Analysing Lightning Data from Two Spatially Separate Magnetic Direction Finders

David Andrew Rice

A dissertation submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in fulfilment of the requirement for the degree of Master of Science in Engineering.

Johannesburg, March 2008

Declaration

I declare that this dissertation is my own, unaided work. 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.

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David Andrew Rice

This ________________________ day ________________________ of 2008

Abstract

Two lightning detectors, of the magnetic direction finder type, form part of a two station system for determining the position of lightning strikes. The detectors are on a baseline of approximately 600 m, and the ultimate aim of the system is to accurately detect and map lightning within a radius of 30 km. Although no real time capability is present, the archive data collected from each separate station is used to find the offset errors in the azimuthal orientation, as well as in time (using processes described in Appendix A). The relative offset errors are determined by shifting the time and azimuthal information for one station's data and calculating the maximum possible matching records (within certain time and azimuth criteria) for each incremental shift. An analysis of the peaks in total matching records, when plotted against the relevant shift increments, is performed in order to obtain the values of the offset errors. Between the two individual stations, the relative offset in orientation is found to be 24.5 degrees, and in time to be 0.001305 days (112.75 seconds). The individual stations, as well as the triangulated data calculated from matching records, can also be calibrated using data from the South African Weather Service Lightning Detection Network (SAWSLDN). Individual station calibration indicated an offset of +6.4 degrees and 0.00575 days (496.8 seconds) for Station 1, with the offsets for Station 2 determined as +29.4 degrees and −0.000105 days (9.07 seconds). Comparison of triangulated data to SAWSLDN data yields unexpected results with regard to resultant shifts, which may point to an error or anomaly in the triangulation calculations. A detailed analysis of the storm data is contained in Appendix B of the dissertation.

For Kerry, and Max.

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The Vaal, As, Orange, Bushmans, Mkomazi, Tugela, Buffels, Sabie, Blyde and Zambezi rivers, and the (mostly) untouched wilderness they carve through, for keeping me sane (crazy?), as well as Neil O'Leary and the many other friends I shared these times with.

Foreword

This dissertation is presented to the University of the Witwatersrand, Johannesburg for the degree of Master of Science in Engineering.

The dissertation is entitled "Analysing Lightning Data from Two Spatially Separate Magnetic Direction Finders", and details a process for determining time and azimuthal offset errors between different sets of lightning data.

Single station magnetic direction finders are known to have reasonably accurate azimuthal information, but can be inaccurate in determining the range of a strike event. Two collaborative stations of this type would allow for a trigonometric calculation in range, improving the accuracy of strike event location. Offset errors are however present in such a system and an approach to deal with these errors is presented in the dissertation.

This document complies with the university's *paper model* format. The paper contains the principal findings of the research, while the appendices present in further detail the work conducted.

Appendix A presents a description of MATLAB code modules implemented.

Appendix B presents a detailed analysis of lighting data captured during a storm, for the purposes of determining offset errors and obtaining a more accurate resultant dataset.

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Part I

Paper: Analysing Lightning Data from Two Spatially Separate Magnetic Direction Finders

ANALYSING LIGHTNING DATA FROM TWO SPATIALLY SEPARATE MAGNETIC DIRECTION FINDERS

D A Rice
University of the Witwatersrand
d.rice@ee.wits.ac.za

School of Electrical and Information Engineering, University of the Witwatersrand, Johannesburg, Private Bag 3, Wits 2050, South Africa.

Abstract - Two lightning detectors, of the magnetic direction finder type form part of a two station system for determining the position of lightning strikes. The detectors are on a baseline of approximately 600 metres, and the aim of the system is to accurately detect and map lightning within a radius of 30 kilometres. Although no real time capability is present, the archive data collected from each separate station is used to find the offset errors in the azimuthal orientation, as well as in time. The relative offset errors are determined by shifting the time and azimuthal information for one station's data and calculating the maximum possible matching records (within certain time and azimuth criteria) for each incremental shift. The relative offset in orientation is found to be 24.5 degrees, and in time to be 0.001305 days (112.75 s). The individual stations, as well as the triangulated data calculated from matching records, can also be calibrated using data from the South African Weather Service Lightning Detection Network (SAWSLDN). Individual station calibration indicated an offset of +6.4 degrees and -0.00575 days (496.8 s) for Station 1, with the offsets for Station 2 determined as +29.4 degrees and 0.000105 days (9.07 s). Comparison of triangulated data to SAWSLDN data yields unexpected results with regard to resultant shifts, which may point to an error or anomaly in the triangulation calculations.

1 INTRODUCTION

This paper illustrates a case study used to investigate the feasibility of using networked magnetic direction finders as a lightning detection system. The system uses two commercially available units, and the main objective in implementing the system is to use the azimuthal information from each device to triangulate cloud-to-ground lightning strikes. This approach should provide improved range information over a single station system using a device of the same type.

A first step towards a real-time multi-station system is correcting offset errors, specifically in azimuthal orientation and time. A method for determining the magnitude of these errors, and a process of correcting for them is presented in the paper. This method can be performed entirely computationally, and reduces the need for expensive time synchronisation hardware. It also avoids complicated procedures to align two separate antennas exactly parallel to each other.

Disadvantages of this method are that it is time consuming to perform the analysis, which makes real-time triangulation more difficult. Future work may be able to optimize these processes however, and it is also possible, in principle, for the offset error analysis to be done once at system set up, in order to calibrate the system. Dependent on network and power stability, the system should then be able to run independently.

The individual station data, as well as the combined, triangulated data is compared to data obtained from the South African Weather Service Lightning Detection Network (SAWSLDN) for a storm period of two hours (16:00 – 18:00) on 27 October 2006. The two sets of individual station data are also compared, to establish the relative offset errors between them. General background of the hardware and software elements used, as well as details of the system process developed to match records from the two stations, is also included in the paper.

2 HARDWARE CONSIDERATIONS

The antenna module is packaged in a sealed unit, which connects to a computer via standard ethernet cable and a dedicated PCI card. Since the antenna is mounted outdoors, it is mounted in a weatherproof (wind and rain) stand. Protection for lightning induced over voltages is also required to prevent possible damage to the antenna and connected equipment.

A. Antenna

The Antenna itself is contained within a sealed plastic case. Similar direction finding type devices consist of a pair of vertically orientated, orthogonal magnetic loop antennas. This arrangement provides reasonable azimuthal information by using the fact that the voltage produced at the terminals of a loop antenna is a cosine of the angle to a radiative source (i.e. a lightning flash). There is a 180 degree phase error associated with this type of direction finding, which is generally solved with the use of an auxiliary sensor, such as a flat plate antenna, to determine the polarity of the charge being lowered to ground [1]. Using this type of antenna, range information can obtained from relative received signal strength. Specifications of the antenna that are known include: centre frequency of 75 kHz [2] (unknown bandwidth); physical size of casing – 75 mm x 50 mm x 45 mm; angular resolution - 1 degree [2]. The fact that the size of the casing is much smaller than the wavelength of operation suggests that magnetic coils are used in this particular antenna. The cable connected to the antenna consists of 8 wires; 1 pair for 12 V d.c. power supply, 2 pairs for "quadriture information" and one pair for polarity information [2].

B. Installation and Protection

The general arrangement of the antenna and weatherproof stand is shown in Figure 1.

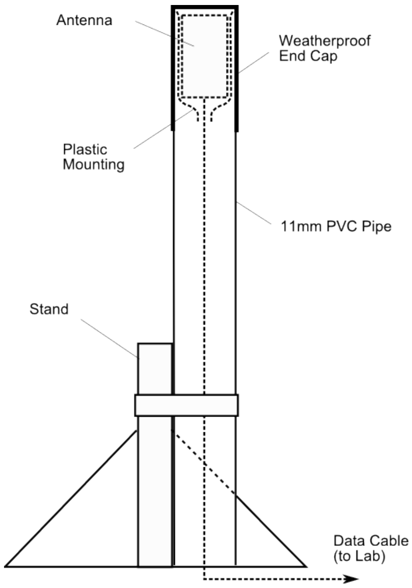

Figure 1: Antenna Installation

Two semi-permanent installations have been implemented on the roofs of two buildings at the University of the Witwatersrand. These are designated Station 1 and Station 2, and have co-ordinates of -26.19183 (S) 28.03097 (E), and -26.191583 (S) 28.03097 (E) respectively. Protection in terms of shielding is provided by enclosing the length of the antenna cable in 22 mm copper pipe, earthed to the buildings' air termination systems. Physical protection from nearby buildings and antenna masts is also provided in terms of the rolling sphere test. This has the obvious compromise of affecting the direction finding characteristic of the antenna through inductive effects. Generally speaking, Station 1 has a clearer view of the surrounding terrain and therefore better direction finding characteristic. Empirical evidence and real-time observation also support this. The two stations are approximately 600 m apart, a relatively small baseline, but useful in terms of measuring strikes within 30 km.

1 SOFTWARE CONSIDERATIONS

A. Standard Software

The standard software package shipped with the unit provides a basic display that maps the location of individual strikes. The presence of a background map can imply to a casual user that the exact geographical co-ordinates of each strike are known, which is not the case. In fact, the operational manual [3] states that individual strike locations are not exactly known, and vary with the range of a particular storm. As a storm approaches, the strikes appear to fit a segment shaped pattern (rather than the circular pattern one would associate with a thunderstorm) with strikes of a higher intensity appearing nearer than they actually are, and strikes of a lower intensity appearing further away. Thus an approaching storm appears as a segment-shaped cluster of strike points. In magnetic direction finding systems, often a statistical average for the intensity of a typical lightning strike is used as a calibration point to calculate range from received signal intensity. This is a well known error associated with calculating the range in this way. This type of calculation would result in the situation above of the segment-shaped storm cluster.

The strike records generated from the standard software are 6 bytes long and contain values for time as well as the rectangular co-ordinates for the strike. The time value is a 2 byte unsigned integer, with the co-ordinate values being 2 byte signed integers. The data file is written in 1 kilobyte blocks, containing 170 strike records and 4 waste bytes. The co-ordinates give the position of a strike in an X-Y plane relative to the measuring station (at [0,0]), with the positive Y-axis pointing north. It is unknown what method of projection is used for calculating these rectangular co-ordinates.

B. *Third Party Software*

The archive file generated by a third party software package, designed for the antenna, contains significantly more information than the standard software, as shown in Table 1.

Table 1: Archive file structure for third party software (*Lightning 2000*)

Field	Size	Description	
Internal Use	2 bytes	-	
Time	8 bytes	Julian Date	
Internal Use	1 byte	-	
Amplitude	2 bytes	Amplitude x 100. Arbitrary units in the range 0 to 655.35	
Bearing	2 bytes	Bearing x 100. Measured anticlockwise from EAST.	
Wavelength	2 bytes	Wavelength x 100	
Polarity	1 byte	3 possible values:	0 – unknown 1 – negative 2 – positive
Stroke Type	2 bytes	8 possible values:	0 – unknown 1 – noise 2 – cloud-to-ground (CG) 3 – inter/intra-cloud (IC) 4 – CG with phase error 5 – IC with phase error 6 – Stroke Leader 7 – compact inter-cloud discharge
Estimated Range	2 bytes	Range (miles) x 10	

The strike records are appended to an archive file in the format YYYYMMDD.ldc. These files may be "played back" within the software display, allowing retrospective viewing of the development of storms at varying speeds. Together with a log of general storm activity, this is helpful in isolating time periods for which there is significant storm activity of interest for development and testing purposes.

Bearing information is referenced counter-clockwise from EAST, as in a Cartesian plane, and not clockwise from North.

The *Julian Date* is a continuous count of days (and fractions thereof) since midday Universal Time on January 1, 4713 BCE (on the Julian calendar). Almost 2.5 million days have occurred since this date (midday on 1 January 2006 corresponds to a Julian Date of 2453737). Julian dates are widely used as time variables within astronomical software and can typically be represented by a 64-bit floating point (double precision) variable to approximately 1 millisecond precision. The time scale that is the basis for Julian dates is Universal Time (Atomic Time), and 0h00 (midnight) corresponds to a Julian date fraction of 0.5 (i.e. Midnight on 1 January 2006 corresponds to 2453737.5) [4].

When considering the scale of the entire span of the Julian Date system, assumptions such as the fact that 7-day weeks have formed an uninterrupted sequence and the exact date of changeovers between different calendar formats are important. However, for the purposes of this application the relative time is sufficient, and the exact Julian date merely forms a useful unique identifier for each archive file. Time is represented with a double precision variable, allowing a resolution of 0.00000001 days (less than 1 ms). This is sufficient precision for hardware that is limited to a resolution of approximately 2 ms [2].

1 SOUTH AFRICAN WEATHER SERVICE

The South African Weather Service Lightning Detection Network (SAWSLDN) has been operational since January 2006. It is a proprietary multi-station system, used in 40 countries. Magnetic direction finding (MDF) and time of arrival (TOA) techniques are both used at 19 sensor sites across South Africa to determine the time and location of lightning flashes. The antennas used have a bandwidth from 1 kHz to 1 MHz. The sharp voltage rise caused by the return stroke affects the electromagnetic signature emitted by a cloud-to-ground flash, and allows the direction finder to distinguish these flashes from other types of lightning and electromagnetic noise [5].

Lightning Data from the detection network is obtained from the SAWS with the following information:

- TIME: Date and Time (text string, millisecond resolution)
- LAT: Latitude and Longitude (decimal degrees to 9 places)
- LON: Latitude and Longitude (decimal degrees to 9 places)
- PEAK_KA: Peak Current (kA)
- CHI_SQUARE: A value for ``chi square"
- ELLIPSE MAJOR AXIS: Major Axes of error ellipse
- ELLIPSE MINOR AXIS: Minor Axes of error ellipse
- ELLIPSE ANGLE: Angle for error ellipse
- NUMBER OF SENSORS: Number of sensors registering the strike

In calibration of individual stations, and comparison to triangulated station data, only time and position (LAT and LONG) information is used.

2 THE TWO-STATION SYSTEM - BACKGROUND

The ideal ultimate aim of the project is to provide a near real-time system to map the location of lightning strokes (or alternatively lightning flashes), for an area of interest described by a 20 km radius from Station 1. A lightning event from an approaching storm that occurs within a 10 km radius is considered dangerous to life and property. In broad terms, this system (consisting of two stations) should at least provide more accurate lightning information than a single station of the same type. Accuracy greater than multi-station systems such as the SAWLDN and field based warning devices is not expected. This paper deals with the retrospective analysis of station data, in order to establish the feasibility of such a real time system.

In general, the location of a probable strike in a two-station system, given two stations with a certain azimuthal error (in this case 1 degree) is shown by the outlined area in Figure 2. Three stations provide greater accuracy by providing true trilateration, while more than three stations use statistical methods [1] to gain improved accuracy.

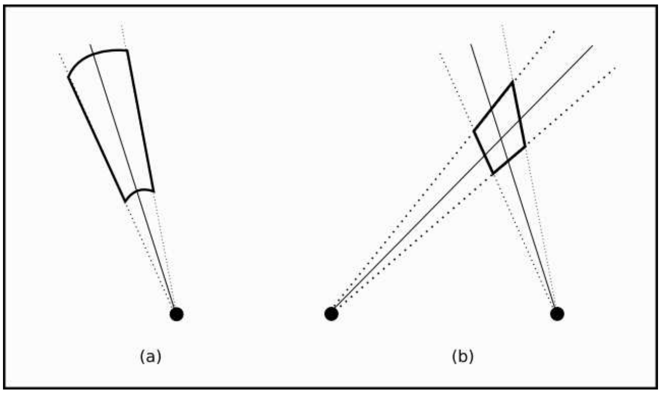

Figure 2: Modified from [1], showing advantage of using two stations (b) over a single station (a)

Two stations have been installed on the roofs of buildings at the University of the Witwatersrand. The baseline is limited logistically, and is relatively small (approximately 600 m) but should be large enough to provide accurate range for lightning events within 30 km. The usefulness of lightning detectors (in terms of warning system applications) decreases at ranges of 60 km or more [6], and although nearby lightning is of more concern, data from events up to 100 km distant is used in the analysis. This provides more available records to match, and therefore a greater confidence in the time and azimuth shifts determined. The stations are synchronised in time using network time protocol (NTP) [7] – however this synchronisation is not entirely robust due to inconsistencies in power supply and network availability. Although much of the data collected was synchronised in time, an unsynchronised dataset was used to illustrate the correction of time offsets. The analysis is also limited to cloud-to-ground events, although for certain applications (especially in the aviation sector), inter/intra-cloud, and triggered lightning are also of concern [6]. However, groups interested in more economical lightning warning systems (such as small scale building and farming operations or sporting events) are likely concerned with direct protection of persons on the ground, and cloud-to-ground lightning is more of a concern in this case.

A. Development of Database and Related Software Components

A simple relational database is used to store strike records generated by the individual stations. This allows conditional retrieval and sorting of strike records to easily isolate relevant information; strokes from a particular time period and also of a particular type (i.e. cloud to ground). The database consists of two tables, namely STATIONRECORD and STATION. The structure of the database is shown in Figure 3, and possible extensions are to include a table for SAWSLDN data, as well as a table for triangulated flashes.

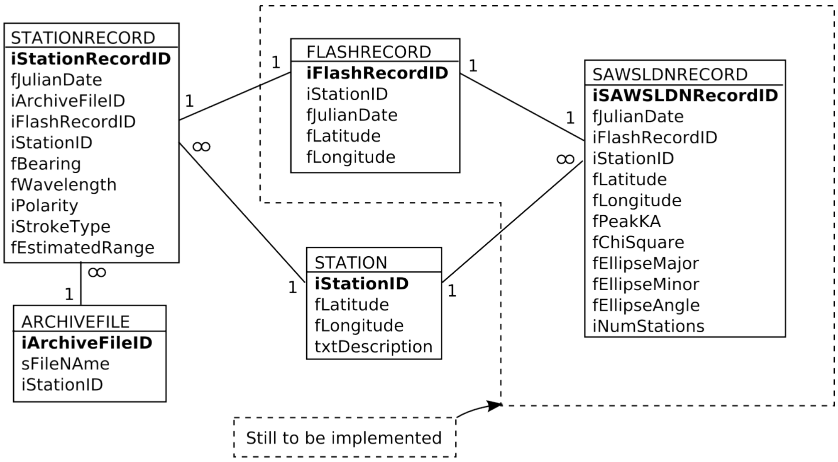

Figure 3: Database Structure for Lighting Event Records

A software module was developed in order to read archive files, and store the data into the database. This consists of a simple GUI, allowing a user to select an archive file and assign it to a particular station. Validation checks are implemented to ensure that duplicate records are not entered into the database, as well as ensuring that records are not assigned to the incorrect station. A limitation of this application is that strike records from particular stations must be stored in a known specific directory in order for part of the error-checking functionality to work. The application displays the number of stroke records added, which can be manually checked against the size of the file (each record is 21 bytes long) to ensure all the records from a particular archive file have been added.

B. Further Software Modules for Analysis of Data

Two principle corrections need to be made, time and azimuthal. These corrections need to be done when matching records from two stations, as well as matching each individual station to the benchmark SAWSLDN data. Data from Station 1 is designated at s1_*range*, Station 2 as s2_*range*, and data from the SAWSLDN as sWS_*range*.

A matching algorithm is used to match records from two spatially separated stations. This isolates pairs of strike records that are within a specified time criterion, as well as those that are trigonometrically resolvable. Strikes that are not resolvable include those occurring on or very near to the baseline, and lines of azimuth (to strikes) that do not intersect. A separate matching algorithm is used to match strike records referenced to the same location. Further details on the software used can be found in [8].

A listing of the variable naming conventions is in *Table 2*, and description of functions written is found in *Table 3*.

Table 2: Variable and Function definitions

Variable Name	Description
s1_range_tshift_azshift	Storm data from Station 1, qualified with _*range*, and also _*tshift*, _*azshift* as necessary. An n x 3 matrix, with columns Time (Julian Date), Bearing and Range respectively.
s2_range_tshift_azshift	Storm Data from Station 2, as for station 1.
s12_range	Combined or triangulated data from Station 1 and Station 2.
sWS1_range	Data from SAWSLDN, within radius _*range* of Station 1. An n x3 matrix, with columns Time (Julian Date), Bearing and Range respectively

sWS2_range	Data from SAWSLDN, within radius *_range* of Station 2. As for sWS1, but referenced to Station 2.
timeCriterion	Value or set of values representing the size of the time buffer used in matching records.
azCriterion	Value or set of values representing the size of the azimuthal buffer used in matching records.

Table 3: Function Description for MATLAB code modules

Function Syntax	Description
MatchExactRecords(sWS, sTest, timeCriterion, azCriterion)	Takes SAWS data, and compares it to sTest (either s1, s2, or s12), returning a dataset with matching records that's simultaneously satisfy timeCriterion and azCriterion
TimeShift_exact(sWS, sTest, timeCriterion, azCriterion)	Shift sTest records in time, iteratively compare to sWS with matchExactRecords. Returns number of matched records (i.e. that satisfy timeCriterion and azCriterion constraint) for each increment in time.
AzimuthShift_exact(sWS, sTest, timeCriterion, azCriterion)	Shift bearing information for sTest records, iteratively compare to sWS with matchExactRecords. Returns number of matched records (i.e. that satisfy timeCriterion and azCriterion constraint) for each increment in bearing information.
MatchRecords (s1, s2, timeCriterion)	returns number of "matched" records. These are trigonometrically resolvable strike data that satisfy the timeCriterion constraint.
TimeShift(s1, s2, timeCriterion)	Takes two sets of storm data, from stations 1 and 2 respectively, and shifts the time information (by adding an incremental offset). matchRecords is called on each iteration and the function returns an array of total matched records for each increment in bearing information.
Azimuthshift(s1, s2, timeCriterion)	Takes two sets of storm data, from stations 1 and 2 respectively, and shifts the bearing information (by adding an incremental offset). matchRecords is called on each iteration and the function returns an array of total matched records for each increment in bearing information.
ShiftByTime(s, TimeOffset)	Function to shift time information for dataset s, by TimeOffset.
ShiftByAz(s, AzimuthOffset)	Function to shift azimuth information for dataset s, by AzimuthOffset.

1 OFFSET ERRORS BETWEEN INDIVIDUAL STATIONS AND SAWSLDN

The SAWS data is converted to a matrix (sWS*_range*), where the time is converted to Julian Date, and GPS co-ordinates converted to range and bearing using the great circle approximation [5]. This is done for each station, with sWS1*_range* being data centred on the co-ordinates of Station 1, and sWS2*_range* being centred on the co-ordinates of station 2. A more detailed analysis can be found in [9].

