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A study of lightning location system (Blitz) based on VLF sferics

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***Abstract*—Blitzortung.org is a worldwide non-commercial low-cost community based Time of Arrival lightning detection and lightning location network. The aim of this project is to accomplish a low budget high accurate worldwide lightning location network based on a high number of receiver sites spaced close to each other, typically separated by 50 km 250km. The stations transmit their data to a central server, where the strike locations are computed by the arrival times of the signals. The station operators are volunteers who bought and assembled the hardware by themselves. We installed this sensor in more than 24 locations throughout Japan, for example Hokkaido, Tokyo, Okinawa, Ogasawara etc. This paper describes the outline of Blitzortung and the evaluation of the position accuracy.**

Keywords—lighting location system (LLS), time of arrival technique, VLF

I. Introduction

The economic losses caused by lightning strikes are enormous. Lightning location equipment are necessary in prevention of disasters due to flood and blackout caused by sudden rainfall and lightning strike.

The conventional commercial lightning location systems are mostly systems owned by weather companies and electric power companies, where the data made publicly available are wide-area information, and detailed data are either private or made available for a fee. Table 1 shows the various lightning location systems available in Japan.

On the other hand, due to progress in IT technology, the control of the equipment and sensors have become easier using networks, and procuring low-cost equipment has also become feasible.

Accordingly, we joined the project "Blitzortung" that aims to realize lightning detection and lightning location network of the world using inexpensive receiver sites that utilize IT. This project was started in 2012 by Prof. Egon Wanke of Heinrich Heine University in Germany, and the network is setup and run by volunteers who build their own receiver sites be buying and assembling kits themselves. Data on lightning such as coordinates of lightning location are being made publicly available in real-time over the internet. Note that the data cannot be used for commercial purposes.

Table 1. Overview of lightning location systems in JAPAN

System	Frequency	Method	Operator	Free/ Fee	Area
JLDN	LF	TOA	Company	Fee	Japan
Electric Power Company	LF	TOA	Company	------	Japan
Meteorological Agency	LF	TOA	Government	Fee	Japan
WWLLN	VLF	TOA	University	------	World
Blitzortung	VLF	TOA	Volunteer	Free	World

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Currently the receiver sites are mainly distributed in USA, Europe, and Oceania region, and as of December 2017, 2000 sites have been registered, about half of which (1000) are currently in operation. In Japan, Shonan Institute of Technology set up the first site (3) in February 2016, and by December 2017, 24 more sites were set up all over Japan from Hokkaido to Okinawa, and four overseas sites were also set up in Mongolia, India, Bangladesh, and Cambodia. Among the electromagnetic waves generated by lightning, only the emissions in the VLF range (sferics) are received, and these signals have the property of propagating over long distances. In particular, since at night using these signals the position of lightning as far as 5000 km away from the receiver site can be determined, computing lightning position is becoming increasingly feasible in Oceania and Asia.

This report provides an overview of the receiver sites in Blitzortung, and describes the results of collating the LLS data from the lightning location network of the TEPCO Power Grid, Inc. with the Blitzortung data.

II. Overview of Receiver Sites

A. *Lightning location principle*

The lightning location systems (LLS) of Blitzortung.org uses the time of arrival technique for lightning location, where the lightning location is determined based on the differences of several time stamps for the same signal received by several different stations. The difference of the time of arrival between two stations (and the positions of these stations) define a hyperbolic curve as the signal trajectory from the source of the electromagnetic emission. Therefore, the intersection point of hyperbolic curves from three stations defines the location of the lightning. Fig. 1 shows the lightning position calculation principle. However, in the project Blitzortung.org, the minimum number of receiver sites is set at six, and if the number of receiver sites is less than six, the signal is processed as noise.

Since the detectors are operated by private persons, who do not always set up the detectors according to a constant quality standard, the data stock consists of a large amount of data, which can be partly faulty. In order to filter out those data records suitable for the lightning location, several quality parameters are used. Two of these parameters are the maximum deviation span (MDS) and the maximum cycle gap (MCG). The parameter MDS indicates the deviation of the calculated position after locating. This value compares the distances between the detectors and the calculated position with the time differences of the time stamps and the time of the impact. Each time difference is converted into a distance according to the propagation speed. That is, the MDS parameter specifies a maximum error limit for the calculated position. The second parameter MCG evaluates the arrangement of the detectors around the calculated impact position. The calculation is much less imprecise if the detectors are equally arranged around the impact location. If all the detectors are positioned in the an almost same direction from the calculated impact position, then even small inaccuracies in the time stamps can lead to large errors. In our calculations, we work with an MDS value of 15km and a MCG value of 270 degrees. Here 270 degrees means that a calculation is rejected if all detectors come within a viewing sector of less than 90 degrees.

