UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Faculty of Electrical Engineering

INVESTIGATION OF WHOLE DURATION AND SUBMICROSECOND STRUCTURE OF UNCOMMON NEGATIVE CLOUD-TO-GROUND FLASH

Abdul Rahim bin Mohamed Ismail

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ABDUL RAHIM BIN MOHAMED ISMAIL

A thesis submitted
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2020

DECLARATION

I declare that this thesis entitled "Investigation of the Whole Duration and Sub-microsecond Structure of Uncommon Negative Cloud-to-Ground Flash" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : ....

Name : ABDUL RAHIM BIN MOHAMED ISMAIL

Date : Oktober 21, 2020

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Electrical Engineering.

Signature : ....

Supervisor Name : TS. DR. ZIKRI ABADI BIN BAHARUDIN

Date : Oktober 21, 2020

DEDICATION

To my beloved mother and father

ABSTRACT

This thesis potrayed analysis of uncommon negative cloud-to-ground flash by considering the whole duration of flashes which commonly were reported by majority of investigators to have less than 1 second. In order to get more understanding on these matters, the author attempted to identify and investigate the relationship of the fine structure of commencement (or also known as subsidiary peak) of the first return stroke with this uncommon profile. The subsidiary peak was suggested by the early investigator as current oscillation or by a reflection of a traveling wave in the return stroke just after its commencement. However, this subsidiary peak was not well understood in the scientific lightning study. This analysis is important as a scientific value for electromagnetic compatibility's community and lightning protection in designing a proper lightning detection system and lightning scheme protection. This thesis is also important in lightning study in order to comprehend the initiation process of lightning ground flashes. Therefore, two locations have been selected for the measurement. Both two locations are in Paya Rumput Perdana, Melaka and Faculty of Technology Engineering (Universiti Teknikal Malaysia Melaka). The electric fields generated by lightning negative ground flashes were measured. The data were measured with nanosecond resolution using the combination of flat plate antenna, fast electric field buffer and high-speed recorder (Yokogawa DL850E and HDO 4040 LeCroy). The total of 938 flashes which composed of 799 negative ground flashes, 26 positive ground flashes and 113 cloud flashes were analyzed in term of wideband radiation electric field (also known as fast electric field). From 51 out of 799 samples of negative ground flashes were considered rare where the duration of the flashes was uncommon case (6 %) which had the duration of more than 1 second. Furthermore, the number of strokes varies from 4 to 19 strokes. Next, the subsidiary peaks of 50 of uncommon samples were analyzed by using the terminology that has been introduced by Krider (1980). It was consistently shown the existence of small second peak or alpha (α) for all samples followed by several larger subsidiary peaks (a peak, b peak and c peak). Interestingly, this thesis reported the finding of new features of subsidiary peaks which have more than 5 larger of subsidiary peak. Statistically, all the features of alpha and other larger peaks were discussed in this thesis. From the first contribution of the thesis was found that the numbers of subsidiary peaks are depending on the duration of zero crossing. In addition, the secondary new contribution was found that the subsidiary peak is related with the number of the production of the return stroke. However, the higher numbers of subsidiary peak have no correlation with uncommon duration (more than 1 second).

