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Location Accuracy Improvement of Long-range Lightning Detection Network In China by Compensating Ground Wave Propagation Delay

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Abstract: Very low frequency (VLF) electromagnetic waves distort along the long propagation path, and that causes the arrival time of the signals measured by the long-range lightning system to be delayed. In this paper, based on the propagation correction method by compensating the peak time delay of the ground wave, the location accuracy of the long-range lightning detection network in China is greatly improved. The improvement of the relative location accuracy and location offsets are evaluated by comparing with the Advanced Direction Time Lightning Detection System (ADTD) datasets. It shows that the mean relative accuracy is improved from 7.74 km to 4.32 km, and the median relative accuracy is improved from 7.28 km to 2.46 km. The mean westwards offset of the total lightning location data drops from 2.05 km to 0.93 km, and the mean southwards offset drops from 1.19 km to 0.63 km. In addition, it is found that the location accuracy will be greatly improved if the observation site affected by the terrain is removed. The mean relative location accuracy is further improved to 4.11 km and the median to 2.32 km.

Keywords: long-range lightning detection network; location accuracy; ground wave peak time delay; propagation effects correction

1. Introduction

Lightning discharges emit a wideband of energetic electromagnetic radiation in the frequency range from lower-than-very-low frequency (VLF), through low frequency (LF), to greater-than-very-high frequency (VHF). The VLF electromagnetic waves propagate with a combination of the ground wave and sky wave. The ground wave propagates along the surface of the earth and have been used to detect and locate return strokes in cloud-to-ground (CG) lightning for many years [1], while the sky wave travels over thousands of kilometers in the Earth-Ionospheric Waveguide (EIWG) by reflecting between the ionosphere and the ground [2]. Due to the long-distance propagation characteristics of lightning signals, the VLF waves can be measured by long-range lightning locating systems (LLSs) sensors; thus, convective storms can be monitored and tracked in remote regions or over the oceans where ground-based receivers cannot be installed [3].

Most modern long-range ground-based LLSs employ location algorithms based on the time of arrival (TOA), magnetic direction finding (MDF) or the combination of the two methods [4]. The major challenge for the TOA systems is the need for the precise time synchronization of multiple remote sensors, as an error in the time measurement results.
in an error in the calculated position. The primary factors introducing timing error are variations in terrain elevation and propagation over finite conductivity soil, as well as ionosphere conductivity and height variations [5,6]. The result of these propagation effects is that the received lightning signal would be significantly attenuated and distorted and, therefore, affect the ability to identify the signal characteristics and produce the delay of arrival time [7–10]. Moreover, because of the variations in electron density distribution in the ionosphere for day and night times, the sferic features are much different. The ionosphere in the nighttime has a relatively higher reflection rate at high frequencies than in the daytime, resulting in a sharper skywave in the nighttime than in the daytime [11]. Additionally, the skywave during nighttime propagation arrives later than during daytime. Nighttime propagating VLF waves have different propagation characteristics due to the earth’s magnetic field. The westward propagating first-hop skywave of the sferic tends to have a multiple-peaked waveform [12,13]. The ionospheric effects make it difficult to determine the arrival time of the sferic with a complicated pattern. The Zeus long-range network [14] and the U.K. Met Office [15] use an arrival time difference (ATD) technique, and ATD is found directly by cross-correlating two sferic waveforms received at different outstations [16]. The requirement for similarity between two waveforms is fundamental to the ATD technique. However, the waveforms distort along the long propagation path, compromising the ATD calculation and positioning performance. The Asia-Pacific Lightning Location Network (APLLN) employs the multi-site TOA technology and determines the maximum energy point of the sferic waveform as the arrival time. The Hilbert transform is used to compute the envelope of waveforms, which contains crucial information about signal energy [17]. In the Global Lightning Dataset (GLD360), the TOA and MDF as well as a sferic waveform recognition algorithm are combined to geolocate lightning [18]. A set of waveform banks was cataloged to estimate the propagation distance and accurately determine the arrival time. The World Wide Lightning Location Network (WWLLN) utilizes the time-of-group-arrival (TOGA) method to locate lightning discharges. This method is based on the fact that lightning VLF sferics propagating in the EIWG experience dispersion, and the TOGA of a sferic is that instant when the regression line of phase versus frequency over the range 6–22 kHz has zero slope [19].

