Performance Evaluation for a Lightning Location System Based on Observations of Artificially Triggered Lightning and Natural Lightning Flashes

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ABSTRACT

Performance evaluation for the lightning location system (LLS) of the power grid in Guangdong Province, China, was conducted based on observation data of the triggered lightning flashes obtained in Conghua, Guangzhou, during 2007–11 and natural lightning flashes to tall structures obtained in Guangzhou during 2009–11. The results show that the flash detection efficiency and stroke detection efficiency were about 94% (58/62) and 60% (97/162), respectively. The arithmetic mean and median values for location error were estimated to be about 710 and 489 m, respectively, when more than two reporting sensors were involved in the location retrieval (based on 87 samples). After eliminating one obviously abnormal sample, the absolute percentage errors of peak current estimation were within 0.4%–42%, with arithmetic mean and median values of about 16.3% and 19.1%, respectively (based on 21 samples).

1. Introduction

Lightning location systems (LLSs) have been widely applied in many countries and regions as pivotal equipment for lightning detection. The detection efficiency and location accuracy are considered to be the most important performance indices for LLSs. One of the directly effective methods for objectively evaluating performance of LLS is to compare the reliable observation of lightning ground truth with the corresponding LLS records. Triggered lightning observation experiments can accurately indicate the position and time of actual lightning, as well as the directly measured value of various physical parameters such as lightning current, electric field change, and so on. Although no stepped downward leader-initial return stoke occurs as natural lightning, triggered lightning has the same physical mechanism in the return stroke process as the subsequent return stroke of natural cloud-to-ground (CG) lightning (Rakov and Uman 2003). Observations of natural lightning to tall towers can also accurately show the position and time of lightning and, possibly, the directly measured value of return stroke peak current and various physical parameters (Diendorfer 2010). When GPS synchronous time information is stamped, video camera recording can also provide some information about the natural lightning

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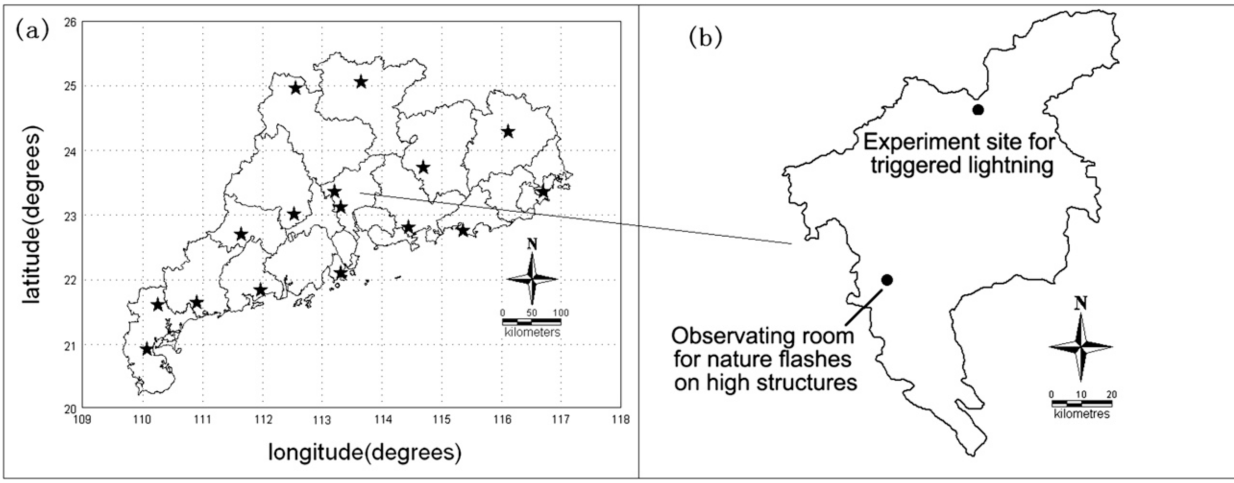

FIG. 1. Distribution of (a) sensors at the Guangdong power grid LLS and (b) observation experiment sites for lightning.

for comparison with LLS records. During recent years, researchers have evaluated the performance of different LLSs based on various ground-truth observation data of natural or triggered lightning. For instance, Jerauld et al. (2005) and Nag et al. (2011) evaluated the performance characteristics of the U.S National Lightning Detection Network (NLDN) using observation data on lightning triggered at the International Center for Lightning Research and Testing (ICLRT) in Florida. Chen et al. (2009) conducted a comparative analysis between the lightning location data from the power grid in Guangdong Province, China, and the observation data from a triggered lightning experiment in Conghua, Guangzhou, China, during 2007–08. Since then, comprehensive lightning data have been accumulated for the objective evaluation of LLS performance. In this paper, the performance characteristics of the Guangdong power grid LLS were evaluated based on observations of lightning flashes triggered at the Guangzhou Field Experiment Site for Lightning Research and Testing during 2007–11, and natural lightning flashes to tall structures in Guangzhou during 2009–11.

