Journal of Telecommunication, Electronic and Computer Engineering
ISSN: 2180 – 1843 e-ISSN: 2289-8131 Vol. 16 No. 3 (2024) 27-33
jtec.utem.edu.my
DOI: https://doi.org/10.54554/jtec.2024.16.03.004

Design and Development of Lightning Detection System Utilizing Slow Atmospheric Electric Field Waveform at Legoland Malaysia

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Article Info

Article history:
Received Jan 3rd, 2024
Revised July 30th, 2024
Accepted Sep 2nd, 2024
Published Sep 30th, 2024

Index Terms:
Lightning
Slow antenna
Electromagnetic
Theme Park
Legoland

Abstract

Conventional lightning localization and detection techniques, including Magnetic Direction Finder (MDF), Time of Arrival (TOA), Interferometer (ITF), and Distance of Arrival (DOA), predominantly rely on fast atmospheric electric fields, magnetic fields, and very high frequency (VHF) signals. This paper pioneers a novel approach by delving into the analysis of the slow atmospheric electric field, aiming to develop a waveform analysis utilizing this field to estimate the distance and radius of lightning occurrences at LEGOLAND Malaysia Resort. The newly implemented lightning detection system at LEGOLAND leverages a straightforward and cost-effective setup, incorporating a capacitive antenna, slow and fast atmospheric electric field sensors, and dedicated data analysis software. The system's efficacy and accuracy have undergone a rigorous comparison with LEGOLAND's existing online lightning detection service. Achieving accurate data necessitates proper grounding and isolation from electrical noise, as signal interference from power lines, towers, or machinery can potentially trigger false signals. This research has contributed detailed documentation on the analysis of slow atmospheric electric field data, encompassing waveform patterns and key characteristics. This documentation is expected to serve as a valuable resource for future research endeavors and the continuous refinement of lightning detection systems. The comparative evaluation between the novel system and the current online service at LEGOLAND Malaysia Resort has shed light on the efficiency and capabilities of the newly introduced methodology.

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I. INTRODUCTION

The issue of lightning strikes in Malaysia has prompted the government's meteorological department to acquire lightning detection devices from foreign suppliers, often at a significantly high cost. Despite existing solutions, such as preemptive educational initiatives and the installation of rods for on-site lightning protection, fatalities from lightning incidents persist. The current localization methods, employing Magnetic Direction Finding (MDF), Time of Arrival (TOA), Interferometer Technique (ITF), and Direction of Arrival (DOA), rely on variations, derivative values, and waveform analyses of the fast atmospheric electric field, magnetic field, and very high frequency (VHF) to predict the distance and location of lightning strikes [1-20]. However, none of these techniques incorporate the slow atmospheric electric field as a method for lightning detection.

Recognizing the needs of the industry and the specific requirements of LEGOLAND Malaysia Resort, a short-range lightning detection system (with a range of 7-8 km or less) [1-3,20] was developed using slow atmospheric electric field measurements. This approach deemed sufficient for the resort's purposes, particularly for providing early warnings during heavy rain, lightning, or potential flooding events. With a priority on guest safety, LEGOLAND Malaysia Resort intends to utilize this data to promptly alert visitors to seek shelter in safe areas, such as buildings or covered spaces, and to avoid open and wet areas. The choice of slow electric field detection is based on its simplicity, effectiveness, and cost-efficiency in predicting lightning strikes within this range. The analysis of slow electric field data, encompassing waveforms, key elements, and specific characteristics, will be comprehensively reviewed and documented. This detailed documentation serves as a valuable resource for future research and for refining lightning detection and early warning systems. To evaluate the efficiency of this new system, a comparative assessment will be conducted against the online system subscribed by LEGOLAND Malaysia Resort.

II. METHODOLOGY

The lightning detection system, illustrated in Figures 1 to 5, presents a simple yet highly effective and cost-efficient approach to lightning detection. This system comprising a capacitive parallel plate antenna, a buffer circuit equipped with both slow and fast atmospheric electric field sensors, a PicoScope oscilloscope, and a desktop computer, offers a streamlined and economical approach [3,20]. The capacitive antenna serves to capture the analogue electromagnetic radiation emitted by lightning strikes, transmitting it to the buffer circuit.