C. *Station 1*

A first estimate at the time offset is obtained by shifting the time information of sWS1_100km and matching it with s1_100km. Figure 4 shows the result of the first estimate, with an offset of -0.00575 days (496.8 s) yielding a maximum of matched records.

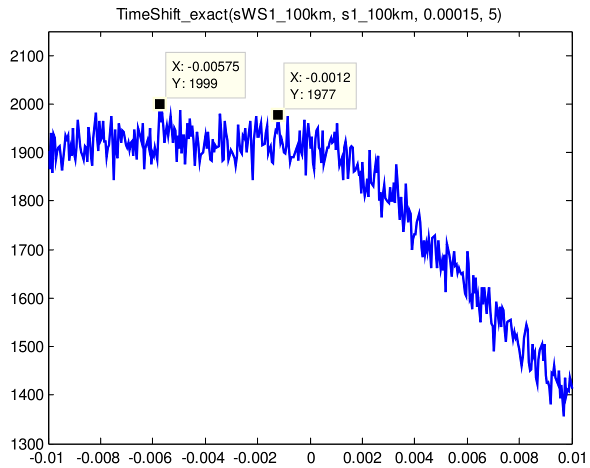

Figure 4: Plot of Matching Records against Time Shift

The s1_100km dataset has the offset time of 0.00575 using the ShiftByTime function. This resultant dataset (s1_100km_0p00575) is then compared to sWS_100km again, this time to find the azimuthal offset in the data. It is noted that the time shift characteristic is quite flat for a large region around the peak, which makes it difficult to ascertain the exact time offset. Figure 1 shows the azimuth shift characteristic for a full rotation. The peak matching records is for s1_100km shifted by +6.4 degrees (using the ShiftByAz function), and the resulting dataset is s1_100km_0p00575_6p4. A second distinct peak is observed at approximately 180 degrees from the main peak, which can be attributed to reflections of strike events. Two sub-peaks on the main peaks are also observed at approximately 50 degrees from either side of the main peak. A possible source of this is two aluminium masts located near to the antenna, in similar azimuth positions to the peaks.

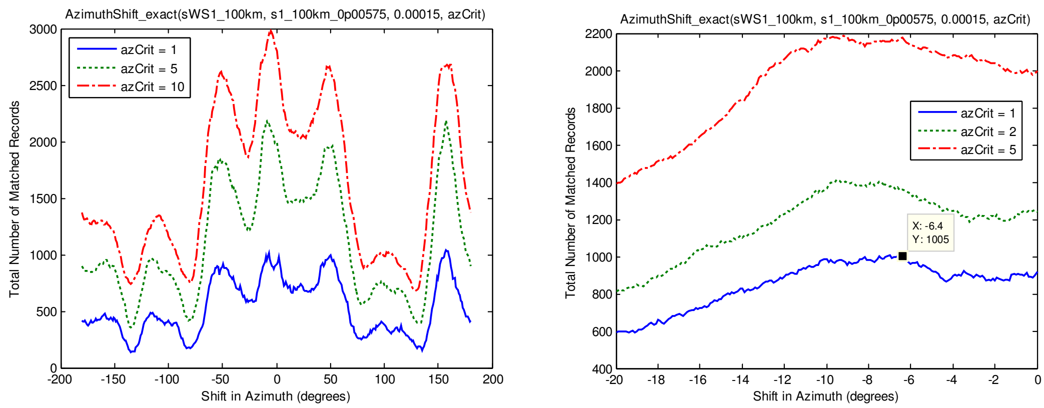

Figure 5: Azimuth shift characteristic for SAWSLDN data shifted against Station 1 data

To further refine the tshift value, the time shift characteristic can again be plotted with the new azimuth shifted dataset being compared to sWS1_100km. Figure 6 below shows the matching records for time shift of sWS1_100km against s1_100km_n0p00575_6p4.

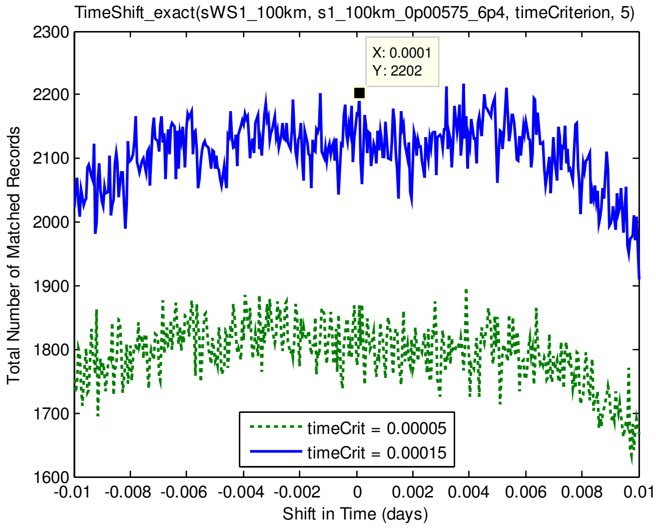

Figure 6: Matching Records for time shift, second iteration.

This new offset can now be adjusted for if necessary, by further offsetting the time information for s1_100km. There is no clear peak for this characteristic, and it is difficult to determine the time offset between the SAWSLDN data and data from Station 1. The azimuth shift characteristic however provides a clear peak, and it is therefore possible to determine with confidence the azimuth offset between the two sets of data.

D. Station 2

Following a similar process to above, the following results are obtained for calibration of Station 2. Figure 7 and show the peak matched records to be at a time offset of -0.003505. The resultant shifted dataset is s2_100km _0p00355.

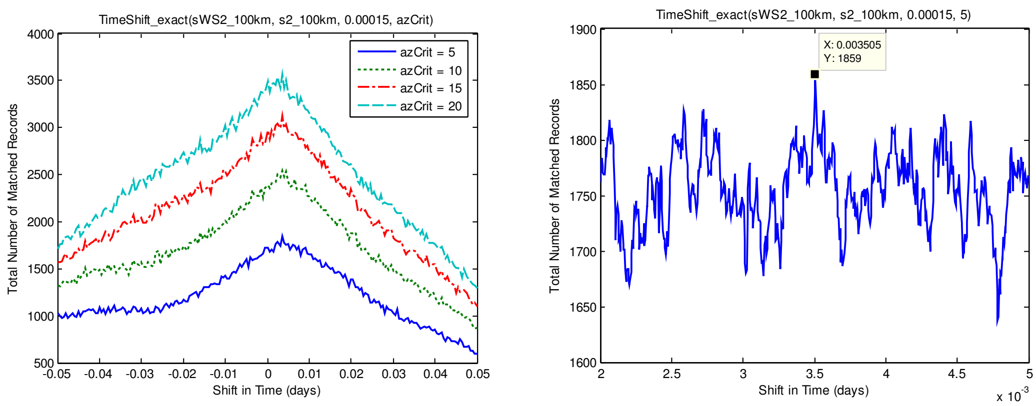

Figure 7: Time shift characteristic for calibration of Station2, with varying azimuth criterion. Windowed on main peak between -0.05 and 0.05 days, and 0.002 and 0.005 days respectively.

The azimuthal offset between this data and sWS_100km is illustrated in Figure 8, and is -30.3 degrees. The resultant dataset is s2_100km_0p003505_30p3.

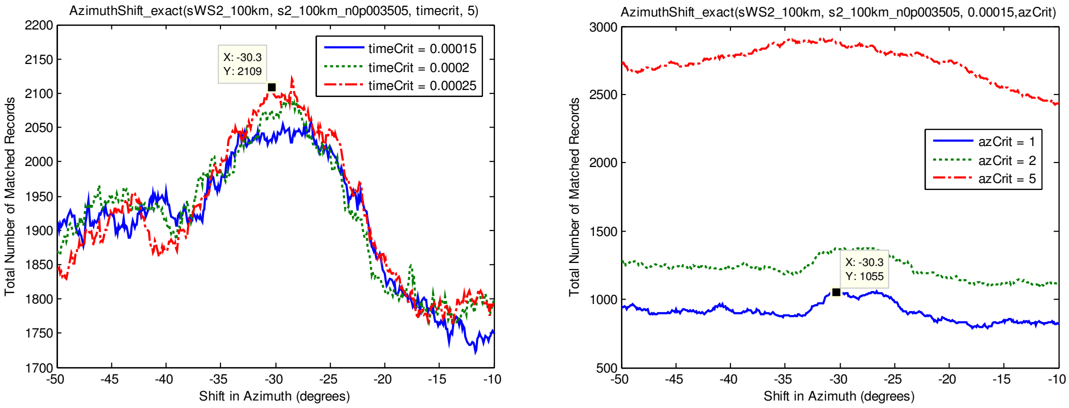

Figure 8: Azimuth shift characteristic for time shifted data

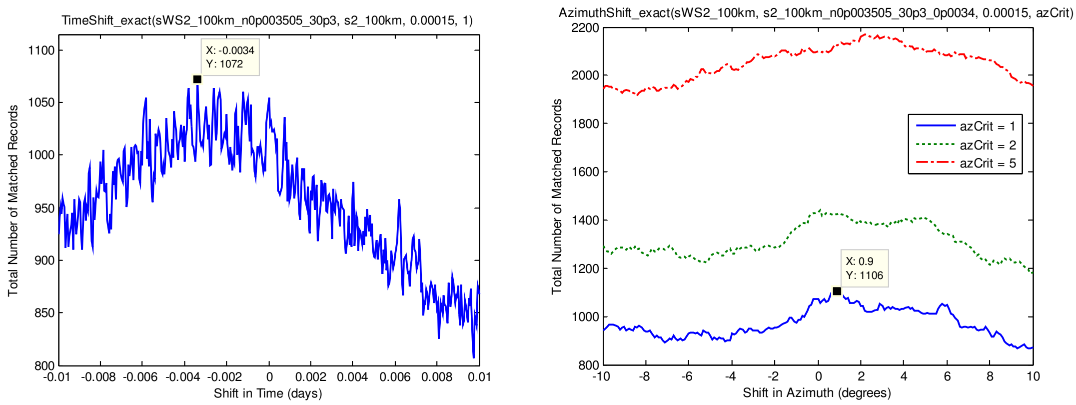

Figure 9: Time shift and azimuth shift characteristic for adjusted data, second iteration.

Figure 9 shows the time and azimuth shift characteristic for time and azimuth adjusted data. Since the peaks are not centred on zero, a second iteration of shifting is necessary. The peak here is more defined, and so a second iteration is done to illustrate the process. The resultant dataset after a second time and azimuth shift is s2_100km_n0p003505_30p3_0p00034_n0p9 or alternatively s2_100km_n0p000105_29p4. This represents an effective overall time offset of -0.000105 days (9.07 s), and an azimuth offset of +29.4 degrees. Figure 10 shows the time shift characteristic for this shifted data, for an azimuth criterion of 5 degrees and 1 degree respectively, and implies that the datasets are now better aligned in time.

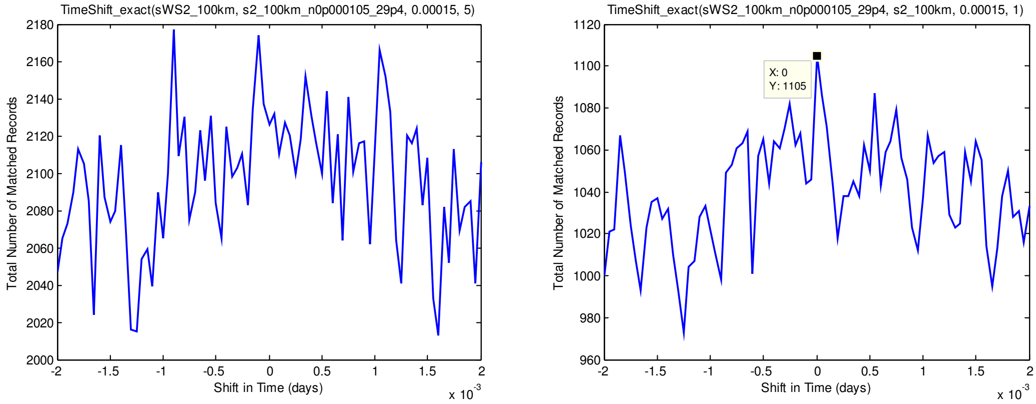

Figure 10: Time shift characteristic for third iteration, showing peak centred on zero for an azimuth criterion of 1 degree.

1 RELATIVE OFFSET ERRORS BETWEEN INDIVIDUAL STATIONS

The initial estimate of the time offset between the two stations is done in a similar way to individual station calibration. Figure 11 shows the time offset between the stations as 0.0014 days (120.9 s), and additionally shows the cut off (for the regions where the records no longer overlap in time). Figure 12 shows two windowed plots of the time shift characteristic, at higher resolution, giving a more accurate value of 0.001305 for time shift.

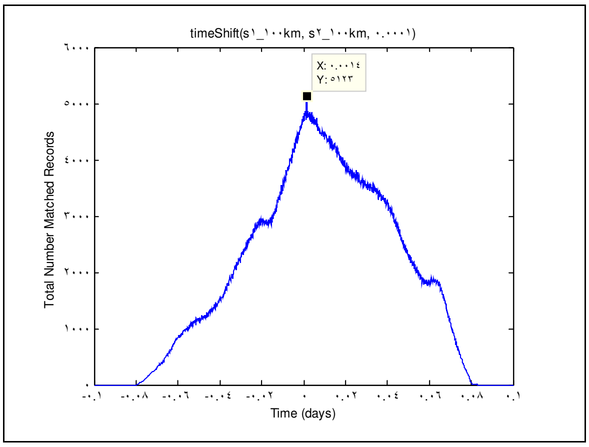

Figure 11: Initial plot of matching records for time shift of Station 1 data, showing cut off regions.

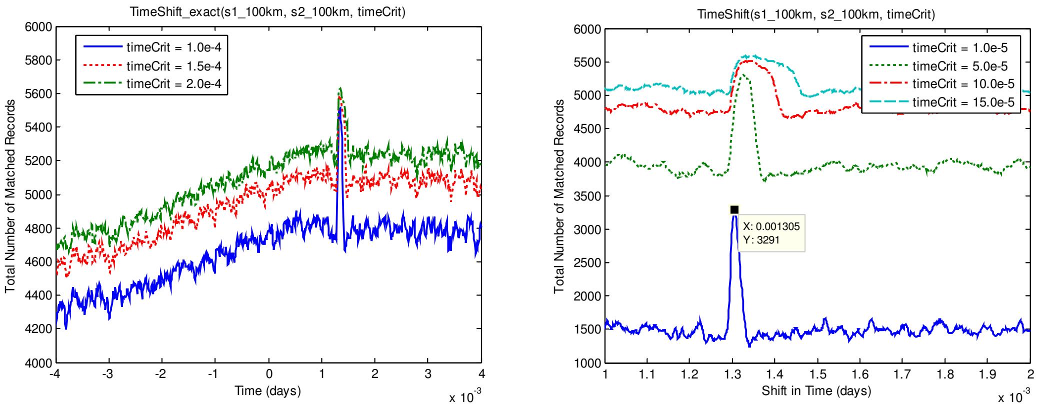

Figure 12: Time shift characteristic for Station 1 against Station 2 data, for varying time criterion and varying azimuth criterion.

Finding the azimuthal offset is then done using the time-shifted data. Figure 13 shows the plot for the time-shifted data for an entire revolution, and also a windowed plot at an increased azimuth shift resolution of 0.1 degrees. The relative azimuthal offset between the two stations is found to be -24.5 degrees.

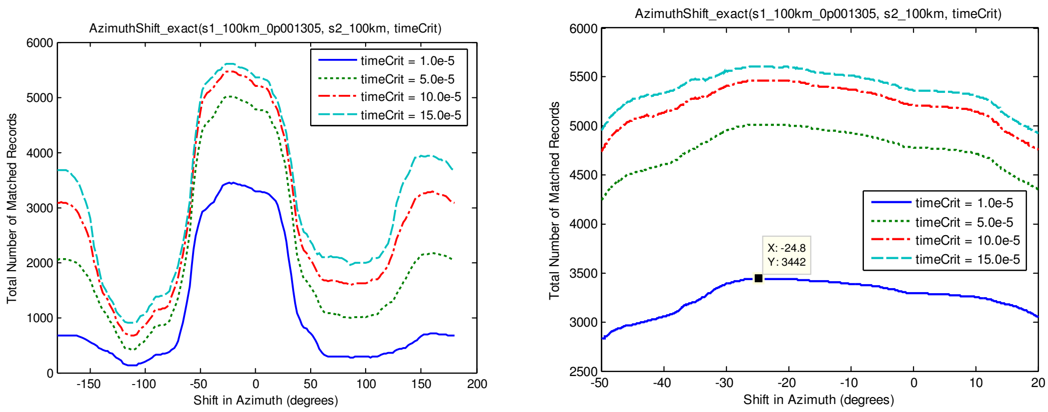

Figure 13: Matched records against azimuth shift, for varying values of time criterion.

The new shifted data (in time and azimuth) can now be shifted again in time. The resultant datasets are either s1_100km_0p001305_n24p5, and s2_100km or alternatively s1_100km_0p001305, and s2_100km_24p5.

Figure 14 shows the result of s1_100km_0p001305_n24p5, shifted in time against s2_100km, and confirms that the datasets are now aligned in time – the maximum amount of matching records is obtained at approximately zero time shift.

The combined dataset s12_30km can now be obtained by removing records from s12_100km that have range greater than 30km. The increase in the number of matching records, after correcting for offset errors, is also shown in Figure 14. This data is independent of the SAWSLDN data and as such will still have an absolute error (in both time and azimuthal orientation), but relative errors between the stations are minimized.

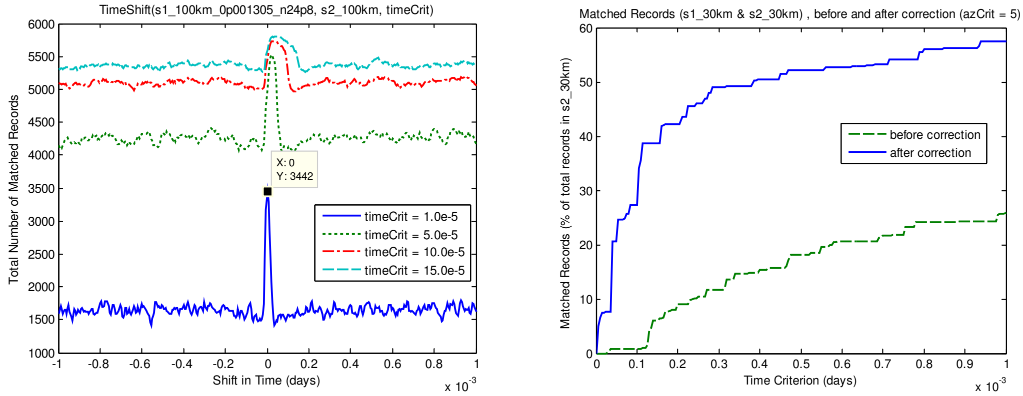

Figure 14: Plot showing time shift characteristic, with peak centred on zero, as well as the effect that the correction of offsets has on total matching records, for a range of 30 km.

2 COMPARING TRIANGULATED DATA TO SAWSLDN DATA

This can be done using the MatchExactRecords function, and comparing the triangulated data (which is referenced to Station 1's location) directly to the SAWSLDN data, and thus removing the absolute error in timing and azimuthal information. The alternate method is to use the offsets determined during individual station calibration, which should mean that no further shifting is required. Both methods are presented for comparison.

s12_100km is obtained from matchRecords(s1_100km_0p001305_n24.5, s2_100km). Figure 15 shows the time shift characteristic of s12_100km and sWS1_100km.

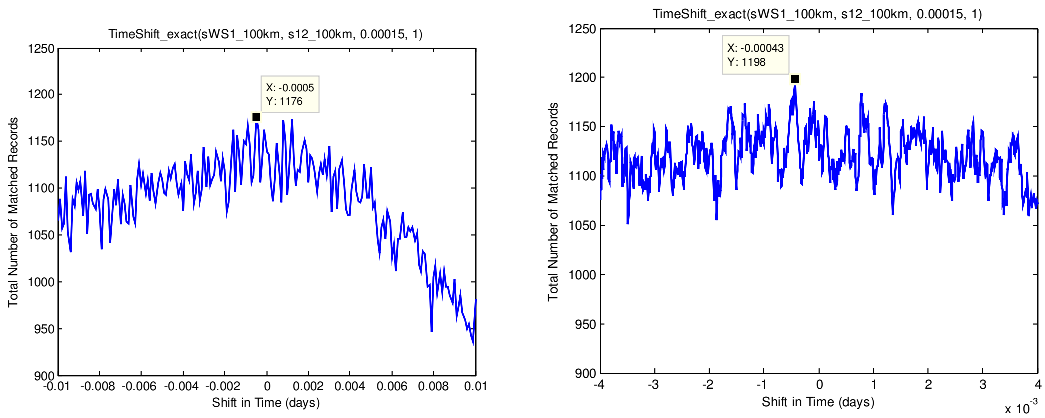

Figure 15: Time Shift Characteristic for SAWSLDN data, shifted against triangulated Station Data

The relative time offset between the combined data is shown again by the peak. Since the Station 1 data was time shifted to match the Station 2 data, the time offset is expected to be similar to that between s2_100km and sWS2_100km (-0.000105 days). It is however approximately 0.00043 days (37.15 s). This discrepancy is likely due to the wide nature of the time shift peak for sWS2_100km and s2_100km. The azimuth shift characteristic can now be plotted (Figure 16), to find the azimuthal offset between sWS1_100km and s12_100km_0p00043.

At peak matching records, azimuth offset is -48.2 degrees, this is also an unexpected result, as the offset between sWS2_100km and s2_100km was determined to be 29.4 degrees. There is however a smaller peak near the expected value (29.4 degrees).