2. Observation system

a. LLS of the Guangdong power grid

The LLS of the Guangdong power grid was originally built in 1997 (Chen et al. 2002). The combined magnetic-direction-finding and time-of-arrival (MDF–TOA) technology is used to detect CG lightning stroke information such as longitude and latitude, GPS time, peak current, polarity, reporting sensors, etc. In 2003, two sensors were added to the network, and the total number of the sensors is currently 16. In 2003, the communication and display software of the LLS was also upgraded. To promote the lightning detection capacity at the junction of surrounding provinces, since 1 June 2010, the LLS of the Guangdong power grid has been merged into a large regional lightning location network covering five provinces (Guangdong, Guangxi, Guizhou, Yunnan, and Hainan) governed by the China Southern Power Grid and started in trial operation. Up to now, the LLS of the Guangdong power grid has had the longest continual and stable operation time in China, and historical observations of lightning location data in Guangdong Province have been accumulated for nearly 15 years. Figure 1 indicates the distribution of the lightning detection sensors, the site of a triggered lightning experiment, and the site of natural lighting observations.

b. Triggered lightning experiment

The rocket-triggered lightning experiment was conducted at Conghua, Guangzhou, using both classical-triggered and altitude-triggered technologies. A wire carried by the rocket was connected to a small lightning rod of 4 m in height and with a grounding resistance of 6.7 Ω. The rockets' launch controller and various data acquisition systems were operated in a control room located about 90 m northwest of the lightning rod. The instruments used in the experiments included electric field mills with a sampling rate of 1 Hz, flat-plate fast antennas with a time constant of 2 ms and a bandwidth of 1 kHz–2 MHz, flat-plate slow antennas with a time constant of 6 s and a bandwidth from 1 to 3 MHz, a wideband loop magnetic antenna with a bandwidth of 100 Hz–5 MHz, and high-speed and common video cameras. A coaxial shunt with a resistance of 1 mΩ was used to measure the base current in the triggered-lightning channel. The output of the shunt was transmitted through an optical fiber system to the control room. An oscilloscope (Yokogawa model DL750) was adopted as the primary recording system (sampling rate of 10 MHz, recording length ≥1 s, pretrigger length = 20%) to synchronously record such data as lightning current, fast and slow electric field changes, wideband magnetic variation, and GPS pulses per second (PPS). The signal of the shunt and the fast antenna are used as the trigger sources of the DL-750 oscilloscope for the rocket-triggered lightning and altitude-triggered lightning experiments, respectively In addition, a data acquisition card (model PCI-5105, sampling rate = 1 MHz, recording length = 1 s, pretrigger length = 20%), which was integrated into a broadband interferometer system locating the VHF radiation sources of the triggered lightning, was also used to record the signal of the fast and slow antennas. A GPS module was used to stamp the trigger time of the data acquisition card with precision < 50 ns. Note that the recording system of the broadband interferometer unit triggered by a signal from the VHF radiation field is independent of that from the DL-750 oscilloscope, and is likely triggered hundreds of milliseconds earlier than the latter For the strokes close to the end of a triggered flash, they might possibly be recorded only by the DL-750 oscilloscope and may be missed by the PCI data acquisition card. Then, the exact GPS time of those strokes could be inferred from the interstroke interval. For all triggered lightning experiments, one observer in the rocket-launcher control room was specially assigned to continuously monitor a GPS clock once the rocket was triggered, and to record the GPS time (accurate to 1 s) manually when the flicker of scatter lightning was observed or the thunder produced by the triggered lightning was heard. A detailed description of the triggered lightning experiment was presented by Zhang et al. (2011).

c. *Observation of natural flashes to tall structures*

Most tall structures in Guangzhou city are located in the Zhujiang New Town area, and a field observation experiment of lightning flashes striking on tall structures was conducted beginning in the summer of 2009 (see Lu et al. 2010, 2012). The observation room was situated at the top of a Guangdong Meteorological Bureau building (about 100 m above the ground). Zhujiang New Town lies about 2–3 km to the southeast of the observation room. Within view of the observation equipment, the International Financial Centre (with a height of 440 m) and the Canton Tower (with a height of 610 m in 2009 and finally 600 m in 2010), as well as many buildings with heights of over 200 m, are included. The main observation equipment included the Lightning Attachment Process Observation System (LAPOS; Wang et al. 2011), a high-speed camera (FASTCOM SA-5, frame rate>1000 frames per second, recording length ≥1 s, pretrigger length = 20%), fast and slow antennas, a wideband magnetic antenna, a thunder acoustics recording system, etc. An oscilloscope (Yokogawa model DL-750) was used as the primary recording system (sampling rate = 10 MHz, recording length ≥1 s, pretrigger length = 20%) to synchronously record LAPOS, fast and slow antennas, wideband magnetic antenna, and GPS in pulses per second. The LAPOS consists of a camera, an optical fiber array, and multiple photodiodes and their amplifiers. The fiber array is mounted at the camera's film plane. When a lightning strike occurs in view of the camera, the image formed by the camera lens is first guided by the optical fibers to the photodiodes. Then it is converted into electrical signals by the photodiodes and used as the trigger source of the DL-750 oscilloscope. When the DL-750 oscilloscope is triggered, it will output the trigger signal to the high-speed cameras, a portable oscilloscope (sampling rate = 100 kHz, recording length = 35 s, pretrigger length = 14%) recording the thunder acoustical signal, and also to a GPS module, which could stamp the trigger time with precision < 50 ns. During 2009–11, at least one high-speed camera was set with a sampling rate greater than 1000 frames per second and recording length greater than 1 s, which could provide optical evidence with sufficient temporal resolution and duration for comparison with LLS data.

