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A statistical Approach for Site Error Correction in Lightning Location Networks with DF/TOA Technique and Its Application Results

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Abstract

Lightning location network (LLN) with DF/TOA (direction-finder/time-of-arrival) combined technique has been widely used in the world. However, the accuracy of the lightning data from such LLNs has still been restricted by "site error", especially for those detected only by two DF/TOA sensors. In this paper we practice a statistical approach for evaluation and correction of "site error" for DF/TOA type LLN based on its lightning data. By comparing lightning locations recorded by at least 4 sensors between DF and TOA techniques, the spatial characteristics of "site error" for each sensor in the network can be obtained. The obtained "site error" then can be used to improve the accuracy of lightning locations especially those recorded by only 2 sensors. With this approach, the “site error” patterns for 23 sensors in Yunnan LLN are obtained. The features of these site error patterns are in good consistency with those in literature. Significant differences in lightning locations before and after “site error” corrections indicate that the proposed approach works effectively.

Keywords: lightning location network, direction finder, site error, time of arrival

1. Introduction

In general, there are two forms of lightning discharges: cloud-to-cloud (CC) discharge and cloud-to-ground (CG) discharge. A typical CG discharge may comprise several electric discharge pulses called return strokes. Magnitude of the return stroke peak current is from few to hundreds of kilo-amperes (Rakov and Uman, 2003). Due to the intensive electromagnetic radiation and large current, lightning strokes have a distinct possibility to destruct human life and possessions (Gomes and Kadir, 2011).

Knowing the locations and occurring times of lightning strokes in a thunderstorm, people can prepare well to protect themselves and devices. To collect lightning location and time information, people have developed different lightning location techniques. Until the early 1970s, the technology for locating lightning on ground was limited to the magnetic direction finder (DF) with the use of very low frequency sferics (Krider et al., 1976). Beginning about 1980s, advances in electronics and computers were coupled with significant insights to improve the existing methods and to provide new methods. By 1990s, in addition to DF technology, lightning can also be located from low and high frequency sferics with time-of-arrival (TOA) (Casper and Bent, 1992; Thomas et al., 2004) and interferometric (Shao et al., 1995, Dong et al., 2003) techniques. Nowadays, many lightning location networks (LLN) in the world are based on DF/TOA combined technique, i.e. DF/TOA network (Cummins and Murphy, 2009; Villarini et al., 2013; Xie et al., 2013; Kuk et al., 2014; Makela et al., 2016). There are also many modern LLN that are in highly successful operation without use of DF technique for stroke locating (e.g., Betz et al., 2009, Sun et al., 2013; Wang et al., 2016).

An important issue of a LLN is the accuracy of lightning stroke location. This is particularly important for those LLNs relying on DF technique, as the DF technique is found to have big inherent azimuthal errors - “site error” (Mach et al., 1986). As long as a LLN relies on DF for stroke locating, the accuracy of stroke location is restricted by the “site error”. In following, we first discuss the necessity of “site error” correction and then propose a practical approach for “site error” correction, for DF/TOA type LLN.

2. Site Error Correction for DF/TOA Network

2.1 Necessity of site error correction

The principle of DF technique is based on the detection of the ratio of magnetic signals on two orthogonal loop antennae thereby to determine the azimuth of lightning source, while the TOA technique is based on the fact that a lightning signal arrives at different stations at different time. However, the DF technique is found to have inherent azimuthal errors of order of 10 more degrees, namely “site error”, which is mainly caused by unwanted magnetic field components due to reflecting effects of non-horizontal topography and conductive objects surrounding the DF station (Mach et al., 1986).

There are two basic approaches for estimation and correction of the "site error", namely "nonparametric approach” and "parametric approach". Nonparametric approach refers to those based on statistical analysis or comparison of lightning data between a DF and other instruments such as video camera or radar (e.g. Mach et al., 1986; Biagi et al., 2007; Wang et al., 2016). Parametric approach refers to those based on optimization of lightning locations by assuming the "site error" of a DF takes on a form of limited order trigonometric series (e.g. Orville, 1987;

Chen et al., 1991). Recently, an electromagnetic dipole model was proposed by Chen et al. (2013a), which can well interpret the azimuthal properties of "site error" reported.

Nowadays, DF/TOA network has been extensively used all over the world. In a DF/TOA network, a lightning stroke detected by 4 or more sensors is usually located with TOA technique, while that detected by 2 or 3 sensors is located with DF/TOA combined technique. The National Lightning Detection Network (NLDN) in United States is a typical DF/TOA network that has very good performance, which experienced 9 times of upgrades between 1989 and 2005 (Biagi et al., 2007). Its flash detection efficiency is as high as 90-95% but its stroke detection efficiency is only 60-80% even since its 2002-2003 upgrade (Cummins and Murphy, 2009). According to a study of a DF/TOA network in China, the highest detection efficiency of the lightning stroke of a sensor is no more than 80% (Chen et al., 2013b). This means that only about 40% of lightning strokes can be detected by 4 more sensors, which can be located by using the TOA technique with high accuracy. More than 60% of lightning strokes can only be detected by 2 or 3 sensors, which should be located by using the DF/TOA combined technique with the “site error” involved. Therefore, “site error” corrections are essential to a DF/TOA network, particularly for those lightning strokes detected by only 2 or 3 sensors.

2.2 A statistical approach for Site Error Correction

The "site error" of a DF sensor is mainly generated by the surrounding structures around the sensor, such as high mountains and the folds of buildings. The precision of time synchronization and the degree of topographical roughness may exert an influence on the accuracy of a TOA sensor. The location accuracy of a VLF/LF lightning detection network with

TOA technique can be less than 200 m (Betz et al. 2009). Honma et al. (2013) managed to correct the error of terrain elevation on TOA sensors and accomplished a location accuracy of 270 m. Therefore, for a network with TOA/DF technique, it is capable of correcting DF "site errors" with TOA location solutions, as TOA solutions have higher location accuracy and are not influenced by “site errors” (Nag et al., 2015). For example, the error in azimuth domain would be less than 0.6 degree if the distance between a lightning source and a sensor is 30 km with a TOA distance error of 300 m.