Within the buffer circuit, unwanted noise is filtered out, and the signal is amplified before being sent to the PicoScope. Acting as a digitizer, the PicoScope transforms the analogue lightning data into digital format. The accompanying PicoScope 6 software, installed on the desktop computer, functions as a real-time analyzer. It is equipped with features such as Fast Fourier Transform (FFT), spectrum analysis, voltage-based triggering, and the ability to save and load waveforms to the hard disk. Configured with specific parameters, the PicoScope 6 software operates as a closed-loop system, automatically triggering, recording lightning events, and storing data for subsequent analysis.

The primary objective of this project was to record and analyze lightning data using the slow electric field method. The collected and stored data was then compared with information obtained from the lightning detection systems subscribed to by LEGOLAND Malaysia Resort based on a monthly basis, which operated through online and web-based platforms. This integration of hardware and software components underscores the practicality and efficiency of the lightning detection system, providing valuable insights for lightning research and monitoring applications.

In the process of collecting data spanning from July 2020 to July 2022, approximately 50,000 datasets were recorded. For the purpose of comparison data from December 2020 was selected, as it typically experiences the highest amount of rain and lightning in Malaysia. This analysis focused on two systems, namely the Data Transmission Network (DTN) and the Lightning Detection System (LDS).

The Data Transmission Network (DTN) is a subscription-based service that provides real-time weather analysis and information, utilized by LEGOLAND Malaysia Resort. In contrast, the Lightning Detection System (LDS) was designed, developed, and installed specifically for this research on the roof of the chemical storeroom at LEGOLAND Malaysia Resort.

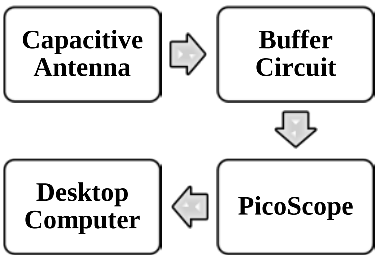

Figure 1. Lightning detection system

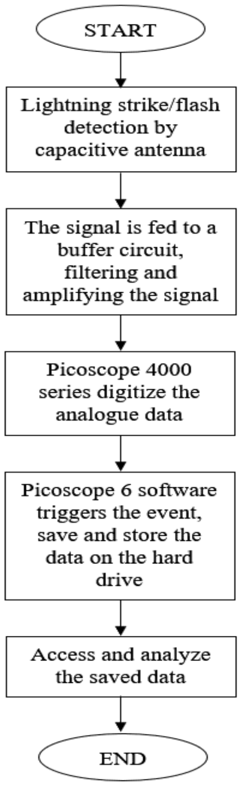

Figure 2. A complete cycle flow chart of how data collection has been done with the lightning detection system

Figure 3. Capacitive antenna

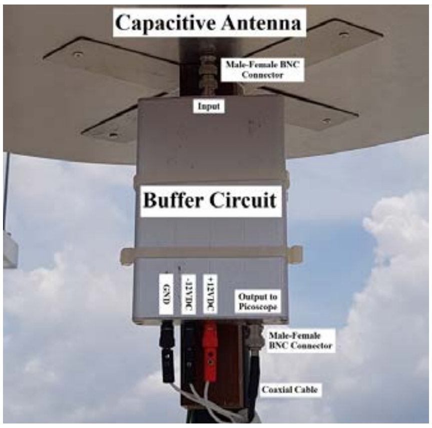

Figure 4. Buffer circuit

Figure 5. PicoScope 4000 series, AC-DC power supply -12VDC +12VDC and desktop computer with PicoScope 6 software installed

III. RESULTS AND ANALYSIS

Figure 6 presents a comparison between the two systems. Notably, the DTN produces limited data, providing only one record for each lightning event, while the LDS captures a more detailed series of lightning events for each occurrence. The information provided by the DTN includes the time, date, distance, and direction of the lightning strike, with a graphical user interface. In contrast, the LDS records additional details such as time, date, amplitude, waveform, and the type of lightning.

An observation from Figure 6 is that the LDS tends to detect lightning events slightly earlier than the DTN. This discrepancy may be due to the fact that the LDS is installed directly at LEGOLAND Malaysia Resort, allowing it to capture lightning events in close proximity. In contrast, the exact location of the DTN system and its distance from LEGOLAND Malaysia Resort remain unknown. Additionally, the DTN transmits information via email, which may potentially cause delays in delivering the data to end-users.

