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Localised Single-Station Lightning Detection by Using TOA Method

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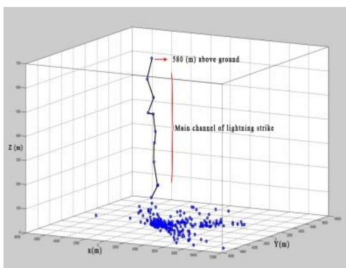
Graphical abstract



Abstrak

Lightning is an electrical discharge during storms that can be monitored continuously from certain distances. It can be either within clouds (intra cloud), or between clouds and the ground (cloud-ground). There are various techniques used nowadays to locate lightning, and to determine various parameters produced from lightning. Each technique provides its own claimed performances. This paper attempts to provide instantaneous detection of lightning strike lightning location using the Time of Arrival (TOA) method of a single detection station (comprises of four antennas). It also models the whole detection system using suitable mathematical equations so as to give some understanding on the differences between the measured and calculated (theoretical) results. The measurement system is based on the application of mathematical and geometrical formulas. Several parameters such as the distance from the radiation source to the station and the lightning path are significant in influencing the accuracy of the results (elevation and azimuth angles). The role of each parameter is examined in detail using Matlab. This study solved the resultant non-linear equations by Newton-Raphson techniques. Methods to determine the radiation source which include the exact coordinate of a given radiation source in 3-dimensions were also developed. Further clarifications on the cause of errors in the single-station TOA method and techniques to reduce the errors are given.

Keywords: Lightning locating; time of arrival; short baseline

Abstrak

Kilat adalah satu pelepasan elektrik semasa ribut yang boleh dipantau secara berterusan dari jarak tertentu. Ia boleh ditentukan sama ada di dalam awan (awan intra), atau antara awan dan tanah (awan-tanah). Terdapat pelbagai teknik yang digunakan pada masa kini untuk mencari lokasi kilat dan untuk menentukan pelbagai parameter yang dihasilkan daripada kilat. Setiap teknik menggunakan cara-cara tertentu yang telah ditetapkan. Kertas kerja ini cuba untuk menyediakan pengesanan serta-merta lokasi kilat dan pancaran kilat menggunakan kaedah masa ketibaan (TOA) sebuah stesen pengesanan tunggal (terdiri daripada empat antena). Ia juga menunjukkan sistem pengesanan keseluruhan yang menggunakan persamaan matematik yang sesuai untuk memberikan sedikit pemahaman tentang perbezaan antara pengukuran dan pengiraan teori. Sistem pengukuran adalah berdasarkan aplikasi formula matematik dan geometri. Beberapa parameter seperti jarak dari sumber radiasi ke stesen dan laluan kilat adalah penting dalam mempengaruhi ketepatan keputusan (ketinggian dan sudut azimut). Peranan setiap parameter dikaji secara terperinci dengan menggunakan Matlab. Kajian ini menyelesaikan persamaan bukan linear yang dihasilkan oleh teknik Newton- Raphson. Kaedah untuk menentukan sumber sinaran yang termasuk koordinat sebenar sumber sinaran yang diberikan dalam 3-dimensi juga telah dibangunkan. Penjelasan lanjut mengenai punca kesilapan dalam stesen tunggal TOA kaedah dan teknik-teknik untuk mengurangkan ralat seperti yang diberikan.

Kata kunci: Penentuan lokasi kilat; masa ketibaan; garis dasar yang pendek

1.0 INTRODUCTION

Nowadays, the higher is the rate of urbanism and building construction especially in tropical areas, the bigger concern is on the safety of facility and human beings due to lightning strikes. Issues related to lightning locating systems are actively being researched. The research is very useful for the purpose of human safety and for lightning protection system. It can also benefit the insurance companies and weather forecast organizations. Stepped leaders propagate electromagnetic waves in the range of kHz-GHz within an electrical discharge [1]. There are several available methods to analyze and locate lightning signals such as the time of arrival [2, 3], magnetic direction finding, and interferometry methods. One possible way to increase the accuracy of the location is to combine two or more locating methods as one measurement system [4]. A new method to determine the location of lightning strike with a better accuracy, based on the measurement of induced voltages due to lightning in the vicinity of an existing overhead telephone lines is proposed [5]. In this work, the TOA method is used for locating lightning due to its many advantages.