PENYIASATAN TERHADAP TEMPOH KESELURUHAN DAN STRUKTUR SUB-MIKROSAAT BAGI KILAT NEGATIF AWAN-KE-BUMI YANG TIDAK LAZIM

ABSTRAK

Tesis ini memaparkan analisa kilat negatif awan-ke-bumi yang bukan lazim dengan mempertimbangkan keseluruhan tempoh kilat. Secara lazimnya, majoriti penyelidik melaporkan tempoh keseluruhan kilat ialah kurang daripada 1 saat. Untuk mengetahui dan memahami perkara ini, penulis cuba mengenalpasti dan menyiasat hubungan di antara struktur halus permulaan penurunan panahan balik (atau juga dikenali sebagai puncak subsidari) dengan bilangan keseluruhan panahan balik bagi sesuatu peristiwa kilat. Puncak subsidari dicadangkan oleh penyiasat yang terdahulu sebagai ayunan arus atau refleksi perjalanan gelombang bagi suatu penurunan isyarat panahan balik. Walau bagaimanapun, puncak subsidari ini masih tidak difahami dengan baik dalam kajian kilat secara saintifik. Analisis ini penting sebagai satu nilai saintifik bagi komuniti keserasian elektromagnetik dan perlindungan kilat dalam merekabentuk sistem pengesanan kilat yang betul. Tesis ini juga penting dalam kajian petir untuk memahami proses permulaan kilat petir. Oleh itu, dua lokasi telah dipilih untuk mengkaji medan elektrik yang dihasilkan oleh kilat awan-ke-bumi iaitu di Paya Rumput Perdana, Melaka dan Fakulti Teknologi Kejuruteraan (Universiti Teknikal Malaysia Melaka, UTeM) yang diukur dengan resolusi nanosaat dengan menggunakan gabungan antena plat rata, penimbal medan elektrik laju dan perakam kelajuan tinggi (Yokogawa DL850E dan HDO 4040 LeCroy). Sebanyak 938 kilat yang terdiri daripada 799 kilat negatif awan-ke-bumi, 26 kilat positif awan-ke-bumi dan 113 kilat di dalam awan dianalisis dalam bentuk radiasi medan elektrik berjalur lebar (atau dikenali sebagai medan elektrik laju). 51 daripada 799 sampel kilat negatif awan ke-bumi dianggap jarang berlaku di mana tempoh kilat tersebut adalah kes yang tidak lazim (6%) yang mempunyai tempoh lebih daripada 1 saat. Selain itu, bilangan panahan balik dalam satu peristiwa kilat mempunyai julat dari 4 hingga 19. Seterusnya sebanyak 50 sampel yang tidak lazim telah dianalisa sifat puncak subsidiari dengan menggunakan istilah yang telah diperkenalkan oleh Krider (1980). Ia secara konsisten menunjukkan kemunculan puncak kecil atau alpha (a) untuk semua sampel diikuti oleh pemisahan puncak subsidari yang lebih besar (puncak a, puncak b dan puncak c). Tesis ini melaporkan penemuan ciri-ciri baru puncak subsidiari yang mempunyai lebih daripada 5 puncak subsidiari yang lebih tinggi. Secara statistik, semua ciri alpha dan puncak besar yang lain dibincangkan dalam tesis ini. Hasil sumbangan utama tesis ini mendapati bahawa lintasan sifar adalah berkadaran secara terus dengan puncak subsidiari. Tambahan pula, hasil daripada sumbangan kajian kedua mendapati bahawa jumlah penghasilan bidang panahan balik bergantung kepada puncak subsidiari dalam sesuatu peristiwa kilat. Walau bagaimanapun, bilangan puncak subsidiari yang lebih tinggi tidak mempunyai kaitan dengan kes yang tidak lazim (tempoh melebihi 1 saat).

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LIST OF ABBREVIATIONS

AFCRC	-	Air Force Cambridge Research Center
ArcGis	-	Aeronautical Reconnaisance Coverage Geographic Information System
B-Field	-	Magnetic Field
BIL	-	(B: Breakdown, I: Intermediate, L: Leader)
BrasilDAT	-	Brazilian Total Lightning Network
CC	-	Cloud-to-Cloud
CG	-	Cloud-to-Ground
DSP	-	Digital Signal Processor
DTOA	-	Different Time of Arrival
E-Field	-	Electric Field
EMC	-	Electromagnetic Compatibility
ENLS	-	Earth Network Lightning Sensors
F	-	Slow Front
FWHMS	-	Full-Width at Half-Maximum
GPS	-	Global Positioning Sytem
HF	-	High Frequency
IB	-	Inter-Breakdown
IC	-	Intracloud
IEC	-	Initial Electric Field Change
L	-	Stepped Leader
LDS	-	Ligthning Detection System
LEMP	-	Lightning Electromagnetic Pulse

