An Improved Distance Finding Technique for Single-Site Lightning Location System Using Reflection Characteristics of the Anisotropic Ionosphere

Mitsunori Ozaki[1], *Satoshi Yagitani*[1], *Kazuhisa Miyazaki*[2], and *Isamu Nagano*[2]
[1] Faculty of Electrical and Computer Engineering, Institute of Science and Engineering,
Kanazawa University, Kakuma-machi, Kanazawa, Ishikawa 920-1192, Japan.
Tel: +81-76-234-4857, Fax: +81-76-234-4859, E-mail: ozaki@reg.is.t.kanazawa-u.ac.jp
[2] Kanazawa University, Kakuma-machi, Kanazawa, Ishikawa 920-1192, Japan.

Abstract

The distance finding technique for a single-site lightning location system is evaluated by using theoretical sferics, which are calculated under the effect of the magnetized ionosphere. The calculated ionospheric reflection coefficients are stable at smaller incident angles, while they exhibit a poor reflection at larger incident angles around 70 degrees. The distance finding accuracy is improved when the 1st reflected pulse of the sferic having the largest incident angle is excluded in the estimation. The errors of the improved distance finding technique become less than 5%, while those of the previous technique using the 1st reflected pulse were 20%.

1 Introduction

Intense electromagnetic pulses are radiated from lightning over a wideband frequency range (from a few Hz to the UHF bands), and the bulk of the energy is distributed in the VLF band [1]. Especially, the lightning-generated electromagnetic pulses in the VLF band propagating in the Earth-ionosphere waveguide are called “sferics.” Various lightning location systems are in operation by using information on the passive detection of lightning-generated electromagnetic fields and radio waves. Lightning location networks have already been put to practical use in many regions of the world, using multiple-site lightning location techniques, which provide high location accuracy (e.g., a typical accuracy of 0.5 km by U.S. NLDN) [2]. However, the facilities become inevitably complex at a relatively high cost.

In contrast, various single-site lightning location techniques have been studied to more easily detect lightning activity under the situations where it is impossible to deploy the multiple-site network [3]. The lighting location is estimated by a combination of direction and distance findings using the electromagnetic field measured at a ground station. Single-site lightning location techniques do not require a number of electromagnetic sensors separated at the distance of the order of wavelength from each other, so they are expected to be appropriate for developing a portable system. However, the accuracy is not as high as that of the multiple-site lightning location techniques. Because the distance finding technique usually uses information on the reflected pulses of the sferics propagating in the Earth-ionosphere waveguide. In fact, the distance between the observation point and the lightning is estimated from the times-of-arrival of the reflected pulses. Thus, the effect of the anisotropic ionosphere would have a major impact on the accuracy.

In the present study, in order to clarify the effect of the anisotropic ionosphere on the sferic propagation, the distance finding accuracy of the single-site lightning location technique proposed by *Nagano et al.* [4] is evaluated by using theoretical sferic waveforms, which are rigorously calculated under the effect of the magnetized ionosphere [5]. Difference in the eastward and westward propagation characteristics in the Earth-ionosphere waveguide is one of the well-known effects of the anisotropic ionosphere. Such ionospheric reflection directly affects the accuracy of the distance finding technique. Especially, we find that the 1st reflected pulse of the sferic, which has the largest incident angle compared with the subsequent ones, is most sensitive to the anisotropic ionosphere due to an extremely poor-reflection angle (just like the Brewster’s angle) existing in the VLF wave propagation. Therefore, we evaluate a new distance finding technique without using the 1st reflected pulse in this study. The validity of the new technique is confirmed by comparing its estimation accuracy with the accuracy obtained in the previous distance finding technique which uses the 1st reflected pulse.

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2 Single-Site Lightning Location Technique

The single-site lightning location technique in this study uses the algorithm proposed by *Nagano et al.* [4]. Lightning location is estimated by the combination of the direction and distance findings using two horizontal magnetic fields and one vertical electric field measured at a single station on the ground. Illustration of a sferic waveform is shown in Figure 1. A sferic consists of the pulse wave directly radiated from the lightning (direct wave) and the subsequent reflected pulses propagating in the Earth-ionosphere waveguide. The direction finding is performed by evaluating the Poynting vector of the direct wave in the time domain. The distance finding (the horizontal distance between the observation point and the lightning: d) is calculated from two or more differences in the times-of-arrival of the reflected pulses as follows,

$$h = \sqrt{\frac{-B + \sqrt{B^2 - 4AC}}{2A}}, \tag{1}$$

$$d = \sqrt{\frac{Eh^4 + Fh^2 + c^4 D^4}{4c^2 D^2}}, \tag{2}$$

$$\begin{cases} A = ET_{n-1}^2 - 16\left(2n-1\right)^2 D^2 \\ B = -8\left(N^2 - n^2\right) c^2 D^2 T_{n-1}^2 \\ C = \left(D^2 - T_{n-1}^2\right) c^4 D^2 T_{n-1}^2 \\ D = \sum_{k=n-1}^{N-1} T_k \\ E = 16\left\{N^2 - \left(n-1\right)^2\right\}^2 \\ F = -8\left\{N^2 + \left(n-1\right)^2\right\} c^2 D^2 \end{cases}$$

