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PERFORMANCE EVALUATION FOR LIGHTNING LOCATION SYSTEM BASED ON OBSERVATION OF ARTIFICIALLY-TRIGGERED LIGHTNING AND NATURAL LIGHTNING FLASHES

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ABSTRACT: Performance evaluation for Lightning Location System (LLS) of Guangdong Power Grid was conducted based on the observation data of the triggered lightning flashes obtained in Conghua, Guangzhou during 2007-2011 and the nature lightning flashes on high structures obtained in Guangzhou during 2009-2011. The results show that the flash detection efficiency and stroke detection efficiency was about 95% (55/58) and 63% (96/152) respectively. The arithmetic mean locating error was estimated to be about 677m when more than 2 reporting sensors involved in the location retrieval (based on 86 samples). After eliminating one obviously abnormal sample, the absolute percentage errors of peak current estimation ranged from 0.4% to 42%, with arithmetic mean value of about 16.3% (based on 22 samples).

1. INTRODUCTION

Lightning location system (LLS) has been widely applied in many countries and regions as pivotal equipment for lightning detection nowadays. The detection efficiency and locating accuracy could be perceived as the most important performance index for LLS. 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 lightning location records. Triggered lightning observation experiment can accurately indicate the position and time of actually occurred lightning, and the directly measured value of various physical parameters such as lightning current，electric field change and so on. Although no stepped downward leader-return stoke occurs as the natural lightning, the triggered lightning has the same physical mechanism in the return stoke process as the subsequent return stroke of natural Cloud-to-Ground lightning (CG) [Rakov and Uman 2003]. Observation experiment of nature 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.

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When GPS synchronous time information video camera recording can also provide reliable natural lightning optics for comparison with LLS records, although video camera studies have some weakness such as insufficient temporal resolution for accurately discriminating short interval strokes and possibly difficulty in validating the grounding point of natural lightning. During the last years, researchers have evaluated the performance of different LLSs based on various ground-truth observation data of nature or triggered lightning. For instance, Jerauld and Rakov [2005] evaluated the performance characteristics of the U.S National Lightning Detection Network (NLDN) using observation data of lightning triggered in International Center for Lightning Research and Testing (ICLRT) during 2001-2003. Chen et al. [2009], conducted comparative analysis between the lightning location data of Guangdong Power Grid and the observation data of triggered lightning experiment in Conghua, Guangzhou during 2007-2008. With the development of lightning research, comprehensive lightning observation data have been continuously accumulated as available objective comparison data for LLS performance evaluation. In this paper, performance characteristics of LLS of Guangdong Power Grid was evaluated based on the observed results of the lightning flashes triggered in the Guangzhou Field Experiment Site for Lightning Research and Testing during 2007-2011 as well as nature lightning flashes on high structures in Guangzhou during 2009-2011. are stamped,

2. OBSERVATION SYSTEM

2.1 LLS of Guangdong Power Grid

The LLS of Guangdong Power Grid was originally built in 1997, which consists of 16 sensors. The combined MDF/TOA technology is used to detect CG lightning strokes information such as longitude and latitude, GPS time, amplitude of peak electromagnetic field, polarity, reporting sensors, etc. To promote the lightning detection capacity at the junction of surrounding provinces, since 1 June 2010, the LLS of Guangdong Power Grid has been merged into a big regional lightning location network covering five provinces (Guangdong, Guangxi, Guizhou, Yunnan and Hainan) governed by China Southern Power Grid and started in trial operation. Currently, the LLS of Guangdong Power Grid has longest continual and stable operation time in China, by which historical observation of lightning location data in Guangdong province for nearly 15 years have been accumulated. A detailed discussion of LLS of Guangdong Power Grid is given by Chen et al.[2002]. Fig. 1 indicates the distribution of the lightning detection sensors, experiment sites of triggered lightning and observing room of nature lighting flashes on high structures.

