2014
23rd International Lightning Detection Conference
18 - 19 March • Tucson, Arizona, USA
5th International Lightning Meteorology Conference
20 - 21 March • Tucson, Arizona, USA

Evaluation for the performance of the Guangdong-Hongkong-Macau Lightning Location System

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Abstract—**In this paper, the performance characteristics of the Guangdong-Hongkong-Macau Lightning Location System (GHMLLS) was evaluated based on observations of lightning flashes triggered at the Guangzhou Field Experiment Site for Lightning Research and Testing during 2007-2013, and natural lightning flashes to tall structures in Guangzhou during 2009-2012. Both experiment sites are located in the center area of the GHMLLS after the upgrade in 2012, but slightly outside of that before 2012. Considering the significant increasing of the number of sensors in 2012, the evaluations were performed according to two different periods of 2007-2011 and 2012-2013 respectively, and the performance characteristics during the two periods were compared. The results show that the flash detection efficiency, stroke detection efficiency, the arithmetic mean value and median value for location error were estimated to be about 64%, 22%, 2 330 m and 1 370 m for triggered lightning during 2007-2011, while the corresponding values were about 86%, 91%, 590 m and 400 m during 2012-2013. The flash detection efficiency, stroke detection efficiency, the arithmetic mean value and median value for location error were estimated to be about 82%, 58%, 2 820 m and 930 m for natural lightning during 2009-2011, while the corresponding values were about 97%, 90%, 950 m and 470 m during 2012. Directly measurement of peak current of return strokes of triggered lightning was not obtained in 2007 due to various reasons. During 2008 to 2011, for 14 return stroke processes of artificially triggered lightning, both the directly measurement of peak currents and the corresponding GHMLLS records were obtained. 13 out of the 14 peak currents were underestimated by GHMLLS and only one was overestimated, and the absolute percentage errors of peak current estimation were within 16.2% to 96.2%, with arithmetic mean value and median value of about 34% and 26%. On the other hand, during 2012-2013, all the 32 peak currents , both the directly measurement of peak currents and the corresponding GHMLLS records were obtained, were overestimated by GHMLLS, and the absolute percentage errors of peak current estimation ranged from 31% to 421%, with arithmetic mean value and median value of about 217% and 220%. When the number of sensors was significantly increased in 2012, the detection efficiency and location precision of GHMLLS were found to be obviously improved, but the peak currents of return strokes were abnormally overestimated.**

Keywords—Lightning Location System; Performance; Triggered Lightning; Natural Lightning

I. INTRODUCTION

The detection efficiency and location accuracy are considered to be the most important performance indexes for Lightning Location System (LLS). Recently, many researchers conducted performance evaluation for LLSs based on different methods. 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 location error was about 95%, 85% and 368 m respectively. Nag et al. (2011) proceeded with the evaluation for performance characteristics of NLDN using rocket-triggered lightning data acquired at the ICLRT during 2004-2009, and found that the flash detection efficiency, the stroke detection efficiency, the median location error, and the median absolute value of peak current estimation errors was 92%, 76%, 308 m and 13% respectively. Chen et al. (2012), conducted performance evaluation for lightning location system of Guangdong Power Grid based on the observation data of the triggered lightning flashes during 2007-2011 and natural lightning flashes during 2009-2011, they found that the flash detection efficiency and stroke detection efficiency were about 94% and 60%, and the median location error, and the median absolute value of peak current estimation errors was 489 m and 19.1%.

The Guangdong-Hongkong-Macau Lightning Location System (GHMLLS) was jointly established by the Guangdong Meteorological Bureau, the Hong Kong Observatory and the Macao Meteorological and Geophysical Bureau since 2005. Recently, the GHMLLS was upgraded in 2012. In this paper, the performance characteristics of the GHMLLS was evaluated based on observations of lightning flashes triggered at the Guangzhou Field Experiment Site for Lightning Research and Testing during 2007-2013, and natural lightning flashes to tall structures in Guangzhou during 2009-2012. Considering the significant increasing of the number of sensors in 2012, the evaluations were performed according to two different periods of 2007-2011 and 2012-2013 respectively, and the performance characteristics during the two periods were compared.

II. OBSERVATION SYSTEM

A. GHMLLS

The GHMLLS was originally built in 2005, when 5 IMPACT sensors were set. Then, in 2007, one more IMPACT sensor was added. In 2012, 11 LS-7000 sensors were also integrated into the lightning location network, 10 sensors of which were set in Jan 2012 and 1 was set in Sep 2012. Up to now, the GHMLLS comprises a total of 17 sensors and covering most areas of Guangdong province, China. The combined MDF/TOA technology is used to detect CG lightning stroke information such as longitude and latitude, GPS time, peak current, polarity, reporting sensors, error ellipse, etc. Figure 1 indicates the distribution of the sensors of GHMLLS, the site of triggered lightning experiment, and site of natural lighting observation.

