A METHODOLOGY FOR MATCHING LIGHTNING DETECTION NETWORK DATA WITH GROUND-TRUTH RECORDS

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Declaration

I declare that this dissertation is my own, unaided work, other than where specifically acknowledged. It is being submitted for the degree of Master of Science in Engineering in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other university.

Signed this _____ day of _______________ 2012

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Hugh Gordon Patrick Hunt

Abstract

In this dissertation a methodology of matching external ground-truth records of lightning events with data reported by a Lightning Detection Network (LDN) is investigated. The methodology allows for matching events where the time of the ground-truth record is unknown. It is shown that the location accuracy of an LDN is affected by the number of sensors that are able to detect lightning strokes and this observation is then used to define criteria for matching lightning strokes with LDN data. An evaluation of the methodology is presented in which the results of applying the methodology are compared with the results of a known methodology (time correlation) to determine if the same data is extracted. Photographs of lightning attachment to the Brixton tower in Johannesburg, South Africa are used as ground-truth events and LDN data is obtained from the South African Lightning Detection Network (SALDN). A practical application, in the context of an insurance claim scenario, is also presented in which the methodology is used to determine whether lightning is the cause of damage to a tree and when this may have occurred. It is found that the methodology extracts many of the possible strokes but that it also returns false positive results and makes some false exclusions. It is concluded that the proposed methodology should be used as a "filter" to reduce a dataset of LDN records but that corroborating evidence is required if the methodology is to be used as intended.

To my loving family: mom, dad, Cordelia and Miranda.

To my brothers: Phillip, Justin and Adam

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Chapter 1

Introduction

Lightning Detection Networks (LDNs) form a large component of research and understanding of the meteorological nature of lightning. They are becoming increasingly used in other applications: specifically, to determine whether lightning was the possible cause of events such as a transmission line fault, property damage or loss of life. In many cases the exact time of these events is not always accurately known making comparison of events with LDN data difficult. It is important that the information provided by a LDN is understood correctly so that the correct information is extracted. This is especially true in cases of property damage or injury/loss of life where LDN data is to be used as the deciding factor in insurance claims or as evidence.

This dissertation proposes a simple methodology to correctly match data provided by a LDN with ground-truth lightning events independent of time information. The structure of the dissertation is as follows:

Chapter 2 discusses background information associated with LDNs. Previous research on LDNs is provided which demonstrates the relationship between number of reporting sensors and location accuracy. A brief outline of the methods used in determining the position of a lightning stroke are described in order to explain these observations. Previous research involving the matching of LDN data with real ground-truth evidence of lightning is provided. Finally, background information on photography of tall towers in Johannesburg, South Africa is provided.

Chapter 3 provides an overview of the work addressed in this dissertation. The problem statement, the proposed solution and the steps taken to investigate the effectiveness of the proposed solution are provided. This involves comparison of photographic evidence of lightning discharges to the Brixton tower, South Africa with reported data from the South African Lightning Detection Network (SALDN).

Chapter 4 proposes a methodology to match data from LDNs with possible lightning events where the exact time of the event is unknown. This chapter discusses the overall methodology as well as the reasons and assumptions behind the necessary steps - these include defining a location of interest, the extracting of the relevant data from the LDN database, determining the distance between locations and the criteria used to match LDN data to the event.

Chapter 5 presents an evaluation of the methodology proposed in *Chapter 4*. Two investigations are performed: one in which ground-truth lightning events are matched to LDN data using time correlation methods and one in which ground-truth lightning events are matched to LDN data using the proposed methodology. A comparison of the results of the two investigations allows for an evaluation of the proposed methodology.

Chapter 6 presents a practical application of the proposed methodology. The methodology is applied to determine if lightning is the possible cause of damage to a tree that appears to have been struck and to see if the date and time of the event may be established. The scenario can be likened to a situation in which the LDN data is to be used as a deciding factor for an insurance claim.

Chapter 7 discusses the observations made in chapters 5 and 6 that were unexpected in the evaluations and revealed possible flaws in the methodology. Solutions to these observations and the future work needed to achieve them are discussed.

Chapter 8 discusses the findings of this dissertation and provides a conclusion to the work.

Appendix A provides the photographs used in *Chapter 5* to perform the evaluation of the methodology proposed in *Chapter 4*. The photographs are of lightning attachment to the Brixton tower in Johannesburg, South Africa.

Appendix B is a paper that was accepted and presented for publication by the *International Conference on Atmospheric Lightning (ICAE)* in 2011, hosted in Rio de Janeiro, Brazil. The paper is entitled: **Investigation of Method for Matching Lightning Detection Network Data with Ground-truth Records**.

Appendix C is a paper that was accepted and presented for publication by the *International Conference on Grounding and Earthing & 4th International Conference* *on Lightning Physics and Effects Conference (LPE)* in November 2010, hosted in Salvador, Brazil. The paper is entitled: **Preliminary Validation of the South African Lightning Detection Network Performance**.

Chapter 2

Background

This chapter discusses background information associated with Lightning Detection Networks (LDNs). Previous research on LDNs is provided which demonstrates the relationship between the number of reporting sensors and location accuracy. A brief outline of the methods used in determining the position of a lightning stroke are described in order to explain these observations. Previous research involving the matching of LDN data with real ground-truth evidence of lightning is provided. Finally, background information on photography of tall towers in Johannesburg, South Africa and the South African Lightning Detection Network (SALDN) is provided.

2.1 Lightning Detection Networks

LDNs can be found in many countries throughout the world. These networks detect lightning using sensors that detect the electromagnetic fields that propagate from lightning discharges. A lightning discharge is the result of many mechanisms and has many facets to a single event. LDNs attempt to provide as much information about a lightning event as possible [3, 4]. The following list discusses some of these aspects that are relevant to the worked presented in this dissertation.

Return Stroke: The return stroke occurs at the point of attachment of the upward streamer or leader and the downward leader. Charge is then transferred to ground. This current produces the electromagnetic signature that is detected by LDN sensors [3, 5].

Subsequent Strokes: Ffter the return stroke, subsequent strokes then follow and also radiate electromagnetic pulses. LDN sensors are able to detect these and hence, detect and differentiate between the first return stroke and subsequent strokes. LDNs report each stroke separately.

Flashes: One flash consists of multiple strokes. Since LDNs detect the electromagnetic pulses that propogate from lightning strokes, there is no way to detect one flash. LDNs use algorithms that group strokes based on their proximity in reported location as well as reported time.

Cloud-to-cloud or Intra-cloud and Cloud-to-ground: LDNs are capable of detecting lightning discharges that occurred between charge centres in clouds and distinguishing them from lightning discharges that attach to the earth. The distinction is made between the rise time and peak magnitude of the current waveform of the two different discharge types [5].

Lightning Leader Direction: Ground based objects with significant height (e.g. tall towers) are observed to initiate upward lightning as opposed to the more frequently occurring downward lightning [3].

Detection Efficiency: The detection efficiency of a LDN is defined as the ratio of true strokes to strokes reported by the network and is given as a percentage by (2.1).

$$DE = \frac{no.\ reported\ strokes}{no.\ actual\ strokes} \times 100\% \tag{2.1}$$

There is a distinguishable difference between a LDN's stroke or flash detection efficiency. The stroke detection efficiency is usually lower than the flash detection efficiency since it only requires one detected stroke to constitute a recorded flash, even if the other subsequent strokes are not detected [6, 7]. The detection efficiency is a indication of how much lightning activity is being detected by the network. The lower the detection efficiency, the less accurate any statistics based on the data of the network will be.

Location Accuracy: Another parameter used to evaluate the performance of a LDN is location accuracy. This is a measure of the error in the reported location of a strike. Since the system calculates the position of the strike using GPS coordinates and timing, any error in time measurements may result in distance errors. Location errors can be described in both longitudinal and latitudinal directions. Since every reported stroke may have a different error, the median error, along with the standard deviation is usually used as a measure of the location accuracy [6, 8, 9].

2.1.1 Locating Lightning Strokes

Two main methods are employed in LDNs for locating lightning strokes: Magnetic Direction Finding (MDF) and Time-of-Arrival (TOA) techniques. These two techniques are combined in a method known as Improved Accuracy from Combined Technology (IMPACT) and information from both techniques is used in locating strokes [10].

Magnetic Direction Finding

Magnetic Direction Finding (MDF) sensors utilise two orthogonal loop antennas which detect the horizontal electromagnetic field produced by lightning. These antenna systems have a wide-bandwidth so as to preserve the shape and polarity of the radiated field. A voltage proportional to the lightning magnetic field multiplied by the cosine of the angle between the loop and the direction of the incoming field is produced in each loop. The azimuth angle describing the direction of the lightning discharge can then be determined by comparing the ratio of the two antenna outputs. By using two or more MDF sensors, the location of the stroke can be determined from the intersection of the two "directions" or azimuth angles as shown in *Figure 2.1* [11, 12].

Also indicated in *Figure 2.1* are the effects of errors in the determined azimuth angle from each sensor on the reported location of a stroke given two MDF sensors. Errors in the reported angle may arise due to a number of reasons: Calibration errors resulting in a constant offset from one particular sensor, measurements of angles relative to either true north or grid north, site and propagation errors [13]. Certain errors, if known, may be corrected for resulting in a more accurate reported location. Other errors, such as site or propagation errors, are more difficult to correct for and are often considered random in nature [8]. The consequence of this is that the intersection of the two directions results in a location error for the reported stroke.

In a typical LDN, three or more sensors will detect and report a lightning event. *Figure 2.2* shows a graphical interpretation of three MDF sensors detecting a stroke.

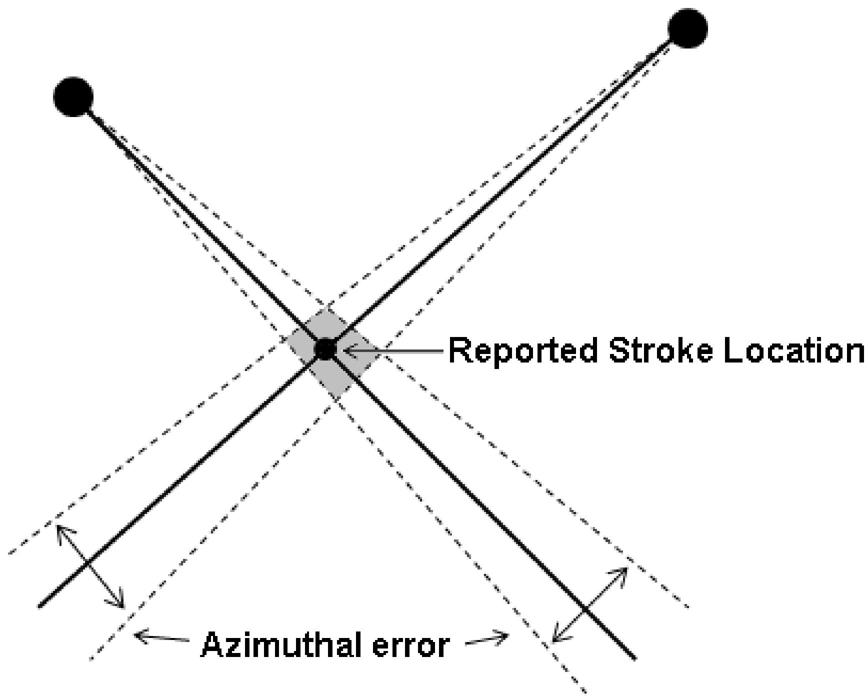


Figure 2.1: Determining the location of a stroke using two magnetic direction finders. Errors in reported azimuth angles are shown.

Due to errors in the reported azimuth angle of each sensor, the reported angles will not all intersect at the same point as shown by the solid lines and open circles in *Figure 2.2*. This results in, what *Stansfield* refers to, as a "triangle of error" or a "cocked hat" [13].

To compute a single location based on the angle information provided by three or more disagreeing sensors, the most probable or optimal position inside this "cocked hat" is determined. This is done by minimising the sum of squares of the reported angle measurements to find agreement between all reporting sensors resulting in a "best fit". This is the reported stroke location shown in *Figure 2.2*. The angles θ_1, θ_2 and θ_3 are the difference between the reported azimuth angle of each sensor and the angles that result in agreement between all reporting sensors.

Stansfield notes that the accuracy of the reported location is enhanced with more reporting sensors since any significant error due to two of the sensors will be reduced by the information provided by the third sensor.

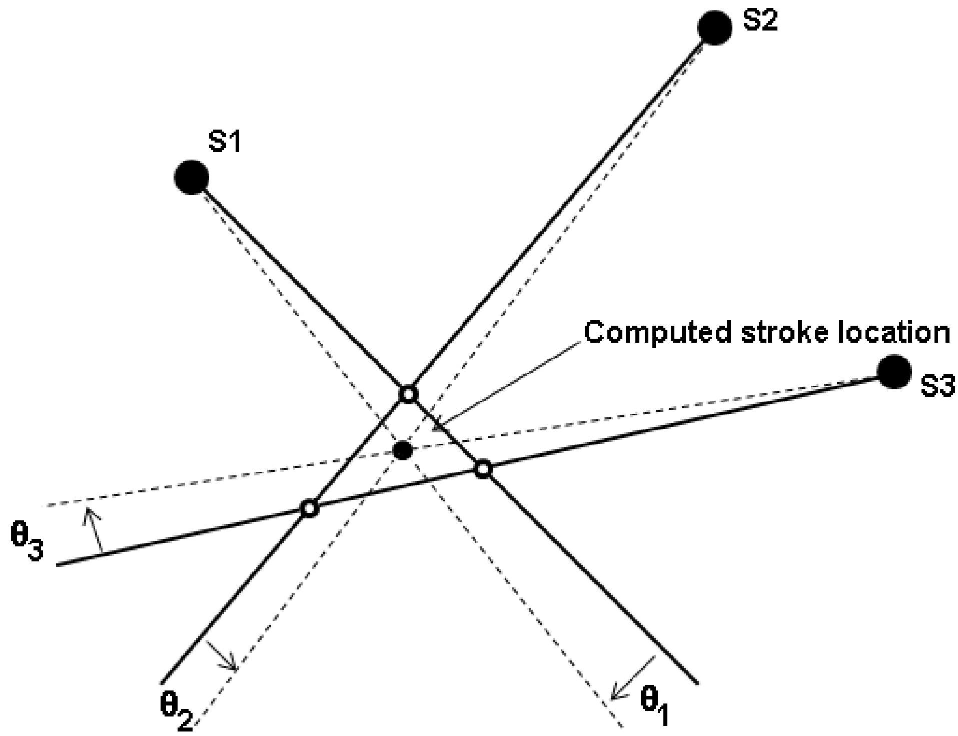


Figure 2.2: Stroke position detection using three magnetic direction finders. Difference between reported azimuthal angle and "best fit" are shown.

Time-of-Arrival

The Time-of-Arrival (TOA) technique determines the location of a lightning stroke based on the difference in detection time of each sensor. When a lightning stroke occurs, an electromagnetic field is radiated. If a number of sensors are located at different distances from the location at which a stroke occurs, the field will arrive at the sensors at different times. If the difference in distance between the sensors is known, and the difference in the time of arrival is known, the location of the stroke can be inferred.

Figure 2.3 shows a stroke detected by three sensors. Based on the arrival times at each sensor, a hyperbola of locations between any two sensors is possible. With three sensors, three hyperbolas of possible positions are available. Where these intersect is the location of the stroke.

As with the MDF sensors, errors occur which may affect the accuracy of the position being reported. In the case of time-of-arrival, any error in the time of detection of a stroke will correspond to an error in the time difference between the sensors. This

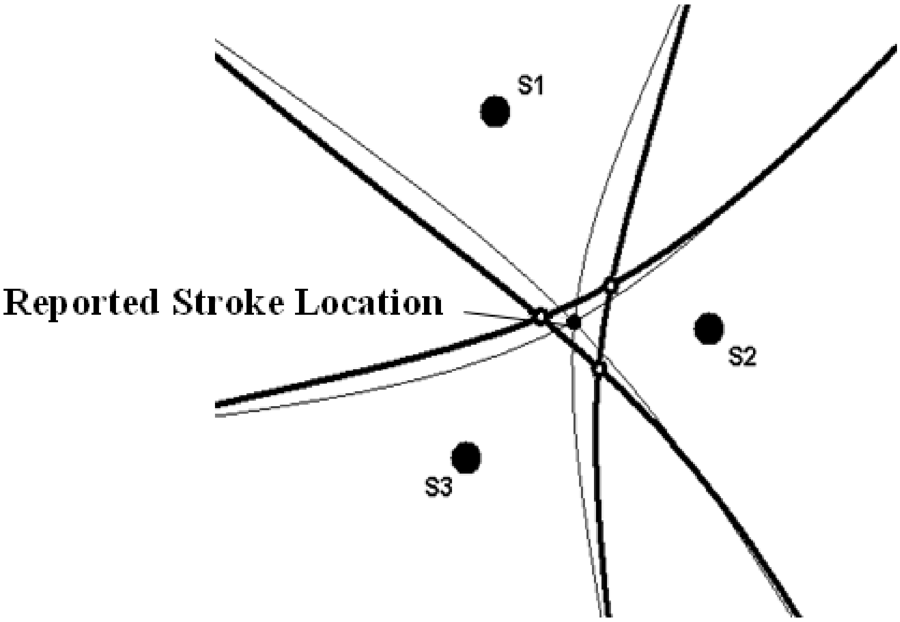


Figure 2.3: Three sensors detect a stroke - the hyperbolas show the possible positions defined by the TOA technique. Disagreement between the sensors results in the "cocked hat". The reported location is the result of minimising the errors.

will then lead to an error in the positions defined by the hyperbolas. Errors in the timing of events will therefore lead to errors in the reported location of the strike. Consequently, the multiple hyperbolas will not intersect at the same location resulting in the "cocked hat" as with the MDF techniques. This is also indicated in *Figure 2.3*. Similarly to MDF, the optimal position or "best fix" is found by minimising the sum of squares of the errors in time to find agreement between all reporting sensors [3, 10].

IMPACT Method

The Improved Accuracy using Combined Technology (IMPACT) method uses both arrival time and azimuthal angle information to resolve the location of a lightning stroke. As with both techniques, the errors in time and angle are minimised to find agreement between all the sensors. Using the combination allows for the location of a stroke to be determined when only two sensors detect it [9, 10].

Location Accuracy Model

LDNs that operate using combined TOA/MDF technology provide a measure of the location accuracy for each stroke. This is provided in the form of confidence or error ellipses which show the median probability area in which the true stroke may have occurred. This is shown in *Figure 2.4*.