In a LLN with DF/TOA technique, each sensor records not only the arrival time of a lightning signal but also the source direction of a lightning. The azimuth to a sensor of a lightning stroke located by 4 or more sensors with TOA method would be different with the azimuth detected by the sensor with DF technique. The difference in azimuth between the TOA method and DF method for a lightning stroke for a DF/TOA sensor can be viewed as the "site error" of the corresponding DF/TOA sensor. This idea does not change the definition of "site error", which is a statistical analysis and evaluation based on redundant lightning data. The pattern of "site error" versus azimuth for each sensor in a LLN can be obtained when enough lightning strokes are detected by the LLN. Then the obtained pattern of "site error" can be used to correct azimuth error for each sensor. More details of this “site error” correction method are given in following section where it is applied to the Yunnan LLN, for easy and better understanding,

3. Application of the Approach and Results

3.1 Yunnan LLN and its lightning data

The approach proposed in Section 2.2 has been applied for a regional LLN in Yunnan, China, which consists of 25 sensors with 23 installed within Yunnan Province and 2 within Guangxi Province in southwest China (Fig. 1). All the 25 sensors are on the basis of DF/TOA combined technique and can locate strokes in CG flashes (Chen et al., 2013b). Each sensor reports the information of the lightning signal arrival time, E field strength, H field strength, source azimuth and the lightning EM pulse peak time, etc. Normally, 2 sensors are needed to locate a lightning stroke at least. For a stroke detected by more than 4 sensors, the 4 sensors leading to a minimum location error-ellipse with TOA algorithm are relied on. The two sensors installed in Guangxi Province have recorded very few strokes owing to bad power supplies so that these data could not be fully processed. Other specifications of the sensor in this network: i) error in timing is less than 0.1μs, ii) error in KA is less than 15%, and iii) the triggering threshold is adjustable from 10 mV to 100 mV depending on the noise level at the site. The 100 mv is equivalent to a return stroke peak current of 5 kA at 100 km. For a stroke detected by 4 or more sensors, its location solution is mainly relying on the TOA algorithm. For a stroke detected by less than 4 sensors, its location solution is relying on the DF + TOA algorithm. The TOA location accuracy is claimed as 400 m (Xie et al., 2013)

INSERT Fig. 1

In 2008, more than 1,000,000 lightning return strokes have been recorded by Yunnan LLN. Among them only about 400,000 strokes were located with the 4-sensor TOA algorithm, more than 330,000 strokes were located with the 2-sensor DF/TOA technique and the remaining were located with the 3-sensor DF/TOA technique. To understand why only 2 and no more sensors responded to so many strokes, statistics of peak current distribution have been done for strokes detected by 4 more sensors, for those by 3 sensors and for those by only 2 sensors, respectively (Fig. 2). The statistics show that the medium value of the current is 28.6 kA, 31.4 kA and 55.7 kA, for strokes detected by 2 sensors, those by 3 sensors and those by 4 more sensors, respectively.

INSERT Fig. 2

3.2 Generation of the site error from lightning data

The patterns of "site error" of each sensor are found by comparing the locations of lightning strokes detected by 4 sensors between DF and TOA algorithm. For example, at 15:11:47 on 07 June, 2008, a lightning stroke was detected by No.08, No. 01, No. 00 and No. 03 sensors. The time of their arrival and DF azimuths have been presented in Table 1. The stroke location was concluded with TOA algorithm, (102.1504E, 24.2017N) to be exact. In turn, this TOA location indicated an azimuth of 62.11 degree to No. 03 sensor, as shown in Table 1. The deviation between the DF azimuth and TOA azimuth, -4.3 degree, is then referred as the "site error" for No. 03 sensor at source azimuth 62.11 degree. Similarly, the “site error” for No.08 sensor at source azimuth 250.18 degree is -1.16 degree, that for No.01 sensor at source azimuth 135.96 degree is -6.5 degree and that for No.00 sensor at source azimuth 209.56 degree is -3.26 degree. Such an approach can be repeated for a sensor at all directions when a large quantity of lightning strokes happened around the sensor at various azimuths and distances.

INSERT Table 1.

For a lightning stroke reported by more than 4 sensors, we need to know which 4 sensors are involved in locating the stroke. According to the arrival time of the stroke signal at each sensor and the distance of the stroke location to each sensor, the occurring time of the stroke can be estimated. The 4 sensors, which led to the minimum deviation in the estimated occurring time are regarded as those being involved in locating the stroke, hence are used for "site error" estimation. Besides, for high accuracy, those strokes that have a location error-ellipse larger than 3 km in diameter (corresponding to a time deviation of ± 5μs) are excluded.

Shown in Fig. 3 are the plots of “site error" versus source azimuth for No.9 sensor at various source-sensor distance ranges. The horizontal axis shows the source azimuth reported by 4-sensor TOA algorithm, and the vertical axis represents the corresponding "site error". As can be seen from Fig. 3a, when the source-sensor distance is in ranges between 30 to 100 km, the "site error" could be 15 degrees at most, with the average being about 3.3 degree. The plots also show that the "site error" against source azimuth is double periodical, which is quite congruous with the model by Chen et al. (2013b). The plots of "site error" in ranges of 30-100 km (Fig.3a) are similar to that of 100-150 km (Fig. 3b) and that of 30-200km (Fig. 3c), indicating that "site error" does not change with the source-sensor distance. However, Fig. 3c is with more scattered points than Fig. 3a and 3b, indicating that using of lightning data at large distances may introduce large random errors in determining the “site error” pattern.

Although "site error" is insensitive to distance, the random error in the "site error" may increase with distance, due to that the lightning signal strength decreases with distance. On the contrary, at small distance (less than 30 km), four-station TOA location error could not be ignored and it will make the "site error" plots blurred. In order to minimize the influence caused by random error and large angle error at a small distance, the "site error" plots at a moderate distance (30 – 100 km) are preferred.

INSERT Fig. 3

Besides, provided that there is no variation in the environment around a sensor, the "site error" of the sensor should not change. This provides an inspiration for improving the accuracy of lightning location by correcting the "site error". What we need to do is to collect the "site error" plots for each sensor in a LLN and then put them into site error correction for further observations. From this point of view, the site error plots for all sensors in Yunnan LLN are assembled and discussed as in following section.

3.3 Site error patterns for each sensor in Yunnan LLN

With the lightning data stated in Section 3.1 and the method stated in Section 3.2, the plots of “site error’ versus source azimuth for all the 23 sensors are obtained, as shown in Fig. 4. The red lines in the figure are curve fittings of the “site error” plots and their fitting parameters are listed in Table 2. The R-square value in the table reflects the goodness of the curve fitting. It is noted that there are only few location results for sensor 16, which makes the fitted “site error” curve for this sensor with low reliability. A possible reason is that the sensor 16 is at the upper left corner of the network and there are high mountains between the sensor 16 and other sensors. As a result, there are very few lightning strokes detected by 4 more sensors including the sensor 16 itself.