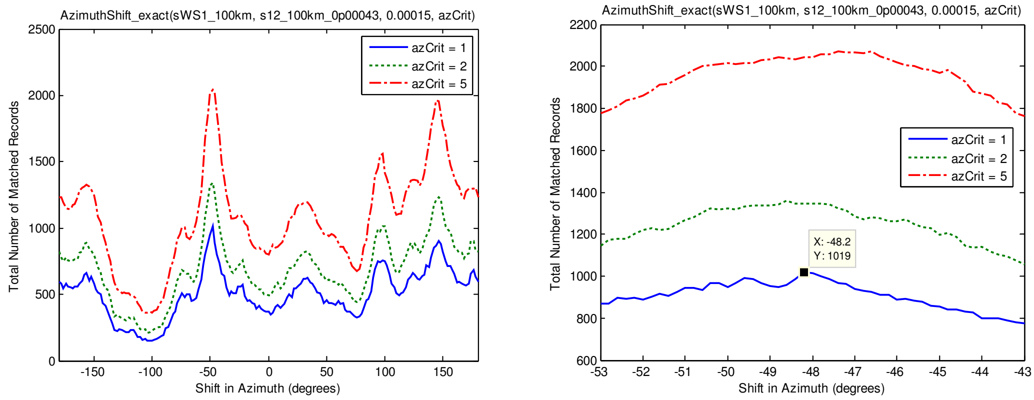

Figure 16: Azimuthal Offset between SAWSLDN and triangulated Station Data.

The dataset s12cal_100km is generated using MatchRecords(s1_100km_0p00575_6p4, s2_100km_n0p000105 _29p4), with the shifts obtained from the individual station calibration. Figure 17 and Figure 18 appear to suggest that the either calibration may not be accurate, or alternatively that there is an error introduced in the triangulation algorithm. The time shift characteristic has a peak approximately centred on zero, however the azimuth shift characteristic has an unexpected offset.

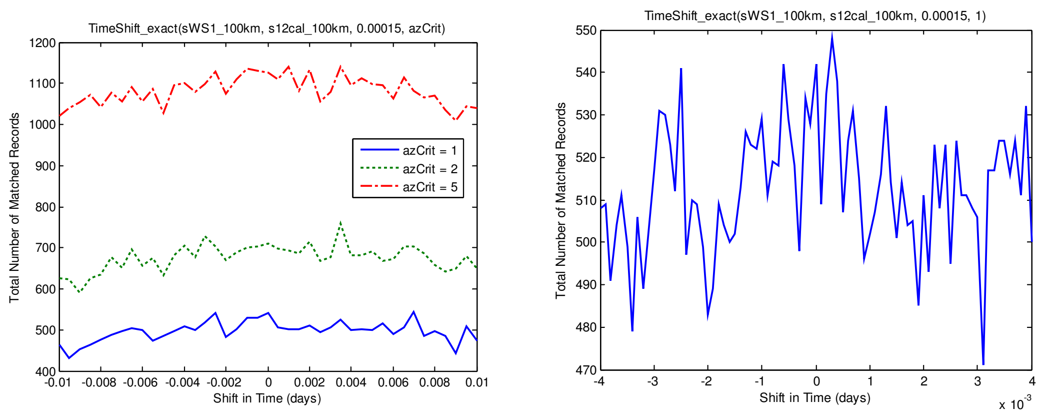

Figure 17: Time Shift Characteristic for Triangulated Data obtained from Initially Calibrated Station Data

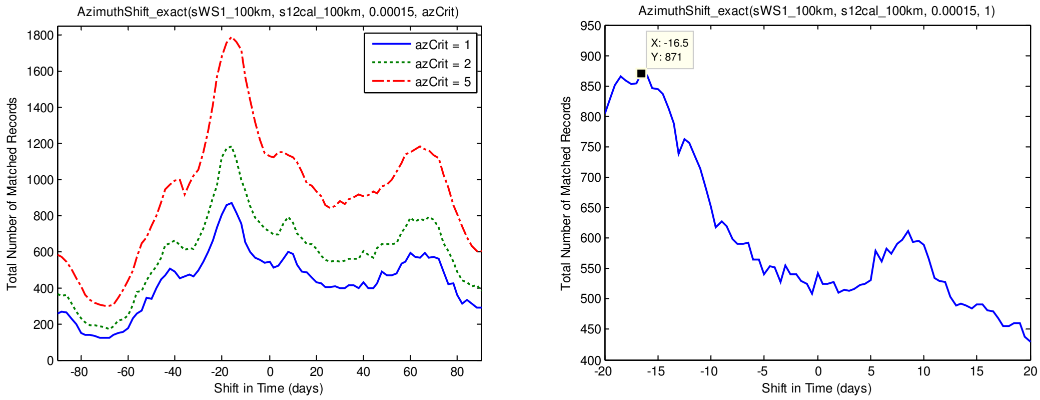

Figure 18: Azimuth shift characteristic for SAWSLDN data against triangulation of calibrated data from Station 1 and Station 2

3 DISCUSSION

In general, the data from the SAWSLDN does not correlate as well with the individual station data as the stations correlate with each other. The individual stations' shifting characteristics have very clearly defined, narrow peaks - which is expected, as the individual stations are similar devices. The SAWSLDN data is also a much larger dataset, containing data often recorded from several stations and the individual stations may miss certain strike events, since they can only process one event at a time. The matching of SAWSLDN records to individual station records therefore results in wider, less well defined peaks in the shift characteristics. A more intelligent matching algorithm, which matches the closest or best strike available from the SAWSLDN data, may improve results for this scenario. This apparent discrepancy also affects the comparison of triangulated data to the SAWSLDN data, although the unexpected results in this case may also point to errors in the position calculation within the matching algorithm. There is a much higher degree of confidence in the values determined for the relative offset errors between the individual stations, than the offset errors between each individual station and the SAWSLDN data. In general, determining the azimuth offset errors produces more predictable results than determining time offset errors. A more detailed analysis of the storm data can be found in [9].

4 CONCLUSION

A method for correcting azimuthal orientation and time offsets for lightning data collected by two separate magnetic direction finders has been presented. This method can be performed computationally, and reduces the need for expensive time synchronisation hardware and complicated antenna alignment procedures. These methods would however result in a more robust real time system.

The relative offset errors are determined by shifting the time and azimuthal information for one station's data and calculating the maximum possible matching records (within certain time and azimuth criteria) for each incremental shift. The relative offset in orientation was found to be 24.5 degrees, and in time to be 0.001305 days (112.75 s). The individual stations, as well as the triangulated data calculated from matching records, can also be calibrated using data from the SAWSLDN as a reference. Individual station calibration indicated an offset of +6.4 degrees and +0.00575 days (496.8 s) for Station 1, with the offsets for Station 2 determined as +29.4 degrees and -0.000105 days (9.07 s).

By triangulating the individual station data, using the relative shifts, and then calibrating the resultant data to sWS1_100km, an offset of 0.0001 days (8.64 s) and -48.2 degrees is observed. The alternative method is to compute the triangulated dataset using the individual calibration offsets (w.r.t the SAWS data). The expected result for this would be a normalised (peak centred on zero shift) time-shift and azimuth-shift characteristic. The actual results are shown in Figure 17 and Figure 18, and indicate an azimuthal offset of approximately 18 degrees, and a time offset of approximately 0.0001 days. This is an unexpected result, and could point to possible errors in either the shifting algorithm or the triangulation algorithm itself. Conditioning the SAWSLDN to match better with the individual station data may also solve this problem to some extent.

Disadvantages of this method of calibration are that it can be time consuming to perform the analysis, which makes real-time triangulation more difficult to implement. Future work may be able to optimize these processes however, and it may be possible for the offset error analysis to be done once, at installation time, in order to calibrate the system. This is especially relevant for the azimuthal offset errors. Time offset errors are more dynamic, and NTP based synchronisation may be improved by ensuring more stable network and power connections for the stations. Installing real time clocks with the stations would also improve time synchronisation stability. On a storm by storm basis however, determining the offset time using the method discussed is useful for retrospective analysis. Experimentation on a more orthogonal surface may also provide more usable data, as site errors caused by the presence of metal and machinery are largely unknown, and difficult to quantify and correct for.

5 ACKNOWLEDGEMENTS

The author would like to thank Eskom TESP, THRIP and the NRF for funding this research, and also express gratitude to CBi-electric: low voltage, for funding of the Lightning/EMC Research Group and for support of the CBi-electric Chair of Lightning. In particular, I would like to thank CBi-electric: low voltage, for their support of this project. Also the author wishes to thank the South African Weather Service, in particular Tracey Gill, Coleen de Villiers and Danelle Minne for assistance in supplying lightning data from the SAWSLDN.

6 REFERENCES

[1] Rakov V. A. and M. A. Uman, *Lightning - Physics and Effects*, Cambridge, Cambridge University Press, 2003.
[2] Gilmour J., *Personal Communication*, Boltek Corporation, February 2006.
[3] *Stormtracker Lightning Detector: Installation/Operator's Guide.* Buffalo, NY, USA, 2004. Boltek Corporation.
[4] U.S. Naval Observatory. "Julian Date Converter", June 2005. URL http://aa.usno.navy.mil/data/docs/JulianDate.html. Last accessed 1 December 2006.
[5] South African Weather Service. "The South African Weather Service Lightning Detection Network", January 2006. URL http://www.weathersa.co.za/Pressroom/2006/2006Jan13LightningDetectNetwork.pdf. Last accessed: 1 September 2006.
[6] Golde R.H., *Lightning – Volume 2:Lightning Protection*, Academic Press New York, 1977.
[7] Mills D. L., "RFC1305: Network Time Protocol (Version 3) - Specification, Implementation and Analysis", March 1992. URL http://rfc.net/rfc1305.html. Last Accessed: 1 March 2008.
[8] Rice D.A., "Analysing Lightning Data from Two Spatially Separate Magnetic Direction Finders", MSc(Eng) Dissertation, University of the Witwatersrand, Johannesburg, 2008, Appendix A: MATLAB Code Modules.
[9] Rice D.A., "Analysing Lightning Data from Two Spatially Separate Magnetic Direction Finders", MSc(Eng) Dissertation, University of the Witwatersrand, Johannesburg, 2008, Appendix B: Detailed Analysis of Storm Data.

Part II

Appendices

Appendix A

MATLAB Code Modules

Abstract

This document details the specific functions (implemented in MATLAB) used to analyse lightning data from two spatially separate stations and compare it to data from the South African Weather Service Lightning Detection Network (SAWSLDN) [1, 2]. Firstly, code modules written to compare individual station data to data from the SAWSLDN are presented. This is followed by modules used to combine data from the two stations, and also the process for comparing combined data to SAWSLDN data is described. These procedures require some manual intervention currently, and may be further automated in future work. The principal reason for combining and comparing the data is to determine offset errors present in time information (due to synchronisation problems) and also in azimuth information (due to the nature of installation). Once these initial offset errors have been corrected for, it may be possible to obtain more accurate real time information. This combined information should be more accurate than information from a single device of the same type.

A.1 Introduction

This document details the specific functions (implemented in MATLAB) used to analyse lightning data from two spatially separate stations. Data from the South African Weather Service Lightning Detection Network (SAWSLDN) is used to compare both individual station data and also combined station data, specifically in terms of time and azimuthal offset errors. Firstly, code modules written to compare individual station data to data from the SAWSLDN are presented, followed by modules used to combine data from the two stations. A timing analysis is also included.

The SAWSLDN data is manipulated in a spreadsheet to convert from a time string to Julian date, and the great circle approximation [3] is used to convert longitude and latitude to bearing and range. The relevant data is then imported into MATLAB from the spreadsheet using built in functionality. The individual station data from the two respective magnetic direction finders, in the form of archive files, is imported into a database. Using Structured Query Language (SQL), the relevant lightning data can then be extracted from the database. The relevant data is all cloud-to-ground records, for the relevant time period, and the relevant range. Ranges of 30km, 50km and 100km are used during testing, and the datasets can be reduced by range in either the SQL statement or in MATLAB itself.

A.2 Variable Naming Conventions

The naming conventions for variables used are summarised in Table A.1

Table A.1: Variable definitions

Variable	Description
sWS1_range	Data from SAWSLDN, within radius _range of Station 1. An n x 3 matrix, with columns Time (Julian Date), Bearing and Range respectively
sWS2_range	Data from SAWSLDN, within radius _range of Station 2. As for sWS1, but referenced to Station 2.
sWSX_range	Data from SAWSLDN, within radius _range of Station 1 or 2.
sX_range_tshift_azshift	Storm data from Station 1, qualified with _range, and also _tshift, _azshift as necessary. An n x 3 matrix, with columns Time (Julian Date), Bearing and Range respectively. a negative shift is designated with a prefix of 'n'
s12_range	Combined or triangulated data from Station 1 and Station 2.
timeCrit	Time Criterion. A value or set of values representing the size of the time buffer used in matching records.
azCrit	Azimuth Criterion. A value or set of values representing the size of the azimuthal buffer used in matching records.

A.3 Function Overview

An overview of the MATLAB functions used in the analysis of the storm data is shown in Table A.2

A.4 Matching SAWSLDN Data to Individual Station Data

This is a process of establishing time and azimuthal offsets between each individual station and the SAWSLDN data. The general flow is a manual process, with `TimeShift_exact`, `AzimuthShift_exact` and `MatchExactRecords` being automated functions within this process.

Table A.2: Function descriptions for MATLAB code modules

Function	Description
MatchExactRecords(sWS,sTest, timeCriterion, azCriterion)	Takes SAWS data, and compares it to sTest (either s1, s2, or s12), returning a dataset with matching records that's simultaneously satisfy timeCriterion and azCriterion
TimeShift_exact(sWS, sTest, timeCriterion, azCriterion)	Shift sTest records in time, iteratively compare to sWS with matchExactRecords. Returns number of matched records (i.e. that satisfy timeCriterion and azCriterion constraint) for each increment in time.
AzimuthShift_exact(sWS, sTest, timeCriterion, azCriterion)	Shift bearing information for sTest records, iteratively compare to sWS with matchExactRecords. Returns number of matched records (i.e. that satisfy timeCriterion and azCriterion constraint) for each increment in bearing information.
MatchRecords (s1, s2, timeCriterion)	returns number of matched records. These are trigonometrically resolvable strike data that satisfy the timeCriterion constraint.
TimeShift(s1, s2, timeCriterion)	Takes two sets of storm data, from stations 1 and 2 respectively, and shifts the time information (by adding an incremental offset). matchRecords is called on each iteration and the function returns an array of total matched records for each increment in bearing information.
AzimuthShift(s1, s2, timeCriterion)	Takes two sets of storm data, from stations 1 and 2 respectively, and shifts the bearing information (by adding an incremental offset). matchRecords is called on each iteration and the function returns an array of total matched records for each increment in bearing information.
ShiftByTime(sX, TimeOffset)	Function to shift time information for dataset sX, by TimeOffset.
ShiftByAz(sX, AzimuthOffset)	Function to shift azimuth information for dataset sX, by AzimuthOffset.
myPol2Cart(sX)	Function to convert sX(time, bearing, range) to sX(time, x, y).
myCart2Pol(sX)	Function to convert sX(time, x, y) to sX(time, bearing, range).

A.4.1 General Flow

The general process is shown in Figure A.1. In practice, values for timeCrit and azCrit are adjusted in each iteration in order to obtain clear, distinct peaks. In general, for time shifting, tighter time criterion values, and looser azimuth criterion values are used. For azimuth shifting, looser time criterion values and tighter azimuth criterion values are used. For increasing iterations increasingly tight criterions are used throughout. With further analysis it may be possible to automate this process.

A.4.2 Shifting in Time

The implementation of the `Timeshift_exact` function is shown in Figure A.2. The time range and resolution are set manually. To save processing time, a general plot at lower resolution can be done to obtain a general peak. The limits can then be set to analyse the peak at a much higher resolution, in order to obtain a more accurate value for time shift.

A.4.3 Shifting in Azimuth

The implementation of the `AzimuthShift_exact` function is shown in Figure A.3. The azimuth range and resolution are set manually. Again, to save processing time, a general plot at lower resolution can be done to obtain a general peak. The limits can then be set to analyse the peak at a much higher resolution, in order to obtain a more accurate value for azimuth shift.

A.4.4 Matching Algorithm

The algorithm for matching "exact" records is shown in Figure A.4. "Exact" records in this case refer to different datasets (of time, azimuth and range information) referenced to the same location. A pair of records is considered matched if within a specified time and azimuth criterion.

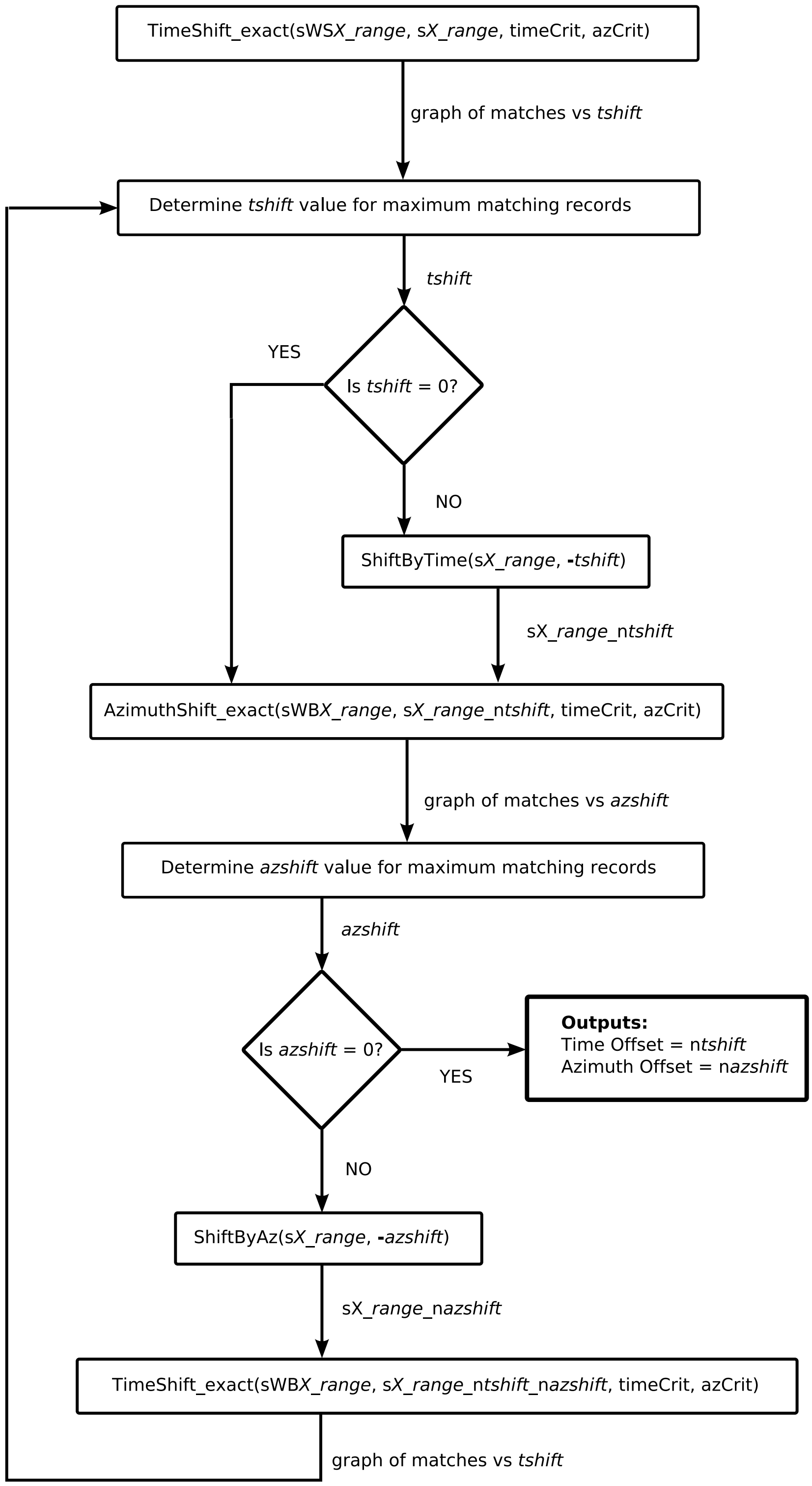

Figure A.1: Flow diagram for determining time and azimuth offsets between individual station data and SAWSLDN data