Applying corrections to the arrival times measured by LLS sensors can address a timing error introduced by terrain and soil conductivity variations and improve the accuracy of lightning location [20–22]. Honma et al. [23] compensated the peak time delays by using conductivity values in the narrow range 0.001–0.003 S/m. It was demonstrated that the location accuracy of lightning by the TOA technique was improved from 4.5 km to 1.5 km by introducing correction to the measured peak times of return stroke electromagnetic waveforms. By using propagation corrections, the median location accuracy of IMPACT LLS in the Tohoku Region of Japan improved from 400 m to 270 m [24]. Schueler and Thomson [25] improved the lightning location goodness of fit by compensating the time tags for propagation effects but had not attempted to measure the improvement in lightning location accuracy. Cummins et al. [26] provides an overview of the propagation correction methodology as applied to the U.S. National Lightning Detection Network (NLDN). The correction process reduced the RMS error in the arrival-time from approximately 1.5 µs to less than 0.7 µs, resulting in approximately a factor-of-two improvement in location accuracy. While Zhu et al. [27] found that by simply assuming a 1µs time delay per 200 km propagation path for all regions, the observed location biases from NLDN in coastal regions were reproduced in in the Monte Carlo simulation. Li et al. [28] analyzed the propagation effects on lightning-radiated electromagnetic fields over a mountainous terrain. It was found that the evaluated location errors associated with amplitude thresholds of 10% and 20% and the time of the linear extrapolation of the tangent at the maximum field derivative were the smallest [29]. In addition, a real-time location error compensation algorithm using an elongated propagation path method was presented to improve the location accuracy of LLSs involving propagation over mountainous terrain. However, these present studies about propagation corrections focus on the short-range and medium-range LLSs, whose
adjacent sensors are separated by distances from several tens to hundreds of kilometers. Because of the above propagation effects, long-range LLSs have inferior positioning performance than those networks. A new long-range lightning location network in China, named the NUIST long-range lightning detection network (NUIST-N300), was established in 2021. Li et al. [30] reported its preliminary application and used the equivalent propagation velocity method to reduce the location error caused by the propagation effect. They had to spend a great amount of calculation time obtaining the optimal location by choosing the lightning ground wave propagation speed from 0.95 \( c \) to 1.01 \( c \) (\( c \) is the speed of light). It is necessary to use a more practical method to take the propagation effects into account and apply arrival-time corrections to improve the network’s performance.

In this paper, a propagation correction method is presented to improve the location estimates of our long-range lightning detection network by compensating the peak time delay of the lightning-radiated VLF ground wave. A model simulation determines the relationship between the peak arrival time delay of the ground wave and the propagation distance. Then, we recompute the lightning locations and measure the improvement in lightning location accuracy by comparing them with the Advanced Direction Time Lightning Detection System (ADTD) datasets. Estimates of relative location accuracy improvements indicate that the relative accuracy and the location offsets are both improved. It is also found that the relative location deviation can be further reduced by removing the sensor greatly affected by terrain.

2. Data and Methods

2.1. Lightning Data and Location Algorithm of Our Long-range Lightning Detection Network

The long-range lightning detection network consisting of seven sensors was installed in September 2021 and was upgraded in the spring of 2022. After the latest upgrades, each sensor is equipped with a magnetic field antenna for receiving the azimuthal magnetic fields in the range of about 100 Hz to 80 kHz, mainly in the VLF band. Additionally, the VLF sferic waveforms are recorded at the sampling rate of 1 ms/s continuously for 1 ms with a 0.3 ms pre-trigger length. The length of most sferic waveforms is less than 1 ms so that each segment of data is used as an independent signal for grouping and geolocating.

The time-of-arrival (TOA) technique is used to determine the position of sferics emitted by lightning return strokes. Moreover, the lightning location is sought by calculating the minimum root mean square (RMS) formula:

\[
X_{RMS} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \left( \Delta t_i - \frac{\Delta d_i}{v} \right)^2}
\]  \hspace{1cm} (1)