INSERT Fig. 4 and INSERT Table 2

A vivid "site error" plot is just the first step. It should be converted into a quantitative curve of "site error" versus detected azimuth for site error correction use. A specific procedure for getting such a site error correction curve is proposed as follow:

Step 1: Plot the "site error" pattern at a moderate distance range for each sensor in a LLN, as shown in Fig. 4. Where the horizontal axis is the azimuth decided by the four-station TOA algorithm, i.e. the true source azimuth, while the vertical axis represents the "site error" at corresponding source azimuth. Positive value means the clockwise displacement of single-DF sensor-detected azimuth to the four-TOA sensor-determined azimuth.

Step 2: Tick out some data points with obvious faults manually. In present study, a data point that is isolated from others with a deviation larger than 30 degrees (site error upper limit reported) is considered as a data point with obvious fault.

Step 3: Conduct curve fitting of the plot of “site error” versus true source azimuth for each sensor. The fitting equation, $A1*\cos(\theta) + A2*\sin(\theta) + A3*\cos(2\theta) + A4*\sin(2\theta) + A5$, is adopted from the work of Chen et al. (2013a), which is in a form of sum of several odd-cycle and dual-cycle trigonometric functions. The curve fitting results for each sensor in Yunnan LLN are shown in red in each plots in Fig. 4 and the curve parameters are listed in Table. 2. The R-square value in the table represents the goodness of the curve fitting results.

Step 4: The "site error" versus source azimuth curve (obtained in Step 3) needs to be converted into “site error” versus sensor-detected azimuth curve by using the sum of "site error" and corresponding source azimuth as the horizontal axis, as shown in Fig. 5a (for No.13 sensor) by the solid-line, which we call it the site error correction curve. The “site error” for a sensor-detected azimuth can then be found from its corresponding site error correction curve as shown by Fig. 5a. The corrected source azimuth can be obtained by subtracting the "site error" from the original detected azimuth as shown in Fig. 5b.

INSERT Fig. 5

With a procedure similar to that shown in Fig. 5 for No. 13 sensor, the curves of "site error" versus detected azimuth for all the other sensors in Yunnan LLN have been generated. Besides, to examine the stability of "site error" pattern in time, curve fittings are also done for sensor 13 for 2 different time windows: January - June and July – December (Table 2). The results show that the site error pattern for this sensor is stable in time at least for the year of 2008.

4. Validation of "Site Error" Correction

Although the "site error" correction has little help in improving the accuracy of lightning locations with three- or four-station DF/TOA locating algorithm, it may help a lot in improving the accuracy of lightning locations with two-station DF/TOA locating algorithm. A specific process of "site error" correction with two-station locating algorithm is represented as below:

Step 1: Collect the azimuths and arrival times of a lightning stroke at the two sensors that detected it.

Step 2: The distinction of the two arrival times at the two sensors will fix a hyperbola on ground.

Step 3: The two detected azimuths with their corresponding "site error" corrections will reach the more accurate azimuths than the detected ones. Each corrected azimuth draws a radial line that intersects with the hyperbola in Step 2 at a point on ground. The mid-point on the hyperbola between the two cross-points is deemed as the stroke location.

In order to demonstrate the significance of "site error" corrections, a case study has been done. Fig. 6a shows a comparison between 2-sensor located strokes with and without "site error" corrections, for 6000 more lightning strokes detected in Yunnan LLN during a thunderstorm on 24 June, 2008. In the figure, black and red points denote the 2-sensor located strokes without and with "site error" corrections, respectively. It can be seen that the stroke locations with "site error" corrections (red) are significantly different from those without "site error" corrections (black). The statistics of distances between stroke locations before and after “site error” corrections for these strokes are shown in Fig. 6b, and the median value is about 6 km.

INSERT Fig. 6a and Fig. 6b

Furthermore, we have done “site error” corrections for all the 330,000 more two-station-detected lightning strokes in Yunnan LLN in 2008. The statistics of distances between lightning locations before and after “site error” corrections for these strokes are shown in Fig. 7, which has a median value of about 7.73 km and a mean value of 14.38 km. This once again shows that for a two-station-detected lightning stroke, the “site error” has significant impact on its location accuracy.

INSERT Fig. 7

5. Summary

In this paper, a method of "site error" estimation and correction for DF/TOA type LLN is proposed. In the method, the “site error" of a DF/TOA sensor as a function of the source azimuth can be obtained by a comparison between the source direction found with the DF technique and that found with the TOA technique. The method works better in the center of a LLN and has obvious limitation when applying it to the peripheral stations in the LLN. The method is applied to the lightning data of about one million lightning strokes recorded by the Yunnan LLN in 2008. The obtained patterns of "site error" versus source azimuth for all the 23 sensors in this LLN are well consistent with previous observations and theories. Since different DF/TOA sensors are installed at different sites, they have quite different “site error” patterns. The “site error” patterns are in the form of either odd-cycle or dual-cycle, or a superposition of both, and are timely stable and insensitive to the distance of source-sensor. The results support the theory that "site error" of a sensor is caused by electric-dipole-wise or magnetic-dipole-wise objects near the sensor. It is this feature that make “site error" corrections practicable.

This study has its significance since large number of LLN location results are given by two-sensor locating algorithm. Comparisons of the two-sensor data with and without “site error” corrections show that the proposed method for “site error” correction has a significant impact on the accuracy of the two-sensor locating algorithm. It should be mentioned that the site error is highly relevant to the environment around the sensor. Thus, when the environment changes, the site error correction should be redone.

Acknowledgments

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Captions

Fig. 1: A regional LLN with 25 DF/TOA type sensors in Yunnan, China.

Fig. 2: The distribution of peak currents for (a) 4-sensor detected stroke, (b) 3-sensor detected strokes and (c) 2-sensor detected strokes, respectively, in 2008 in Yunnan LLN, China.

Fig. 3: Patterns of "site error" versus true source azimuth for sensor No.9 in Yunnan LLN for various distance ranges: (a) for 30-100 km, (b) for 100-150 km and (c) for 30-200 km.

Fig. 4: Patterns of "site error" versus true source azimuth for the 23 sensors in Yunnan LLN for the source-sensor distance range of 30-100 km and their curve fittings (red lines).

Fig. 5: (a) The curve of "site error" versus true source azimuth (dot-line) and that versus DF-detected azimuth (solid-line) for sensor No.13 in Yunnan LLN.

(b) True source azimuth versus DF measured azimuth for sensor No. 13 in Yunnan LLN.

Fig. 6: (a) Comparison of lightning locations before (black) and after (red) "site error" correction, for the 6000 more two-sensor detected lightning strokes on 24 June in 2008 in Yunnan LLN. (b) Statistics of distance difference in lightning location before and after "site error" correction, for the strokes in Fig.6a. The median value is 6 km.

