Evaluation of location efficency by comparing lightning faults on overhead transmission lines and Blitzortung

Tomomi Narita, Shonan Institute of Technology, Japan

Abstract

We evaluated the location efficiency and location accuracy of Blitzortung, a lightning location device introduced in Japan. We compared data from 91 transmission line lightning faults in 2019 that matched LLS with Blitzortung data. As a result, the location efficiency was 88% and the median position accuracy was 1.7 km. Moreover, of the 11 cases that were not located, the six-station-simultaneous conditions were changed to four-station-simultaneous conditions and re-calculated, after which another four cases could be located. Therefore, 84 out of 91 cases (92 %) could be located.

1 Introduction

There are massive economic losses caused by disasters due to lightning discharge. A lightning location device is required for preventing public disasters such as water damage and power outages caused by sudden rainfall and lightning discharges associated with cumulonimbus clouds. Previous commercial lightning location systems (LLS) include those from weather companies [1][2][3] or electric power companies [4][5][6], but only visual information displayed on a coarse-resolution map is available for free, with detailed data either being private or requiring fees. Table 1 shows an overview of the various lightning location devices. LF and VLF bands are the two frequency bands used, and both lightning location methods use the time of arrival (TOA) difference method. Meanwhile, improvements in IT technology have made it easier to control devices and sensors via networks, and devices can now be cheaply obtained. Therefore, we used cheap devices that used IT technology to participate in the "Blitzortung" project, which aimed to achieve a global-scale and high-accuracy lightning location network. This project was started in 2012 by Professor Egon Wanke at the Heinrich Heine University Düsseldorf in Germany and his colleagues, and it is operated by volunteers who manufacture and install lightning observation devices by soldering receiving stations themselves. Lightning-related data, such as the coordinates of lightning locations, are made available free of charge on the Internet in real-time. The version has been changed to a Green-system in 2012, Red-system in 2013, and Blue-system in 2016.

The Blitzortung receiving stations have thus far been deployed mainly in the United States, Europe, and Oceania, and as of December 2023, approximately 2,300 receiving stations have been registered, of which about half, or 1,100, are in operation. In Japan, the Shonan Institute of Technology was the first station to be established in February 2016[9]. By December 2023, 60 stations were established nationwide, from Hokkaido to Okinawa and Ogasawara; and 20 stations were established overseas, in Mongolia, India, Bangladesh, Nepal, Myanmar, Thailand, Cambodia, Vietnam, the Philippines, Indonesia, Guam, Hawaii, and Samoa. Among the electromagnetic waves generated by lightning discharge, those in the VLF band reflect off the ionosphere and can reach long distances, making it possible to locate lightning discharges over a wide range.

In this report, we evaluated the location efficiency of Blitzortung as of 2019 by comparing it with lightning faults on transmission lines. As of 2019, there were 50 receiving stations in Japan.

Table 1. Comparison of lightning Location systems (LLS) in Japan

System	Frequency	Method	Operator	Free/ Fee	Area
JLDN[1][2][3]	LF	TOA	Company	Fee	Japan
Electric Power Company[4][5][6]	LF	TOA	Company	------	Japan
Meteorological Agency (LIDEN) [7]	LF	TOA	Government	Fee	Japan
WWLLN[8]	VLF	GTOA	University	------	World
Blitzortung	VLF	TOA	Volunteer	Free	World

2 Overview of receiving stations

2.1 Principles of lightning location

The Blitzortung LLS uses the TOA difference method[10][11][12] for lightning location, using the time difference when the electromagnetic waves that are generated during lightning discharge arrive at each receiving station. Once the TOA difference between two stations is known, then the locus of the solution of the electromagnetic radiation point becomes a single hyperbola. Therefore, if there are three receiving stations, then the lightning location can be located as the intersection of the hyperbolas. In Blitzortung, the minimum number of receiving stations is set to

