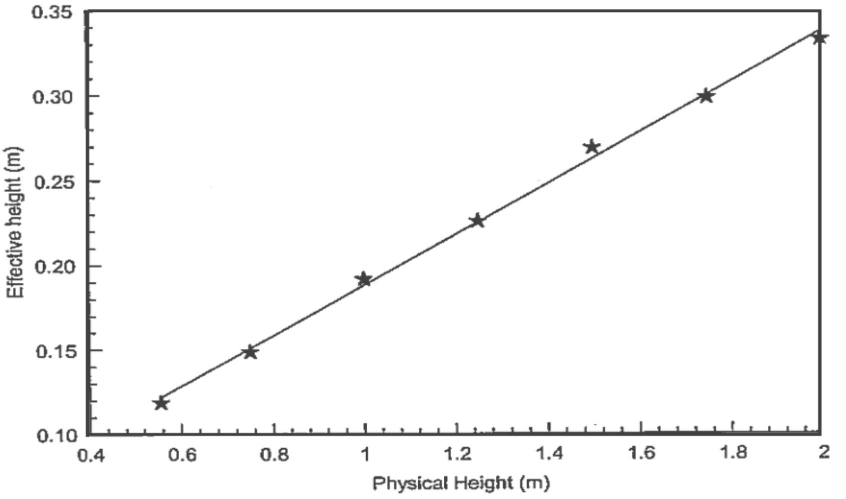


Figure 13. The relationship between the effective height and the physical height of the flat-plate antenna.

Next, the F_{calc} can be obtained by using equations [3.5] and [3.7]. The results of F_{calc} and F_{meas} were plotted in Figure 14, which indicated that the discrepancy between the measured and calculated factors was relatively insignificant.

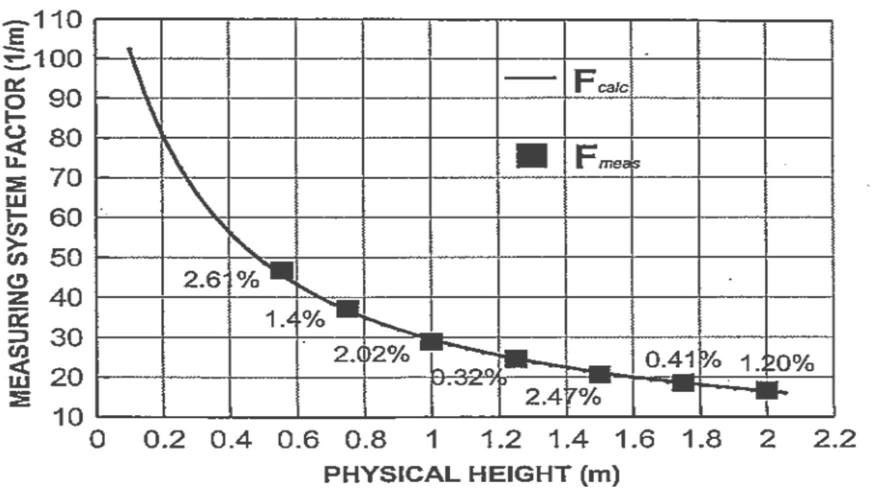


Figure 14. The relationship between the measuring system factor (E_n/V_m) and physical height displayed for indicated the measured and calculated results.

This calibration procedure provides an acceptable regime for equation [3.6] (or equation [3.5]) and [3.7] in estimating the physical height of the antenna and the electric field to be observed (fast or slow field). The physical height of the flat plate antenna was set to 1.5 m which gave the corresponding effective height as 0.27 m (see Figure 13). Therefore, the relationship between the fast electric field and measured voltage was,

$$E_n = 20.6 \cdot V_m \tag{3.8}$$

A detailed description of the calibration of whip antenna for slow electric field measurement was reported by Kanangara et al. (1978)[44] and Pisler (1978)[72]. The whip antenna used in this work and shown in Figures 7 and 8(b) is similar to that mentioned in the literatures cited above. The effective height of the whip antenna was found to be 1.88 m. The analytical factor of the whip circuitry system (see *F* represented by equation [3.5]) used 10 nF for C, then the value for *F* was determined as follows:

$$F = \frac{C_a}{C_a + C_c + C} \cdot \frac{R_{0T}}{R_{0T} + R_m} = \frac{59pF}{59pF + 60pF + 10nF} \cdot \frac{1}{2} = 45.86$$

Therefore, $E_n = 45.86 \cdot V_m$ [3.9]

A detailed explanation of the decay time constant τ of the antenna systems for fast and slow fields was described by Uman[100], Fernando and Galvan[30], and Cooray[26]. The τ was derived from the equivalent circuit of Figure 10 by performing the transfer function of V_m corresponding to the input of antenna (V_g=E_n·h_{eff}) in the frequency domain. The transfer function response for the electric circuitry in Figure 10 was simplified to:

$$\frac{V_m}{V_g} = \frac{s}{s + \frac{1}{R(C_a + C_c + C)}} \cdot \frac{C_a}{C_a + C_c + C} \tag{3.10}$$

The profile of frequency response for equation [3.10] was described in detail by Galvan and Fernando[30]. They reported that the frequency operation for this electronic circuit may cover the range of a few Hz to tens of MHz, which was suitable for a lightning study. By taking the Inverse Laplace Transform of equation [3.10], one can easily obtain the time domain response and the decay time constant *τ* as follows:

$$\frac{V_m}{V_g} = \frac{C_a}{C_a+C_c+C} \cdot e^{-\frac{t}{R(C_a+C_c+C)}} \qquad [3.11]$$

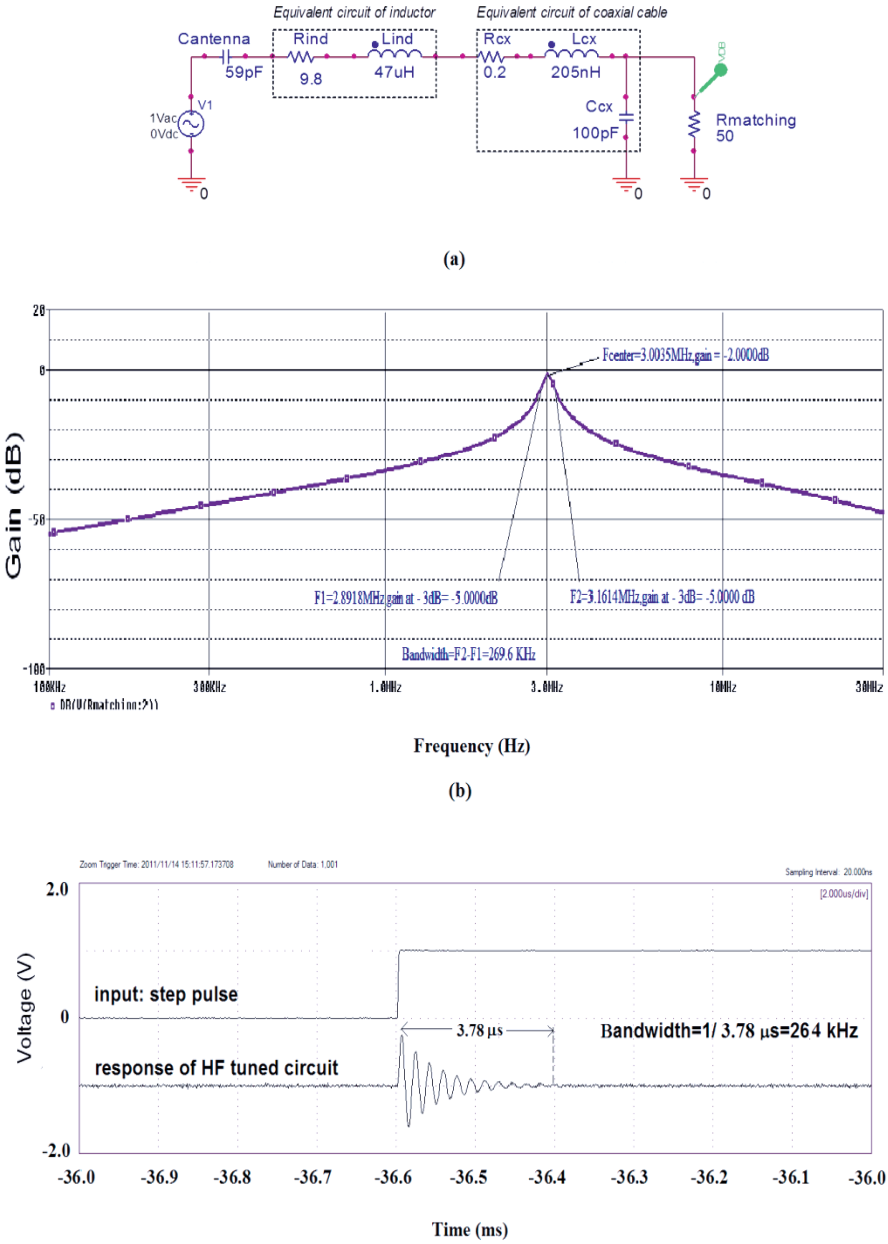
Where, $\tau = R(C_a + C_c + C)$ [3.12]

The decay time constant for the fast electric field (C = 15 pF) and the slow electric field (C = 10 nF) circuit was tuned to 15 ms and 1 s, respectively. The decay time constant for the fast electric field was found to be suitable for faithful reproduction on the micro-second scale, while the value for the slow electric field was long enough to allow certainty in our analysis.