where h is the ionospheric reflection height, n is the number of sferic pulses ($n = 0$ indicates the direct wave as shown in Figure 1), $N(\geq n+1)$ is the number of reflected pulses used in the distance finding technique, T_k is the time difference in the times-of-arrival of the reflected pulses, and c is the light speed. Here, the time difference between the direct wave and the 1st reflected pulse T_0 is not usually used, because the group velocity of the direct wave is slower than the light speed due to the effect of the finite ground conductivity. Thus, the distance finding technique is directly affected by the effect of the anisotropic ionosphere.

The accuracy of the distance finding technique is evaluated by using the theoretical sferic waveforms, which are calculated by the expansion of a spherical wave into a number of plane waves and by the full-wave analysis [5]. The effect of the anisotropic ionosphere is rigorously considered in our computation. We can discuss the effect of the anisotropic ionosphere and the accuracy of the distance finding technique in detail.

3 Estimation Results of Distance Finding Technique

The ionospheric reflection coefficients are calculated by using the full-wave analysis [5] to investigate detailed effect of the anisotropic ionosphere on the sferic propagation. Figure 2 shows the incident angle dependence of the ionospheric reflection coefficients in each of the directions of magnetic North, South, East, and West, which is calculated for transverse magnetic (TM) mode waves using a nighttime ionospheric model at a mid-latitude. The frequency of TM-mode waves is set as 2 kHz, because reflected pulses of sferics propagating in the Earth-ionosphere waveguide are dominated by the frequency components of the integral multiples of about 2 kHz, which indirectly indicates the ionospheric reflection height. With the parallel and perpendicular components of the electric fields to the plane of incidence indicated by the subscripts "$\|$" and "$\perp$," two components (${}_{\|}R_{\|}$ and ${}_{\|}R_{\perp}$) exist to represent the reflection characteristics of the anisotropic ionosphere. Here, the parallel component of the ionospheric reflection ${}_{\|}R_{\|}$, which is the principal one, is analyzed. The following two points should be noted from the calculation results of $\left|{}_{\|}R_{\|}\right|$. At first, the variation in the ionospheric reflection coefficient is stable at smaller incident angles (less than 30 degrees). This suggests that the accuracy of the distance finding technique can be improved by using the reflected pulses having smaller incident angles. Second, there is an extremely poor reflection around 70 degrees. It might not be appropriate to use the reflected pulses having such poor-reflection angles in the estimation, because the apparent ionospheric reflection height for such a poor reflection inevitably seems to become higher. In the following, we verify these hypotheses by using theoretical sferic waveforms.

The dependence of distance-estimation error rates on the number of reflected pulses used in the distance finding technique is analyzed in Figure 3. The distance finding technique was performed at sites with the horizontal distances of 100, 200, 300, and 400 km in each of the directions of magnetic North, South, East, and West, by using the 1st reflected pulse and the subsequent ones. The estimation errors are improved by using larger number of reflected pulses in all cases. To use the larger number of reflected pulses is equivalent to adopting the reflected waves having smaller incident angles, for which the ionospheric reflection coefficient does not vary much as shown in Figure 2. However, it is difficult to use the larger number of reflected pulses in the distance finding technique from the viewpoint of signal-to-noise ratio (SNR). This is because that the amplitude of subsequently reflected pulses gradually attenuates and it becomes difficult to accurately pick up the time differences in the times-of-arrival between two successive pulses.

We propose a new distance finding technique using only the reflected pulses having small incident angles. In this technique, there are two unknown parameters (h and d) as represented in equations (1) and (2), so at least three reflected pulses are required to solve these equations. In the previous technique, the 1st and the subsequent two or more reflected pulses were used in the distance finding from the viewpoint of SNR. The incident angle of the 1st reflected pulse becomes the largest among the reflected pulses of the sferic. As shown in Figure 2, there is an extremely poor-reflection angle around 70 degrees, which coincides with the incident angle of the 1st reflected pulse measured at a site of the horizontal distance of 400 km for the case of the ionospheric reflection height of about 70 km. We try to estimate the distance by using three (the 2nd, 3rd, and 4th) reflected pulses in the new technique.