Figures 7 to 11 depict the data captured by both the DTN and LDS systems, respectively. It is evident that the LDS detects lightning earlier and captures multiple data points for each event, while the DTN only records a single data point for each lightning event.

Date	Data	Time	Type	WRD / BRD	Amp. FF	Amp. SF (RS)	Amp. SF (Static)	Remark
3-Dec-20	DTN	3:42 PM						
	LDS	3:24:21 PM	IC	WRD	4.55E-01	3.33E-01	-1.76E-01	
	LDS	3:09:26 PM	IC	WRD	3.30E-01	2.38E-01	-5.45E-01	
9-Dec-20	DTN	4:33 PM						
	LDS	4:32:25 PM	NBE	WRD	-6.54E-01	2.68E-02	-8.41E-01	
	DTN	6:06 PM						
	LDS	6:06:57 PM	NCG	WRD	5.88E-01	1.33E-02	-4.86E-01	
	LDS	6:06:05 PM	NCG	WRD	3.03E-01	3.09E-01	-5.51E-01	
	DTN	6:37 PM						
	LDS	6:36:23 PM	NBE	BRD	2.41E-01	2.35E-01	-4.76E-02	
	DTN	6:38 PM						
	LDS	6:37:35 PM	NCG	BRD	2.55E-01	2.50E-01	-6.09E-02	
	DTN	6:46 PM						
	LDS	6:40:54 PM	NCG	BRD	2.11E-01	2.05E-01	-3.10E-02	
	DTN	7:03 PM						
	LDS	6:52:15 PM	NBE	BRD	2.15E-01	2.63E-01	-3.14E-02	
10-Dec-20	DTN	2:31 PM						
	LDS	2:31:32 PM	NCG	BRD	1.65E-01	2.04E-01	-4.44E-01	
	DTN	3:35 PM						
	LDS	3:26:32 PM	NCG	WRD	8.78E-01	9.60E-01	-5.60E-01	
	LDS	3:15:16 PM	NCG	WRD	1.15E-01	8.61E-02	-3.98E-01	
15-Dec-20	DTN	3:42 PM						
	LDS	3:37:23 PM	NCG	BRD	6.65E-01	2.33E-01	-3.65E-02	
	LDS	3:35:26 PM	NBE	BRD	7.72E-01	2.74E-01	-6.33E-04	
	LDS	3:35:06 PM	NCG	BRD	7.83E-01	2.93E-01	-6.93E-04	
	LDS	3:34:36 PM	NCG	BRD	7.47E-01	2.63E-01	-5.43E-04	
	LDS	3:33:18 PM	NCG	BRD	7.07E-01	2.40E-01	-2.27E-04	
	LDS	3:33:13 PM	NCG	BRD	7.48E-01	2.67E-01	-1.52E-04	
	LDS	3:33:05 PM	NCG	WRD	7.80E-01	2.83E-01	-4.58E-02	
	DTN	3:53PM						
	LDS	3:53:58PM	NCG	WRD	9.99E-01	8.53E-01	-8.63E-02	
17-Dec-20	DTN	3:56 PM						
	LDS	3:55:40 PM	NCG	BRD	3.28E-01	3.19E-01	-3.09E-03	
	LDS	3:55:30 PM	NCG	BRD	2.60E-01	2.60E-01	-4.54E-01	
	LDS	3:52:08 PM	NCG	BRD	4.22E-01	4.12E-01	-3.70E-03	
	LDS	3:48:56 PM	NCG	BRD	2.20E-01	2.20E-01	-1.76E-01	
	LDS	3:45:36 PM	PCG	WRD	2.68E-01	2.70E-01	-1.00E+00	
	LDS	3:45:01 PM	NCG	BRD	2.79E-01	2.84E-01	-4.15E-01	