3.2 Narrowband radiation field antenna system

The narrowband radiation field of a high frequency antenna system tuned at 3 MHz, as in this study was similar to the descriptions in the literature by Cooray[20], Hugo and Cooray[22], Endridge[28] and Azlinda[3]. The narrowband radiation field with the system at 3 MHz was operated simultaneously with the system for the broadband radiation field (fast field), which was purposely used to detect a small structure especially for the first preliminary breakdown pulse. The combination of measurements of the narrowband and broadband radiation fields made it possible to considerably decrease the uncertainty in identifying a small structure[4,5,6].

Figure 15(a) shows a circuit tuned at 3 MHz while the simulation and experimental results are shown in Figures 15(b) and 15(c). Note that the circuit tuned at 3 MHz is a combination of passive elements where the inductance (47 µH) is connected in a series with the antenna (58 pF) and 50 Ω termination forming a simple *RLC*-bandpass filter circuit. Table 3.3 summarizes a comparison between the simulation and experimental results of tune frequency and bandwidth operation for 1 meter cable between the antenna system and the transient recorder. The experimental result was considered acceptable as it was similar to the simulation result. Through experimental work, the bandwidth of this bandpass filter is 264 kHz.



(c)

Figure 15. (a) Schematic model of tuned circuit at 3 MHz, and (b) the corresponding simulated result. (c) The experimental result with the circuit tuned to 3 MHz.

Table 3.3 Simulation and experimental parameters for 3 MHz bandpass filter for the narrowband radiation field antenna system.

Frequency of interest	Tuned frequency (MHz)		Bandwidth (kHz)	
	Simulation	Experimental	Simulation	Experimental
3 MHz	3.0005	2.9411	269.6	264

3.3 Data

The data used in this thesis is explained in detail in all of the publications referred to paper 1 to 5. The measurement set-up in the USA, Malaysia and Sweden was identical (see Figure 8). In USA, the measuring station was located at the Florida Institute of Technology, in the vicinity of the eastern coast of Florida (27°N, 80°W). The measurements were recorded during the summer of 2009, i.e. in July and August. In Malaysia, the measurements of electric fields generated by lightning flashes were recorded from April to June, 2009, during the southwest monsoon period in the Johor state at the southern part of Malaysian Peninsular, which is in close proximity to the equator (Latitude: 1°N; Longitude: 103°E; altitude: 132 m). The measurements in Sweden were conducted during the summers of 2010 and 2011, from May to September, in Uppsala. In Uppsala (latitude: 59.8 N; longitude: 17.6 E; altitude: 13 m), the site was located 70 km inland from the Baltic Sea.

Signals from all antennas were fed with 10 m long coaxial cables (RG-58) into a 4-channel 12-bit digital transient recorder (Yokogawa SL1000 equipped with DAQ modules 720210) with proper termination (50 Ω termination). The sampling rate was set to 20 or 100 MS/s with the total length recorded being either 0.25 or 1 s. The transient recorder was operated either at 125 or 300 ms in the pre-trigger mode. The trigger setting of the oscilloscope was set such that the signals from both polarities could be captured. The close distance of the negative ground flashes, at a distance of less than 16 km was calculated using the thunder ranging method. In this method, the elapsed time between the arrivals of the electrical pulses and the acoustic signals were divided by the speed of sound to arrive at the distance of the flash. There was a possible error of approximately 1 s delay when the first electric pulse was displayed in the scope. The trigger level was set in the range 500 mV to 2 V, to ensure that only close flashes could be recorded.

4 Preliminary breakdown pulse trains at different geographical regions

The terminology of the preliminary breakdown pulse, PBP, is described in detail in Section 2.1.1. It is generally thought that the first RS in a negative CG strike is preceded by the initial or preliminary breakdown, which can be defined as the in-cloud process that initiates the commencement of the downward-moving stepped leader[15,36,66,95,100]. In general, this breakdown is thought to arise from the interaction between the main negative charge and LPCR that may result in either a CG or intracloud flash. The preliminary breakdown process in ground flashes usually[4,5,6,7,15,31,54,57,59,61] produces a train pulse with microsecond-scale-electric field pulses as depicted in Figure 16. The pulses are typically bipolar, with the polarity being the same as that of the following RS pulse. Other lightning events, such as hybrid flashes[17] with regular intracloud (IC) discharges occurring prior to the negative CG flash are considered to be anomalous cases, and are not examined in this study.

4.1 The relationship of LPCR and PBP trains with the occurrence of negative CG (Paper 1 and Paper 4)

It is significantly important to investigate the relationship between the amplitudes of a PBP pulse train and that of the corresponding first RS, especially to define the relationship of the characteristics of lightning based on geographical location, latitude and storm type. The suggestion by Cooray and colleagues[24,25]and the hypothesis of Nag and Rakov[60] were used to examine the findings in Paper 1. The latter researchers explained that the probability of ground flashes increased if the breakdown possibility was high between the negative charge center and the LPCR. Cooray and Scuka[24] speculated that, by knowing the strength of the ground-flash-initiation breakdown process in the cloud, measured with respect to the peak radiation field of the resulting RS (ratio of PBP/RS), one can know the strength of the LPCR. The ratios of PBP/RS measured from the observations obtained in Sweden[31],

