TEMPORAL ANALYSIS OF MICROWAVE RADIATION EMITTED BY STEPPED LEADERS OF A CLOUD-TO-GROUND FLASH

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ABSTRACT: Lightning emits electromagnetic waves at various frequency spectrum band. In this paper, we report observational study of microwave radiation emitted by lightning. The lightning measurement is conducted by using an air-gap parallel plate antenna that resonate at around 1 GHz with a bandwidth of 20 MHz. The recorded microwave radiation waveform is analyzed based on the waveform of Fast E-field Antenna (FA). Although the stepped leader (SL) discharge process radiates well at microwave radiation, there is a higher microwave radiation preceded the stepped leader which is identified as Quiet Period, (QP). The average duration of QP is 3.707 μs while the average duration of SLs recorded is 2.883 μs. The percentage ratio of the peak amplitudes of the microwave bursts during QP is between 34.3% and 49.5% larger than the amplitude of the microwave bursts during SLs. Microwave radiation is seen to initiate the stepped leader process as the largest amplitudes of microwave burst is recorded during the QP. The characteristics

of the microwave waveforms of SL and QP are observed to be oscillating individual pulses but the peak amplitudes of the microwave radiation bursts during the QP are larger than during SLs.

KEYWORDS: *Cloud-To-Ground Flash; Lightning; Microwave Radiation*

1.0 INTRODUCTION

Research about radio frequencies (RF) have turned out to be one of the important topics in lightning field. Various lightning discharges process radiate well at microwave radiation. Based on theoretical modelling in [1], they reported that electron avalanche which is the key procedure of electrical discharges process produced significant radiation in microwave band that peaked around 1 GHz. Note that electron avalanche is the beginning stage in electrical breakdown process which initiates the lightning process.

Previously, as in [2], reported that observations of microwave radiation at 0.4 GHz and 0.85 GHz. They used helical antennas with a bandwidth of 200 kHz. At these frequencies, they observed strong microwave radiation accompanied with the negative stepped leaders, dart leaders, return stroke, K changes, and cloud flashes (ICs). The IC activities were recorded to emit stronger microwave radiation than cloud-to-ground flash (CG) activities. Slow and fast field that they used has 70 μsec and 12 sec decay time constant respectively. In order to measure accordingly all frequency ranges, they constructed two helical antennae and successfully observe a strong impulsive radiation with pulses that can be noticed easily which appeared before the stepped leader process. Despite the matter that dart leaders were likewise observed to radiate very strong, yet they frequently covered with other signals and noises causes hard to extinguish between the pulses. Return strokes were also found to radiate strongly but it is not continuous. The IC discharge activity has also been observed to emit radiation, but the radiation is seen to emit more strongly than what was measured during CG discharge. The authors did not manage to distinguish on the individual pulses even though they managed to discover all these findings due to the limitations of previous technology on the instruments and equipment. Besides, the duration of the pulses captured is short which indicated that lightning activities before and after the captured signals duration failed to be observed.

Reference [3] recorded the observation at 0.4 GHz, 0.7 GHz, and 0.9 GHz by using vertically polarized omnidirectional dipole antennas with a 1 MHz bandwidth. They observed noise-like bursts of radiation with the durations from a few hundreds of microseconds up to 10ms. They could not decide the source of Ultra High Frequency (UHF) radiation although they detected a radiation at 1.3 GHz, but the data was unsatisfactory for analysis.

Later, as shown in [4], reported that microwave radiations at 2.2 GHz associated with CG and IC using high gain parabolic antenna. They observed a significant burst of impulsive activities during preliminary breakdown process (PBP), stepped leaders, K changes, dart leaders, and initial return strokes. In general, the burst occurred several tens of milliseconds during the preliminary breakdown and lasts between 5 and 10 ms. The steerable parabolic antenna is 7.3 m in diameter, having a half-power beamwidth of 1.4° and a gain 42 dB at 2.2 GHz. Two linearly polarized feeds of the antennas which were orthogonal to each other at 45° were connected to the radiometer and the receiver each separately. Signal were recorded on analog magnetic tape with tape speed of 152 cm/s and frequency response of 400 to 300 kHz. The captured signals were presented into a four-channels transient waveform analyzer (Biomation Model 1015) and photographing an x-y oscillograph display.