where \( N \) is the number of stations participating in the solution, \( \Delta t_i \) is the arrival time difference of the sferics between the \( i \)th station and the central station, \( \Delta d_i \) is the difference of the propagation distance for the sferics between the lightning \( i \)th station and the central station, and \( v \) is the propagation speed of the sferics and is set from 0.95 \( c \) to 1.01 \( c \) (\( c \) is the speed of light). Meanwhile, a waveform bank was simulated by using the finite difference time domain (FDTD) to identify the ground wave peak point of the measured waveform and estimate the propagation distance. In the simulation, the simulation domain is 3200 km \( \times \) 100 km, the grid size is set to 500 m and the time step is set to 1 \( \mu \)s. More details of the FDTD model can be found in Hou et al. [12]. Li et al. [30] detailed the characteristics of the waveform bank, which was simulated under the typical daytime and nighttime ionospheric conditions at the propagation path of 100 km to 3000 km. The sferic waveforms distort along the long propagation path. Additionally, the low similarity of the sferic waveforms results in ambiguous matching in the time window, and there is error in the estimated time difference measured by the cross-correlation method. Therefore, the arrival time is measured by the peak time of the ground wave. Using the waveform bank, the peak time can be accurately determined.
Figure 1a plots a set of normalized waveforms for a lightning source inside the network recorded by the receivers, as well as the ground wave peak points (marked by yellow hexagrams), the estimated distance (left) recognized by the matched waveform bank and the actual distance (right). The estimated distance of the lightning sferic is estimated by the propagation distance of the most similar waveform in the waveform bank, and the actual distance is the distance between the stations and the lightning occurrence position. The recognition result is further shown in Figure 1b–g. The average propagation distance to the sensor is less than 1000 km. As the propagation distance increases, the sferic waveforms produced by the same lightning source are less similar. However, the measured signals are well matched with the waveform bank, and the ground wave peak points are accurately found.

Figure 2 plots another set of normalized waveforms for a lightning source outside the network and the recognition result of the ground wave peak point. The minimum distance between the source and sensors is greater than 1000 km, and the farthest distance is about 2820 km. After propagating several thousand kilometers, the ground wave attenuates into the noise, resulting in substantial distortions of the measured waveforms and the difficulty of accurately identifying the ground wave peak point from the shape. Although there is an
error of several hundred kilometers in the propagation distance estimated by the waveform bank, the ground wave peak points are also well found.

![Figure 2](https://example.com/figure2.png)

**Figure 2.** (a) Normalized waveforms for a lightning source outside the network at 16:48:13 on 3 October 2021, Beijing time. The minimum distance between the source and sensors is greater than 1000 km. The ground wave peak points are marked by yellow hexagrams, and the estimated distance (left) and the actual distance (right) are marked between parentheses. (b–g) The recognition result of the ground wave peak point for each measured waveform by the matched waveform bank.

The hyperbolic geometry model described by Proctor [31] is used to evaluate the positioning performance of the cross-correlation method and the arrival time of the ground wave peak method, herein referred to as the peak time method. The constant difference in the arrival time at every two stations can define a hyperboloid equation, and the location of the source can be determined from the intersection of three or more such hyperboloids obtained from four or more stations [32]. However, due to the timing errors resulting from the time delays and time measurement errors in every station, the location of the source tends to be constrained to lying in an enclosed region that is three-dimensional.

Figure 3 demonstrates how the network restrains the source inside or outside the network by hyperbolic geometry. The horizontal projection of hyperbolas associated with the difference in arrival time between the central sensor (CD) and others is shown in the Figure 3, and the other hyperbola of each pair is not plotted. As shown in Figure 3b, the misestimation of the propagation distance of about 100 km by the peak time method had little effect on the determination of the arrival time of the ground wave peak and the position of the source. However, due to the distortion of the lightning signal waveform,
the similarity between the sferic waveforms drops; thereby, the waveforms are incorrectly aligned in the time window. The time difference obtained by the waveform cross-correlation method might be much different from the real-time difference. This mistakenly causes the hyperbolas to be biased outward, thereby resulting in a larger area of the intersection of hyperbolas than the peak time method and a great location deviation. In Figure 3d, the sources occurring outside the network tend to be constrained to lie in a large region and bias towards the wrong position, resulting from the more parallel intersection of the hyperbolas. The ambiguous features of the ground wave and the complex shape of the sky wave cause cross-correlation difficulties. The hyperbolas are more scattered, forming a larger area than by the peak time method. Compared with the cross-correlation method, though the peak time method displays better performance, location errors due to propagation effects still exist and will be exacerbated with the increasing time delay over longer propagation paths. It is necessary to apply propagation correction by compensating the peak time delay to further improve performance. The advantage of the hyperbolic geometry model is that it provides a visual method for analyzing the location error without a reference system. Therefore, in the following sections, this model will be used to investigate the performance of compensating the peak time delays resulting from the propagation effects in the optimization procedure of lightning location.

