

# Electric Field Waveforms of Very Close Negative Cloud-to-Ground Flashes

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## Abstract

Negative cloud-to-ground is a phenomenon that releases negative charge from cloud to the ground. Therefore, this study aimed to observe the characteristics of fast and slow electric fields in reversal distance (RD) of less than 7-8 km from the lightning sensors. A total of four negative cloud-to-ground flashes detected very close to the measurement site in Universiti Teknikal Malaysia Melaka on 12<sup>th</sup> November 2019 were selected for analysis. The captured waveforms were compared with the location data provided by Tenaga Nasional Berhad Research (TNBR) for validation purposes. The results showed that electric field changes of stepped leader and return stroke were often positive beyond or within RD. However, electric field change was often negative in RD for cloud activities.

**Keywords:** cloud-to-ground flash, electric field, lightning

## I. INTRODUCTION

Lightning flash is divided into two main types which are cloud such as intra-cloud (IC) and cloud-to-ground (CG). This classification also depends on the type of cloud with cumulonimbus identified to be the most common in Malay Peninsula. Moreover, the negative cloud-to-ground (-CG) flash releases negative charge from cloud to the ground. The process starts with an initial breakdown (IB) in cloud followed by the discharge of the stepped leader. The last step is the neutralization of the downward leader with the upward leader through attachment that causes an immediate current surge known as the return stroke (RS). The first study to observe ground-based measurements of electric fields of thunderclouds was reported in [1-4] and lightning discharges near the sensors were observed to cause negative electric field changes. Meanwhile, far lightning flashes had positive field changes. The study suggested that thunderclouds typically had negative charge below positive charge. The situation led to the classification as a configuration of a positive dipole charge structure of a cloud. Therefore, this study was motivated to observe the same pattern of electric field change in very close tropical lightning flashes.

## II. REVERSAL DISTANCE (RD)

The ideal structure for a cumulonimbus cloud is three vertically stacked point charges which include positive at the top, negative at the middle, and an additional pocket positive at the bottom located above a conducting ground or the surface of the Earth as presented in Figure 1. Where,  $Q$  is the quantity of electric charge in Coulomb (C) and  $H$  is the height of the charge region approximately from the ground.

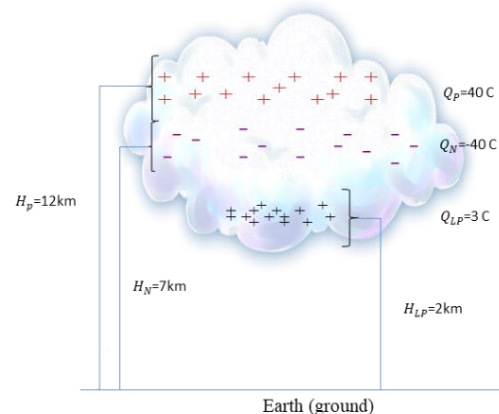


Figure 1: Charge structure of a cumulonimbus cloud.

Electric field intensity  $E$  can be determined by replacing the conducting ground with three image charges. Figure 2 shows that the total electric field is a sum of six vectors including three from actual charges and three from the images based on the principle of superposition and the process is explained in Equation 1. Where,  $H$  is the height of the charge region to the ground,  $R$  is the distance, and  $\alpha$  is the azimuth angle [5].

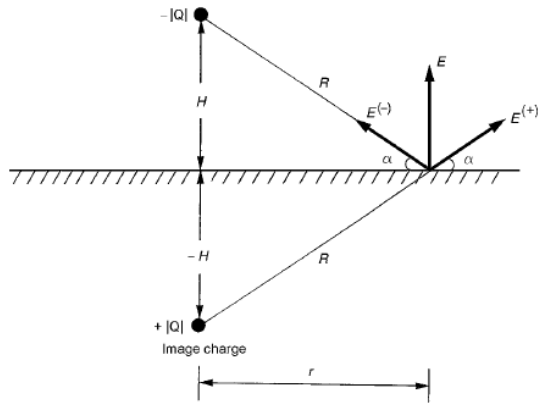


Figure 2: The method of image to determine the total electric field.