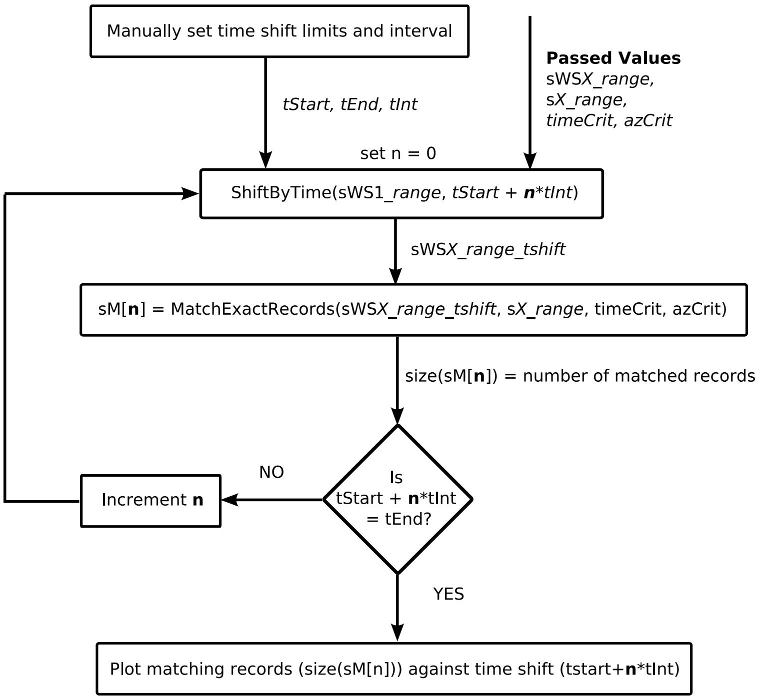

Figure A.2: Flow diagram for implementation of Timeshift_exact function

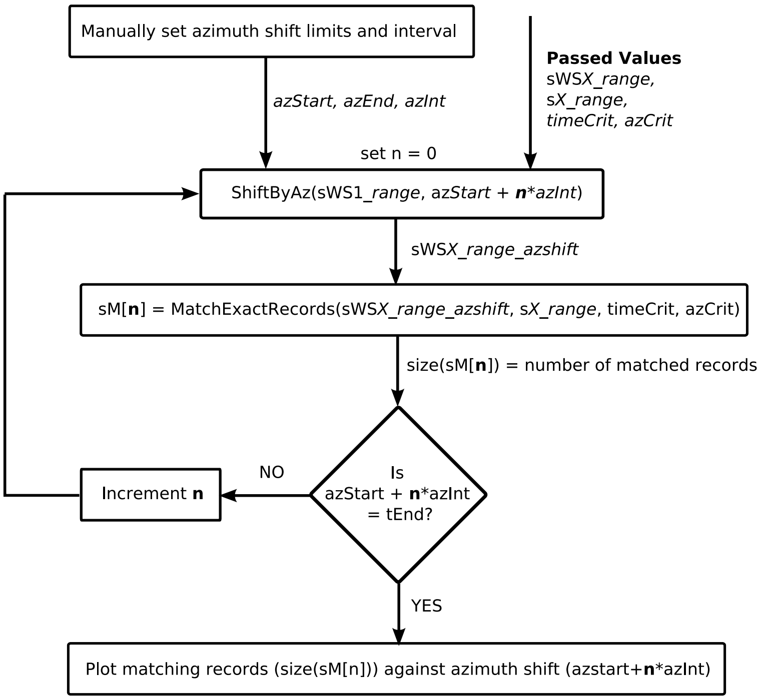

Figure A.3: Flow diagram for implementation of AzimuthShift_exact function

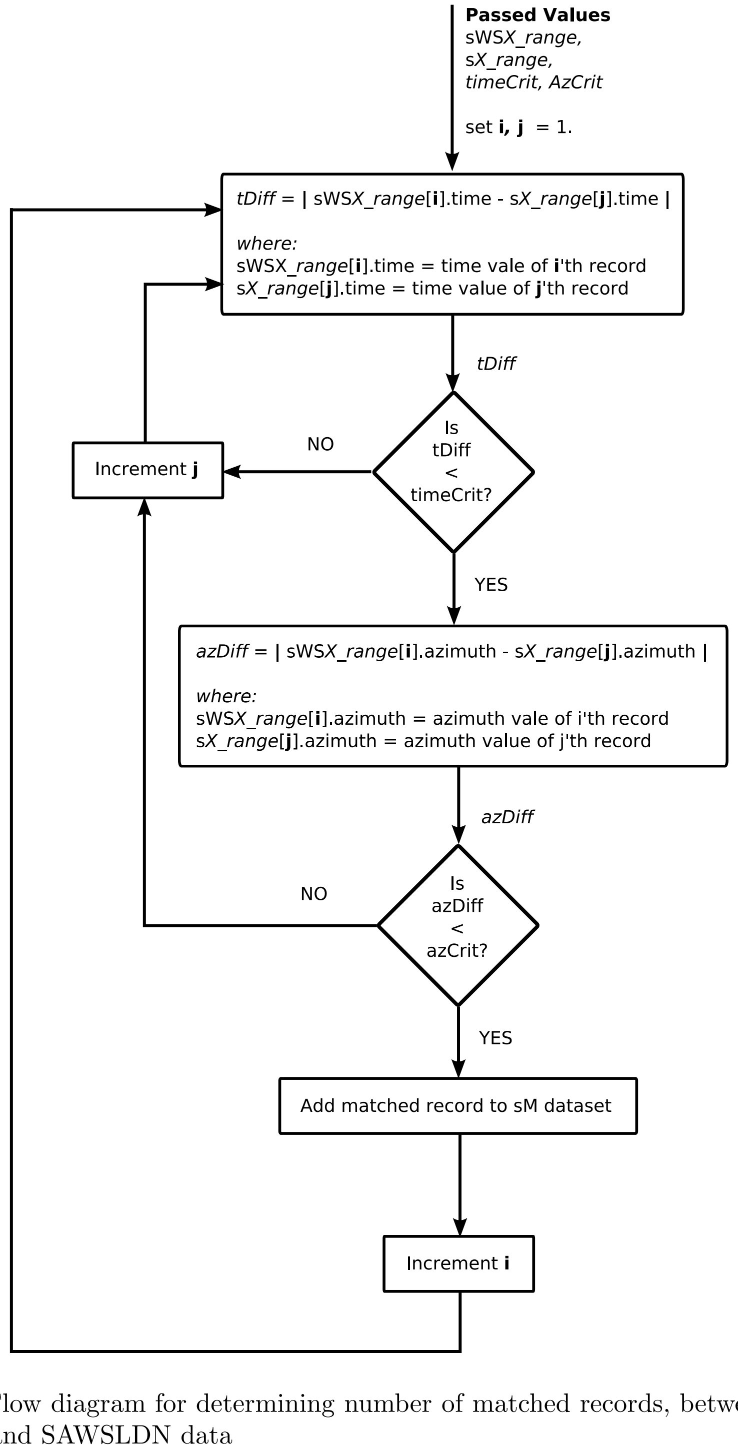

Figure A.4: Flow diagram for determining number of matched records, between individual station data and SAWSLDN data

A.5 Matching Data from Individual Stations

This process determines the relative time and azimuth offsets between the two stations. The general flow contains functions `TimeShift`, `AzimuthShift`. These functions also make use of `ShiftByTime`, `ShiftByAz`, `MatchRecords`, `CheckIntersection` and `FindQuadrant`.

A.5.1 General Flow

The general flow is seen in Figure A.5. The data is first shifted in time, and then in azimuth, recursively if necessary.

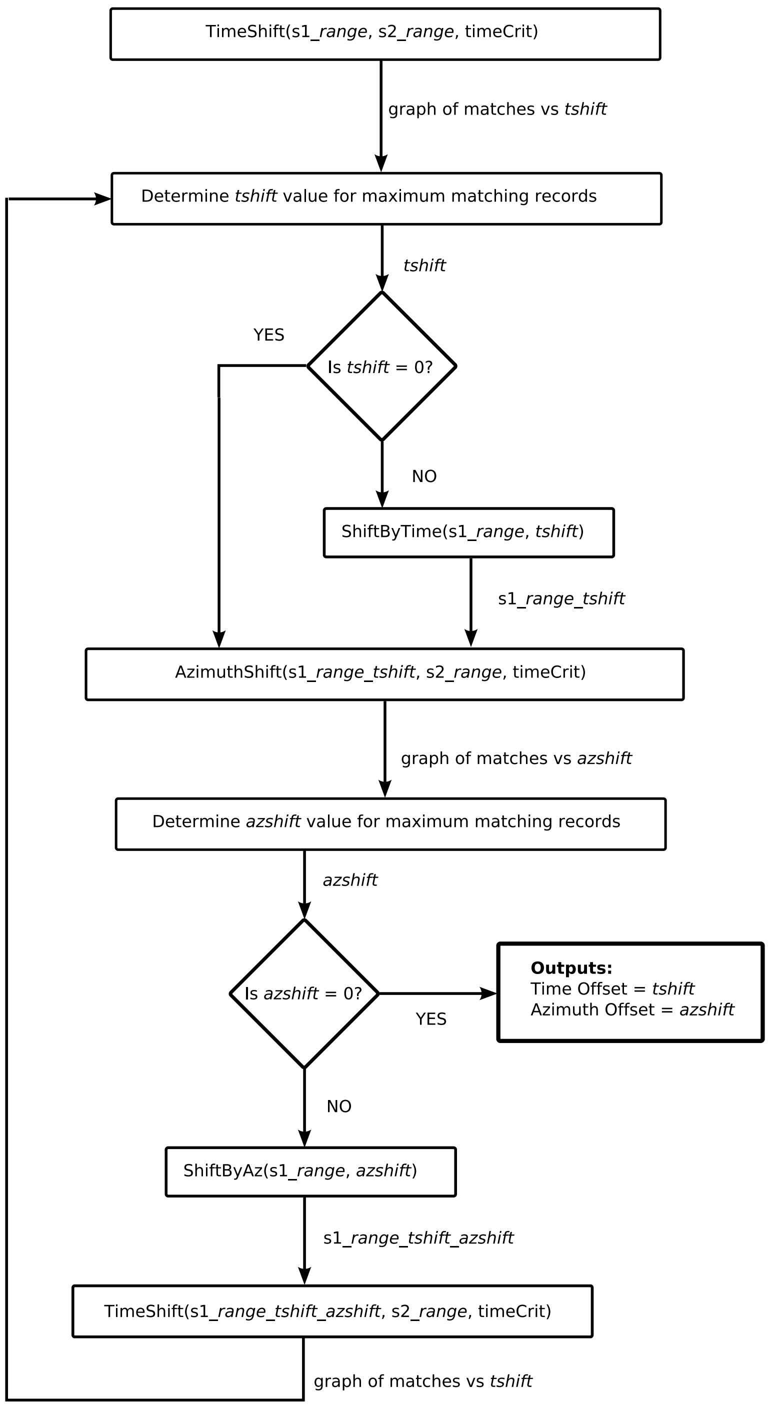

Figure A.5: Flow diagram for determining time and azimuth offsets between two individual stations' data

A.5.2 Shifting in Time

The implementation of the `TimeShift` function is shown in Figure A.6. The limits and resolution of the shift are again manually set, as for the `Timeshift_exact` function.

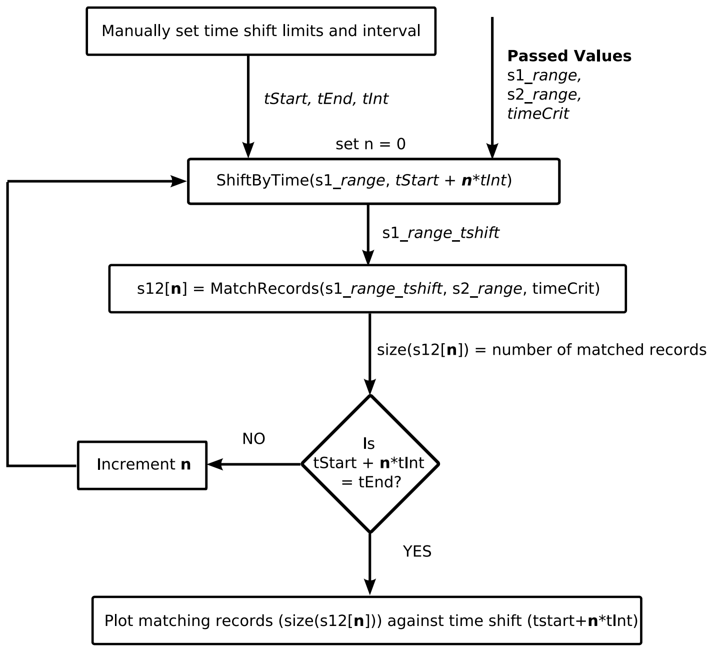

Figure A.6: Flow diagram for implementation of TimeShift function

A.5.3 Shifting in Azimuth

The implementation of the `AzimuthShift` function is shown in Figure A.7. The limits and resolution of the shift are again manually set, as for the `AzimuthShift_exact` function.

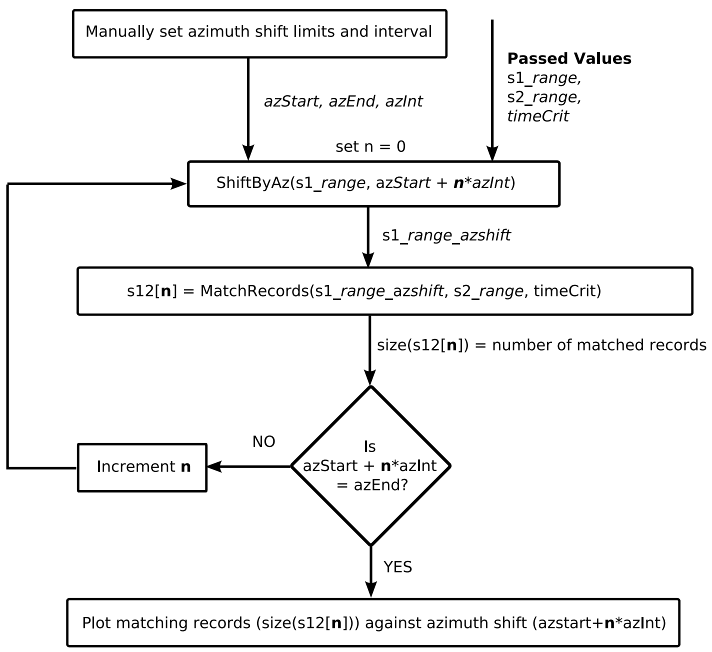

Figure A.7: Flow diagram for implementation of AzimuthShift function

A.5.4 Matching Algorithm

The algorithm for matching and triangulating records from two spatially separate stations is shown in Figure A.8. This algorithm checks for matching records within a specified time criterion that are also trigonometrically resolvable. A dataset is returned from this function that contains pairs of matching strikes in the same row, as well as the respective rectangular co-ordinates of the triangulated strike.

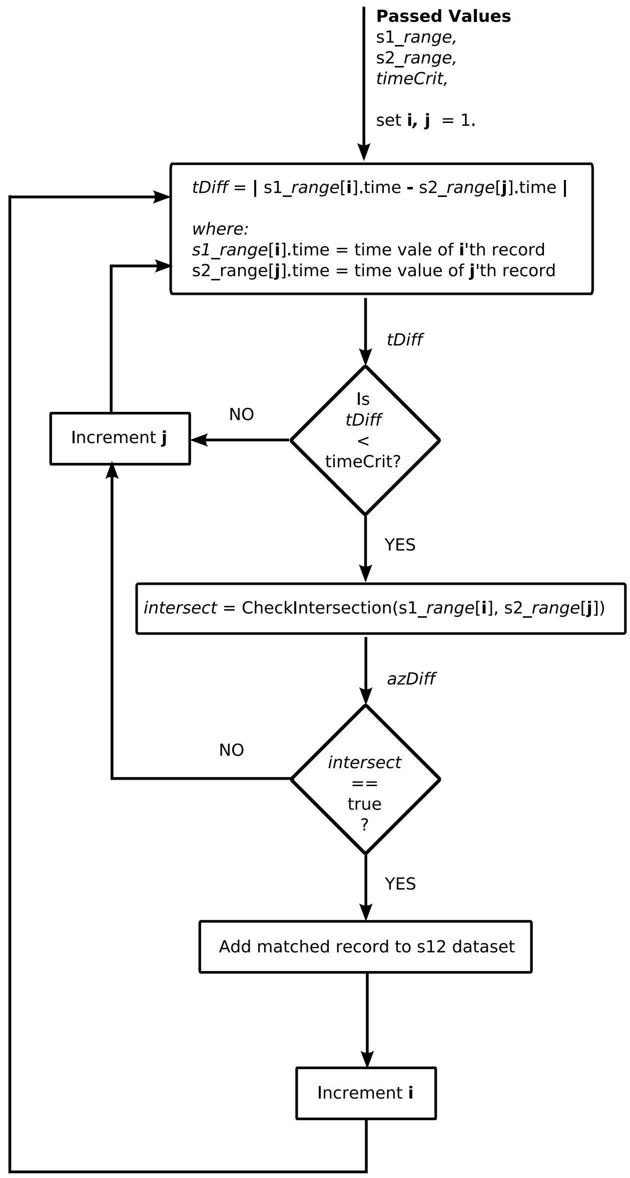

Figure A.8: Flow diagram for determining time and azimuth offsets between individual stations' data

Checking Trigonometric Resolvability

In order to elimate matching pairs of strike records (in time) that are not trigonometrically resolvable, two functions are used. `CheckIntersection` is called by `MatchRecords` and determines if a particular set of time-matched records have lines of azimuth that intersect. This is done by determining the quadrant in which each azimuth value lies (using `FindQuadrant`). If both azimuth values lie in the same quadrant (relative to their respective stations), or in either of the "inner" quadrants (between the stations) then the strike is considered resolvable. If a strike is near the baseline, it is not resolvable.

CheckIntersection and FindQuadrant are illustrated in Figure A.9 and Figure A.10 respectively.

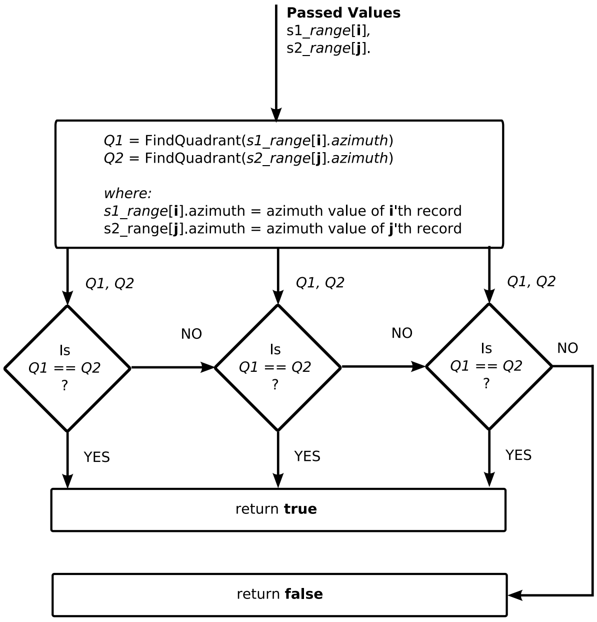

Figure A.9: Flow diagram for CheckIntersection Function

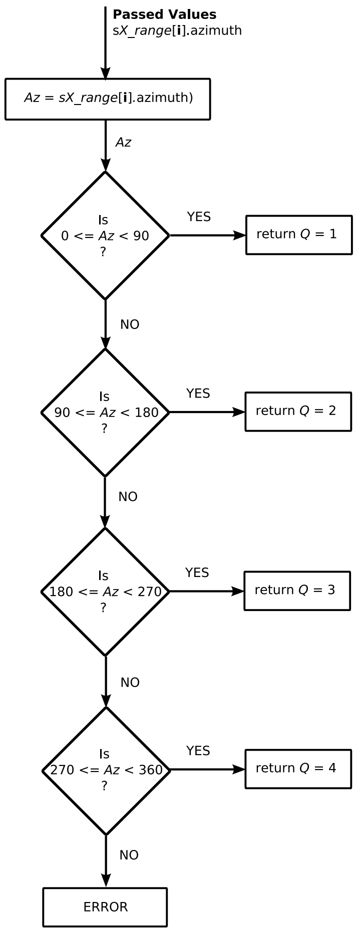

Figure A.10: Flow diagram for FindQuadrant function

A.6 Comparing Triangulated Data to SAWSLDN Data

This can be done using `MatchExactRecords` (through `TimeShift_exact` and `AzimuthShift_exact`), and comparing the triangulated data (s12_100km, which is referenced to Station 1's location) directly to the SAWSLDN data (method 1), and thus removing the absolute error in timing and azimuthal information. The alternate method (method 2) is to use the offsets determined during individual station calibration to obtain a calibrated dataset (s12cal_100km)using `MatchRecords`, and compare this pre-shifted dataset directly to the SAWSLDN (again using `TimeShift_exact` and `AzimuthShift_exact`). This should mean that no further shifting is required.

A.7 Timing

Equation A.1 shows the time taken to generate a plot using the `TimeShift` and `TimeShift_exact` functions, and it's dependence on the size of the datasets tested as well as the number of tests done. The number of tests depends on both the time shift limits set, as well as the size of the intervals between these limits (the resolution, in time, of the plot).

$$\text{Time}_{\text{ plot generation}} \propto N_{ds1}\left(N_{ds2} - \frac{N_{matched}}{2}\right)\frac{\text{T}_{\text{end}} - \text{T}_{\text{start}}}{\text{T}_{\text{resolution}}} \tag{A.1}$$

where;

- Time $_{plot\ generation}$ = Time taken to generate plot for batched time shift
- N_{ds1} = Number of records in first dataset
- N_{ds2} = Number of records in second dataset
- $N_{matched}$ = Number of total matched records
- T_{start} = Lower limit of time shift value tested in the batch
- T_{end} = Upper limit of time shift value tested in the batch
- $\text{T}_{resolution}$ = Increment of time shift values tested in the batch

For zero matching records, the plot generation time is proportional to the product of N_ds1 and N_ds2, since the algorithm must cycle through each record in the second dataset for every record in the first. When matched records are found, only the records before the matched one are cycled through, which will be a small number initially, tending toward the total number of records in the dataset as the algorithm progresses. To approximate this effect, half of the number of matched records are subtracted from the number of records in the second dataset. This assumes an even spread of matched records throughout the second dataset.

Similarly, Equation A.2 shows the time taken to generate a plot using `AzimuthShift` and `AzimuthShift_exact`function, and its dependence on the size of the datasets tested as well as the number of tests done. The number of tests depends on both the azimuth shift limits set, as well as the size of the intervals between these limits (the resolution, in time, of the plot).

$$\text{Time}_{\text{ plot generation}} \propto N_{ds1}\left(N_{ds2} - \frac{N_{matched}}{2}\right)\frac{\text{Az}_{\text{end}} - \text{Az}_{\text{start}}}{\text{Az}_{\text{resolution}}} \tag{A.2}$$

where;

- Time $_{plot\ generation}$ = Time taken to generate plot for batched time shift
- N_{ds1} = Number of records in first dataset

- N_{ds2} = Number of records in second dataset
- $N_{matched}$ = Number of total matched records
- Az_{start} = Lower limit of azimuth shift value tested in the batch
- Az_{end} = Upper limit of azimuth shift value tested in the batch
- $\text{Az}_{resolution}$ = Increment of azimuth shift values tested in the batch

Table A.3 shows the number of records in the relevant datasets.

Table A.3: Number of records for datasets used in analysis

	Number of Records	
Dataset	range = 100km	range = 30km
sWS1_range	31947	51
sWS2_range	31947	55
s1_range	6308	602
s2_range	6529	486

Table A.4 shows the number of iterations for the batched shift algorithms, assuming zero matched records (worst-case boundary condition). It can be seen that to calculate offsets using data within 100 km range can take up to 8000 times longer than using data from a 30 km range. To increase the number of matched records, it is necessary to match sWSX_30km to sX_100km [2]. This is due to range inaccuracies of the individual station data. Using these datasets requires approximately 10 to 15 times more iterations than using sWSX_30km and sX_30km.

Table A.4: Number of iterations required for matching datasets

		Thousands of Iterations	
Dataset 1	Dataset 2	range = 100km	range = 30km
sWS1_range	s1_range	201521	30
sWS2_range	s2_range	208581	26
sWS1_range	s1_100km	-	321
sWS2_range	s2_100km	-	359
s1_range	s2_range	41184	292

A.8 Conclusion

The MATLAB code modules used for detailed analysis of storm data have been presented. These procedures have some manual elements, but are largely automated, and may be further automated in future work. The procedures provide a means for correcting of offset errors present in time information (due to synchronisation problems) and also in azimuth information (due to the nature of installation). Once initial offset errors have been corrected for, it may be possible to obtain real time information that is also corrected (and presented) in real time. Timing considerations, illustrating the dependence of process time on number of dataset records and plot resolution have also been discussed. Detailed analysis of storm data, to illustrate the implementation of the functions described, is discussed in [2].