2.2 Triggered Lightning Experiment

The rocket-triggered lightning experiment was conducted at Conghua, Guangzhou, employing both classical-triggered and altitude-triggered method. The lightning current of triggered lightning could be directly measured with the 1mΩ coaxial shunt. A oscilloscope named DL750(Yokogawa) was adopted as the recording system (sampling rate: 10M, record time≥1s), and could synchronously record such data as lightning current, fast and slow electric field change and broadband magnetic variation. Specially assigned persons were in the rocket launching control room and the optical observation room to record the triggered lightning process with high-speed cameras and common video cameras. For all triggered lightning experiments, the GPS seconds information at the moment of successfully triggering lightning were also recorded manually. A detailed discrimination of the triggered lightning experiment was presented by Zhang et al. [2011].

2.3 Observation of Nature Flashes on High Structures

Most high structures in Guangzhou city are located at Zhujiang New Town area, and an observation experiment of lightning flashes on high structures was conducted since the summer of 2009 [see Lu et al., 2010]. The observation room was situated at the top of a Building of Guangdong Meteorological Bureau (about 100m over the ground). Zhujiang New Town Lies about 2-3 km to the south-east of the observation room. Within the view of observation equipment, the International Financial Centre (432m) and CANTON Tower (with a height of 610 m in 2009 and finally 600 m in 2010) as well as many buildings with a height of over 200m are included. The main observation equipments consist of Lightning Attachment Process Observation System (LAPOS, Wang et al., 2011), high-speed camera, fast and slow electric antenna, broadband magnetic antenna, thunder acoustics recording system, etc., all of which could synchronously record optical, electrical, thunder acoustical and other comprehensive observation data with accurate GPS time information. During 2009-2011, at least one high speed camera was set with sampling rate greater than 1,000 frames per second and recording time greater than 1 second, which could provide optical evidence with sufficient temporal resolution and duration for comparison with LLS data.

3. DATA AND METHODOLOGY

A total of 43 lighting discharges were triggered successfully during 2007-2011, out of which 28 contained at least one or more return stroke process. The return stroke process as well as the inter-stroke interval time could be independently or comprehensively identified according to such records as lightning current, fast and slow electric variation as well as waveform of magnetic field. But for various reasons, not all observation data records could be achieved in each experiment.

During 2009-2011, a total of 30 natural lightning flashes were acquired for comparison with lightning location records, and all of them contained confirmable one or more return stroke process. Every return stroke event and the corresponding occurrence time of natural lightning flashes could be identified from the GPS time-synchronously observed records of electric-magnetic variation and high-speed camera. For recorded natural lightning flashes occurred within the view range of high-speed cameras, most grounding points of which were on the top of high-rise buildings (the height is over 100m, and the maximum height about 610m), and could be directly confirmed. In case that obstructed by nearer buildings or ground objects, a small number of natural lightning grounding points could not be directly confirmed, and the view angle of high-speed cameras, thunder acoustical difference, etc. would be adopted to confirm them. If the main channel of return stroke of natural flash was out of the view range of all high-speed cameras, but near the observation room, the location of grounding points could possibly be determined according to the view angle, thunder acoustical difference, actual distribution of buildings around the observing room, etc.

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

a) As for return strokes of natural lightning or triggered lightning with precise GPS time information, directly search records from the LLS database within 100ms before and after the occurrence time.

b) As for return strokes of triggered lightning without precise GPS times information, considering the uncertainty of the manually recorded time, first search the LLS records in such scope limited to 5 seconds before and after the manually recorded time of triggered lightning, and then comprehensively judge whether the record corresponds to the stoke event in conjunction with inter-stroke intervals and the number of reporting sensors.

4. RESULTS

4.1 Detection Efficiency

During 2007-2011, the LLS detected 25 flashes out of 28 triggered flashes which contained at least one return stroke processes, and 37 return strokes out of the affirmable all 82 return strokes. The flash detection efficiency was about 92%, and stroke detection efficiency about 45%, for triggered lightning. Table 1 showed the detection of triggered lightning by LLS.

During 2008-2011, the directly measured peak currents were obtained for a total of 29 strokes in triggered lightning, out of which 22 were detected by LLS. Fig. 2 showed the stroke detection efficiency as a function of measured peak current. When the absolute peak current of return stroke was greater than 15kA, the detection efficiency was 100%, but decreased to 50% (7/14) when the peak current was less than 15kA, and only 33% (1/3) in case the peak current less than 10 kA.