	LDS	3:41:21 PM	NCG	BRD	1.39E-01	1.40E-01	-4.51E-01	
	LDS	3:36:12 PM	IC	BRD	2.40E-01	2.40E-01	-2.70E-01	
	DTN	4:04 PM						
	LDS	3:59:36 PM	NBE	BRD	1.61E-02	4.98E-03	-1.95E-01	
	LDS	3:59:04 PM	NCG	BRD	3.11E-01	3.03E-01	-2.83E-03	
	DTN	4:19 PM						
	LDS	4:13:15 PM	NCG	BRD	3.32E-01	3.22E-01	-2.17E-03	
24-Dec-20	DTN	11:38 AM						
	LDS	11:30:04 AM	PCG	BRD	2.29E-01	2.33E-01	-1.00E+00	
	LDS	11:25:25 AM	NCG	BRD	4.18E-01	4.14E-01	-5.69E-01	
	LDS	11:23:43 AM	PCG	WRD	3.20E-01	3.20E-01	-1.00E+00	
	LDS	11:22:23 AM	PCG	WRD	4.18E-01	4.17E-01	-2.59E-01	
26-Dec-20	DTN	2:52PM						
	LDS	2:52:24PM	NCG	WRD	7.48E-01	8.34E-01	-4.56E-01	
	LDS	2:48:53PM	NCG	WRD	2.95E-01	3.59E-01	-4.95E-01	
	DTN	3:07PM						
	LDS	3:04:51PM	NCG	BRD	2.60E-01	2.59E-01	-2.12E-02	
	DTN	3:08PM						
	LDS	3:08:56 PM	NCG	WRD	5.87E-01	6.50E-01	-5.64E-01	
	DTN	3:49PM						
	LDS	3:33:54PM	NCG	WRD	1.00E+00	1.00E+00	-5.36E-01	
	LDS	3:30:25PM	NCG	WRD	1.00E+00	1.00E+00	-5.39E-01	
	DTN	3:56PM						
	LDS	3:56:56PM	NCG	WRD	1.00E+00	1.00E+00	-5.71E-01	
	LDS	3:52:20PM	NCG	BRD	2.77E-01	2.96E-01	-4.39E-01	
	LDS	3:51:03PM	NCG	BRD	7.47E-01	7.50E-01	-1.97E-01	
	DTN	4:57PM						
	LDS	4:56:04PM	NCG	BRD	1.98E-01	1.52E-01	-3.03E-01	
	LDS	4:54:15PM	NCG	BRD	1.63E-01	1.40E-01	-4.32E-01	
	LDS	4:51:07PM	NCG	BRD	2.08E-01	1.15E-01	-4.16E-01	
	LDS	4:48:37PM	NCG	BRD	1.71E-01	1.31E-01	-3.17E-01	
	LDS	4:44:39PM	NCG	BRD	2.96E-01	2.96E-01	-2.84E-01	
	LDS	4:42:03PM	NCG	WRD	1.00E+00	1.00E+00	-6.26E-01	
	DTN	7.33PM						
	LDS	7:33:00PM	IC	WRD	2.25E-01	2.25E-01	-3.80E-01	
27-Dec-20	DTN	3:52PM						
	LDS	3:52:25PM	NCG	WRD	1.74E-01	2.66E-01	-4.26E-01	
	DTN	4:15PM						
	LDS	4:02:01PM	NCG	WRD	6.98E-01	7.62E-01	-4.47E-01	
	LDS	4:00:12PM	NCG	WRD	1.00E+00	1.00E+00	-4.03E-01	
	DTN	6:14PM						
	LDS	5:58:49PM	NCG	BRD	2.23E-01	2.24E-01	-1.97E-01	
	DTN	6:29PM						
	LDS	6:28:27PM	NBE	BRD	2.04E-01	2.29E-01	-2.99E-02	
	LDS	6:25:31PM	NCG	BRD	2.16E-01	2.16E-01	-4.57E-02	
	DTN	6:44PM						
	LDS	6:33:00 PM	NCG	WRD	3.62E-01	3.60E-01	-3.77E-01	