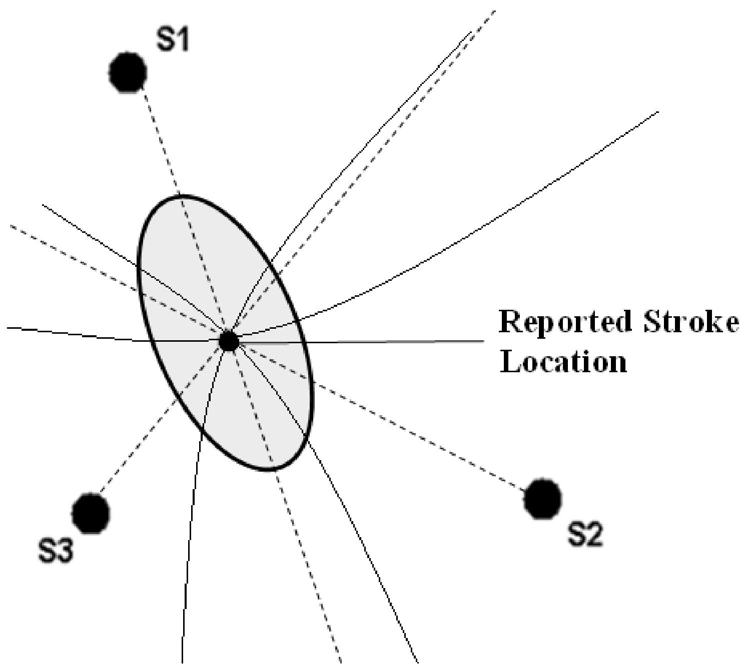


Figure 2.4: Confidence or error ellipse for a detected stroke showing the area in which there is a 50% probability that the true stroke occurred.

It is assumed that the location errors follow a Gaussian distribution. The confidence ellipse shows the area for median or 50 % errors in location. The reported location of every stroke detected by the LDN is the result of finding agreement between the sensors and the quality of this "best fix" is evaluated. The quality of the "fix" is then used to scale the Gaussian distribution and provide the area encapsulated by the ellipse [10, 13].

2.1.2 Lightning Detection Network Characteristics

An evaluation of the U.S. National Lightning Detection Network (NLDN), conducted by *Jerauld et al.* in 2005, used data collected over the years 2001 - 2003. Rocket triggered lightning events at the International Center for Lightning Research and Testing (ICLRT) at Camp Blanding, Florida were used as ground-truth records for comparison with the NLDN reports. A flash and stroke detection efficiency of 84% and 60% respectively was found and a median location error of 600 m [6]. A similar analysis was conducted again in 2008 using data recorded for 2004, 2005 and 2007 [7].

In both these evaluations, a comparison of the absolute location error against number of sensors showed that fewer sensors detecting a stroke resulted in a greater absolute error in the reported location of the stroke. Strokes detected by 3 or more sensors tended to have location errors between 0.1 and 2 km whereas strokes detected by only two sensors had location errors of 2 km or more. Similarly, it was seen that strokes with large peak currents had smaller absolute location errors and were detected by a greater number of sensors than strokes with low peak currents.

These observations fit with the operation of TOA/MDF systems - if more sensors detect a stroke then there are more errors that are minimized to determine the "best fit". Consequently, the difference between the reported location and the true location is less than if fewer sensors detect the stroke. The magnitude of the electromagnetic field radiated by a lightning stroke is proportional to the peak current in the lightning channel. Strokes with low peak currents will be detected by fewer sensors since the radiated electromagnetic fields will not propagate as far as strokes with large peak currents.

2.2 Existing Methods of Matching

While data from LDNs is used extensively in climatological research on lightning, it is used to investigate true ground-truth lightning records - be it for evaluation of the performance of the network or to investigate an event where the cause is unknown. Two existing methods are generally used to do this; correlation in time of the ground-truth event and the reported stroke and determining whether the confidence ellipse of a reported stroke overlaps the location of the ground-truth event.

2.2.1 Time Correlation

The most common method of matching LDN stroke reports with ground-truth events is correlating the time stamp of the event with the reported time of the stroke detected by the LDN. This requires an accurate time stamp of the event so that it can be correctly matched with the LDN report.

This method is used extensively when ground-truth records are video footage or photographs and it is possible to synchronise the recording of an event to a GPS clock. Such is the case for an evaluation of the U.S. NLDN performed by *Idone et al.* in 1998. The study compared video recordings of lightning events with the NLDN reports. Particular attention was paid to the time-stamping of the video recordings so that individual strokes could be distinguished and a stroke detection efficiency for the network could be accurately determined. It was noted that this procedure was a particularly “tedious task” [14].

This method becomes less effective when accurate timing information is not available for the ground-truth data. A study performed by *Makela et al.* used observations of trees that were struck by lightning to evaluate the performance of the Finnish Lightning Location System (LLS) [15, 16]. Volunteer groups examined forest areas for lightning damage where the Finnish LLS had reported a storm to have occurred and the Finnish Meteorological Institute website was used to collect public observations and reports of lightning flashes to trees. There were concerns that the results of the study were over-optimistic given the matching of the LLS reports to the observations.

2.2.2 Confidence Ellipses

The other method of matching lightning detection records with ground-truth events is the use of the median confidence ellipse, described in the location accuracy model, reported for each stroke. The area that the ellipse covers is investigated and it is determined whether this overlaps with the location of the ground-truth event as shown in *Figure 2.5.* If it does not overlap, it is not considered a match.

Recent research discusses the effectiveness of this method given that the median error ellipse is used - there is equal probability that the stroke occurred within the area described by the ellipse as outside the area [17].

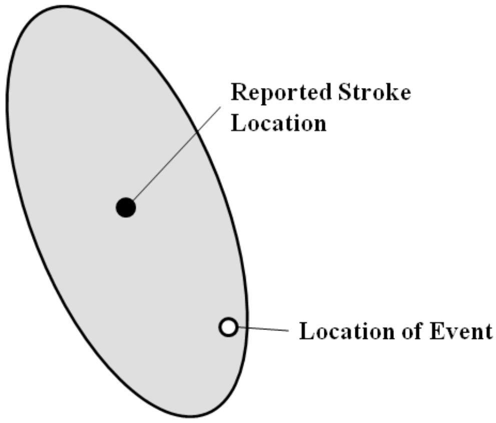


Figure 2.5: Location of ground-truth event falling in error ellipse of a reported stroke. This would be considered a match.

2.3 Lightning Detection in Johannesburg, South Africa

2.3.1 South African Lightning Detection Network

The South African Weather Service (SAWS) operates the South African Lightning Detection Network (SALDN). The network currently (2012) consists of 25 Vaisala LS7000 sensors situated across the country, one of which is located in Swaziland. During the period of 2009 - early 2010, the network consisted of 22 sensors. This is shown in *Figure 2.6* given that the data used for the evaluation presented in this work uses ground-truth lightning events from late 2009 - early 2010.

Previously, the Council for Scientific and Industrial Research (CSIR) implemented a network of lightning flash counters across the country. The efficiency of this network was never calculated [1]. The nature of the measurement system also did not allow for the number of strokes per flash to be determined [18]. Eskom previously operated a Lightning Position and Tracking System (LPATS) over the north eastern parts of the country. There was much debate over how the data obtained from the LPATS system should be interpreted [19].

2.3.2 The Johannesburg Region

Figure 2.7 shows a silhouette of the Johannesburg skyline. As can be seen in the image, two tall structures stand significantly higher than any of the other buildings in Johannesburg city. These two buildings are the Brixton Tower on the right and

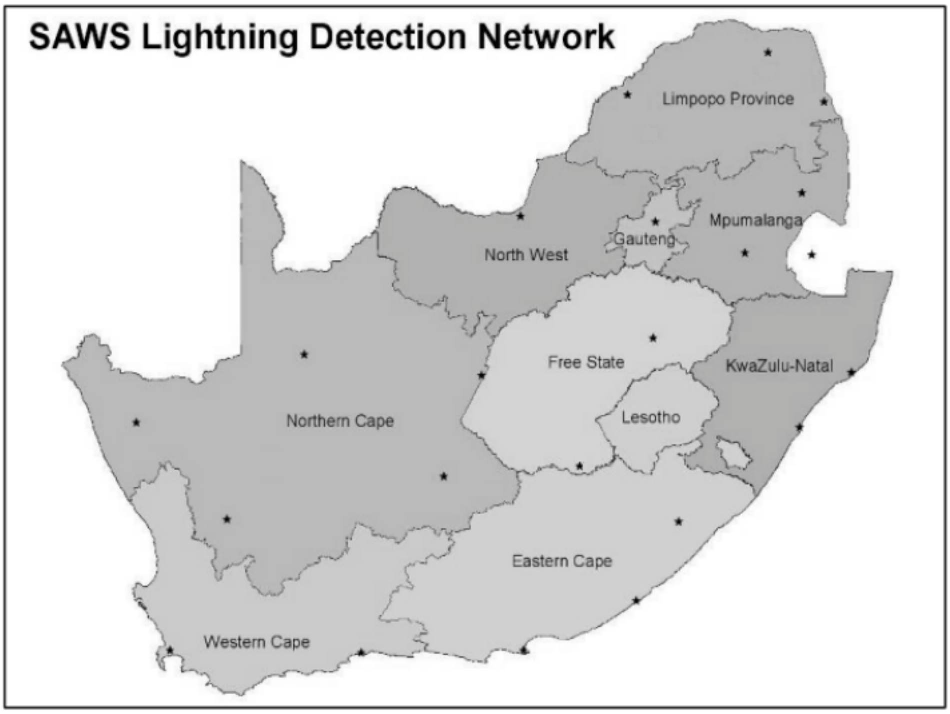


Figure 2.6: Location of LS7000 sensors in South Africa for 2009 - 2010. Adapted from [1]

the Hillbrow Tower on the left. Both buildings are approximately 250 m tall and approximately 4.8 km apart from each other.

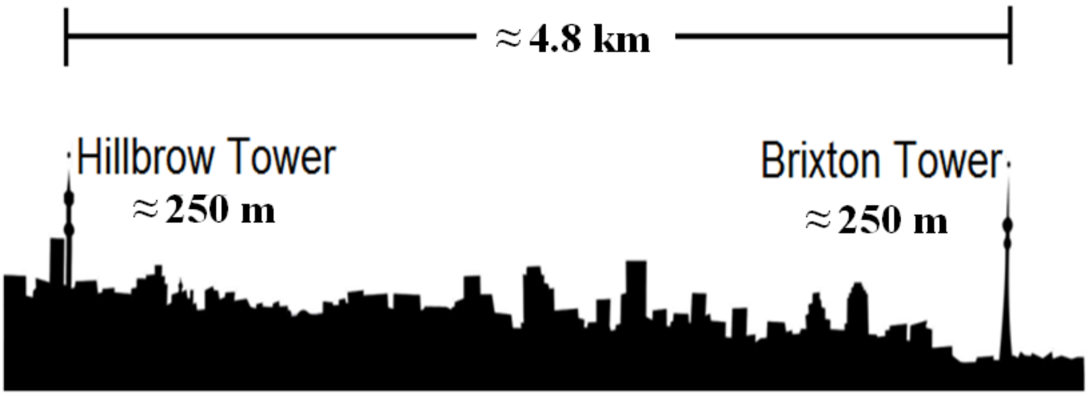


Figure 2.7: Silhouette of the Johannesburg City Skyline from the North

A study performed using data from the previous Lightning Position and Tracking System (LPATS) network installed in South Africa was able to show that there was a notable increase in the ground flash density in the vicinity of the two towers [20].

2.4 Summary

Lightning Detection Networks (LDNs) use TOA/MDF techniques to determine the location at which lightning strokes attached. Both these sensors require information from multiple sensors to resolve the location of a stroke. Agreement between the information coming the sensors is achieved by minimising the errors in azimuth angle and time to achieve an optimal position. This means that the reported location will be more accurate if more sensors detect a stroke and this characteristic has been observed in evaluations of the U.S. NLDN using rocket triggered lightning.

Matching LDN data with ground-truth lightning events is done using time correlation and the confidence ellipse provided by the LDN's location accuracy model.

Finally, the South African Weather Service operates a LDN in South Africa consisting of 25 Vaisala sensors.

The following chapter defines the problem statement and the proposed solution. The approach taken to evaluate this solution is also described.

Chapter 3

Approach Taken

In this chapter, an overview of the work addressed in this dissertation is discussed. The problem statement, the proposed methodology and the steps taken to investigate the effectiveness of the proposed methodology are provided. This involves comparison of photographic evidence of lightning discharges to the Brixton tower, South Africa with reported data from the South African Lightning Detection Network (SALDN).

3.1 Problem Statement

The effects of lightning are often severe - resulting in system failures and possibly loss of life. The data provided by Lightning Detection Networks (LDNs) is often of use since it may provide insight into whether lightning was the cause of these cases. Insurance claims may be made for such cases and will depend on whether a natural phenomenon like lightning was the cause or not.

However, the preferred method of matching reported data from LDNs with real occurrences is by time correlation methods. In the case of lightning damage or loss of life, there may be no record of the exact time the event occurred - all that is known is the location of the event. If insurance claims are to be based on the results returned by LDNs, it is imperative that the data is matched to the correct event.

This presents the problem addressed in this dissertation - how to match reported lightning data from LDNs to the location of a possible lightning event when no timing information of the real event is available.

3.2 Proposed Methodology

The proposed methodology involves comparing the number of reporting sensors with the error in location of the reported strokes - if the location of a possible event is known, then it is possible any data reported by the LDN represents this event (since no timing information is available). Every stroke detected by the network is reported at a location. These strokes may then be represented as having a location offset from the location of the possible event.

It is known that strokes detected by more sensors will be more accurately located as discussed in *Chapter 2*. It follows then that, by representing all strokes as location errors from a specific location (the possible event), a distinction can be made between strokes that do match to the possible event and strokes that do not since strokes that do will have small location errors while strokes that do not will have large location errors if detected by many sensors.

In this way, it may be established whether there was a real lightning event that occurred at the known location and the data from the network may be retrieved.

3.3 Evaluating the Methodology

To evaluate the proposed methodology it is necessary to determine whether the reported LDN strokes chosen by applying the methodology to a ground-truth event will be the same reported LDN strokes chosen by another method of matching.

Photographs of lightning attachment provide ground-truth records of lightning attachment to a known location and have a record of the time the event occurred. These ground-truth records can then be matched with LDN data using time correlation methods.

The methodology is then applied to match LDN data with the same ground-truth records (photographs). The methodology may then be evaluated based on the number of strokes it extracts that correspond with the strokes extracted using time correlation methods.

The methodology is also evaluated by applying it to a case of property damage seeing whether it is possible to determine lightning as the cause and which strokes caused it.

3.4 Summary

Matching LDN data with events that were possibly the results of lightning attachment is difficult when the exact time of the event is unknown. It is important to do this correctly if LDN data is to be used as the basis for decisions such as granting insurance claims.

A methodology is proposed using the relationship between the number of sensors detecting a stroke and the error of the reported location of the stroke that would allow for LDN data to be matched with ground-truth lightning events where the time of the event is unknown.

Evaluating the methodology is done by comparing the results of applying the methodology with the results of time correlation methods.

The following chapter discusses the necessary steps to be followed in order to apply the proposed methodology successfully. The reasoning and assumptions behind each step is explained.

Chapter 4

Proposed Methodology

A methodology is proposed to match data from Lightning Detection Networks (LDNs) with possible lightning events where the exact time of the event is unknown. This chapter discusses the overall methodology as well as the reasons and assumptions behind the necessary steps - these include defining a location of interest, the extracting the relevant data from the LDN database, determining the distance between locations and the criteria used to match LDN data to the event.

4.1 Methodology Overview

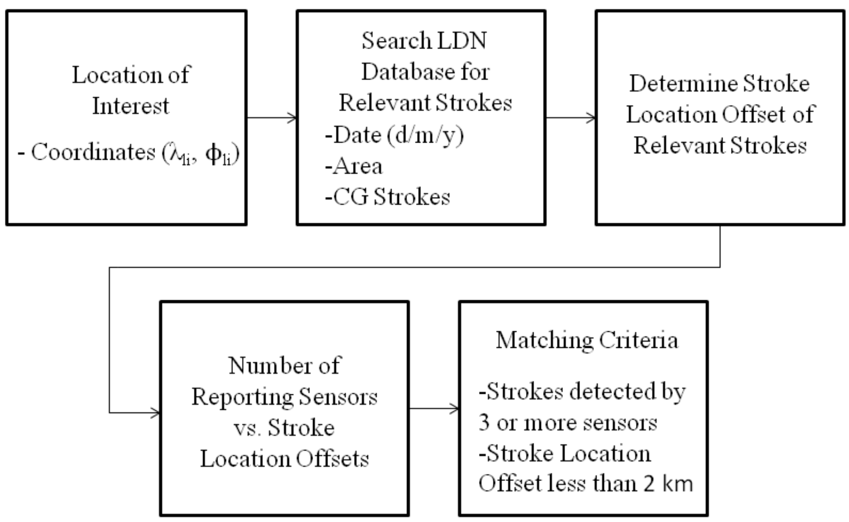


Figure 4.1: Block diagram demonstrating the steps of the proposed methodology

Figure 4.1 shows a block diagram overview of the proposed methodology. The methodology requires that: the location and date of the event in question (property damage, struck tree) be determined, the relevant data from the LDN extracted, the difference in distance between the location of interest and the locations of the reported strokes be calculated and comparing this difference with the number of reporting sensors of each stroke. Strokes detected by 3 or more sensors and with a difference in location less than 2 km are then extracted as a potential match to the lightning event. This results in a dataset of strokes reported by the LDN that potentially attached to the location of the event - the time of this event can now be established as well as other parameters provided by the network (such as current magnitude and polarity). An evaluation of the methodology is presented in *Chapters 5* and *6*.

4.2 Location of Interest

The goal of the proposed methodology is to locate strokes from an LDN database that were detected as lightning attachments to a specific location of interest. For the purposes of this text, a location of interest is defined as a location on the surface of the earth surface and can described by latitudinal and longitudinal coordinates as shown:

$$Location\ of\ Interest = (\lambda_{li}, \varphi_{li}) \tag{4.1}$$

where

$$\lambda_{li} = \text{Latitude of Location of Interest (decimal degrees)}$$
$$\varphi_{li} = \text{Longitude of Location of Interest (decimal degrees)}$$

This location of interest could be the site of damage, loss of life or any location that may have been struck by lightning. By extracting the correct strokes from the LDN database, the time and current can be found from the LDN.

The images shown in *Figure 4.2* are examples of locations of interest. *Figure 4.2(a)* shows an image of the Brixton tower. As discussed in *Chapter 2*, the Brixton tower is a tall structure in the Johannesburg area and has regular lightning attachments to it during thunderstorms over Johannesburg [20]. Therefore, it may constitute a location of interest and the methodology could be used to determine if there was any lightning attachment to the tower on a certain day, what time the attachment occurred and the magnitude and polarity of the current in the stroke. *Figure 4.2(b)* shows another example of a location of interest: a tree that has been struck by lightning. Once again, the methodology may be employed to determine if there was lightning attachment to the tree and when it may have occurred.

(a) (b)

Figure 4.2: Locations of interest. (a) Shows the Brixton tower and (b) shows a tree.

The coordinates of these two examples are given in *Table 4.1.*

Table 4.1: Coordinates of the locations of interest shown in *Figure 4.2*

Location of Interest	Brixton Tower	Struck Tree
Latitude (λ_{li})	-26°11'32.82"	-26°8'32.48"
Longitude (φ_{li})	28°0'24.73"	28°10'52.22"

Figure 4.3 shows a "birds eye-view" of the Johannesburg area. The two locations of interest are shown in the figure. The Brixton tower is located at a longitude of 28°0'24.73" East and a latitude of 26°11'32.82" South. The struck tree is located at a longitude of 28°10'52.22" East and a latitude of 26°8'32.48" South.