$$|E^{(-)}| = |E^{(+)}| = \frac{|Q|}{4\pi\epsilon_0(H^2 + r^2)} \quad (1)$$

The total normal field magnitude doubled either from the actual charge or its image due to the status of the surface of the ground as a perfect conductor. The condition ensures that the components of electric field tangential to the ground plane cancel each other.

$$|E| = 2|E^{(-)}| \sin(\alpha) = \frac{|Q|H}{2\pi\epsilon_0(H^2+r^2)^{3/2}} \quad (2)$$

Equation 2 is further simplified as  $H$  and  $r$  ( $|Q|$ =constant) as follows:

$$|E| = k \frac{\sin\alpha}{R^2} \quad (3)$$

Where,  $k=|Q|/(2\pi\epsilon_0)$  and  $R^2=H^2+r^2$ .

$E$  depends on  $r$  when  $r$  equals to 0 and this shows electric field is dominated by the lower charge. However, when  $r$  increases to a certain distance, the contribution from the upper charge becomes dominant and the total electric field which is the sum of the contributions by the two charges changes its polarity with the distance defined as RD. For the case of two vertically stacked charges of equal magnitude but opposite polarity RD,  $D_0$  is stated as follows:

$$D_0 = [(H_p H_N)^{2/3} + (H_p^{2/3} + H_N^{2/3})]^{1/2} \quad (4)$$

Figure 3 shows electric field on the ground due to the vertical tripole charge distributions of cloud. Meanwhile, Figure 1 shows that the main negative and positive charges are set at 40 C with 7 and 12 km above ground, respectively. The pocket positive is also 2 km above ground with a magnitude of 3 C. The total electric field exhibits polarity reversals which depend on the distance. Figure 3 also shows the contributions to the total electric field from each of the three charges [5].

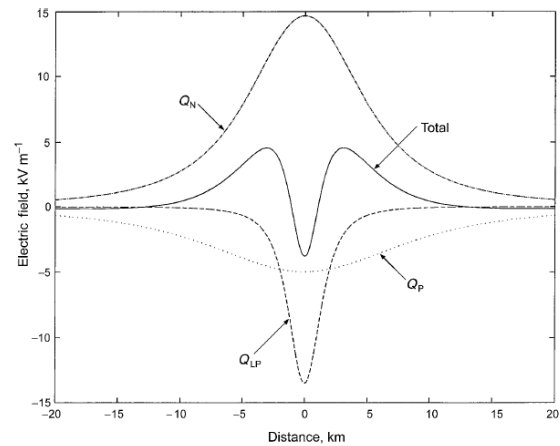


Figure 3: Electric field on the ground based on a tripole charge distribution cloud [5].

### III. MATERIALS AND METHODS

The measurement campaign was conducted during the rainy season in November 2019 and four close -CG lightning flashes were selected on 12<sup>th</sup> November 2019. The lightning signal that beamed on the sensors was in analog form. Therefore, the PicoScope 5000 series was used as a digitizer to convert the analog signal into digital form. The waveforms could be monitored remotely using the computer. Analysis was also conducted on the computer because it was more convenient to use the PicoScope 6 software. The waveform was sampled with a sampling rate of 125 Mega Samples/second and the visual diagram of the measurement setup is presented in Figure 5.

A total of two buffer circuits were deployed with capacitive parallel plate antennas [6-8]. Fast-field (FF) buffer circuit operating frequency is between several Hertz up to 3 Mz with a decay time constant of 13 ms while the slow-field (SF) buffer circuit operated between a few Hertz to 1 kHz with a decay time constant of 1s. The circuit diagram of FF buffer circuit is presented in Figure 2. Moreover, the difference between FF and SF is the value of C1, 15 pF, and 0.1  $\mu$ s and the list of components used in constructing the buffer circuits is presented in Table 1. The type of lightning flashes measured was determined using FF record.