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six, and if six stations did not receive a signal, then the result is treated as noise. Additionally, data with a calculated location error of over 15 km when the time accuracy was assumed to be 1 µs were excluded. This explanation is shown in Fig. 1. We set two receiving stations as site_1 and site_2, and we assume that the distance between them is 100 km, and that there is an underestimation by both stations of 1 µs, or 300 m. When calculating the distance from the midline of the line segment connecting site_1 and site_2 to the black circle where the lightning position is assumed, then $\sqrt{111503^2 - 50000^2}$ = 99664.0. Similarly, if both are overestimated by 1 µs, then $\sqrt{112103^2 - 50000^2}$ = 100334.9 = 100334.9. The difference between both is 671 m, which is defined as the deviation. The two black circle examples on the right side of the figure are the results calculated for the directions of 45 degrees and 60 degrees from site_2, and their deviations are 1878 m and 4318 m, respectively. The deviation becomes larger as the black circle locations move further to the right. In other words, the error in the location calculation due to the TOA difference becomes larger. Furthermore, in this estimation, the baseline length between site_1 and site_2 was set to 100 km, but if the baseline length changes, then the results will also change, and the deviation will become larger when locating a site far away or close to the baseline direction using a short baseline. Therefore, a large deviation will result in a large error even when calculating the lightning location, so the settings as such that there is no output. This standard is defined as the maximum deviation span (MDS), with a value of 15 km set for Blitzortung. Furthermore, cases where all the receiving stations used for orientation are within 90 degrees of the azimuth angle from the location point have large errors and were excluded as a result. This is defined as the maximum cycle gap (MCG), with an upper limit of 360 degrees – 90 degrees = 270 degrees, and location calculations are not output if the value is greater than this.

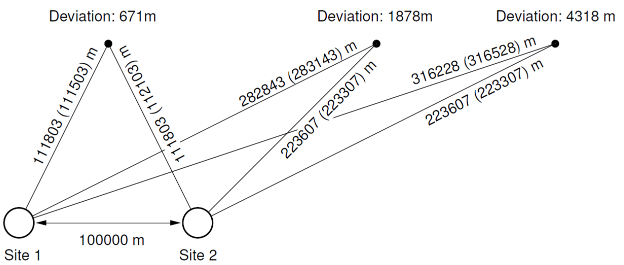

Figure 1. Deviation due to positional relationship between receiving station location and lightning point

2.2 System configuration

System configuration: The device consists of a magnetic field antenna amplifier, electric field antenna amplifier, GPS, GLONASS(13), and controller. The magnetic field antenna and electric field antenna were used to receive the magnetic and electric field components of the VLF band-electromagnetic waves generated by lightning discharge. A trigger is activated when the value exceeds a threshold, and at which point the time, receiving station coordinates, and waveform are recorded. The background noise varies depending on the surrounding environment of the receiving station, so the trigger level was automatically changed according to the background noise level. These data are sent to the server using the UDP method, and when lightning discharge waveforms are observed at six or more stations, then statistical processing is conducted so as to minimize the error, and the lightning location is calculated. This lightning position is displayed in almost real-time. The distance calculation also uses spherical coordinates. GPS and GLONASS are used to synchronize the receiving station time.

Table 2 displays the system specifications. The TOA difference method was used for the location method. For GPS and GLONASS, the Global Top PA6H GPS module was used to output a 1PPS signal. The synchronization accuracy was 10 ns on average. The magnetic field antenna consisted of two ferrite antennas approximately 20 cm long installed parallel to the ground in the east-west and north-south directions so that lightning discharge radio waves could be received from all directions. The electric field antenna was installed perpendicular to the ground in order to detect the vertical component of the electric field.

The sampling frequency for analog-to-digital conversion was 525 kHz. The Blitzortung system is a mixture of the old-version Red-System and the current-version Blue-System. A user purchases a printed circuit board and basic electronic components from Blitzortung, and the GPS antenna and other parts are purchased separately and assembled by the user themselves. The core CPU and A/D conversion used general-purpose ARM chips. These chips operated at a clock frequency of 168 MHz, had a 12-bit A/D converter, and a maximum performance of 1 Mbps (1-µs sampling possible).

Moreover, cloud-to-cloud does not involve a return stroke, so the current value is small, so the peak value of the magnetic field is small, and Blitzortung hardly locates.

