Design and Development of Magnetic Field Derivative Direction Finder for Lightning Discharges

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***Abstract*—This paper presents the design and development of magnetic direction finder (MDF) system utilizing sensors of magnetic field derivatives (dB/dt) located at two stations (ST1 and ST2) separated by a distance of 13 km in Melaka. The dB/dt sensors were designed with copper coils and ferrite core has been placed in the middle of the coils. The impedance of the dB/dt sensors was obtained by using impedance analyzer between 10 Hz and 1 MHz and the response peaked at around 100-200 kHz. Two sets of dB/dt sensors were manufactured where each set consisted of perpendicular ferrite core coils oriented to North-South (NS) and East-West (EW). The measurement campaign conducted between 10 and 18 September 2024 showed that the dB/dt sensors detected all types of lightning discharges accurately when compared to the established fast electric field antenna system.**

***Keywords*—ferrite core coil, lightning, magnetic field derivative, magnetic direction finder**

I. Introduction

Lightning is an electrical discharge that occurred between objects with opposite polarities. These discharges can occur between the ground and a cloud, known as cloud-to-ground (CG) flashes, between two clouds, referred to as cloud-to-cloud (CC) flashes, or within the same cloud, known as intra-cloud (IC) flashes. As the discharge occurs, electromagnetic wave radiation is generated, ranging from a few hertz to visible wavelengths [1-3].

The immense electromagnetic energy produced by lightning is a significant source of electromagnetic interference, which can disrupt various electronic systems and sometimes cause harm to humans. To protect both individuals and valuable assets, various lightning detection and localization systems have been developed over the years. Lightning localization systems are based on three techniques namely Time-of-Arrival (TOA), Interferometry (ITF), and magnetic direction finder or MDF [4-10]. These lightning localization systems are developed based on either low-frequency and very-low-frequency (LF/VLF) sensor or very high frequency (VHF) sensor technology [7, 9-11].

A sensitive ferrite core coils magnetic field sensor has been developed by [12] that can determine the location of lightning up to 1000 km. By implementing a single station, it is more cost effective compared to installing systems at multiple stations such as in TOA and ITF systems. Moreover, a single MDF sensor can cover a much larger radius than TOA and ITF systems, which have very limited ranges.

On the other hand, the accuracy of single station MDF is much lower than TOA and ITF. The typical accuracy of both TOA and ITF systems is less than 500 meters and the accuracy can be increased as the number of stations increased [4-10]. A study in [13] utilizing single station MDF shown that the accuracy was between 7.14 and 8.14 km for measured lightning discharges below within 50 km. Moreover, the location and placement of MDF sensor are one of important factors. The coils must be placed at higher ground such as on rooftop or hilly area with clear horizontal view without any obstacles. The reason is to make sure that the coils able to receive clear horizontal components of magnetic fields from lightning discharges.

The MDF is capable of capturing direct dB/dt fields for localization, whereas TOA and ITF systems require the application of advanced signal processing of time delay and phase difference techniques for localization. In term of processing time, the ITF system has the highest delay in producing location of lightning discharges due to complexity of signal processing used. Thus, for real time purpose, the MDF system has the lowest processing delay and cost but at the cost of poor accuracy.

In this paper, we present a design a new high sensitivity two-station MDF system utilizing magnetic field derivative (dB/dt) technique. The sensor is more cost effective (no filter circuit and power supply needed), which can detect all types of lightning flashes and able to locate the lightning strikes more accurate with two-station configuration compared to single-station MDF system in [12, 13].

II. METHODOLOGY

A. Design of ferrite core coils

Four identical ferrite cores, each with a length of 140 cm, were used for the design. Each core was wound with a copper wire of 0.5 mm diameter and 20 turns were applied to each core as shown in Fig. 1. The wounded ferrite cores were designated as North-South (N-S) and East-West (E-W) to align accordingly. It is important to twist the remaining coils preceding the cable connector to make sure the interference cancellation.

Fig. 1. Ferrite core coils with 20 turns winding.

B. Frequency response of impedance

Fig. 2 shows the plot of frequency response of the ferrite core coil impedance. The peak impedance was around 80 kΩ at around 300 kHz. Below 100 kHz, the impedances were below 1 kΩ which is good enough to detect clear electromagnetic fields from lightning discharges. Based on this result, the minimum sampling frequency of the digitizer must be above 200 kHz in order to sample the waveform clearly.