Fig. 7: Statistics of distance difference in lightning locations before and after "site error" correction, for the 330,000 more two-sensor-detected lightning strokes in 2008 in Yunnan LLN. The median value is 7.73 km and the mean value is 14.38 km.

Table 1: The source azimuth retrieved from the location by four-station-TOA algorithm and that detected by each DF/TOA sensor for a lightning stroke detected by 4 sensors in Yunnan LLN at 15:11:47 on 07 June 2008. The difference between DF azimuth and TOA azimuth for a stroke is considered as the "site error" at that azimuth for that DF.

Table 2: Curve fitting results for "site error" versus source azimuth for the 23 sensors in Yunnan LLN in 2008 and that for sensor 13 for different time windows.

Figures

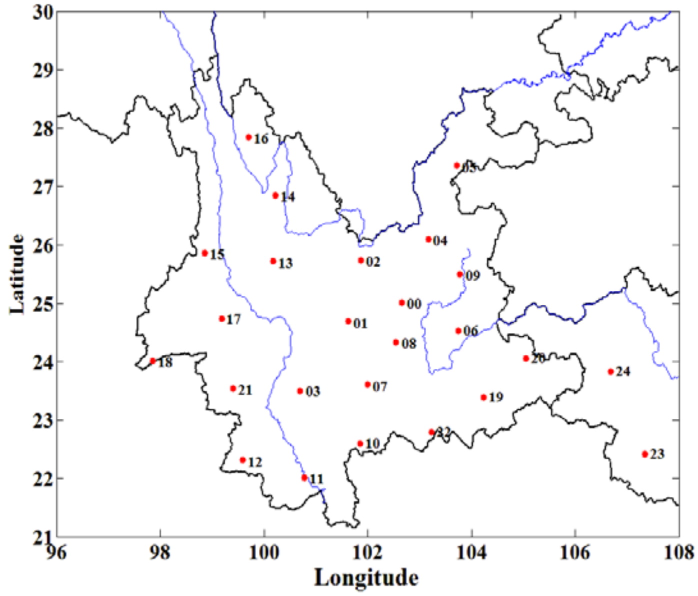
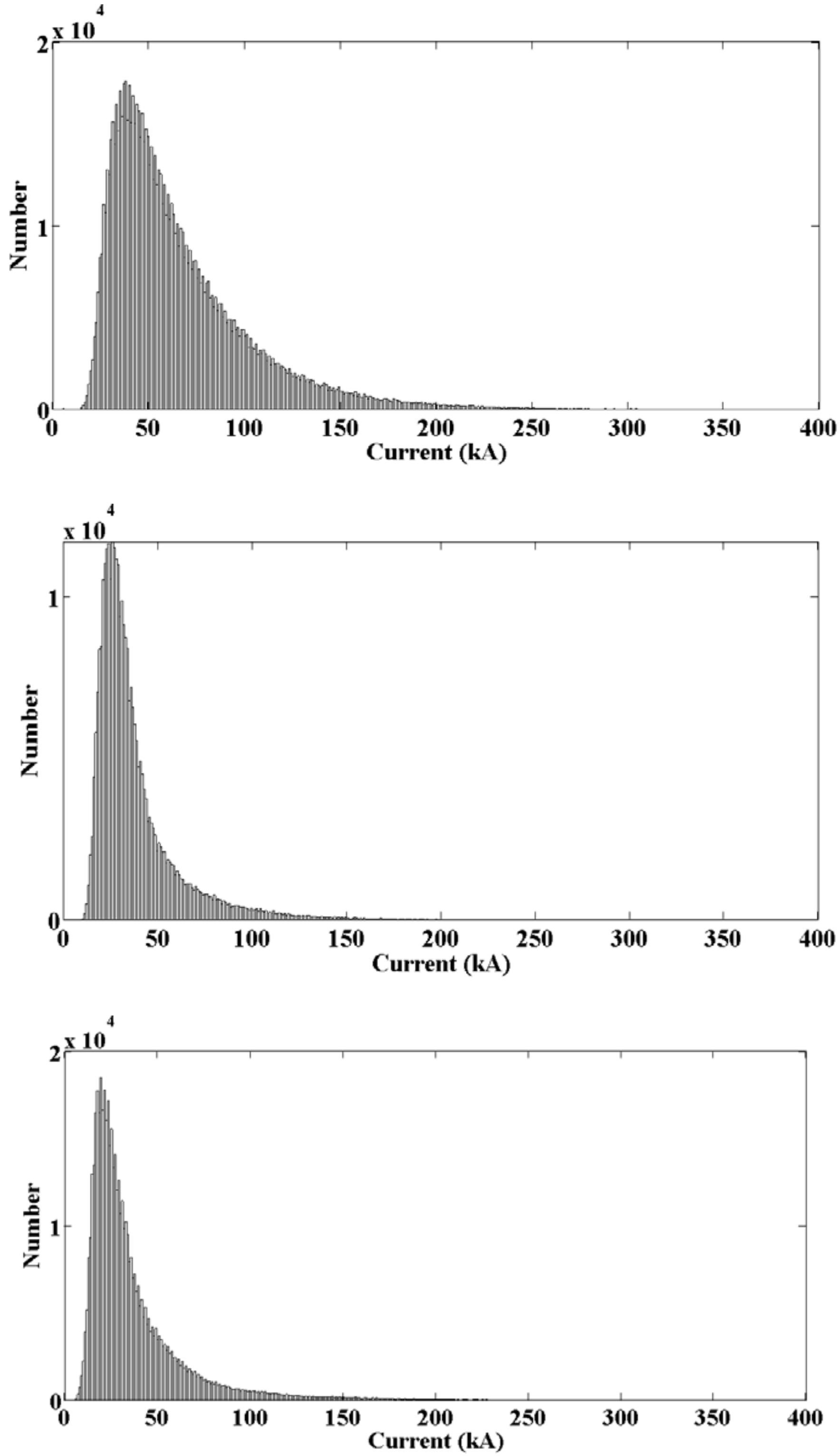


Fig. 1: A regional LLN with 25 DF/TOA type sensors in Yunnan, China.



(a)

(b)

(c)

Fig. 2: The distrubution of peak currents for (a) 4-sensor detected stroke, (b) 3-sensor detected strokes and (c) 2-sensor detected strokes, respectively, in 2008 in Yuanan LLN, China.