LF - Low Frequency

LLS - Lightning Location System

LPCC - Lower Positive Charge Center

LPCR - Low Positive Charge Region (*p*)

MCS - Mesoscale Convective System

MDF - Magnetic Drection Finder

MSE - Multi-Station Experiment

N - Negative Charge Region

N_g - Lightning ground flash density

NBEs - Narrow Bipolar Events

NBPs - Narrow Bipolar Pulses

NNBP - Narrow Negative Bipolar Pulse

NPBP - Narrow Positive Bipolar Pulse

P - Positive Charge Uppermost Region

PB - Preliminary Breakdown

PBP - Preliminary Breakdown Pulse

RS - Return Stroke

SHATLE - SHandong Artificially Triggered Lightning Experiment

SRS - Subsequent Return Stroke

TLM - Transmission Line Model

TLF - Triggered Lightning Flash

TOA - Time of Arrival

VHF - Very High Frequency

VLF - Very Low Frequency

WWLLN - World Wide Lightning Location Network

LIST OF SYMBOLS

dB/dt	-	Magnetic Field Derivative
dE/dt	-	Electric Field Derivative
dI/dt	-	Current Derivative
Hz	-	Hertz
kHz	-	Kilo Hertz
km	-	Kilometer
m	-	Meter
MHz	-	Mega Hertz
ms	-	Millisecond
ms/div	-	Milliseond/division
m/s	-	Meter/second
MS/s	-	Mega sample/ second
mV	-	Millivolt
ns	-	Nanosecond
pF	-	Pico Farad
s	-	second
μH	-	Micro Tesla
μs	-	Microsecond
μs/div	-	Microsecond/division
V	-	Volt
V/m	-	Volt/meter
Ω	-	Ohm

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CHAPTER 1

INTRODUCTION

Lightning is a transient, high current electric discharge whose path length is measured in kilometres. The most common source of lightning is the electric discharge separated in ordinary thunderstorm clouds (cumulonimbus). Well over half of all lightning discharges occur within the cloud (intracloud discharges, IC). Cloud-to-ground, CG lightning has been studied more extensively than other forms because of its practical interest such as the cause of human injuries and death, disturbances in power and communication systems and the ignition of forest fires. Cloud-to-cloud and cloud-to-air discharges are less common than intracloud or cloud-to-ground lightning (Uman 1982).

The phenomenon of lightning has been the subject of intensive studies by electrical and electronic engineers as well as researchers all around the world. In principle, the behaviors of lightning are consistently able to be predicted. However, the exact physical description of the 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. In addition, as there is no certainty of evidence that lightning could be prevented. Therefore, one must recognize the possibility of a lightning strike with appropriate measures to ensure that the accuracy of lightning location and the parameters are presented to implement lightning protection system in proper action.

Many of the characteristics of lightning flashes, such as the 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 work for electrical and electronic engineers as well as researchers. This is because the knowledge obtained significantly improves the investigator's 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.

1.1 Background

In general, the negative CG lightning flash may consist of a single stroke or several strokes. Each stroke involves a combination of a downward leader and an upward return stroke, or better known as the leader-return-stroke sequence. In a leader return-stroke sequence, the negative charge is lowered from the cloud by the leader process; creating a conductive path between the cloud charge source and the ground. The following return-stroke rapidly neutralizes the negative charge which traverses in that path by moving from the ground towards the cloud charge source. Cooray (2014) stated the overall discharge, termed a flash, is composed of a number of processes such as preliminary breakdown, stepped leaders, connecting leaders, return strokes, dart leaders and subsequent return strokes.

Consequently, the basic variations of charge distributions of storm to storm may affect the characteristics of the negative cloud-to-ground lightning flashes, such as the number of strokes per flash and inter-stroke intervals (time separation between strokes). Furthermore, these characteristics combined with the relationship between the season, location and storm type, are beginning to be of interest to researchers for the purpose of weather forecast, climatology and the designing of lightning protection systems. Darveniza et al. (1997) showed that the failure modes of surge-protective devices deployed in power systems depend on the number of strokes per flash and interstroke intervals. This study notes that the number of strokes per flash and the interstroke intervals are very important parameters to consider in coordinating the circuit breakers in power distribution systems.