3. Data and methodology

A total of 43 lightning flashes were successfully triggered during 2007–11, out of which 28 contained at least one or more return strokes. The return stroke process, as well as the interstroke interval time, could be independently or comprehensively identified according to such records as lightning current, the waveform of fast and slow changes, as well as the magnetic field. But for various reasons, not all observation data records could be achieved in each experiment. In Table 1, the basic record information for triggered lightning experiments is summarized. Note that the exact number of return strokes for seven triggered lightning flashes [Table 1, marked with an asterisk (*)] could not be confirmed, for various reasons, including that some strokes close to the end of a triggered flash might be missed by the recording system. However, it could be confirmed that at least one stroke exists in each of those seven triggered flashes with the aid of the available observation data. Then, in the following sections, those seven triggered flashes were included in the evaluation for flash detection efficiency, but excluded in the stroke detection efficiency.

TABLE 1. Summary of the basic information obtained from an observation experiment of triggered lightning during 2007–11. For the relative observation data, D1, D2, D3, D4, D5, and D6 denote the data are from fast and slow antennas, a magnetic antenna, a high-speed camera, video, the lightning current, and GPS time information, respectively.

Date	Time of occurrence (LT, recorded manually)	Trigger method	No. of strokes	Relative observation data
13 Jun 2007	1636:05	Classical	12	D1, D3, D4, D6
30 Jun 2007	1358:33	Altitude	0	D1, D2, D3, D6
1 Jul 2007	1206:05	Classical	1	D1, D2, D3, D4
6 Jul 2007	1253:24	Classical	*	D4
8 Aug 2007	1503:05	Classical	1	D1, D4, D6
8 Aug 2007	1514:42	Classical	1	D1, D2, D3, D4, D6
21 Aug 2007	1938:22	Classical	8	D1, D2, D3, D6
21 Aug 2007	1943:28	Classical	7	D1, D2
24 Aug 2007	1438:41	Classical	7	D1, D2, D3
24 Aug 2007	1443:35	Altitude	6	D1, D6
24 Aug 2007	1451:12	Altitude	8	D1, D3, D6
24 Aug 2007	1452:22	Classical	1	D1, D6
29 Jun 2008	1451:08	Classical	*	D4
29 Jun 2008	1501:47	Altitude	0	D4
4 Aug 2008	2128:51	Classical	2	D1, D2, D4, D5, D6
12 Aug 2008	1709:21	Classical	8	D1, D2, D3, D4, D5, D6
4 Sep 2008	1842:49	Classical	0	D1, D3, D4, D6
12 Jun 2009	1116:11	Altitude	0	D1, D2, D4
22 Jun 2009	1632:47	Classical	2	D1, D2, D4, D5
22 Jun 2009	1642:22	Classical	0	D1, D2, D3, D4
23 Jun 2009	1201:39	Altitude	0	D1, D2, D3, D4
27 Jun 2009	1449:41	Classical	0	D1, D2, D3, D4, D5
27 Jun 2009	1508:28	Classical	0	D1, D2, D3, D4, D5
28 Jun 2009	1351:40	Classical	0	D1, D2, D3, D4
22 May 2010	1049:00	Altitude	2	D1, D2, D3, D4
22 May 2010	1100:40	Altitude	*	D1, D2, D4
15 Jun 2010	1654:25	Classical	*	D1, D2, D3, D4, D5
21 Jul 2010	1515:09	Classical	2	D1, D2, D3, D4, D5
27 Jul 2010	1007:54	Altitude	0	D1, D2, D3, D4, D5
27 Jul 2010	1018:35	Classical	1	D1, D2, D3, D4, D5
7 Jun 2011	1747:09	Classical	*	D1, D2, D3, D4
7 Jun 2011	1756:32	Classical	1	D1, D2, D3, D4, D5
7 Jun 2011	1802:27	Classical	0	D1, D2, D3, D4
7 Jun 2011	1814:45	Altitude	*	D1, D2, D3, D4
11 Jun 2011	1852:22	Classical	1	D1, D2, D3, D4, D5
11 Jun 2011	1858:05	Classical	0	D1, D2, D3, D4
11 Jun 2011	1904:00	Classical	1	D1, D2, D3, D4, D5
29 Jun 2011	1241:46	Classical	8	D1, D2, D3, D4, D5
29 Jun 2011	1252:54	Classical	*	D1, D2, D3, D4
29 Jun 2011	1301:39	Altitude	1	D1, D2, D3, D4, D5
16 Jul 2011	1823:02	Classical	0	D1, D2, D3, D4
16 Jul 2011	1825:51	Classical	0	D1, D2, D3, D4
30 Jul 2011	1800:26	Classical	0	D1, D2, D3, D4

* The exact number of strokes in the triggered flash could not be confirmed accurately.

During 2009–11, a total of 34 natural lightning flash observations were successfully acquired for comparison with lightning location records, and all of them contained one or more return strokes. The entire return stroke event and the corresponding occurrence time of natural lightning flashes could be identified from the GPS time-synchronous observed records of electric–magnetic change and high-speed cameras. For recorded natural lightning flashes that occurred within the view range of the high-speed cameras, most grounding points were at the tops of high-rise buildings (the height is over 100 m, and the maximum height was about 610 m), and could be directly confirmed. When obstructed by other buildings or ground objects, natural lightning grounding points could not be directly confirmed. Then, the direction from the observation room to the grounding point was derived from the high-speed cameras data, and the distance from the observation room to the

TABLE 2. Summary of the basic information obtained during an observation experiment for natural flashes at tall structures during 2009–11. For the relative observation data, D1, D2, D3, D4, D5, and D6 denote the data are from fast and slow antennas, a magnetic antenna, a high-speed camera, thunder acoustics microphone arrays, and LAPOS, respectively.