For the 30 nature flashes on high-rise buildings observed during 2009-2011, LLS successfully detected all of them with 100% flash detection efficiency. According to the comprehensive photoelectromagnetic observation data, we could affirm that these nature flashes contained a total of 70 return strokes, out of which the LLS detected 59 strokes. The stroke detection efficiency for nature lightning was estimated to be about 84%. Table 2 showed detection results of natural lightning by LLS.

From 2007 to 2011, we obtained observation of 58 lightning flashes (both triggered flashes and nature flashes) with at least one or more return stroke process. The LLS detected 53 flashes out of them. Wherein, 96 in the all 152 confirmable return strokes were detected. The flash detection efficiency of the LLS was about 95%, and the stroke detection efficiency was about 63%.

4.2 Locating Accuracy

From 2007 to 2011, 33 return strokes of classical-triggered lighting were detected by the LLS with more than 2 reporting detection sensors involved in the location retrieval. The locating error was within the range of 111 to 5,250m, and the arithmetical mean locating error was about 759m. The situation is shown in Fig. 3a.

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. From 2007 to 2011, 13 return strokes of altitude-triggered lightning were detected by the LLS with more than 2 reporting detection sensors. The distance from the locating point to the rocket launcher was within the range of 343 to 1,271m, and the arithmetical mean distance was about 675m. This relatively accorded with the actual situation. The locating result of altitude-triggered strokes was shown in Fig. 3b.

During 2009-2011, 53 return strokes of natural lightning with affirmable grounding points were detected by the LLS with more than 2 reporting detection sensors. The location errors were in the range of 76-3,109m, among which, 31 locating errors were less than 500m, 14 were in the range of 500-1,000m, 5 were in the range of 1,000-1,500m and 2 were greater than 2,000m. The arithmetical mean location error was about 626m. 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, without so distinctly south-directional abnormal tendency as shown in Fig. 3.

. Fig. 5 showed the absolute location error plotted versus the number of reporting LLS sensors involved in location retrieval, for a total of 96 lightning strokes with affirmable grounding points. It can be found from this figure that major errors may occur in the records with only 2 reporting sensors. However, with the increase of the number of reporting sensors, absolute location errors were not on a distinct decline. When more than 2 reporting sensors were involved in the location retrieval, the arithmetic mean locating error was calculated at about 677m (based on 86 samples).

4.3 Peak current estimates

In the 2007 triggered lightning experiment, directly measurement of peak current of return stroke was not obtained due to various reasons. From 2008 to 2011, for 22 return stroke processes of artificially triggered lightning, both the directly 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 16:32:47 on 22 June 2009, the direct measurement (-13.7kA) of the peak current was considerably different from that value estimated by the LLS (-44.0kA). To avoid possible mistakes, this abnormal sample was not presented in the following statistical analysis. Fig.6 showed the peak current estimated by LLS versus peak current measured directly (based on 21 samples). From this figure it could be found that 11 peak currents were over-estimated while 10 under-estimated. The absolute percentage errors of peak current estimation were within the range of 0.4%-42%, and the arithmetic mean value was about 16.3%. Furthermore, the two datasets, of the directly or indirectly measurement of peak currents, showed a good linear relationship, with the correlation coefficient of about 0.92.

5. SUMMARY AND DISCUSSION

In this paper, the performance characteristics of LLS of Guangdong Power Grid was evaluated based on the observation data of triggered lightning obtained in Conghua during 2007-2011 as well as nature lightning flashes on high structures obtained in Guangzhou during 2009 to 2011. The results showed that the flash detection efficiency was about 95% (55/58), and stroke detection efficiency was about 63% (96/152). The arithmetic mean locating error was estimated to be about 677m when more than 2 reporting sensors involved in the location retrieval (based on

86 samples). After eliminating the one obviously abnormal sample, the absolute percentage errors of peak current estimation were within 0.4% to 42%, with arithmetic mean value of about 16.3% (based on 22 samples).