Table 2. System specifications

Calculation method	Time of arrival
GPS&GLONASS (Time)	10ns
Antenna	Magnetic Field Antenna (East-West) Magnetic Field Antenna (South-North) Electric Field Antenna (Vertical antenna)
Sampling rate	525kHz
Observation frequency	1-50kHz (Magnetic Field) 5-50kHz (Electric Field)

The current-version Blue-System had a smaller surface mount device (SMD) than the Red-System, which facilitated assembly and installation. The size was 13 cm × 14 cm, making it small and lightweight. Power consumption was approximately 5 W.

2.3 Amplifier frequency characteristics

Figure 2 shows the frequency characteristics of the magnetic field amplifier. The magnetic field amplifier had a 1-kHz high-pass filter and a 50kHz low-pass filter, exhibiting almost flat frequency characteristics without falling below -3 dB from 1 kHz to 50kHz. The electric field amplifier had a 5kHz high-pass filter and 18kHz, 44kHz, and 50kHz low-pass filers, which allowed for reception in the 5kHz to 50kHz band range.

2.4 Amplifier input and output (I/O) characteristics

Figure 3 shows the I/O characteristics of the magnetic field amplifier. There is a linear relationship between the wavefront length of the input waveform and the wavefront length of the output waveform, and when the wavefront length of the input waveform is 9 µs or more, then the input wavefront length and output wavefront length become equal, so a value of 9 µs or more enabled a correct recording of the correct lightning discharge TOA. Generally, the wavefront length of the electromagnetic wave pulse associated with a return lightning strike is approximately 1–4 µs, so it is estimated that a delay of 2–1.5 µs would be present when applying this amplifier. However, in the TOA difference method, a hyperbola is drawn based on the difference in reception time of each receiving station, with the intersection used as the location point. Therefore, since all receiving stations record the same delay time even when less than 9 µs, it is estimated that there will be little impact on location calculations using the TOA difference method.

2.5 Dead time of receiving station

In the LLS, the location count changes depending on whether multiple lightning strikes are treated as a flash or a stroke. In a flash, all the multiple lightning strikes are counted as a single lightning strike; and in a stroke, the multiple lightning strikes are counted as individual lightning strikes. In order to evaluate how well Blitzortung can locate strokes, we set the pulse interval as a parameter and calculated the ratio of inputs to the magnetic field amplifier and the output count to the server in order to obtain the dead time, which is the time when data were missed. Specifically, a 100mV pulse wave was input to the magnetic field amplifier, the input count was set to 10, and the pulse interval time was changed from 1 ms to 20 ms in 1ms intervals, and the number of transmissions to the server was counted. Fig. 4 shows the verification results. The horizontal axis is the pulse interval time, and the vertical axis is the ratio between the output count and the input count. The dead time threshold was when the input and output ratio was 1, which was 8 ms for the Blue-System and 14 ms for the Red-System. According to references (14)(15), multiple lightning strikes mainly occurred at intervals of 30–80 ms. Additionally, their median values were 51–90 ms, and a dead time of 14 ms would be able to locate over 90% of lightning strikes. Therefore, it could be determined that Blitzortung was generally able to capture multiple lightning strikes and locate them at the stroke level.