The latest study recorded in [5], author measured lightning radiation at 1.63 GHz with a 2 MHz bandwidth using circularly polarized ceramic patch antenna. They found microwave radiation occurred during preliminary breakdown, negative stepped leader breakdown, negative dart leader breakdown and return strokes. The microwave impulses from preliminary breakdown, negative stepped leaders and impulsive dart leader are shown to be trains of individually resolvable impulses while return strokes were observed to generate higher amplitude impulses with continuous burst-noise like bursts. They compared their accumulated data with data from Oklahoma Lightning Mapping Array (OLMA) lightning mapping system and co-located Earth Networks Total Lightning Network (ENTLN) broadband electric field antenna that enables distinctive microwave radiation signatures for different lightning discharge processes to be identified. After reviewing all these papers, it is asserted that many lightning discharge process radiates at microwave radiation band. The frequency bandwidth of receivers used were at 2 MHz and below. Note that such small bandwidth limits the time resolution of impulse width which restrict the observation of impulses that have less width.

After reviewing previous study about microwave measurement, only few that use receiver with bandwidth more than 2 MHz. The time accuracy of the data presented also until microseconds only. Thus, in this paper, we motivated to use a wider frequency bandwidth of antenna to capture high resolution individual impulses which has time accuracy within picoseconds scale with total window time captured of 5 ms. Based on the findings in [5], they briefly observed the characteristic of microwave radiation during stepped leader which is individually resolvable impulses. Thus, we are determined to observe the same characteristic of microwave impulses but with additional temporal analysis of the stepped leader from the Fast E-field Antenna (FA) records. Stepped leaders are found to radiate a noisy individually impulses in microwave band too but, we later found a higher amplitude of oscillating microwave bursts during quiet period, (QP) that preceded the stepped leader impulse. The QP could be seen as initiating the stepped leader process. This experiment was conducted by using air-gap parallel plate antenna that act as remote sensing application which resonate at 1 GHz with 20 MHz bandwidth.

2.0 METHODOLOGY

The apparatus consisted of four air-gap parallel plate antennae which are FA, Very High Frequency (VHF) antenna, finite-length antenna for UHF and one derivative electric field system [6]. To ensure all the antennae are at the same height, they are placed on the same size of plastic chairs. The distance of the antennae from the grounds must be uniformed so that the electromagnetic radiation waves beam on the antennae at the same time. For FA system, 60 cm cable wire was connected to its buffer circuit while for VHF and microwave antennae, both were connected to their respective Low Noise Antenna (LNA) and bandpass filter which is between 50-70 MHz for VHF and between 800-1050 MHz for microwave. Then, the FA buffer circuit, LNAs and bandpass filters were connected to the oscilloscope (LeCroy Wavesurfer 3054) to be sampled with the sampling rate of 2 GS/s and the input signal waveforms were saved in 5 ms time length.

The length of cable used for FA and VHF was 10 m while length of cables used for derivative electric field and microwave were 2 m and 5 m, respectively. Next, the cables were linked to channels A, B, C and D for FA, VHF, microwave and derivative electric field, respectively. The measurement system was setup on the rooftop of Pascasiswazah Lab I, in Faculty of Electronics Engineering and Computer Engineering (FKEKK), UTeM, Durian Tunggal, Melaka, Malaysia (2.314077° N,

102.318282° E). The parameter lists of finite-length antenna is shown in Table 1. The visual diagram of the measurement setup is shown in Figure 1.