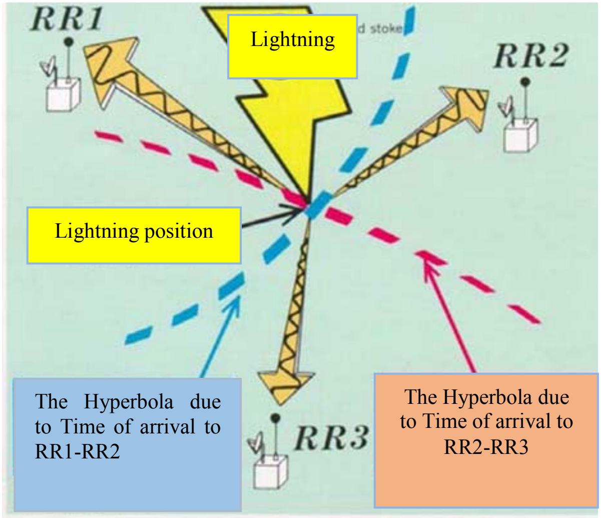

Fig. 1. Lightning position calculation principle

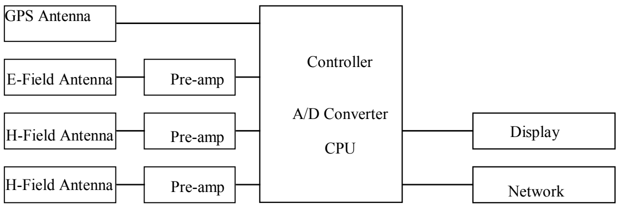

Fig. 2. System configuration

Table 2. System specification

Calculation method	Time of arrival
GPS (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)

Fig. 3. Electric field amplifier (Red system)

Fig. 4. Magnetic field amplifier (Red system)

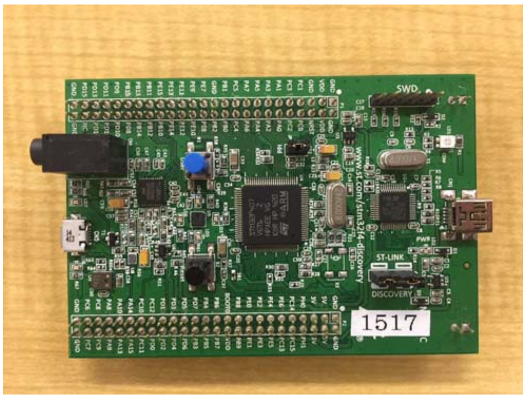

Fig. 5. CPU, A/D convertor (STM discovery board) (Red system)

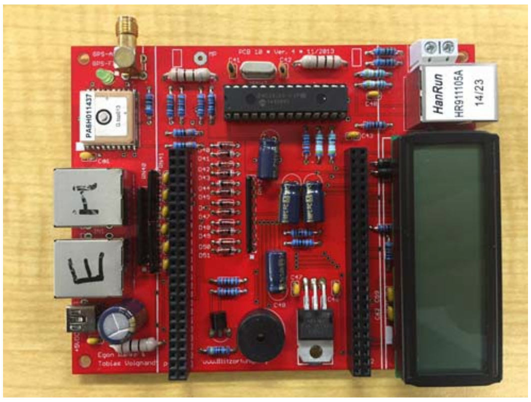

Fig. 6. Controller Board (Red system)

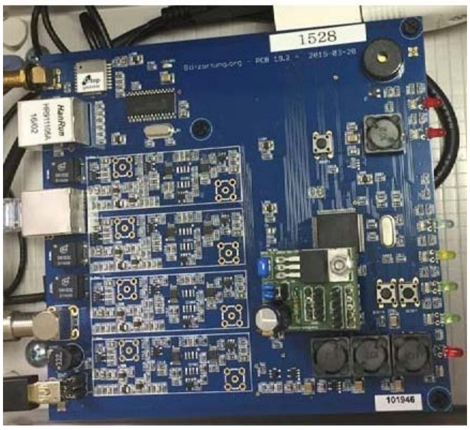

Fig. 7. Current Blue system

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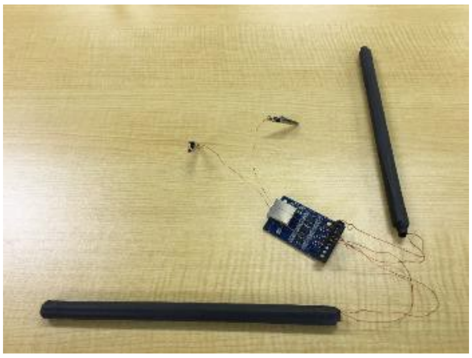