However, there are many factors that influence the accuracy of the TOA technique using the short baseline configuration. Among the factors are the mathematical models of measurement system adopted, the length of recorded lightning signal and the origin of lightning signal.

The TOA method detects the electromagnetic waves arrival at the antennas and computes the time difference of arrival. To accomplish this, the detected signals should be properly captured and stored. Generally, the amount of data storage involved is huge and costly. The sequential triggering method had been used to overcome the problem. Various methods can be used to analyze the captured waves.

With the help of several geometric formulas, the azimuth and elevation angles of the radiation source can be determined. Together these angles specify the locus of the radiation source [6]. The 3D results can be further analyzed and examined to achieve more exact results [7]. This involves analyses of the 3D waves, application of mathematical formulas and non-linear equations [1].

The Newton-Raphson and Gauss-Seidel techniques can be used to solve the non-linear equations. However, some problems may result, such as the existence of negative coordinates.

Genetic algorithm is another method to solve the non-linear equations [8]. Using this method, errors, such as due to the interferences during wave propagation can be eliminated. Extinguished branches within a step leader can be a source of interference since their corresponding electromagnetic radiation signals will also be captured along the main lightning channel [9]. In the modeling work, significant errors for the azimuth and elevation angles determination based on the TOA method were found. These errors are also previously reported in the 3D lightning locating analyses [10-14]. In this work, LabVIEW based cross correlation technique is used to determine the time delays. The LabVIEW software has the advantage of low cost and short processing time [15]. This paper aims to map a cloud-to-ground lightning strike for short base-line configuration.

■2.0 METHODOLOGY

The geometry of the installed antennas is shown in Figures 1 and 2. The system consists of four circular plate antennas. Three of them are placed 14.5 meter apart to form two perpendicularly base lines, and the fourth one is diagonally located at 75.58 meter distance away. The antenna output signals were fed into a four-channel digital oscilloscope (Tektronix MSO4104) operating at 8-bit, 5Gs/s using three 50 m long coaxial cables (RG 59, 75 Ω), and one 100 m coaxial cable connected to the fourth antenna.

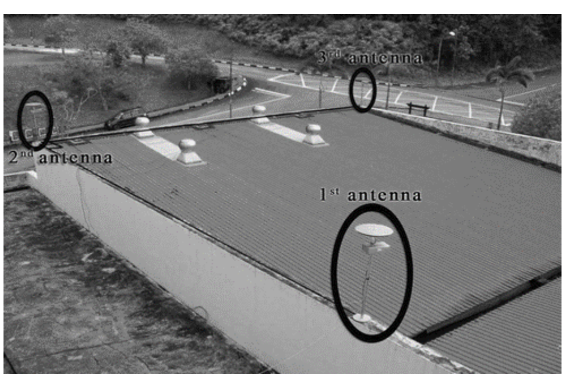


Figure 1 The location of 1st, 2nd and 3rd antennas

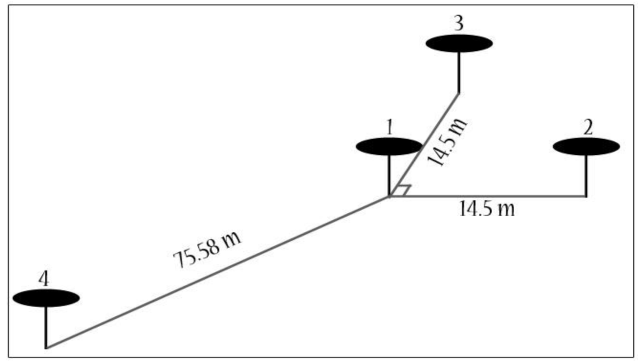


Figure 2 The baseline geometry for lightning locating using four antennas

2.1 Direction Analysis

The fundamental concept of this TOA technique is to determine the time delay of arrival between signals impinging on a pair of antenna. The simple TOA is composed of two antennas. Consider two broadband antennas set apart in a horizontal position on the ground by a distance d, as shown in Figure 3. The signals which come from a common source detected by antenna 1 is r_1 (t) and by antenna 2 is r_2 (t). Assuming that the radiation source is very far compared to the distance d, the incident angle can be expressed by:

$$\theta = \cos^{-1}\left(\frac{c.\Delta t}{d}\right) \quad (1)$$

where 'c' is the light speed in space ($3*10^8$ m/s), and □t is the time delay of arrival. By applying two-antenna sensors, only one dimension localization can be obtained [3].