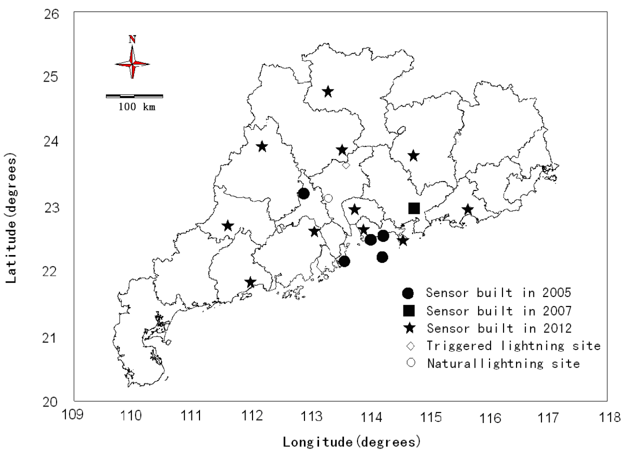

Fig.1 Distribution of sensors of GHMLLS, observation experiment sites for triggered lightning and natural lightning on tall structures.

B. Triggered Lightning Experiment

The rocket-triggered lightning experiment was conducted at Conghua, Guangzhou, using both classical-triggered and altitude-triggered technology. 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 to the lightning rod. The instruments used in experiments included electric field mills with a sampling rate of 1 Hz, flat-plate fast antennae with a time constant of 2 ms and a band-width of 1 kHz–2 MHz, flat-plate slow antennae with a time constant of 6 s and a band-width from 1 Hz to 3 MHz, wide-band loop magnetic antenna with a band-width of 100 Hz–5MHz, high-speed cameras and common video cameras. A coaxial shunt with a resistance of 1 mΩ, measurement range of 0-100 kA, and bandwidth of 0-200 MHz, 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:10MHz, recording length ≥1 s, pre-trigger length=20%), to synchronously record such data as lightning current, fast and slow electric field change, wide-band magnetic variation and GPS pulses per second (PPS). A GPS module was used to stamp the trigger time of the Data Acquisition Card with precision<50 ns. A detailed description of the triggered lightning experiment was presented by Zhang et al. (2014).

C. Observation of Natural Flashes to Tall Structures

Most tall structures in Guangzhou city are located at Zhujiang New Town area, and a field observation experiment of lightning flashes striking on tall structures was conducted since the summer of 2009 (see Lu et al., 2010, 2013). 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 (with a height of 440m) 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 equipment included Lightning Attachment Process Observation System (LAPOS, Wang et al., 2011), high-speed camera (FASTCOM SA-5, frame rate>1000fps, recording length≥1s, pre-trigger length=20%), fast and slow antenna, wide-band magnetic antenna, thunder acoustics recording system, etc. An oscilloscope (Yokogawa Model DL-750) was used as the primary recording system (sampling rate: 10MHz, recording length≥1s, pre-trigger length=20%) to synchronously record LAPOS, fast and slow antenna, wide-band magnetic antenna, and GPS pulses per second (PPS). The LAPOS consists of a camera, an optical fiber array, multiple photodiodes and their amplifiers. The fiber array is mounted at the camera's film plane. When a lightning occurs in the view of camera, its image formed by the camera lens is first guided by the optical fibers to the photodiodes. Then it is converted to 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 put out trigger signal to high speed cameras, a portable oscilloscope (sampling rate: 100kHz, recording length =35s, pre-trigger length=14%) recording the thunder acoustical signal, and also to a GPS module which stamp the trigger time with precision<50 ns. During 2009-2012, at least one high speed camera was set with sampling rate greater than 1,000 frames per second and recording length greater than 1 second, which could provide optical evidence with sufficient temporal resolution and duration for comparison with LLS data

III. DATA AND METHODOLOGY

A total of 35 lightning flashes, each of which contained at least one return stroke, were successfully triggered during 2007 -2013. 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, waveform of fast and slow change as well as magnetic field. But for various reasons, not all observation data records could be achieved in each experiment.

During 2009-2012, a total of 70 natural lightning flash observations were successfully acquired for comparison with lightning location records, and all of them contained one or more return strokes. All the 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 change and high-speed camera. For recorded natural lightning flashes that occurred within the view range of high-speed cameras, most grounding points were on the top of high-rise buildings (the height is over 100m, and the maximum height about 610m), 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 grounding point was deduced from the time difference between trigger and the thunder acoustical signal arrival (acousto-optic time difference), and the obstructed lightning grounding points could be possibly confirmed taking into account the actual distribution of 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.