Date	Time of occurrence (LT)	Grounding point confirmable	No. of strokes	Relative observation data
25 Jun 2009	1053:12	Yes	1	D3, D4, D5
6 Aug 2009	1043:48	Yes	7	D1, D2, D3, D4, D5
24 Aug 2009	1908:04	Yes	1	D1, D2, D3, D4, D5
24 Aug 2009	1935:53	Yes	1	D1, D2, D3, D4, D5
25 Aug 2009	1454:14	Yes	1	D1, D2, D3, D4, D5
25 Aug 2009	1457:43	Yes	2	D1, D2, D3, D4, D5
30 Aug 2009	1513:02	Yes	1	D1, D2, D3, D4, D5
30 Aug 2009	1520:25	No	1	D1, D2, D3, D4, D5
7 May 2010	0423:25	Yes	1	D1, D3, D4, D5
21 Jun 2010	1618:20	Yes	2	D1, D3, D4, D5
21 Jun 2010	1639:35	Yes	1	D1, D3, D4, D5
21 Jun 2010	1644:02	Yes	2	D1, D3, D4, D5
21 Jun 2010	1657:15	Yes	1	D1, D3, D4, D5
23 Jun 2010	1814:56	Yes	1	D1, D3, D4, D5
29 Jul 2010	1754:15	Yes	6	D1, D3, D4, D5
7 Aug 2010	2201:15	Yes	1	D1, D3, D4, D5
7 Aug 2010	2201:16	No	2	D1, D3, D4, D5
22 Aug 2010	1842:10	Yes	1	D1, D2, D3, D4, D5
16 Sep 2010	1537:15	Yes	1	D1, D2, D3, D4, D5
10 Jul 2011	2126:38	Yes	4	D1, D2, D3, D4
10 Jul 2011	2152:24	Yes*	7	D1, D2, D3, D4
10 Jul 2011	2156:42	Yes	1	D1, D2, D3, D4
10 Jul 2011	2156:42	Yes	5	D1, D2, D3, D4
10 Jul 2011	2338:45	Yes	1	D1, D2, D3, D4
10 Jul 2011	2338:45	Yes	3	D1, D2, D3, D4
12 Jul 2011	1306:21	Yes	4	D1, D2, D3, D4, D5
12 Jul 2011	1321:11	Yes	1	D1, D2, D3, D4, D5
18 Jul 2011	1506:02	Yes	3	D1, D2, D3, D4, D5
18 Jul 2011	1513:32	Yes	8	D1, D2, D3, D4, D5
18 Jul 2011	1517:09	Yes	1	D1, D2, D3, D4, D5
18 Jul 2011	1520:26	No	1	D1, D2, D3, D4, D5
18 Jul 2011	1524:33	Yes	6	D1, D2, D3, D4, D5
18 Jul 2011	1527:15	No	1	D1, D2, D3, D4, D5
10 Sep 2011	1858:49	Yes	1	D1, D2, D3, D4, D5

* This natural flash contained seven strokes. The grounding point of the first return stroke was outside the view of the high-speed camera and only the grounding points of six subsequent return strokes with new paths to the ground could be confirmed.

grounding point was deduced from the time difference between the trigger and the thunder acoustical signal arrival (acousto-optic time difference), and the obstructed lightning grounding points could possibly be confirmed by taking into account the actual distribution of the buildings. If the main channel of a return stroke of a natural flash was out of the view range of all high-speed cameras, but very close to the observation site, the grounding point could also possibly be determined according to the view angle, acousto-optic time difference, actual distribution of buildings around the observing room, etc. Table 2 presents a summary of the basic record information of the natural lightning observation experiment on tall structures.

The return strokes of triggered lightning or natural lightning were matched with lightning location records in the following steps:

(a) For triggered lightning flashes with a precise GPS trigger time stamp, LLS database records were first searched within ± 2 s before and after trigger time. Then, the interstroke intervals were used to match each triggered stroke to the corresponding LLS record. The time difference between a triggered stroke and the matched LLS record was found to be within ± 1 ms for the matching results.
(b) For triggered lightning flashes without a precise GPS trigger time stamp (e.g., when the data acquisition card of the broadband interferometer system was not triggered), while the GPS PPS along with the electromagnetic field synchronously recorded by the DL-750 oscilloscope was available, the LLS database record were first searched within a time period ± 5 s before and after the manually recorded trigger time and within 20-km radius around the

TABLE 3. Summary of flashes and strokes recorded during a triggered lightning experiment during 2007–11, along with the corresponding LLS detection efficiency. Flashes that contained no return strokes were not included.

Year	No. of flashes triggered	No. of LLS detected flashes	Flash detection efficiency (%)	No. of strokes confirmed*	No. of LLS detected strokes confirmed*	Stroke detection efficiency (%)
2007	11	10	91	52	16	31
2008	3	3	100	10	9	90
2009	1	1	100	2	2	100
2010	5	4	80	5	3	50
2011	8	7	88	12	7	58
2007–11	28	25	92	81	37	46

* Flashes for which the exact number of return strokes could not be confirmed were not included.

experiment site. Though the second piece of information could not be proved by the waveform of PPS, the millisecond information of occurrence time of each stroke could be derived by comparing the waveforms of the PPS and electromagnetic fields. Then, the interstroke intervals were used to match each triggered stroke with the corresponding LLS record, considering the millisecond information of occurrence time of each stroke. As a result, a second difference between a triggered stroke and the matched LLS record was found to be within ±1 s, and the millisecond difference was within ±1 ms for all matching results.