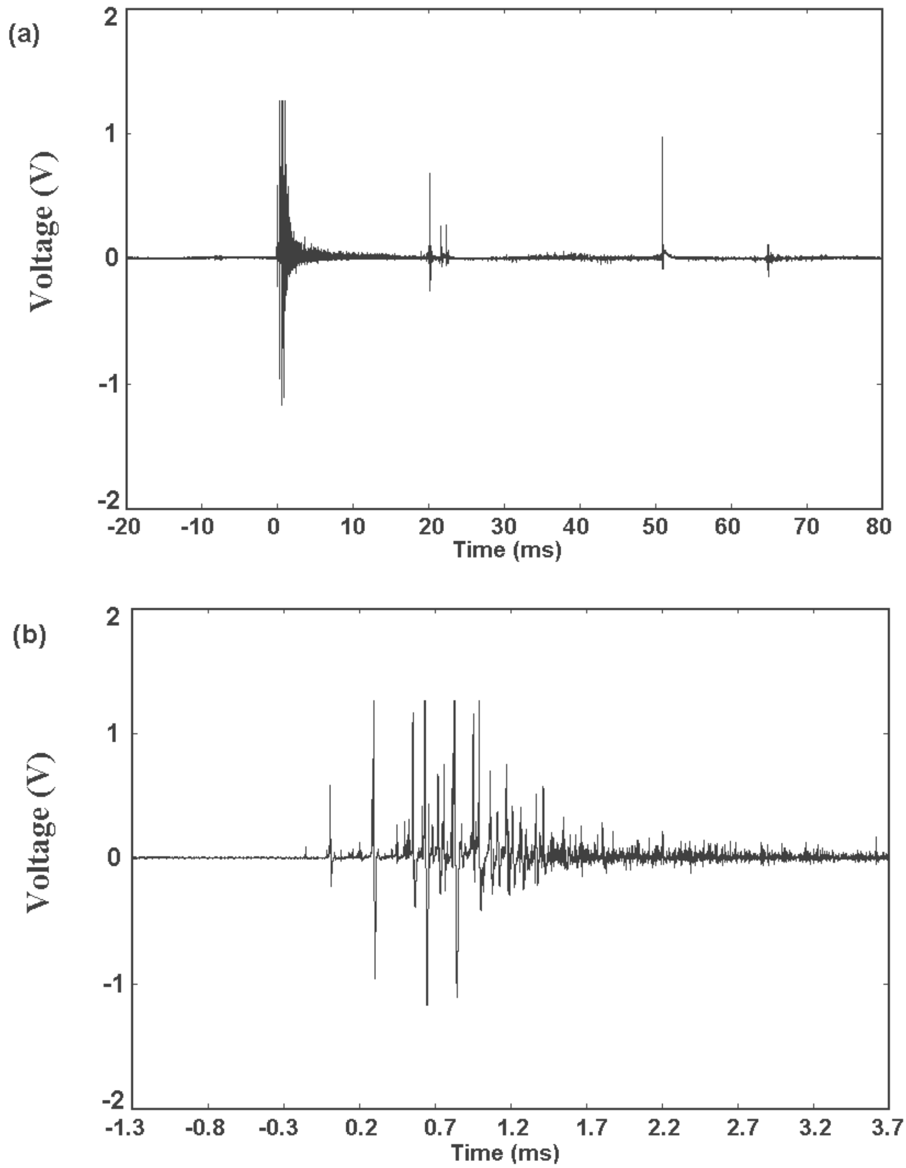


Figure 16. Example of electric field due to negative ground flashes. The preliminary breakdown process produces a train pulse with electric field pulses on the microsecond scale.

Finland[57], Florida[5,59,61], Sri Lanka[31] and Malaysia[5] showed that there was a variation that was attributable to the geographical region. Cooray and Jayaratne[25] speculated that the production of strong LPCR was more likely in subtropical regions and high latitude locales than in the tropics. Furthermore, the hypothesis of Nag and Rakov[60], which was also based on the measurements performed at the locations mentioned above, interpreted the PBP train as the indication of the presence of LPCR in the thundercloud. Furthermore, they suggested that a significant LPCR may produce a very prominent PBP train for negative ground flashes, especially at higher latitudes such as Sweden, Finland, and Austria. On the other hand, when the LPCR is small, a detectable weak PBP train may be produced probably owing to an insignificant LPCR, such as those found in Sri Lanka.

From Paper 1, it is inappropriate to relate the latitude effect and LPCR with the simple fact of detectable PBP at different latitudes and the presence of LPCR (as suggested in [60]), since a PBP train also detected in Malaysia. The number of detectable PBP train in Malaysia was found in 97 out of 100 flashes, which was very much higher than the number of detectable PBP trains in Sri Lanka. As a result, this thesis used the hypothesis by Cooray and co-workers[24,25,26] to study the relationship of the latitude effect with the associated factors from the strength of PBP and the strength of LPCR in terms of the amount of charge [14]. From the large number of data analyzed in Paper 1, it has been proven that the strength of PBP train measured with respect to the first RS was significantly larger at the northern and subtropical regions considered (see Paper 1, Table 3) than in the tropics. Furthermore, this finding agreed with the work of Chauzy and Soula[14], who used numerical modeling and the measured electric field when estimating the amount of charge produced by corona-producing positive charge at ground level during thunderstorms in Florida (lower latitude) and France (higher latitude). The value of corona-producing positive charge at ground level in France (ranging from 106 to 362 C, with 214 C on average) was found to be almost double the charge value in Florida (range 63 to 124 C with 94 C on the average). Additionally, Rakov and Dulzon[77] reported that the height of the main negative charge tended to be smaller at a higher latitude, so this condition can increase the electric field at the ground and make positive corona production at ground level more efficient at a higher latitude than in the tropics[26,80,81]. Now, this relationship can be comprehended appropriately using four terminologies for PBP preceded first RS as proposed by Nag and Rakov[60], as illustrated in Figure 17. Basically, the type of PBP preceding the first RS might depend upon the magnitude of the LPCR when a negative leader channel extends downward from the negative charge region.

The LPCR in Figure 17 (a) is considered to be abnormally large, or in other words comparable in magnitude to that of the main negative charge. This condition showed that the presence of excessive LPCR might prevent the occurrence of negative CG flashes by blocking the progression of negative downward leaders from reaching the ground. If this condition occurs, the attempted leaders, known as the inverted IC discharges, which were not followed by the RS, could be found. This type of lightning was reported in detail by Qie et al.[74] and Nag and Rakov[60]. The work of Tessendorf et al.[95] and Coleman et al.[17] observed that this lightning appeared to be vertical and changed its direction of propagation to predominantly horizontal while interacting with LPCR. Overall, based on the Malaysian data analyzed in Papers 1 and 2, it can be affirmed that this type of flash might not occur in tropical countries. In presenting Figure 17(b), Nag and Rakov[60] suggested that these discharges can be viewed as a hybrid flash, where the regular IC pulses occur prior to the CG discharges, especially in cases where there were tens to hundreds of milliseconds between the alleged PBP train and the RS[17,74].

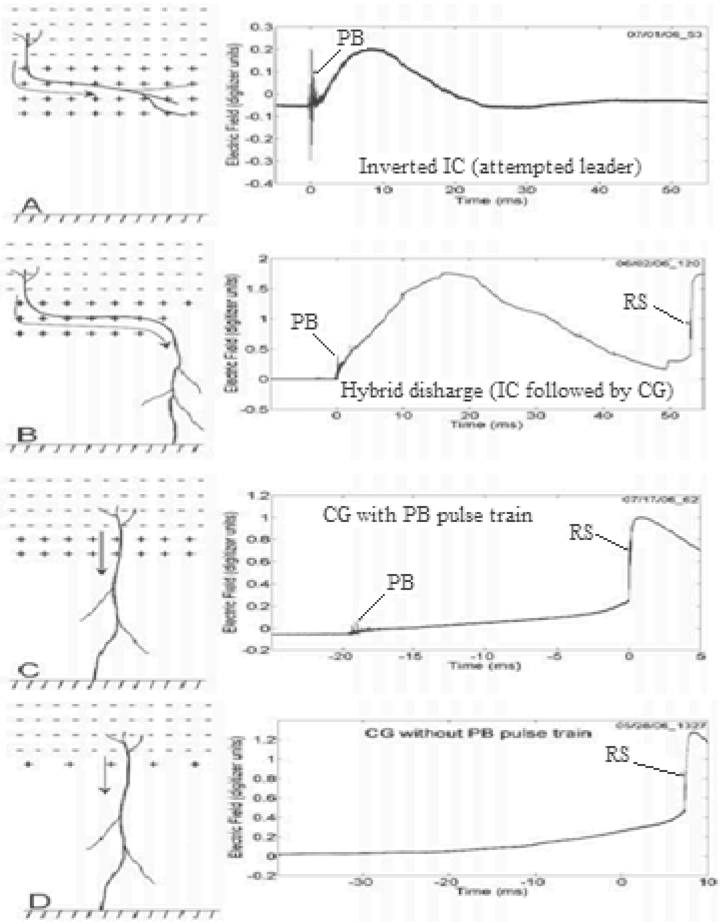


Figure 17. Signatures characteristic of the four types of PBP preceded by a first RS, that depended on the magnitude of the LPCR (adapted from [60]) and showing the terminologies used to describe them.

Table 4.1. Long pre-RS duration prior to the RS without association of IC regular pulses and flashes with only single-stroke. In total, 16 out of 97 of the individual times measures were over hundreds of milliseconds in duration.