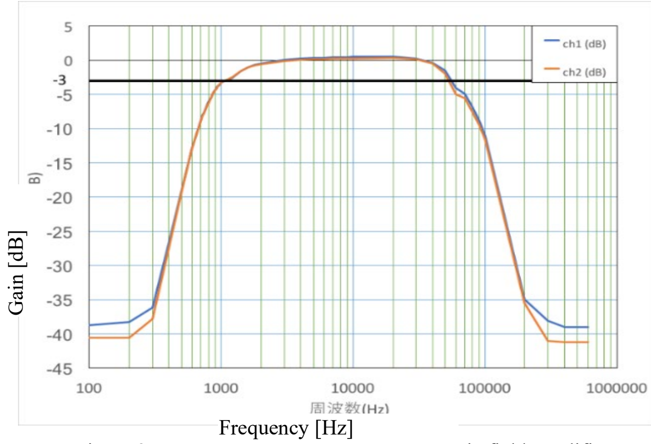

Figure 2. Frequency characteristics of magnetic field amplifier

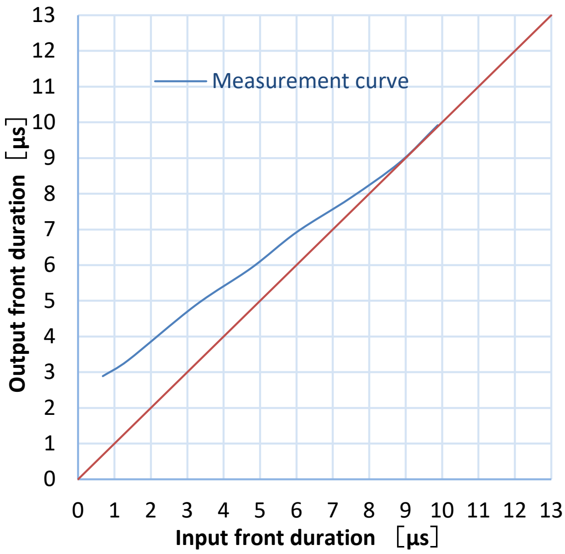

Figure 3. I/O characteristics of magnetic field amplifier

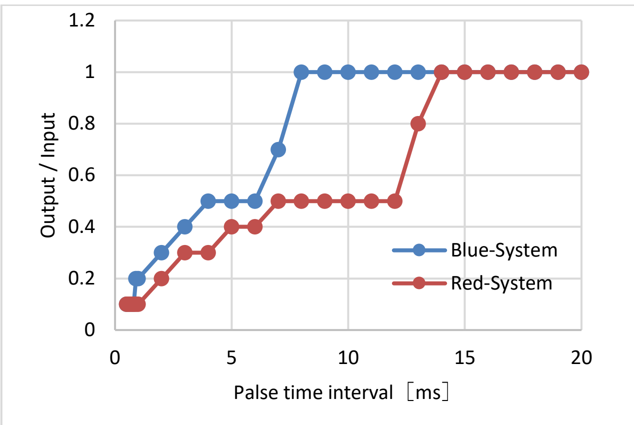

Figure 4. Blitzortung dead time

The above-mentioned amplifier, antenna, controller, etc., were combined and placed in its entirety in a waterproof box, which was then installed on the university rooftop. The power source used was a USB power supply of about 5 V and 1 A, with the device connected to the Internet. Fig. 5 shows the layout of the Blitzortung receiving stations in Japan as of 2019. The red circles are the receiving stations, with the stations places as far north as Hokkaido, as far south as Okinawa, and as remote as Chichijima on Ogasawara, with a total of 50 stations used to capture radio waves associated with lightning strikes that occur all over Japan.

3 Verification of location efficiency

Accurately determining the time and location of lightning strikes is necessary for evaluating the location accuracy of Blitzortung. However, this is difficult in practice, so we conducted evaluations using lightning fault data from electric power company transmission lines. The lightning faults point of the transmission line was compared with the Blitzortung lightning discharge time and position as the lightning strike time and position.

3.1 Comparison data

Of the lightning faults on 66–500-kV transmission lines in the Kanto region that occurred in 2019, 91 cases that matched the LF-band LLS were used for comparison. The target area was the area inside the square with latitudes of 34.68° to 37.15°, and longitude of 138.3° to 141.0°. Fig. 6 shows this range. Additionally, the concordance conditions for matching were that the LLS and Blitzortung time difference was within 100 µs, and the LLS and Blitzortung distance difference was within 20 km.

3.2 Location accuracy evaluation

Location accuracy evaluation: Of the 91 cases, 80 cases (approximately 88%) were located by Blitzortung. Of the 11 cases that were not located, the six-station-simultaneous conditions were changed to four-station-simultaneous conditions and re-calculated, after which another four cases could be located. Therefore, 84 out of 91 cases (92%) could be located.