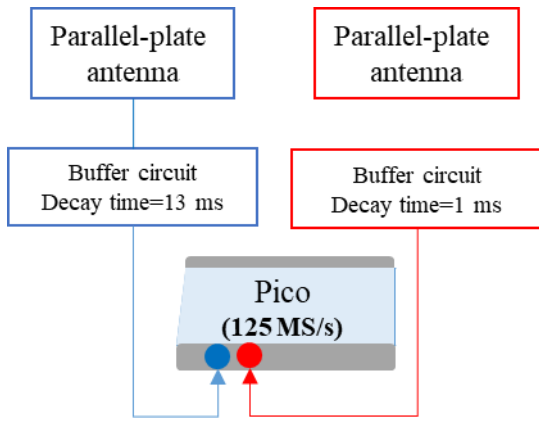


Figure 5: Visual diagram of the measurement setup

Table 1: List of components

Fast & Slow Field	
Component	Unit
100 MΩ resistor	2
100 Ω resistor	4
50 Ω resistor	4
IC OPA 633 KP	2
Capacitor 15 pF	1
Capacitor 0.1 μF	4
Capacitor 10 nF	1

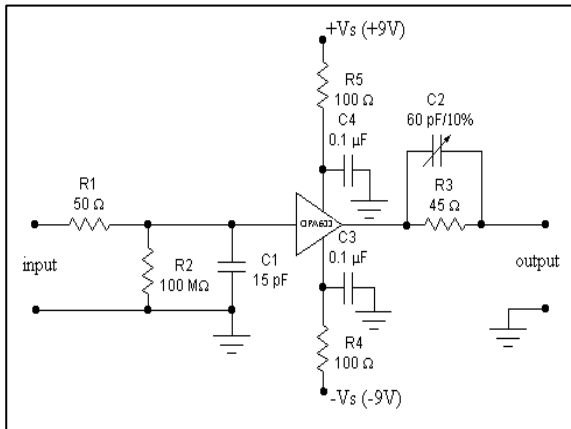


Figure 6: Circuit diagram of FF buffer circuit [9]

Electric field from lightning flashes was measured using the circular parallel plate antenna. Furthermore, the size of the antenna was calculated using Equation 5 with the radius  $r_A$  set at 0.25m. The antenna was able to capture radiation, static, and induction components

from lightning flashes using a fast and slow electric field system deployed during the measurement campaign. Moreover, the capacitance value of the antenna was calculated using Equation 6.  $\epsilon_0$  is the permittivity of the space set at  $8.8542 \times 10^{-12}$ ,  $A$  is the area of the plates obtained from Equation 5 and  $d$  is the gap between the plates which was 0.05 m. The impedance of the antenna from 1 kHz to 100 kHz was also calculated using Equation 7, where  $f$  was the frequency value and  $C$  was the capacitance value. The value and the response of the impedance are presented in Table 2 and Figure 7. The example of a completed antenna is shown in Figures 8 (a) and (b).

$$A = \pi r_A^2 \tag{5}$$

$$C = \frac{(\epsilon_0 A)}{d} \tag{6}$$

$$Z_C = \frac{1}{2\pi f C} \tag{7}$$

Table 2: Value of impedance of circular parallel plate antenna

Frequency (kHz)	Impedance, $Z_c$ (Ω)
10	4577316.24
20	416119.66
30	217967.44
40	147655.36
50	111641.86
60	89751.30
70	75037.97
80	64469.24
90	56510.08
100	50300.18