No of flash	Time Recording	PBP/RS	Pre-RS duration	No. of stroke
1	078-090526-05:11:22.524544	6.4%	65	1
2	051-090521-11:21:20.931132	26.3%	93	1
3	010-090521-05:03:04.442784	105.9%	17	1
4	085-090526-05-28:09.406323	14.1%	112	1
6	014-090529-06:52:57.271381	20.8%	158	3
7	020-090529-07:00:06.867864	2.6%	60	1
8	022-090529-07:02:19.274204	4.7%	53	1
9	026-090529-07:09:13.62573	3.9%	102	8
10	028-090529-07:14:40.753631	28.5%	230	1
11	039-090529-07:26:33.506932	9.9%	51	1
12	045-090529-07:32:53:071399	36.4%	138	6
13	057-090529-07:53:20.046231	34.7%	109	4
15	000-090530-02:08:38.149224	22.6%	132	1
16	008-090530-02:20:30.673367	36.5%	33	1
17	013-090530-02:28:21.470384	19.8%	21	1
18	018-090530-02:42:35.042689	4.5%	105	4
19	040-090526-04:24:18.972857	218.3%	33	1
20	084-090526-05:25:20.837565	14.3%	161	1
22	004-090523-05:14:38.278207	5.4%	193	5
23	005-090523-05:15:36.198544	56.3%	136	3

24	006-090523-05:18:17.779887		220	1
25	022-090523-05:46:48.761038	8.8%	112	5
26	025-090523-05:52:25.947143	10.8%	188	1
27	032-090523-06:05:10.101409	8.5%	132	2
28	035-090523-06:12:02.672665	11.1%	131	6
29	060-090529-07:59:06.925552	26.5%	44	1

Furthermore, this scenario has a similar profile to that of A in Figure 17, where, in the beginning, a negatively-charged leader channel exhibited vertical progress in the main negative charge regions, then changed to become a horizontal extent, leading to termination on the ground. In B, the magnitude of LPCR was considered to be smaller than it had been in A. However, this scenario and the characteristic signature also made it possible to explain Table 4.1 in which the findings from Papers 1 and 4 for the duration of long pre-RS (which comprised 16 of 97 data events registered had pre-RS duration over hundreds of milliseconds) prior to the RS, without associated IC regular pulses and flashes, and with only a single-stroke, as summarized in Table 4.1. Similarly, the earlier studies by Krehbiel et al.[47], Proctor et al.[73], Rustan et al.[76], and Rhodes and Krehbiel[75] also reported a long pre-RS duration preceding the first RS, but without the existence of hybrid flashes (there were no reports the relevant literature regarding hybrid flashes), interpreted this as corresponding to the formation of a horizontal channel during the development of the preliminary breakdown process preceding the stepped leader. Now, the criteria for long pre-RS duration are analyzed in Table 4.1 to determine the relationships between the data for stroke counts.

Table 4.1 indicates that there were six instances with a long pre-RS duration, defined as being over hundreds of milliseconds, exhibited as a single flash and 10 instances were in connection with a multiple-stroke. If the long duration was taken into account as the 50th percentile (over 50 ms) and also by considering the ranges of four to six as a typical number of strokes in a flash (as concluded in Paper 4), then 17 samples were determined to have a very low occurrence of strokes in negative CG (see Table 4.1). This scenario indicates that the presence of LPCR for this type terminology may have a tendency to limit the number of strokes in a flash. On the other hand, there were seven samples of long pre-RS duration having a high number of strokes in each flash. These results were different from the evidence reported by Takeuti et al.[90] and Thomson[97] who found that the long pre-RS duration had fewer strokes. This thesis suggests that an event with many strokes during the duration of the long pre-RS may have several access channels to the ground.[78,79,83,99]

Figure 17(c) illustrates the negative CG, which may have a smaller LPCR than the main negative charge, which may move predominantly in a vertical direction to the ground. As shown in Table 3 of Paper 1, the highest strength PBP train was found in the northern region, followed by the subtropical region, which suggested that the downward negative leaders from the main negative charge region, especially those in higher latitudes, needed to have a considerable amount of energy to break the “blocking” agent created by LPCR in order to continue propagating to the ground (see Table 3 in Paper 1).

The final type of PBP preceded the first RS as shown in Figure 17(d), suggesting that some negative CG flashes were either weak or without any PBP signature possibly due to an insignificant LPCR magnitude. In this situation, preliminary breakdown processes with a low energy level between the negative charge region and the LPCR, especially in tropical countries such as in Sri Lanka[23,31] and Malaysia[5] (see Table 3 in Paper 1), do not need to struggle to break the “blocking” agent in LPCR. This terminology is thought to have a similar propagation progress as the terminology in Figure 17(c), which had a horizontal channel during the development of the preliminary breakdown process preceding the stepped leader.

4.2 Characteristics of the PBP train (Paper 1)

Even though the strength of PBP trains measured with respect to the peak radiation field of the resulting RS (ratio of PBP/RS) were the major consideration of Paper 1, it is also important to address the parameter of PBP the classification of BIL terminology, the number of pulses in the train, the total pulse train duration, the interpulse interval and the individual pulse duration. Interestingly, the characteristics of the PBP train reported in Paper 1 are novel information that was observed in Malaysia. The details of this work are described on pages 3 to 6 of Paper 1.

The illustrative information regarding the characteristics of PBP trains only appeared in work published by Nag and co-workers [59,61] recently, and in the information presented here, in Paper 1. The data set observed in Florida that was used in the work presented in this thesis was similar to other findings reported by Beasley et al.[7], Rakov et al.[80], and Nag and Rakov[59,61]. To satisfy the selection criteria for the PB pulse train in the negative CG lightning flash for the Malaysian data set, the methodologies and guidelines performed by Nag and Rakov[59,61] were followed (detail on page 3, Paper 1). In addition, the work also assumed that the pulses in the train were bipolar, as reported by many investigators[3,4,5,7,31,57,59,61].

The BIL (B: breakdown, I: intermediate and L: leader) model was found to be an important tool for the analysis in Paper 1 as it incorporated the total pulse train, and the individual pulse and the interpulse durations. The findings for fitting three successive discharge processes into a BIL-type terminology model was consistent with the very recent work performed by Makela et al.[57] and Ting Wu et al.[96]. From a total of 97 flashes with detectable PB pulse trains in the data set obtained in Malaysia, almost 50 % were found to be consistent with the complete form of BIL. Figure 18 shows two examples of typical patterns for electric field changes preceding the first negative CG flashes. In the BIL-form, 24 (24 %) out of 97 flashes were characterized as having regular pulses in the PBP train inside the time period labeled B, corresponding to the breakdown.

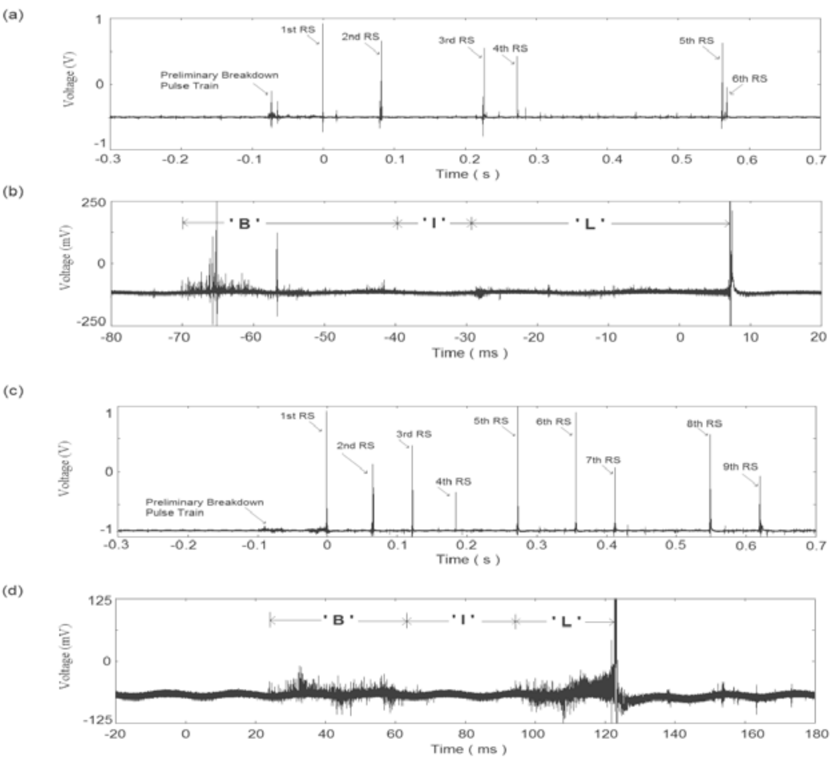


Figure 18. Two examples of negative CG lightning flashes show a pronounced PBP train, an intermediate one , and step leader that can be fitted to BIL terminology. Adapted from [5].