Fig. 7 shows the Blitzortung location positions plotted with LLS as the center (reference). The median value of the 80 data points was 1.7 km. There was a tendency of an eastward bias in the plot. The main reason was thought to be that when the electromagnetic waves associated with lightning strikes in the Kanto Plain cross over the mountain range, a time delay occurred due to the propagation of surface waves along the mountain range. Fig. 8 also shows the distance distribution with distance as the horizontal axis. The data were approximately distributed from 1 km to 3 km. Table 3 shows the results of comparing lightning fault data on transmission lines and Blitzortung. For the 91 lightning faults, 80 were located by Blitzortung, for a location efficiency of 88%. The median location value for these data was 1.7 km.

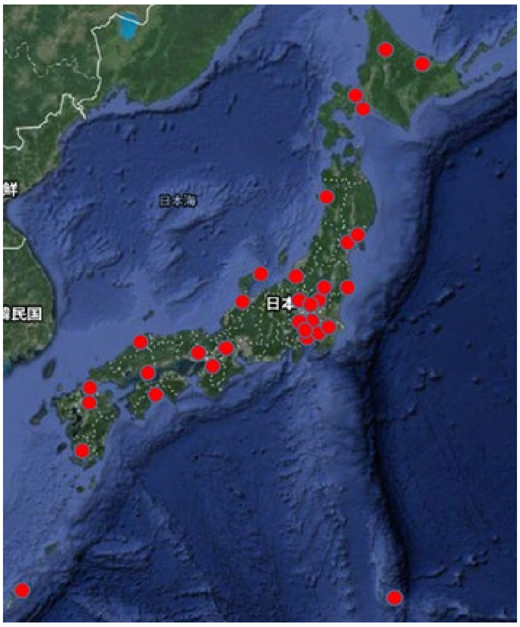

Figure 5. Locations of Blitzortung receiving stations in Japan (2019)

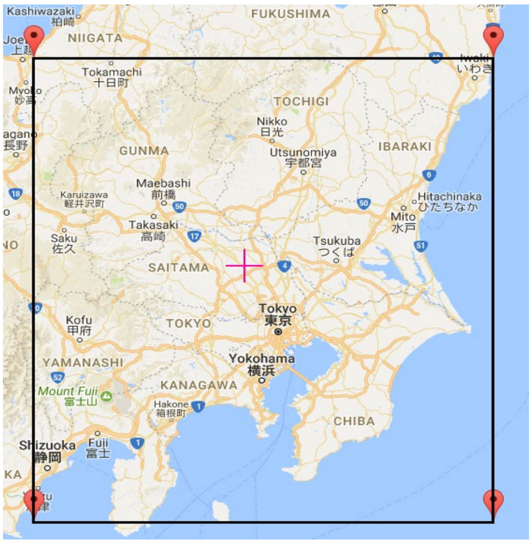

Figure 6. Area used for accuracy verification

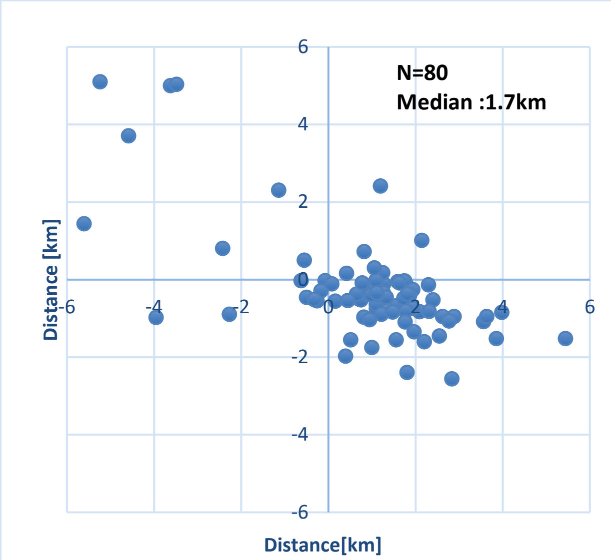

Figure 7. Blitzortung distribution with LLS as reference (N=80)

3.3 Current value evaluation

Figure 9 shows the distribution of estimated current values for the 91 cases located using LLS. At a current value of 50 kA or higher, all cases were located with Blitzortung.