Fig. 8. H-field antenna (20 cm ferrite antenna)

Fig. 9. E-field antenna

B. *System configuration*

The system consists of magnetic antenna (H-field) and amplifier, electric field (E-field) antenna and amplifier, GPS, and controller. Fig. 2 shows the system configuration. The magnetic and electric components of the VLF band electromagnetic wave emitted by lightning discharge are received using the H-field and E-field antennas. When the received signal strength exceeds a threshold value, a trigger sets in, recording the time stamp, the coordinates of the receiver site, and the wave form. These data are then sent to the server using UDP protocol, and if the lightning wave form is detected at more than six sites, statistical analysis is performed to minimize error, and the lightning strike location is calculated.

The identification of whether a signal is a lightning signal or noise is done using techniques from the field of artificial intelligence. For each detector, a collection of signals is created and preprocessed, which were especially well-suited for lightning detection. New signals are then compared to the generated reference signals to determine if it is with high probability a lightning signal. All calculations use spherical coordinates. The time synchronization at the receiver sites is done using GNSS modules. The calculated locations are displayed in near real-time.

Electromagnetic waves in the VLF range are reflected by the ionosphere and are therefore still receivable at distances of more than 5000 km. This makes it possible under certain circumstances to locate lightning at very long distances. In such cases, however, it must be recognized that these are reflected signals.

Table 2 shows the system specification. The GPS time synchronization accuracy is 1us, and the H-field antennas set to capture magnetic signals from all directions are two or three 20cm long horizontally arranged ferrite rod antennas. It is not necessary to align the antennas in north-south east-west direction. They only should cover well all directions. These systems are used because they are very robust and can be positioned in many places without much effort. The analog-to-digital converter sampling frequency is set at 500kHz.

The current system is called System Blue, the previous system is called System Red. Since there were always problems during assembling the systems, we developed the System Blue, where over 95\% of the parts are SMD parts already soldered on the board. As a result, the setup of the boards by the participants has been significantly simplified. Now only about 20 THT parts need to be soldered manually. With this change, also the STM discovery board was omitted and the processor is now placed on the board. Currently, both systems coexist. The E-field amplifier, H-field amplifier, CPU, and controllers used in Red-system are shown in Fig. 3 to 6. For the Red-System, printed circuit boards are sold, and the users need to buy the necessary parts and assemble the system themselves. For the CPU and the A/D conversion, general purpose STM discovery board is used, which was procured from Akihabara for 2000 yen. This chip running at a clock frequency of 168MHz, is capable of 12-bit A/D conversion, and can produce a maximum throughput of 1000 ksps (1µs sampling possible).

C. *Amplifier frequency characteristics*

Figure 10 shows the frequency characteristics of the magnetic amplifier. The magnetic field amplifier of System Red is equipped with a 1kHz high-pass filter and a 50kHz low-pass filter, and within the range of 1kHz～50kHz never drops below -3dB, showing nearly flat frequency characteristics. The electric field amplifier is equipped with a 5kHz high-pass filter and low-pass filters of 50kHz, 44kHz, and 18kHz, with signal receiving possible in 5kHz-50kHz band. The H-field and E-Field amplifiers of System Blue is equipped with a 5kHz high-pass filter and optionally with a digital tunable 10th order low-pass filter. By using different filters, there are usually different signal delays. These delays are, however, also taken into account since the filter settings (System Blue) are also transmitted to the server.

By using different filters, there are usually different signal delays. These delays are, however, also taken into account since the filter settings (System Blue) are also transmitted to the server. This problem can also be circumvented by using the same settings for all amplifiers.