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 precise GPS trigger time stamp, GHMLLS database records were directly searched within ±2 ms before and after trigger time. As the result, the matched GHMLLS record was found to be within ±1 ms for the matching results.

b) For triggered lightning flashes without precise GPS trigger time stamp, while the GPS pulses per second （PPS） along with the electromagnetic field synchronously recorded by DL-750 oscilloscope was available, GHMLLS database records were firstly searched within a time period ±5 s before and after the manually recorded trigger time and 20km radius around the experiment site. Though the second information could not be proved by the wave form of PPS, the millisecond information of occurrence time of each stroke could be derived by comparing the waveforms of PPS and electromagnetic field. Then the inter-stroke intervals were used to match each triggered stroke with the corresponding GHMLLS record considering the millisecond information of occurrence time of each stroke. As a result, second difference between triggered stroke and the matched GHMLLS record was found to be within ±1 s, and millisecond difference within ±1 ms for all matching results.

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

d) For natural lightning flashes, GPS stamped trigger time were available in all experiments, and a procedure similar to a) was performed.

IV. RESULTS

A. *Detection Efficiency*

During 2007-2013, the GHMLLS detected 24 flashes out of 35 triggered flashes which contained at least one return stroke processes. Furthermore, the exact number of return strokes in 28 flashes out of 35 triggered flashes could be confirmed and summed to be 116, while 50 out of them were detected by GHMLLS. Table 1 shows the detection of triggered lightning by GHMLLS.

Table 1. Summary of Flashes and Strokes Recorded in Triggered Lightning Experiment during 2007-2013, Along with Corresponding GHMLLS Detection Efficiency

Year	Number of Triggered flashes	Number of detected flashes	Flash detection efficiency	Number of confirmed strokes	Number of detected strokes	Stroke detection efficiency
2007	11	5	45%	52	5	9%
2008	3	3	100%	10	6	60%
2009	1	1	100%	2	1	50%
2010	5	4	80%	5	2	40%
2011	8	5	62%	12	4	33%
2012	2	2	100%	8	7	87%
2013	5	4	80%	27	25	93%

For the 70 natural flashes to high-rise buildings observed during 2009-2012, GHMLLS successfully detected 63 out of them. According to the comprehensive photo-electromagnetic observation data, it could be confirmed that these natural flashes contained a total of 188 return strokes, out of which the GHMLLS detected 143 strokes. Table 2 shows detection results of natural lightning by GHMLLS.

Table 2. Summary of Flashes and Strokes Recorded in Observation Experiment for Natural Lightning to Tall Structures during 2009-2012, Along with Corresponding LLS Detection Efficiency

Year	Number of natural flashes	Number of detected flashes	Flash detection efficiency	Number of confirmed strokes	Number of detected strokes	Stroke Detection efficiency
2009	8	8	100%	15	13	87%
2010	11	9	82%	19	17	89%
2011	15	11	73%	47	17	36%
2012	36	35	97%	107	96	90%

During 2007 to 2011, before the GHMLLS was upgraded in 2012, observation of 62 lightning flashes (both triggered flashes and natural flashes) with at least one or more return stroke process was obtained, and the GHMLLS detected 46 flashes out of them. The exact number of return strokes for 55 lightning flashes was affirmable and amount to 162, wherein, 65 were detected by GHMLLS. The flash detection efficiency was about 74%, and the stroke detection efficiency was about

40% before 2012. After the GHMLLS was upgraded in 2012, the flash detection efficiency and stroke detection efficiency was improved to be 95% (41/43) and 90% (128/142) respectively.

B. Location Accuracy

During 2007 to 2011, 20 return strokes of classical-triggered lighting were detected by the GHMLLS. The location errors were in the range of 330 - 7,750 m . The arithmetical mean location error was about 2,330 m, while the median location error was about 1,350 m. During 2007 to 2011, 5 return strokes of altitude-triggered lightning were detected by the GHMLLS. 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 2009-2011, 41 return strokes of natural lightning with affirmable grounding points were detected by the GHMLLS. The location errors were in the range of 200 - 14,450 m. The arithmetical mean location error was about 2,830 m, while the median value was about 1,005 m.

After the GHMLLS was upgraded in 2012, the location errors was found to be within the range of 60-3,530 m for 32 classical-triggered lighting strokes during 2012-2013, with the arithmetical mean and median value of 590 m and 300m respectively. Furthermore, 66 return strokes of natural lightning with affirmable grounding points were detected by the GHMLLS in 2012, and the location errors were in the range of 10 – 3,850 m. The arithmetical mean location error was about 940 m, while the median value was about 410 m.

In a whole, the arithmetical mean and median value of location error of GHMLLS was 2,660 m and 1,290 m respectively (based on 61 classical-triggered or natural strokes) before GHMLLS was upgraded in 2012, while 830 m and 410 m after the upgrade (based on 98 classical-triggered or natural strokes).

Figure 2 shows the special distribution of location errors for both triggered and natural lightning strokes. As a matter of convenience, the actual lightning stroke points are unified to the original point (0,0).