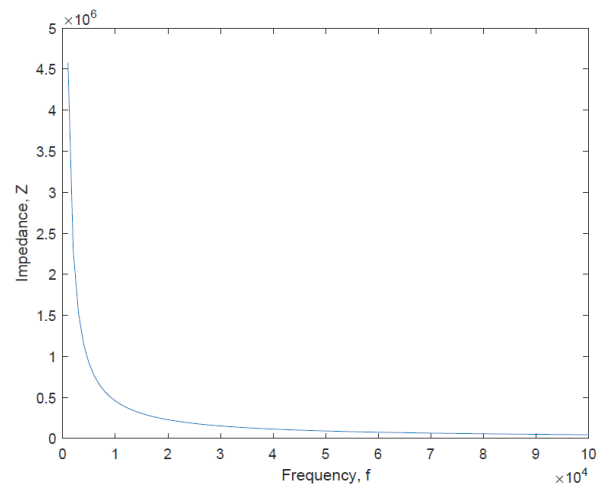


Figure 7: Impedance response of the antenna as a function of frequency

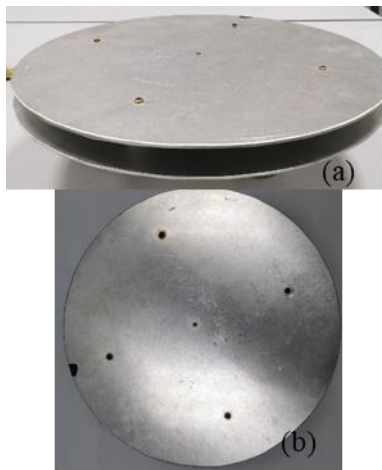


Figure 8: Circular parallel plate antenna (a) Side view with air gap and (b) Top view.

#### IV. RESULTS AND DISCUSSIONS

##### A. Validation of Lightning Flashes

A total of four -CG flashes in RD close to the lightning measurement system on 12<sup>th</sup> November 2019 were selected. The samples were validated through a comparison with the data provided by Tenaga Nasional Berhad Research (TNBR) [10]. The locations of the first RS and distances from the sensors are presented in Figure 9. The distances of the lightning strikes ranged between 1.936 and 4.196 km and were captured from 3:37:45 PM to 4:19:47 PM. The details of -CG lightning flashes are presented in Table 3.

Table 3: Details of -CG lightning flashes

Flash No.	Time (UTC+8)	Distance (km)
F1	15:37:45	2.152
F2	16:05:28	1.936
F3	16:07:15	3.137
F4	16:19:47	4.196

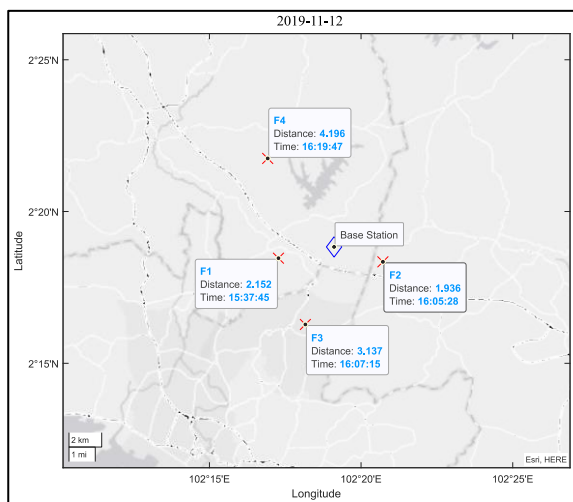


Figure 9: Locations of the first RS of -CG lightning strikes to the location of the base station.

##### B. Observations of Electric Field Change Waveforms

Electric field waveforms for close -CG lightning flashes were observed by analyzing the shape of SF waveforms. The measurement system consisted of two sensors which were FF (blue) and SF (red) as plotted in Figures 11 to 14. The analysis was conducted by comparing SF records obtained with the shape of electric field changes as reported by [11]. For -CG, the polarity of RS was positive according to the atmospheric sign convention. Stepped leader (SL) and RS processes maintained the reversed polarity but the IB and cloud activities discharged were negative polarity in RD as analytically discussed in [12].

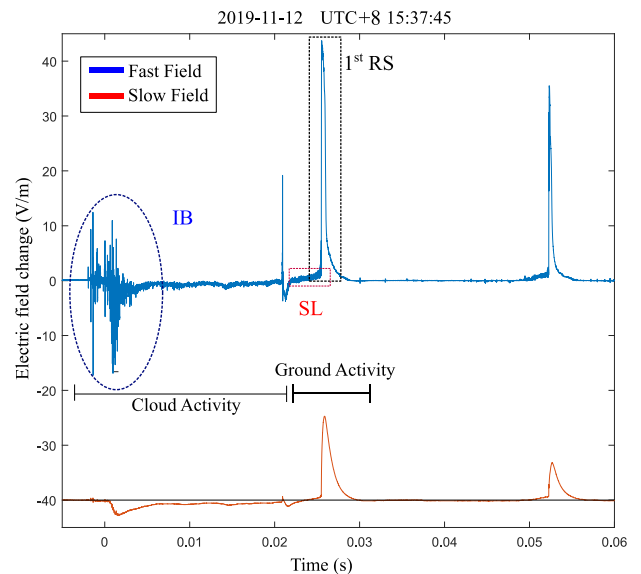


Figure 11: FF (blue) and SF (red) records for F1.