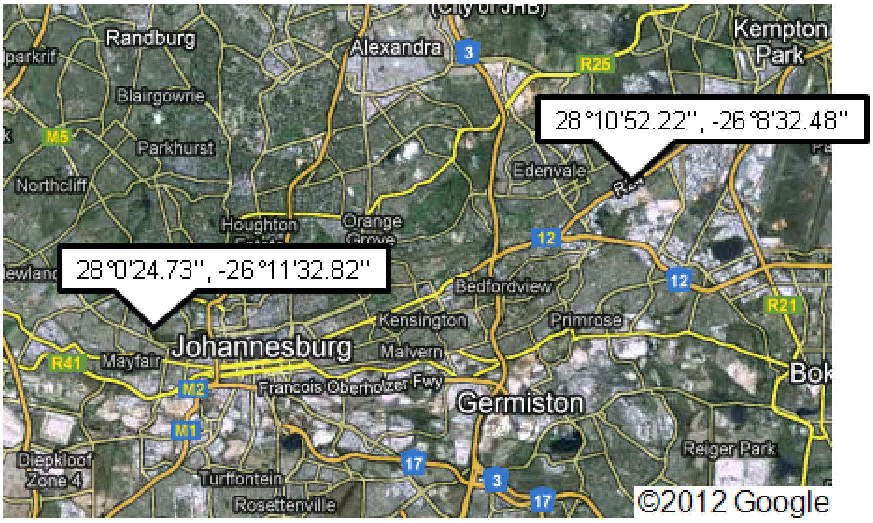


Figure 4.3: Examples of locations of interest, (λ_{li}, φ_{li}), in table 4.1 in the Johannesburg region.

4.3 Selecting Relevant Lightning Detection Network Data

LDNs provide many different parameters for the each stroke that is detected. For the proposed methodology, the following parameters are of interest:

- **LAT** (λ): Latitude of reported stroke (decimal degrees).
- **LONG** (φ): Longitude of reported stroke (decimal degrees).
- **DATE**: The date the stroke occurred (Day/Month/Year).
- **TIME**: The time the stroke occurred (Hour/Minute/Second/Microsecond).
- **CURR**: Peak current of the stroke and its polarity (kA).
- **CG or CC**: Whether the stroke was cloud-to-ground or cloud-to-cloud lightning.
- **NUMBER OF SENSORS** (N_{SENS}): The number of sensors that detected the stroke.

To apply the methodology, a dataset of LDN data needs to be established that is relevant to the location of interest. This involves searching the network database by certain criteria: date, area and cloud-to-ground or cloud-to-cloud strokes.

4.3.1 Date

The aim of the methodology is to extract strokes from the LDN database without timing information. However, there is always the possibility that a given location of interest has had multiple lightning attachments. Therefore, it becomes useful to reduce the dataset of possible strokes by searching for all reported data detected on the day or days in question. This is a valid assumption since it is usually possible to obtain eyewitness reports of the possible day or days in which a lightning event (damage etc) may have occurred, even if exact timing is not available.

4.3.2 Area

As discussed in *Chapter 2*, LDNs are prone to location errors. It is not sufficient, therefore, to search LDN databases for the coordinates of the location of interest (λ_{li}, φ_{li}) since it is unlikely attachments to this location will be reported to have occurred at the exact coordinates. Strokes reported to have occurred in the surrounding area could potentially be strokes that attached to the location of interest and, due to the factors discussed, have errors in their reported location. However, as discussed in *Chapter 2*, it is seen that the location accuracy greatly decreases as the number of reporting sensors decreases [6, 9].

Selection Criteria: The following search criteria are implemented to extract all reported strokes within an approximate 494.57 km^2 area around the location of interest.

$$\lambda_{li} - 0.1 < \lambda < \lambda_{li} + 0.1 \tag{4.2}$$

$$\varphi_{li} - 0.1 < \varphi < \varphi_{li} + 0.1 \tag{4.3}$$

where

λ = The latitude of a stroke returned by the LDN (decimal degrees)

φ = The longitude of a stroke returned by the LDN (decimal degrees)

λ_{li} = The latitude of the location of interest in (decimal degrees)

φ_{li} = The longitude of the location of interest in (decimal degrees)

Equation 4.2 and *4.3* define an area, with the location of interest at its centre, in which all reported strokes should be selected. *Equation 4.2* stipulates that any stroke with a latitude, λ, that falls within 0.1 decimal degrees in either direction from the location of interest, is to be included in the dataset. Similarly, *Equation 4.3* stipulates the same criteria for any stroke with longitude, φ. Any strokes that fall within this area are to be treated as possible attachments to the location of interest. *Figure 4.4* shows an example of the area defined by these criteria.

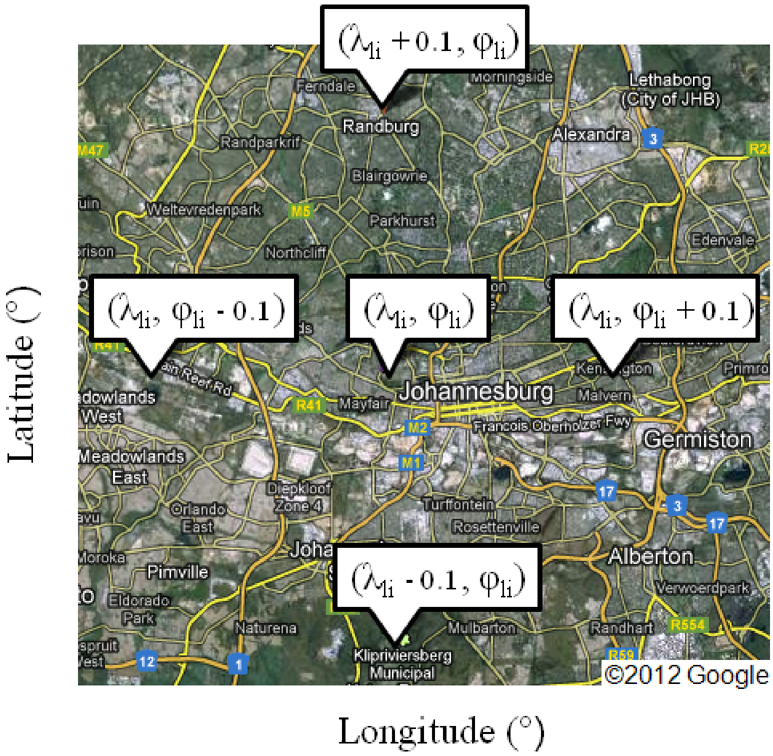


Figure 4.4: Coordinates of location of interest and the area of selection.

Figure 4.5 shows a description of the area that needs to be investigated. If the location of interest is to be found at the coordinates, $(\lambda_{li}, \varphi_{li})$, then 11.12 km to the north will be found at $(\lambda_{li} + 0.1, \varphi_{li})$ since 0.1 decimal degrees is approximately equivalent to 11.12 km if the shape of the earth is assumed to be spherical. Similarly, 11.12 km to the east will be found at $(\lambda_{li}, \varphi_{li} + 0.1)$. This defines the 495 km^2 area shown in *figure 4.4* and *4.5*.

The choice of selecting data from an area of this size requires an assumption - no error in reported location for any given stroke will exceed 11.12 km from the location of interest. This assumption is based on previous evaluations of LDNs using different forms of ground-truth data. An evaluation of the U.S. National Lightning

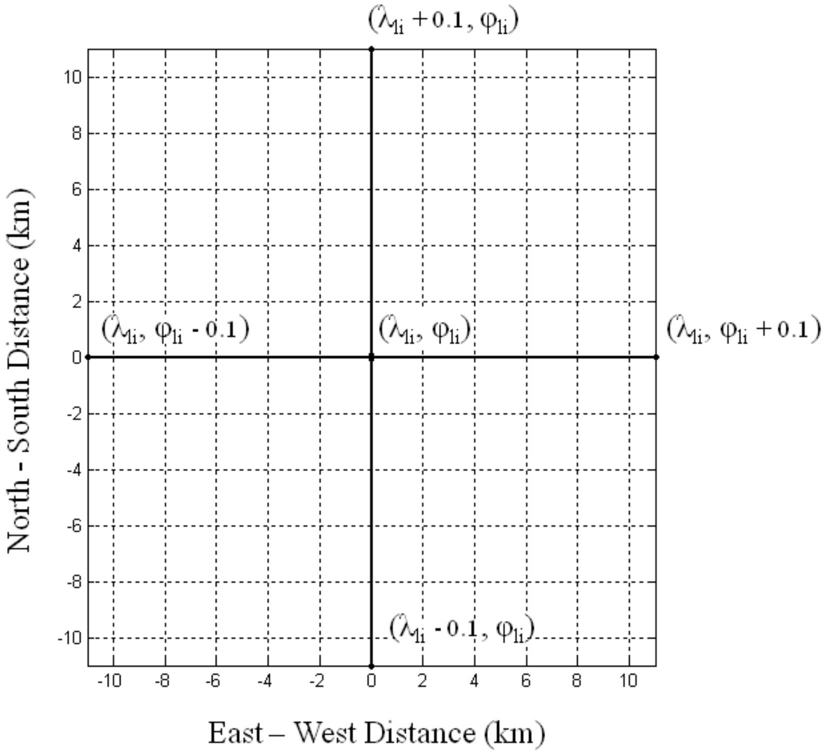
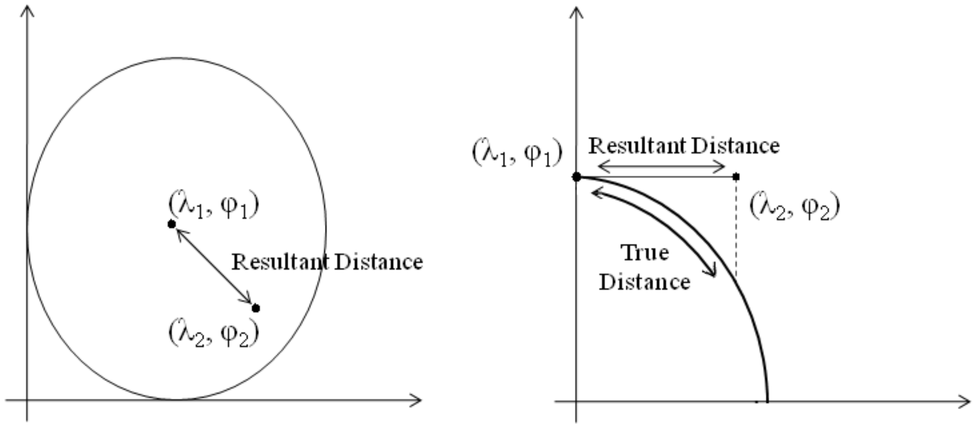


Figure 4.5: Area defined by latitudinal and longitudinal selection criteria. Distances in kilometres.

Detection Network (U.S. NLDN) using rocket triggered lightning determined a median location accuracy of 600 m. An evaluation of the North American Lightning Detection Network (NALDN), a combination of the U.S. NLDN and the Canadian Lightning Detection Network (CLDN), using lightning attachments to the Canadian National (CN) Tower showed a median location accuracy of 395 m. Location errors determined for the Nordic Lightning Information System (NORDLIS) - which covers the Scandinavian penninsula, Finland and Estonia - using struck trees as ground-truth data did not exceed 2 km [6, 15, 21]. It is therefore decided that a 495 km^2 area is significantly greater than any errors that may occur in the positioning of lightning strokes and that no potential attachments to the location of interest are discarded by only examining an area of this magnitude.

Decimal Degrees to Kilometres: Determining the distance between two co-ordinates is not a trivial calculation given the curvature of the surface of the earth as shown in *Figure 4.6*.

In general, the assumption is made that the earth is spherical and this allows for



(a) Top View

(b) Side View

Figure 4.6: Curvature of the surface of the earth; the difference in distance between two coordinates.

the *haversine* formula to be used (*Equation 4.4*).

$$haversin(\frac{d}{R}) = haversin(\lambda_2 - \lambda_1) + cos(\lambda_1)cos(\lambda_2)haversin(\varphi_2 - \varphi_1) \qquad (4.4)$$

where

$$d = \text{Distance between two coordinates (km)}$$

$$R = \text{Radius of the Earth (km)}$$

$$\lambda_{1,2} = \text{Latitude of coordinates (radians)}$$

$$\varphi_{1,2} = \text{Longitude of coordinates (radians)}$$

The *haversine* formula relates the ratio of the distance between two coordinates and the radius of the earth to the difference in latitude and longitude of the coordinates. While it becomes less accurate for large distances across the surface of the earth (since the earth is geoid and not spherical), these inaccuracies are considered negligible for small distances.

4.3.3 Cloud-to-Ground

LDNs make a distinction between cloud-to-ground and cloud-to-cloud activity. For the purposes of the methodology, all cloud-to-cloud strokes are discarded. Only strokes which could possibly have attached to the location of interest are relevant and, given that the location of interest is on the earth, this limits the dataset to cloud-to-ground strokes only.

4.4 Stroke Location Offset

The Stroke Location Offset (SLO) is defined in this text as the difference in distance between the location of interest, (λ_{li}, φ_{li}) and the location of a stroke reported by the LDN, (λ, φ) as demonstrated in *Figure 4.7*.

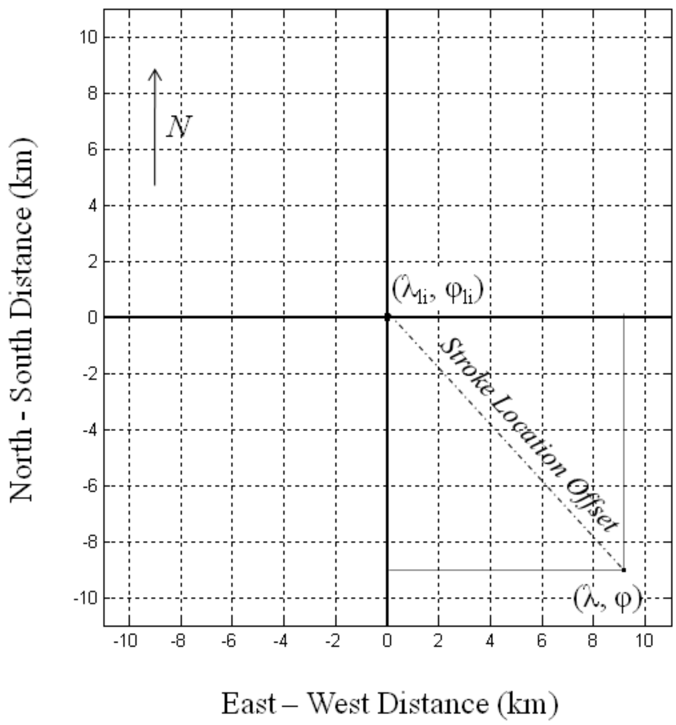


Figure 4.7: The location of interest, (λ_{li}, φ_{li}) and the location of a reported stroke, (λ, φ). The SLO is the difference in distance between the two locations.

The location of interest is represented at the origin with the coordinates, (λ_{li}, φ_{li}). A stroke is reported to have occurred at (λ, φ). The SLO can then be described as the difference between two coordinates on a sphere.

Therefore, from *Equation 4.4*, the SLO is given by:

$$SLO = 2 \times R \times arcsin \times \sqrt{haversin(\lambda_{li} - \lambda) + cos(\lambda)cos(\lambda_{li})haversin(\varphi_{li} - \varphi)} \tag{4.5}$$

where

$$SLO = \text{Stroke Location Offset (km)}$$
$$R = \text{Radius of the earth (km)}$$
$$\lambda = \text{The latitude of a stroke returned by the LDN (radians).}$$
$$\varphi = \text{The longitude of a stroke returned by the LDN (radians).}$$
$$\lambda_{li} = \text{The latitude of the location of interest (radians).}$$
$$\varphi_{li} = \text{The longitude of the location of interest (radians).}$$

It is important to note the difference between SLO and location error. SLO, as defined in this text, may be calculated for any stroke even if the stroke did not attach to the location of interest. Location error refers specifically to the difference in distance between the reported location of a stroke and its true location of attachment. If a stroke did attach to the location of interest, its SLO will be equal to its location error.

4.5 Number of Sensors vs. Stroke Location Offset

Figure 4.8 shows a plot of number of sensors (N_{SENS}) against SLO. The plot does not contain any data but displays three regions:

- **Region A**: SLOs less than 2 km but detected by more than two sensors.
- **Region B**: SLOs greater than 2 km but detected by more than two sensors.
- **Region C**: SLOs detected by two sensors or less.

All strokes are candidates for attachment to the location of interest. However, strokes that fall in Region A are strokes that are likely to have attached to the location of interest. Strokes occurring in Region B are unlikely to have attached to the location of interest. Strokes occurring in Region C may or may not have attached to the location of interest. In *Chapter 2*, it was discussed how the error in the reported location of strokes decreased if the strokes were detected by a greater number of sensors. The results of a study on the U.S. National Lightning Detection Network (NLDN) in *Section 2.1.2* showed that strokes detected by three or more sensors had location errors between 0.1 and 2 km [6].

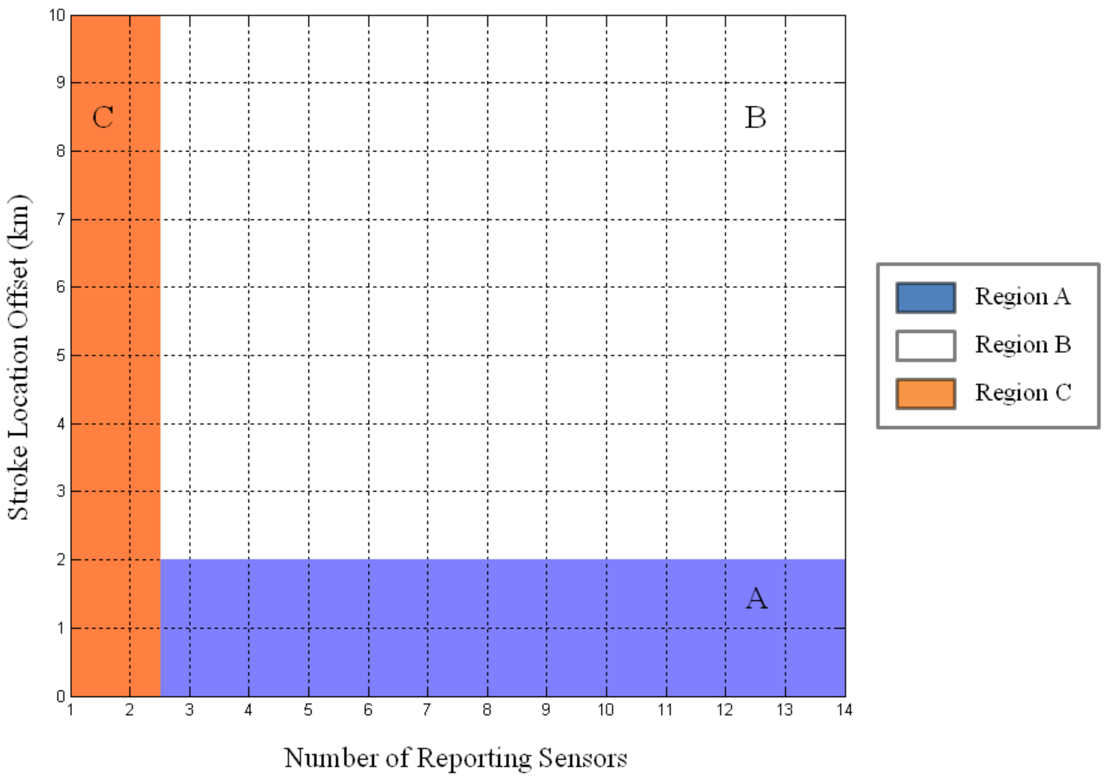


Figure 4.8: Number of reporting sensors vs. stroke location offset. Three regions (A, B and C), defining the matching criteria, are shown.