**Figure 3.** The horizontal projection of the hyperbolic map for the peak time method (solid line) and cross-correlation method (dashed lines). (a) Locating a source inside the network. Five hyperbolas of the different colors that are the same as in Figure 1 are shown corresponding to the following sensor pairs: CD–CF, CD–JQ, CD–NJ, CD–TY and CD–WH. (b) The partial enlargement of (a) and the optimum locations sought by the peak time method (“×” in red) and cross-correlation method (“+” in blue). (c) Locating a source outside the network. Five hyperbolas of the different colors that are the same as in Figure 2 are shown corresponding to the following sensor pairs: CD–CF, CD–JQ, CD–NJ, CD–TY and CD–CWP. (d) The partial enlargement of (c) and the optimum locations sought by the peak time method (“×” in red) and cross-correlation method (“+” in blue).
2.2. The Advanced Direction Time Lightning Detection System (ADTD)

The ADTD of the Institute of Electrical Engineering of the Chinese Academy of Sciences works in the VLF/LF band. It consists of 371 detection stations with a baseline of about 100 km [17], and each station is equipped with a VLF/LF electric field antenna and a magnetic antenna. The system adopts the trigger sampling method with a 1 ms sampling time length and 100 µs pre-trigger length. The detection range covers most of China and some countries in Southeast Asia. The system geolocates lightning discharges by the combined techniques of MDF and the time difference of arrival (TDOA). ADTD can classify events between CG strokes and intracloud (IC) lightning strokes. The CG stroke detection efficiency is higher than 90%, and the IC stroke detection efficiency is higher than 45% [33]. The average horizontal location error within the network is less than 500 m.

2.3. Propagation Correction

In order to take the propagation effects into account, we apply a model simulation based on the theories of ground wave propagation along the spherical earth surface with finite conductivity presented by Hill and Wait [34]. The model simulation is expected to predict the ground wave with long-distance propagation with more satisfactory accuracy than by using the FDTD method.

The lightning discharge channel observed over ranges of hundreds to even thousands of kilometers can be equivalent to a dipole. Thus, the azimuthal magnetic field \( H \) at a great circle distance \( d \) for a dipole source located on the surface of a smooth earth can be expressed as [35]

\[
H = H_0 W
\]

where \( W \) is the attenuation function and \( H_0 \) is the free-space radiation magnetic field of the dipole source situated on the perfectly conducting plane surface. For the simulation of CG lightning propagation, where both the source and the receivers are on the ground, \( W \) is expressed as [36]

\[
W = e^{-j\pi/4}(\pi x)^{1/2} \sum_{s=1}^{\infty} e^{-jt_s - q^2}
\]

where \( x = (k_0 R/2)^{1/3}(d/R) \), \( R \) is the radius of the earth, and \( k_0 \) is the wavenumber in the free space, \( q = -j(k_0 R/2)^{1/3} \Delta \); \( \Delta \) is the normalized earth surface impedance

\[
\Delta = k_0 / k (1 - (k_0/k)^2)^{1/2},
\]

\( k \) is the wavenumber in the earth \( k = \omega(\varepsilon r \varepsilon_0 \mu_0 - j\sigma \mu_0 / \omega)^{1/2} \), where \( \omega \) is the angular frequency, \( \varepsilon_0 \) and \( \mu_0 \) are the dielectric constant and magnetic permeability of free space, respectively, \( \varepsilon_r \) and \( \sigma \) are the relative dielectric constant and conductivity of earth, respectively, and \( t_s \) are the roots of

\[
w_1'(t) - q w_1(t) = 0
\]

The way to obtain the roots \( t_s \) is described in detail in [34,37,38] and is not repeated here. The propagation distances were assumed to be in the range of 100 km to 3000 km, and this simulation did not consider the reflection of the ionosphere. The ground conductivity was set to be 0.01 S/m and homogeneous, and both the source and receivers are located on the earth’s surface. The lightning return stroke current distribution along the channel was specified according to the transmission-line model with an exponential current decay with the height (MTLE model) [39,40], and the length of the channel was assumed to be 7.5 km. The return stroke discharging current is set as the first return stroke and subsequent return stroke current [41], as well as a current moment [42].