The distance from the sensors used to the location of RS strike for F1 was 2.152 km. Figure 11 shows that the zero line is represented as a horizontal line in black from SF records. Electric field change of IB process propagated near the sensors in RD but moved farther (still in RD) during cloud activities to the occurrence of SL and RS discharge processes. It was observed that IB and cloud activities for SF records of -CG lightning flashes were negative while SL and RS were positive.

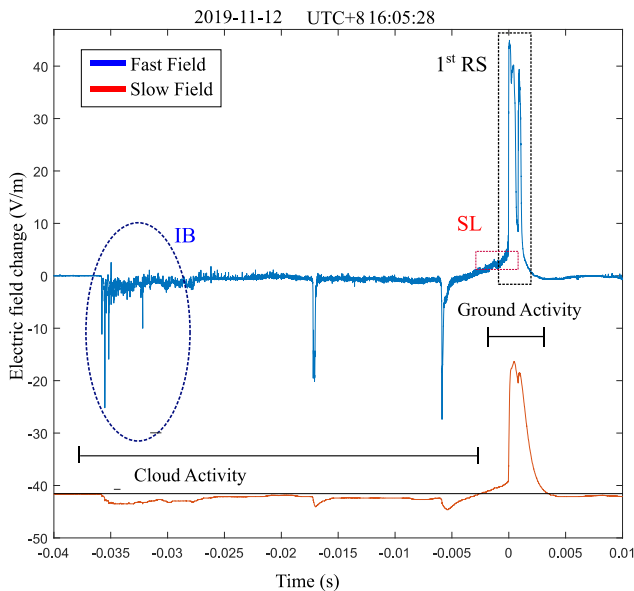


Figure 12: FF (blue) and SF (red) records for F2

SL and RS for F2 struck at 1.936 km from the sensors. Figure 12 shows that electric field change of IB was in RD. This was because SF record was negative while positive during SL and RS. The propagation of electric change of IB and cloud flash was away from the sensors but within RD. However, electric change of leaders was closer to the sensors before SL and RS occurred.

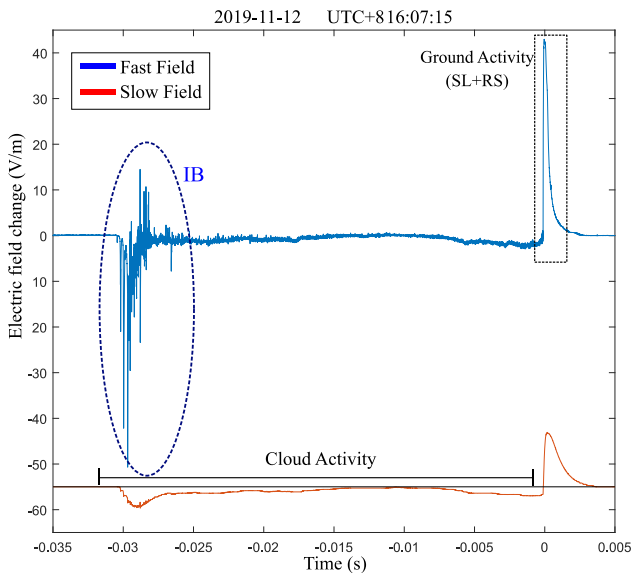


Figure 13: FF (blue) and SF (red) records for F3

The distance of SL and RS that struck the ground was 3.137 km away from the sensors for F3. It can be observed from Figure 13 that electric field change propagated closer to the sensors during IB but moved farther away at cloud flash. However, electric field change during the leader moved closer again to the sensors immediately before SL and RS occurred.

