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Discussion on Location Accuracy Improvemed by Propagation Delay Corrections for the Japanese Lightning Detection Network

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Abstract— **The location accuracy of the Japanese Lightning Detection Network (JLDN) has been evaluated for a long time. It was reported that the average location accuracy of the JLDN was approximately 0.44 km for return strokes of negative downward lightning striking wind turbines in summer and 0.58 km for return strokes associated with upward lightning initiated from wind turbines in winter. However, the authors found that many stroke positions calculated by the JLDN tended to be located in specific directions. Therefore, we assumed this was caused by differences in the propagation speed of the electromagnetic waves that emitted from lightning discharges, passing along surfaces of varying conductivity. We recalculated the lightning positions of strokes that hit the wind turbines after applying propagation delay corrections. The difference between the times measured at the sensor and calculated times was smaller after the recalculation. As a result, location accuracy was improved from 0.44 km to 0.31 km for downward lightning strokes in summer, and it was improved from 0.79 km to 0.12 km for lightning strokes in winter**

Keywords - propagation delay correction; location accuracy; LLS

I. INTRODUCTION

The Japanese Lightning Detection Network (JLDN) is a commercial lightning detection network observing lightning events in Japan and the surrounding areas. The JLDN is owned and operated by a commercial weather company in Japan. The JLDN started to observe lightning events in the areas of central and western Japan in 1998. Additional sensors were added in the northern part of Japan in 1999 and in the southwestern island "Ryukyu" region in 2003 [1]. The JLDN uses thirty LF sensors installed all over the Japanese Islands and consisted of ten TLS200's, eleven LS7001's, six IMPACT-ESP's and three LPATS-IV's as of January 31st, 2016. Figure 1 shows the allocation of sensors in the JLDN in January 2016.

The location accuracy of the JLDN has been discussed for a long time. It has been reported that the nominal location accuracy was approximately 500 m and the relative detection

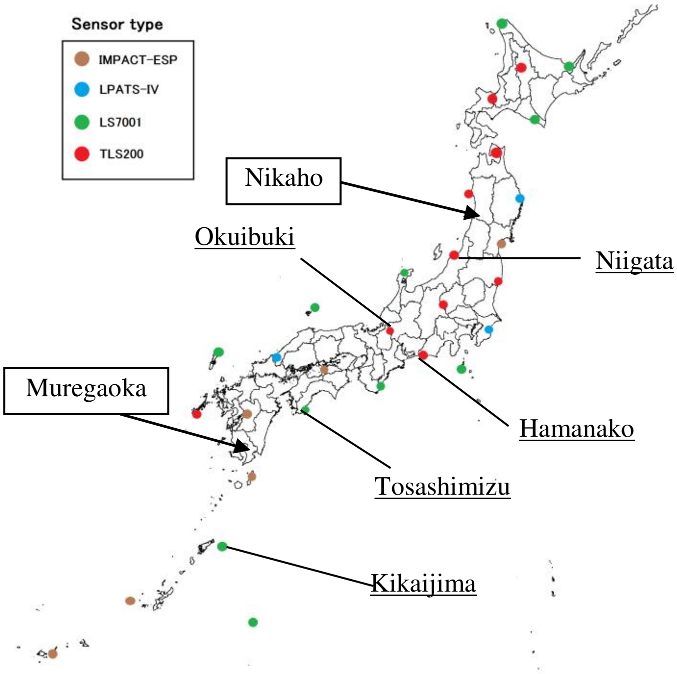


Figure 1: JLDN sensor locations in January 2016. The boxes show the location of the wind farms where we evaluated the improvement in location accuracy. The underlined location names show the sensors where the differences between times measured at the sensors and the calculated times were evaluated.

efficiency was 90% and more in most areas of the four major islands of Japan. It was reported that the location accuracy of the JLDN for negative downward strokes hitting wind turbines in summer was approximately 0.44 km [2] and 0.58 km for upward lightning strokes developing from wind turbines in winter [3]. We have observed lightning current waveforms using Rogowski coils installed at wind turbines in the Muregaoka wind farm in Kagoshima [4] and the Nikaho wind farm in Akita [5].