This defines the criteria for Region A and B in *Figure 4.8*. Strokes that definitely attached to the location of interest and were detected by more than three sensors are likely to have errors in their reported locations that are under 2 km. If these strokes definitely did attach to the location of interest, then the error in reported location will be equal to their stroke location offset - hence, strokes detected by more than three sensors with stroke location offsets less than 2 km are potential attachments to the tower (Region A). Conversely, strokes that have stroke location offsets greater than 2 km and were detected by three or more sensors (Region B) are unlikely to have attached to the location of interest since their error in reported location is not expected to be more than 2 km.

Strokes that are only detected by two sensors (Region C) may have significantly large errors in their reported location. This leads to two problems for matching:

1. Strokes that did not attach to the tower but were reported to have occurred near the location of interest. These strokes will have stroke location offsets less than 2 km even though they did not attach to the tower.
2. Strokes that did attach to the location of interest but have large location errors (due to only two sensors) and, consequently, large stroke location offsets. This makes them indistinguishable from other strokes with large stroke location offsets.

This means that only strokes that fall in Region A can be extracted as strokes that potentially attached to the location of interest but that strokes that fall in Region C cannot be discarded as unlikely attachments.

4.6 Summary

A methodology is proposed to extract data from the LDN database that corresponds to known ground-truth events where the location of the event is known to have occurred but the exact time of the event is unknown.

The methodology involves defining the location of the known event as the location of interest and extracting LDN data that is relevant to the event: date, cloud-to-ground strokes and area. SLO is defined as the distance between the reported location of any stroke in the database and the location of interest. By comparing the stroke location offset of each stroke with the number of sensors reporting the stroke, it is proposed that it can be established which strokes attached to the location of interest and which did not based on the characteristics of LDN locating methods.

Strokes detected by three or more sensors with stroke location offsets less than 2 km are proposed to be the strokes that potentially attached to the location of interest. Strokes with location offsets greater than 2 km are unlikely to have attached to the location of interest. Strokes detected by only two sensors cannot be separated into strokes that attached to the location of interest and strokes that did not since these strokes may have large location errors due to the few number of reporting sensors.

The following chapter provides an evaluation of the methodology by using it to match LDN data with photographs of lightning attachment to the Brixton tower in Johannesburg, South Africa. The data extracted by the methodology is then compared with data that has been matched to the photographs using time correlation methods.

Chapter 5

Evaluation of Methodology: Photographs of Ground-Truth Events

An evaluation of the methodology proposed in *Chapter 4* is presented here. Two investigations are performed: one in which ground-truth lightning events are matched to Lightning Detection Network (LDN) data using time correlation methods and one in which ground-truth lightning events are matched to LDN data using the proposed methodology. A comparison of the results of the two investigation allows for an evaluation of the proposed methodology.

5.1 Overview

This chapter describes an evaluation of the methodology proposed in *Chapter 4*. The proposed methodology aims to extract data from LDNs that match with ground-truth lightning events where no timing information is available. To evaluate the methodology, it needs to be established whether the methodology would extract the same data from the LDN as would be extracted if another known method, such as time correlation, were used.

A dataset of photographs of lightning attachment to the Brixton tower, Johannesburg, provide the ground-truth data necessary for the evaluation. LDN data is provided from the South African Lightning Detection Network (SALDN).

Three investigations are required to perform the evaluation of the proposed methodology:

- **Investigation 1:** Time correlation of photographs with SALDN data.
- **Investigation 2:** Applying the methodology.
- **Investigation 3:** Comparison of **Investigation 1** and **2** results.

Investigation 1 provides a data set of strokes that are known to have attached to the tower and have corresponding ground-truth events in the form of photographs. By applying the methodology in **Investigation 2**, another dataset of strokes is extracted. The effectiveness of the proposed methodology is evaluated by comparing how many of the strokes extracted from **Investigation 1** are also extracted by **Investigation 2**.

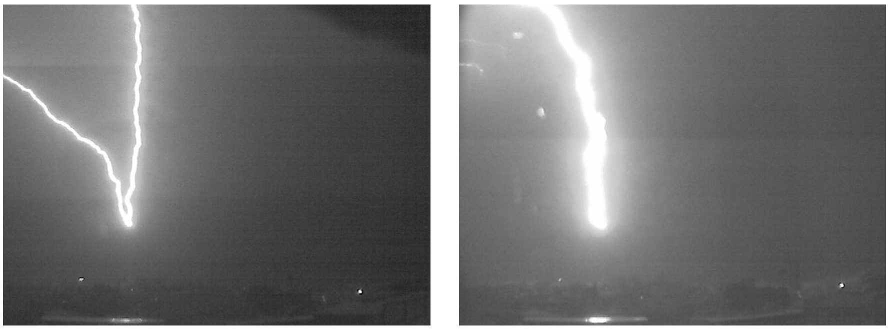
5.2 Investigation 1: Time Correlation of Photographs with SALDN Data

The focus of this investigation is to extract lightning strokes detected by the SALDN that match with photographs of lightning attachment to the Brixton Tower. In this investigation, matching is achieved by selecting the relevant data and finding strokes that were reported to have occurred at the same time the photographs were taken.

5.2.1 Photograph Data Set

Figure 5.1 shows two photographs of lightning attachment to the Brixton tower in Johannesburg, South Africa. *Figure 5.1(a)* and *Figure 5.1(b)* were taken on the 10 May 2010 and the 2 February 2010 respectively.

Twelve flashes, made up of 53 photographs in total, to the Brixton tower were photographed from December 2009 to May 2010. The date and time, as well as the number of photographs, of each flash is given in *Table 5.1* and the photographs can be found in *Appendix A*. The events are grouped into “flashes” since the difference in time between photographs for one “flash” is approximately 12 milliseconds. As can be seen from *Table 5.1*, five of the twelve flashes were obtained on the 28 December



(a) Photograph of lightning attachment to Brixton tower on 10 May at 2010 00:39:49 UTC

(b) Photograph of lightning attachment to Brixton tower on 2 February 2010 at 2010 21:01:34 UTC

Figure 5.1: Photographs of lightning attachment to the Brixton tower in Johannesburg, South Africa. Photograph by Yu-Chieh Liu [2].

2009. Each one of these flashes is made up of several photographs all occurring within milliseconds of each other.

Table 5.1: Photographs of lightning attachment to Brixton tower obtained from December 2009 to May 2010. Photographs in *Appendix A*

Photograph (Flash)	Date	Time (UTC)	Number of Photographs
1	28/12/2009	16:49:04	5
2	28/12/2009	16:52:53	3
3	28/12/2009	17:07:35	5
4	28/12/2009	18:40:45	6
5	28/12/2009	18:49:14	2
6	07/01/2010	21:27:39	2
7	02/02/2010	21:01:34	6
8	16/02/2010	20:03:52	5
9	31/03/2010	16:23:17	5
10	18/04/2010	19:33:31	5
11	20/04/2010	14:35:56	3
12	10/05/2010	00:39:49	5

5.2.2 Flash vs. Stroke

It is important to make the distinction between the concept of the flashes shown in *Table 5.1* and the concept of strokes. The fact that multiple photographs of lightning attachments to the tower were obtained within milliseconds of each other implies that attachment occurred to the tower, followed by subsequent strokes. However, the detection efficiency and time resolution of the camera itself is unknown meaning that it is not possible to determine the number of subsequent strokes based on the number of photographs. All that is known, is that a flash occurred to the tower.

5.2.3 South African Lightning Detection Network Data

The SALDN provides the data necessary for the investigation. Over the period of December 2009 to May 2010, the SALDN consisted of 19 sensors across South Africa. SALDN data is selected from the databases for the days shown in *Table 5.1*.

5.2.4 Time Correlation of Data with Photographs

Table 5.2 shows the number and time of strokes reported by the SALDN that correlate with times of the photographed flashes.

Table 5.2: Reported SALDN strokes time correlated with photographs

Photograph (Flash)	Date	Time (UTC)	Number of Matched Strokes	Reported Stroke Time (UTC)
1	28/12/2009	16:49:04	3	16:50:22
2	28/12/2009	16:52:53	6	16:54:12
3	28/12/2009	17:07:35	3	17:08:53
4	28/12/2009	18:40:45	2	18:42:04
5	28/12/2009	18:49:14	-	-
6	07/01/2010	21:27:39	1	21:29:42
7	02/02/2010	21:01:34	4	21:03:11
8	16/02/2010	20:03:52	-	-
9	31/03/2010	16:23:17	2	16:25:54
10	18/04/2010	19:33:31	-	-
11	20/04/2010	14:35:56	1	14:36:35
12	10/05/2010	00:39:49	6	00:40:00

Of the twelve photographed events to the tower, nine are matched to SALDN reports. This seems to indicate a flash detection efficiency of 75 %. This is possibly due to the fact that the lightning events are attaching to a tall tower and are therefore upward lightning. Nonetheless, there are lightning attachments occurring that are undetected by the SALDN. Each of these matches consist of one or more strokes occurring milliseconds apart from each other resulting in a total of 28 strokes reported by the SALDN being matched to photographs of lightning attachment to the Brixton tower from December 2009 to May 2010. Matching of photographs with SALDN data using time correlation is also described in *Appendix B*.

5.2.5 Time Synchronisation Issues

The camera setup used to capture the photographs was originally established for another project involving photographic observations of lightning attachments to a tall tower and was not originally intended for time correlation with the SALDN data. The clock of the camera was therefore not synchronised to GPS time and, as a result, there is a time offset between the SALDN and the photographs. This was quantified to be 90 seconds on average.

5.3 Investigation 2: Applying the Methodology

The aim of this investigation is to extract lightning strokes detected by the SALDN that match with photographs of lightning attachment to the Brixton tower. In this investigation, matching is achieved by applying the methodology proposed in *Chapter 4*.

5.3.1 Location of Interest

The first step of the methodology requires that a location of interest be chosen. Since the photographs are of lightning attachment to the Brixton tower, the coordinates of the Brixton tower are chosen as the location of interest. From *Equation 4.1*:

$$Location\ of\ Interest = \ (-26.1925°, 28.0068°) \tag{5.1}$$

This now allows for relevant data to be selected and for the stroke location offset to be calculated.

5.3.2 Selecting Relevant Data

All data detected by the SALDN that is relevant to lightning attachment to the Brixton tower is selected by the following criteria:

Date: For this investigation, the events that are being investigated are lightning attachments to the Brixton tower recorded as photographs. The exact date of each of these events is known *Table 5.1*. Therefore, all data recorded by the SALDN on the dates of the photographs in *Table 5.1* is selected.

Area: Given a location of interest ($-26.1925°$, $28.0068°$), the data occurring within a 495 km^2 area around this location is extracted. From *Equation 4.2* and *4.3*, the data from the SALDN needs to extracted for the following latitude and longitude:

$$-26.2925° < \lambda < -26.0925° \tag{5.2}$$

$$27.9068° < \varphi < 28.1068° \tag{5.3}$$

where

λ = The latitude of a stroke returned by the SALDN (decimal degrees)

φ = The longitude of a stroke returned by the SALDN (decimal degrees)

As discussed in *Chapter 4*, the choice of a search area of 495 km^2 is based on evaluations of LDNs present in other countries. As of yet, no evaluation of the SALDN's location accuracy has been performed using ground-truth data. The SALDN uses the same sensors (Vaisala LS7000s) as the formentioned networks but it does not have the same number of sensors in the network which is an important factor in the location accuracy of the network. The chosen area of 495 km^2, however, is significantly large as compared to observed location errors in other networks and it is decided that this should not discard any relevant data.

Cloud-to-ground: All cloud-to-cloud strokes are discarded from the dataset leaving only cloud-to-ground strokes.

A relevant dataset of 754 cloud-to-ground strokes in total is reported by the SALDN on the dates of the photographs as shown in *Table 5.3*. Contained in this dataset, are the 28 strokes that were time correlated to the photographed events in *Section 5.2*.

Table 5.3: Relevant strokes for methodology

Photograph (Flash)	Date	Number of Strokes
1	28/12/2009	33
6	07/01/2010	361
7	02/02/2010	8
8	16/02/2010	-
9	31/03/2010	155
10	18/04/2010	-
11	20/04/2010	34
12	10/05/2010	163

5.3.3 Stroke Location Offset

The SLO for each stroke of the dataset shown in *Table 5.3* is calculated using *Equation 4.5* as described in *Chapter 4*. *Figure 5.2* shows the reported locations of the selected data plotted as a function of the stroke location offset for the 495 km^2 area around Brixton tower. Brixton tower, the location of interest, is located at the origin. All 754 strokes are shown in the figure.

A magnified image of the immediate 4 km^2 area around the tower is also shown for clarity. The 28 strokes that were time correlated with the photographs are indicated as $\triangledown^{1-28}$. All other strokes are shown as points. It can be seen that the majority of strokes correlated in time with the photographs have small stroke location offsets and were reported within 1 km^2 of the location of the tower. Strokes $\triangledown^{4-9}$, $\triangledown^{20}$, $\triangledown^{22-23}$ fall outside of this area with greater stroke location offsets.

5.3.4 Number of Sensors vs. Stroke Location Offset

Figure 5.3 shows the calculated stroke location offsets plotted against the number of reporting sensors for each of the strokes in the data set. Once again, strokes

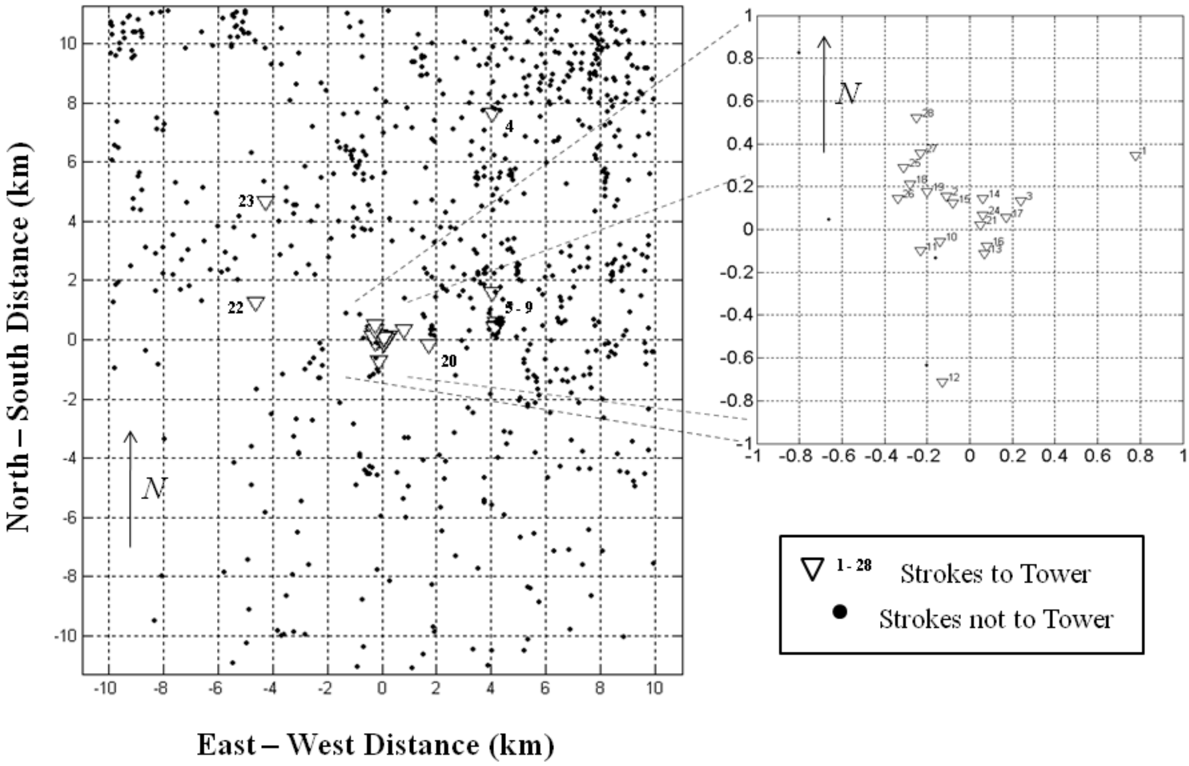


Figure 5.2: Location of reported strokes in relation to the Brixton tower (SLO). The tower is located at the origin.

correlated in time with the photographs are indicated as ∇^{1-28}.

To extract strokes that attached to the tower or location of interest, the criteria described in *Chapter 4*, is applied. *Figure 5.4* shows the same dataset as *Figure 5.3* but with the matching criteria indicated by the three regions which are:

- **Region A**: Stroke location offsets less than 2 km but detected by more than two sensors.
- **Region B**: Stroke location offsets greater than 2 km but detected by more than two sensors.
- **Region C**: Stroke location offsets detected by two sensors or less.

A total of 34 strokes fall into Region A, 614 into Region B and 106 into Region C. By the claims of the methodology, all strokes that fall into Region A should be the 28 strokes time correlated with the photographs.

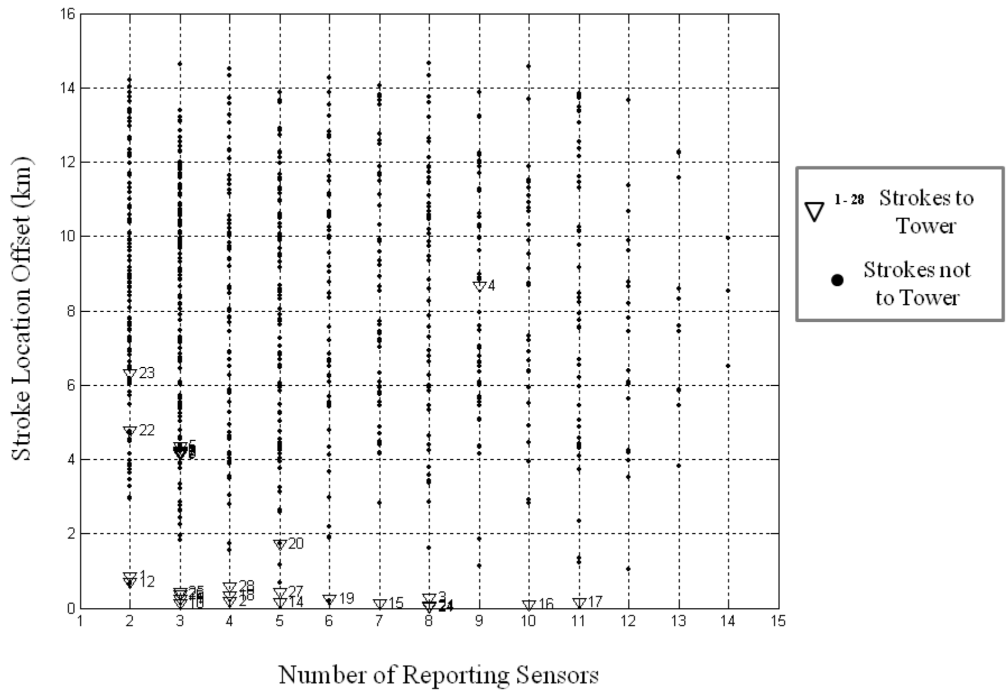


Figure 5.3: Number of reporting sensors vs. stroke location offset.