References

[1] D. A. Rice, "Analysing Lightning Data from Two Spatially Separate Magnetic Direction Finders," MSc(Eng) Dissertation, University of the Witwatersrand, Johannesburg, 2008, Paper: Analysing Lightning Data from Two Spatially Separate Magnetic Direction Finders.

[2] ——, "Analysing Lightning Data from Two Spatially Separate Magnetic Direction Finders," MSc(Eng) Dissertation, University of the Witwatersrand, Johannesburg, 2008, Appendix B: Detailed Analysis of Storm Data.

[3] Eric W Weisstein. (1999) Azimuthal Equidistant Projection. Last Accessed 1 December 2006. [Online]. Available: http://mathworld.wolfram.com/AzimuthalEquidistantProjection.html

Appendix B

Detailed Analysis of Storm Data

Abstract

Two lightning detectors, of the magnetic direction finder type form part of a two station system for determining the position of lightning strikes. The detectors are on a baseline of approximately 600 metres, and the aim of the system is to accurately detect and map lightning within a radius of 30 km. Although no real time capability is present, the archive data collected from each separate station is used to find the offset errors in the azimuthal orientation, as well as in time. The relative offset errors are determined by shifting the time and azimuthal information for one station's data and calculating the maximum possible matching records (within certain time and azimuth criteria) for each incremental shift. The relative offset in orientation is found to be 24.5 degrees, and in time to be 0.001305 days (112.75 seconds). The individual stations, as well as the triangulated data calculated from matching records, can also be calibrated using data from the South African Weather Service Lightning Detection Network (SAWSLDN). Individual station calibration indicated an offset of +6.4 degrees and 0.00575 days (496.8 seconds) for Station 1, with the offsets for Station 2 determined as +29.4 degrees and −0.000105 days (9.07 seconds). Comparison of triangulated data to SAWSLDN data yields unexpected results with regard to resultant shifts - which may point to an error or anomaly in the triangulation calculations or a mismatch between the SAWS and direction finder data. Alternative approaches to calculating the offset errors, not included in [1], are also presented.

B.1 Introduction

This document contains a detailed analysis of lightning data from a two hour period during a storm in the Gauteng area on 27 October 2006. Data was collected from two spatially separate magnetic direction finders (installed at Wits University) and compared to data from the South African Weather Service Lightning Detection Network (SAWSLDN). Station 1 is located on the roof of the Chamber of Mines Building (−26.19183 degrees South, 28.03097 degrees East) at the University of the Witwatersrand - Main Campus, Gauteng, South Africa, while Station 2 is located on the roof of the Physics Building (−26.191583 degrees South, 28.03097 degrees East). The antennas are located on an approximately 600 m baseline. This is a relatively small baseline, but is useful in locating strikes within a working range of 10 km to 30 km. Data from ranges of up to 100 km (from Station 1) is included in the analysis however, to provide a larger body of data for determining offset errors.

Offset errors between individual stations and the SAWSLDN, as well as relative errors between the two stations are determined. Triangulated data from the two station system is also compared the SAWSLDN data, and the errors compared to those previously determined.

The number of records for the datasets used are shown in Table B.1

Table B.1: Number of records for datasets used in analysis

	Number of Records	
Dataset	range = 100km	range = 30km
sWS1_range	31947	51
sWS2_range	31947	55
s1_range	6308	602
s2_range	6529	486

B.2 Offsets between Individual Stations and SAWSLDN

B.2.1 Station 1

A first estimate at the time offset is obtained by shifting the time information of sWS1_100km and matching it with s1_100km. Figure B.1 shows the result of the first estimate, with an offset of −0.00575 days (496.8 seconds) yielding a maximum of matched records. The matched records are compared using `MatchExactRecords`, a function which isolates pairs of matched records, from each data source, which fall within a specified time and azimuth envelope (or criterion) [2].

The s1_100km dataset has the offset time of 0.00575 using the `ShiftByTime` [2] function. This resultant dataset (s1_100km_0p00575) is then compared to sWS_100km again, this time to find the azimuthal offset in the data. It is noted that the time shift characteristic is quite flat for a large region around the peak, which makes it difficult to ascertain the exact time offset. Figure B.2 shows the azimuth shift characteristic for a full rotation. The peak matching records is for s1_100km shifted by +6.4 degrees (using the `ShiftByAz` [2] function), and the resulting dataset is s1_100km_0p00575_6p4. A second distinct peak is observed at approximately 180 degrees from the main peak, which can be attributed to reflections of strike events. Two sub-peaks on the main peaks are also observed at approximately 50 degrees from either side of the main peak. A possible source of this is two aluminium masts located near to the antenna, in similar azimuth positions to the peaks. Figure B.3 is the plot used to determine the exact offset, and is generated for a higher azimuth resolution of 0.1 degrees.

To further refine the time shift value, the time shift characteristic can again be plotted with the new azimuth-shifted dataset being compared to sWS1_100km. Figure B.4 below shows the matching records for time shift of sWS1_100km against s1_100km_n0p00575_6p4.

This new offset can now be adjusted for if necessary, by further offsetting the time information for s1_100km. There is no clear peak for this characteristic, and it is difficult to

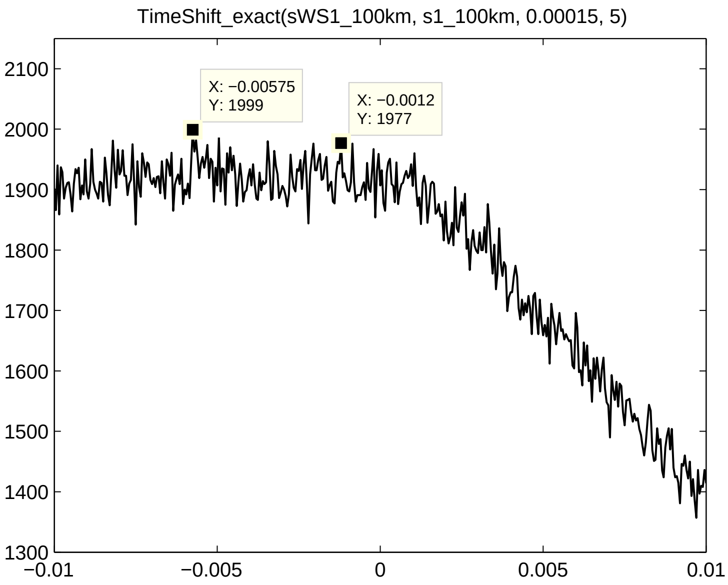

Figure B.1: Time shift characteristic for SAWSLDN data shifted against Station 1 data

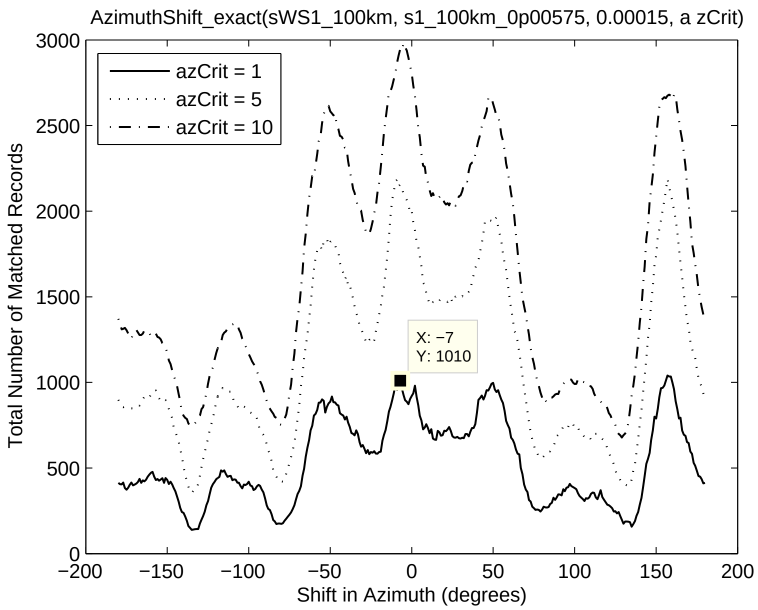

Figure B.2: Azimuth shift characteristic for SAWSLDN data shifted against data from Station 1

determine the time offset between the SAWSLDN data and data from Station 1. The azimuth shift characteristic however does provide a clear peak, and it is therefore possible to determine with confidence the azimuth offset between the two sets of data.

The percentage of matched records (with respect to the total number of records in sWS1_30km, i.e. 51) is plotted against time criterion in Figure B.5 for an azimuth criterion of 1 and 5 degrees. A significant improvement in the number of matched records is observed in the data after time and azimuth offset correction.

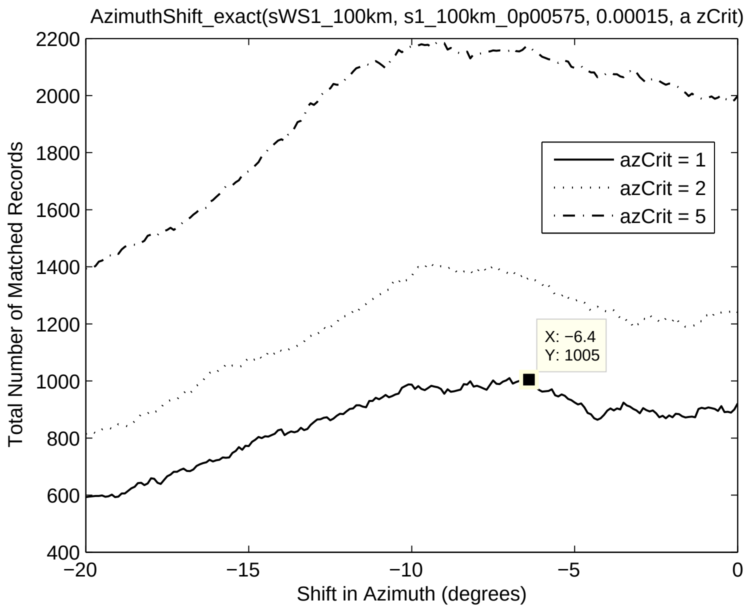

Figure B.3: Windowed azimuth shift characteristic for SAWSLDN data shifted against Station 1 data

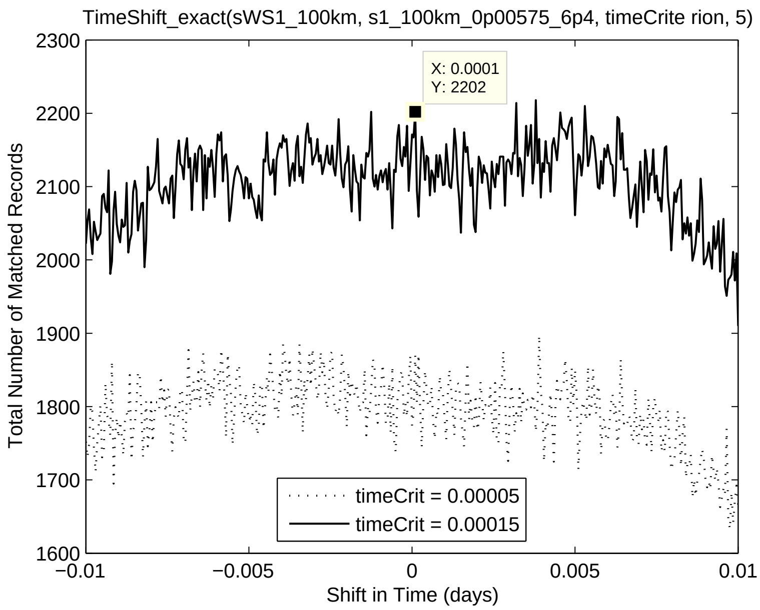

Figure B.4: Time shift characteristic for SAWSLDN data shifted against time and azimuth shifted Station 1 data, second iteration

An Alternative Approach

An alternative approach to determining the offset errors, relative to the SAWSLDN data, is to choose more relaxed (i.e. greater) initial values for azimuth criterion. Figure B.6 shows the time shift characteristic of the SAWSLDN shifted against Station 1 data, for an azimuth criterion of 15 degrees. The time criterion is kept constant at 0.00015 days. This illustrates the effect of using different criterions in the correction process.

The resulting, time shifted dataset is s1_100km_n0p00063, and the azimuth shift criterion of the SAWSLDN against the time shifted Station 1 data is shown in Figure B.7. In general the shape is very similar to the previous set of curves generated, showing the two sub-peaks, as well as the secondary peak at approximately 180 degrees.

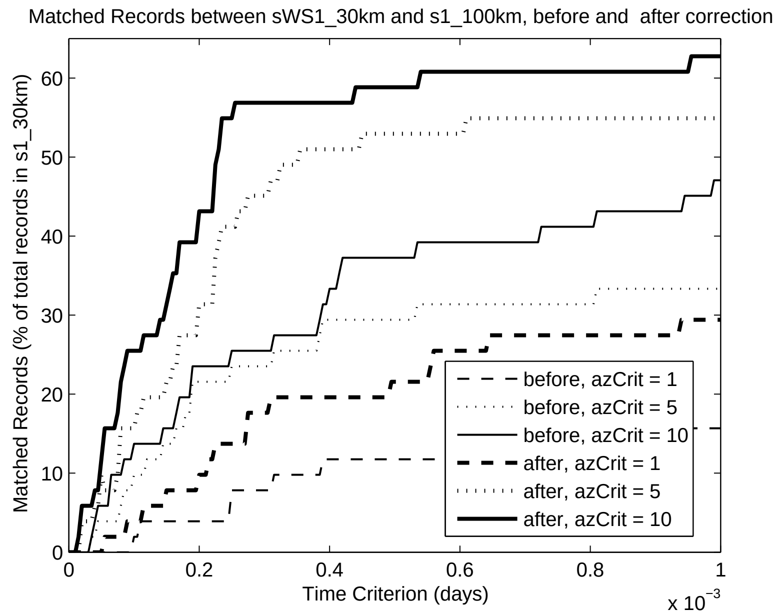

Figure B.5: Percentage matched records against time criterion, with and without time and azimuth correction

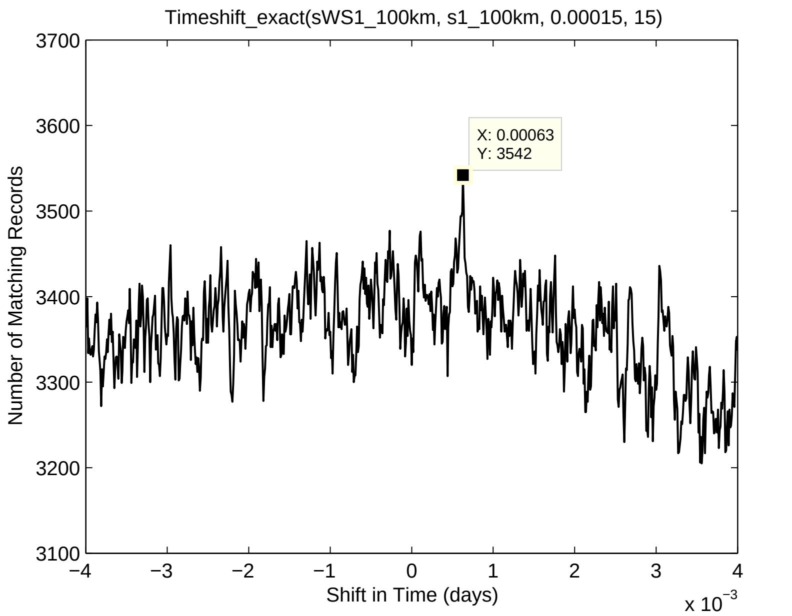

Figure B.6: Time shift characteristic for SAWSLDN data shifted against Station 1 data

Figure B.8 shows a windowed plot of the azimuth shift characteristic, with increased resolution (0.1 degrees). The plot is generated for azimuth criterion values of 1, 2 and 5 degrees. A tighter azimuth criterion is used to obtain a more accurate value for azimuth shift, however no distinct peak is present.

The effect of changing time criterion, for an azimuth criterion of 1 degree, is illustrated in Figure B.9. A clearer peak is visible for greater values of time criterion. This value of azimuth shift can be used to adjust the Station 1 dataset, which can then be checked for time synchronisation using the `TimeShift_exact` function [2]

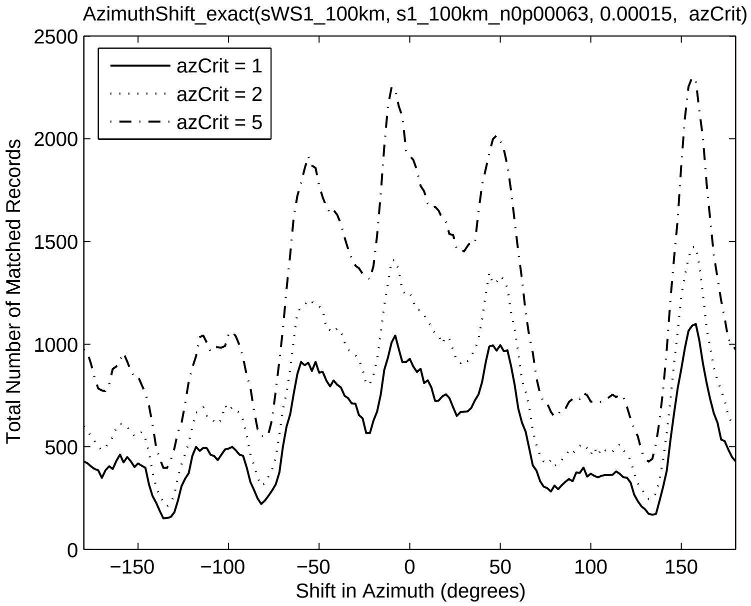

Figure B.7: Azimuth shift characteristic for SAWSLDN data shifted against time shifted Station 1 data

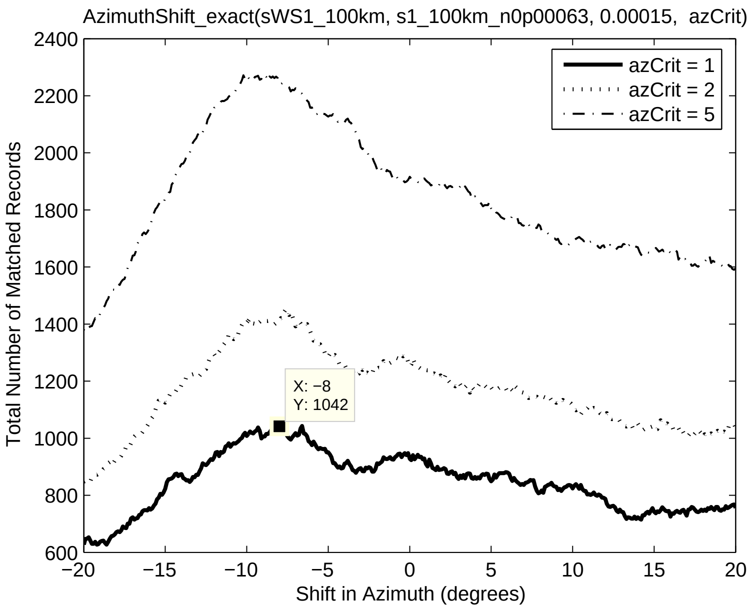

Figure B.8: Windowed azimuth shift characteristic for SAWSLDN data shifted against Station 1 data, for varying azimuth criterion

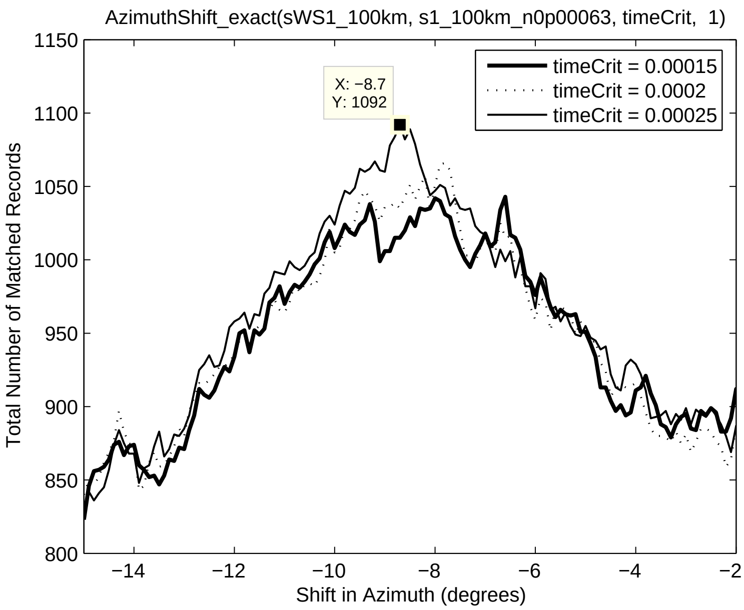

Figure B.9: Windowed azimuth shift characteristic for SAWSLDN data shifted against Station 1 data, for varying time criterion

B.2.2 Station 2

Following a similar process to above, the following results are obtained for calibration of Station 2. Figure B.10 and show the peak matched records to be at a time offset of −0.003505. The resultant, shifted, dataset is s2_100km_n0p003505.