Considering that our network works in the VLF band, a bandpass filter is set to filter the azimuthal magnetic field predicted by the model. Then, the relative time delay defined by the time difference between the peak time of the ground wave radiated by the three current sources, and the arrival time of the particular propagation speed (the reference speed) was calculated. Figure 4 demonstrates the relative time delay versus propagation
distance with two reference speeds of 0.998 \( c \) and \( c \). Due to the propagation effects from ground finite conductivity and the curvature of the earth, the arrival time of the ground wave peak is increasingly delayed for longer propagation paths, meaning that the traveling speed of the ground wave is less than the reference speed. For applying the arrival-time correction of the ground wave peak, an average curve of the relative time delay is displayed to relate the peak time delay with propagation distance. Figure 4b demonstrates a roughly linear relationship between the average relative delay referred to the speed of light and propagation distance; that is, the peak time is delayed by an average of 0.9 \( \mu s \) over the 100 km of propagation. Uman et al. [43] noted that the 10% to 90% risetime of return stroke electric field pulses was increased by about 1 \( \mu s \) by propagation over the 200 km in Florida between stations. Honma et al. [23] showed that the peak of return stroke pulses was delayed by an average of 1.8 \( \mu s \) over the 130 km of propagation over the land with a conductivity of about 0.003 S/m in Japan. The simulation results presented by Shao and Jacobson [38] show that the peak of the waveform, which is dispersed and low-pass filtered by the ground path, is delayed by about 13 \( \mu s \) at 1000 km with an assumed conductivity of 0.02 S/m. The time delay simulated in this paper is about the same as the above results and therefore could be used to correct the propagation effect.

Once the propagation distance is estimated by the waveform bank, the relative time delay could be determined. Then by subtracting the relative time delay from the arrival time of measured signals to compensate the time delay, a more accurate arrival time
difference between two sensors is calculated. The lightning locations are recomputed by using Equation (1), where \( v \) is the reference speed of the relative time delay.

3. Performance Analysis by the Hyperbolic Geometry

The hyperbolic geometry model is used to analyze the performance of compensating the time delay in this section. Figure 5 shows the hyperbolic map of corrected and uncorrected results for the arrival time of the signals shown in Figure 1. A longer distance from the lightning source to the sensor is associated with a larger compensation peak time delay. As shown in Figure 5a, after correcting the arrival time with the reference speed of \( c \), these hyperbolas bias inward obviously. The farther the lightning source is from the sensor, the greater the offset of the hyperbola. So that the intersection forms a much smaller area than the uncorrected, the arrival-time error is reduced, resulting in an improvement in location accuracy. In addition, Figure 5b shows a smaller intersection size of these five hyperbolas by applying arrival-time corrections with a slower reference speed, which means a greater improvement in timing errors and location accuracy. This also indicates that the traveling speed of the ground wave is less than the speed of light.

For sources outside the network, the greater effects of traveling along longer distances cause larger time delays and location errors. Figure 6 further shows the improvement of location error after applying arrival-time corrections for the lightning signals plotted in Figure 2. The time delay is proportional to propagation distance, and thus a greater offset is set for the hyperbola if there is a longer distance difference between the central sensor (CD) and others. After compensating the time delays, the hyperbolas bias inward instead, forming a much smaller area. It is much different from Figure 3d, where the hyperbolas determined by the cross-correlation method bias irregularly. This indicates that using propagation correction enables improving the timing error and location accuracy for sources outside the network as well. In addition, as seen in Figure 6b, it will provide a greater improvement by compensating the peak time delay with a slower reference speed than \( c \).
Figure 6. Same as Figure 5, but for the signals shown in Figure 2. (a) Compensating the peak time delay with a reference speed of \(c\). (b) Compensating the peak time delay with a reference speed of \(0.998\ c\).