The experimental data relating to return strokes can be arbitrarily devided into four categories: (i) electric and magnetic fields, (ii) current, (iii) speed and (iv) luminosity and optical spectra. Return stroke variations on millisecond or as sub-microsecond structure time scale have been published since 1962 to 2016 (Brook et al. 1962, Kitagawa et al. 1962, Krehbiel et al. 1979, Lin et al. 1979, Cooray and Lundquist 1985, Master et al. 1984, Thottappillil et al. 1992, Cooray and Perez 1994, Rakov and Huffines 2003, Baharudin et al. 2014, and Wooi et al. 2016). The electric fields on this time scale have been used in purpose of coordinating the lightning standard parameters for lightning and protection; determine the magnitude and location of charge lowered to earth by individual or multiple strokes as well as to determine values for millisecond scale channel currents. Table 1.1 summarized extensive statistical data for the characteristics of the overall return stroke parameters that have been reported by the investigators since the year as mentioned above.

Table 1.1 Statistical of return stroke vertical electric field from stroke lowering negative charge to earth

Parameters	First Return Stroke			Subsequent Return Stroke		
	Number of Return Stroke	Mean	Standard Deviation	Number of Return Stroke	Mean	Standard Deviation
Initial Peak, Normalized to 100 km (V/m)						
Master et al. (1984)	112	6.2	3.4	237	3.8	2.2
Krider and Guo (1983)	69	11.2	5.6	84	4.6	2.6
Cooray and Lundquist (1982)	553	5.3	2.7	-	-	-
Lin et al. (1979)	51	6.7	3.8	83	5.0	2.2
Zero Crossing time (μsec)						
Lin and Uman (1979)	46	54	18	77	36	17
Cooray and Lundquist (1985a)-Sweden	102	49	12	94	39	8
Cooray and Lundquist (1985b)-Sri Lanka	91	89	30	143	42	14
Zero-to-peak rise time (μsec)						
Master et al. (1984)	105	4.4	1.8	220	2.8	1.5
Cooray and Lundquist (1982)	140	7.0	2.0	-	-	-
Lin et al. (1979)	51	2.4	1.2	83	1.5	0.8
10 – 90 % rise time (μsec)						
Master et al. (1984)	105	2.6	1.2	220	1.5	0.9
Slow Front duration (μsec)						
Master et al. (1984)	105	2.9	1.3	-	-	-
Cooray and Lundquist (1982)	82	5.0	2.0	-	-	-
Cooray and Lundquist (1985)	104	4.6	1.5	-	-	-
Weidman and Krider (1978)	62	4.0	1.7	44	0.9	0.5
Slow Front, amplitude as percentage of peak						
Master et al. (1984)	105	28	15			
Cooray and Lundquist (1982)	83	40	11			
Cooray and Lundquist (1985)	108	44	10	44	0.6	0.2
Weidman and Krider (1978)	62	52	20	120	0.9	0.5
Fast Transition , 10-90 % rise time (nsec)						
Master et al. (1984)	108	970	680	217	610	270
Weidman and Krider (1978)	38	200	100	80	200	40
Weidman and Krider (1980, 1984)	125	90	40	-	-	-

From Table 1.1, the mean of the electric field initial peak value of the return stroke normalized to 100 km is generally found to be in the range 6 – 8 V/m for first return stroke and 4 – 6 V/m for subsequent stroke. Higher observed mean values may be an indication of the fact that small strokes were not observed due to an equipment threshold trigger level that was too high. However, Peckham et al. (1984) have reported experimentally that for the fix threshold value characteristic of their equipment, the mean of the normalized initial peak field increased with the distance from about 7 V/m in the 25 to 75 km range and to about 9 V/m in the 100 to 150 km range because at the greater ranges, more of the smaller fields fell below the threshold and were lost from the distribution. On the other hand, some compensation for this effect is caused by the fact that distant waveforms that propagate over poorly conducting ground will have their peak fields attenuated due to propagation over a non-perfectly conduction surface.