II. Motivation

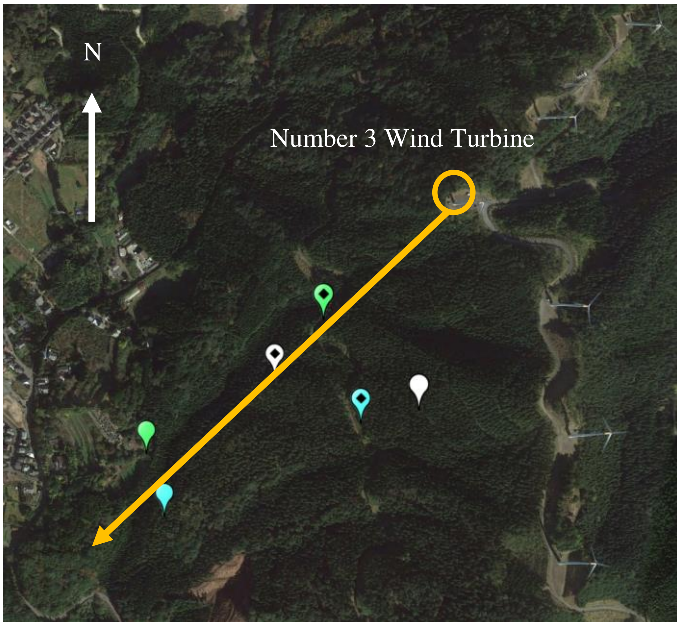


Figure 2: Stroke positions located by the JLDN near the Muregaoka wind farm before propagation delay corrections

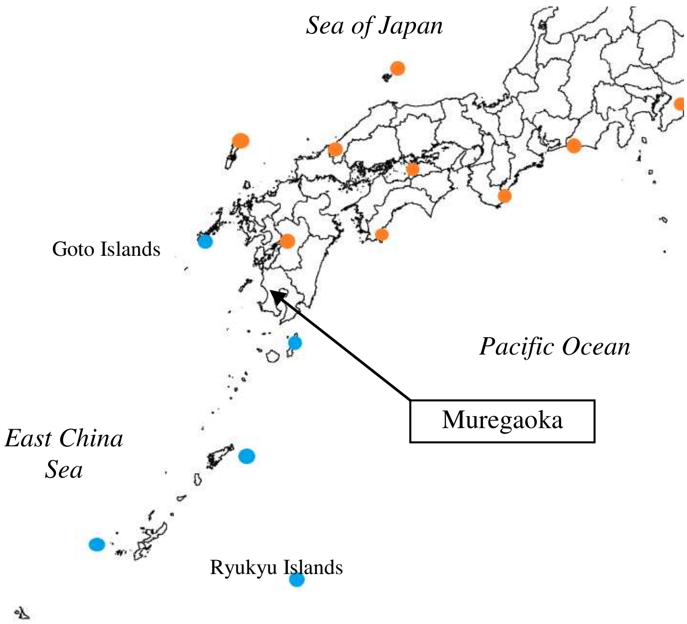


Figure 3: The sensors that participated in locating the positions of lightning strokes that hit the Number 3 wind turbine in the Muregaoka wind farm, are shown in Figure 2. The blue dots are the sensors installed on the outlying islands. The orange dots show sensors installed on the main lands.

Figure 2 shows the position of the Number 3 wind turbine in Muregaoka that was hit by lightning and the positions of the lightning strokes as estimated by the JLDN. We found that all stroke positions reported by the JLDN were to the southwest of the Number 3 wind turbine. In this region, lightning strokes

TABLE I. Relative Permittivity and Conductivity of Various Surfaces

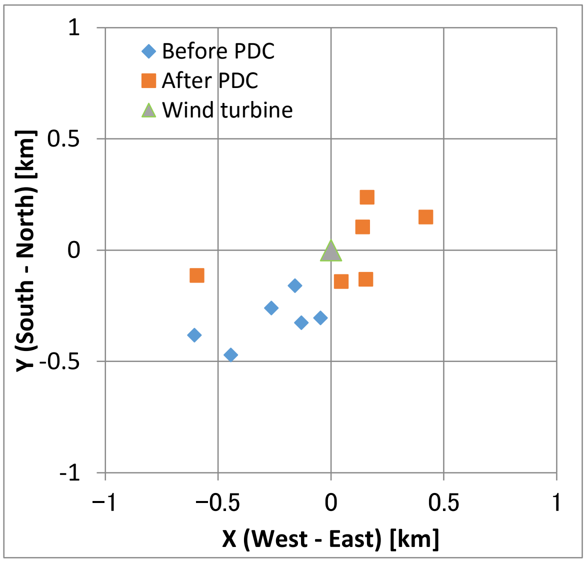
Surface	*Relative permittivity*	*Conductivity [S/m]*
Sea water	80	5
Plains	15	0.005
Mountain	15	0.001