Compared with the cases of artificially triggered lightning, both the flash detection efficiency and the stroke detection efficiency seemed to be higher for nature lightning. This may be due to the fact that first strokes in nature lightning typically have larger peak currents than the subsequent ones, which could be considered to have similar characteristics of return strokes in the triggered lightning. Considering that triggered lightning usually occurs under such immature electrical environment that nature CG flash would not be initiated instantly without the presence of fast ascending wire-connected rocket, the peak current of return strokes of triggered lightning may possibly be relatively weak. We found that the stroke detection efficiency was 100% (30/30) for first strokes in the nature lightning flashes observed, and 73% (29/40) for subsequent strokes. However, seen from the arithmetic mean locating error, there is a slight difference between the triggered lightning strokes and the nature ones.

Since June 1, 2010, the LLS of Guangdong Power Grid has been incorporated into a big regional lightning location system network covering five provinces under the administration of China Southern Power Grid (Guangdong, Guangxi, Guizhou, Yunnan and Hainan). However, based on the lightning observation given above, no obvious increase has been found in lightning detection efficiency of LLS after 2010. This may be partly because that the areas benefit from the LLSs incorporation will mainly located at the junctions of the provinces, not the lightning observation experiment sites in the central area of Guangdong Province referred to in this paper.

According to the comprehensive experimental observation data, all the nature and the triggered lightning strokes were with negative polarity except that the first return stroke of natural lightning happened at 17:54:15, July 29, 2010 was with positive polarity. All these polarities were identified accurately by the LLS. The only one bipolar nature lightning flash mentioned above includes 6 return strokes in total, while the LLS detected the first return stroke with positive polarity and 4 subsequent return strokes with negative polarity, and the locating errors were all in the range from 300m to 500 without distinct difference.

Diendorfer [2010] made a performance validation for Austrian Lightning Detection & Information System (ALDIS) based on observation of lightning on Gaisberg Tower during 2000-2005, and pointed out that the flash detection efficiency, stroke detection efficiency and median locating error was about 95%, 85% and 368m respectively. Nag et al. [2011] recently proceeded with the evaluation for performance characteristics of NLDN using rocket-triggered lightning data acquired at the ICLRT during 2004-2009. They found that the resultant flash and stroke detection efficiency were about 92% and 76% respectively. They also calculated the median location error to be about 308 m and the median absolute value of peak current estimation errors to be about 13%. Thus, in comparison with the mentioned two LLSs which have been put into operation for many years, the LLS of Guangdong Power Grid seemed to have similar performance characteristics in flash detection efficiency as well as the peak current estimation, but slightly low stroke detection efficiency and bigger location error. With the constant development of lightning experiments, observation data will be accumulated continuously. This will be good for more reliable performance evaluation of LLS.

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Table 1. Summary of Flashes and Strokes Recorded in Triggered Lightning Experiment during 2007-2011, Along with Corresponding LLS Detection Efficiency [a]

Year	Number of Flashes Triggered	Number of LLS Detected Flashes	Flash Detection Efficiency	Number of strokes confirmed	Number 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%	6	3	50%
2011	8	7	88%	12	7	58%
2007-2011	28	25	92%	82	37	45%

[a] Flashes which contained no return strokes were not included in this study.

Table 2. Summary of Flashes and Strokes Recorded in Observation Experiment for Nature Lightning On High Structures during 2009-2011, Along with Corresponding LLS Detection Efficiency.

Year	Number of Flashes	Number of LLS Detected Flashes	Flash Detection Efficiency	Number of strokes confirmed	Number of LLS detected strokes confirmed	Stroke Detection Efficiency
2009	8	8	100%	15	15	100%
2010	9	9	100%	15	14	93%
2011	13	13	100%	40	30	75%
2009-2011	30	30	100%	70	59	84%