Another 21 (22%) cases of the BIL-form were characterized as having irregular pulses with complicated shapes in the PB pulse train in the section labeled B. The irregular features, shown in Figure 19, were found to include small pulses, either unipolar or bipolar, that were superimposed on other distinct bipolar pulses in the train. Paper 1 stated that 52 flashes (54 %) exhibited the ‘B, L’ form, suggesting the possibility that the duration of the section labeled ‘I’ had decreased to zero. The features of the ‘B, L’ form are depicted in Figure 20.

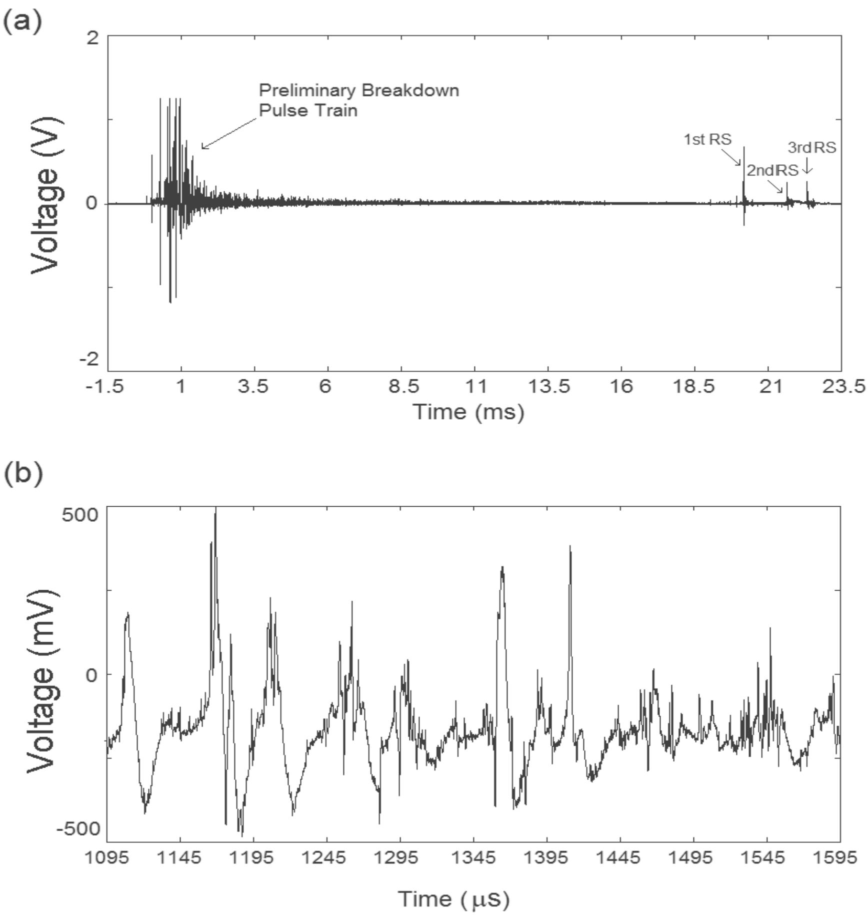


Figure 19. (a). Close up figure with 25 ms of time frame for the negative ground flash recorded in 26/05/2009 at 05:18:27.580181 (utc), shows a pronounced PBP train, an intermediate period with no activity, and then a step leader that can be considered to have the BIL characteristic signal. (b). A close up from (a) shows irregularity of the pulses and demonstrates it to have a complex shape. Adapted from [5].

The flashes that are profiled in Figures 19 and 20 were considered to be complicated cases, requiring complex methods of analysis, especially for parameters such as the pulse train duration, individual pulse duration and interpulse duration. It was for this very reason that the authors decided to focus on just 24 samples of the best-known typical flashes (i.e., those consistent with the BIL-type) which were characterized as regular pulses in the PBP train. Furthermore, this thesis suggests that the irregular features of pulses in a PBP train can cause confusion to recognize the correct type of pulses, as well as the polarity.

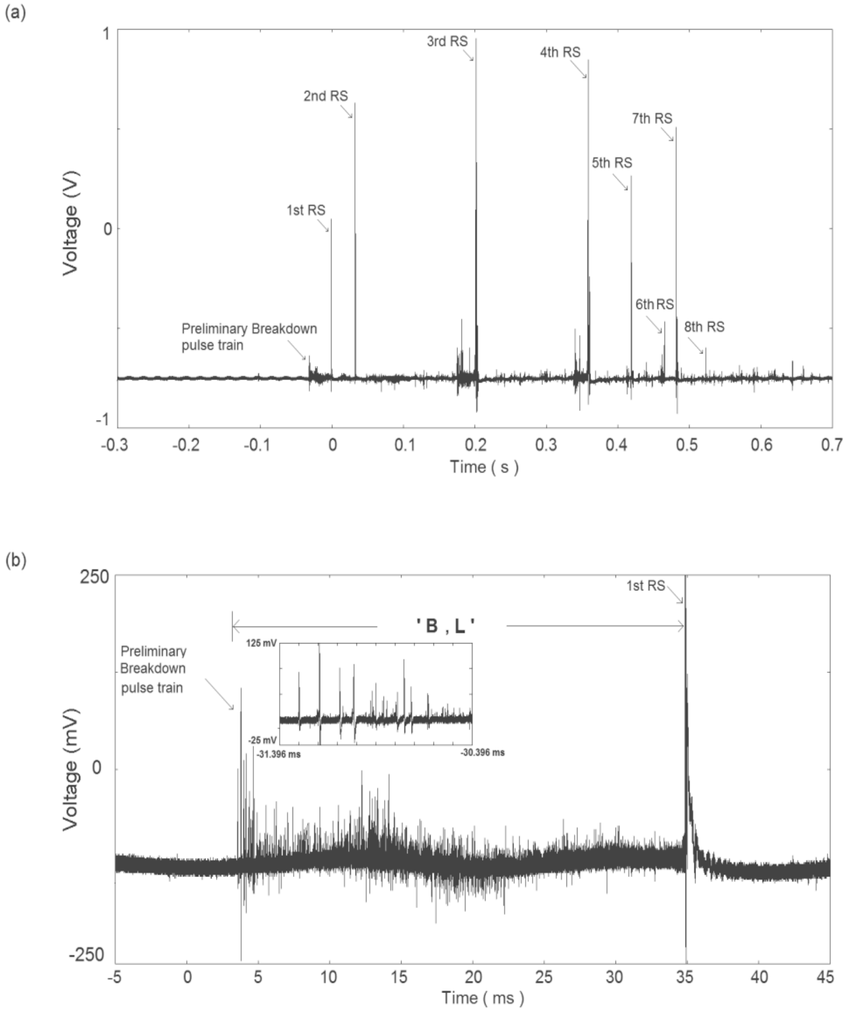


Figure 20. (a). A pronounced PBP train and step leader that can be fitted to BL terminology (b). Close up from (a) with 50 ms. Adapted from [5].

This might be the reason why previous researchers such as Krehbiel et al[47], Thomson[97], Beasley et al[7], and Proctor et al.[73] were unable to fit the process prior to the first RS in the BIL-type terminology. In addition, it is demonstrated that the use of 12 bit transient recorders, as utilized by Baharudin et al.[5,6] and Ting Wu[96] had allowed one to solve an analysis that dealt with the uncertain and complex profile of the waveform as mentioned above. The characteristics of PBP trains in the negative CG flashes observed in Malaysia and Florida have been summarized in Table 1 of Paper 1. The result stated that the duration for the initiation of the preliminary breakdown processes in negative CG flashes in Malaysia was three times greater than those in Florida (see Table 1, page 6 in Paper 1). This result supported those shown in Figure 14 (Paper 1), which explained the characteristics of PBP trains in Malaysia and Florida as not similar to each other.