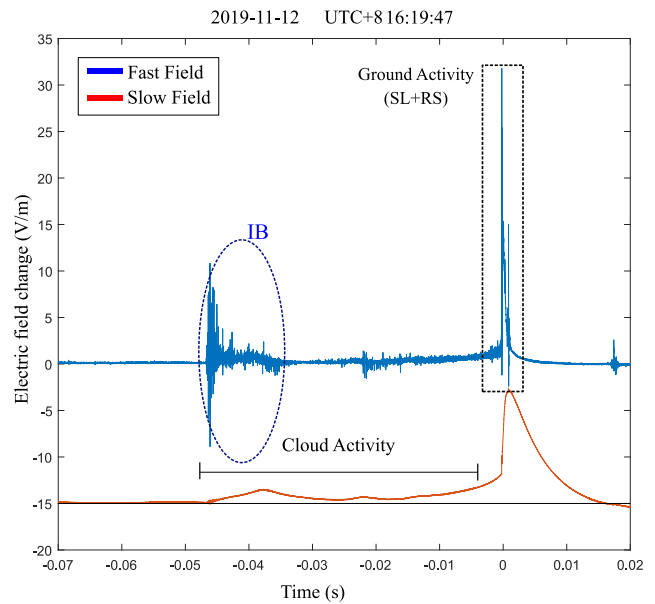


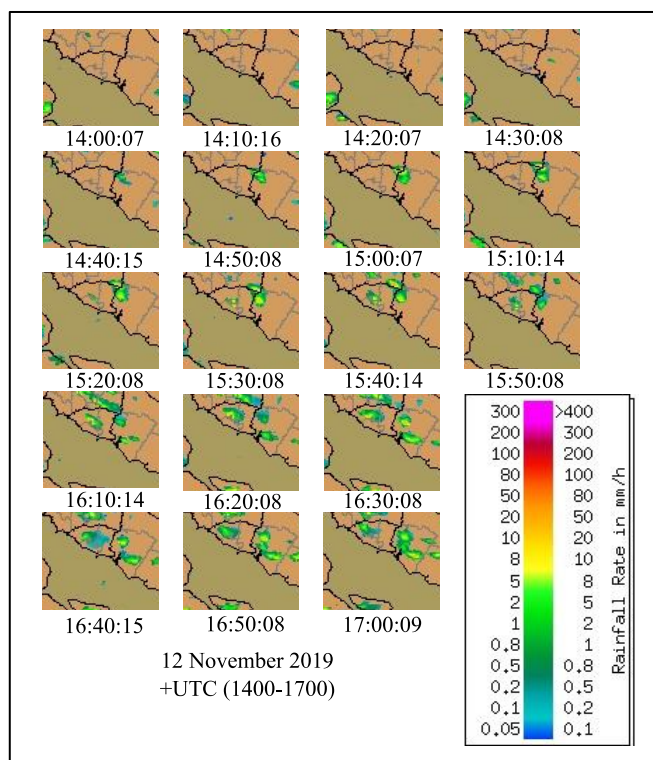
Figure 14: FF (blue) and SF (red) records for F4

SL and RS for F4 struck the farthest from the sensors at 4.196 km but were within RD. However, electric field change during IB and cloud flashes occurred beyond RD because electric change value was positive as shown in Figure 14. The leaders gradually propagated past RD border at approximately 7 to 8 km and struck 4.196 km from the sensors. This shows that cloud activities before SL and RS which is a part of -CG flash can occur beyond RD but propagate to strike in RD.

## V. CONCLUSIONS

In conclusion, this observation proved that electric field change in RD was often negative and opposite when beyond RD. Meanwhile, the value for SL and RS reversed the polarity of charges that propagated from cloud to the ground according to the atmospheric sign convention. Future improvement should be made by installing high-frequency sensors to investigate the correlation between the characteristics of high frequency associated with the lightning flashes in RD.

## APPENDIX



CAPPI radar format at 2 km altitude for Malay Peninsula, focusing on the area surrounding Melaka state and Malacca Strait for 3 hours Malaysia time UTC+8 on 12<sup>th</sup> November 2019. Adapted from the official website of MMD. (This result shows the intensity of the thundercloud when lightning occurred and the movements of cloud for a period of 3 hours).

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