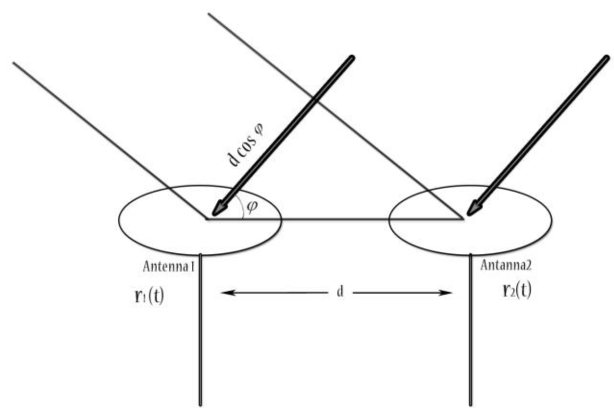


Figure 3 Direction of radiation source estimated using two antennas sensors in TOA technique

2.2 Direction Finding by Three Antennas

By implementing two-antenna sensors, only one-dimension localization can be obtained. To provide the location in a two-dimension (2D), a third antenna should be added. This extra antenna can determine the elevation and azimuth angles. The first and second antennas form the first base line, while the second and third antennas form the second base line. These two base lines are perpendicular to each other. This is shown in Figure 3.

As can be seen in equations (2) and (3) the time differences between antennas 1, 2 and 3, are as follows:

$$t_{21}=t_2-t_1 \tag{2}$$

$$t_{23}=t_2-t_3 \tag{3}$$

Here, t_1, t_2, and t_3 are the arrival times of signals at antennas 1, 2, and 3, respectively. With the help of Figure 4, the incident angles of the radiation source for the base lines of antennas 2 and 1 (θ_{21}), and antennas 2 and 3 (θ_{23}), can be determined by the following relations:

$$t_{21}=\frac{d\cos\theta_{21}}{c} \tag{4}$$

$$t_{23}=\frac{d\cos\theta_{23}}{c} \tag{5}$$

It is more comprehensible to describe the lightning source in the elevation and azimuth format compared to the incident angles. Hence, the incident angles obtained by above equations were converted to elevation and azimuth. From Figure 4:

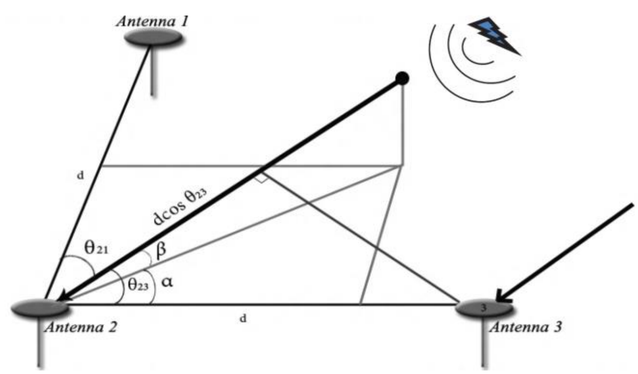


Figure 4 Schematic description of the geometry of three antennas location and the radiation source direction

$$\cos\theta_{21}=\cos\beta\sin\alpha \tag{6}$$

$$\cos\theta_{23}=\cos\beta\cos\alpha \tag{7}$$

Using equations (4) to (7) the elevation (β) and azimuth (α) can be obtained.