(c) For triggered lightning flashes where the GPS time information was the manually recorded trigger time only, LLS database records were first searched within a time period of ±5 s before and after the manually recorded trigger time and 20-km radius around the experiment site. Further, LLS records with more than two reporting sensors and within 2-km radius around the experiment site, and the LLS records with only two reporting sensors and within 20-km radius around the experiment site (considering that LLS record with only two reporting sensors may lead to large location error), were chosen as corresponding ones preliminarily. Then, the interstroke intervals were used to reexamine the chosen records. As a result, a second difference between manually recorded trigger time and the matched LLS record was found to be within ±1 s.

(d) For natural lightning flashes, GPS-stamped trigger times were available in all experiments, and a procedure similar to that in step (a) was performed.

In total, 58 LLS records were found to be matched with triggered lightning events, and 60 LLS records matched the natural lightning events.

4. Results

a. Detection efficiency

During 2007–11, the LLS detected 25 flashes out of 28 triggered flashes that contained at least one return stroke process. The seven triggered lightning flashes (Table 1, marked with an asterisk) for which the exact number of return strokes could not be confirmed, though a total of 21 LLS records were matched with those seven triggered flashes, were excluded from the evaluation of the stroke detection efficiency. The total number of return strokes in the other 21 triggered flashes was found to be 81, and 37 of them were detected by LLS. The flash detection efficiency was about 92%, and the stroke detection efficiency was about 46%, for triggered lightning. Table 3 shows the detection of triggered lightning by LLS.

During 2008–11, the directly measured peak currents were obtained for a total of 29 strokes in triggered lightning, out of which 22 were detected by LLS. Figure 2 gives the stroke detection efficiency as a function of measured peak current. When the absolute peak current of a return stroke was greater than 15 kA, the detection efficiency was 100%, but decreased to 50% (7/14) when the peak current was less than 15 kA, and only 33% (1/3) in cases where the peak current was less than 10 kA.

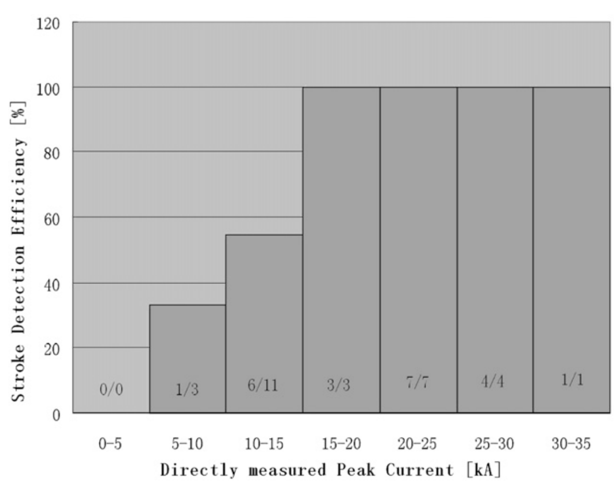

FIG. 2. Stroke detection efficiency as a function of peak current measured directly in the triggered lightning experiment. The ratio given inside the column indicates the number of strokes detected by the LLS (numerator) and the number of strokes recorded in the triggered lightning experiment (denominator).

TABLE 4. Summary of flashes and strokes recorded in an observation experiment for natural lightning at tall structures during 2009–11, along with the corresponding LLS detection efficiency.

Year	No. of flashes	No. of LLS detected flashes	Flash detection efficiency (%)	No. of strokes confirmed	No. of LLS detected strokes confirmed	Stroke detection efficiency (%)
2009	8	8	100	15	15	100
2010	11	10	91	19	15	79
2011	15	15	100	47	30	64
2009–11	34	33	97	81	60	74

For the 34 natural flashes at high-rise buildings observed during 2009–11, LLS successfully detected 33 of them with 97% flash detection efficiency. According to the comprehensive photoelectromagnetic observation data, it could be confirmed that these natural flashes contained a total of 81 return strokes, out of which the LLS detected 60 strokes. The stroke detection efficiency for natural lightning was estimated to be about 74%. Table 4 shows the detection results of natural lightning by the LLS.

During 2007–11, observations of 62 lightning flashes (both triggered flashes and natural flashes) with at least one or more return stroke process were obtained, and the LLS detected 58 flashes among them. The exact number of return strokes for the 55 lightning flashes was affirmable and amounted to 162, wherein 97 were detected by LLS. On the whole, the flash detection efficiency was about 94%, and the stroke detection efficiency was about 60%.

b. Location accuracy

Twenty-one LLS records matched with the seven triggered lightning flashes (Table 1, marked with an asterisk), of which the exact number of return strokes could not be confirmed, were included in the evaluation for location accuracy. Furthermore, as it is generally accepted that LLS records with only two reporting sensors will possibly lead to large location errors, and those records account for just a minor part of the total amount, statistics based on LLS records with at least three reporting sensors may be more reasonable.