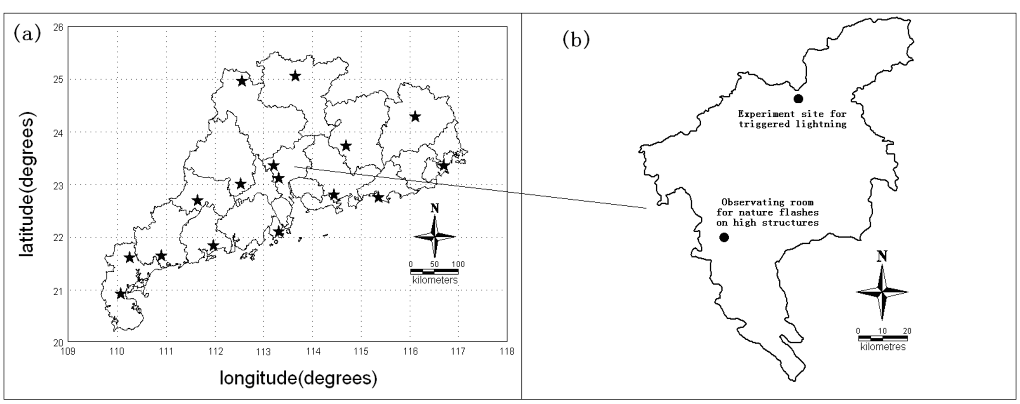

Figure 1. Distribution of sensors of LLS of Guangdong Power Grid (a), and observation experiment sites for lightning (b).

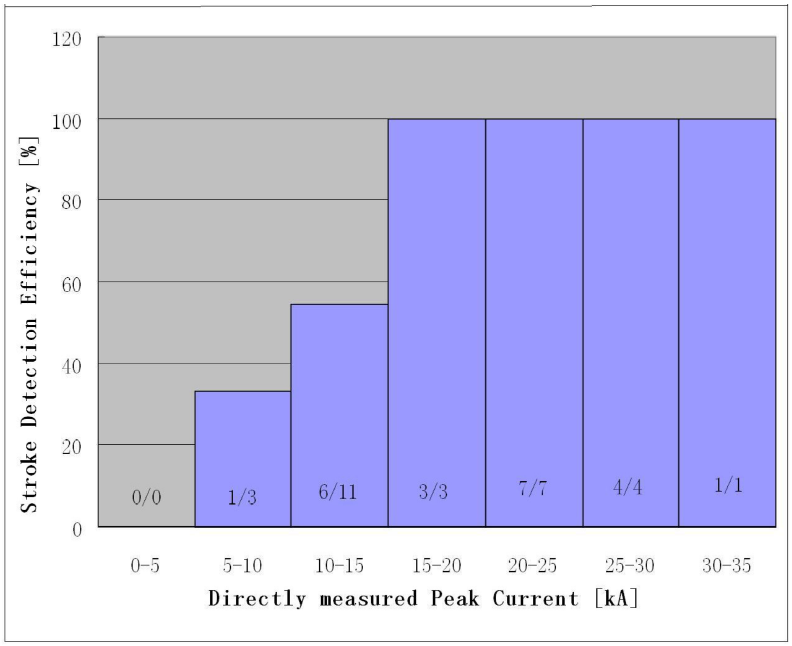

Figure 2. Stroke detection efficiency as a function of peak current measured directly in the triggered lightning experiment. The ratio given inside the column indicates the number of strokes detected by LLS (numerator) and the number of strokes recorded in the triggered lightning experiment (denominator).

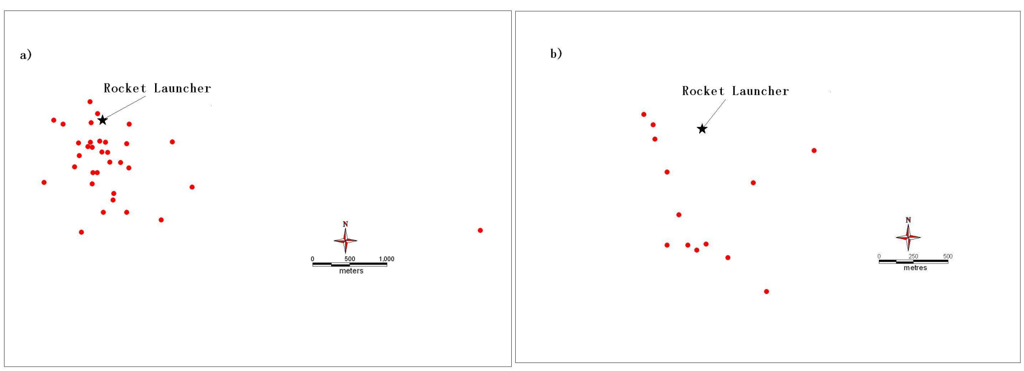

Figure 3. Plot of 33 stroke locations in Classical-triggered Lightning Experiment (a) and 13 strokes locations in Altitude-triggered Lightning Experiment (b) during 2007-2011.