The average current value for cases that were located with Blitzortung was -37 kA. Meanwhile, the average current value for cases that were not located with Blitzortung was -23 kA. Therefore, although it was thought that there were cases that could not be located in Blitzortung location when the current value was small, the location could be determined at almost the same level as LLS.

Additionally, lightning accidents occurred on transmission lines when the current value of a lightning strike was approximately 30 kA or higher, so it is estimated that there are issues with the current value estimated by LLS.

Table 3. Location efficiency of Blitzortung with respect to transmission accident data

Number of Faults	91
Blitzortung	80
Coverage Efficiency	88[%]
Median distance	1.7[km]

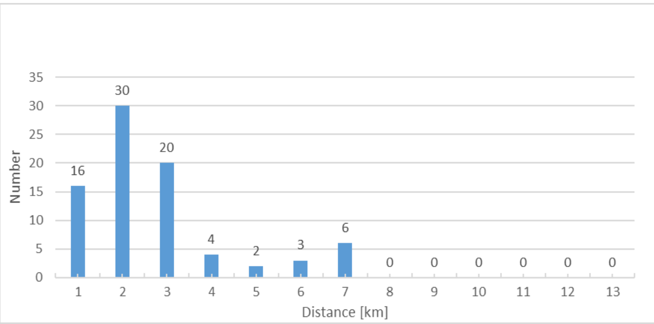

Figure 8. Blitzortung distance distribution based on LLS lightning strike location

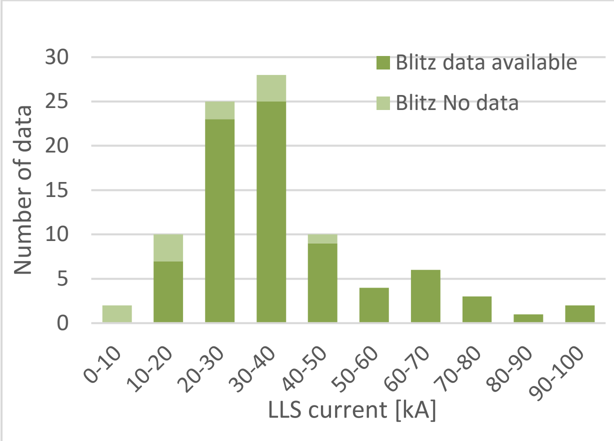

Figure 9. LLS estimated current value distribution

4 Conclusion

Advanced information-oriented societies are vulnerable to lightning. Therefore, information about lightning strikes is necessary for preventing power outages and equipment damage caused by lightning strikes, ensuring the stable operation of electronic equipment that supports social infrastructure networks, and protecting human lives from lightning strikes. However, data on lightning strikes are difficult to obtain. The Blitzortung system was introduced to Japan in order to solve these issues.

The Blitzortung system is a device that uses small and simple sensors to locate lightning locations with high precision. The Shonan Institute of Technology was the first to introduce this system to Japan, and as of December 2023, the device has been deployed nationwide, with a total of 80 receiving stations installed across Japan and in Asia. This has enabled the acquisition of various data regarding lightning strikes for free. Furthermore, VLF-band electromagnetic waves have the characteristic of propagating to faraway places such as Japan, Southeast Asia, and Australia, which enable the determination of locations over a wide geographic range.

In this study, we evaluated the lightning strike data located by Blitzortung by comparing the 91 transmission line lightning faults in 2019 that matched with LLS with Blitzortung data. Results showed a location efficiency of 88% and median location accuracy value of 1.7 km. Furthermore, after re-calculation, we were able to improve the location efficiency to 92%.

The information that is freely available to the public in commercial systems displays lightning strikes every 10–20 minutes, but Blitzortung allows for the zooming in and out on lightning strike maps free of charge and in real-time, so it is thought to become reference information for patrolling for lightning strikes on transmission lines.

In the future, we will examine how to improve lightning strike location accuracy and estimate current values.

5 Literature

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