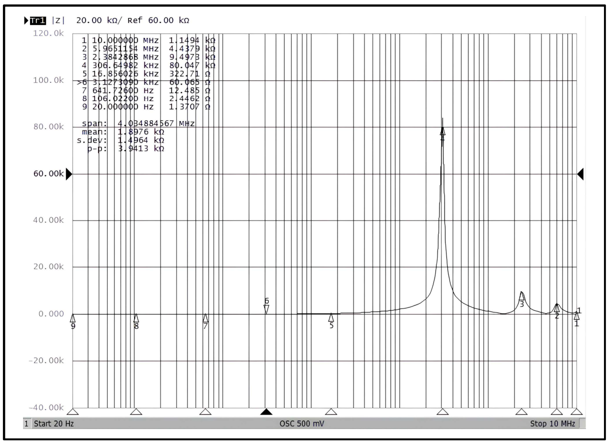

Fig. 2. Frequency response of ferrite core coils impedance.

C. Development of dB/dt sensor

Fig. 3 shows the placement of the ferrite core coils inside a plastic box. To ensure a minimum separation of 5 cm between the cores, the NS ferrite core coil was elevated above the EW ferrite core coil using non-metal pipes attached to each end. This arrangement was designed to maintain the required distance and stability. The entire assembly was housed in a sealed box to protect it from rain and strong winds that might otherwise affect the core positions and consequently the accuracy of the dB/dt sensor.

Fig. 3. Placement of the ferrite core coils inside a plastic box.

D. Site installation

The dB/dt sensors were deployed at two locations namely Universiti Teknikal Malaysia Melaka (UTeM), Melaka, Malaysia (2°18'50.6"N 102°19'06.1"E; ST1), and Paya Rumput, Melaka (2.3044°N, 102.1991°E, ST2). The location and placement of MDF sensor are one of important factors. The coils have been placed at rooftops of both ST1 abd ST2 stations with clear horizontal view without any obstacles. The reason is to make sure that the coils able to receive clear horizontal components of magnetic fields from lightning discharges.

Radar reflectivity data (CAPPI format at 2 km altitude), along with HIMAWARI satellite images, were obtained from the Malaysia Meteorological Department (MMD). Both sites are 13 km apart as shown in Fig. 4 labelled as ST1 (red circle) and ST2 (blue circle).

E. Lightning data collection

For recording lightning discharges data, the dB/dt sensor box was connected to a digitizer using a 10-meter 50 Ω coaxial cable. The termination impedance is 1 MΩ. The output from each ferrite core coil connected to different channels of the digitizer. In total, three channels have been utilized to collect the fast electric field (FA) [3, 9-10] and two components of dB/dt (NS and EW). The lightning record was timestamped with GPS clock and local time UTC+8 format was used.

III. RESULTS AND ANALYSIS

A collection of lightning discharges detected by the dB/dt sensors is chosen from tropical storm on 12 September 2024 is discussed in this section. The validation that the storm existed on that day was verified by using CAPPI radar echo and satellite Himawari images as shown in Figs. 4 and 5.

A. Storm reflectivity

The storm appeared on radar echo at around 01:30 west of both stations ST1 and ST2 (see Fig. 4D) where light rain can be observed. After the storm inception, radar reflectivity data revealed that the storm reached maximum values at 60 dBZ at around 02:30 and lasted about an hour until 03:30 (see Fig. 4J-P). After 03:30, the storm started to decay.

B. *Cloud top height (CTH)*

The cloud of the analysed storm appeared on Himawari satellite image at around 01:00 on top of both stations ST1 and ST2 (see Fig. 5A) where the maximum cloud top height was around 10 km. After the storm inception at 01:30, the cloud top height reached maximum values between 15 and 16 km around 02:50 and lasted about an hour until 04:00 (see Fig. 5F-K). After 04:00, the cloud top height started to decrease.

C. *Frequency response of lightning discharges*

Fig. 6 shows the frequency responses of recorded fast electric field (blue plot) and magnetic field derivate dB/dt (green plot) from the same lightning discharge. The response of the fast electric field was flat before 1 MHz due to the filter circuit used while the response of the dB/dt field was resonated with peak between 100 and 200 kHz. This result is expected as the dB/dt sensor was not equipped with filter and amplifier, so that the direct measured field would be resonated.