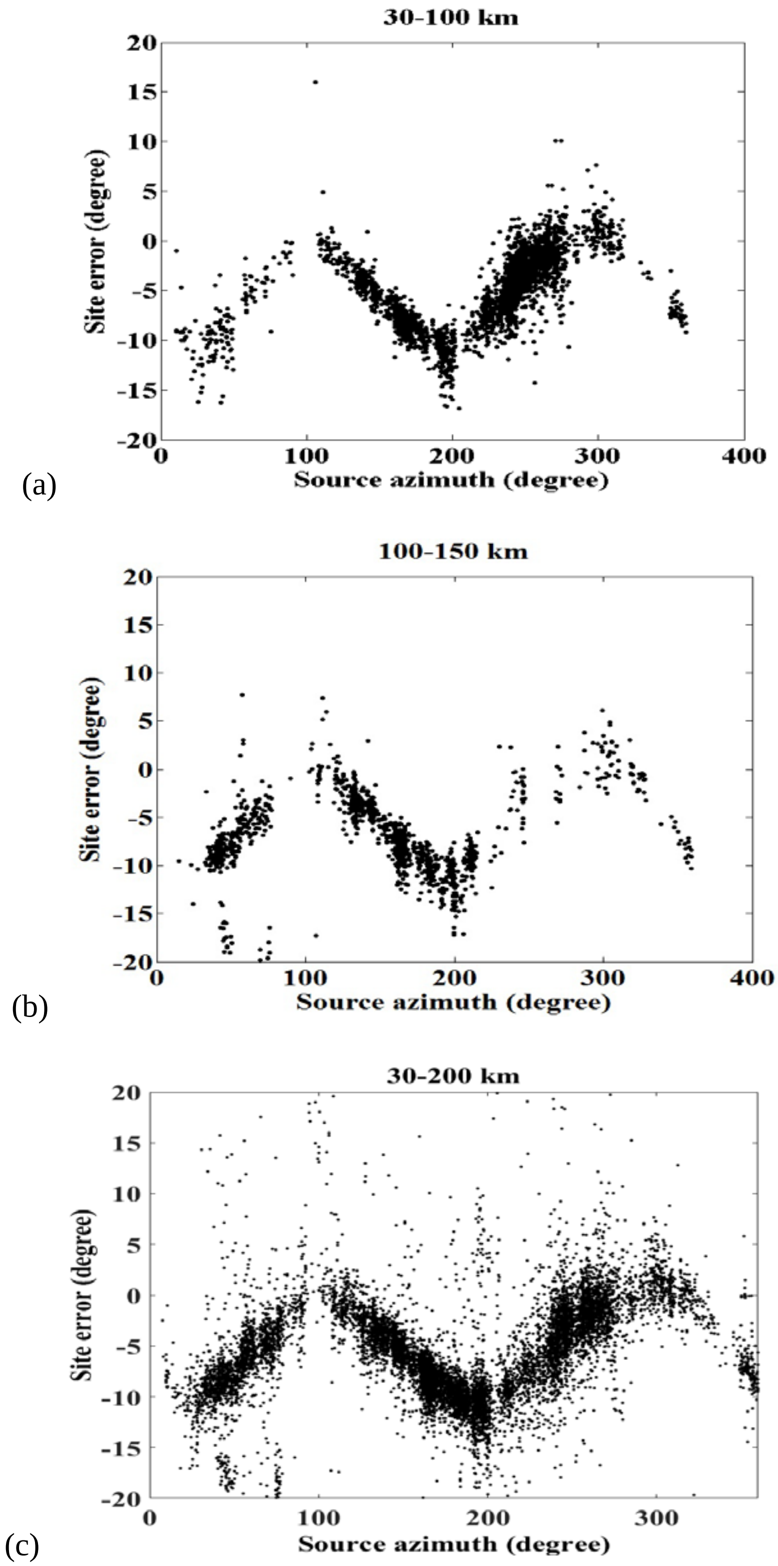


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