were located using information obtained from sensors in Ryukyu and Goto Islands (outlying islands) and from sensors on the main islands of Japan. Figure 3 shows sensors located in the outlying islands (colored with blue) and main lands (colored with orange). The average percentage of sea segments of the propagation paths between the lightning position (the wind turbine location) and the sensors in the outlying islands was 85%. However, the average percentage of sea segments in the paths between the lightning position and sensors on the main islands was only 46%. Table I shows relative permittivity and conductivity of three surfaces. The propagation speed of electromagnetic waves emitted by lightning discharges is usually slower than the speed of light and it varies slightly depending on the finite conductivity of the surface along the propagation path [6]. Therefore, there is a difference between the propagation speed over the sea and that over land. The changes in propagation speed cause differences between the actual times measured at the sensors and the calculated time of arrival. This may be one of the causes of the deviation of the JLDN's estimated lightning locations toward the southwest.

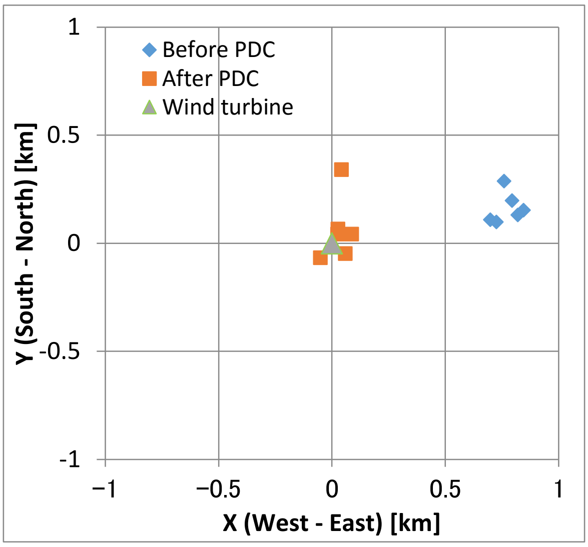
Honma et al reported that the location accuracy of the Lightning Location System (LLS) of an electric power company in Japan was improved from approximately 400 m to 270 m using the propagation delay corrections when they upgraded their LLS network [7]. This indicates that propagation delay correction is a significant method to improve location accuracy of an LLS network. Thus, we recalculated the positions of the lightning strokes to the wind turbines instrumented with Rogowski coils to evaluate the improvements in location accuracy of the JLDN resulting from the application of propagation delay corrections. The JLDN also detected lightning strokes that hit wind turbines in the Nikaho wind farm instrumented with Rogowski coils. Therefore, we used the Nikaho turbines as ground truth data and compared the location accuracy in Muregaoka with that in Nikaho after the recalculation using propagation delay corrections.

III. Recalculation Results after Propagation Delay Corrections for Strokes that Hit the Wind Turbines

We have observed the waveforms of lightning current hitting the wind turbines using Rogowski coils. Rogowski coils were installed at the wind turbines in the Muregaoka wind farm and the Nikaho wind farm shown in Figure 1. We have evaluated the location accuracy and the accuracy of the peak current estimates of the JLDN by comparing JLDN results with ground truth data obtained from the Rogowski coils installed at those locations. In Muregaoka, all of the strokes shown in Figure 2 were observed by the Rogowski



(a) Relative location error of downward strokes that hit the wind turbine in the summer season in the Muregaoka wind farm before and after Propagation Delay Corrections (PDC)



(b) Relative location error of downward strokes that hit the wind turbine in the winter season in the Nikaho wind farm before and after Propagation Delay Corrections (PDC)

Figure 4: Relative location error of lightning strokes that hit the wind turbines in the Muregaoka and Nikaho wind farms. Blue squares show positions reported by the JLDN before applying Propagation Delay Corrections (PDC's). Orange squares show the stroke positions located by the JLDN after applying PDC's. The green triangles are the locations of the wind turbines.