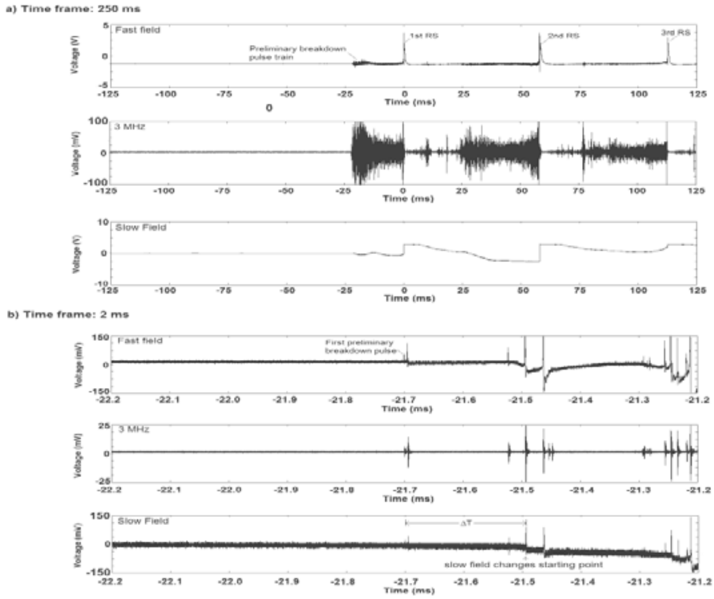
5 Electric field changes generated by the preliminary breakdown pulse for CG flashes (papers 2 and 3)

The association of the changes in the electrostatic field, i.e. the changes in the slow field, as presented in Papers 2 and 3. This is the first time where the bulk of the data, comprising 1685 negative CG recorded in Malaysia and Sweden, and 107 positive CG flashes recorded in Sweden was examined. The aim was to improve the unclear features of the early signature of the slow field changes generated by preliminary breakdown processes in ground flashes was successfully achieved with the same conclusion as reported in Paper 2 and 3 (respectively concerning slow field changes in negative and positive CG), where the slow field change always started after the initial preliminary breakdown process.

Earlier in 1982, the work of Beasley and co-workers[7], who used to call the study of slow field changes generated by PBP "preliminary variations", appeared to be the only adequate statistical data. The complexity of the data was such that Beasley and co-workers came out with their results based on a very subjective and intuitive decision. Further, they found that all of their selective data on the slow field changes started before the process of preliminary breakdown, with the exception of seven cases that were found to be uncertain. Overall, Beasley et al.[7] was unable to make a significant conclusion on this study. The results of this thesis, which are based on a large set of data from two different locations, provided clear evidence that none of the slow field changes associated in the preliminary breakdown began before the preliminary breakdown section. The results were summarized in Table 1, page 23 and Table 1, page 18 for Papers 1 and 2, respectively. The evidence was supported by the existing criteria on the so-called pre-starting time, i.e. for the duration between the first PBP and the starting time of the slow field changes.

The pre-starting time from negative CG in Malaysia occurred after the first PBP, ranging from 0.22 to 32.9 ms (see Figures 20 and 21). Similarly, the pre-starting from negative CG in Sweden also occurred after the first PBP, in the interval between 0.24 and 9.80 ms (see Figures 22 and 23).

(A)



(B)

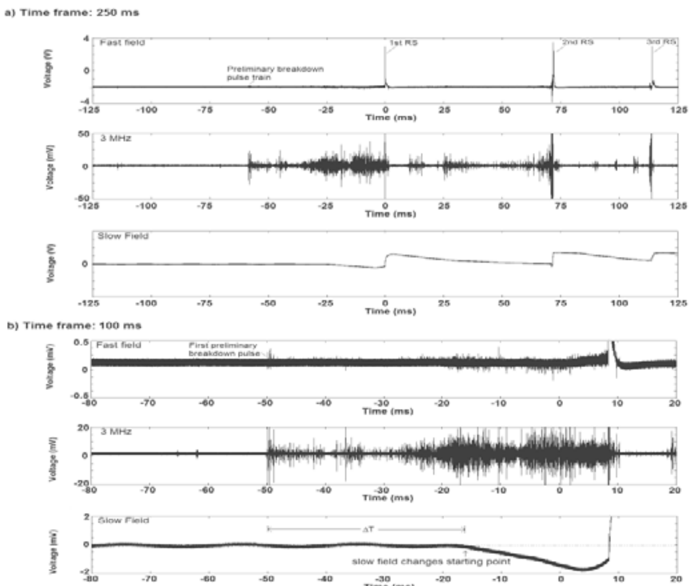
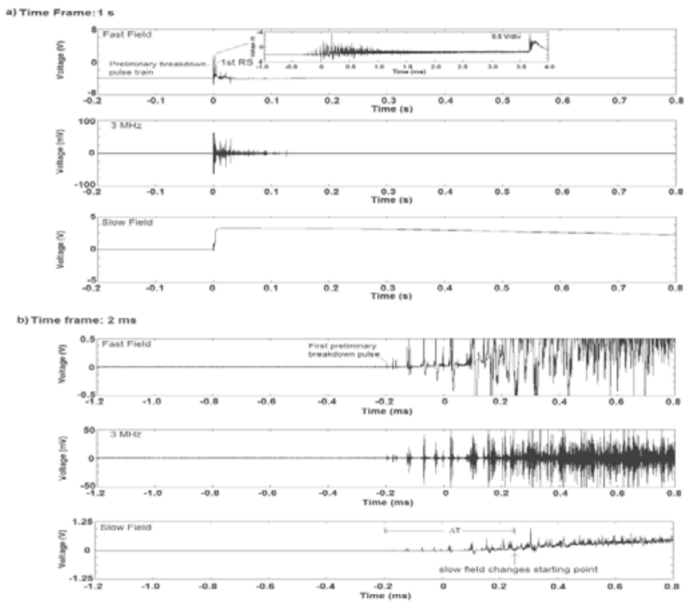


Figure 21. The minimum (A) and maximum (B) pre-starting time (ΔT) from negative CG recorded in Malaysia. Adapted from [6].

(A)



(B)

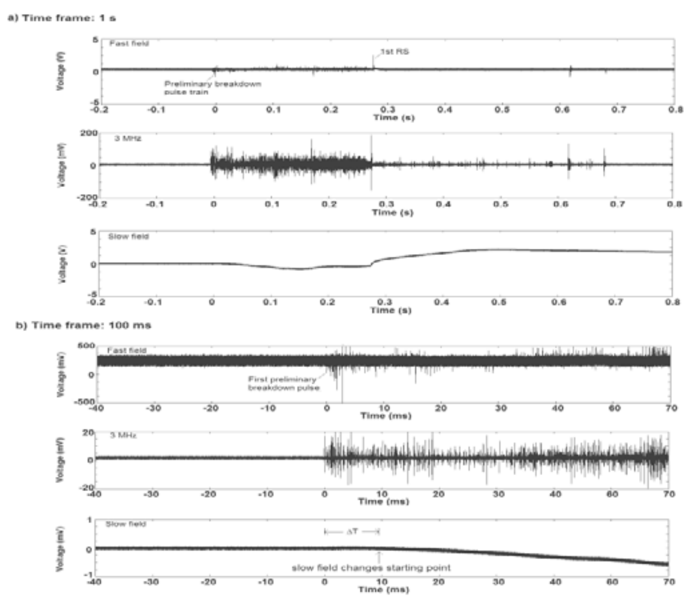
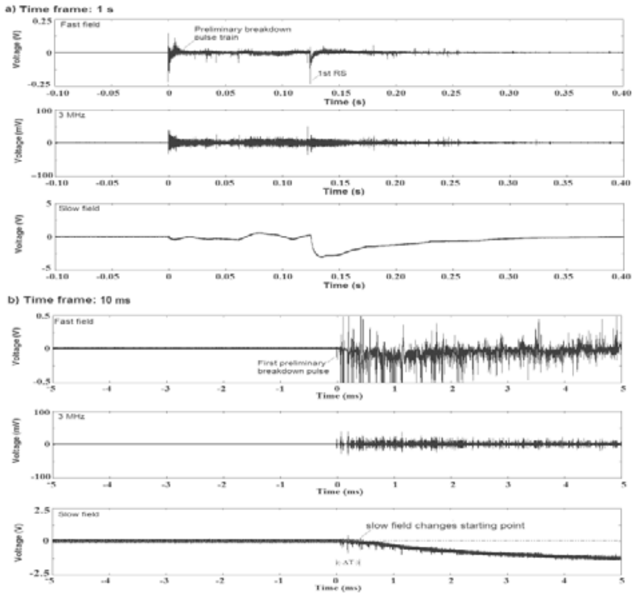


Figure 22. Minimum (A) and Maximum (B) pre-starting time (ΔT) from negative CG recorded in Sweden. Adapted from [6]

(A)



(B)