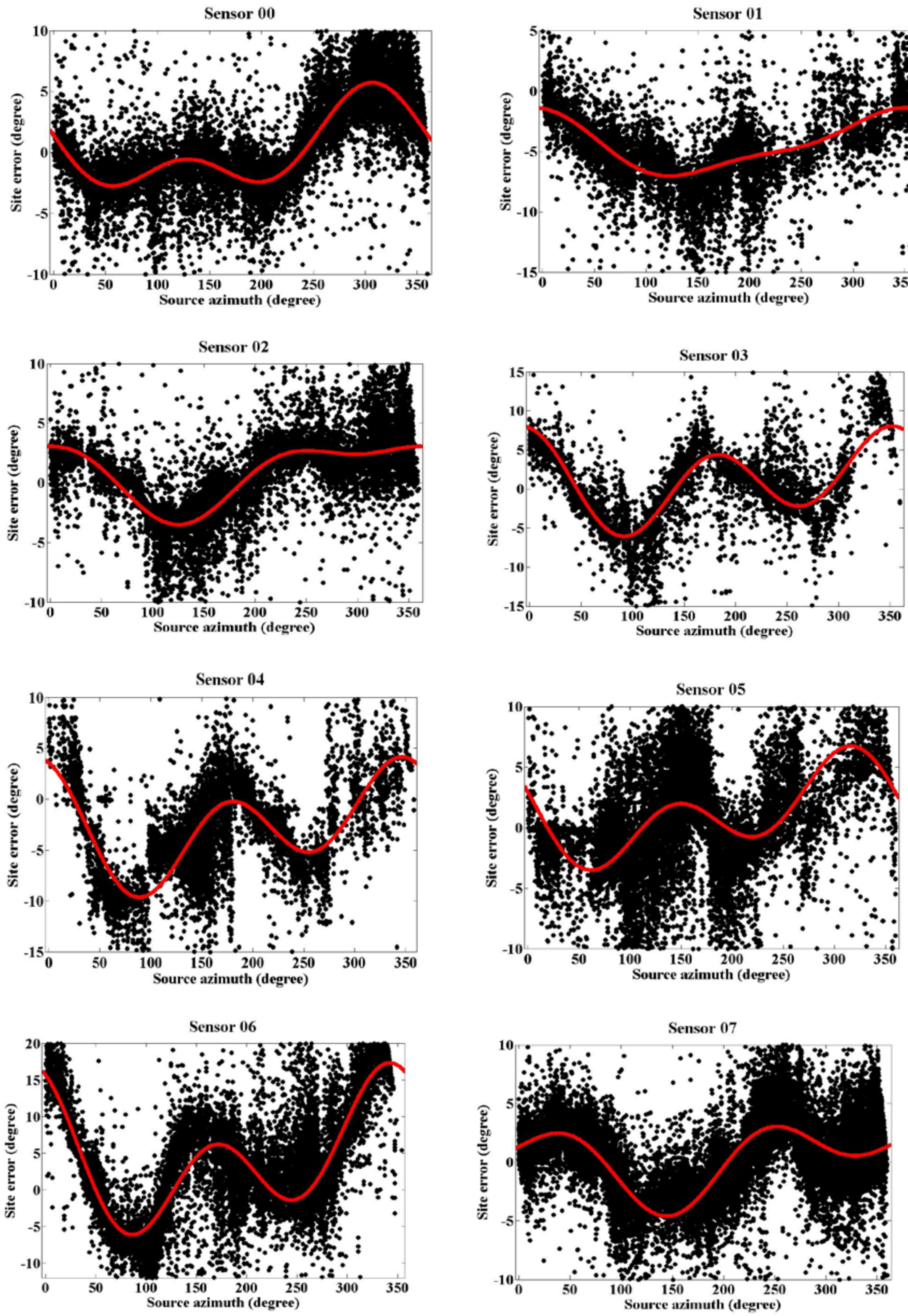
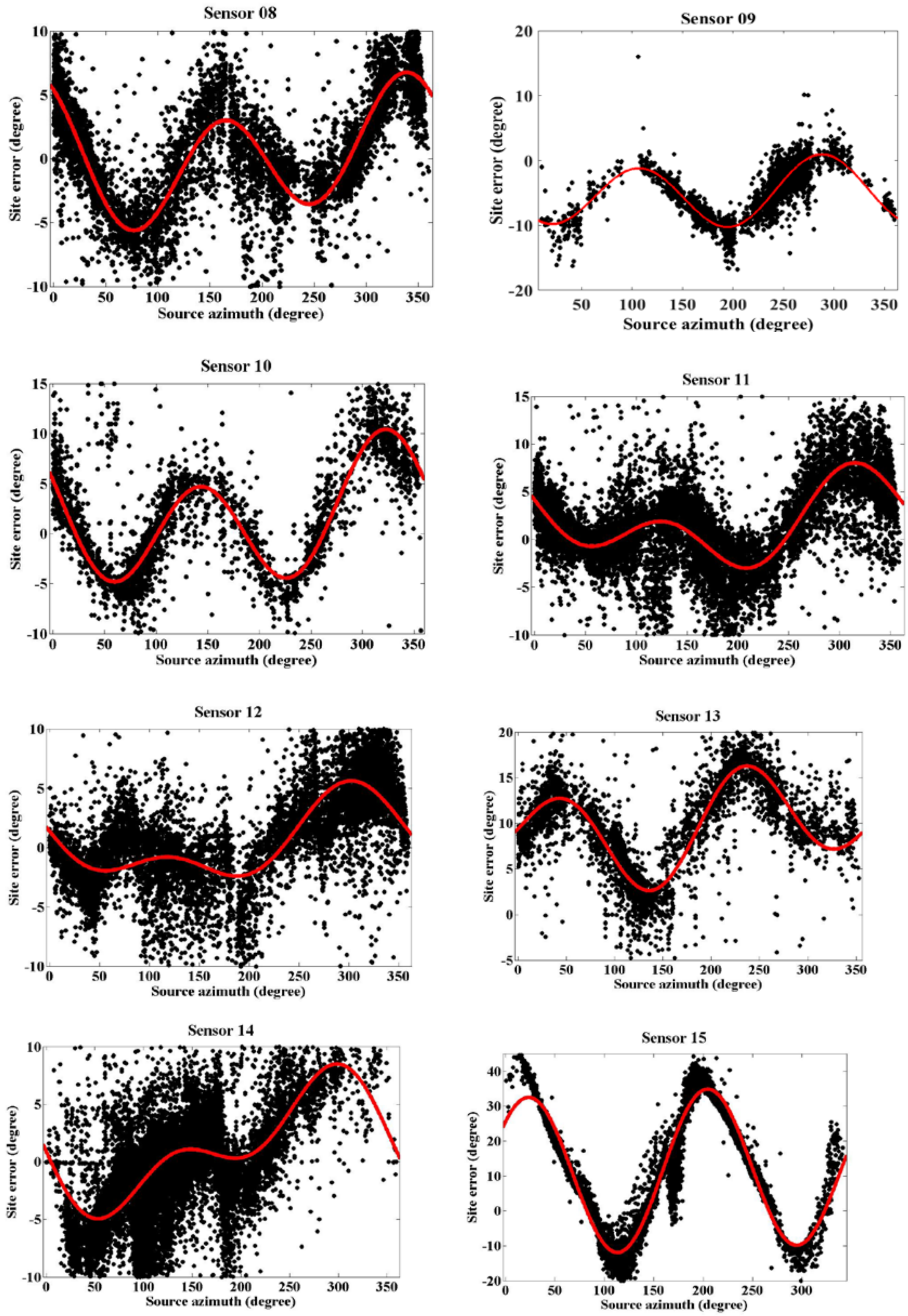
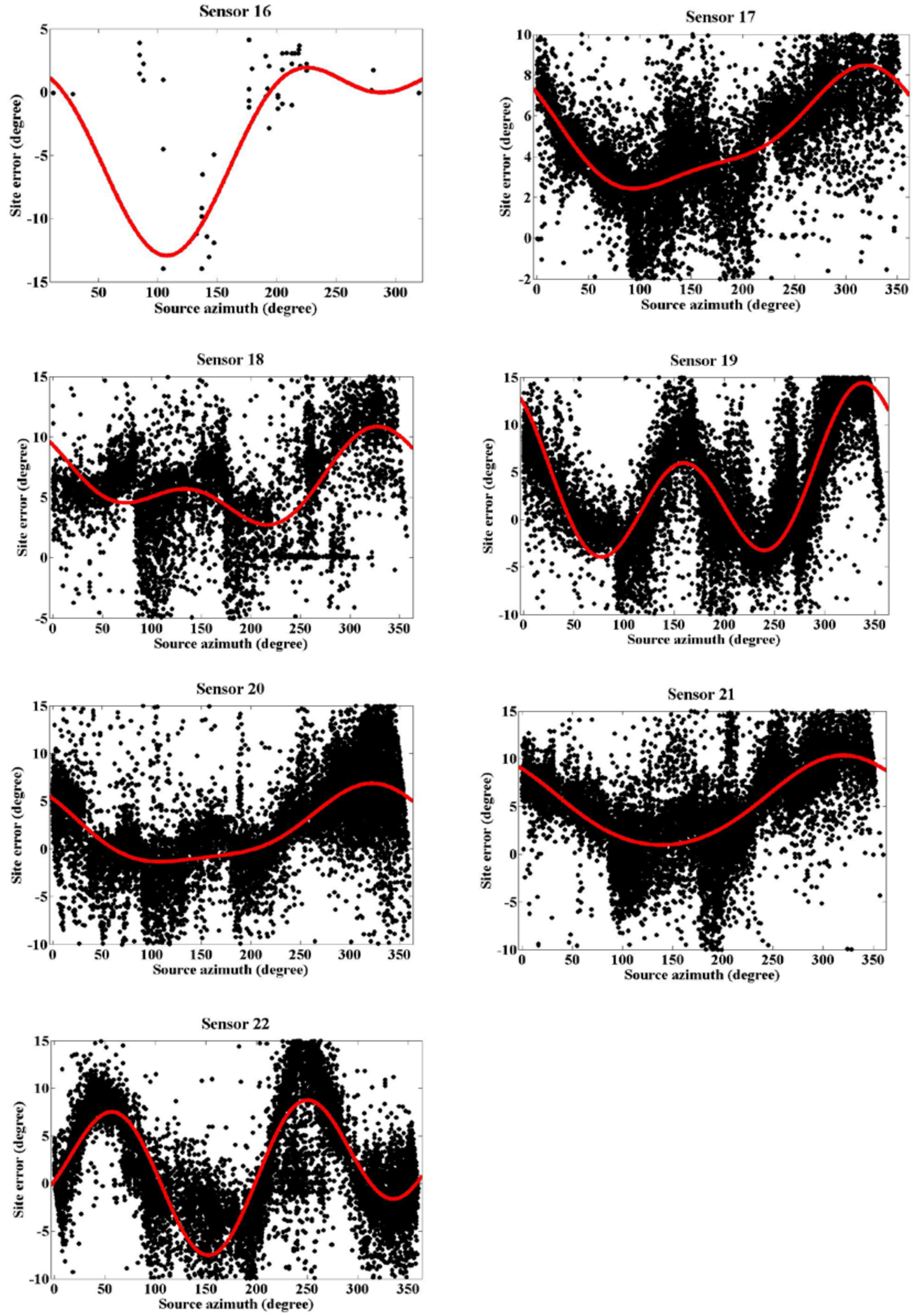
Fig.4