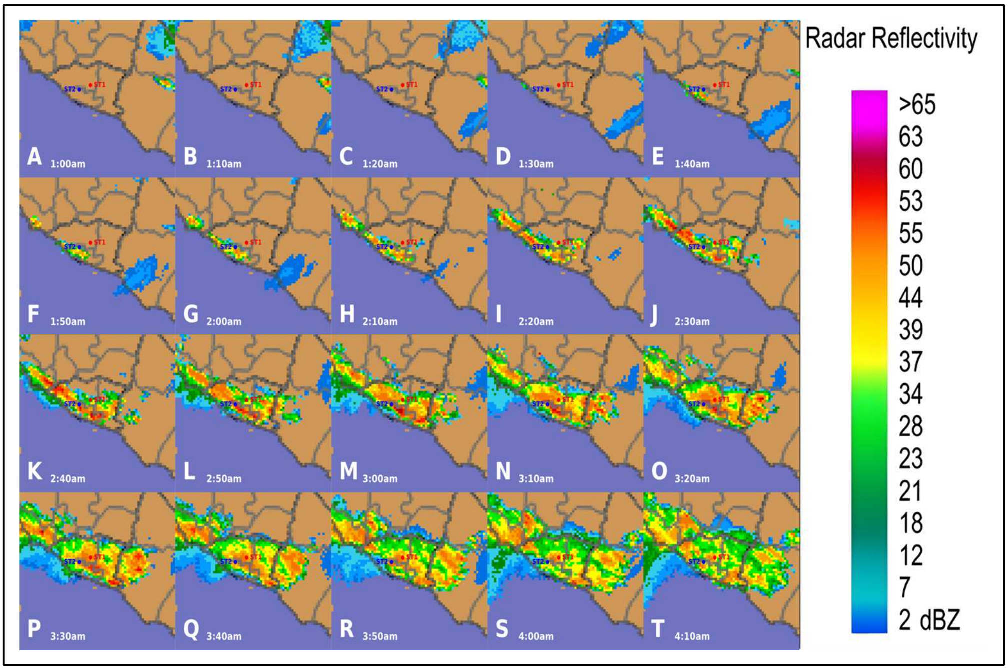

Fig. 4. Development of reflectivity values of analyzed storm on 12 September 2024.

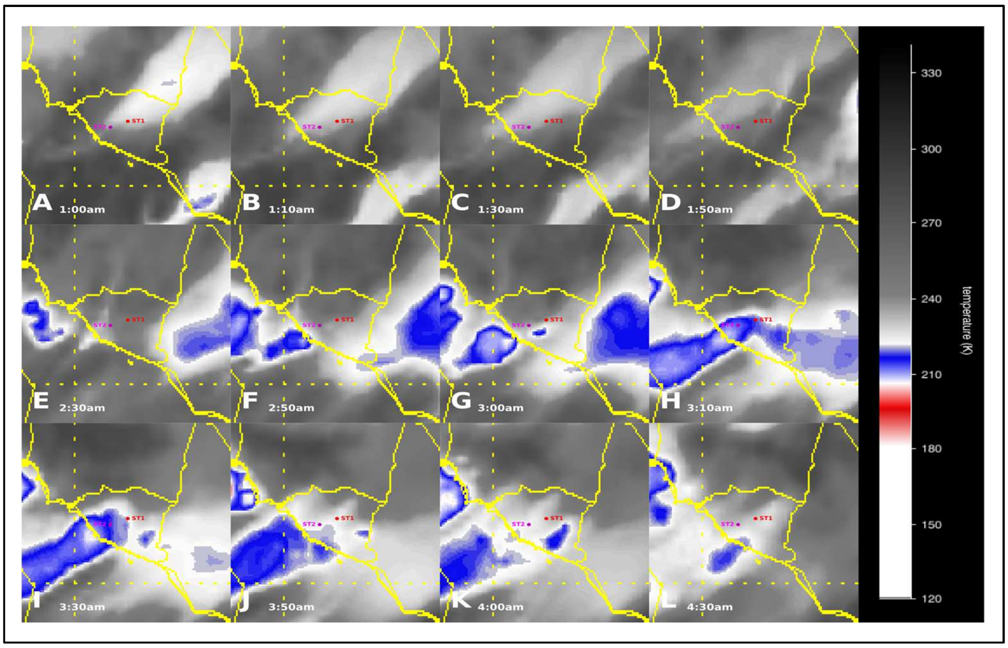

Fig. 5. Development of cloud top height (CTH) of analyzed storm on 12 September 2024.