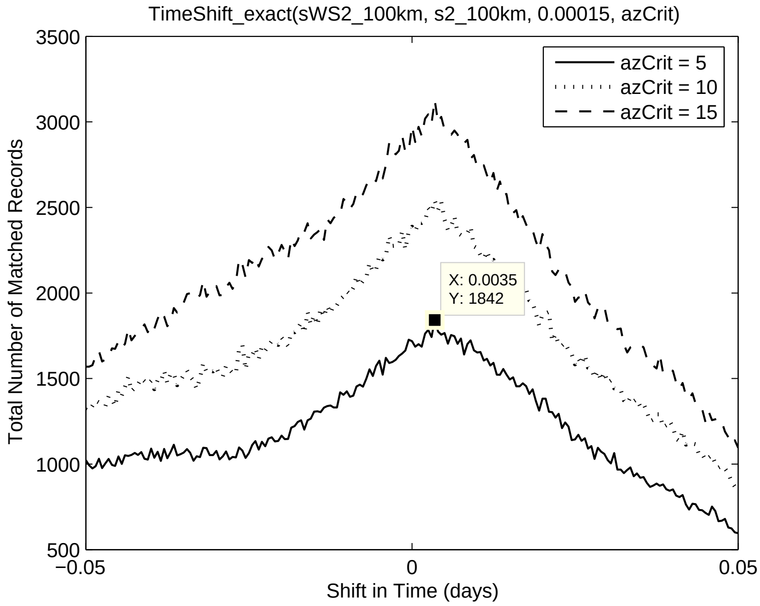

Figure B.10: Time shift characteristic for SAWSLDN data shifted against Station 2 data

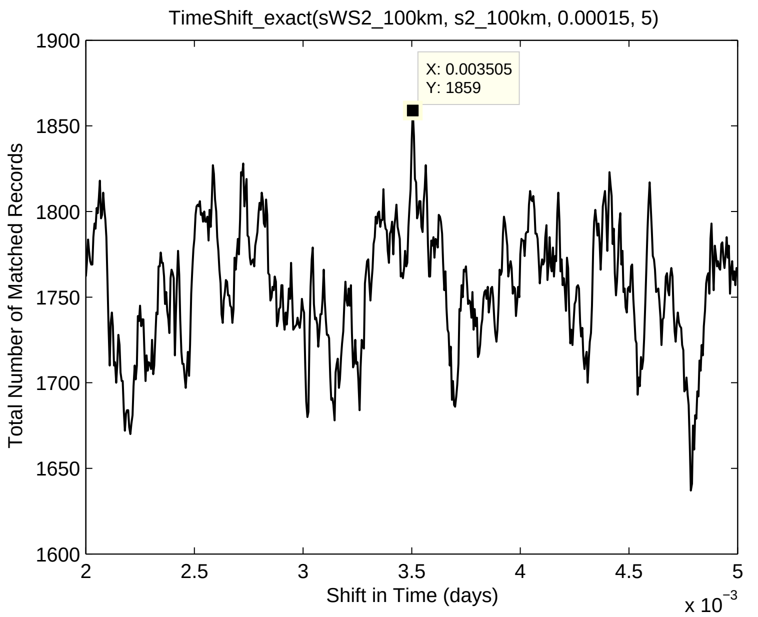

Figure B.11: Time shift characteristic for SAWSLDN data shifted against Station 2 data

The azimuthal offset between this data and sWS2_100km is illustrated in Figure B.12, and Figure B.13 shows a windowed plot at increased azimuth resolution (0.1 degrees) for the peak region. These plots are done for varying time criterion. The peak is found at −30.3 degrees. The resultant time and azimuth shifted dataset is s2_100km_0p003505_30p3. Figure B.14 shows a windowed plot of the azimuth shift criterion for varying azimuth criterion. It is noted that for looser criterion, the peaks are generally more defined, but there is a reduced level of accuracy for the matched records at these peaks.

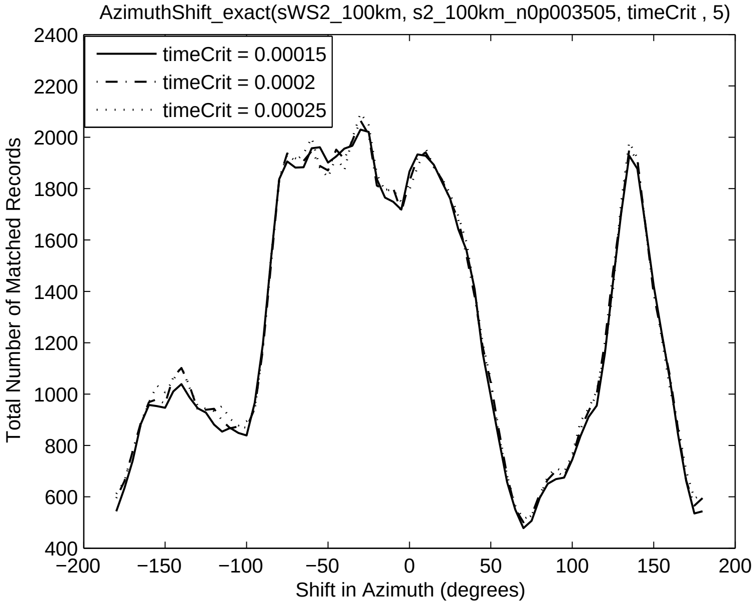

Figure B.12: Azimuth shift characteristic for SAWSLDN data shifted against time shifted Station 2 data

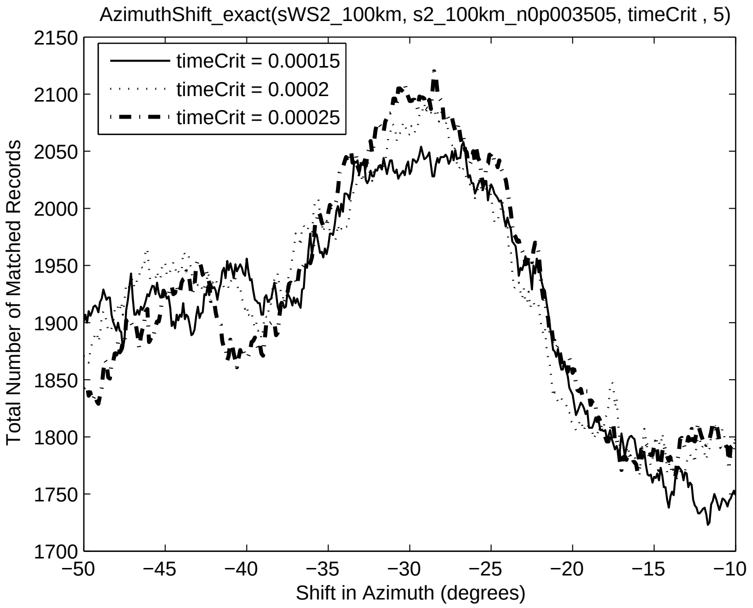

Figure B.13: Azimuth shift characteristic for time shifted SAWSLDN data shifted against Station 2 data

Figure B.15 shows the time shift characteristic for the time and azimuth adjusted data. Since the peaks are not centred on zero, a second iteration of shifting is necessary. The peak here is more defined, and so a second iteration is done to illustrate the recursive process. The resultant dataset after a second time shift is s2_100km_n0p003505_30p3_0p00034 or alternatively s2_100km_n0p000105_30p3. This represents an effective overall time offset of −0.000105 days (9.07 seconds).

Figure B.16 and Figure B.17 azimuth shift characteristic for the new time and azimuth adjusted data. A small azimuth offset is still present, and a second iteration of shifting is necessary. The resultant dataset after a second azimuth shift is s2_100km_n0p003505_30p3_0p00034_n0p9 or alternatively s2_100km_n0p000105_29p4. This represents an effective overall azimuth offset of +29.4 degrees.

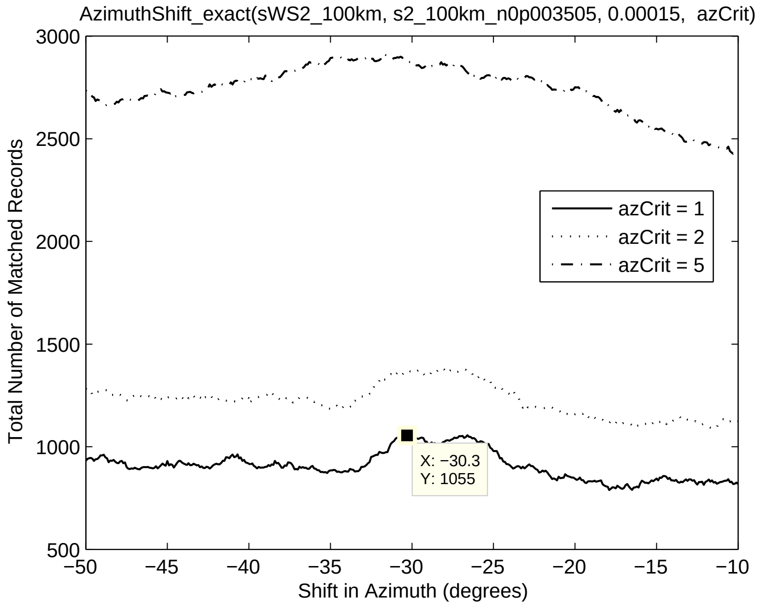

Figure B.14: Azimuth shift characteristic for time shifted SAWSLDN data shifted against Station 2 data

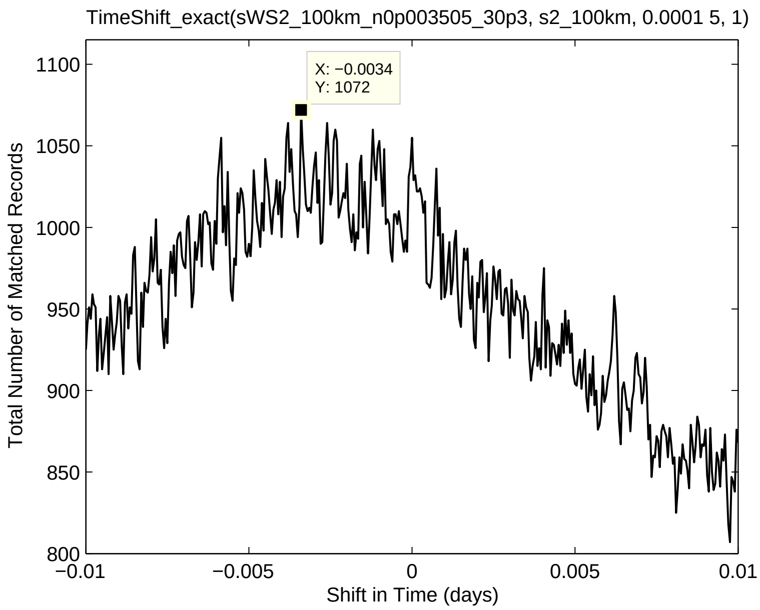

Figure B.15: Time shift characteristic for SAWSLDN data shifted against Station 2 data

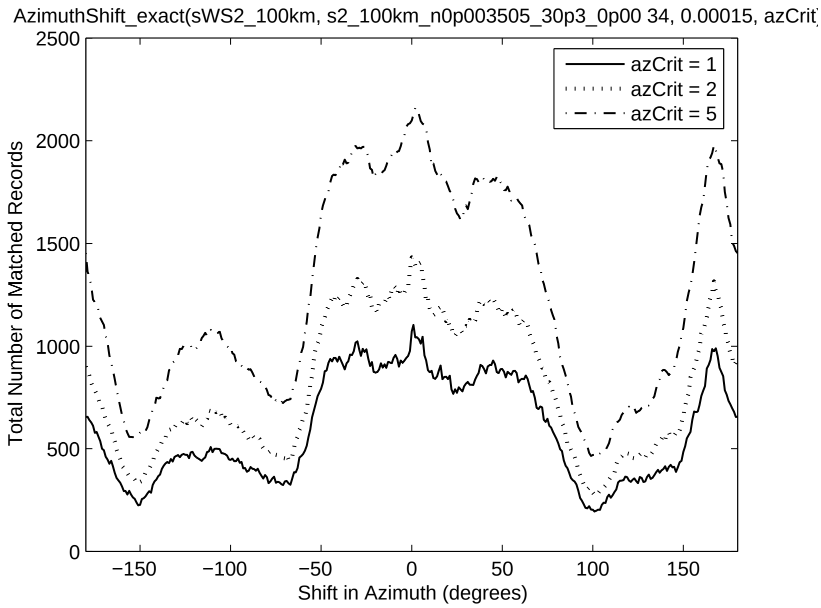

Figure B.16: Azimuth shift characteristic for time shifted SAWSLDN data shifted against Station 2 data

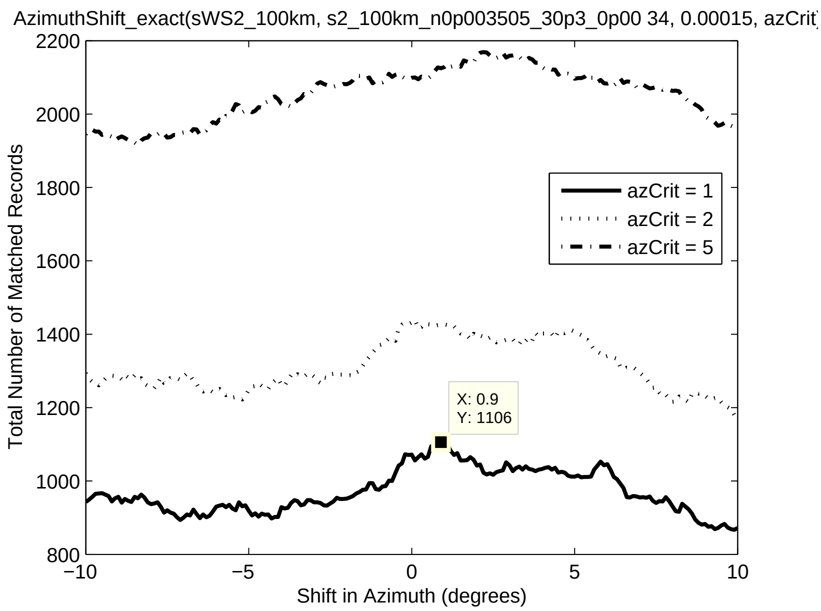

Figure B.17: Windowed azimuth shift characteristic for time shifted SAWSLDN data shifted against Station 2 data

Figure B.18 and Figure B.19 shows the time shift characteristic for this shifted data, for an azimuth criterion of 5 degrees and 1 degree respectively, and implies that the datasets are now better aligned in time. The more precise azimuth criterion yields the more definite peak, which implies an increased accuracy in matched records using this method.

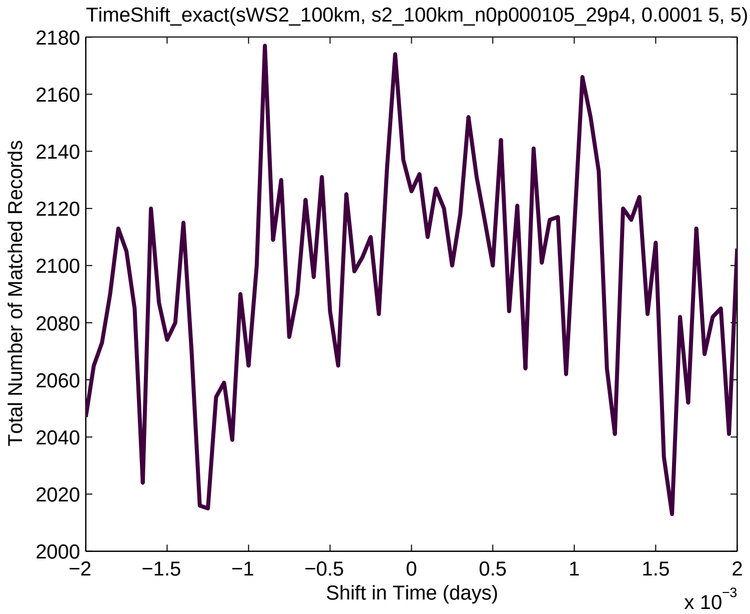

Figure B.18: Time shift characteristic for SAWSLDN data shifted against Station 2 data, third iteration, for an azimuth criterion of 5 degrees

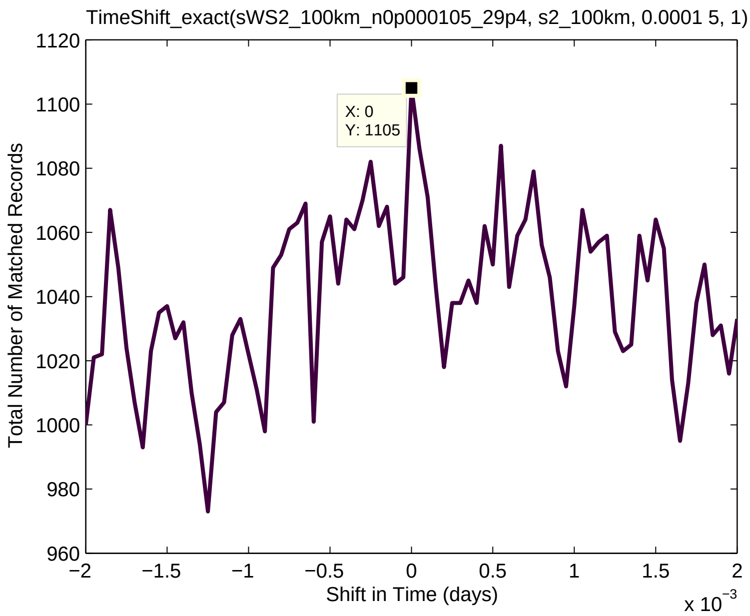

Figure B.19: Time shift characteristic for SAWSLDN data shifted against Station 2 data, third iteration, for azimuth criterion of 1 degree

The percentage of matched records (with respect to the total number of records in sWS2_30km, i.e. 55) is plotted against time criterion in Figure B.20 for an azimuth criterion of 1, 5 and 10 degrees. It is interesting to note that for tighter azimuth criterion (1, 5 degrees) there is a decrease in number of matching records. There is only an improvement in the corrected data for an azimuth criterion of 10 degrees, indicating that the shifted data is not necessarily more accurate than the unshifted data.

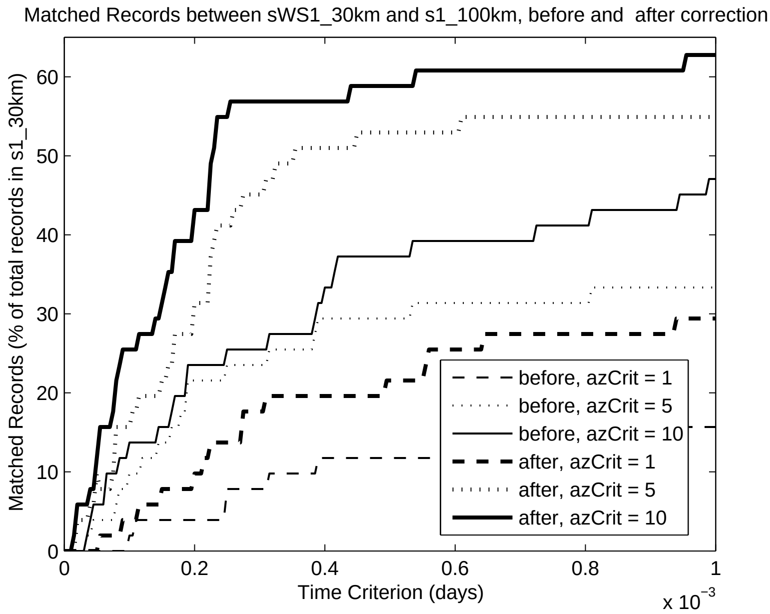

Figure B.20: Percentage matched records against time criterion, with and without time and azimuth correction

B.3 Relative Offsets between Station 1 and Station 2

The initial estimate of the time offset between the two stations is done in a similar way to individual station calibration. The records are matched in time, using `MatchRecords` a function which establishes pairs of matched records (from spatially separate sources) within a certain time criterion, that are also trigonometrically resolvable [2]. Figure B.21 and Figure B.22 show two windowed plots of the time shift characteristic, at time resolutions of 0.00001 and 0.000001 days respectively, giving an accurate value of 0.001305 for time shift. The characteristic is shown for varying values of time criterion, and a similar peak is present for looser time criterion. However, the peak becomes much more distinct at lower time criterion.

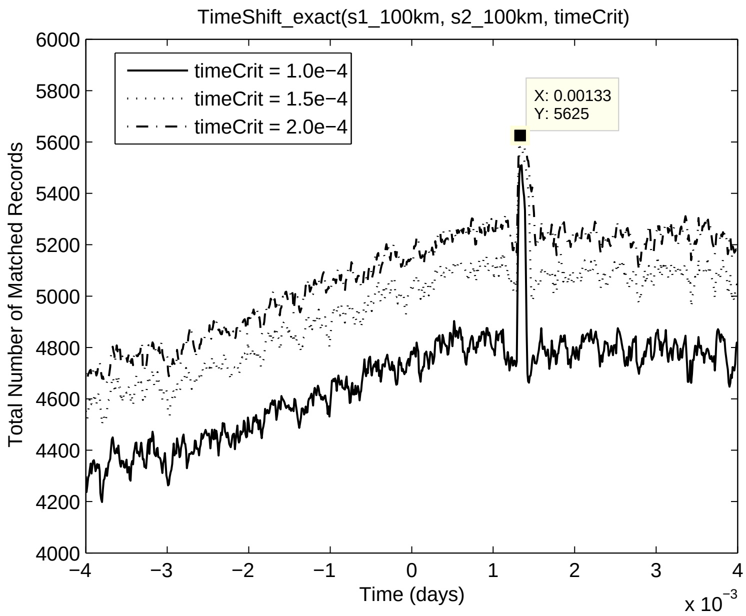

Figure B.21: Time shift characteristic for Station 1 data shifted against Station 2 data

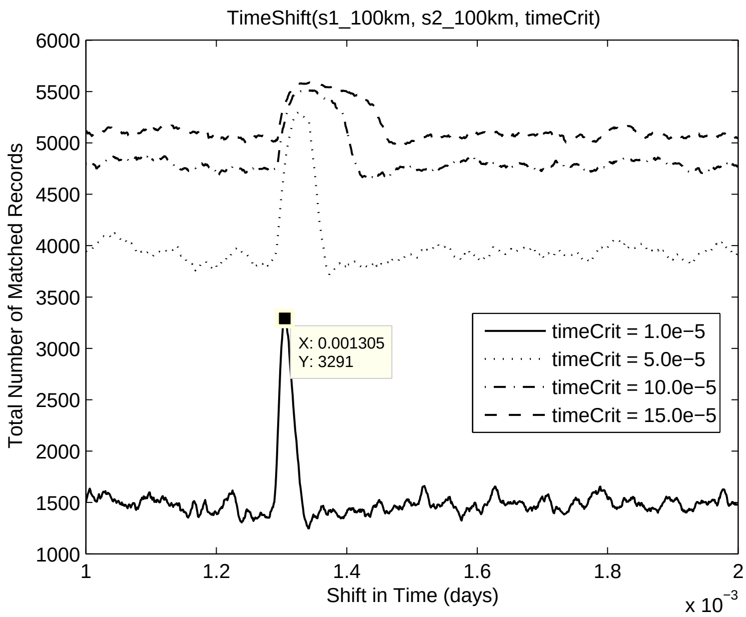

Figure B.22: Time shift characteristic for Station 1 data shifted against Station 2 data

Finding the azimuthal offset is then done using the time-shifted data. Figure B.23 shows the azimuth shift characteristic for the time shifted data, and Figure B.24 shows a plot a higher resolution(0.1 degrees), to accurately calculate the azimuth shift. The relative azimuthal offset between the two stations is found to be -24.5 degrees.