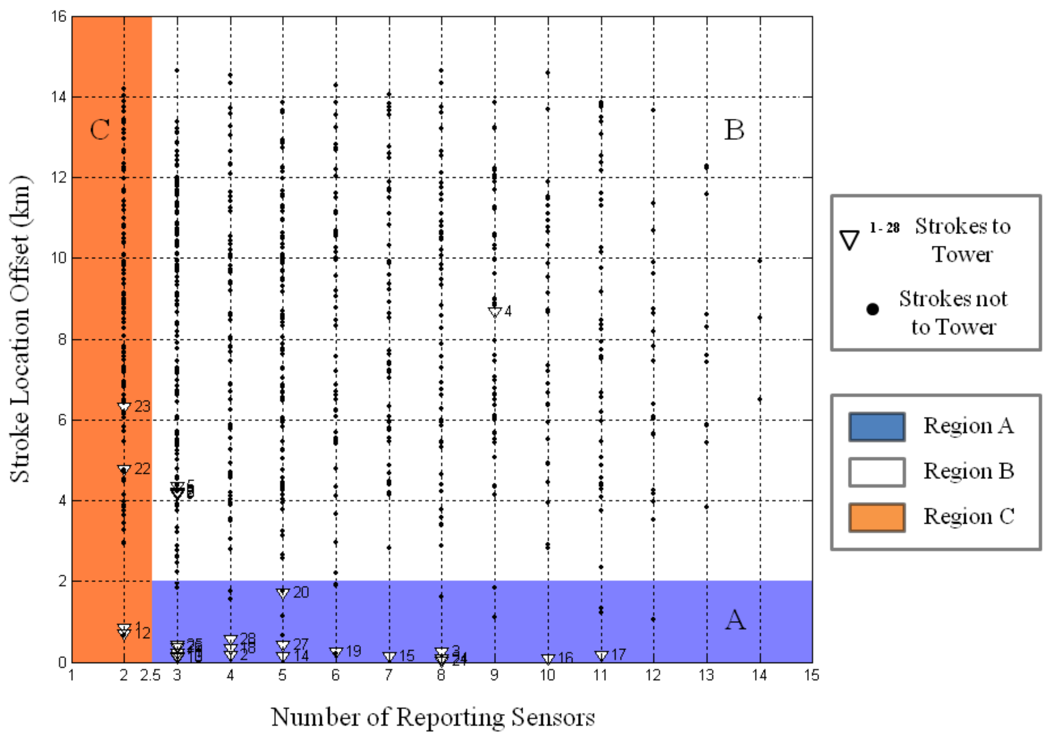


Figure 5.4: Number of reporting Sensors vs. stroke location offset with selection regions shown

Table 5.4 shows all the strokes extracted by the methodology (strokes that fall in Region A) matched with the photographs of lightning attachment to the Brixton tower. The methodology extracted strokes that could be matched to seven of the twelve photographs - two less than the number of matches made in **Investigation 1**. This implies that the methodology makes false exclusions since it is known that these strokes were detected by the SALDN for the time correlation investigation.

Table 5.4: Reported SALDN strokes matched to photographs using methodology (Region A).

Photograph (Flash)	Date	Time (UTC)	Number of Matched Strokes (Region A)	Reported Stroke Time (UTC)
1	28/12/2009	16:49:04	2	16:50:22
2	28/12/2009	16:52:53	-	-
3	28/12/2009	17:07:35	2	17:08:53
4	28/12/2009	18:40:45	2	18:42:04
5	28/12/2009	18:49:14	-	-
-	07/01/2010	-	1	19:27:08
-	07/01/2010	-	4	20:55:54
6	07/01/2010	21:27:39	1	21:29:42
7	02/02/2010	21:01:34	4	21:03:11
8	16/02/2010	20:03:52	-	-
-	31/03/2010	-	1	14:45:09
-	31/03/2010	-	4	14:53:10
-	31/03/2010	-	4	14:53:11
-	31/03/2010	-	2	15:07:06
9	31/03/2010	16:23:17	2	16:25:54
10	18/04/2010	19:33:31	-	-
11	20/04/2010	14:36:56	-	-
12	10/05/2010	00:39:49	6	00:40:00

The methodology also extracted strokes that could not be matched to any of the photographs. A total of 16 strokes fall in Region A that were not reported at the time of any of the photographs. The methodology therefore possibly extracts false positive results since there are no records of lightning attachment to the Brixton tower for 16 of the strokes that fall in Region A.

The methodology extracted 34 strokes in total, 18 of which could be matched to seven of the photographed lightning attachments to the Brixton tower. Another 16 strokes were extracted that could not be matched to any of the photographs. This indicates two observations of the methodology: it falsely excludes some relevant data as well as returning some false positive results.

5.4 Investigation 3: Comparison of Investigation 1 and Investigation 2 Results

Investigations 1 and **2** have been performed to extract strokes from the SALDN and match them with the photographs. This is done to compare the results of the investigations and evaluate the effectiveness of the proposed methodology. This section looks at two comparisons: how many of the photographs were matched to SALDN data by the investigations and how many of the strokes extracted by the methodology are the same as the strokes extracted by **Investigation 1**.

5.4.1 Photographs

Table 5.5 shows the results of **Investigation 1** and **2** for extracting strokes that can be matched to photographs of lightning attachment to the Brixton tower. **Investigation 1** matched strokes with nine of the twelve photographs. **Investigation 2** matched strokes with seven of the twelve photographs found in *Appendix A*. As can be seen in *Table 5.5*, strokes from both the investigations were matched to the same photographs except for photograph 2 and 11, which **Investigation 1** matched strokes to but **Investigation 2** did not.

Matches were found for all the corresponding photographs as in **Investigation 1** except for photograph 2 and 10. This implies that the methodology falsely excluded some results since matches to the SALDN data were made using time correlation methods..

5.4.2 Strokes

Table 5.6 shows how the complete dataset of 754 strokes was divided among the three regions *Figure 4.8*. Also shown is how the strokes time correlated with the photographs in **Investigation 1** are divided among the three Regions. 18 of

Table 5.5: Photographs matched to strokes for both investigations. Photographs in *Appendix A*

Photograph	Investigation 1	Investigation 2
1	Match	Match
2	Match	-
3	Match	Match
4	Match	Match
5	-	-
6	Match	Match
7	Match	Match
8	-	-
9	Match	Match
10	-	-
11	Match	-
12	Match	Match

these were extracted by the methodology (Region A) and 10 were discarded by the methodology.

Table 5.6: Number of matched strokes

	Total Number of Strokes	Time Correlated Strokes	Uncorrelated Strokes
Region A	34	18	16
Region B	614	6	608
Region C	106	4	102

Region A Strokes

Table 5.7 shows the 34 strokes extracted from the data set using the methodology compared with the 18 strokes that were previously time correlated with the photographs. As can be seen, strokes ∇^{1}, ∇^{4-9}, ∇^{12} and ∇^{22-23} did not fall into Region A. Otherwise, the methodology extracted the same strokes that were extracted by the time correlation investigation and matched them to the same photographs.

The methodology also extracted 16 strokes that did not match with the time correlated strokes or the photographs. Five of these strokes occurred on the 7 January 2010, the same day as one of the photographs that was matched and another

Table 5.7: Reported SALDN strokes matched to **Investigation 1** strokes using the methodology (Region A)

Number of Matched Strokes (Region A)	Reported Stroke Time (UTC)	Time Correlated Strokes	Stroke Number
2	16:50:22	Yes	$\triangledown^{2-3}$
2	17:08:53	Yes	$\triangledown^{10-11}$
2	18:42:04	Yes	$\triangledown^{13-14}$
1	19:27:08	No	-
4	20:55:54	No	-
1	21:29:42	Yes	$\triangledown^{15}$
4	21:03:11	Yes	$\triangledown^{16-19}$
1	14:45:09	No	-
4	14:53:10	No	-
4	14:53:11	No	-
2	15:07:06	No	-
2	16:25:54	Yes	$\triangledown^{20-21}$
6	00:40:00	Yes	$\triangledown^{24-28}$

eleven on 31 March 2010 - also a day in which a photograph was obtained and matched.

Region B Strokes

Strokes $\triangledown^{4-9}$ from **Investigation 1** fall into Region B. These strokes were time correlated with photograph 2 in **Investigation 1**. In **Investigation 2**, they fall into Region B and are discarded - hence the reason why **Investigation 2** did not match strokes to Photograph 2.

Region C Strokes

Of all the strokes extracted in **Investigation 1**, $\triangledown^{1,12,22,23}$ were detected by only two sensors. Therefore, they fall in Region C and are discarded from the methodology results. These strokes constitute the false exclusions. This demonstrates the problem when strokes are detected by only two sensors - these strokes were time correlated with the photographs and should be included as matches to the location of interest.

However, due to only being detected by two sensors, the stroke location offsets of stroke $\triangledown^{22-23}$ are much greater than any of the strokes falling in Region A. It is therefore not possible to distinguish these strokes from any of the other 102 strokes that were detected by only two sensors.

5.5 Summary

In this chapter, an evaluation of the proposed methodology has been presented. This is done by extracting LDN data for known ground-truth lightning events (photographs) using the proposed methodology and comparing this dataset with LDN data matched to photographs of lightning attachment.

Photographs of lightning attachment to the Brixton tower are used as ground-truth lightning events. The photographs are time stamped so time correlation with the SALDN is possible as well as the location of the Brixton tower being known, meaning that the proposed methodology may be applied to this location of interest. This allowed nine photographs to be matched to SALDN data. It is noted that, even using time correlation methods, SALDN data was not found for three of the photographs implying that the SALDN did not detect these flashes.

The methodology was applied and 34 strokes were extracted as lightning attachments to the tower, 18 of which matched the strokes extracted using time correlation methods. Only seven of the photographs were matched to SALDN data using the methodology. The other 10 strokes extracted using time correlation were discarded by the methodology. Some of the strokes that were time correlated were discarded because they were detected by only two sensors. The methodology also extracted strokes that did not match any of the photographs. The methodology therefore extracts partly the correct information but also returns false positives as well as making false exclusions

The following chapter discusses a practical scenario in which the methodology is applied to extract data from the SALDN to determine if lightning was the cause of damage to a tree and when the event occurred.

Chapter 6

Case Study: Damaged Tree

> A practical application of the proposed methodology is presented here. The methodology is applied to determine if lightning is the possible cause of damage to a tree that appears to have been struck and to see if the date and time of the event may be established. The scenario can be likened to a situation in which the Lightning Detection Network (LDN) data is to be used as a deciding factor for an insurance claim.

6.1 Overview

This chapter describes a practical application of the proposed methodology. A damaged tree that appears to have been struck by lightning has been observed but there was no observation of lightning attachment to the tree. The methodology is applied to investigate the South African Lightning Detection (SALDN) data and determine whether:

- Lightning activity could have caused the damage.
- The date and time the damage was caused.

All that was observed is a damaged tree and no observation of lightning attachment was made. In the hypothetical situation of an insurance claim, it is important to establish whether there was lightning during the time period and in the area that may have attached to the tree and caused the damage otherwise the damage may have been caused by some other event. Establishing which strokes detected by the

SALDN actually attached to the tree will then allow for the exact time and day of the event to be established.

6.2 Damaged Tree

Figure 6.1 shows two pictures of a tree that appears to have been struck by lightning. There exists no ground-truth record (observation, photograph etc) of attachment to the tree, only the observation that the tree is now damaged. It is unknown when the event that caused the damage occurred - observations report that the damage to the tree was observed after the 16 March 2011 but that the tree was still intact before the 11 March 2011 - the event that caused the damage occurred sometime between the 11 and 16 March 2011.

(a) (b)

Figure 6.1: Damaged tree which appears to have been struck by lightning.

6.3 Applying the Methodology

The proposed methodology described in *Chapter 4* is now applied to establish:

- SALDN data available that could have caused the damage.
- When the event that caused the damage occurred.

6.3.1 Location of Interest

The tree is located at a longitude of 28°10'52.22" East and a latitude of 26°8'32.48" South, therefore, the location of interest becomes:

$$Location\ of\ Interest \ = \ (-26.1424°, 28.1812°) \tag{6.1}$$

As described by *Equation 4.1*.

6.3.2 Selecting Relevant Data

All data detected by the SALDN that is relevant to the event is selected by the following criteria:

Date: Eyewitness reports claim the event that caused the damage occurred between the 11 - 16 March 2011, therefore all data recorded by the SALDN during this period is selected.

Area: Given a location of interest (−26.1424°, 28.1812°), the data within a 495 km^2 area around this location of the tree is extracted from the SALDN. From *Equation 4.2* and *4.3*, all data occurring within the following latitude and longitude is selected:

$$-26.2424° < \lambda < -26.0424° \tag{6.2}$$

$$28.0812° < \varphi < 28.2812° \tag{6.3}$$

where

λ = The latitude of a stroke returned by the SALDN (decimal degrees)

φ = The longitude of a stroke returned by the SALDN (decimal degrees)

Cloud-to-ground: Cloud-to-cloud strokes are discarded from the dataset leaving only cloud-to-ground strokes.

Table 6.1 shows the number of strokes selected from the SALDN for the time period 11 - 16 March 2011.

Table 6.1: Days of relevant data

Date	Number of Strokes
11/03/2011	4
12/03/2011	173
13/03/2011	737
14/03/2011	54
15/03/2011	543
16/03/2011	63
Total	1574

6.3.3 Stroke Location Offset

The Stroke Location Offset (SLO) is calculated for each of the selected strokes in *Table 6.1*. *Figure 6.2* shows the reported locations of all the selected strokes as a function of their stroke location offset from the location of interest, found at the origin. Many strokes occur within 4 km^2 around the location of the tree.

6.3.4 Number of Sensors vs. Stroke Location Offset

Figure 6.3 shows the calculated stroke location offsets against the number of reporting sensors for all the selected strokes. The three regions for extracting strokes are also shown. *Table 6.2* shows how the complete set of 1958 strokes is distributed between the three Regions. All strokes that fall in Region A are extracted as strokes that attached to the location of interest, in this case, the tree. Strokes that did not are in Region B and strokes that are detected by only two sensors fall into Region C - these strokes could potentially have attached to the location of interest but have a large error in reported location or they may not have attached to the location.

Table 6.2: Number of strokes in each region

	Region A	Region B	Region C
Number of Strokes	61	1581	316

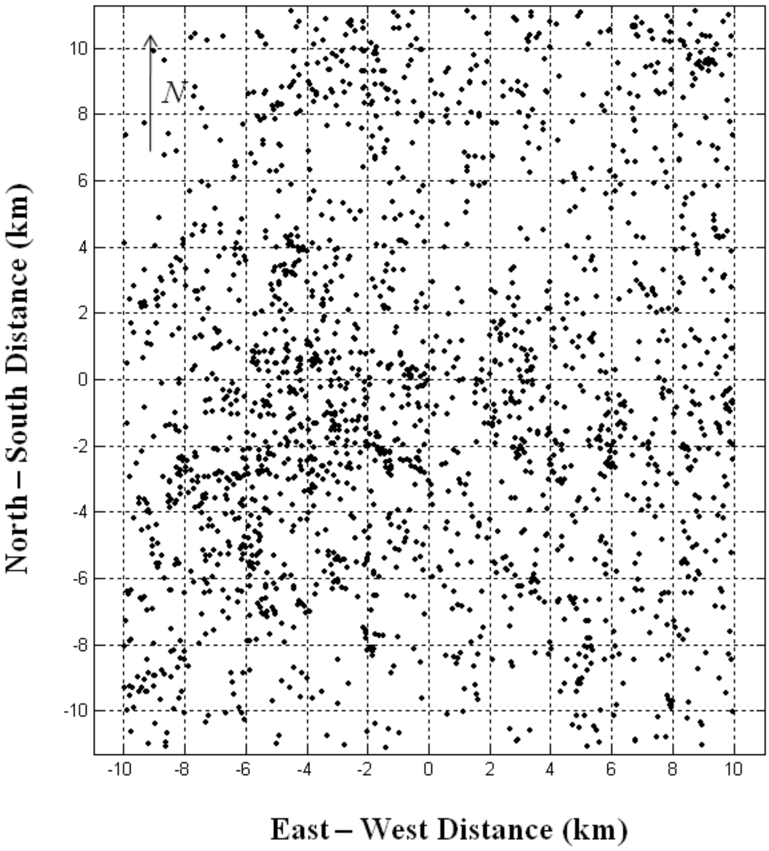


Figure 6.2: Reported location of strokes in area surrounding the tree (tree located at origin).

6.4 Results

Table 6.3 shows all the strokes that fall into Region A and are therefore extracted as strokes that attached to the location of interest. A total of 61 strokes fall into Region A and, of these, 31 flashes can be established. Strokes are grouped into flashes if they occur within milliseconds of each other. As seen in *Table 6.3*, multiple flashes on one day implies many strokes in the area at different times throughout the day.

Table 6.3: Number of strokes and possible flashes (Region A)

Date	Number of Strokes	Number of Possible Flashes
13/03/2011	34	14
15/03/2011	9	4
16/03/2011	9	9
20/03/2011	9	4

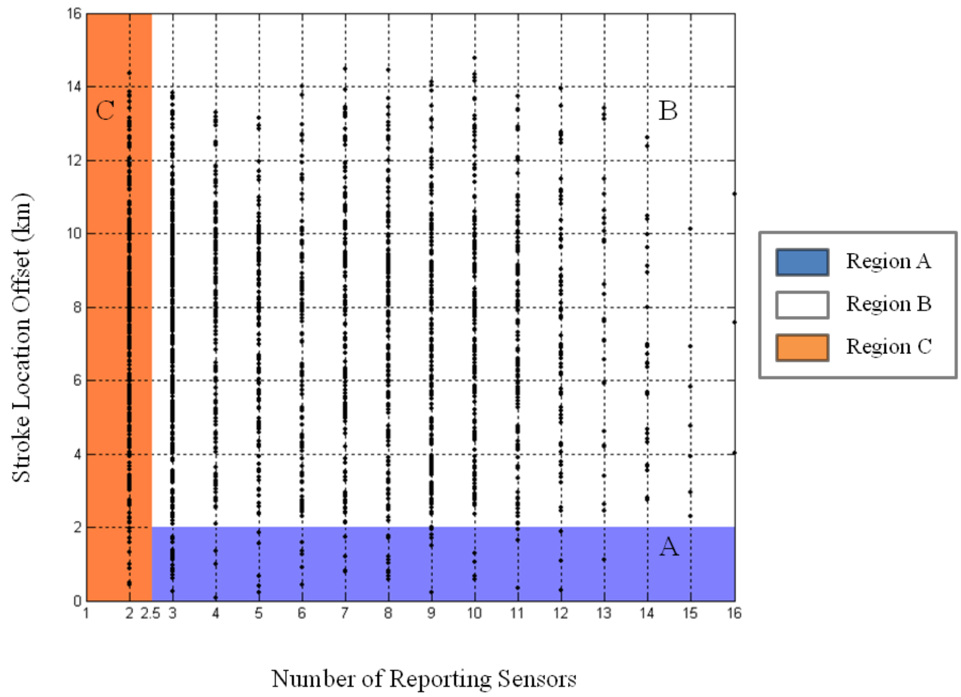


Figure 6.3: Number of reporting sensors vs. stroke location offsets. Regions A, B and C are shown

The methodology extracted a large number of strokes over the time period that could have attached to the location of interest. It is not possible to establish the exact time and day of the event since there are lightning records over the whole period that could have caused the damage. The most strokes were extracted for the 13 March 2011 but these happened at different times throughout the day. It is highly unlikely that there were as many attachments to the tree as there are flashes shown in *Table 6.3*. Once again, it is seen that the methodology extracts false positives. The reasons for this is that the stroke location criteria used in the methodology for Region A is not strict enough - strokes that did not attach to the location of interest but attached nearby, are being extracted.