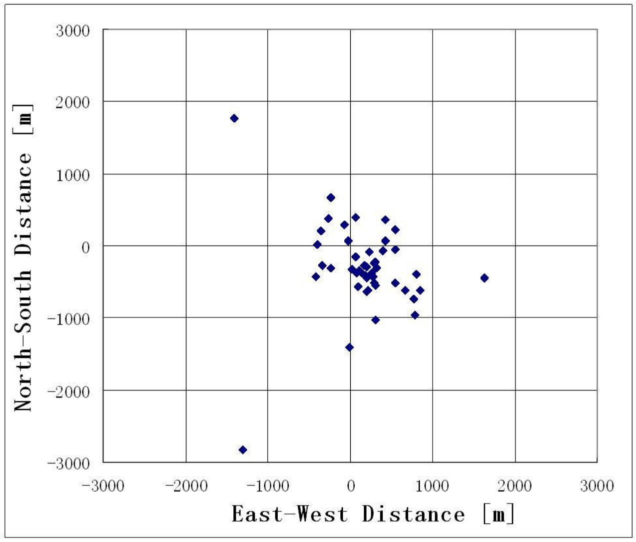

Figure 4. Plot of 53 stroke locations in nature lightning on high structures during 2009-2011. The origin corresponds to the stroke grounding point.

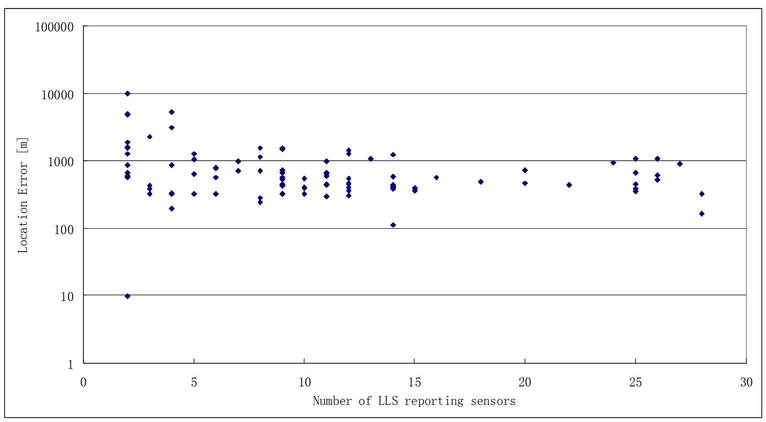

Figure 5. Absolute location error versus number of LLS reporting sensors for 96 strokes observed in triggered lightning and nature lightning during 2007-2011.

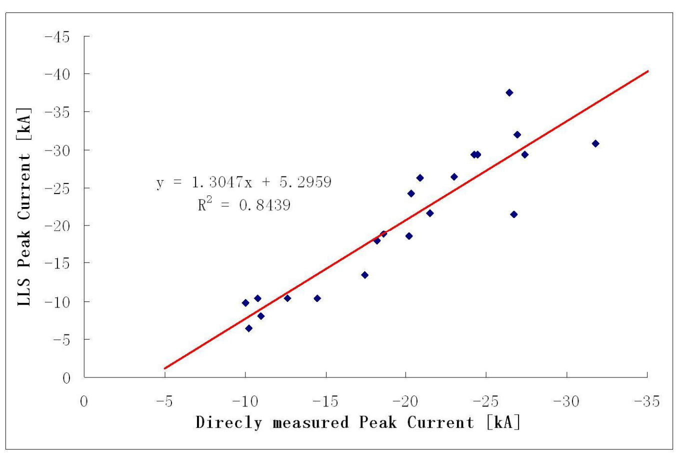

Figure 6. LLS-reported peak current versus directly measured in triggered lightning experiment.