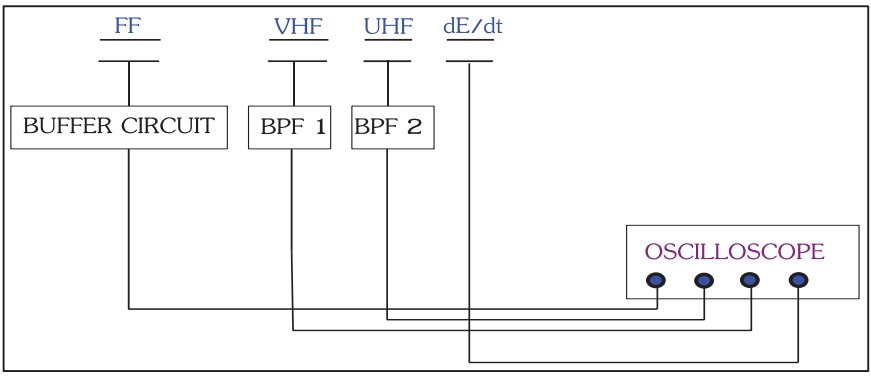

Figure 1: Visual diagram of the measurement setup

Table 1: Parameters list of the finite-length antenna

Parameter	Description	Dimensions Values
Lf	FR-4 length	420mm
Wf	FR-4 width	297mm
tf	Thickness of FR-4	1.6mm
tCu	Thickness of copper	0.0035mm
Lt	Top plate copper length	300mm
Wt	Top plate copper width	297mm
Lg	Bottom plate copper	420mm
Wg	Bottom plate copper	297mm
d	height of air gap	16mm

3.0 RESULTS AND DISCUSSION

3.1 Characterization of Stepped Leader from Fast Antenna Waveform

The onset time and period of three stepped leaders before the first return strokes are recorded. The onset time is regulated according to the noise level. The noise level is the black-coloured horizontal lines along the x-axis. The onset time, end time, onset of peak amplitude and its peak amplitude for three stepped leaders are recorded as in Table 2.

Figure 2 shows FA and microwave plots of a negative cloud-to-ground flash (-CG) on 17th December 2018 at 19:06:02 MYT recorded by our lightning measurement system while the magnified view of stepped leader and QP is shown in Figure 3. The duration of 1st stepped leaders is 1.823 μs which is the period from the end time of 1st QP to the onset

time of 1st return stroke while the duration of 2nd stepped leader is 2.922 μs which is the period from the end time of 2nd QP to the onset time of 1st QP and lastly the duration of 3rd stepped leader is 3.904 μs which is the period from the end time of 3rd QP to the onset time of 2nd QP. The QP is identified as a period between two stepped leaders. For example, the duration of the 1st QP is from the end time of 2nd stepped leader to the onset time of 1st stepped leader. The duration of QPs are 3.173 μs, 3.202μs and 4.745μs for 1st QP, 2nd QP and 3rd QP, respectively. All the results are tabulated in Table 3. The mean duration of stepped leader is 2.883 μs while the mean duration of quiet period, which preceded the stepped leader, is 3.707 μs. The equations to calculate the duration of stepped leader (SL) and QP can be written as follows:

$$\text{Duration of SL(s)} = \text{end time(s)} - \text{onset time(s)} \quad (1)$$

$$\text{Duration of QP} = \text{onset time of SL(n)} - \text{end time of SL(n + 1)} \quad (2)$$

Table 2: Temporal analysis of 3 stepped leaders from FA record

FA record	Onset (s)	End (s)	Onset of Peak Amplitude (s)	Peak Amplitude (V)
1st stepped leader	0.003436212	0.003438035	0.003437	0.231
2nd stepped leader	0.003430117	0.003433039	0.003431408	0.232
3rd stepped leader	0.003423012	0.003426916	0.003424788	0.198