Figure 6. Comparison on studies used Lightning Detection System (LDS) and Data Transmission Network (DTN) system

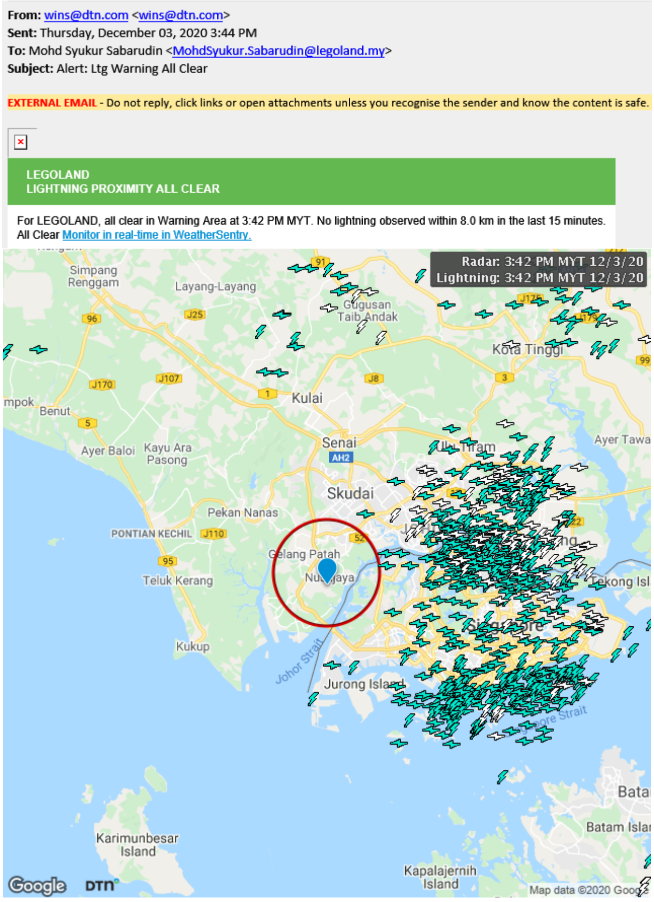

Figure 7. DTN data, no lightning observed within 8 km in the last 15 minutes captured at 3:42 PM on December 3rd, 2020

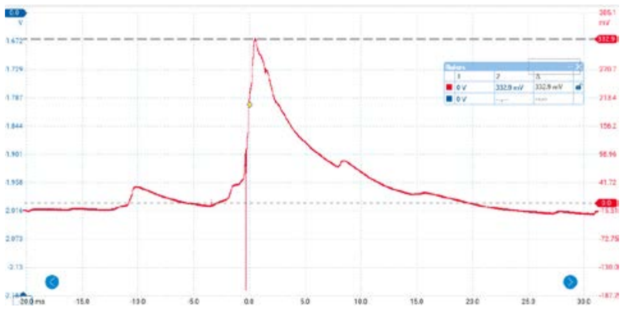

Figure 8. LDS data, slow electric field waveform captured at 3:24:21 PM on December 3rd, 2020, type of lightning is intracloud (IC) and it is within reversal distance (WRD) with return stroke amplitude 3.33E-01 and static amplitude -1.76E-01

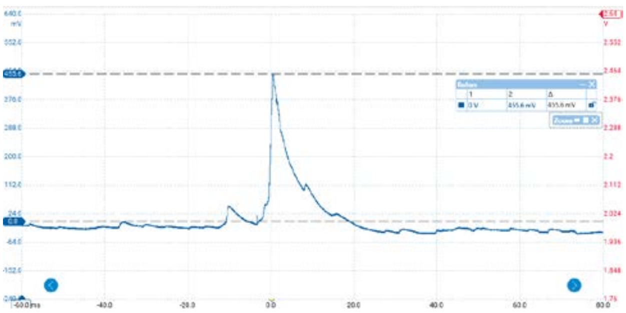

Figure 9. LDS data, fast electric field waveform captured at 3:24:21 PM on December 3rd, 2020, type of lightning is intracloud (IC) and it is within reversal distance (WRD) with amplitude 4.55E-01

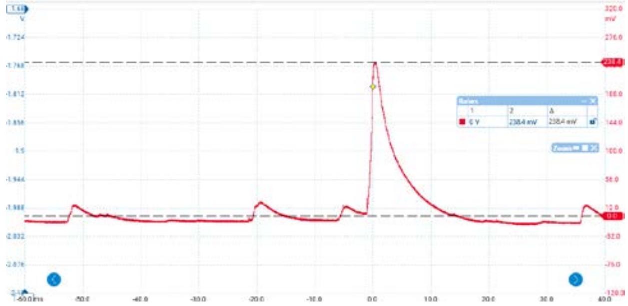

Figure 10. LDS data, slow electric field waveform captured at 3:09:26 PM on December 3rd, 2020, type of lightning is intracloud (IC) and it is within reversal distance (WRD) with return stroke amplitude 2.38E-01 and static amplitude -5.45E-01