$$\alpha=\tan^{-1}\left(\frac{t_{21}}{t_{23}}\right) \tag{8}$$

$$\beta=\cos^{-1}\left(\frac{c\sqrt{t_{21}^2+t_{23}^2}}{d}\right) \tag{9}$$

2.3 Direction Finding by Four Antennas

A principle of mapping the radiation sources in three spatial dimensions is shown in Figure 5. The position of the antenna 2 is assigned to be the reference point with the coordinate of (0, 0, 0). The antenna 4 and the radiation source coordinates are represented by (x_1, y_1, z_1), (x, y, z) respectively. Since the direction of the radiation is known, y and z can be written as type of scanning

$$y=x\times\tan\alpha \tag{10}$$

$$z=\sqrt{x^2+(x\tan\alpha)^2}\tan\beta \tag{11}$$

which are the functions of x. The distance from the antenna 2 and antenna 4 to the radiation source (r_1 and r_2, respectively) are given by:

$$r_1=\sqrt{x^2+y^2+z^2} \tag{12}$$

$$r_2=\sqrt{(x-x_1)^2+(y-y_1)^2+(z-z_1)^2} \tag{13}$$

The coordinates of the radiation sources can be determined by the following equation:

$$r_1 - r_2 = ct_{24} \tag{14}$$

where t_{24} is the difference of arrival time of the pulses between antennas 2 and 4 if we substitute r_1 and r_2 from equations (12) and (13) in equation (14) and use relations (10) and (11), the equation can be rearranged to yield f(x)= 0.

This nonlinear equation can be solved for x by the numerical techniques. The values y and z can be determined by equations (10) and (11), respectively after getting the x value [3].

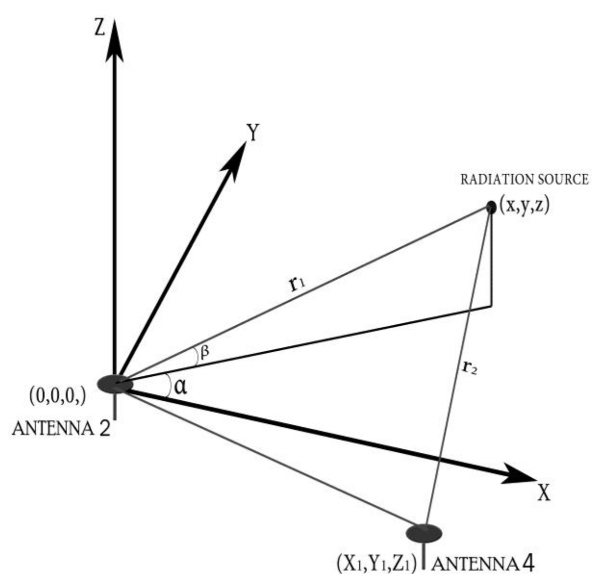


Figure 5 Schematic descriptions of the geometry of two antennas and the position of radiation source

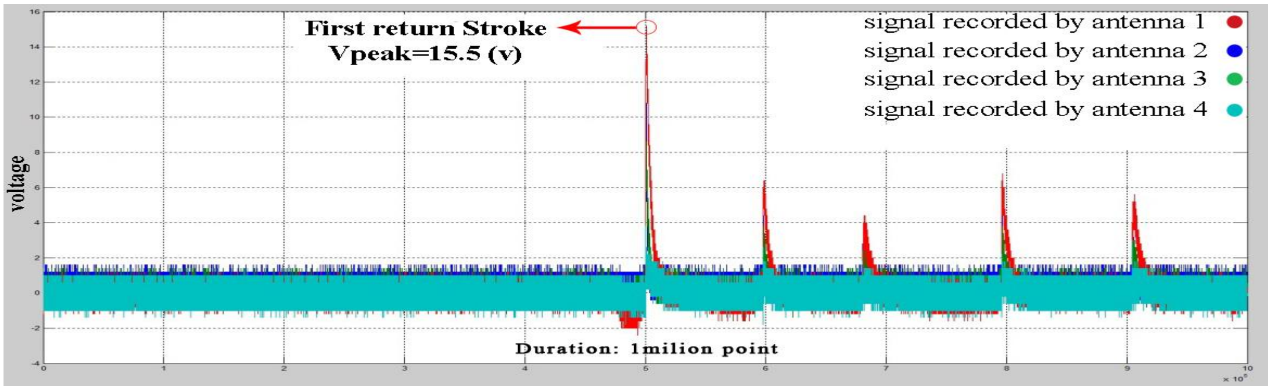


Figure 6 Signals recorded by the total of four antennas on 16 April 2011 with 400 ms of time frame(one million point recorded with 400ns sampling rate)