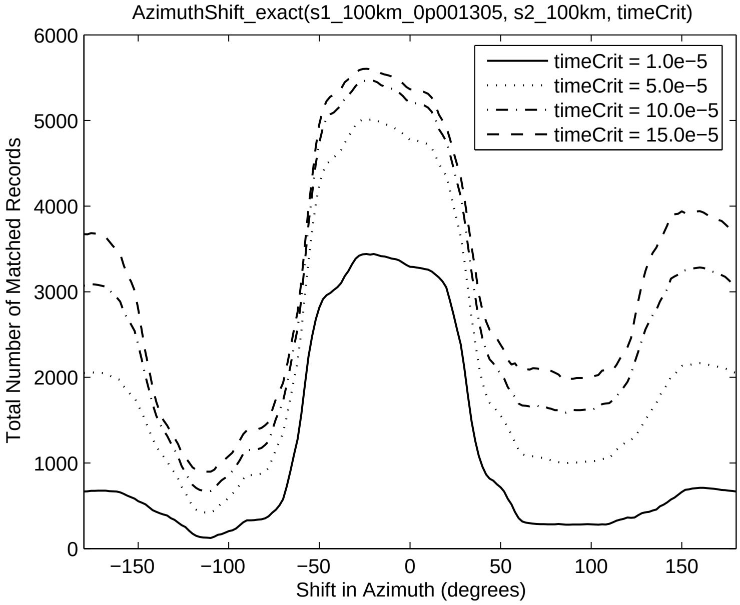

Figure B.23: Azimuth shift characteristic for Station 1 data shifted against Station 2 data

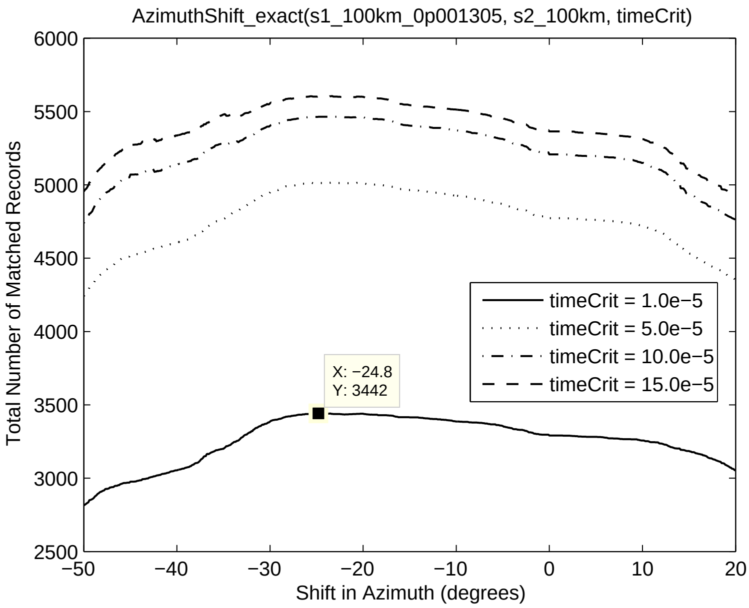

Figure B.24: Azimuth shift characteristic for Station 1 data shifted against Station 2 data

The new shifted data (in time and azimuth) can now be shifted again in time. The resultant datasets are either s1_100km_0p001305_n24p5, and s2_100km or alternatively s1_100km _0p001305, and s2_100km_24p5.

Figure B.25 shows the result of s1_100km_0p001305_n24p5, shifted in time against s2_100km, and confirms that the datasets are now aligned in time - the maximum amount of matching records is obtained at approximately zero time shift.

The combined dataset s12_30km can now be obtained by removing records from s12_100km that have range greater than 30km. The increase in the number of total matching records,

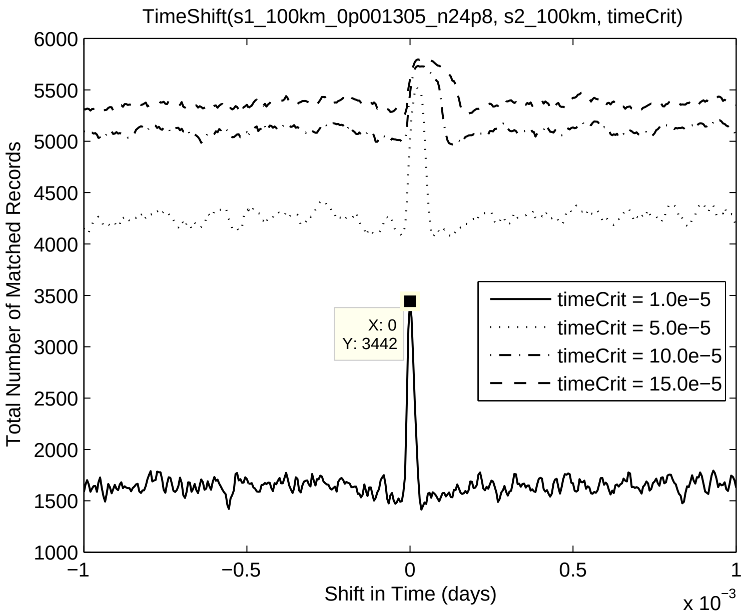

Figure B.25: Time shift characteristic for time and azimuth shifted Station 1 data, shifted against Station 2 data

after correcting for offset errors, is shown in Figure B.26. This data is independent of the SAWSLDN data and as such will still have an absolute error (in both time and azimuthal orientation), but relative errors between the stations are minimized. The percentage is relative to the total number of records in s2_30km (486), the smaller dataset of the two.

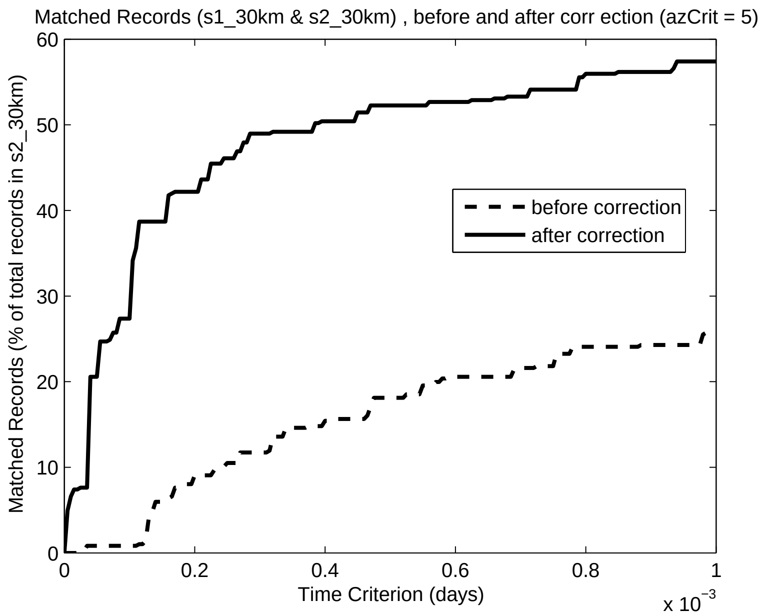

Figure B.26: Percentage matched records against time criterion, with and without time and azimuth correction

B.3.1 An Alternative Method

Using time and azimuth characteristics generated at lower time and azimuth resolution results in a quicker process time, but less accurate results for shift. The results of this quicker analysis are shown.

Figure B.27 shows the time offset between the stations as 0.0013 days (112.32 seconds), and additionally shows the cut off (for the regions where the records no longer overlap in time). This value is very close the more accurate value calculated previously (0.001305 days). Clear, distinct peaks are visible for the time shift characteristic, at varying values of time criterion. The total number of matched records increases with looser time criterion (as expected), but the peak occurs at the same value of time shift for all time criterion tested. Figure B.27 is plotted at a reduced time shift resolution of 0.0001 days (8.64 seconds)

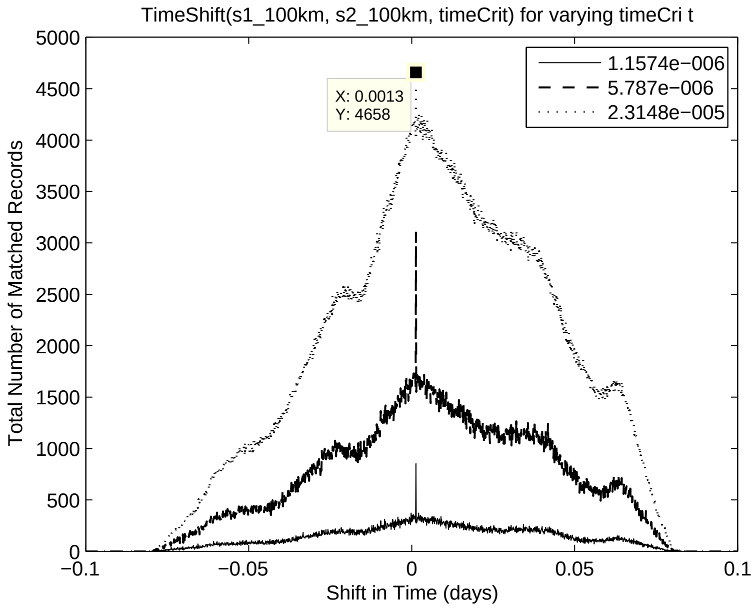

Figure B.27: Time shift characteristic for Station 1 data, shifted against Station 2 data

Figure B.28 shows the azimuth shift characteristic for the unshifted station 1 data against the unshifted station 2 data. The azimuth shift characteristic for the time shifted data is shown in Figure B.29, and shows more total matched records for all time criterion, as well as a more defined peak for determining the azimuth shift for maximum matched records (22.5 degrees). This is 2 degrees less than the value calculated using more precise plots with higher resolution.

A second plot of the time shift characteristic, for the time and azimuth shifted data, shows a clear peak at 0.00005. This is within the margin of error (±0.00005) for a peak centred on zero time shift.

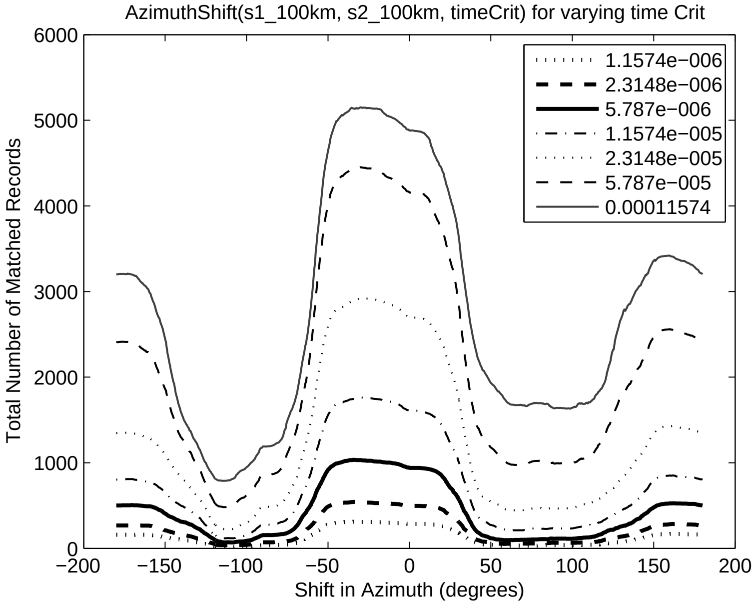

Figure B.28: Azimuth shift characteristic for Station 1 data, shifted against Station 2 data

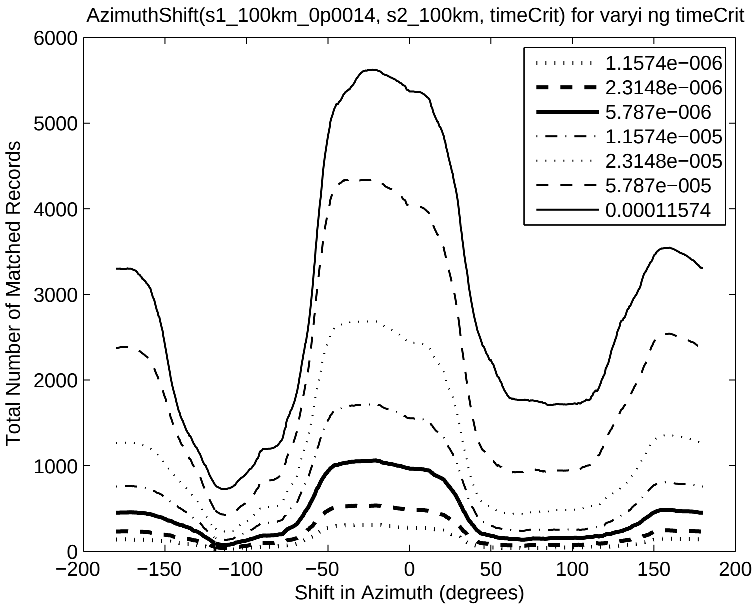

Figure B.29: Azimuth shift characteristic for time shifted Station 1 data, shifted against Station 2 data

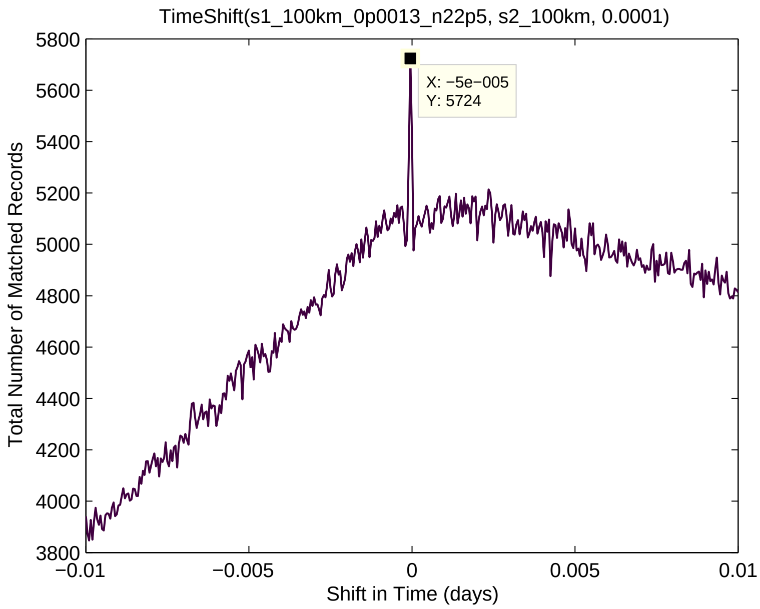

Figure B.30: Time shift characteristic for Station 1 data, shifted against Station 2 data

B.4 Comparing Triangulated Data to SAWSLDN Data

This can be done using `MatchExactRecords` [2], and comparing the triangulated data (which is referenced to Station 1's location) directly to the SAWSLDN data (method 1), and thus removing the absolute error in timing and azimuthal information. The alternate method (method 2) is to use the offsets determined during individual station calibration, which should mean that no further shifting is required. Both methods are presented for comparison.

B.4.1 Method 1

s12_100km is obtained from combining the dataset s1_100km_0p001305_n24.5 and the dataset s2_100km using the `MatchRecords` function [2]. To obtain a single dataset of lighting records, the time information from station 1, for each matched pair, is used, and the cartesian co-ordinates calculated from the triangulation are converted to polar co-ordinates (using `myCart2Pol` [2]. Figure B.31 and Figure B.32show the time shift characteristic of sWS_100km shifted against s12_100km.

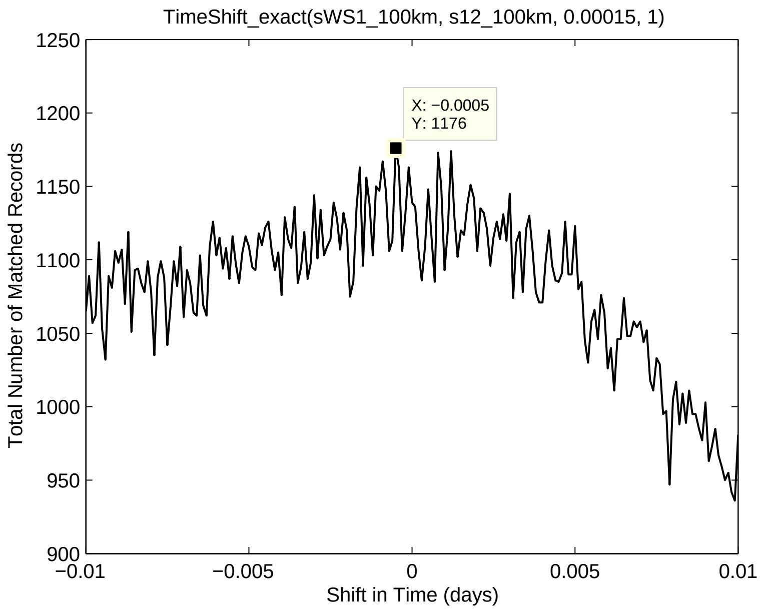

Figure B.31: Time shift characteristic for SAWSLDN data shifted against combined Station data

The relative time offset between the combined data is shown again by the peak. Since the Station 1 data was time shifted to match the Station 2 data, the time offset is expected to be similar to that between s2_100km and sWS2_100km (-0.000105 days). It is however approximately 0.00043 days (37.15 seconds). This discrepancy is likely due to the wide nature of the time shift peak for sWS2_100km and s2_100km, and the difficulty in determining an accurate value for time shift. The azimuth shift characteristic can now be plotted (Figure B.33 and Figure B.34), to find the azimuthal offset between sWS1_100km and s12_100km_0p00043.

At peak matching records, azimuth offset is -48.2 degrees, this is also an unexpected result, as the offset between sWS2_100km and s2_100km was determined to be 29.4 degrees. There is however a smaller peak near the expected value (29.4 degrees).

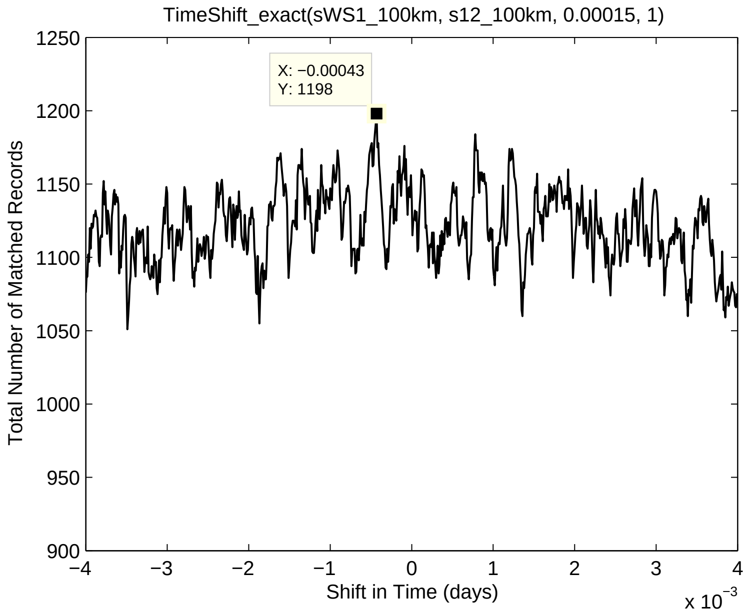

Figure B.32: Windowed time shift characteristic for SAWSLDN data shifted against combined Station data

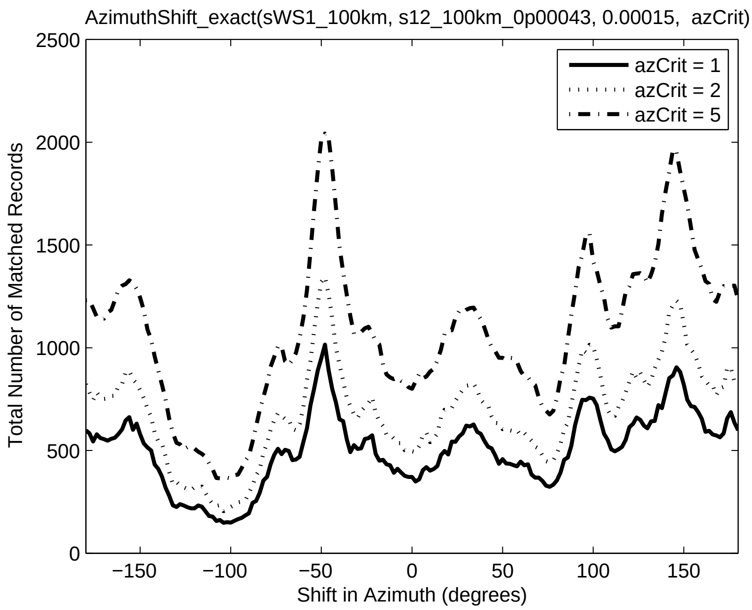

Figure B.33: Azimuth shift characteristic for SAWSLDN data shifted against combined Station data

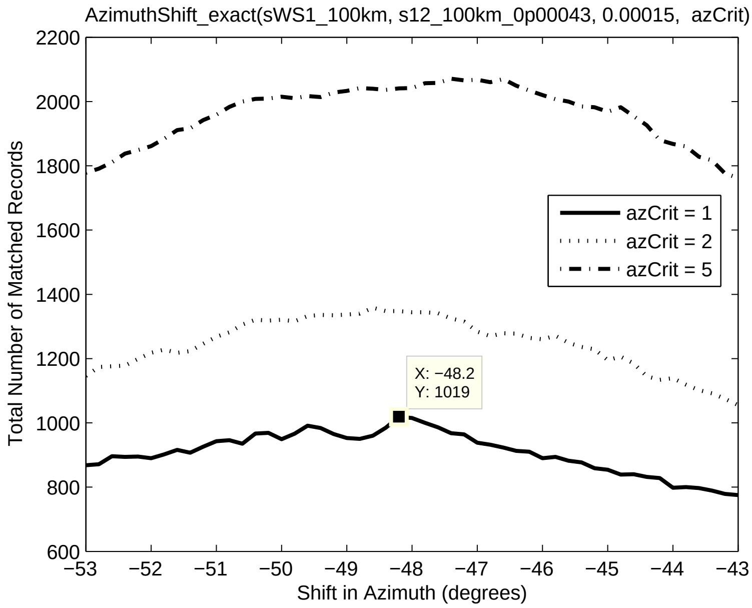

Figure B.34: Windowed azimuth shift characteristic for SAWSLDN data shifted against combined Station data

B.4.2 Method 2

The dataset s12cal_100km is generated using the MatchRecords function [2] with the time and azimuth shifted (relative to the SAWSLDN data) datasets s1_100km_0p00575_6p4 and s2_100km_n0p000105_29p4. Figure B.35 and Figure B.36 show the time shift characteristic. This is approximately centred on zero, as expected, but there is no clearly defined peak. Figure B.37 and Figure B.38 also do not show the expected azimuth shift characteristic. These plots suggest that the either calibration may not be accurate, or alternatively that there is an error introduced in the triangulation algorithm.