Sensor 00
Sensor 01
Sensor 02
Sensor 03
Sensor 04
Sensor 05
Sensor 06
Sensor 07
Site error (degree)
Source azimuth (degree)

Fig.4 continue





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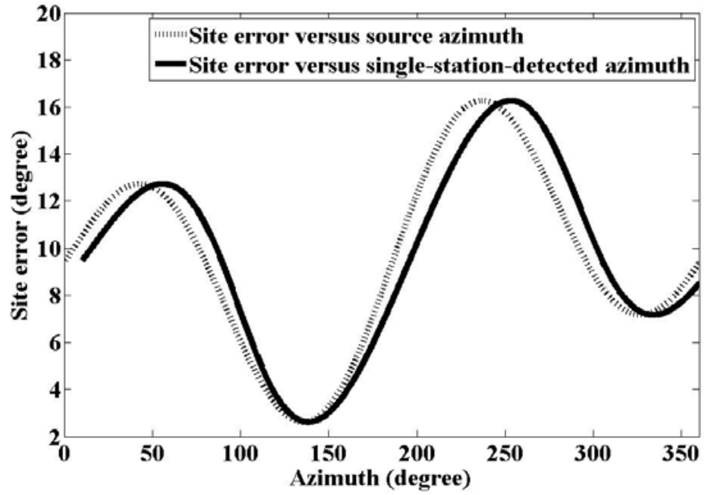
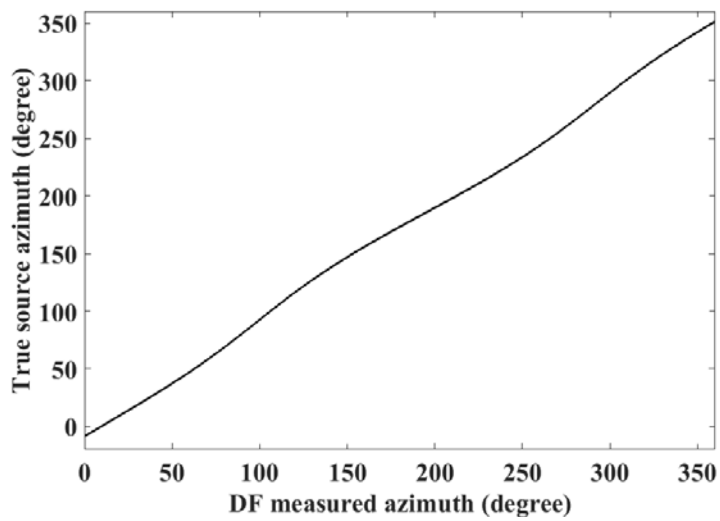
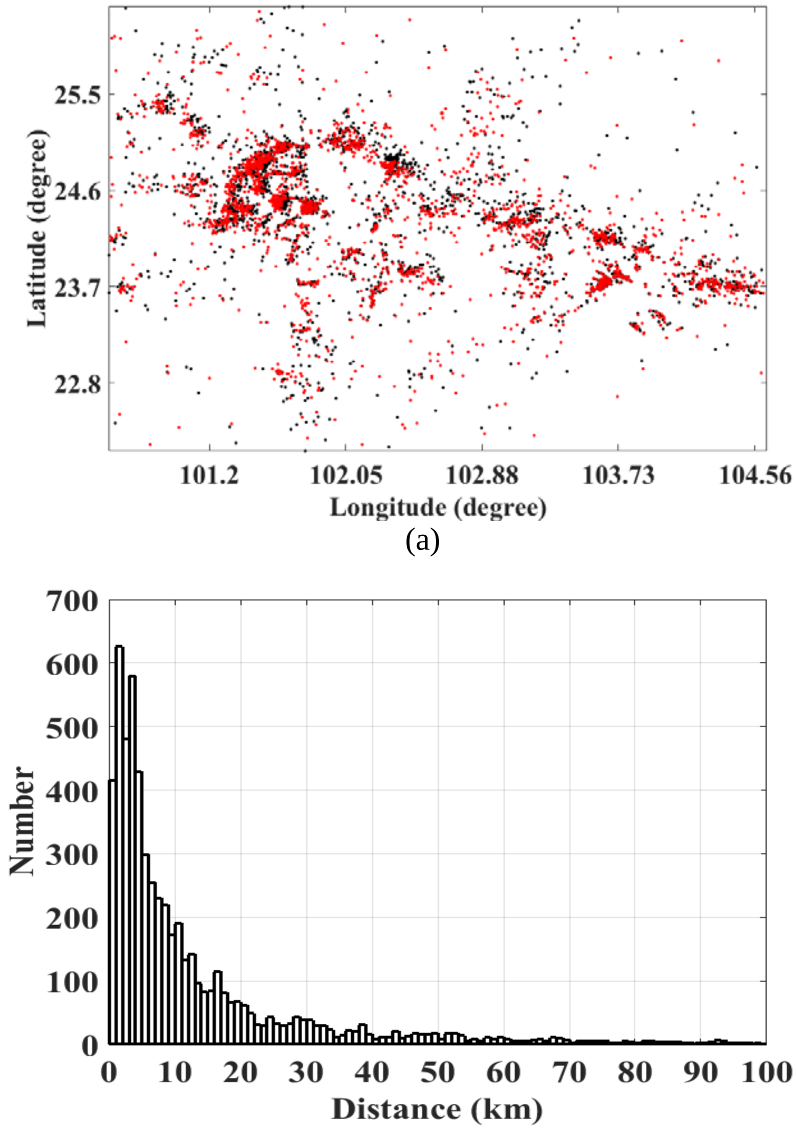