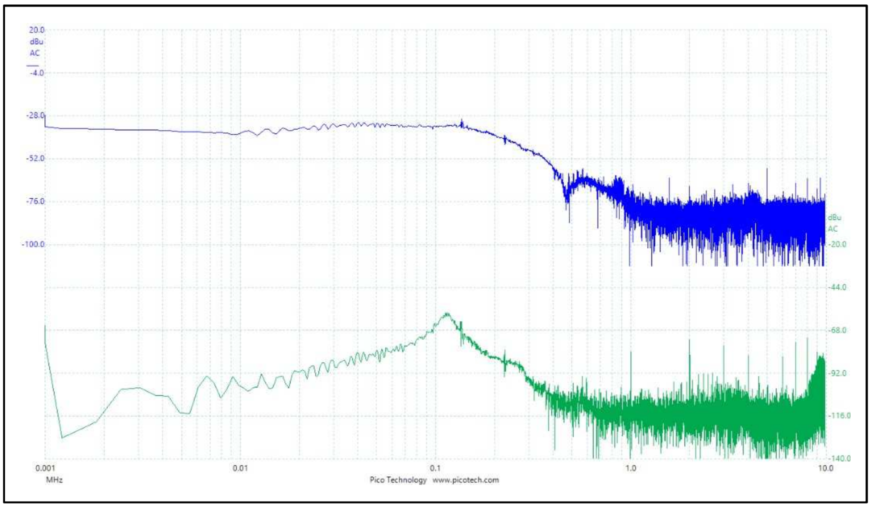

Fig. 6. Frequency response of recorded fast electric field (blue plot) and magnetic field derivative (dB/dt) from a lightning dicharge.

D. Lightning discharge electromagnetic waveforms

Fig. 7 shows example of a return stroke of a positive CG flash recorded by the dB/dt sensors at both observation stations ST1 (top) and ST2 (bottom). The waveform shapes of the magnetic field derivatives (green and orange plots are EW and NS waveforms, respectively) the same as the waveform shape of fast electric field waveform (blue plots in Fig. 7) as reported in [3, 9-10].

The positive return stroke was located over Malacca Strait at 27.3 km from ST1 and 14.3 km from ST2. The occurrence of this positive CG flash was during the highest reflectivity value (60 dBZ) and cloud top height (16 km) as shown in Fig. 4 and Fig. 5.

Several negative return strokes from CG flashes were located together with the positive return stroke between 02:00 and 04:00 as shown in Fig. 8. All negative return strokes were observed to strike over land while the positive return stroke occurred over Malacca Strait. As can be seen from Fig. 5F, the cloud top height was maximum over Malacca Strait compared to the land. The positive return stroke might have been initiated at height above 10 km as the maximum cloud top height was 16 km. On the other hand, the cloud top height for negative return strokes was below 10 km which indication that all negative CG flashes have been initiated at altitude below than 10 km.

Between 02:00 and 03:00, negative return strokes were detected very close to station ST2 ranging between 0.9 and 3.7 km as plotted as blue dots in Fig. 8. The distances of these negative return strokes from station ST1 were ranging between 12.5 and 16.3 km. From the fast electric field waveform shape at station ST1, all negative return strokes exhibited electrostatic component. Moreover, during the same hour, the positive return stroke was detected over Malacca Strait (red dot in Fig. 8) with distances of 27.3 km and 14.3 km from ST1 and ST2 stations, respectively.

Later, between 03:00 and 04:00, only two negative return strokes were able to be detected at both ST1 and ST2 with the distance quite far from both stations. Both negative return strokes were located at south of both ST1 and ST2 stations.

IV. Conclusion

A new high sensitivity two-station MDF system utilizing magnetic field derivative (dB/dt) technique has been designed, developed, and experimented with real thunderstorms and lightning discharges. Lightning discharges have been able to be captured and located successfully by using magnetic field derivative (dB/dt) technique.