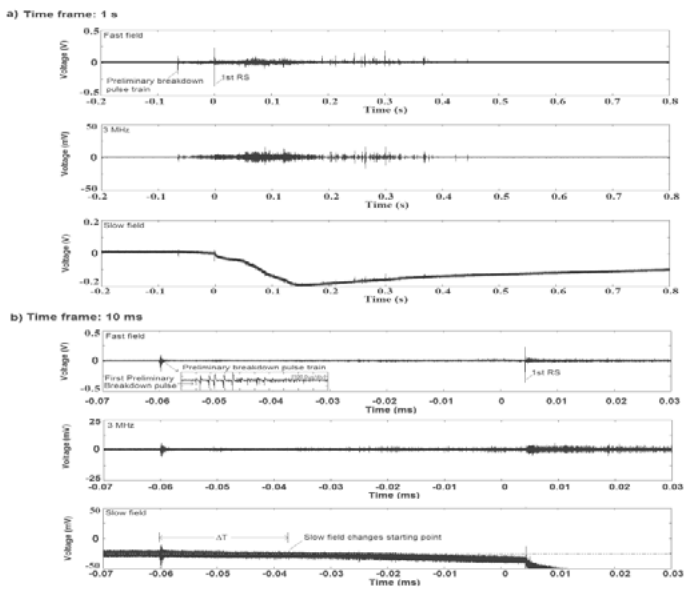


Figure 23. Minimum pre-starting time (ΔT) from positive CG recorded in Malaysia. Adapted from Paper 3.

Interestingly, the profile for the slow field changes in positive CG flashes also had similar findings to that of negative CG where the slow field changes do not start before the preliminary breakdown process. Figure 22 shows the features of the slow field changes generated by PBP for positive CG, which indicates that the pre-starting time ranged between 0.24 and 9.8 ms with the geometric mean of 1.8 ms.

A comparison of the data sets for Johor, Malaysia and Uppsala, Sweden reveals that the mean values (arithmetic and geometric) of the pre-starting time in Malaysia were three times higher than the mean values in Sweden (see Table 1, page 23 in Paper 3) for the negative ground flashes. On the one hand, the pre-starting time in Malaysia for negative ground flashes, which had a geometric mean of 3.36 ms, was about 1.9 times greater than the geometric value of positive ground flashes in Sweden. However, this value does not obviously differ from the negative ground flashes and the positive ground flashes at the same location.

Papers 2 and 3 investigated the correlation between the slow field changes and the distance of flashes (see Figure 7, in Paper 2 and Figure 5 in Paper 3). It was found that the pre-starting time had no correlation with the distance for either positive or negative ground flashes, which means that the beginning of the slow field changes was not influenced by the ground propagation.

The clear evidence mostly presented the selection of samples having a quiet mode of more than 100 ms duration prior to the first PBP. This means that there no evidence was found of activity either from ICs' activities or of man-made preceded PBP section. This fact allows conclusions to be drawn from the findings in Papers 2 and 3 to strengthen the suggestions made by Kitagawa and Brook[45] and other investigators[47,73,75,76] (whose reports regarding the long pre-RS field changes by more than 100 ms) where the IC flashes' activities have no connection to the ground ones.

Finally, it is important to state that the use of single-station electric field measurement provided a narrowband radiation field measurement and high resolutions of 12 bits transient recorder, recorded with several nanoseconds accuracy, provided the evidence for determining the position of the slow field changes. Further, from this evidence one is able to distinguish between the IC's activities and the preceding processes of ground flashes.

6 Statistical information for cloud-to-ground lightning flashes from the tropics to northern regions (papers 4 and 5)

From year to year, scientists allied to the study of atmospheric discharges have provided information about the basic variations of charge distributions from storm to storm that may affect the characteristics of cloud-to-ground lightning flashes (CG)[11,34,69,91,98]. These characteristics are related to the types of lightning (negative or positive), seasons, locations and storm types which, until recently, have been of interest to researchers for the purpose of weather forecasting, climatology and the design of lightning protection systems[13,26,81,98].

The work of Darveniza et al.[27] showed that the failure modes of surge-protective devices deployed in power systems depended on the number of strokes per flash and interstroke intervals. This study noted that the number of strokes per flash and the interstroke intervals were very important parameters to consider in coordinating the circuit breakers in power distribution systems. Furthermore, positive lightning flashes gave rise to larger currents and charge transfers compared to their more abundant counterpart, the negative ground flashes. The highest currents reported so far in the literature were from positive ground flashes. Thus, the extreme protection procedures recommended in lightning protection standards were based on the features of positive ground flashes.

The main objectives of the study presented here were to provide statistical information on negative and positive CG flashes by using "accurate-stroke-count" studies (classified by Rakov and Huffines[82]. The latter are based on two types of measurement techniques:

i. measurements based on the correlated electric field recording on the electric fields generated by the whole flash with high levels of temporal resolution. This technique was previously performed by Thomson[98] in Papua New Guinea, Cooray and Perez in Sweden[21], Cooray and Jayaratne in Sri Lanka[23], Heidler et al. in Germany[37,38],Qie et al.[74] in China, and Nag et al.[62] and Tottapalill et al.[99] in USA.

ii. a combination of (i) and high speed photographic records, as utilized by Kitagawa et al. in New Mexico[46], Saba et al.[83,84] and Miranda et al.[56] in Brazil, Rakov and Uman[78], Rakov et al.[79] and Fleenor et al. in USA[29].

A similar measuring technique (method and sampling) as that in type-i was utilized to reduce the differences in the results arising from the use of different measurement methods and sampling techniques by different investigators. Interestingly, the work in Paper 4 had reported on the occurrences of negative ground flashes in the proximity of the equator (1°N, 103°W), which appeared to be new information on the electromagnetic fields generated by whole flashes. Due to the scarcity of positive ground flashes, it is difficult to collect a large sample of electric fields generated by positive ground flashes. The work in Paper 5 concentrated on using the type-i field measurement technique in 2010 and 2011 to gather a significant number of positive RS electric fields so that statistically significant information on stroke characteristics could be gathered.

In this study, the number of stroke per flash, interstroke intervals and the amplitude distribution of the SRS were examined. The stroke per flash was analyzed to find the average, maximum multiplicity and the percentage occurrence of single flashes. The interstroke intervals were examined for time separation between strokes. The analysis of the amplitude distribution of SRS was done for the relative intensity of the first RS and SRS field peak. The approach adopted in Papers 4 and 5 is to form the ratio for individual SRS and then to find the resultant statistical distribution.

6.1 Negative Ground flashes (Paper 4)

The geometric and arithmetic means for the Malaysian dataset were 67.11 and 86 ms, respectively, from 405 interstroke intervals in the Malaysian data set. The statistical results for the intervals between two strokes were analyzed and described in Section 3.1 of Paper 4. Paper 4 stated that the statistical results for the interstroke intervals according to the stroke order were similar to the statistical results for the interstroke intervals from the total number of strokes. Note that the interstroke intervals from the total number of strokes did not depend on the stroke order.

Taking into account the 301 negative SRS, the geometric and arithmetic mean of the subsequent peak fields to that of the first RS peak field ratio was 0.60 and 0.73, respectively. Paper 4 stated that 38 % of the negative ground flashes for multiple strokes had at least one subsequent stroke with a peak electric field larger than the first RS. Furthermore, 19 % of the SRS had a peak electric field larger than those of the first RS. The mean number of strokes per flash was four, and 16 % of the flashes were single-stroke flashes.

Comparative studies of the observations made in Malaysia, New Mexico, Florida, Sweden, Sri Lanka, China, Austria and Brazil are summarized as follows: The geometric mean of the time interstroke intervals ranged from 46.6 to 67 ms. The ratio of the geometric mean for the electric field peak of the SRS to that of the electric field peak of the first RS varied between 0.42 and 0.60. The percentage occurrences for a single stroke per flash, the maximum multiplicity and the mean multiplicity varied from 14 to 39.8 %, 10 to 26, and 3.4 to 6.4, respectively. The multiple-stroke negative ground flashes having at least one SRS with a peak electric field larger than the first RS varied from 24 to 54 %. The SRS with a peak electric field larger than those of the first RS were found to range between 12.3 and 32 %. Finally, it was found that the results for the interstroke intervals, the amplitude distribution of the SRS and the number of strokes per flash in the tropics, subtropics and northern regions were similar.