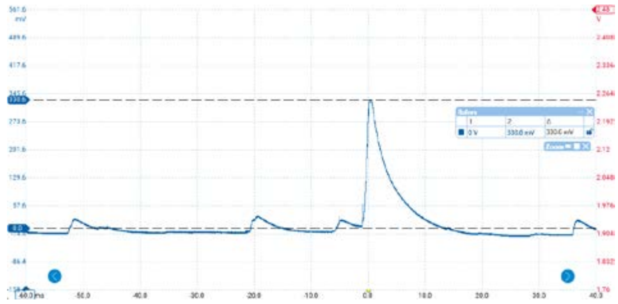

Figure 11. LDS data, fast electric field waveform captured at 3:09:26 PM on December 3rd, 2020, type of lightning is intracloud (IC) and it is within reversal distance (WRD) with amplitude 3.30E-01

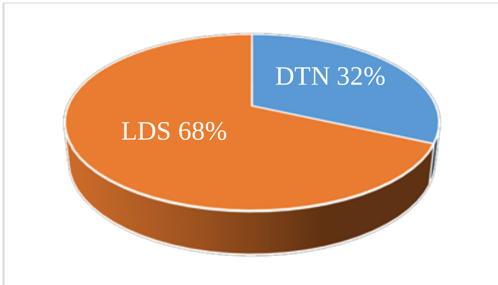

Figure 12. Pie chart shows the percentage of lightning detection efficiency between DTN and LDS

Figure 12 illustrates a comparison of lightning detection efficiency between DTN and LDS, revealing a significant difference, with the LDS achieving a detection efficiency of 68.9%. This efficiency was supported by research published by M.H.M.Sabri [3] and Shamsul Ammar Shamsul Baharin [20]. The data suggests that the LDS is significantly more effective in detecting lightning strikes compared to the DTN. A pie chart accompanying the figure demonstrates that the LDS detects 68% of lightning strikes, while the DTN captures only 32%. This heighten sensitivity of LDS suggests its ability to identify weaker lightning signals and filter out potential noise and interference, indicating superior performance in lightning detection.

The strategic installation of the LDS within LEGOLAND Malaysia Resort contributes to its efficiency by enabling direct and immediate data capture and analysis. In contrast, the undisclosed location of the DTN introduces uncertainties regarding its proximity to LEGOLAND Malaysia Resort, potentially impacting its overall effectiveness. Moreover, the DTN's reliance on email for information transmission can cause delays in delivering data to end-users.

Based on Figure 6 and the undisclosed location of the DTN system and sensors, it can be concluded that the data produced by DTN provides only a single data point for each lightning event, whereas the LDS recodes a detailed series of data points for each occurrence. The LDS's ability to capture multiple data points for each lightning event contrasts with the DTN's limitation of recording only one lightning event at a time.

The enhanced detection efficiency of the LDS offers several benefits, including more accurate and timely lightning strike warnings, detailed information on lightning strike distribution, and precise data on strike intensity. Conversely, the DTN fails to detect the majority of lightning strikes, primarily due to its limited detection range. Various factors, such as insufficient detectors in certain areas, terrain obstacles, and the weakness of lightning signals, contribute to this limitation. Inefficiencies in the detection device used by the DTN may also play a role.

The implications of the DTN's inability to detect the majority of lightning strikes are significant. It hampers the study of lightning strike distribution, complicates the development of accurate lightning forecasting models, and undermines efforts to warn people about the dangers of lightning strikes. Given that this research focuses on LEGOLAND Malaysia Resort, where visitor safety is a paramount priority, an inefficient lightning detection system poses potential risks. Improving lightning detection through technological advancements, enhanced education, and awareness campaigns is recommended. Strategically placing lightning detection systems within LEGOLAND Malaysia Resort and prioritizing public education about lightning dangers are crucial steps to ensure faster and more accurate dissemination of lightning-related information.