The zero-crossing time for the first return strokes as listed in Table 1.1 in general found to have mean value ranging from 54 to 89 μsec while the subsequent return stroke ranging between 36 to 42 μsec. Cooray and Lundquist (1985) suggest that the meteorological conditions may attribute the value in different locations. The subsequent stroke zero-crossing times were similar for three locations (see Table 1.1).

In addition, the return strokes have a slow front that rises in a few microseconds to an appreciable fraction of the peak field magnitude. Master at al. (1984) found a mean slow front duration of 2.9 μsec with about 30 % of the initial peak of the return stroke. On the other hand, Cooray and Lundquist (1982, 1985) reported that the corresponding values of about 5 μsec and 40 %. Weidman and Krider (1978) found that the mean of slow front duration of about 4 μsec with 40 to 50 % of the initial peak field peak attributable to the slow front. The slow front is followed by a fast transition to peak field with 10 to 90 % rise time of about 200 nsec when the field propagation path is over salt water. Weidman and

Krider (1980, 1984) presented a mean rise time of 90 nsec with a standard deviation of 40 nsec for 125 of first return strokes.

Overall, according to the summary by Rakov and Uman (2003), transportation of negative charge to earth was thought to have 90 % of global cloud-to-ground flashes. The return stroke that lowers negative charge to earth Uman (1987) has been the most researched and consequently, is the best understood of all the processes that make up flash to earth. Scientifically, it has been proven that the return stroke current contribute damage attributable to the electrical system as well as tall structures. Interestingly, most of all the process of cloud-to-ground lightning flashes comparing the return stroke and itself are most easily to measure. Indeed, the return stroke is optically brightest lightning process visible outside the cloud, and it produces the most readily identifiable electromagnetic signature.

1.2 Problem statement

In principle, the characteristics of the negative cloud-to-ground lightning flashes, as reported by the majority of the investigators or as mentioned in Background Section (Section 1.1), utilized "accurate-stroke-count" for the measurements which based on the correlated electric field recording on the electric fields generated by the whole flash with high levels of temporal resolution analysis. The definition of the whole flash commonly was taken within one second duration. However, based on measurement that has been carried out by Baharudin et al. (2018) found that there were some flash events to have few numbers of return strokes after one second. These profiles were considered as a rare or uncommon negative cloud-to-ground flash. Therefore, in order to get more understanding on these matters, the author attempted to identify and investigate the whole flash within two second (which is uncommon). In addition to this attempt, the author tries to fine the relationship between the uncommon whole flash with the fine structure of commencement (or also known as subsidiary peak) of the first return stroke with this uncommon profile. The subsidiary peak was suggested by the early investigator as current oscillation or by a reflection of a traveling wave in the return stroke just after its commencement. However, this subsidiary peak was not well understood in the scientific lightning study. This analysis is important as a scientific value for electromagnetic compatibility's community and lightning protection in designing a proper lightning detection system and lightning scheme protection.

1.3 Objectives of research

The objectives:

(a) To analyze the uncommon of whole duration for negative cloud-to-ground lightning in tropic region.

(b) To investigate the characteristics sub-microsecond structure of negative cloud-to-ground lightning.

(c) To evaluate the relationship of uncommon whole flash with sub-microsecond structures.

1.4 Motivation of research

The shapes of the electric and magnetic fields produced by the stepped and dart-stepped leader processes which immediately precede return strokes in lightning discharges to ground have been discussed in two previous papers by Weidman and Krider (1978, 1980). As the stepped leader nears the ground, the electric field at the surface becomes very large, and usually one or more upward propagating discharges are initiated which rise and join the leader channel at a point a few tens of meters above the surface (Uman, 1982).