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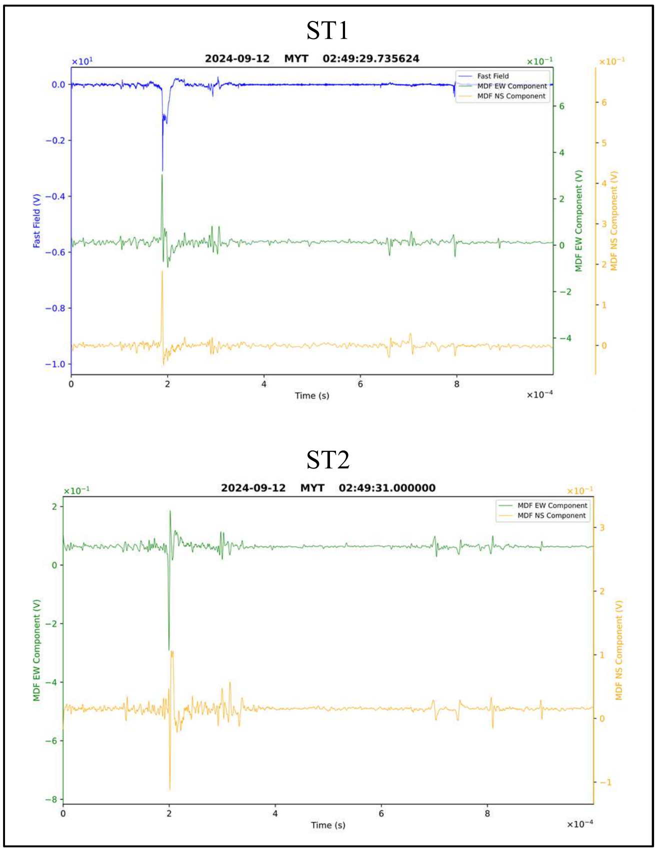

Fig. 7. Recorded fast electric field (blue plot) and magnetic field derivatives (green and orange plots) of a return stroke from a positive CG flash at two observation stations ST1 and ST2. The positive return stroke was located over Malacca Strait at 27.3 km from ST1 and 14.3 km from ST2.

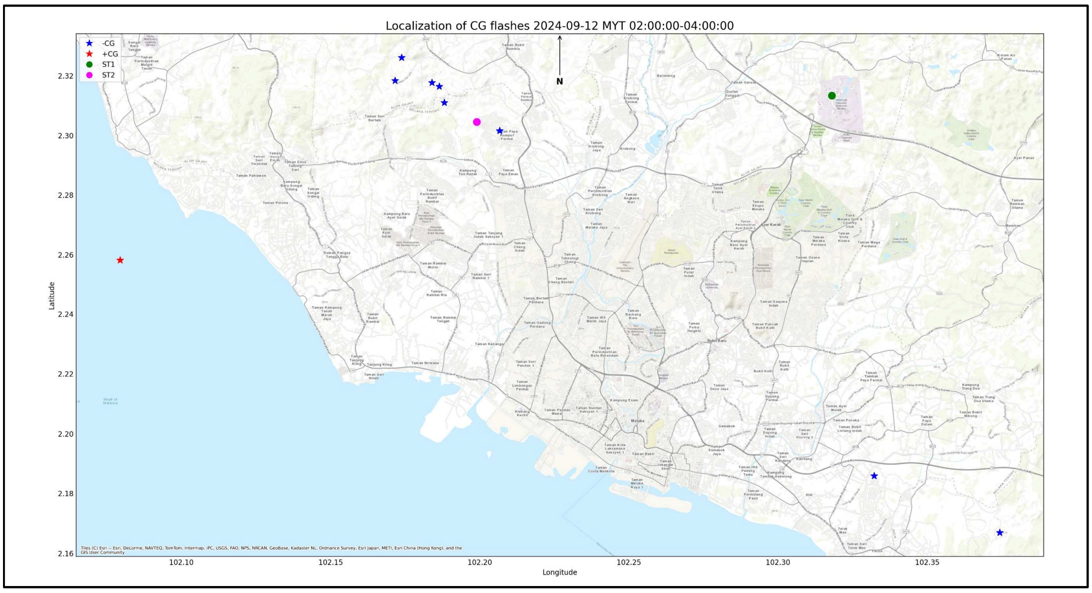

Fig. 8. Locations of return strokes of eight negative CG flashes (blue dot) and one positive CG flash (red dot) detected within two-hour period between 02:00 and 04:00. The electromagnetic waveform of the positive return stroke is shown in Fig. 7. Station ST1 is shown as green dot while station ST2 is shown as magenta dot.

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