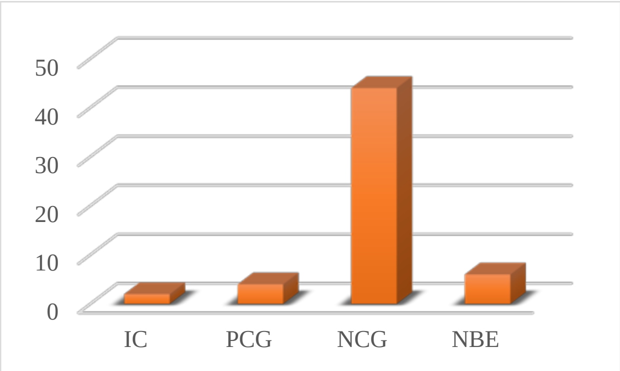

Figure 13. Bar chart shows the frequency of lightning types that occurred in LEGOLAND Malaysia Resort for the month of December 2020

The bar chart in Figure 13 provides insights into the types of lightning occurrences at LEGOLAND Malaysia Resort during December 2020. Negative cloud-to-ground (NCG) lightning emerges as the most prevalent type, constituting over three-quarters of all lightning strikes. Narrow bipolar event (NBE) lightning follows as the second most common, accounting at 11%. Positive cloud-to-ground (PCG) lightning is the least common among cloud-to-ground strikes, representing 7%, while intracloud (IC) lightning makes up 4% of the strikes.

Negative cloud-to-ground (NCG) lightning is a widespread phenomenon globally, comprising approximately 70% of all lightning strikes. It results from the discharge of a negatively charged region in the lower part of a thunderstorm cloud towards the positively charged ground, creating a luminous, branched channel. NCG lightning is typically more powerful and can be hazardous.

Narrow bipolar events (NBE) are intriguing and relatively mysterious lightning events that occur entirely within the cloud. Their short duration, typically lasting only around 10-20 microseconds, makes them barely visible to the naked eye. NBEs exhibit a bipolar waveform in their electrical discharge signature, with a rapid positive pulse followed by a negative one. These events often happen in the upper regions of thunderstorms and are generally less powerful than other types of lightning but can still pose a danger.

Positive cloud-to-ground (PCG) lightning, while less common, involves a positive charge transfer from the cloud to the ground. This occurs due to complex interactions within the storm cloud, leading to a buildup of positive charge at the bottom. PCG lightning is powerful and potentially dangerous, emphasizing the need for vigilance and precautions during thunderstorms, particularly in open areas or near trees.

Intracloud (IC) lightning, often referred to as "sheet lightning," is a mesmerizing phenomenon that stays entirely within the cloud, illuminating its depths with brilliant flashes. IC lightning results from charge imbalances within a thunderstorm cloud, with strong updrafts and collisions between ice particles separating positive and negative charges. While IC lightning is not a direct threat to people on the ground, it serves as an indicator of the presence of a thunderstorm capable of producing cloud-to-ground strikes.

It is crucial to note that all types of lightning can be dangerous, and taking shelter during a thunderstorm is essential for safety.

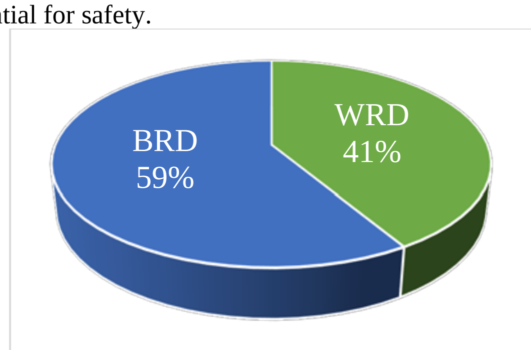

Figure 14. Pie chart shows the percentage of lightning distance that occurred in LEGOLAND Malaysia Resort for the month of December 2020

The pie chart in Figure 14 provides insights into the distribution of lightning strikes based on their proximity to the reversal distance (RD). Within the reversal distance (WRD), which refers to the distance from the cloud base where conditions favor branching or changes in the lightning channel's direction, 41% of lightning strikes occur. In this region, the electric field is sufficiently strong, and the density of charged particle is high, supporting the formation of new channels or redirection of existing ones. This often results in intricate branching patterns and forks commonly observed in lightning.

On the other hand, 59% of lightning strikes occur beyond the reversal distance (BRD), where conditions for branching or redirection are less favorable. In this region, the electric field weakens, and the density of charged particles decreases, making it less likely for new channels to form or for existing channels to change course. Lightning strikes beyond the reversal distance tend to exhibit a more linear and less branched pattern.