coils installed at the number 3 wind turbine. We succeeded in observing the current waveforms of six strokes that hit the wind turbine in the 2013 and 2014 summer seasons. All flashes are shown to be initiated by downward propagating leaders by the correlated measurement of the electric fields [8]. The JLDN detected all the strokes that hit the wind turbine during the same period of time. Figure 4 shows the comparison of location accuracy in Muregaoka (a) and Nikaho (b) with and without recalculation using the propagation delay corrections. According to Matsui et al [2], the average location error, which means the distance between the wind turbine and the six lightning stroke positions reported by the JLDN, was approximately 436 m and all strokes were located in a southwestern direction from the wind turbine prior to recalculation using the propagation delay corrections. The average location error was improved to 310 m by applying the propagation delay corrections. Figure 4(a) shows that the stroke positions were not located in a specific direction after the recalculation.

Nikaho is located in the coastal area of the Sea of Japan about 10 km away from the shoreline. Several instances of serious damage associated with winter lightning were reported in this region [9]. We installed Rogowski coils on wind turbines in the Nikaho wind farm to measure lightning current waveforms. We succeeded in observing current waveforms of lightning strokes on a day in February 2015. The JLDN detected all lightning strokes with an absolute estimated peak current value as measured by the Rogowski coil of 8 kA or more. The average location error of all strokes that hit the wind turbine and were located by the JLDN was 791 m and, prior to applying propagation delay corrections, all strokes were located to the east of the wind turbine by the JLDN as shown in Figure 4(b). We recalculated those stroke positions using propagation delay corrections and the average location error was reduced to approximately 120 m. In addition, the strokes were no longer located in a specific direction away from the turbine. Figure 4 shows that the propagation delay corrections improved the location accuracy of the JLDN and eliminated the tendency to locate lightning stroke positions in a specific direction in both regions.

IV. Discussion

A. Difference between the time meaured at the sensors and the calculated time

According to the results of recalculation, the average location errors of lightning stroke positions located by the JLDN were improved in both regions after the application of the propagation delay corrections. The process of applying optimized locating algorithms based on the time information reported by the sensors is affected by large time of arrival (TOA) errors. Errors in the system's timing information are caused by the following [10].

a) The distance that the electromagnetic waves travel calculated without considering the undulating terrain is different from the actual propagation distance.

b) Electromagnetic waves propagate at different speeds over surfaces whose finite conductivity varies along the path from the lightning stroke position to the sensor.

c) Time error may also be caused by incorrect calculations of the so called onset time.

The propagation delay correction algorithm improves the time errors described in a) and b). Therefore, it reduces the time difference between the time measured at the sensor and the calculated time and improves the accuracy of the TOA locating algorithm. The location error tended to be larger when the standard deviation of the difference between the actual measured time at the sensor and the calculated time after the application of propagation delay corrections increased. [11].

We recalculated the positions of lightning strokes that occurred on August 2nd, 2015 to evaluate those values at several JLDN sensors. Table II shows the average deviation between the actual measured time at the sensor and the calculated time, the standard deviation, the maximum and minimum time differences before and after recalculation using the propagation delay corrections for the sensors at Niigata, Hamanako, Okuibuki, Tosashimizu and Kikaijima. Those sensors were not located on the edge of the network and they participated in locating a sufficient number of lightning strokes to evaluate the time differences before and after recalculation using the propagation delay corrections. The locations of the sensors used in the evaluation are shown in Figure 1. The average deviation (AD) and the standard deviation shown in Table II were calculated using Equation (1) and Equation (2), respectively.

$$AD = \frac{1}{n}\sum_{i=1}^{n}\left|Tm - Tc\right| \quad (1)$$

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(Tm - Tc\right)^2} \quad (2)$$

where Tm is the time measured at sensor and Tc is the calculated arrival time expressed as Equation (3).

$$Tc = Ts + D/c \quad (3)$$

where Ts is the estimated time of occurrence of the lightning stroke, D is the distance between estimated position of the stroke and the sensor and c is the speed of light.

As shown in Table II, the average deviation, standard deviation, maximum value and minimum value at each sensor was reduced after the application of propagation delay corrections. This means the number of timing data points having large differences decreased, and the JLDN could locate lightning strokes with timing information that had smaller differences between the times measured at the sensors and the calculated times after applying the corrections. This is a clear indication that the application of the propagation delay corrections succeeded in reducing the amount of timing information with large differences caused by the propagation delay effect. Therefore, the JLDN lightning stroke location errors were reduced as shown in Figure 4.