6.2 Positive ground flashes (Paper 5)

The features of 107 successive positive CG flashes in Uppsala, Sweden obtained from 14 thunderstorms in 2010 and 2011, including the number of strokes per flash, the interstroke interval, and the relative magnitudes of the field peaks for the SRS and the first RS were examined. Paper 5 stated that the mean number of strokes per flash was 1.5, comprised of a total of 160 strokes with 63 % single-stroke, 28 % two strokes, 6 % three strokes, and 3% four strokes. Note that the mean number of strokes per flash in Sweden, Germany, Brazil and the United States was similar and ranged from 1.0 to 1.5. The geometric mean for the interstroke intervals of positive ground flashes was 70 ms, which appeared to be comparable to the interstroke intervals in the negative ground flashes. From 53 positive SRS, the ratio of the geometric and arithmetic means of the subsequent peak fields to those of the first RS peak field were 0.36 and 0.48, respectively, which was reasonably similar to the values for negative ground flashes. However, the percentage of negative ground flashes having at least one SRS with a peak electric field larger than the first RS was greater than the percentage of positive ground flashes, by a factor of approximately 5. Furthermore, the percentage of SRS with a peak electric field larger than the first RS in negative ground flashes was greater than the positive ground flashes by more than twice. In addition, Paper 5 revealed that a peak electric field of SRS larger than the first RS was a very rare occurrence in Sweden, as the number of SRS being larger than the first RS was very small.

7 Conclusion and recommendation

It is important to investigate the relationship between the amplitudes of the PBP pulse train and those of the corresponding first RS, especially to define the relationship of the characteristics of lightning as a function of geographical location, latitude and storm type. The results of Papers 1 and 4 have improved the knowledge of the association of LPCR and PBP trains with the occurrence of negative CG. Paper 1 found that stronger PBP trains appeared in the northern region and that this was followed by the subtropics, which suggested that the downward negative leaders from the main negative charge regions, especially at higher latitude locations, needed to have considerable energy to break the “blocking” agent created by LPCR in order to continue propagating to the ground. Some negative CG flashes with either a weak PBP strength or without the PBP signature may be caused by the insignificant magnitude of the LPCR (see type-D in Figure 17(d)). In this type of PBP train terminology, the preliminary breakdown process with low energy level between the negative charge region and the LPCR, especially in tropical countries that did not need to struggle to break the “blocking” agent in LPCR to extend the downward propagation to the ground. These features have been reported in Paper 4 where the majority of the count analyses for the strokes were associated with a PBP-train of type-D. In contrast, type-B (of long pre-first stroke duration) was considered in small samples and none of type-A (attempted leader) existed in tropical countries. The characteristics of the PBP train reported in Paper 1 are novel information, from observations made in Malaysia. The details of this work are described on pages 3 to 6, of Paper 1. In addition, Paper 1 provides a comprehensive data set used for the identification and selection of PBP trains in the data set. The important parameters of PBP trains included the classification of BIL terminology, the number of pulses in the train, the total pulse train duration, the interpulse interval and the individual pulse duration. Additionally, it was demonstrated that the use of a 12-bit transient recorder allowed one to solve an analysis that dealt with uncertainty and complexity of the profile of waveform as mentioned in Paper 1. The results showed that there were some differences in the PBP characteristics in Johor, Malaysia and Florida, USA.

The aim of improving the unclear features of the starting position of the slow field changes generated by the preliminary breakdown process in positive and negative ground flashes was successfully achieved. Papers 2 and 3 state that the slow field changes did not commence before the initial process of the preliminary breakdown. This study gave evidence that the use of single-station electric field measurements, complete with narrowband radiation field measurements and high resolutions of 12 bits transient recorder and recording with several nanoseconds accuracy, allowed one to distinguish between the ICs' activities and the preceding process of ground flashes. The distribution of the pre-starting times might have some tendency to be dependent on a certain thunderstorm event (thunderstorm on 15/05/2009 (Figure 7a) with a correlation of 0.72. It conveyed that the pre-starting time decreased as the distance of the flash increased. Moreover, the majority of events from the two data sets showed neither of the thunderstorm events had any consistency in the distribution either from storm to storm, or for each of the thunderstorm events. Nevertheless, the data set in Papers 2 and 3 is not sufficiently effective to signify the relationship between the pre-starting time and the thunderstorm event. Therefore, one would have needed a large data set for this relationship to have been better understood.

Studies of the occurrences of negative and positive ground flashes emphasized the importance of performing measurements with a similar measuring technique in order to reduce the variations in the results due to differing measurement methods and sampling techniques. The characteristics of the negative CG lightning flashes, which were related to the different locations, revealed that the results of interstroke intervals, amplitude distribution of SRS and the number of strokes per flash in the tropics, subtropics and northern regions were similar. The work in Paper 5 examines a significant number of positive RS electric fields, which produced statistically significant information on stroke characteristics of scientific value. However, certain features of the relative intensity of the SRS and the first RS in Austria and China were different from those in Sweden, Sri Lanka and Florida. The explanation of these features is presently unknown and further investigations are needed for clarification of these issues relating to the relative intensity of SRS and first RS.

Svensk sammanfattning

Denna avhandling skildrar ny information om moln-till-jord (”cloud-to-ground”, CG)-blixtar eller jordblixtar producerade av åskmoln. Den betonar vikten av att karakterisera blixtstudier som förhållandet mellan blixtmekanismer, och att inkludera påverkan av det geografiska läget, latituden och typ av storm. Sverige, Malaysia och USA valdes som de huvudsakliga platserna för fältexperiment för att insamla data från ett stort antal negativa och positiva CG-blixtar under åren mellan 2009 och 2011. Genom dessa fältexperiment samlades data på sammanlagt 1792 CG-blixtar (1685 negativa och 107 positiva) från totalt 53 olika åskväder genom att registrera både det långsamma och det snabba elektriska fältet samt smalbandstrålningen vid frekvenserna 3- och 30 MHz samtidigt. Denna avhandling består av: (i) förhållandet av den lilla positiva laddningsfickan i molnets bas (”Low Positive Charge Region”, LPCR) och det förberedande sammanbrottskedjor (”Preliminary Breakdown Pulse”, PBP) till uppkomsten av negativa CG, (ii) de långsamma elektriska fältförändringarna genererade av det förberedande sammanbrottsprocesser i positiva och negativa jordblixtar, och (iii) förekomsten av positiva och negativa jordblixtar. Det avslöjades att PBP-kedjorna visade sig ha en högre styrka i Sverige. Styrkan i PBP-kedjan orsakades av LPCR. Däremot var svaga-PBP-kedjor typiska i tropiska länder som innehar obetydliga LPCR och behöver mindre energi för att bryta den "blockerande" komponenten, vilket tillåter att blixten kommer nedåt mot marken. Det andra bidraget avser egenskaperna hos PBP-kedjan nämnd tidigare. Detta inkluderar ny information för Malaysia. Det anges vidare att egenskaperna gällande PBP-kedjor i Johor, Malaysia och i Florida, USA är olika i vissa avseendet. Studierna av de långsamma fältförändringarna genererade av det förberedande sammanbrottsprocesser klargör oklara kännetecken om startpositionen för de långsamma fältförändringarna genererade av det förberedande sammanbrottsprocesser i positiva och negativa jordblixtar. Det konstaterades att de långsamma fältförändringarna inte inträffar innan den första processen av inledandet av det förberedande sammanbrottet. Elektriska fältmätningar vid en mätstation, vilka även inkluderar mätningar av smalbandstrålningsfält, och fältregistrering med hjälp av en högupplöst transient mätinstrument (12 bitar) med en noggrannhet på flera nanosekunder gör det möjligt att skilja mellan elektriska aktiviteter i molnblixtar och de föregående processerna i jordblixtar. Resultaten för tidsintervallet mellan olika huvudurladdningar i blixten, amplituddistributionen av efterföljande huvudurladdningar och antalet urladdningar per blixt i tropikerna, subtropikerna och norra regionerna var likartade. Slutligen gav elektriska fälten från ett betydande antal positiva huvudurladdningar statistiskt signifikant information om vad som kännetecknar dessa urladdningar.

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“If you have good knowledge about lightning – electromagnetic field measurement and good skill for handling the transient recorder....then only you would get an excellent data”. I quote this special word from Dr. Fernando Mahendra who plays a big role for teaching me to become an expert in handling this measurement campaign. My special thank goes to Dr. Fernando for his spending moment with me during measurement campaign in Florida (2008, 2009), Malaysia (2009) and Sweden (2008, 2009).

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