However, considering that the effect of the hundreds of meters of estimated propagation distance error would result in an inaccurate time delay compensation, which would introduce extra timing error and location error instead, the optimum location after applying correction is regarded as the initial solution, and the compensation peak time delays is integrated into Equation (1). The final lightning location is found by minimizing the modified formula:

\[
X_{\text{RMS}} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \left( \left( \Delta t_i^{\text{delay}} - \Delta t_i^{\text{delay,c}} \right) - \frac{\Delta d_i}{v} \right)^2}
\]

where \(\Delta t_i^{\text{delay,c}}\) is the difference of relative time delay between \(i\)th station and the central station \(\Delta t_i^{\text{delay}} = t_i^{\text{delay}} - t_c^{\text{delay}}\), and \(t_c^{\text{delay}}\) is calculated from the relationship between relative time delay and propagation distance at the particular reference speed \(v^{\text{delay,c}} = f(R, v_r)\), where \(R\) is the propagation distance and \(v_r\) is the reference speed. Moreover, the restriction of the equal of the propagation speed \(v\) and the reference speed \(v_r\) is removed; in other words, the propagation speed is variable, which is expected to obtain a combination of the two speeds for the best positioning performance.

4. Results

4.1. Relative Location Accuracy

In this section, the performance analysis focuses on the relative location accuracy of the lightning data obtained by our long-range lightning detection network during a week in October 2021. Here, two metrics have been developed to evaluate the relative location accuracy. One is relative position deviation, which is determined by the deviations of the lightning data obtained by our long-range lightning detection network during a week. The second metric is named the effective rate, which is defined as the ratio of the amount of data with a relative deviation reduction to the sum of matched data. When comparing events from different networks, it is a necessity to have a common definition of a lightning source. In this paper, events in two datasets were considered the same if they occurred within 0.5 ms and 30 km [44], and 21,334 matched lightning events were found finally. Figure 7 contains histograms of relative position deviation before propagation correction and after applying propagation correction with a reference speed of \(0.998\ c\). The propagation speeds are chosen from among \(0.998\ c\), \(c\) and \(1.002\ c\), respectively. The number of matched events decreases with the increase in the distance difference between the ADTD and the long-range lightning detection network datasets. Additionally, the averages and the medians of the relative deviations as well as the effective ratio are shown in Table 1. As shown in Figure 7,
the relative position deviations before correction are mainly below 10 km, and about half are below 5 km. The average relative deviation for the uncorrected is 7.74 km, and the median is 7.28 km. After applying correction, the number of lightning strokes with a relative positioning deviation of less than 5 km has significantly increased, especially those with a relative positioning deviation of less than 2.5 km, which has almost doubled. When setting the propagation speed as the speed of light, the fraction of relative positioning deviation greater than 20 km is reduced most, though the improvement of location with a small relative positioning deviation is not as good as with 0.998 \( c \), generating a smaller average relative deviation as well as a larger median relative deviation and effective ratio. Although the performance of choosing the propagation speed as 1.002 \( c \) is worse than that of choosing the other two speeds, it is also better than that before correction. The effective ratio reaches the highest by using correction with a combination of 0.998 \( c \) for the reference speed and \( c \) for the propagation speed, and the average relative deviation is the smallest at 4.32 km, with a median of 2.46 km. These two metrics prove that after applying propagation correction, the relative location accuracy of our long-range lightning detection network is significantly improved.

![Distribution of relative position deviation before propagation correction and after applying propagation correction with a reference speed of 0.998 \( c \) and different propagation speeds.](image)

**Figure 7.** Distribution of relative position deviation before propagation correction and after applying propagation correction with a reference speed of 0.998 \( c \) and different propagation speeds.

**Table 1.** Relative location accuracy metrics for uncorrected and propagation corrected with a reference speed of 0.998 \( c \).

<table>
<thead>
<tr>
<th>Propagation Speed</th>
<th>Effective Ratio</th>
<th>Averages Relative Deviation (km)</th>
<th>Median Relative Deviation (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncorrected</td>
<td>( c )</td>
<td>/</td>
<td>7.74</td>
</tr>
<tr>
<td>Corrected with the reference speed of 0.998 ( c )</td>
<td>0.998 ( c )</td>
<td>72.72%</td>
<td>4.35</td>
</tr>
<tr>
<td></td>
<td>( c )</td>
<td>74.69%</td>
<td>4.32</td>
</tr>
<tr>
<td></td>
<td>1.002 ( c )</td>
<td>69.34%</td>
<td>4.51</td>
</tr>
<tr>
<td>Equivalent propagation velocity method</td>
<td>Variable ²</td>
<td>59.83%</td>
<td>6.36</td>
</tr>
</tbody>
</table>