The implications of this on the hypothetical insurance claim scenario is that the methodology could not be used to prove that lightning was the cause of damage to the tree since the many of the strokes returned by the methodology are false positives. An argument could be made that the methodology shows that there was at least lightning attachments that potentially could have attached to the tree but this would need to be combined with corroborating evidence, confirmation that the damage to the tree was indicative of lightning damage for example, in order to claim that lightning was a likely cause of damage. However, without the evidence of a struck tree, the data extracted from the SALDN by the methodology is not strong enough to indicate whether lightning attached to the location of interest given that it is seen to return false positive results.

6.5 Summary

In this chapter, the proposed methodology is applied to extract data from the South African Lightning Detection Network (SALDN) to determine if damage to a tree was caused by lightning and when it occurred. The scenario demonstrates a hypothetical insurance claim situation in which the decision is to be based on the SALDN data.

Applying the methodology is to the SALDN data resulted in a large data set of potential attachments to the tree. Clearly, the methodology returns false positive results and could therefore potentially indicate that lightning was the cause of damage when it was not. The methodology is therefore not capable of providing evidence of lightning being the cause of damage without corroborating evidence that lightning could be the potential cause of damage.

The following chapter discusses the observations made in the evaluation of the methodology in *Chapter 4* and the practical application of the methodology presented here. Further work to improve the methodology based on these observations is discussed.

Chapter 7

Discussion and Further Work

This chapter discusses the observations of the methodology made in *Chapters 5* and *6*. The reasons for unmatched photographs, discarded strokes and extra strokes extracted by the methodology are presented. Solutions to these observations and the challenges in the further work needed to achieve them and improve the methodology are discussed.

7.1 Overview

In *Chapters 5* and *6*, the methodology was evaluated and applied. The methodology was able to extract the same strokes that time correlation methods extracted and determine whether lightning was a possible cause of damage. Some other observations were also made in these investigations:

- Photographs which were not matched to strokes.
- Time correlated strokes detected by two sensors discarded.
- Strokes that could not be matched to photographs.

In this chapter, these observations are discussed and explanations for them are sought. Solutions for these observations and future work that could lead to the improvement of the methodology are also discussed.

7.2 Unmatched Photographs

In *Chapter 5*, **Investigation 1**, strokes reported by the SALDN were matched to nine of the twelve photographs. In **Investigation 2**, strokes were only matched to seven of the twelve photographs. These seven matches were the same matches made in **Investigation 1** except for two - strokes on the 28 December 2009 at 16:52:53 UTC and a stroke on 20 April 2010 at 14:36:56 UTC. These correspond to strokes $\triangledown^{4-9}$ and stroke $\triangledown^{22}$ from **Investigation 1**.

Stroke $\triangledown^{22}$ was detected by only two sensors and was therefore discarded since it falls into Region C. Strokes $\triangledown^{4-9}$, however, fall in Region B - detected by more than two sensors but with stroke location errors greater than 2 km. This seems to imply a flaw in the methodology - strokes that were matched to photographs of lightning attachment to the tower (time correlation) are being discarded. There are two possibilities for this: the stroke location offsets of strokes being detected by three sensors and the possibility of attachment to the Hillbrow Tower.

7.2.1 Three Sensor Detections

Strokes $\triangledown^{5-9}$ were detected by three sensors. These five strokes all have stroke location offsets (relative to Brixton tower) slightly greater than 4 km. In the evaluation of the U.S. National Lightning Detection Network (NLDN) by *Jerauld et al.*, it was seen that the location errors became less when more sensors detected a stroke as discussed in *Chapter 2*. It was seen that strokes detected by a greater number of sensors had location errors within a range of 0.1 to 2 km - hence the proposed criteria for the methodology. However, strokes detected by three or four sensors still had location errors of up to 4 km [6].

There is the possibility that strokes $\triangledown^{5-9}$ did attach to the tower but, since they were detected by three sensors, they have location errors larger than 2 km. This implies that the criteria for defining Region A in the methodology should be improved to accommodate possible larger stroke location errors for three and four sensor detections but still have stricter criteria for higher number sensor detections. To determine the correct criteria for three and four sensor detections would not be trivial and would require a statistically significant amount of ground-truth data.

Stroke $\triangledown^{4}$ was detected by nine sensors and had a stroke location error of almost 8.5 km. There is no other explanation for this other than it was incorrectly matched to a photograph of lightning attachment to the tower.

7.2.2 Hillbrow Tower

The other possibility for strokes $\triangledown^{4-9}$ is that they were incorrectly matched to a photograph in **Investigation 1**. As discussed in *Chapter 2*, there is another tall tower, the Hillbrow tower, in the Johannesburg region that lies 4.8 km east of the Brixton tower. The strokes $\triangledown^{4-9}$, were also reported to lie east of the Brixton Tower and near to the location of the Hillbrow tower. It is possible that there was a lightning attachment to the Hillbrow tower at the same time the photograph of lightning attachment to the Brixton tower was captured and that strokes $\triangledown^{4-9}$ should actually be matched to the Hillbrow tower. No record of attachment to the Hillbrow tower at this time is available, but a similar camera setup to the one observing Brixton tower has subsequently been commissioned and many photographs of attachment to the Hillbrow have been captured.

Applying Methodology to Hillbrow Tower

The location of interest is chosen to be that of the Hillbrow tower, (-26.1868°, 28.0494°. All data reported by the South African Lightning Detection Network (SALDN) on the 28 December 2009 used in *Chapter 5* is selected for this investigation. The Stroke Location Offset is now calculated with respect to the Hillbrow tower, not the Brixton tower. *Figure 7.1* shows the stroke location offsets with the Hillbrow tower located at the origin. Once again, all the strokes that were matched to the photographs using time correlation methods are indicated as $\triangledown^{1-14}$.

Strokes $\triangledown^{5-9}$ were reported to have occurred close to the Hillbrow tower. These strokes were discarded by the methodology as attachments to the Brixton tower even though they occurred at the same time as a photograph. Strokes $\triangledown^{1-3}$ and $\triangledown^{10-14}$ cluster around what would be the location of the Brixton tower, approximately 4.8 km from the Hillbrow tower. *Figure 7.2* shows the calculated stroke location offsets against the number of reporting sensors with the matching criteria.

Strokes $\triangledown^{5-9}$ are clearly extracted (fall into Region A) as attachments to the Hillbrow tower while strokes $\triangledown^{2-3,10-14}$ are clearly discarded. This provides a strong argument that attachment to the Hillbrow occurred at the same time as attachment to the

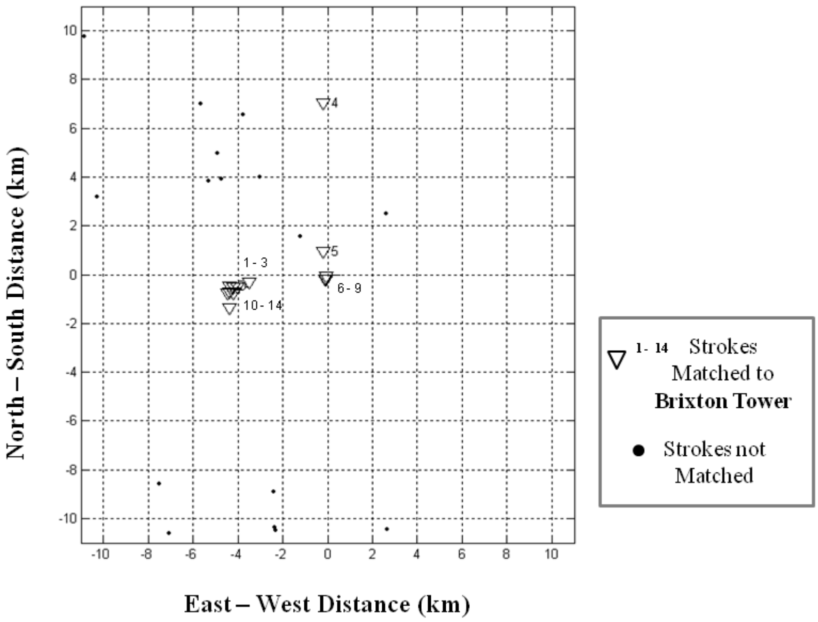


Figure 7.1: Stroke location offsets with respect to the Hillbrow tower, located at the origin.

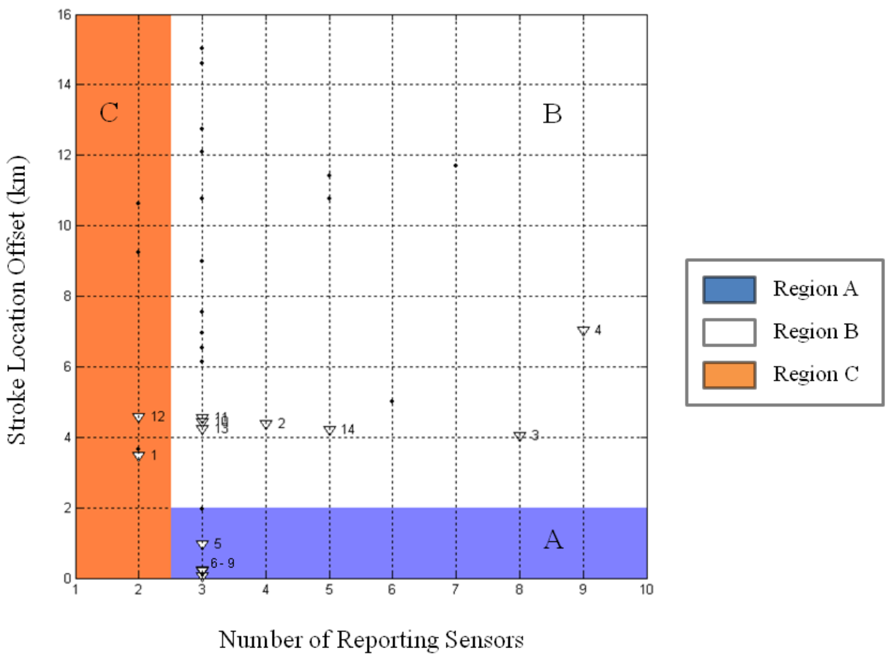


Figure 7.2: Number of reporting sensors vs. stroke location offset with matching criteria shown.

Brixton tower was photographed. Strokes ∇^{5-9} have been incorrectly time correlated with the attachment to the Brixton tower.

7.3 Discarded Two Sensor Detections

In **Investigation 2**, four of the strokes matched to photographs in **Investigation 1** were detected by only two sensors and, therefore, were discarded by the methodology. The methodology discards strokes that are detected by two sensors since it is not possible to make a distinction between strokes that attached to the location of interest and strokes that did not using stroke location offset.

The four strokes are strokes $\nabla^{1,12,22,23}$. Strokes ∇^{1} and ∇^{12} had stroke location offsets less than 2 km but strokes ∇^{22} and ∇^{23} had stroke location offsets of approximately 5 and 6 km respectively. Many other strokes detected by two sensors that were not time correlated to the photographs had stroke location offsets less than 2 km and many have greater than 2 km.

For this reason, strokes detected by only two sensors are discarded from the methodology. However, it is possible that strokes detected by only two sensors may still be included if they can be found to be part of a group of strokes that are extracted by the methodology. *Table 7.1* shows strokes matched in **Investigation 1** to the photographs (that were detected by only two sensors). Also included are any strokes extracted (Region A) by the methodology that happened on the same day and time.

Strokes $\nabla^{1,12,23}$ were all reported at the same time (millisecond difference) as a number of strokes that were extracted as matches by the methodology. Clearly, these strokes are part of that same group but were only detected by two sensors and should still be included. Stroke ∇^{22} was detected by only two sensors but no other strokes that could be extracted by the methodology were reported at that time and should be discarded.

Table 7.1: Strokes detected by 2 sensors and surrounding Region A strokes

Photograph (#)	Date	Stroke (#)	Reported Stroke Time (UTC)	Number of Reporting Sensors
1	28/12/2009	∇^1	16:50:22	2
		∇^2	16:50:22	4
		∇^3	16:50:22	8
3	28/12/2009	∇^{10}	17:08:53	3
		∇^{11}	17:08:53	3
		∇^{12}	17:08:53	2
11	20/04/2010	∇^{22}	14:36:56	6
12	10/05/2010	∇^{23}	00:40:00	2
		∇^{24}	00:40:00	8
		∇^{25}	00:40:00	3
		∇^{26}	00:40:00	3
		∇^{27}	00:40:00	5
		∇^{28}	00:40:00	4

7.4 Unmatched Strokes

In both *Chapter 5* and *6*, the methodology returned false positive results in the form of extra strokes that did not correspond with any of the ground-truth photographs.

7.4.1 Photographs of Brixton Tower (Chapter 5)

In *Chapter 5*, **Investigation 2**, 16 potential false positives were extracted as attachments to the tower by the methodology that could not be matched to any of the photographs. Five of these strokes occurred on the 7 January 2010, the same day that a photograph was obtained and matched to SALDN data, and eleven of them occurred on the 31 March 2010, another day on which a photograph and a corresponding data was obtained. This has two possible explanations; either the camera setup does not capture every attachment to the tower or the methodology includes strokes that attach to nearby locations but not to the location of interest itself.

7.4.2 Damaged Tree (Chapter 6)

In *Chapter 6*, a total of 61 strokes occurring over four days were extracted as lightning attachment to the location of interest. Given that the event in question was a tree that appeared to have been struck by lightning, it is unlikely that 61 strokes attached to the same location over four days. Clearly, the methodology extracted many strokes that did not attach to the location of interest but occurred in the same area.

7.4.3 Implications on Forensic Applications

This observation of the methodology returning false positive results is of particular concern in the proposed application of forensic scenarios. If the methodology is used, it is possible that it could indicate the lightning did attach to the location of interest and was therefore the cause of damage even in the situation that it did not. However, the methodology may very well return the correct result if lightning was the cause of damage. This implies that the methodology should be used as a "filter" in conjunction with other corroborating evidence so as to disregard any possible false positive results.

7.4.4 Possible Solution

The main criteria used to select strokes for Region A is the 2 km restriction on the stroke location offset. As discussed above in *Section 7.2*, this does not necessarily hold true for all strokes detected by more than two sensors - strokes detected by eight sensors will have even less error in reported location than strokes detected by three sensors for example.

Many of the 16 strokes unmatched to photographs in **Investigation 2** have stroke location offsets of 1 to 2 km but were detected by six or more sensors. The same is seen in *Chapter 6*. These strokes should more correctly fall into Region B and be discarded. *Figure 7.3* shows a revised version of the regions that determine the selection of matching strokes for the methodology. The stroke location offset criteria should be made more specific, depending on the number of reporting sensors and not just 2 km. Strokes detected by more than six sensors will have much lower location errors.

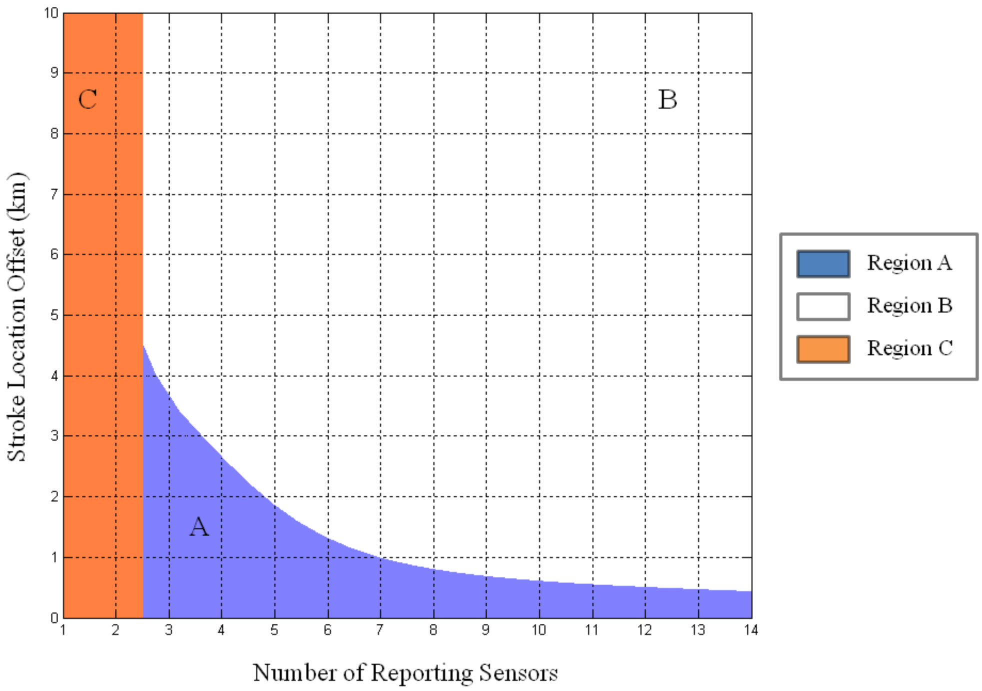


Figure 7.3: Number of reporting sensors against stroke location offset with proposed Region A criteria. Values are demonstrative and do not indicate actual criteria - obtaining them would be an extensive investigation.

The actual values of the stroke location offsets for each number of reporting sensors defining Region A in *Figure 7.3* are only demonstrative and do not reflect actual values that should be applied - to establish these values, a statistically significant amount of data would be required.

This data is not easily obtained - it would require a statistically significant amount of location error data for each possible case of reporting sensors (three sensors reporting, four sensors reporting etc.). This means that this amount of LDN data would need to be matched to ground-truth events and the location error for each stroke calculated. It is unlikely that any one location will have this many lightning attachments in a single lightning season. It would also be required to obtain ground-truth data at different locations since a single location will frequently have the same number of strokes attaching to it.

7.5 Summary

This chapter discusses some of the observations made in the evaluations of the methodology. It was observed that two of the photographs matched to SALDN reports in the time correlation investigation were not matched using the methodology. This was discussed and it was decided this was either because of too strict criteria for stroke location offsets for strokes detected by three sensors or because the strokes actually attached to the Hillbrow tower and were incorrectly matched to photographs of attachment to the Brixton tower.

Strokes detected by two sensors that were matched to attachments to the Brixton tower using time correlation were discarded by the methodology. It was shown, however, that if these strokes could be shown to be part of a group of strokes that had been extracted by the methodology, they could be included as attachments to the location of interest.