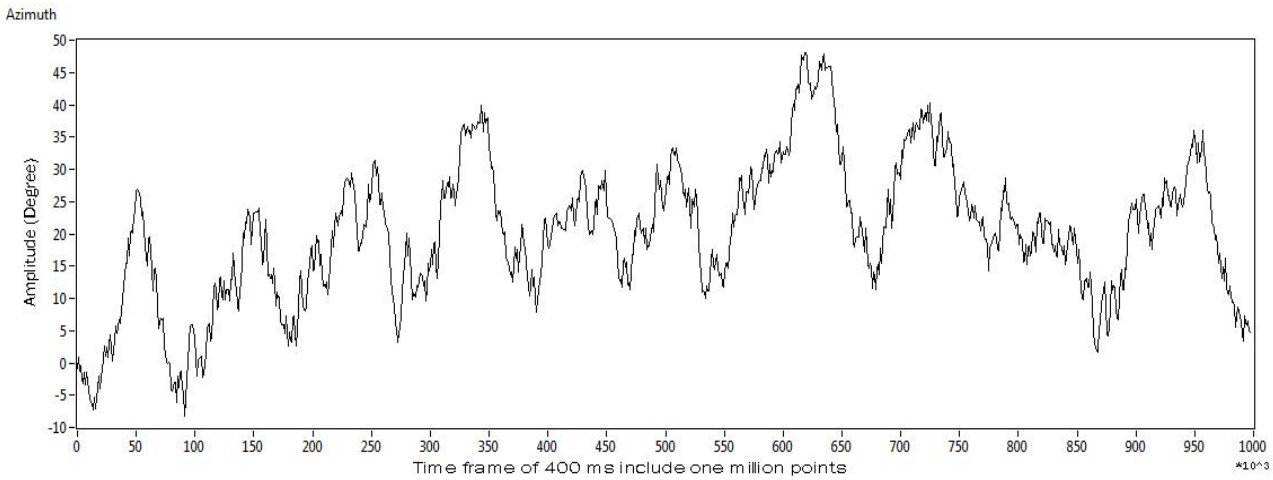


Figure 7 The azimuth of signals recorded by the total of four antennas on 16 April 2011 with 400 ms of time frame(one million point recorded with 400ns sampling rate) via cross-correlation method in the time domain