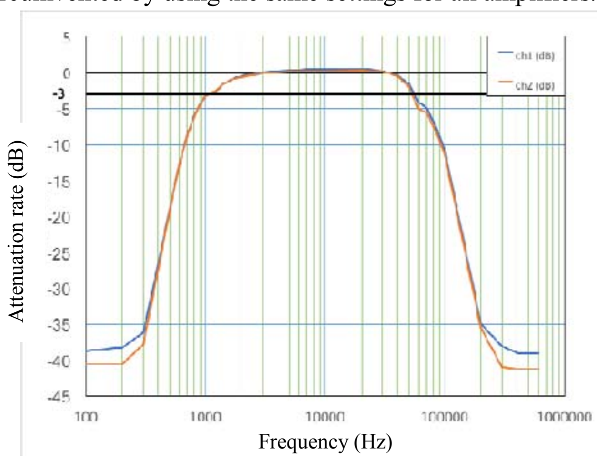

Fig. 10. Frequency characteristics of magnetic field amplifier

D. *Receiver site installation status*

Figure 11 shows the location of the receiver sites worldwide. All over the world, about 2000 sites are registered. The maximum number of sites is in Europe, exceeding 1000. The next highest is the USA, followed by Australia. Note that, the number of sites that are being actively operated all over the world, is about 1000 only. The installation status of receiver sites in Japan is shown in Fig. 12. Moreover, Fig. 13 shows the actual installation in Fujisawa city, and Sendai city. The main equipment and the GPS antenna are housed inside a watertight case, while the E-field and H-field antennas with waterproof coating are placed outside.

After the first installation in Japan at the Shonan Institute of Technology in February 2016, as of December 2017, 22 more receiver sites have been installed at the following areas in Japan: Nayoro city (Hokkaido), Kitami city (Hokkaido), Sapporo city (Hokkaido), Tomakomai city (Hokkaido), Sendai city (Miyagi prefecture), Iwaki city (Fukushima prefecture), Utsunomiya city (Tochigi prefecture), Saitama city (Saitama prefecture), Higashimurayama city (Tokyo), Kiyose city (Tokyo), Bunkyo ward (Tokyo), Chuo ward (Tokyo), Chichijima (Tokyo), Fujisawa city (Kanagawa prefecture), Yamato city (Kanagawa prefecture), Komoro city (Nagano prefecture), Kahoku city (Ishikawa prefecture), Miki city (Hyogo prefecture), Amagasaki city (Hyogo prefecture), Yame city (Fukuoka prefecture), Kagoshima city (Kagoshima prefecture), and Nakagami county (Okinawa prefecture). Other collaborators have set up receiver sites at Niigata city (Niigata prefecture), and two locations in Yokohama city (Kanagawa prefecture), and third parties have set up sites at four other places in Ishinomaki city (Miyagi prefecture), Tomisato city (Chiba prefecture), Kashiwa city (Chiba prefecture), and Yugawara town (Kanagawa prefecture). As mentioned above, there are now in total 28 receiver sites in Japan, and the number is growing every month.

As for overseas installations, sites were installed in Mongolia in August 2017, in India and Bangladesh in November 2017, and in Cambodia in December 2017. Using these four sites along with the sites in Japan, Kazakhstan, Australia, Hong Kong, Thailand, and the Philippines, lightning location calculation in Southeast Asia is gradually becoming possible.

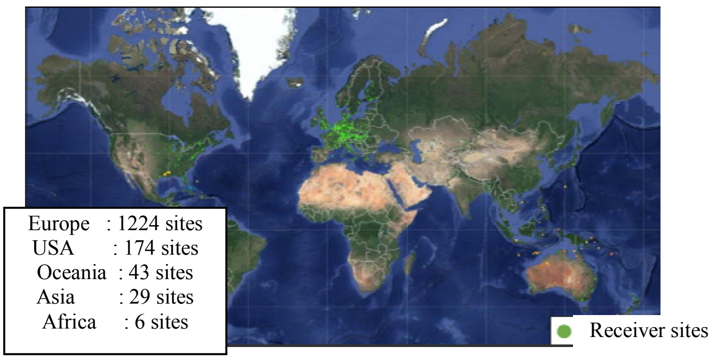

Fig. 11. Distribution map of receiver stations in the world

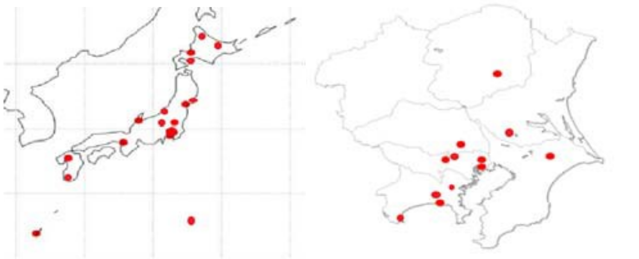

Fig. 12. Location of receiver stations in JAPAN (2017/12)