Finally, both the results of *Chapters 5* and *6* showed that the methodology extracted extra strokes that did not correspond to attachments to the location of interest. It is proposed that the stroke location offset criteria be investigated depending on the number of reporting sensors and not just be 2 km. This would be an extensive investigation requiring a significant amount of LDN data to be matched to ground-truth events.

The following chapter summarises the findings of this work in regards to the proposed methodology and provides a conclusion to the dissertation.

Chapter 8

Conclusion

Lightning Detection Networks (LDNs) use Time-of-Arrival (TOA) and Magnetic Direction Finding (MDF) methods to determine the location of a lightning stroke. These methods require information from multiple sensors in order to resolve the position of a stroke. Characteristics observed in evaluations of LDNs show that the location accuracy of these networks is greatly effected by the number of sensors that detect a stroke - more sensors detecting a stroke result in greater accuracy of its reported location.

This observation is used to propose a methodology for extracting data from LDNs to match with ground-truth events of lightning attachment when no information is available about the time at which the ground-truth event occurred. The methodology proposes that any stroke that did potentially attach to the location of the event in question will have a location error less than 2 km if detected by more than two sensors. Therefore, the stroke location offset with respect to this location can be examined for all strokes and the ones that are less than 2 km away from the location, potentially attached to the location.

An evaluation of the methodology is performed by comparing the strokes selected by the methodology to strokes that were matched using time correlation. The ground-truth events used for the evaluation are photographs of lightning attachment to the Brixton tower in Johannesburg, South Africa. The methodology extracted strokes that could be matched to seven of the nine photographs that were detected by the SALDN. These were the same strokes that were matched to the photographs using time correlation. The methodology also extracted 16 strokes that did not match to any of the photographs indicating that the methodology returns some false positive results.

The methodology also discarded some of the strokes that were matched to the photographs using time correlation as they were detected by only two sensors indicating that it also makes some false exclusions. It was discussed that, if a stroke detected by only two sensors could be shown to be part of a group of strokes that were extracted by the methodology, it should be included as a match.

A practical application of the methodology is also presented in which, it is used to determine whether lightning could be the cause of damage to a tree and at what time this damage may have occurred. The methodology extracted a large number of strokes as potential attachments to the tree once again indicating that the methodology returns false positive results. The individual strokes that caused the damage could not be discerned.

It is concluded that the proposed methodology is able to extract strokes from a LDN database that attached to a specific location without using timing information. However, the methodology also extracts false positive results as well as making some false exclusions. The implications of this on the intended application in forensic and insurance claim scenarios is that the methodology could potentially provide false positive results or falsely excluded correct results. However, the methodology is still capable of extracting many correct results. It is therefore recommended that the methodology be used as "filter" to reduce a large dataset of LDN records but that it needs to be used in conjunction with corroborating evidence to account for possible false positive results or falsely excluded results.

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Appendix A

Photographs of Lightning Attachment to Brixton Tower

A.1 Introduction

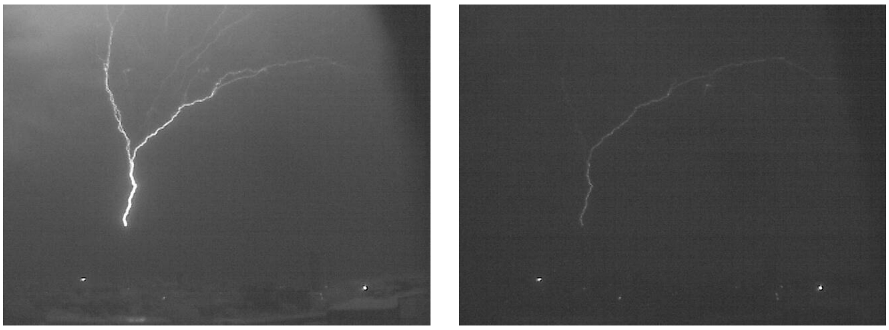
This appendix provides the photographs used in *Chapter 5* to perform the evaluation of the methodology proposed in *Chapter 4*. The photographs are of lightning attachment to the Brixton tower in Johannesburg, South Africa.

A.2 Photographs

Photographs of lightning attachment to the Brixton tower in Johannesburg, South Africa were captured over the period of December 2009 to May 2010. A total of 53 photographs were obtained and these were able to be grouped into twelve flashes where there were millisecond differences between the time the photograph is captured. Two photographs from each flash are shown here making a total of 24 photgraphs contained in this appendix. These photographs, grouped as flashes, are used as ground-truth records of lightning attachment to a location to evaluate the proposed methodology in *Chapter 5*.

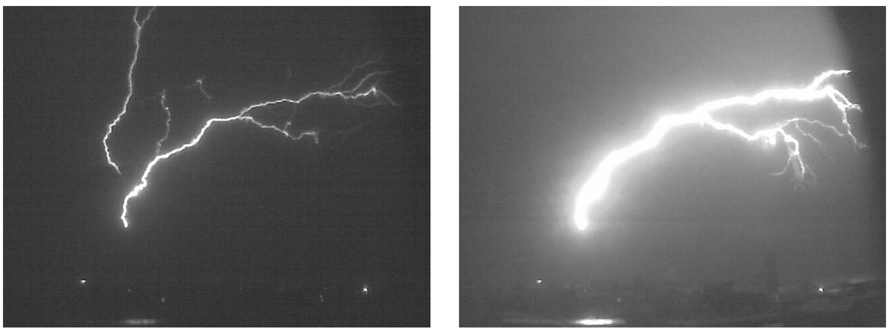
(a) (b)

Figure A.1: Photograph 1: 28 December 2009 at 16:49:04 UTC



(a) (b)

Figure A.2: Photograph 2: 28 December 2009 at 16:52:53 UTC



(a) (b)

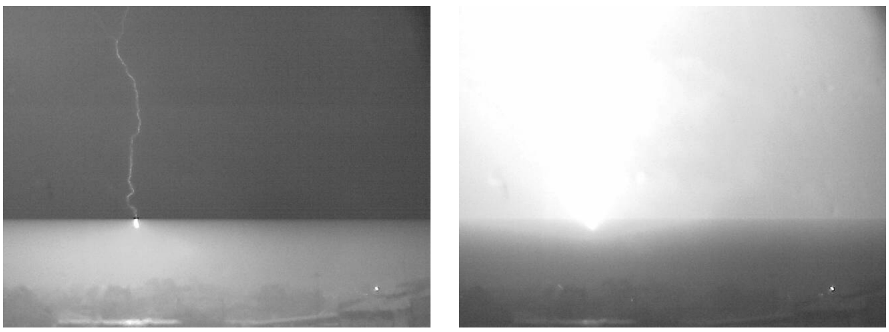
Figure A.3: Photograph 3: 28 December 2009 at 17:07:35 UTC

(a) (b)

Figure A.4: Photograph 4: 28 December 2009 at 18:40:45 UTC

(a) (b)

Figure A.5: Photograph 5: 28 December 2009 at 18:49:14 UTC



(a) (b)

Figure A.6: Photograph 6: 7 January 2010 at 21:27:39 UTC

(a) (b)

Figure A.7: Photograph 7: 2 February 2010 at 21:01:34 UTC

(a) (b)

Figure A.8: Photograph 8: 16 February 2010 at 20:03:52 UTC

(a) (b)

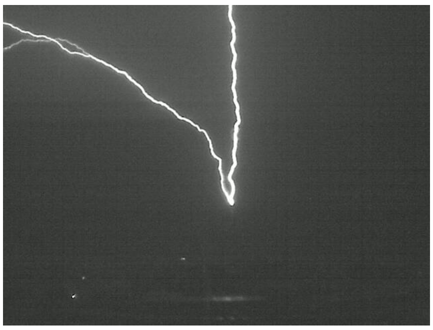
Figure A.9: Photograph 9: 31 March 2010 at 16:23:17 UTC


(a) (b)

Figure A.10: Photograph 10: 18 April 2010 at 19:33:31 UTC


(a) (b)

Figure A.11: Photograph 11: 20 April 2010 at 14:35:56 UTC

(a) (b)

Figure A.12: Photograph 12: 20 May 2010 at 00:39:49 UTC

Appendix B

Using Photograph of Lightning Attachment to Investigate Lightning Detection Network Data Matching Methodology

B.1 Preamble

This appendix is a paper that was accepted and presented for publication by the *International Conference on Atmospheric Lightning (ICAE)* in 2011, hosted in Rio de Janeiro, Brazil. The paper is entitled: **Investigation of Method for Matching Lightning Detection Network Data with Ground-truth Records**.

B.2 Paper Description

This paper describes the investigation of a method to match Lightning Detection Network (LDN) data with ground-truth records using a photograph of lightning attachment to the Brixton tower on the 10 May 2010. The lightning detection network data is time correlated with the time of the photograph and it is shown that a distinction can be made between LDN data that attached to the tower and data that did not by comparing the location errors of the data with the number of reporting sensors.

Investigation of Method for Matching Lightning Detection Network Data with Ground-Truth Records

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School of Electrical & Information Engineering, University of the Witwatersrand, Johannesburg, South Africa.

ABSTRACT: This paper investigates a method for matching the data reported by a Lightning Detection Network (LDN) with ground-truth photographs. Previous investigations of LDNs show that the more sensors that detect a stroke, the greater the accuracy in the reported location of the stroke. The method is investigated by comparing the number of reporting sensors with the location errors of a data set of strokes that were reported around the time a lightning event was photographed. It is seen that the strokes matched to the photograph follow the expected relationship between location error and number of reporting sensors whereas strokes that do not correspond to the photograph in time do not. It is suggested that this observation may be further developed as a means of matching LDN data with true lightning events.

1. INTRODUCTION

Lightning Detection Networks (LDNs) are implemented in many countries throughout the world. Evaluation of the performance of these networks is important to ensure that the data provided gives an accurate reflection of the true nature of the lightning phenomenon (Jerauld, 2005). One of the most successful ways of achieving this is to compare the detection network records with an external lightning measurement (or ground-truth data). Matching the data to the correct event is not always trivial – most notably, when timing information is not available. This may be the case when the ground-truth data available is from objects that have been damaged by lightning. For example, struck trees (Makela, 2008). This paper investigates a method for matching LDN data with ground-truth data (in this case, a photograph) that does not require precise accuracy in timing information.

2. BACKGROUND

The data that is used for this investigation is obtained from the South African Lightning Detection Network (SALDN) and is compared with photographic records of lightning attachments to the Brixton Tower in Johannesburg, South Africa.

2.1 South African Lightning Detection Network

The South African Lightning Detection Network (SALDN) was first installed in 2006 and is operated by the South African Weather Service (SAWS). Currently, it consists of 22 Vaisala LS7000 sensors located around the country, one of which is located in Swaziland (Gill, 2008).

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2.2 Previous Evaluations of Lightning Detection Networks

An evaluation of the U.S. National Lightning Detection Network was conducted by *Jerauld et al.* (2005) using data from 2001 - 2003. An important characteristic was seen in this evaluation – the greater the number of reporting sensors, the smaller the location error of the reported stroke. This characteristic was again seen in an evaluation performed by *Nag et al.* (2010) using data from 2004, 2005 and 2007.

2.3 Network Position Detection

The SALDN uses Time-of-Arrival (TOA) as well a Magnetic Direction Finding (MDF) techniques to determine the location of a detected stroke. In both cases, it is required that more than one sensor detects the lightning event in order to resolve the position of the stroke. Given that both TOA and MDF are used, it is possible to determine a stroke location using information from only two sensors (Rakov, 2003). To resolve a position given any errors in time and angle measurements, the network minimizes the chi-square function (Cummins, 1998). The more information that is included in this calculation, the more accurate the reported location of the stroke will be. Hence, more sensors reporting the location of a stroke means that the reported position is more likely to be correct or, at least, have a small location error.

2.4 Brixton Tower and Photographs

Figure 1 shows a photograph of lightning attachment to the Brixton Tower in Johannesburg, South Africa. The Brixton Tower is a tall tower in the Johannesburg region standing approximately 250 m tall. It is located at 28°0’24.73’’E longitude and 26°11’32.82’’S latitude. The photograph shown in the figure is the result of a motion-triggered surveillance camera installed to capture lightning attachments to the Brixton Tower. The photograph was taken on the 10 May 2010 at 00:39:33 UTC.

Figure 1: Lightning flash to the Brixton Tower on 10 May 2010 at (a) 00:39:49:04 UTC and (b) 00:39:49:17 UTC. Courtesy of Yu-Chieh Liu.

3. METHODOLOGY

Table 1 shows the data reported by the SALDN on the 10 May 2010 from the time 00:39:33 UTC within a 400 km^2 area around the Brixton Tower. Since the photograph occurred at 00:39:49, it is unlikely that any of the data reported by the network before this time is representative of the flash in the photograph. None of the reported times correspond exactly to the time of the photographs (00:39:49:04 UTC and 00:39:49:17 UTC) however, a number of strokes occur at within microseconds of each other 00:40:00 UTC. The photograph time stamp was not synchronized to UTC and this could explain this slight error in time.

The first two strokes in table 1 (shaded) were detected as intra-cloud events and should be discarded since they are not representative of the photograph which shows a cloud-to-ground attachment. Also, the last two (also shaded) were reported to have occurred just after 00:47:00 UTC – significantly later than the time of the photograph. These are also not representative of the flash to the tower.

Table 1: SALDN data for flash on the 10/05/2010.

Latitude	Longitude	Time (hrs/min/sec)	Current (kA)	No. of Sensors	CC or CG
-26.1599	28.0791	00:39:33	7	2	CC
-26.2003	28.0143	00:40:00	-8	2	CC
-26.1506	27.9639	00:40:00	-9	2	CG
-26.1919	28.0074	00:40:00	-17	8	CG
-26.1899	28.0037	00:40:00	-13	3	CG
-26.1912	28.0034	00:40:00	-15	3	CG
-26.1893	28.0045	00:40:00	-15	5	CG
-26.1878	28.0043	00:40:00	-15	4	CG
-26.1454	28.0747	00:41:18	-8	4	CG
-26.1712	27.9503	00:47:04	-19	2	CG
-26.1298	28.0077	00:47:39	-40	9	CG

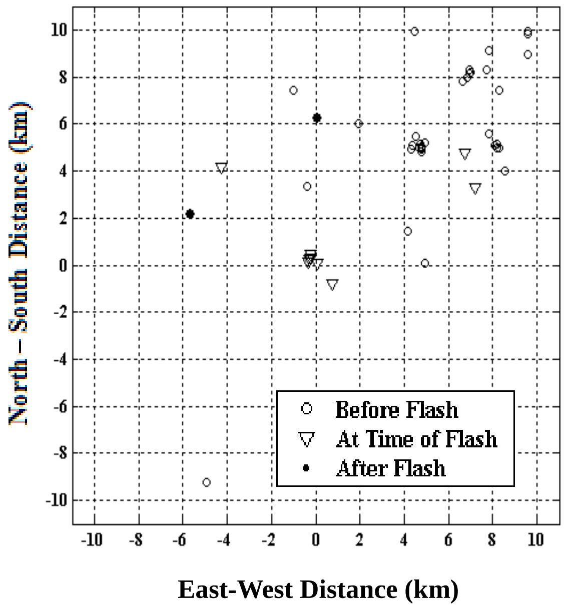

Figure 2: Location errors (km) for strokes shown in table 1. Brixton Tower is located at the origin.

Figure 2 shows a plot of the reported positions of the data presented in table 1. The origin of the plot corresponds to the location of the Brixton Tower all other points are then shown relative to this location in kilometers. This shows the location errors given in the last column of table 1. Included in the figure, are the strokes reported to have occurred 10 minutes before 00:39:33 and, therefore, before the photograph. These are indicated with open circles. The strokes occurring at 00:40:00 UTC (represented by open triangles), apart from a two of them, are mostly seen to have smaller location errors.

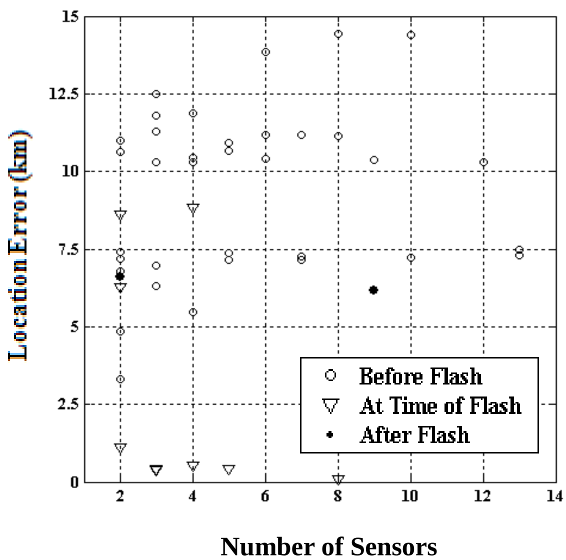

Figure 3: Location error (km) against number of reporting sensors.

Figure 3 shows a plot of the number of reporting sensors against the location errors of the reported strokes. Given the discussion in Section 2, it is expected that strokes detected by a greater number of sensors will have smaller location errors. In figure 4, we see that the strokes occurring at the time of the flash, indicated by the triangles, follow this relationship. The other strokes, indicated by the circles, which are known to have occurred before the flash and do not represent the photograph, have consistently large location errors regardless of the number of sensors by which they were detected. The same observation is made for the two strokes occurring at 00:47:00 UTC (closed circles). These are known not to represent the flash since they occur significantly later in time. The one stroke is detected by only two sensors and has a location error of 6.6 km. The other stroke, however, is detected by 9 sensors but also has a location error of 6.17 km.

4. CONCLUSION

It is concluded that the number of reporting sensors can be used to match ground-truth records with events reported by a Lightning Detection Network (LDN) without using the time stamping of ground-truth events. If the location of an event is known, the location errors of the data reported by the network can be compared with the number of reporting sensors. Reports that do not decrease in location error but are detected by a number of sensors should be discarded as they do not constitute a match. It must be noted, however, that strokes detected by few sensors with large location errors are indistinct and could be representative of the ground-truth event or not.

ACKNOWLEDGMENTS

The authors would like to thank the South African Weather Service (SAWS) for their support and for providing the SALDN data used in this paper. They would also like to thank CBI-electric for funding the Chair of Lightning at the University of the Witwatersrand and for direct support of the Research Group. They would also like to thank Eskom for the support of the Lightning/EMC Research Group through the TESP programme. Thanks are extended to the department of Trade and Industry (DTI) for THRIP funding as well as to the National Research Foundation (NRF) for direct funding of the Research Group.

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Nag, A., Mallick, S., Rakov, V.A., Howard, J., Biagi, C.J., Hill, D., Uman, M.A., Jordan, D.M., Rambo, K.J., Jerauld, J., Decarlo, B.A., Cummins, K.L., Cramer, J.A., "NLDN Responses to Rocket-Triggered Lightning at Camp Blanding, Florida, in 2004-2009", *30th International Conference on Lightning Protection,* Cagliari, Italy, 2A - 1336, September 2010

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Appendix C

Applying the Methodology to Match Lightning Detection Network Data for Performance Evaluation Purposes

C.1 Preamble

This appendix is a paper that was accepted and presented for publication by the *International Conference on Grounding and Earthing & 4^{th} International Conference on Lightning Physics and Effects Conference (LPE)* in November 2010, hosted in Salvador, Brazil. The paper is entitled: **Preliminary Validation of the South African Lightning Detection Network Performance**.