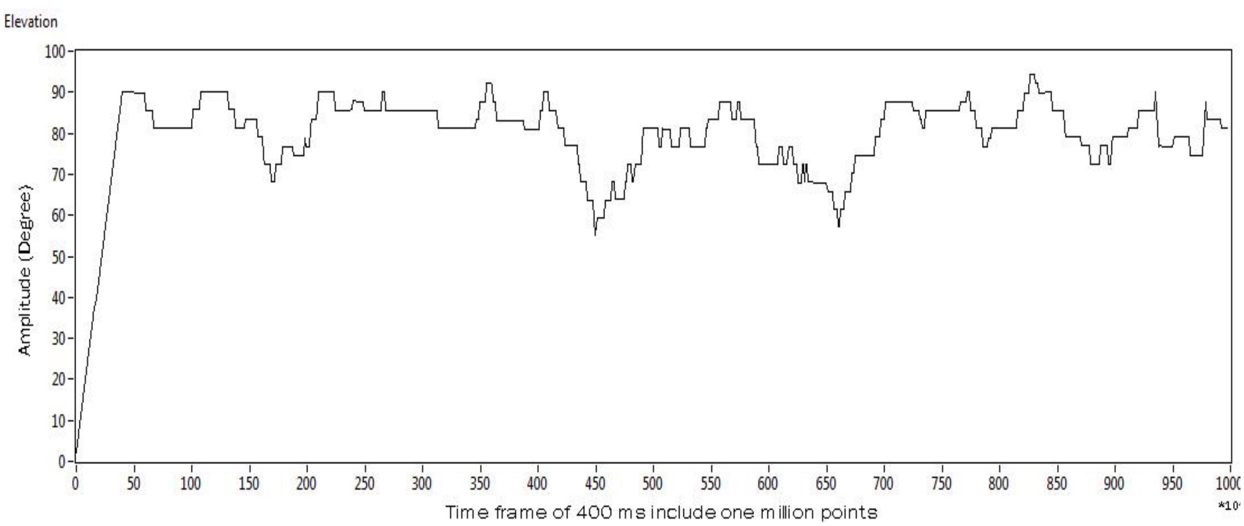


Figure 8 The elevation of signals recorded by the total of four antennas on 16 April 2011 with 400 ms of time frame(one million point recorded with 400ns sampling rate) via cross-correlation method in the time domain

3.0 RESULTS AND DISCUSSION

This part explains how the verifications for lightning signals are made. When lightning occurs, the antennas start to capture a variety of shapes of lightning signals; the magnitude of the signal is dependent on the lightning strength and its distance from the antennas. The following signals (shown in Figure 6) were recorded on 16 April 2011 (during thunderstorm in a total of one hour duration) one lightning sample was analyzed by measuring the peak voltage. The maximum peak voltage is 15.5 V. Figures 7 and 8 illustrate the calculated azimuth and elevation angles of lightning signals based on mentioned formula (α, β) in time domain. The amplitude is in degrees. Although Figures 7 and 8 displays the location of radiation source, it can be observed that the quantity of degree is fluctuated between 60 to 90 and -8 to 48 and these transforms are due to some reasons such as rapid changing in lightning path, noise effect, and signal interferences. In this work, using mathematical simulation with LabView, it is shown that, the TOA method is roughly accurate to calculate azimuth and elevation. The distance between antennas, and also the use of long cables are among the causes of problems which affect the results.

The coordinate of lightning source is plotted in Figure 9. From the result, it can be seen that the coordinate of lightning location source is totally random. Most of the points are distributed on the ground and the pattern of the coordinate is strange. The Matlab programming already show that the beta equation has some error, and this error contribute to the huge error when it comes to calculate the x, y and z points. So, the coordinate of lightning source is including some wrong points.

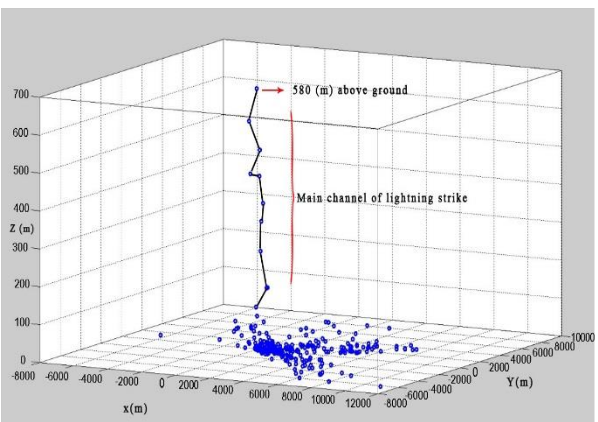


Figure 9 Three-dimensional mapping of flash in x–y–z space

The errors observed can be attributed to two factors, namely the limitation of the measuring system, and the assumptions made in deriving the equations for the azimuth and elevation. In particular, in deriving the equation for azimuth (Eqn. 9), it was assumed that the signal source is very far away and hence the two arriving signals are in parallel (Figure 3).

4.0 CONCLUSION

A parallel plate antenna system with the aim of locating the cloud-to-ground lightning strike has been utilized for short base-line configuration. The time domain signal analysis in this study was conducted to determine the time difference of the broadband VHF electromagnetic pulses detected by the sensors. The cross correlation technique was applied with the purpose of maintaining the high resolution analyses. According to the conducted experiment, the TOA method is suitable for lightning locating system in 2D mode. However there are many considerations before and during detection of lightning location. The lightning position due to lightning detection must be within certain area which is not affected by other signals or noises. As the results of this study illustrated, the present system successfully maps a cloud-to-ground lightning discharge in 3D mode.

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