(a)



(b)

Fig. 5: (a) The curve of "site error" versus true source azimuth (dot-line) and that versus DF-detected azimuth (solid-line), and (b) the true source azimuth versus DF measured azimuth, for sensor No. 13 in Yunnan LLN.



(b)

Fig. 6: (a) Comparison of lightning locations before (black) and after (red) "site error" correction, for the 6000 more two-sensor detected lightning strokes on 24 June in 2008 in Yunnan LLN. (b) Statistics of distance difference in lightning locations before and after "site error" correction, for the strokes in Fig.6a. The median value is 6 km.

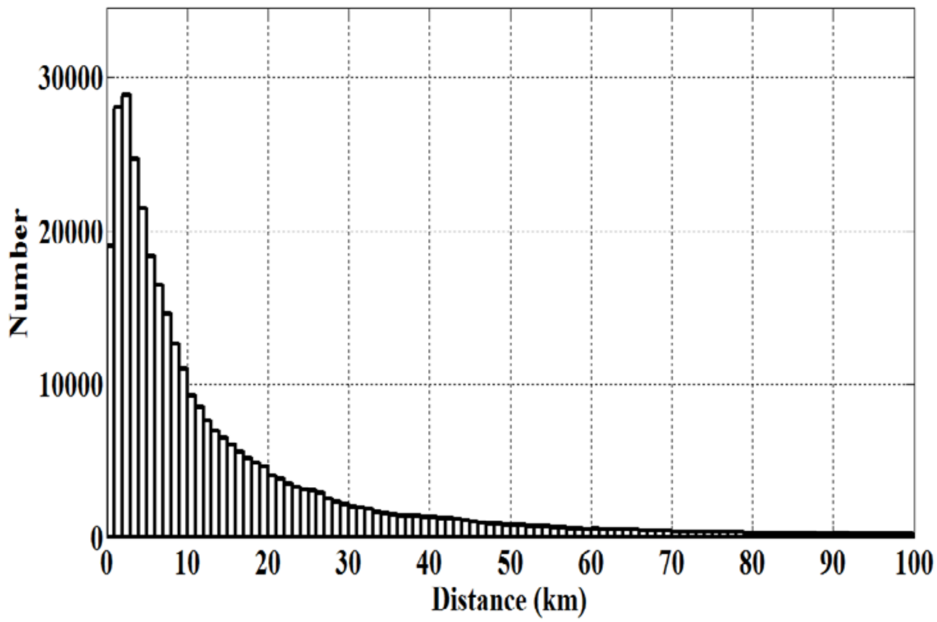


Fig. 7: Statistics of distance difference in lightning locations before and after "site error" correction, for the 330,000 more two-sensor-detected lightning strokes in 2008 in Yunnan LLN. The median value is 7.73 km and the mean value is 14.38 km.

Tables

Table 1: The source azimuth retrieved from the location by four-station-TOA algorithm and that detected by each DF/TOA sensor for a lightning stroke detected by 4 sensors in Yunnan LLN at 15:11:47 on 07 June 2008. The difference between the DF azimuth and TOA azimuth for a stroke is considered as the "site error" at that azimuth for that DF.

Sensor	Arrival time(second)	DF azimuth	TOA azimuth	Site error
No.08	47.9469667	249.02	250.18	-1.16
No.01	47.9470746	129.46	135.96	-6.5
No.00	47.9471681	206.30	209.56	-3.26
No.03	47.9473804	57.82	62.11	-4.3

Table 2: Curve fitting results for "site error" versus source azimuth for the 23 sensors in Yunnan LLN in 2008 and that for sensor 13 for different time windows.

$A1*\cos(\theta)+A2*\sin(\theta)+A3*\cos(2\theta)+A4*\sin(2\theta)+A5$						
Sensor	A1	A2	A3	A4	A5	R-square
00	1.768	-2.603	-0.6129	-2.239	0.2489	0.8325
01	2.218	-1.142	0.7596	0.14	-4.446	0.6917
02	1.821	-2.349	0.4997	1.186	0.7318	0.7508
03	1.73	-2.042	5.061	-0.5554	1.02	0.737
04	1.895	-2.505	4.401	-1.172	-2.746	0.5395
05	1.017	-2.587	0.7182	-3	1.171	0.4491
06	4.838	-3.675	6.603	-3.459	4.198	0.7116
07	1.965	-1.694	-0.8063	2.045	0.1632	0.6441
08	1.457	-1.581	3.734	-2.808	0.1768	0.7931
09	0.8266	-1.02	-4.09	-2.964	-5.002	0.8301
10	2.171	-1.88	1.611	-5.784	1.54	0.8645
11	2.903	-1.575	-0.491	-3.156	1.703	0.7126

12	1.866	-2.625	-0.9275	-1.733	0.4308	0.6307
13	2.636	-2.823	-0.9157	4.602	9.67	0.7981
Jan.–Jun.	3.205	-3.266	-1.292	4.083	9.28	0.9256
Jul.–Dec.	2.399	-2.855	-0.7733	4.643	9.25	0.9072
14	0.1867	-4.702	-0.6962	-2.98	1.365	0.5666
15	-0.6531	-1.448	14.92	16.57	11.38	0.9475
16	1.902	-6.2	2.85	1.958	-3.081	0.7884
17	1.685	-2.177	0.4101	-0.7108	5.008	0.7241
18	2.651	-0.8124	0.5529	-2.013	6.126	0.396
19	3.807	-1.866	4.937	-4.561	3.452	0.687
20	2.908	-2.697	0.4168	-0.8852	1.938	0.7489
21	3.574	-3.047	0.08072	-0.3701	5.273	0.6764
22	2.374	-1.875	-3.782	4.996	1.681	0.6093