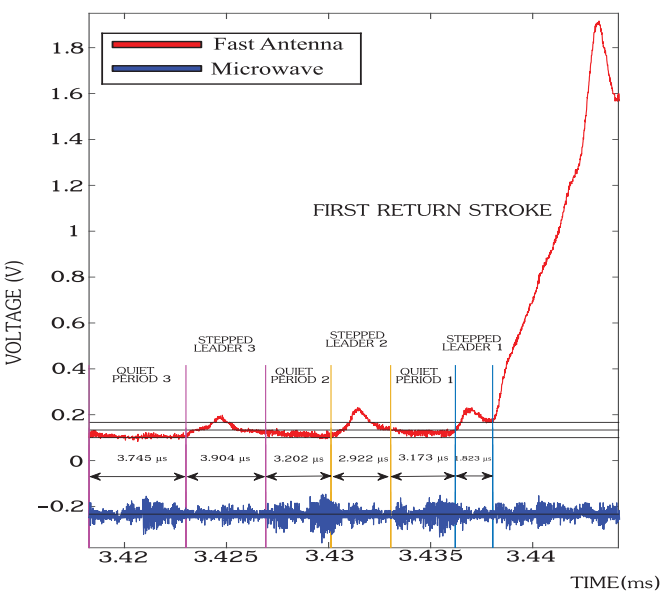

Figure 2: Waveform of stepped leaders and quiet periods captured on 17th December 2018 at 19:06:02 MYT where FA (red) and microwave (blue)

Table 3: Duration of the stepped leaders and quiet period

Stepped leader	Duration (s)	Quiet period	Duration (s)
1st stepped leader	1.823E-06	1st quiet period	3.173E-06
2nd stepped leader	2.922E-06	2nd quiet period	3.202E-06
3rd stepped leader	3.904E-06	3rd quiet period	4.745E-06
Mean	2.883E-06	Mean	3.707E-06

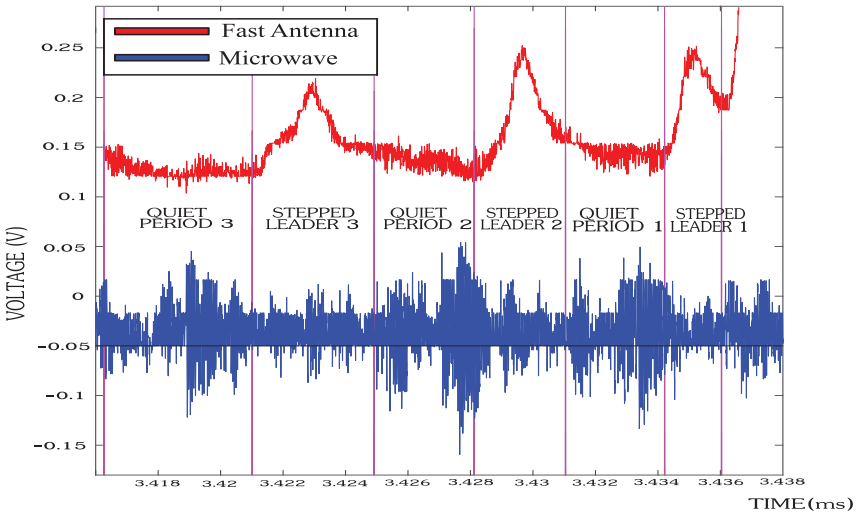

Figure 3: Magnified view of stepped leaders and quiet periods of –CG captured on 17th December 2018 at 19:06:02 MYT where FA (red) and microwave (blue)

The rise time and decay time for 1st, 2nd and 3rd stepped leaders are 0.7725 μs, 1.291 μs, 1.7755 μs and 1.051 μs, 1.631 μs, 2.128 μs respectively. Table 4 shows the tabulated results for the rise time and decay time of the stepped leaders. The equations to calculate the rise time and decay time are as follow:

$$\text{Rise time} = \text{onset peak amplitude(s)} - \text{onset time(s)} \quad (3)$$

$$\text{Decay time} = \text{end time(s)} - \text{onset peak amplitude(s)} \quad (4)$$

Table 4: Characterization of stepped leaders by determining the rise time and decay time

FA record	Rise Time (s)	Decay time (s)
1st stepped leader	7.725E-07	1.051E-06
2nd stepped leader	1.291E-06	1.631E-06
3rd stepped leader	1.7755E-06	2.128E-06

3.2 Amplitude of Microwave Burst for Stepped Leaders and Quiet Periods

It is observed that there are more than one bursts of microwave radiation during stepped leaders and QPs. The characterization of the microwave bursts is demonstrated in Figure 4 and Figure 5.