Fig. 13. Example of Blitzortung installation (Left: Fujisawa city, Right: Sendai city)

III. EVALUATION OF POSITION ACCURACY

To verify the lightning position accuracy of Blitzortung, the data were collated with LLS data from TEPCO Ltd. The LLS data and Blitzortung lighting location data were extracted for an area (as shown in Fig. 14) in Kanto region (north latitude 34.46° ～37.15°, east longitude 138.3° ～ 141.0°), where there were many lightning strikes on four days of April 3, June 16, August 19, and September 25, 2017, during the time span of JST 00:00:00 Hrs thru 23:59:59 Hrs. Note that only cloud-to-ground data were used from the LLS. Table 3 shows the number of lightning locations from LLS and Blitzortung, their ratio, and the number of Blitzortung stations in Japan. Overall, the number of lightning locations in LLS was larger, and the ratio of Blitzortung number to the LLS number was approximately 20%-30%. Moreover, the ratio tends to increase as the number of Blitzortung stations increases.

The difference in location numbers between LLS and Blitzortung, is presumed to be due to the difference in frequency bandwidth of the systems, and the difference in multiple lightning location rate due to dead time, besides the difference in algorithms used. For example, LLS calculation is based on four receiver stations, whereas in Blitzortung, the number of receiver stations used is at least six. Moreover, in Blitzortung, other differences besides the difference in algorithm used, such as, the location is not determined when the signals are not received from sites surrounding the lightning location, are also presumed to contribute to the difference in number of lightning locations.

Moreover, to evaluate the position accuracy of LLS and Blitzortung, data that met the conditions to consider the signals in the LLS and Blitzortung as originating from the same lightning discharge, i.e., time stamp difference of less than 10μs，and distance difference less than 10km, were extracted. The results are shown in Table 4.

The percent of match between the two systems was in the range of 5%-26%, and the distance difference with LLS as the reference was approximately 1.4km-2.2km.

With respect to position accuracy of Blitzortung as shown in the 4th column, the distributions with LLS as the reference are shown in Fig. 15-18. In all the cases, the data are concentrated near the origin which is the LLS reference point. Moreover, the distribution (scatter) is in an oval shape extending from the north-west towards the south-east direction. Whether this is due to LLS or Blitzortung is unknown, and it is presumed that the position of the receiver stations may have affected the results. Earth conductivity, and delay in propagation time over mountainous terrain may be considered as probable factors, but at this point the factors are unknown.

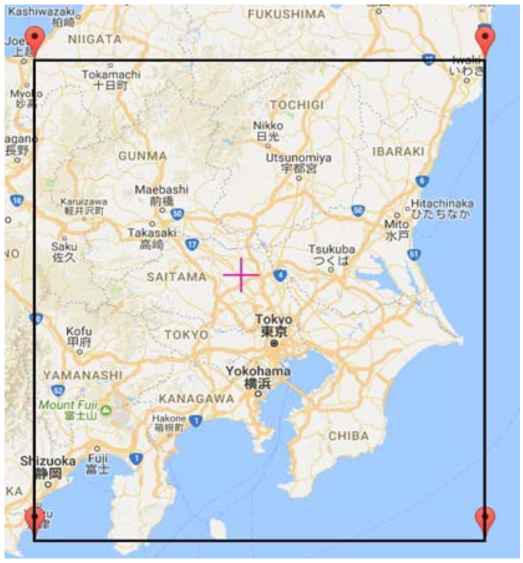

Fig. 14. Area used for accuracy verification

Table 3. Comparison between TEPCO LLS and Blitzortung data

y/m/d	TEPCO LLS	Blitzortung	Ratio (Blitz/LLS)	Blitzortung Station in Japan
2017/4/3	802	95	12%	13
2017/6/16	2599	1008	39%	15
2017/8/19	12408	2782	22%	20
2017/9/25	5336	1256	24%	24

Table 4. Position accuracy of Blitzortung

y/m/d	TEPCO LLS	Blitzortung	Match	Position accuracy
2017/4/3	802	95	43	2.23km
2017/6/16	2599	1008	679	1.47km
2017/8/19	12408	2782	2083	1.43km
2017/9/25	5336	1256	1034	1.48km