During 2007–11, 33 return strokes of classical-triggered lighting were detected by the LLS with more than two reporting detection sensors involved in the location retrieval. The location errors were in the range of 76–3109 m. The arithmetical mean location error was about 759 m, while the median location error was about 649 m. Figure 3a shows the spatial distribution of locations for those 33 classical-triggered strokes.

Since the fact that grounding points of return strokes in altitude-triggered lightning could not be accurately confirmed, they were excluded from the statistical scope for location accuracy. During 2007–11, 13 return strokes of altitude-triggered lightning were detected by the LLS with more than two reporting detection sensors. The distance from the locations of the LLS records to the rocket launcher was within the range of 343–1271 m, and the arithmetical mean distance was about 675 m, while the median value was about 646 m. This accorded relatively well with the actual situation. Figure 3b shows the spatial distribution of locations for those 13 altitude-triggered strokes.

During 2009–11, 54 return strokes of natural lightning with affirmable grounding points were detected by the LLS with more than two reporting sensors. The location errors were in the range of 76–3109 m. The arithmetical mean location error was about 633 m, while the median value was about 453 m. Compared with the retrieved location results of artificially triggered strokes (Fig. 3), the location errors of strokes in natural lightning (Fig. 4) seemed to be more uniformly distributed around the actual grounding points, and without such a distinctly south-directional abnormal tendency as shown in Fig. 3.

Figure 5 shows the absolute location error plotted versus the number of reporting LLS sensors involved in the location retrieval, for a total of 99 lightning strokes with affirmable grounding points. It can be seen from Fig. 5 that major errors may occur in the LLS records with only two reporting sensors. However, with the increasing number of reporting sensors, absolute location errors did not decrease significantly. When more than two reporting sensors were involved in the location retrieval, the arithmetic mean location error was calculated at about 710 m, while the median location error was about 489 m (based on 87 samples).

c. Peak current estimates

For the estimation of peak current, the formulation for range-normalized signal strength (RNSS) is applied in the Guangdong power grid LLS via the following expression (Chen et al. 2008):

$$\mathrm{RNSS} = \mathrm{SS} \times \left(\frac{r}{I}\right)^{p} \times \exp\left(\frac{r-I}{A}\right), \tag{1}$$

where SS is the signal strength reported by the sensor, r is the range in kilometers, I is the normalization range

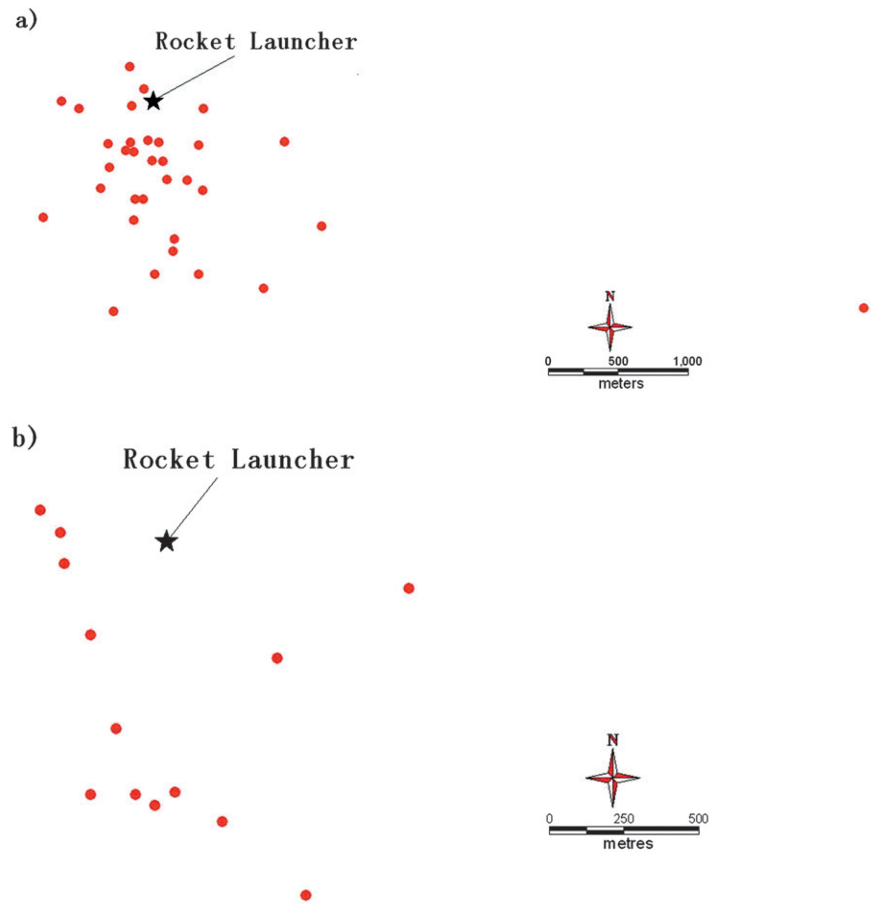

FIG. 3. Plots of (a) 33 stroke locations in a classical-triggered lightning experiment and (b) 13 stroke locations in an altitude-triggered lightning experiment during 2007–11.

(set to 100 km), p is an attenuation exponent (set to 1.13), and A is the space constant (set to 1000 km).