C.2 Paper Description

This paper describes a pre-liminary validation of the South African Lightning Detection Network (SALDN). The validation uses photographs of lightning attachment to the Brixton tower as ground-truth records so that the detection efficiency and location accuracy of the network may be investigated. The methodology described in *Chapter 4* is used to match SALDN data with the ground-truth events.

GROUND'2010
&
4th LPE

International Conference on Grounding and Earthing
&
4th International Conference on
Lightning Physics and Effects

Salvador - Brazil November, 2010

PRELIMINARY VALIDATION OF THE SOUTH AFRICAN LIGHTNING DETECTION NETWORK PERFORMANCE

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Abstract – Photographs of lightning attachment to the Brixton Tower are used as ground-truth data to perform a preliminary validation of the location accuracy of the South African Lightning Detection Network (SALDN). Due to issues with synchronising the time stamps of the photographs and the SALDN timing, a method for matching the SALDN reported strokes to the photographs is presented using the assumptions that a stroke is reported by the network within 2.5 minutes of the photograph and within a specified area. The effectiveness of this method is discussed and it is seen that strokes with large location errors that do not represent a photograph may be discarded by comparison with the number of reporting sensors. A preliminary validation of the location accuracy is made using the data with a median location error of 0.265 km.

1 – INTRODUCTION

The South African Weather Service (SAWS) operates a Lightning Detection Network (LDN) across the Republic of South Africa to facilitate investigations into the lightning phenomenon. The system became operational in early 2006 and has since provided researchers with much needed data. The improved location accuracy and detection efficiency has supplemented the previous data set from the decommissioned Lightning Position and Tracking System (LPATS) [1].

A thorough investigation of the performance of the SALDN needs to be conducted in order to fully determine the usefulness of the data. Similar validation investigations have been conducted on networks around the world. Most notable are the evaluations of the U.S. National Lightning Detection Network (NLDN). At Camp Blanding in Florida rocket triggered lightning results have been compared with the NLDN data [2, 3]. Photographic lightning records have also been used to make evaluations of the NLDN data [4].

In order to evaluate the performance of the SALDN, a comparison with ground-truth data or some other reliable record of lightning activity needs to be made.

Photographs of lightning attachment to the Brixton Tower in Johannesburg, South Africa are available from November 2009 to May 2010. The work presented here discusses a method for matching reported SALDN events with the photographs of flashes to the Brixton Tower. The photographs are then used as ground-truth data to perform a preliminary evaluation of the location accuracy of the SALDN.

2 – SOUTH AFRICAN LIGHTNING DETECTION NETWORK (SALDN)

The Council for Scientific and Industrial Research (CSIR) previously operated a network of flash counters across the South Africa. Subsequent to this, a Lightning Position and Tracking System (LPATS) was operated by the national power utility, Eskom. In both cases, the interpretation of the reported data posed significant challenges [1].

The SALDN network consists of 22 Vaisala LS7000 sensors situated across the country and an additional sensor is being installed in Swaziland. The system uses Time-of-Arrival (TOA) and Magnetic Direction Finding (MDF) methods to determine the location of a stroke [5]. Given that multiple sensors take part in each event, the possibility of timing (TOA) and angle (MDF) errors between sensors may lead to errors in the reported location [2,5].

3 – BRIXTON AND HILLBROW TOWER

Figure 1 shows a silhouette of the Johannesburg city skyline. The notable feature here is the two tallest structures at the left and the right of the image. These correspond to Hillbrow Tower (left) and the Brixton Tower (right). The Brixton Tower is a tower in the Johannesburg region located at 28.0068°E longitude and -26.1925°S latitude and is approximately 250 m high. The Hillbrow Tower is a second tower also in the Johannesburg region and is of similar height to the Brixton Tower. It is located at 28.049°E longitude and -26.1869°S latitude.

Figure 1 – The Johannesburg city skyline in silhouette. The Hillbrow Tower can be seen on the left and the Brixton Tower on the right.

4 – DATA

A surveillance camera has been recording lightning attachment to the Brixton Tower from an observation point at the University of the Witwatersrand in order to obtain lightning images for 3D-modeling purposes. This is described in greater detail in [6]. The camera is motion sensitive and is triggered by any pixel change above a user defined threshold that occurs within its frame. It is located 1.84 km from the Brixton Tower. From November 2009 until May 2010, a total of 19 flashes to the tower were photographed. In many cases, the camera captured several frames within approximately 120 milliseconds of each other. However, the time resolution between photographs is not small enough to discern individual strokes and is only sufficient to indicate a flash to the tower had occurred. Since the surveillance setup was not initially intended for comparison with the SALDN, the time stamping of events was not synchronized with the time of the SALDN network. This yielded a significant problem when attempting to correlate the time stamps of the photographs with those of the reported events.

The South African Weather Service has provided the University of Witwatersrand with the SALDN data from 2007 until 2010. The data contains records of all strokes reported by the network. Each record gives the time stamp, longitude, latitude and current measurements. The number of sensors that registered the stroke is given as well as information about the error ellipse calculation. It is important to note the distinction between flashes and strokes in the following analysis. Given the time resolution of the surveillance, only ground-truth flashes are recorded. The SALDN only reports strokes. The analysis involves matching a number of reported strokes to a known flash to the Brixton Tower.

5 – METHODOLOGY

The photographed events and the SALDN were examined to determine preliminary performance characteristics of the SALDN. These include: the detection efficiency of the network, the location accuracy and the current measurement accuracy. Since the actual detection efficiency of the surveillance system is not known, an accurate measurement of the detection efficiency using the photographs is not possible. Also, since no current information can be obtained from the photographs, this characteristic cannot be evaluated. The focus, therefore, lies in the validation of the location accuracy of the network.

To determine the location error between the known location of a stroke and what is reported by the network, correlation between a reported event and a photographed event needs to be made. Time correlation of the events has often been used in many studies given that it is the only common information between reported strokes and a ground-truth event. However, the camera setup used was not initially intended for comparison with the SALDN data as mentioned.

It was noted that the camera time was approximately 2.5 minutes ahead of the SALDN network time. The SALDN data was searched for all strokes reported within a 20 minute window of the photographic event within a 400 km^2 (20 km × 20 km) area around the Brixton Tower. It was seen that, in nearly all cases, strokes were reported to have occurred approximately 2 minutes after the time stamp recorded on the photograph. Any other strokes returned from the search were reported to have occurred several minutes before or after the photograph – on the fringes of the 20 minute window period. Given that a photographed event had occurred at that approximate time, it seems likely that these reported strokes represent the event.

The proposed method is based on two assumptions – that the time delay between the camera set-up and the network timing is within approximately 2 minutes and that the location error will not exceed the examined area. For the majority of photographs, there was reported stroke data significantly close in time and position to the tower to qualify as a match. However, some of the strokes reported within 2 minutes of the photograph time stamp had significantly larger location errors. The possibility then that these strokes do not represent the photograph becomes likely. The location errors of these strokes are then compared to the number of sensors that detected the stroke in order to determine whether these strokes do represent a flash to the tower or not. The more sensors that detect a stroke, the more accurate its reported location becomes [3].

As mentioned, a total of 19 flashes to the tower were photographed from November 2009 to May 2010. Using the methods described above, 51 reported SALDN strokes were matched to the photographs. Of these 51 strokes, 14 were noted to have occurred within the region of the Hillbrow Tower. These reported strokes may represent flashes to the Hillbrow Tower that may have occurred within the same time frame as the photographed flashes to the Brixton Tower. Consequently, these 14 strokes were discarded from the data set leaving a total of 37 reported strokes matched to the photographs.

By comparing the location errors with the number of reporting sensors, some of these strokes were discarded. This updated data set was then used to perform a preliminary evaluation of the location accuracy of the network by determining the median location error of the data set. This was then compared with the stated median location accuracy of the network (500 m) [5].

6 – RESULTS AND DISCUSSION

Figure 2 shows a plot of the SALDN stroke location errors for the 51 matched strokes. The origin corresponds to the location of the Brixton Tower at 28.0068°E longitude and -26.1925°S latitude. The horizontal axis represents the east-west or longitudinal error component (east being positive) and the vertical axis represents the north-south or latitudinal error component (north being positive). A total area of 784 km^2 is shown. The cluster of strokes that occur at approximately 4 km east and 0.5 km north (grouped within the square are within the area of the Hillbrow Tower. These are discarded leaving 37 matched strokes.

The majority of these strokes fall around the origin or in the region of Brixton Tower. A number of strokes have large location errors and are shown circled in the figure.

Due to the assumptions made in matching the strokes, it is questionable whether these strokes actually represent a flash to the tower.

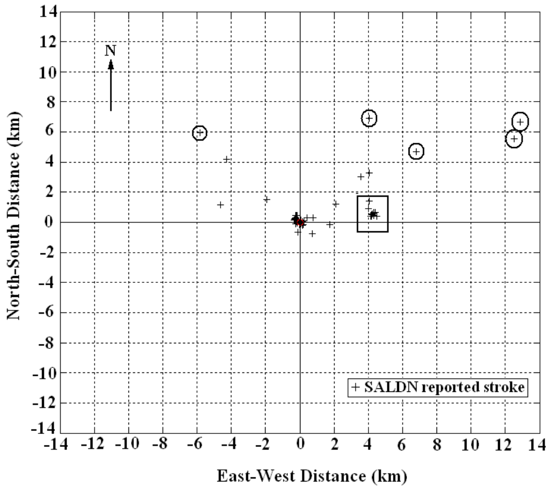

Figure 2 – Plot of SALDN location errors for the 37 matched strokes. The Brixton Tower is located at the origin. The circled stroke locations indicate strokes reported a large distance from the tower. The area enclosed by the square shows the region of the other tower, the Hillbrow Tower. The total area shown is 784 km^2 (28 km × 28 km).

Figure 3 shows a histogram of the absolute location errors for these 37 matched strokes. The absolute location error is the shortest distance between the location of the Brixton Tower and the location of the stroke reported by the SALDN. The majority of the distribution is less than 1 km with a median location error of 0.37 km. These represent the strokes with smaller location errors. The distribution has a mean location error of 1.993 km and is seen to have a "tail" due to the strokes with large location errors. As discussed, the reliability of the matching process makes it questionable whether these strokes truly represent a flash to the tower.

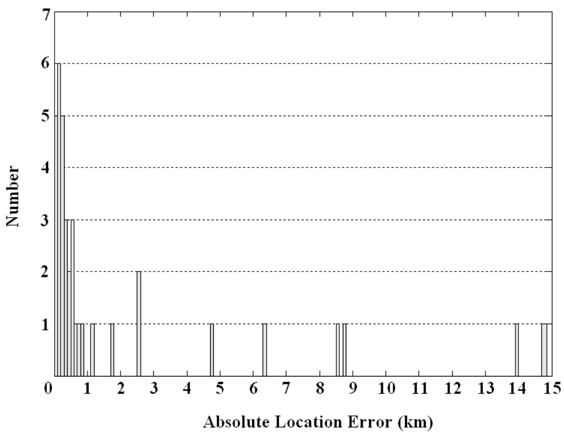

Figure 3 – Histogram of the SALDN absolute location errors. Bin sizes are 100 m.

Figure 4 shows a plot of the number of reporting sensors against the absolute location errors. There is a general trend showing that the more sensors that detect the stroke, the smaller the location error is. This is to be expected since more sensors taking part in the solution of the position will provide more information. This has been observed in many other evaluations of Vaisala networks – more specifically, the work of *Jerauld et al.* (2005) and more recently *Nag et al.* (2010) in their evaluation of the NLDN using rocket-triggered data [3,7].

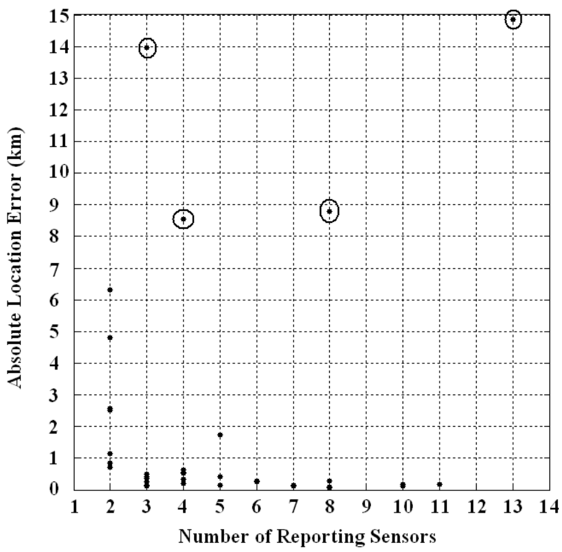

Figure 4 – Number of SALDN sensors reporting against the location errors. Circle points show strokes detected by numerous sensors yet still have a large location error.

In Figure 4, there are some strokes that were reported by numerous sensors yet have large location errors. These data points are shown circled in the figure. This brings into question the reliability of the matching process for strokes with large location errors. Given what is seen in other evaluations, it seems most probable that these strokes are not representative of lightning attachment to the tower. It is more likely that they represent some other stroke that occurred a significant distance from the tower within the same time frame. Given the number of sensors that detected the stroke, it seems unlikely that there would be such a large location error. The matching process can therefore be improved by examining the number of sensors reporting the stroke to determine whether it does, in fact, represent a strike to the tower. Consequently, these strokes are then discarded from the data set.

Figure 5 shows a plot of the SALDN stroke location errors. However, strokes with large location errors and numerous reporting sensors have been discarded. Consequently, only the central 16 km^2 (4 km × 4 km) area around the tower is shown. The majority of the strokes occur within a 1 km × 1 km area of the tower with a slight biasing to the north-west.

Figure 6 shows a histogram of the updated data set. These are absolute location errors up 1.2 km. The distribution has a median location error of 0.265 km with the majority of the data between 0.1 and 0.4 km. The distribution has a mean location error of 0.344 km.

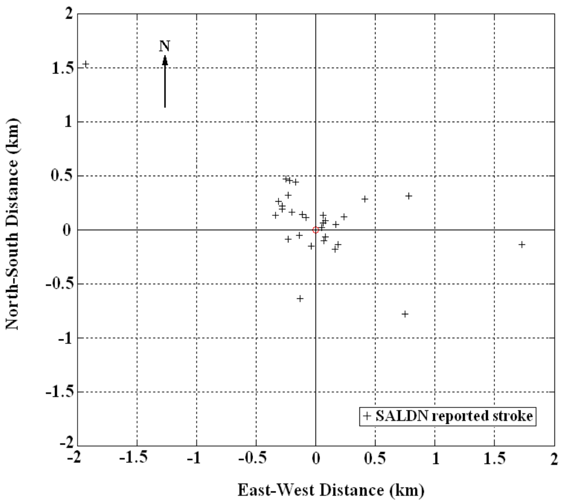

Figure 5 – Plot of SALDN stroke location errors for central 16 km^2 (4 km × 4 km) area. Strokes with large location errors and numerous reporting sensors are discarded.

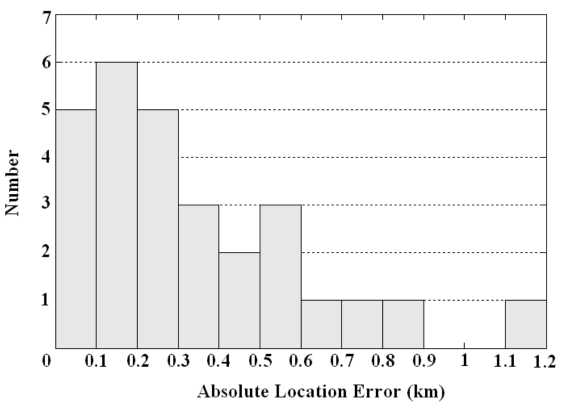

Figure 6 – Histogram of the SALDN absolute location errors for updated data set. Bin sizes are 100 m.

Table 1 shows the statistical properties for the total data set as well as the updated set in which strokes with large location errors and numerous reporting sensors were discarded. As expected, there is a difference between the arithmetic mean of the complete distribution and the limited one (1.993 km and 0.344 km respectively) due to the larger location errors or the "tail" of the distribution shown in Figure 3. However, the median values do not differ by such a large amount, being 0.37 km and 0.265 km respectively. As a preliminary analysis, it can be seen that the median location error is in the region of 0.3 km. Whether the stroke data with larger location errors represent a flash to the Brixton Tower or not, the location error is still less than the median location error of 0.5 km stated by Vaisala.

Table 1 – Statistical properties for the total absolute location error distribution as well as the updated data set.

Total Data Set		Updated Data Set	
Arithmetic Mean, km	1.993	Arithmetic Mean, km	0.344
Geometric Mean, km	0.563	Geometric Mean, km	0.269
Standard Deviation, km	3.738	Standard Deviation, km	0.254
Median, km	0.37	Median, km	0.265
Min, km	0.054	Min, km	0.054
Max, km	14.85	Max, km	1.14
Sample Size	37	Sample Size	28

7 – HILLBROW TOWER

As mentioned in Section 5, a number of strokes reported by the SALDN correspond to a flash in the region of the Hillbrow Tower. Figure 7 shows a plot of the 14 strokes that could possibly be attachments to the Hillbrow Tower. Since there is no ground-truth indication that a flash to the Hillbrow Tower did occur, no solid conclusions can be drawn from this data. Ongoing surveillance of the tower will allow for more ground-truth data to be captured.

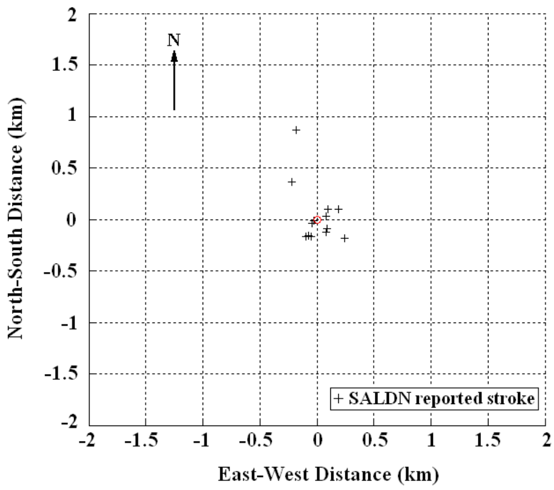

Figure 7 – Plot of SALDN location errors in the region of the Hillbrow Tower.

8 – CONCLUSIONS

Photographs of lightning attachment to the Brixton Tower are available for use as ground-truth data for comparison with the SALDN. A method for matching the reported SALDN events with the corresponding photographs given unsynchronized time stamps has been presented and discussed. It was seen that the network reported strokes within the area of the tower within approximately 2.5 minutes of photograph. Using these as criteria, 37 strokes were matched to the 19 photographs. This matching process was discussed and it was seen that comparison with the number of reporting sensors could help discard strokes that do not represent photographs but occur within the same time frame. This data was then used to perform a preliminary validation of the location accuracy of the SALDN. A median location error of 0.265 km is found. This falls within the 0.5 km location error stated by Vaisala.

Finally, it is seen that a number of strokes are reported to have occurred in the vicinity of the Hillbrow Tower. No ground-truth record exists so no comparison may be made, however, observation of the Hillbrow Tower may also provide a means for further evaluation of the SALDN performance.

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