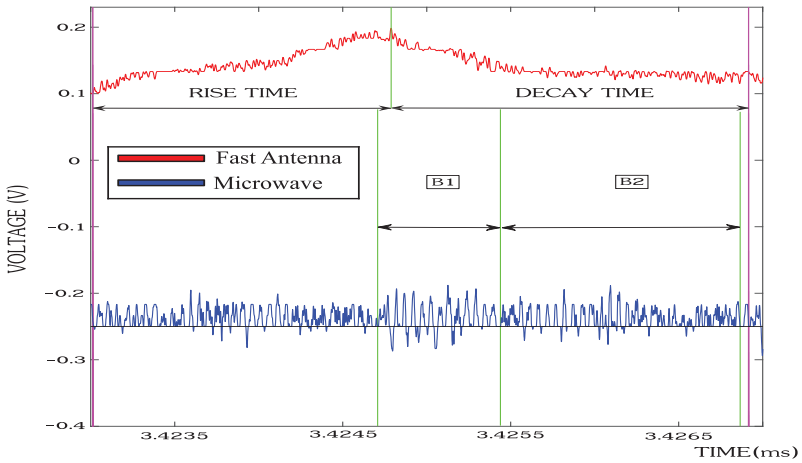

Figure 4: Example of determining microwave radiation burst during stepped leader of –CG captured on 17th December 2018 at 19:06:02 MYT where FA (red) and microwave (blue)

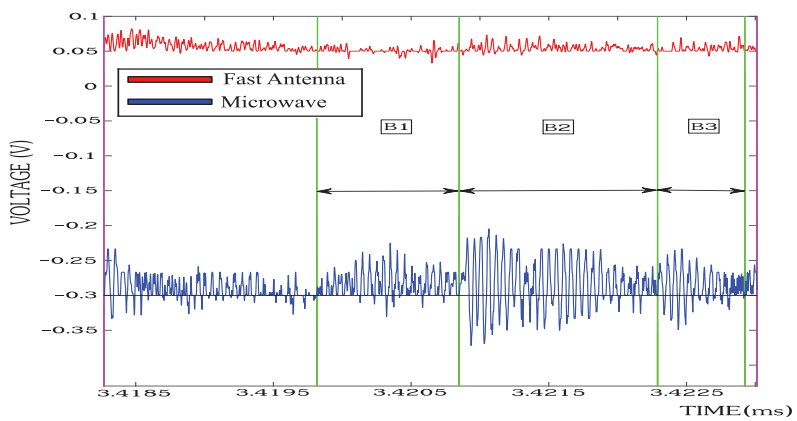

Figure 5: Example of determining microwave radiation burst during QP of –CG flash captured on 17th December 2018 at 19:06:02 MYT where FA (red) and microwave (blue)

The amplitude of microwave bursts 1 and 2 during 1st stepped leader and during 1st QP are 0.065 V, 0.050 V and 0.088 V, 0.099 V, respectively. During 2nd stepped leader, only one microwave burst could be observed, which its amplitude is 0.067 V while the amplitude of

microwave bursts 1 and 2 during 2nd QP are 0.074 V and 0.104 V respectively. The amplitude of microwave bursts 1 and 2 during 3rd stepped leader is 0.062 V and 0.061 V respectively while during 3rd QP, there are three microwave bursts that were recorded which are 0.075 V, 0.095 V and 0.067 V for microwave bursts 1, 2 and 3, respectively. All the records are tabulated in Table 5. The percentage ratio of amplitude of microwave radiation burst during stepped leaders correspond to the peak amplitude of microwave radiation during QP is calculated. The peak amplitude of microwave bursts during 1st QP is larger than the amplitude of microwave burst during the 1st stepped leader by 34.3% and 49.5% for burst 1 and 2 respectively while the peak amplitude of microwave burst during 2nd QP is larger by 35.6% than the amplitude of microwave burst during the 2nd stepped leader. The peak amplitude of microwave burst during 3rd QP is larger than the amplitude of microwave burst during 3rd stepped leader by 34.7% and 35.8% for burst 1 and 2 respectively. All this information is tabulated in Table 6.