TABLE II. CENTROID POSITIONS AND DISTANCESFROM THE WIND TURBINE BEFORE AND AFTER APPLYING PROPAGATION DELAY CORRECTIONS (PDC)

(a) Niigata

	Before[μsec]	*After[μsec]*
Average deviation.	1.02	0.433
STD	1.41	0.555
Max	9.88	2.40
Min	-9.93	-2.89
Number of samples	44903	38668

(b) Hamanako

	Before[μsec]	*After[μsec]*
Average deviation	0.999	0.553
STD	1.49	0.715
Max	8.75	5.33
Min	-9.99	-6.08
Number of samples	30694	24608

(c) Okuibuki

	Before[μsec]	*After[μsec]*
Average deviation	0.938	0.433
STD	1.43	0.555
Max	9.91	2.40
Min	-9.88	-2.89
Number of samples	34712	38668

(d) Tosashimizu

	Before[μsec]	*After[μsec]*
Average deviation	0.833	0.414
STD	1.33	0.598
Max	9.64	4.77
Min	-9.81	-9.77
Number of samples	14822	13227

(e) Kikaijima

	Before[μsec]	*After[μsec]*
Average deviation	0.783	0.368
STD	1.14	0.470
Max	6.58	1.60
Min	-9.14	-2.20
Number of samples	1324	949

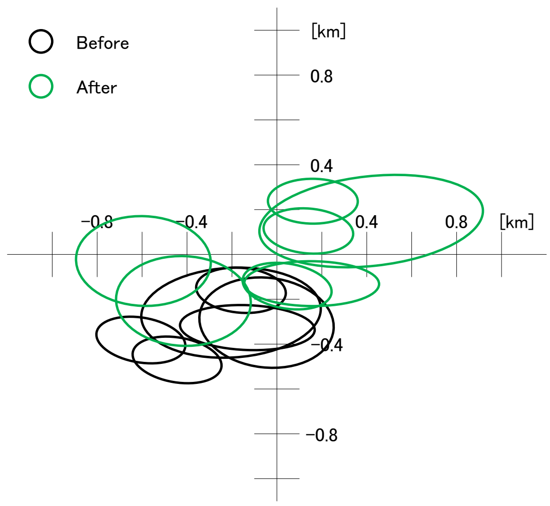
B. Confidence ellipse

The location processor of the LLS provides the parameters of a median (50%) confidence ellipse defining a region centered on the calculated position, within which there is a 50% probability that the stroke occurred. The confidence ellipse is determined by the number of sensors participating to locate the stroke and by the standard deviation of the time and angle measurements for each sensor [12]. Figure 5 shows the relative locations of the 50% confidence ellipses of the strokes to the wind turbines in Muregaoka (a) and Nikaho (b) before and after applying the propagation delay corrections. The location of the wind turbine is at (0, 0) km in these figures. In

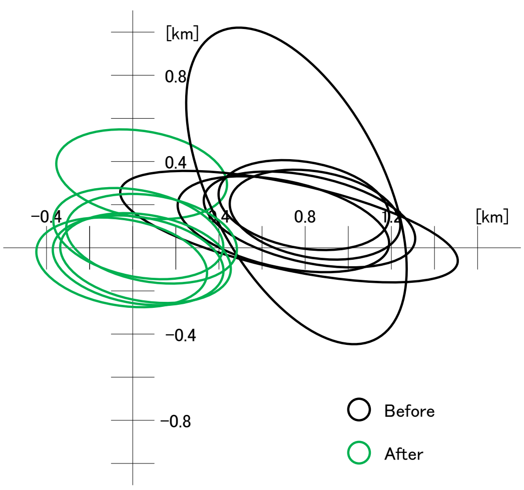
Muregaoka, none of the 50% confidence ellipses included the location of the wind turbine before using the propagation delay corrections. One confidence ellipse included the location of turbine after applying the corrections. Also in Nikaho, none of the 50% confidence ellipses included the location of the wind turbine prior to applying the corrections. However, five of the six confidence ellipses included the turbine after applying the corrections. The confidence ellipse can be calculated for probabilities other than 50% by scaling the semi-major axis and semi-minor axis using Equation (4)

$$SC = \frac{\sqrt{-2 \cdot \ln(1-P)}}{1.177} \quad (4)$$

where SC is the scaling constant and P is the probability expressed as a fraction rather than as a percent (for example: 0.9 rather than 90%) [13].