C. Peak current estimates

Directly measurement of peak current of return strokes of triggered lightning was not obtained in 2007 due to various reasons. During 2008 to 2013, for 46 return stroke processes of artificially triggered lightning, both the directly measurement of peak currents and the corresponding GHMLLS records were obtained. Figure 3 shows the peak current estimated by GHMLLS versus peak current measured directly. From this figure it can be seen that peak currents were a little under-estimated during 2008-2011, but significantly over-estimated during 2012-2013 after the GHMLLS was upgrade. The arithmetic mean and median value of absolute percentage errors of peak current estimation were calculated to be 34% and 26% during 2008-2011, while 217% and 220% during 2012-2013.

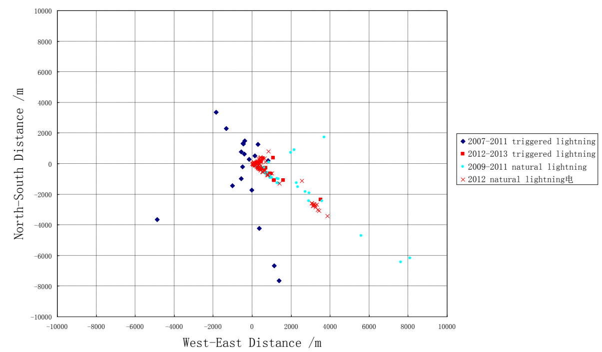

Fig 2. Plots of GHMLLS locations versus the corresponding actual strike point （0,0）

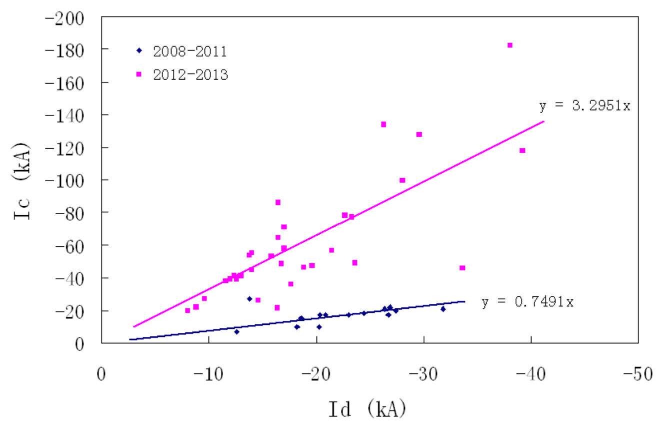

Fig 3. GHMLLS-reported peak current versus directly measured in the triggered lightning experiment.

Note that the lightning current measurement system for the trigger lightning remained unchanged before and after 2012. Base on the same data obtained from the triggered lightning experiment during 2008-2011, Chen et al (2012) found that the linear regression between the peak current estimated by the LLS of Guangdong Power Grid and the directly measurement system was $y = 1.3047x + 5.3$ (based on 21 samples). Furthermore, when we use the data obtained during 2012-2013, the linear regression was found to be $y = 1.3568x + 5$ (based on 32 samples). The linear relation between the peak current estimated by the LLS of Guangdong Power Grid and the directly measurement system seems to be very close between 2008-2011 and 2012-2013. On the other hand, this situation shows that the directly measurement of peak current of return strokes of triggered lightning was reliable, and the abnormally over-estimated peak currents of GHMLLS may be due to the upgrade in 2012.

V. SUMMARY AND DISCUSSION

In this paper, the performance characteristics of GHMLLS were evaluated based on the observation data of triggered lightning obtained in Conghua during 2007 to 2013 as well as natural lightning flashes to tall structures obtained in Guangzhou during 2009 to 2012. The results showed that the flash detection efficiency and stroke detection efficiency was about 74% (46/62) and 40% (65/162) during 2007-2011, while 95% (41/43) and 90% (128/142) during 2012-2013. The arithmetic mean and median value of location error was estimated to be about 2,660 m and 1,290m during 2007-2011, while 830 m and 410 m during 2012-2013. The arithmetic mean and median value of absolute percentage errors of peak current estimation was 34% and 26% during 2008-2011, with 217% and 220% during 2012-2013.

As the result, the detection efficiency and the location precision of GHMLLS were greatly improved after the upgrade in 2012. In comparison with the three LLSs mentioned in the introduction, which have been put into operation for many years, the GHMLLS seemed to have the similar performance characteristics in detection efficiency and location precision.

On the other hand, after the GHMLLS was upgraded in 2012, the peak currents were abnormally over-estimated. The reason is not clear.

ACKNOWLEDGMENT

This research is supported by National Natural Science Foundation of China (41030960), National Key Basic Research Program of China (2014CB441406) and Project Supported by the Special Project for Commonweal Industry Scientific Research of China (GYHY201006005).

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