Table 5: Amplitudes of microwave radiation bursts for stepped leader and quiet period

Points	Stepped Leader 1 (V)	Quiet Period 1 (V)	Stepped Leader 2 (V)	Quiet Period 2 (V)	Stepped Leader 3 (V)	Quiet Period 3 (V)
B1	0.065	0.088	0.067	0.074	0.062	0.075
B2	0.050	**0.099**	-	**0.104**	0.061	**0.095**
B3	-	-	-	-	-	0.067

Table 6: Percentage ratio of amplitude of microwave radiation bursts during stepped leaders correspond to the peak amplitude of microwave radiation during QP

Points	Stepped leader 1	Stepped leader 2	Stepped leader 3
B1	$(1-\frac{0.065}{0.099})\times 100\% = 34.3\%$	$(1-\frac{0.067}{0.104})\times 100\% = 35.6\%$	$(1-\frac{0.062}{0.095})\times 100\% = 34.7\%$
B2	$(1-\frac{0.050}{0.099})\times 100\% = 49.5\%$	-	$(1-\frac{0.061}{0.095})\times 100\% = 35.8\%$

3.3 Discussion

Electrical breakdown is the process that initiates lightning leader (hot conducting electrical channel) [7-8]. Previously, as in [9], author managed to record a pulse at the initial stage of lightning. Electrical breakdown starts with electron avalanche then grows into streamer and lastly becomes leader [10-12]. The electrical current flows on a leader emits electromagnetic fields at frequency lower than 3 MHz (can be measured with FA system). On the other hand, electrical current flows on a streamer and electron avalanche emits VHF and microwave

radiation fields, respectively [13-15]. Thorough analysis in Sections 3.1 and 3.2 found that microwave radiation detected (associated with electron avalanche and streamer processes) before the onset of a stepped leader. The duration before the onset of a stepped leader is known as quiet period or QP. The mean duration of QP is 3.707 μs which appears to be longer than the mean duration of stepped leader which is 2.883 μs. Besides, the amplitude of microwave radiation during QP is larger than the amplitude of microwave radiation during stepped leader. Microwave radiation is seen to initiate the stepped leader process due to the microwave burst radiates intensely during QP. The peaks of electromagnetic spectrum band of electron avalanche is around 1 GHz based on what reported in [1].

Our lightning sensor resonate at 1 GHz while the microwave radiation at 1.63 GHz as reported in [5]. Other observations such as [2-4], cannot be used for comparison because the sampling devices used were low resolution and it was impossible to get individual oscillating pulses (in the form of noisy bursts and cannot be analysed temporally) The characteristic of the microwave radiation pulses during stepped leader and QP is observed to be an oscillating individual pulse that made up of many microwave bursts. Based on the article in [5], author observed a few isolated and relatively strong impulses appeared before the onset of stepped leaders. In this study, we also managed to observe the same strong microwave impulses before the stepped leader during QP. However, the findings in [5] did not specify the QP process and thoroughly characterize the stepped leader and microwave radiation in temporal domain. Amplitude of microwave bursts are higher during QP demonstrating that the oscillating individual pulses of microwave radiation are bursting intensely during QP associated with the process of electron avalanche.

4.0 CONCLUSION

This study reports measurement of microwave radiation from real lightning which is negative cloud-to-ground flash at 1 GHz by using air-gap parallel plate antenna. In this report, we observed three stepped leaders and the QP that its' preceded. The duration of stepped leader recorded is between 1.823 μs to 3.904 μs with mean duration of 2.883 μs while the duration of QP is between 3.173 μs to 4.745 μs with mean duration of 3.707 μs. Besides, the time for the stepped leaders to decay is longer than its rise time for all the three stepped leaders. The microwave radiation is identified to consist of many microwave bursts.

The percentage ratio of the peak amplitudes of the microwave burst during QP is between 34.3% and 49.5% larger than the amplitude of the microwave bursts during stepped leaders. This suggests that in electrical breakdown process, electron avalanche and streamer emit strong UHF radiation as they occurred before stepped leader. This abides the fact that the QP initiates the stepped leader process. Various related future work could be accomplished and improved, such as observing the VHF records to observe the behaviour of VHF radiation.

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