(a) 50% confidence ellipses of strokes to the wind turbine in Muregaoka

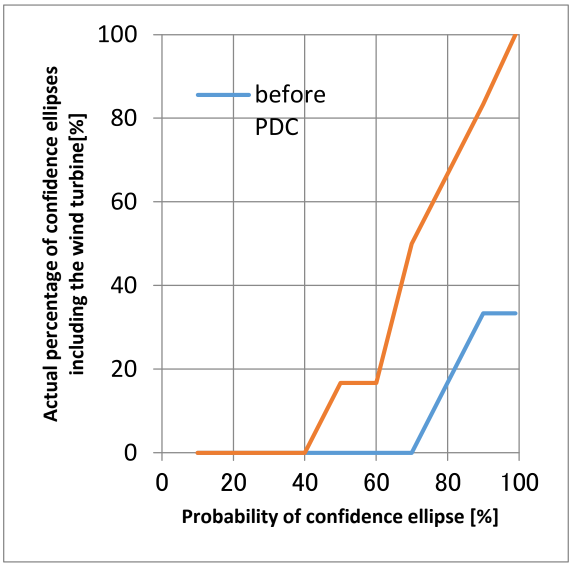


(b) 50% confidence ellipses of strokes to the wind turbine in Nikaho

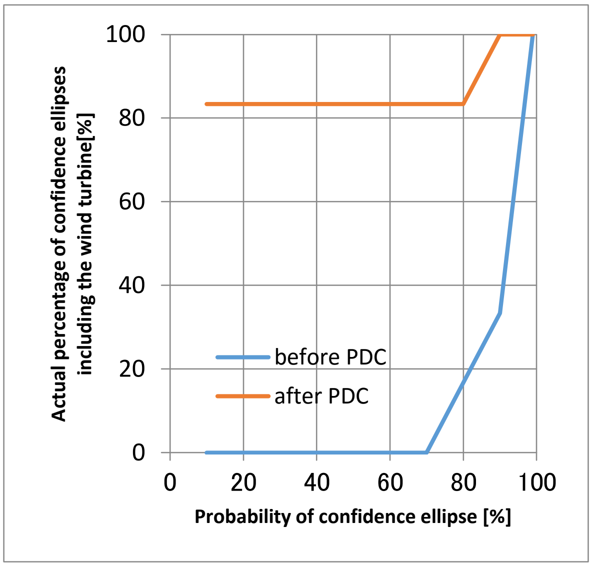
Figure 5: Relative locations of 50% (median) confidence ellipses of strokes, which hit the wind turbines in Muregaoka and Nikaho, located by the JLDN before and after recalculation using propagation delay corrections.

We evaluated the degree of improvement in location accuracy making changes in confidence ellipse percentages and observing the number of strokes included in the ellipses. Figure 6 shows the confidence ellipse percentages and the percentage of ellipses that included the wind turbines at Muregaoka and Nikaho before and after recalculation using the propagation delay corrections.

The percentage of confidence ellipses that included the turbine locations was higher after recalculation using the propagation delay corrections in both regions. This means the propagation delay corrections improved location accuracy and



(a) Muregaoka (N=6 strokes)



(b) Nikaho (N=6 strokes)

Figure.6: Percentage confidence ellipse including the wind turbines hit by lightning strokes before and after the recalculation using the propagation delay correction (PDC) the calculated stroke positions defined by the intersections of the semi-major axis and the semi-minor axis of the confidence ellipses of the strokes detected by the JLDN were closer to the wind turbines which were the actual stroke locations. Therefore, the percentage of confidence ellipses that included the turbines increased after PDC application. However, there was a difference in the percentage of the confidence ellipses including the turbines in the two regions. The percentage of confidence ellipses that included the wind turbine at Nikaho was higher than the same percentage in Muregaoka after recalculation using propagation delay corrections. There were not any 40% confidence ellipses that included the wind turbine at Muregaoka after the propagation delay corrections. However, at Nikaho, approximately 83% of the 10% confidence ellipses included the wind turbine after the propagation delay corrections. This result indicates that the location accuracy improvements achieved using the propagation delay corrections in the JLDN depend on the region observed.