Figure 4 shows the estimation results obtained in the new distance finding technique compared with those in the previous technique. The different errors in the directions of magnetic North (South), East, and West were obtained in the previous technique using T_1 and T_2 including the 1st reflected pulse, due to the effect of the anisotropic ionosphere. The distance error rate gradually increases at the horizontal distances more than 300 km from the lightning especially for westward propagation of the sferics. The distance error rate reaches up to 20% at the horizontal distance of 400 km. This is caused by the effect of an extremely poor-reflection angle for the 1st reflected pulse in the ionosphere, which clearly appears for the westward propagation in Figure 2. On the other hand, the estimation errors in the four directions obtained in the new distance finding technique using T_2 and T_3 without the 1st reflected pulse become almost the same. The distance error rates are distributed within ±5%, so that the estimation errors are drastically improved without using the 1st reflected pulse. Therefore, we can clearly see that the new distance finding technique improves the accuracy of the distance estimation when used in the single-site lightning location system.

4 Conclusion

To mitigate the effect of the anisotropic ionosphere on the sferic propagation, a new distance finding technique without using the 1st reflected pulse has been proposed. Although the accuracy is not so high compared with the multiple-site lightning location technique, (e.g., a typical accuracy of 0.5 km by U.S. NLDN [2]), the new distance finding technique has been shown to be of sufficient performance (less than the distance error rate of 5%) to detect lightning activity within about several hundred kilometers. We have been developing a compact lightning location system with the attitude detection capability to take advantage of the single-site lightning location technique. This portable lightning location system will be described in the future study.

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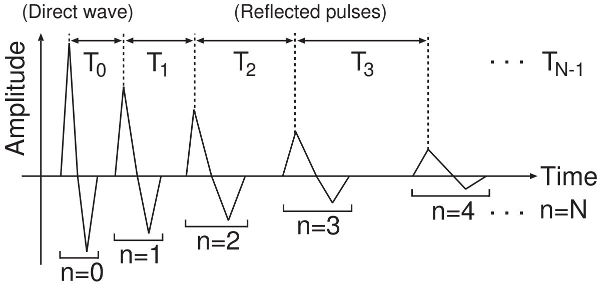

Figure 1: A sferic waveform.

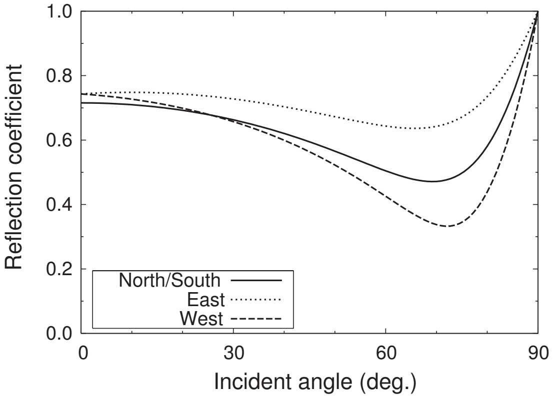

Figure 2: Dependence of the ionospheric reflection coefficient $\left|{}_{\parallel}R_{\parallel}\right|$ on the incident angle.

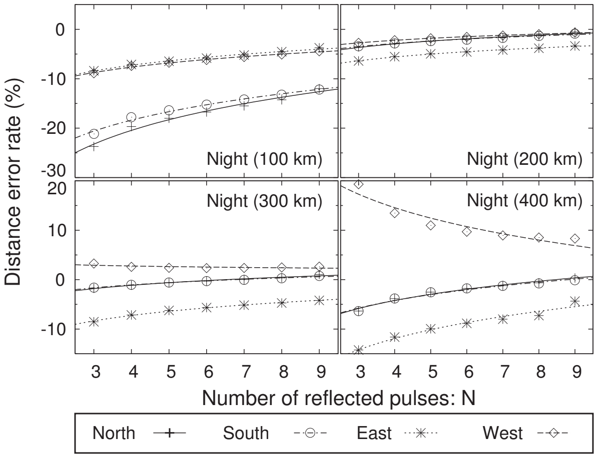

Figure 3: Distance error rates versus the number of reflected pulses used in the previous distance finding technique.

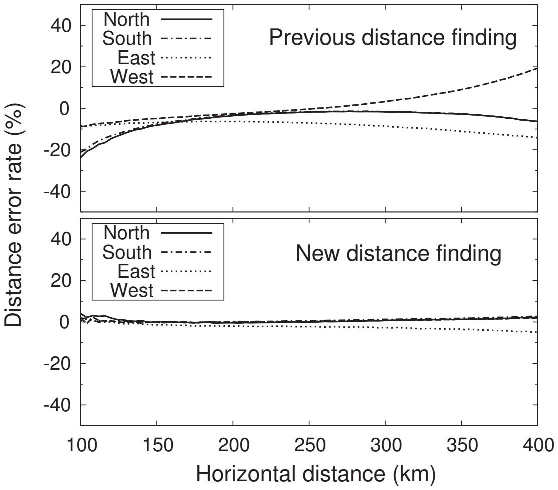

Figure 4: Distance error rates obtained by the previous and new distance finding techniques.

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