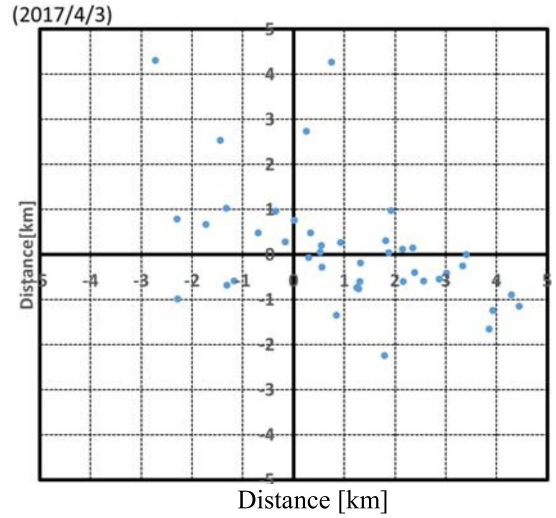

Fig. 15. Distribution of Blitzortung with LLS as reference (2017/4/3)

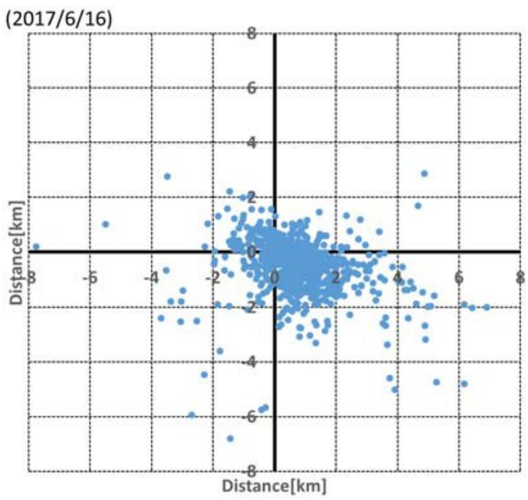

Fig. 16. Distribution of Blitzortung with LLS as reference (2017/6/16)

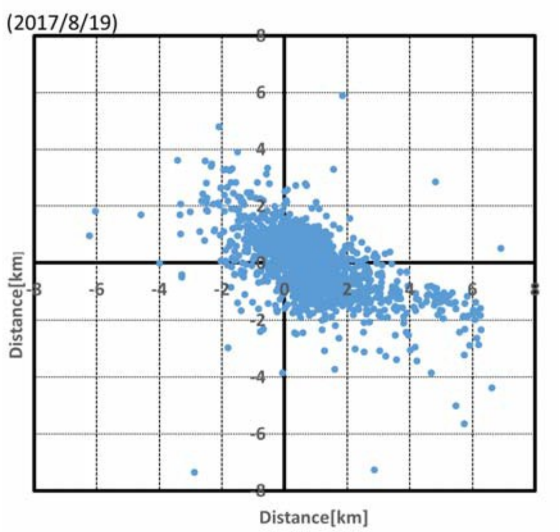

Fig. 17. Distribution of Blitzortung with LLS as reference (2017/8/19)

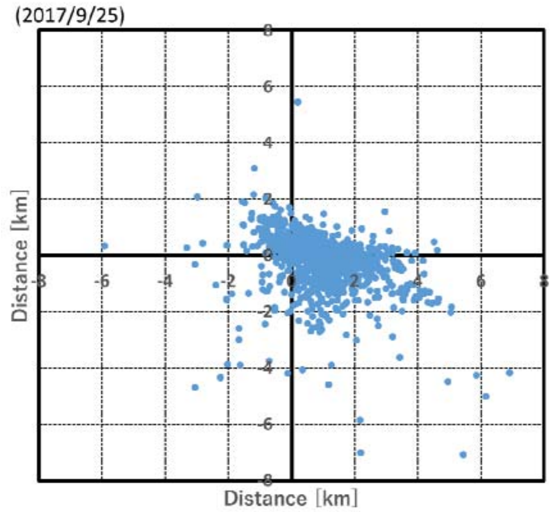

Fig. 18. Distribution of Blitzortung with LLS as reference (2017/9/25)

IV. CONCLSION

Blitzortung was first introduced in Japan based on voluntary participation, and the position accuracy of the system was verified. Blitzortung refers to a small receiver equipment that utilizes low-cost sensors for high accuracy lightning detection and lightning location, and 24 domestic and 4 international receiver sites were set up. Since the VLF band electromagnetic waves have the characteristic to propagate over long distances covering Japan, South-east Asia, and Australia, the lightning location data calculated for a vast region could be made public in near real-time and free of charge.

Moreover, to verify the accuracy of the location, the data were compared to LLS data from TEPCO Inc., and the position accuracy was found to be around 1.4km. In the future, the plan is to set up more receiver sites, undertake original location determination, and evaluate waveforms and position accuracy.

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