Typically, the reversal distance within the WRD is considered to be less than 1 kilometer from the cloud base. Within this distance, the electric field is strong enough to facilitate branching and reformation of the lightning channel, resulting in a forked and jagged appearance. Beyond the reversal distance (BRD), the distance is typically greater than 1 kilometer from the cloud base. Here, the weakening electric field makes significant branching less likely, leading to a more linear appearance of the main lightning channel.

It is important to note that the exact value of the reversal distance can vary based on factors such as the strength of the electric field, the density of charged particles, and the humidity of the air. Additionally, lightning patterns can be influenced by geographical and seasonal factors.

IV. DISCUSSION

The introduction of the new lightning detection system at LEGOLAND Malaysia Resort signifies a significant leap forward in lightning detection technology. This cutting-edge system integrates both fast and slow electric field sensors, providing a holistic approach to analyzing lightning event. The fast electric field sensor captures frequencies ranging from 0 to 30MHz, while the slow electric field sensor focuses on frequencies from 0 to 10kHz. This dual-sensor setup offers a more comprehensive and precise understanding of lightning occurrences [3,20].

The decision to combine these sensors serves multiple purposes. Firstly, the complementary frequency ranges ensure that a wider spectrum of lightning phenomena is captured, enhancing the system's overall effectiveness. Secondly, the fast electric field sensor acts as a reference for data validation, verifying the accuracy and utility of the slow electric field sensor data. This validation is pivotal for conducting rigorous research and facilitates meaningful comparisons with other lightning detecting systems. Additionally, the simultaneous detection requirement by both sensors serves as a robust fault detection mechanism, flagging potential issues or noise in the system that may require troubleshooting.

Proper grounding emerges as a fundamental consideration in the functionality of the system. It serves as the bedrock for a reliable electronic setup, ensuring seamless signal flow and optimal device performance. The strategic placement of the lightning detection system is highlighted as another critical factor. By locating the system strategically, accurate detection and tracking of lightning strikes in high-priority areas become possible, minimizing interference from other electrical sources.

A noteworthy aspect of the analysis is the comparison of the system's efficiency with that of the DTN. The system installed at LEGOLAND Malaysia Resort, which is the LDS outperforms the DTN, with the advantage of being situated in a known and specific area. This strategic placement enables the system to provide early warnings, proactive measures, and real-time detection of lightning strikes. Moreover, the project is recognized for pioneering the analysis of slow electric field data for lightning detection, contributing valuable insights to the broader field of research and development in lightning detection technology.

V. CONCLUSION

In conclusion, this research marks a significant achievement in the development and evaluation of a real-time short-range lightning detection system. The incorporation of novel slow atmospheric electric field waveform analysis has resulted in the successful implementation of this cutting-edge system at LEGOLAND Malaysia Resort. The system demonstrates a high level of accuracy and efficiency in detecting lightning strikes within a critical 7-8km radius [1-3,20], making substantial contributions to guest safety and operational effectiveness.

The unique insights derived from the analysis of slow atmospheric electric field waveforms not only validate the system's effectiveness but also open avenues for substantial advancements in lightning detection technology. The successful application of this system in a real-world setting underscores its practicality and reliability. The research outcomes encourage further exploration, particularly in expanding the system's range and investigating its potential application in broader contexts beyond the specific setting of LEGOLAND Malaysia Resort.

This research serves as a foundation for ongoing efforts to enhance lightning detection capabilities, emphasizing the importance of continuous innovation in ensuring public safety and operational resilience. The successful deployment of this lightning detection system in a renowned international theme park exemplifies the practical implications and benefits of cutting-edge technological solutions in real-world scenarios.

ACKNOWLEDGMENT

This research work is funded by Ministry of Higher Education (MOHE) by Fundamental Research Grant Scheme (FRGS) with reference code FRGS/1/2022/TK07/UTEM/02/15. This research extends its gratitude to LEGOLAND Malaysia Resort for their cooperation and granting permission to install sensors on their premises, facilitating the collection of valuable data for this study.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

AUTHOR CONTRIBUTION

The authors confirm contribution to the paper as follows: study conception and design: Erman Ramli, Mohd Riduan Ahmad; data collection: Erman Ramli; analysis and interpretation of findings: Erman Ramli, Mohd Riduan Ahmad; draft manuscript preparation: Erman Ramli, Mohd Riduan Ahmad, Muhammad Abu Bakar Sidik. All authors had reviewed the findings and approved the final manuscript.

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