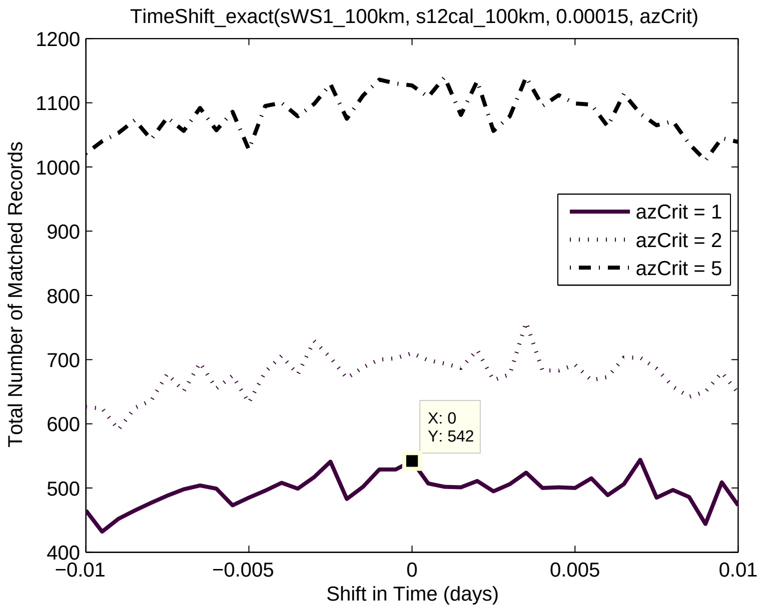

Figure B.35: Time shift characteristic for SAWSLDN data shifted against corrected and combined station data

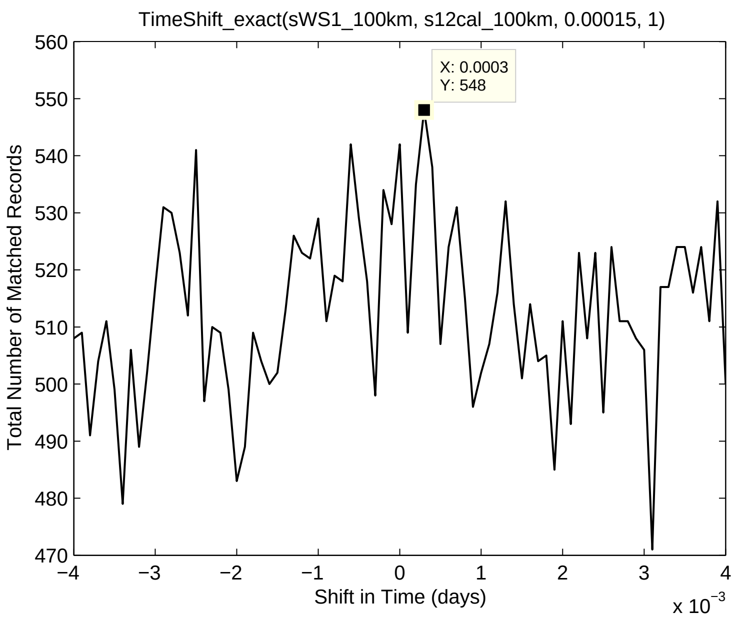

Figure B.36: Windowed time shift characteristic for SAWSLDN data shifted against corrected and combined station data

In general, the data from the SAWSLDN does not correlate as well with the individual station data as the stations correlate with each other. The individual stations' shifting

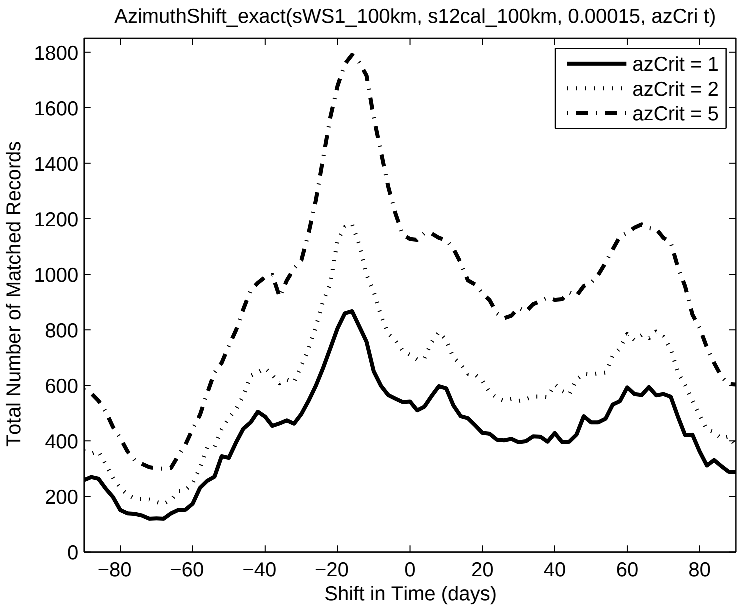

Figure B.37: Azimuth shift characteristic for SAWSLDN data shifted against corrected and combined Station data

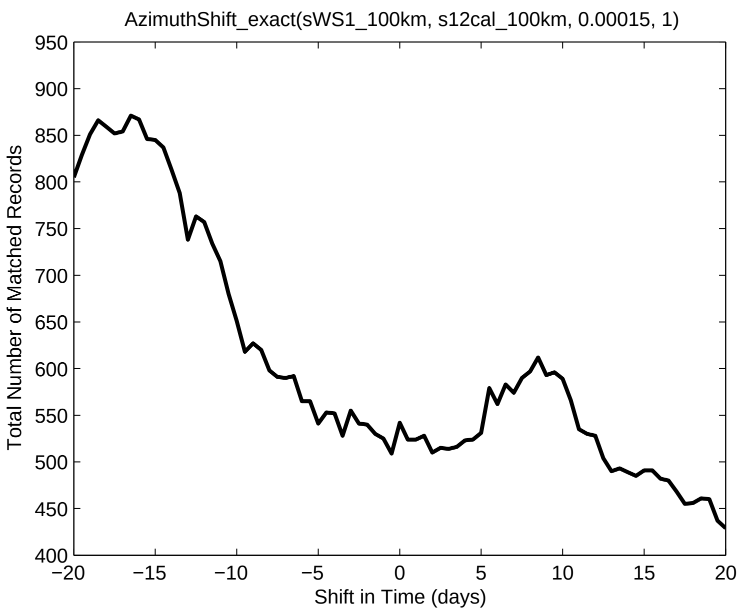

Figure B.38: Windowed azimuth shift characteristic for SAWSLDN data shifted against corrected and combined station data

characteristics have very clearly defined, narrow peaks - which is expected, as the individual stations are similar devices. The SAWSLDN data is also a much larger dataset, containing data often recorded from several stations and the individual stations may miss certain strike events, since they can only process one event at a time. The matching of SAWSLDN records to individual station records is therefore results in wider, less well defined peak in the shift characteristics. A more intelligent matching algorithm, which matches the closest or best strike available from the SAWSLDN data, may improve results for this scenario. This apparent discrepancy also affects the comparison of triangulated data to the SAWSLDN data, although the unexpected results in this case may also point to errors in the position calculation within the matching algorithm. There is much higher degree of confidence in the values determined for the relative offset errors between the individual stations, than the offset errors between each individual station and the SAWSLDN data. In general, determining the azimuth offset errors produces more predictable results than determining time offset errors.

B.5 Effect of Varying Time and Azimuth Criterion

The effect that the value of time criterion has on the total number of matched records, between the two individual stations, is shown in Figure B.39. Choosing a time criterion of 0.00015 days (12.96 seconds) results in approximately 70% of the records in s2_100km being matched to records in the shifted station 1 dataset. It can be seen that for decreasing time criterion (increasing precision) a decrease in overall matched records occurs. The total number of matched records also saturates above a time criterion of approximately 0.0002 days, indicating that no advantage is gained by choosing precision lower than this. The saturation characteristic is illustrated in Figure B.40 and Figure B.41.

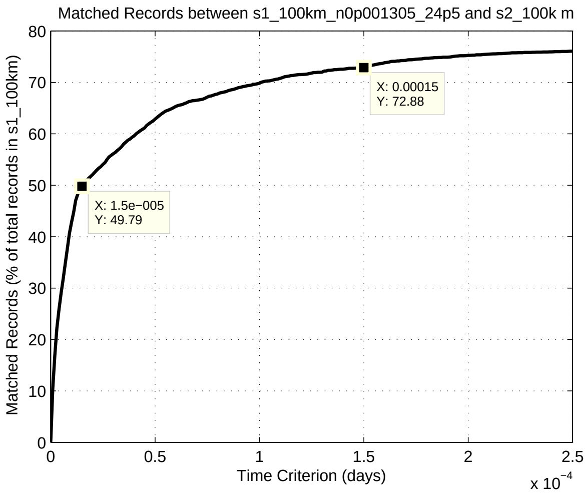

Figure B.39: Percentage matched records against time criterion

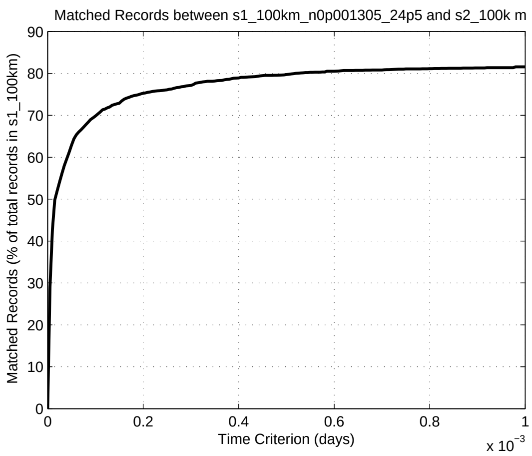

Figure B.40: Percentage matched records against time criterion

In the case of matching individual station data to SAWSLDN data, the effect of varying both time and azimuth criterion is shown in Figure B.42 and Figure B.43. A similar relationship is observed. Approximately 15% of records are matched at an azimuth criterion of 1 degree and time criterion of 0.00015 days.

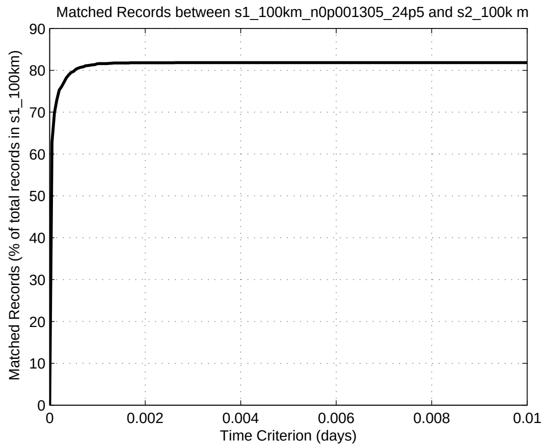

Figure B.41: Percentage matched records against time criterion

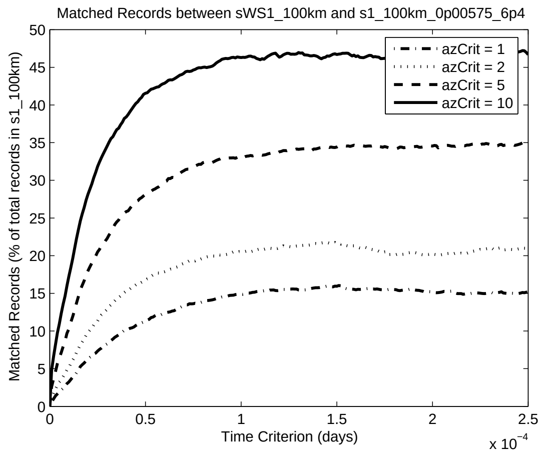

Figure B.42: Percentage matched records against time criterion, varying azimuth criterion

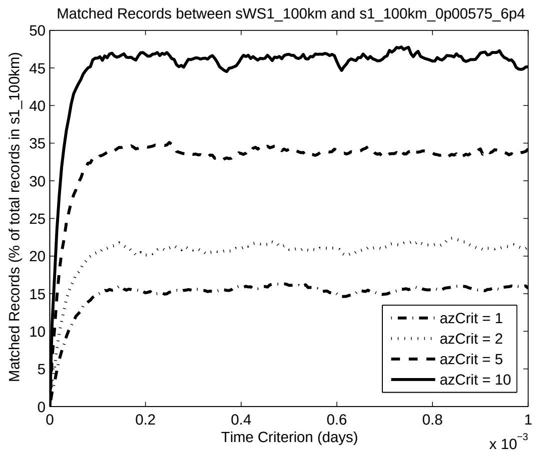

Figure B.43: Percentage matched records against time criterion, varying azimuth criterion

B.6 Conclusion

A method for correcting azimuthal orientation, and time offsets, for lightning data collected by two separate magnetic direction finders has been presented. This method can be performed computationally, and reduces the need for expensive time synchronisation hardware and complicated, time consuming, antenna alignment procedures. Although the latter methods would result in a more robust real time system, they are less suitable for temporary installations of lightning protection systems.

The relative offset errors are determined by shifting the time and azimuthal information for one station's data and calculating the maximum possible matching records (within certain time and azimuth criteria) for each incremental shift. The relative offset in orientation was found to be 24.5 degrees, and in time to be 0.001305 days (112.75 seconds). The individual stations, as well as the triangulated data calculated from matching records, can also be calibrated using data from the SAWSLDN as a reference. Individual station calibration indicated an offset of +6.4 degrees and +0.00575 days (496.8 seconds) for Station 1, with the offsets for Station 2 determined as +29.4 degrees and −0.000105 days (9.07 seconds).

By triangulating the individual station data, using the relative shifts, and then calibrating the resultant data to sWS1_100km, an offset of 0.0001 days (8.64 seconds) and −48.2 degrees is observed. The alternative method is to compute the triangulated dataset using the individual calibration offsets (w.r.t the SAWSLDN data). The expected result for this would be a normalised (peak centred on zero shift) time-shift and azimuth-shift characteristic. The actual results are shown in B.4.2, and indicate an azimuthal offset of approximately 18 degrees, and a time offset of approximately 0.0001 days. This is an unexpected result, and could point to possible errors in either the shifting algorithm or the triangulation algorithm itself. Conditioning the SAWSLDN to match better with the individual station data may also solve this problem to some extent.

Disadvantages of this method of calibration are that it can be time consuming to perform the analysis, which makes real-time triangulation more difficult to implement. Future work may be able to optimize these processes however, and it may be possible for the offset error analysis to be done once, at installation time, in order to calibrate the system. Also, if a reasonably accurate initial value is known, this can speed up the process by shifting through less effective values. One way of achieving an initial guess is to do a large scale initial plot across the entire range of the storm, to determine a general peak. This is especially relevant for the azimuthal offset errors. Time offset errors are more dynamic, and NTP based synchronisation may be improved by ensuring more stable network and power connections for the stations. Installing real time clocks with the stations would also improve time synchronisation stability. On a storm by storm basis however, determining the offset time using the method discussed is useful for retrospective analysis. Experimentation on a more orthogonal surface may also provide more usable data, as site errors caused by the presence of metal and machinery are largely unknown, and difficult to quantify and correct for.

References

[1] D. A. Rice, “Analysing Lightning Data from Two Spatially Separate Magnetic Direction Finders,” MSc(Eng) Dissertation, University of the Witwatersrand, Johannesburg, 2008, Paper: Analysing Lightning Data from Two Spatially Separate Magnetic Direction Finders.

[2] ——, “Analysing Lightning Data from Two Spatially Separate Magnetic Direction Finders,” MSc(Eng) Dissertation, University of the Witwatersrand, Johannesburg, 2008, Appendix A: MATLAB Code Modules.

Bibliography

[1] R. B. Anderson, "Measuring Techniques," in *Lightning, Volume 1: Physics of Lightning*, R. H. Golde, Ed. Academic Press New York, 1977.

[2] ——, "Does a fifth mechanism exist to explain lightning injuries?" *Engineering in Medicine and Biology Magazine, IEEE*, vol. 20, pp. 105–113, 2001.

[3] R. B. Anderson, I. R. Jandrell, and H. E. Nematswerani, "The upward streamer mechanism versus step potentials as a cause of injuries from close lightning discharges," *The Transactions of the SAIEE*, March 2002.

[4] *Lightning/2000: User's Manual*, Huntland, TN, USA, 2004, aninoquisi Software Design.

[5] C. E. Baum, J. P. O'Neill, E. L. Breen, D. L. Hall, and C. B. Moore, "Electromagnetic measurement of and location of lightning," in *Lightning Electromagnetics*, R. L. Gardner, Ed. Hemisphere Publishing Corporation, 1990.

[6] E. M. Bazelyan and Y. P. Raizer, *Lightning Physics and Lightning Protection.* Institute of Physics Publishing, 2000.

[7] K. Berger, "The Earth Flash," in *Lightning, Volume 1: Physics of Lightning*, R. H. Golde, Ed. Academic Press New York, 1977.

[8] *StormTracker Lightning Detector: Installation/Operators Guide*, Buffalo, NY, USA, 2004, boltek Corporation.

[9] R. L. Gardner, "Effect of the propagation path on lightning-induced transient fields," in *Lightning Electromagnetics*, R. L. Gardner, Ed. Hemisphere Publishing Corporation, 1990.

[10] R. H. Golde, "Lightning Currents and Related Parameters," in *Lightning, Volume 1: Physics of Lightning*, R. H. Golde, Ed. Academic Press New York, 1977.

[11] E. P. Krider, R. C. Noggle, and M. A. Uman, "A gated wideband magnetic direction finder for lightning return strokes," *J. Appl. Meteor.*, vol. 15, p. 301306, 1976.

[12] G. Labaune, P. Richard, and A. Bondiou, "Electromagnetic properties of lightning channels formation and propagation," in *Lightning Electromagnetics*, R. L. Gardner, Ed. Hemisphere Publishing Corporation, 1990.

[13] Penn State University. (2005, June) The lightning cluster mapper - 2. Last Accessed 1 December 2006. [Online]. Available: http://lcm.met.psu.edu/default.htm

[14] M. Le Boulch, J. Hamelin, and C. Weidman, "UHF-VHF radiation from lightning," in *Lightning Electromagnetics*, R. L. Gardner, Ed. Hemisphere Publishing Corporation, 1990.

[15] W. R. Lee, "Lightning Injuries and Death," in *Lightning, Volume 2: Lightning Protection*, R. H. Golde, Ed. Academic Press New York, 1977.

[16] H. Baatz, "Protection of Structures," in *Lightning, Volume 2: Lightning Protection*, R. H. Golde, Ed. Academic Press New York, 1977.

[17] C. Leteinurier and J. Hamelin, “Experimental study of the electromagnetic characteristics of lightning discharge in the 200 hz 20 mhz band,” in *Lightning Electromagnetics*, R. L. Gardner, Ed. Hemisphere Publishing Corporation, 1990.

[18] D. J. Malan, *Physics of Lightning*. English Universities Press, 1963.

[19] C. B. Moore and B. Vonnegut, “The Thundercloud,” in *Lightning, Volume 1: Physics of Lightning*, R. H. Golde, Ed. Academic Press New York, 1977.

[20] J. E. Nanewicz, E. F. Vance, and J. M. Hamm, “Observation of lightning in the frequency and time domains,” in *Lightning Electromagnetics*, R. L. Gardner, Ed. Hemisphere Publishing Corporation, 1990.

[21] T. Ogawa, “Lightning currents,” in *Atmospheric Electrodynamics*, H. Volland, Ed. CRC Press, 1995.

[22] R. E. Orville, “Lightning detection from ground and space,” in *Atmospheric Electrodynamics*, H. Volland, Ed. CRC Press, 1995.

[23] E. T. Pierce, “Atmospherics and Radio Noise,” in *Lightning, Volume 1: Physics of Lightning*, R. H. Golde, Ed. Academic Press New York, 1977.

[24] ——, “Lightning Location and Warning Systems,” in *Lightning, Volume 2: Lightning Protection*, R. H. Golde, Ed. Academic Press New York, 1977.

[25] S. A. Prentice, “Frequency of Lightning Discharges,” in *Lightning, Volume 1: Physics of Lightning*, R. H. Golde, Ed. Academic Press New York, 1977.

[26] V. A. Rakov, “Lightning protection of structures and personal safety,” in *International Lightning Detection Conference*, Tucson, Arizona, November 2000.

[27] V. A. Rakov and M. A. Uman, *Lightning: Physics and Effects*, 1st ed. General Publishing Company Ltd, 2003.

[28] M. E. Redelinghuys, W. C. van der Merwe, and I. R. Jandrell, “Optimisation of transmission lines for lightning coordination using LPATS,” in *Proceedings of 9th ISH*, Graz, August 1995.

[29] C. P. R. Saunders, “Thunderstorm electrification,” in *Atmospheric Electrodynamics*, H. Volland, Ed. CRC Press, 1995.

[30] B. F. J. Schonland, *The Flight of Thunderbolts*. Oxford University Press, 1950.

[31] ——, *Atmospheric Electricity*. Methuen, 1953.

[32] M. A. Uman, *The Lightning Discharge*, Dover ed. General Publishing Company Ltd., 2001.

[33] J. R. Wait, “Review of propagation effects for pulse transmission,” in *Lightning Electromagnetics*, R. L. Gardner, Ed. Hemisphere Publishing Corporation, 1990.

[34] E. W. Weisstein. (1999) Azimuthal Equidistant Projection. Last Accessed 1 December 2006. [Online]. Available: http://mathworld.wolfram.com/AzimuthalEquidistantProjection.html

[35] E. R. Williams, “The Electrification of Thunderstorms.” *Scientific American*, vol. 259, no. 5, pp. 88–99, 1988.

[36] ——, “Meteorological aspects of thunderstorms,” in *Atmospheric Electrodynamics*, H. Volland, Ed. CRC Press, 1995.