Direct measurement of the peak current of return strokes of triggered lightning was not obtained in 2007 for various reasons. For 22 return stroke processes of artificially triggered lightning during 2008–11, both the direct measurement of peak currents and the corresponding LLS records were obtained. It should be pointed out that for the secondary return stroke in the flash triggered at 1632:47 LT on 22 June 2009, the direct measurement (−13.7 kA) of the peak current was considerably different from the value estimated by the LLS (−44.0 kA). To avoid possible mistakes, this abnormal sample was not presented in the following statistical analysis. Figure 6 shows the peak current estimated by LLS versus the peak current measured directly (based on 21 samples). From this figure it is found that 11 peak currents were overestimated while 10 were underestimated. The absolute percentage errors of peak current estimation were within the range of 0.4%–42%. The arithmetic mean value was about 16.3%, while the median value was about 19.1%. Furthermore, there is a strong positive linear relationship between the directly and LLS-estimated and directly measured peak currents, with the correlation coefficient being about 0.92.

5. Summary and discussion

In this paper, the performance characteristics of the Guangdong power grid LLS were evaluated based on the observation data of triggered lightning obtained in Conghua during 2007–11, as well as from natural lightning flashes to tall structures obtained in Guangzhou during 2009–11. The results show that the flash detection efficiency was about 94% (58/62), and the stroke detection efficiency was about 60% (97/162). The arithmetic mean location error was estimated to be about 710 m, while the median value was about 489 m, when more than two reporting sensors were involved in the location retrieval (based on 87 samples). After eliminating the one obviously abnormal sample, the absolute percentage errors of peak current estimation were within

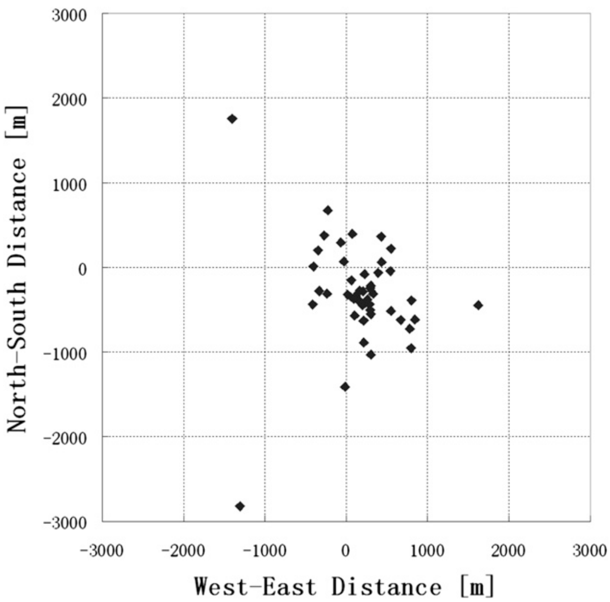

FIG. 4. Plot of 54 natural lightning stroke locations at tall structures during 2009–11. The origin corresponds to the ground strike point.

0.4%–42%, with an arithmetic mean value of about 16.3% and a median value of about 19.1% (based on 21 samples).

Both the flash detection efficiency and the stroke detection efficiency seemed to be higher for natural lightning than that for artificially triggered lightning. Considering that triggered lightning usually occurs under a weak electrical environment where natural CG flashes would not be initiated instantly without the presence of a fast-ascending wire-connected rocket, the peak current of the return strokes of triggered lightning may possibly be relatively weak. Furthermore, the first strokes in natural lightning typically have larger peak currents than those of the subsequent strokes, which could be considered to have similar characteristics of return strokes in the triggered lightning. The stroke detection efficiency was 97% (33/34) for first strokes in natural lightning flashes, and 57% (27/47) for subsequent strokes in natural lightning flashes. However, there is no significant difference in the arithmetic mean or median location errors between triggered lightning strokes and natural lightning strokes.

Since 1 June 2010, the LLS of the Guangdong power grid has been incorporated into a large regional lightning location system network covering five provinces under the administration of the China Southern Power Grid (Guangdong, Guangxi, Guizhou, Yunnan, and Hainan). However, based on the lightning observations given above, no obvious increase has been found in lightning detection efficiency by the LLS after 2010. This may be partly because the areas that benefit from the LLS's incorporation are mainly locate at the junctions of the provinces, while the lightning observation experiment sites are located in the center of Guangdong Province.

According to the comprehensive experimental observation data, all of the natural and the triggered lightning strokes had a negative polarity except for the first return stroke of natural lightning (positive polarity), which happened at 1754:15 LT 29 July 2010. All of these polarities were identified accurately by the LLS. The sole bipolar natural lightning flash mentioned above contained six return strokes, while the LLS detected the first return stroke with positive polarity and four subsequent return strokes with negative polarity; the location errors were all in the range from 300 to 500 m without distinct difference.

Diendorfer (2010) made a performance validation for the Austrian Lightning Detection and Information System (ALDIS) based on observations of lightning at

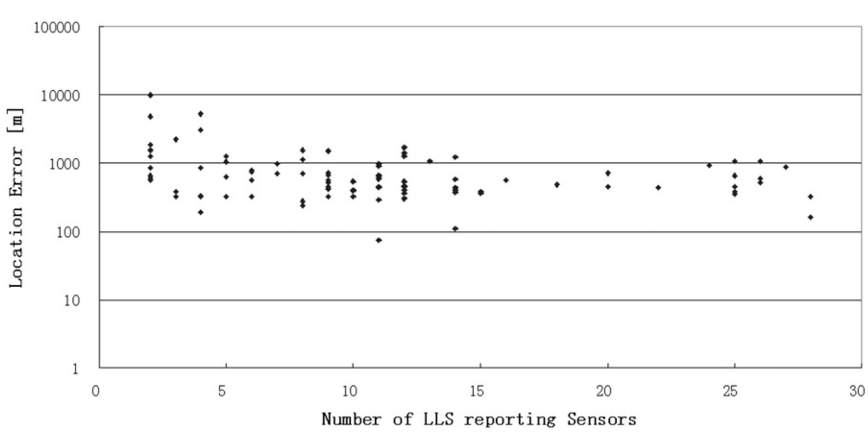

FIG. 5. Absolute location error vs number of LLS reporting sensors for 96 strokes observed in triggered lightning and natural lightning during 2007–11.