V. CONCLUSION

The location accuracy of the JLDN was improved from 436 m to 310 m for downward lightning strokes to the wind turbine in the Muregaoka wind farm in Kagoshima in summer. Location accuracy was improved 791 m to 120 m for lightning hitting a wind turbine in the Nikaho wind farm in Akita in winter after reprocessing the data using propagation delay corrections. The difference between the time measured at the sensor and the calculated time was reduced. This means the number of events having large timing differences was reduced, and the JLDN could locate lightning strokes with more accurate timing after the application of the propagation delay corrections. The location accuracy of the JLDN was improved, but that improvement varied from region to region within the JLDN's area of observation.

VI. FUTURE TASK

The authors recognized the scale of location accuracy improvements using the propagation delay corrections varied depending on the region observed by the JLDN. However, the cause of that variation was not clearly defined in this study. We will continue to study the regional differences in improvements in location accuracy achieved by implementing propagation delay corrections.

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REFERENCES

[1] M. Matsui, K. Michishita, and S. Kurihara, "The Comparisons of Location Accuracy between the JLDN and Other Continental Scale Lightning Detection Network" , 9th Asia Pacific International Conference on Lightning (APL) , 1019, Nagoya, Japan, 2015

[2] M. Matsui, K. Michishita, S. Kurihara, "Accuracies of Location and Estimated Peak Current for Negative Downward Return-Strokes to Wind Turbine Observed by JLDN", IEEJapan Transactions on Power and Energy., vol. 135. No.10, pp.644-645, 2015 (in Japanese)

[3] M. Ishii, F. Fujii, M. saito, D. Natsuno and A. Sugita, "Detection of Lightning Return Strokes Hitting Wind Turbines in Winter by JLDN", IIEJapan Transaction on Power and Energy, vol. 133, No12, pp.1009-1010, 2013. (in Japanese)

[4] K. Michishita, S. Kurihara, Y. Hashimoto, "Measurement of Current Associated with Negative Downward Lightning Flash on Summer", IEEJ, Trans. on Power and Energy, Vol. 134 No..9, pp841-842, 2014 (in Japanese)

[5] K. Michishita, M. Furukawa, N. Honjo and S. Yokoyama, "Measurement of Lightning Current at Wind Turbine near Coast of Sea of Japan in Winter" , 33rd International conference on lightning protection, Estoril, portugal (2016.9)

[6] W.Schulz and G.Diendorfer, "Evaluation of a lightning location algorithm using an elevation model", the 25th International Conference on Lightning Protction (ICLP), Rhodos, September, 2000.

[7] N. Honma, K.L. Cummins, M. J. Murphy, A. E. Pifer, T. Rogers, "Improved Lightning Locations in Tohoku Regions of Japan using Propagation and Waveform Onset Corrections", IEEJapan Transaction on Power and Energy, Vol.133, No.2, pp.195-202, 2013

[8] K. Michishita, N. Nagatsuma, T. Murakami and T. Harada, "Characteristics of Vertical E-Field Waveform Associated with Return Strokes on Southeastern Sea of Kyushu", IEEJ Trans. On Power and Energy, p.p. 298-304, Vol128, No.1, 2008 (in Japanese)

[9] The investigation committee for characteristics of winter lightning in Tohoku region, "Invetsigation on Outage Aspects Due to Winter Lightning in Tohoku Region," The Journal of IEIEJapan Trans., Vol.34, No.4, pp.268-275, 2014 (in Japanese)

[10] Pifer B. "Correction of Propagation Effects in Lightning Locatioin System", International Lightning Detection Conference, 1996

[11] M. Matsui, K. Michishita and S. Kurihara, "Comparison of Location Accuracy of the Japanese Lightning Detection Network with Large Scale Lightning Detection Network,"the 2015 International Conference on Lightning and Static Electricity (ICOLSE2015), TOU15-27, Toulouse, France September 9th, 2015

[12] G. Diendorfer, H. Pichler, W. Schulz, "EUCLID Located Strokes to the Gaisberg Tower Accuracy of Location and its assined Confidence Ellipse", 23rd International Lightning Detection Conference, Tucson, Arizona, U.S.A., 18-19 March, 2015

[13] VAISALA, "TLP Series User's Guide", M211055EN-A, September, 2009