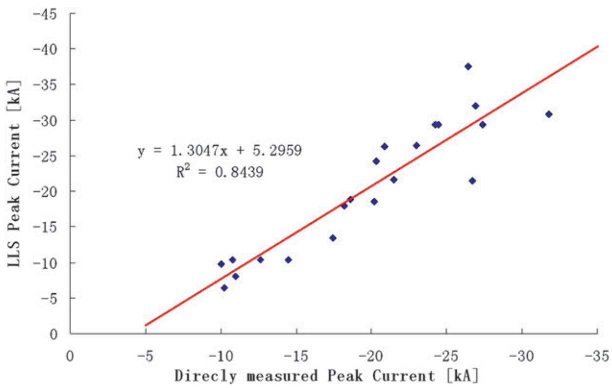

FIG. 6. LLS-reported vs directly measured peak currents in the triggered lightning experiment.

Gaisberg Tower near Salzburg during 2000–05, and pointed out that the flash detection efficiency, stroke detection efficiency, and median location error were about 95%, 85%, and 368 m, respectively. Nag et al. (2011) recently proceeded with the evaluation of performance characteristics of the NLDN using rocket-triggered lightning data acquired at the ICLRT during 2004–09, and found that the flash detection efficiency, the stroke detection efficiency, the median location error, and the median absolute value of the peak current estimation errors were 92%, 76%, 308 m, and 13%, respectively. Thus, in comparison with the two LLSs mentioned above, which have been in operation for many years, the LLS of the Guangdong power grid seemed to have similar performance characteristics in flash detection efficiency, but slightly low stroke detection efficiency and larger location and peak current estimation errors. With the constant development of lightning experiments, observation data will be accumulated continuously. This is likely to result in more reliable performance evaluations of the LLS.

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REFERENCES

Chen, J.-H., Q. Zhang, W.-X. Feng, and Y.-H. Fang, 2008: Lightning location system and lightning detection network of China power grid (in Chinese). *High Voltage Eng.,* **34,** 425–431.

Chen, L. W., Y. J. Zhang, W. T. Lu, W. S. Dong, D. Zheng, Z. H. Huang, and S. D. Chen, 2009: Comparative analysis between LLS and observation of artificial-triggered lightning (in Chinese). *High Voltage Eng.,* **35,** 1896–1902.

Chen, S. M., Y. Du, L. M. Fan, H. M. He, and D. Z. Zhong, 2002: Evaluation of the Guang Dong lightning location system with transmission line fault data. *IEE Proc. Sci. Meas. Technol.,* **149,** 9–16.

Diendorfer, G., 2010: LLS performance validation using lightning to towers. *Proc. 21st Int. Lightning Detection Conf.,* Orlando, FL, Vaisala. [Available online at http://www.vaisala.com/Vaisala 20Documents/Scientific 20papers/1.Keynote-Diendorfer.pdf.]

Jerauld, J., V. A. Rakov, M. A. Uman, K. J. Rambo, D. M. Jordan, K. L. Cummins, and J. A. Cramer, 2005: An evaluation of the performance characteristics of the U.S. National Lightning Detection Network in Florida using rocket-triggered lightning. *J. Geophys. Res.,* **110,** D19106, doi:10.1029/2005JD005924.

Lu, W., Y. Zhang, L. Chen, E. Zhou, D. Zheng, Y. Zhang, and D. Wang, 2010: Attachment processes of two natural downward lightning flashes striking on high structures. *Proc. 30th Int. Conf. on Lightning Protection,* Cagliari, Italy, ICLP.

——, and Coauthors, 2012: Characteristics of unconnected upward leaders initiated from tall structures observed in Guangzhou. *J. Geophys. Res.,* **117,** D19211, doi:10.1029/2012JD018035.

Nag, A., and Coauthors, 2011: Evaluation of U.S. National Lightning Detection Network performance characteristics using rocket-triggered lightning data acquired in 2004–2009. *J. Geophys. Res.,* **116,** D02123, doi:10.1029/2010JD014929.

Rakov, V. A., and M. A. Uman, 2003: *Lightning: Physics and Effects.* Cambridge University Press, 687 pp.

Wang, D., T. Watanabe, and N. Takagi, 2011: A high speed optical imaging system for studying lightning attachment process. *Proc. Seventh Asia-Pacific Int. Conf. on Lightning,* Chengdu, China, IEEE, 937–940.

Zhang, Y. J., S. J. Yang, W. T. Lu, and D. Zheng, 2011: Experiment and application of artificially triggering lightning in Guangdong. *Proc. XIV Int. Conf. on Atmospheric Electricity,* Rio de Janeiro, Brazil, Int. Commission on Atmospheric Electricity.