\(^1\) \( c \) is the speed of light. \(^2\) Variable means the propagation speed for the minimum RMS in Equation (1) is variable.
Compared with the equivalent propagation velocity method, the location accuracy is much better with the time delay correction method presented in this paper. Using the equivalent propagation velocity method, the location accuracy of the sources at close range has been greatly improved. However, for sources at a long range, the location accuracy is poor, resulting in a high average relative deviation and a low median relative deviation. Although adjusting the propagation speed can optimize the lightning location, it costs a lot of calculation time and is not efficient. In order to improve positioning efficiency, it is necessary to decide on the best combination of reference speed and propagation speed. Figure 8 further shows the average relative position deviations and the effective ratios at different reference speeds along with their best improved propagation speeds. The position deviations of the sources inside and outside the network are both dramatically reduced, so the average and median relative deviations are smaller than the equivalent propagation velocity method. The average relative deviations are not much different with the increase in reference speed, while the effective ratios increase at first, then decrease. The best matched equivalent propagation speed also increases as the reference speed increases. Based on the results, the combination of a reference speed of 0.998c and a propagation speed of c will be considered in the positioning process of the long-range lightning detection network. Additionally, the time that this method spends calculating the optimal locations for sets of signals after grouping is about 1 s, while the equivalent propagation velocity costs more than 1 min.

![Figure 8. Relative location accuracy metrics for propagation corrected with different reference speeds combined with their best combined propagation speed.](image)

4.2. Location Offsets

The positions of the corrected events detected by our long-range lightning detection network on 3 October 2021, as well as the matched ADTD events, are shown in Figure 9. The long-range lightning detection network successfully determines the location of lightning discharges, even those that are outside the network. Next, the matched ADTD events are plotted as origin to determine the east–west and north–south offsets of the uncorrected and corrected matched events. As shown in Figure 10, the corrected events cluster closer to the origin, while the uncorrected events are more scattered. The average westwards offset drops from 2.05 km to 0.93 km, and the average southwards offset drops from 1.19 km to 0.63 km. The location offsets due to VLF propagation effects are well improved. After applying propagation correction, there is still an offset mainly towards the southwest. It might be related to the distribution of the network, since the sensors are mainly concentrated in the northeast.
Figure 9. The positions of the matched events on 3 October 2021.

Figure 10. Location offsets of all matched events. Each matched ADTD event is taken to be at (0,0), and the corresponding event’s location is plotted relative to this point. The dotted lines indicate the average offsets. (a) For the uncorrected events, the average westwards offset is 2.05 km, and the average southwards offset is 1.19 km. (b) For the corrected events, the average westwards offset is 0.93 km, and the average southwards offset is 0.63 km.

5. Discussion

5.1. Effect of the Terrain on the Location Accuracy

This section discusses the reasons for the increase in the relative positioning deviation after the propagation effect correction. It is found that half of the location results involving the signal received by CWP station are unimproved. As shown in Figure 11b, after applying correction, the area formed by hyperbolas has an excursion to the southwest and becomes larger, so the relative position deviation is increased from 6 km to 8 km instead. Current research has shown the effects of the terrain on lightning electromagnetic
waves by the elongation of the propagation path of the signals [20]. Figure 12 shows the vertical topographic profiles along propagation paths from the source to each sensor. The propagation path to the CWP station is different from others because of the terrain envelope fluctuating significantly.

Figure 11. The horizontal projection of the hyperbolic map as well as the optimum locations for corrected (dashed lines/“+” in blue) and uncorrected (solid line/“×” in red) for propagation of an unimproved case. (a) Five hyperbolas of different colors are shown corresponding to the following sensor pairs: CD–CF, CD–JQ, CD–WH, CD–TY and CD–CWP. Compensating the peak time delay with a reference speed of 0.998 $c$, and the propagation speed is $c$. (b) The partial enlargement of (a) and the optimum locations.

Figure 12. (a–f) Vertical topographic profiles from the source to the following sensors: CD, CF, JQ, WH, TY and CWP.

The sferics received by corresponding stations were removed in turn during positioning to confirm the effect of the terrain. Figure 13a shows that the position of the source is constrained to lying in a very small region after propagation correction and eliminating the sferic from the CWP station, indicating that the location accuracy is well improved.
Figure 13b depicts the overall positioning results. Only when the signal from the CWP station is removed, the relative positioning deviation is reduced to less than 1 km, whereas the deviations in other cases might be increased several times. These results demonstrate that the arrival time of the VLF ground wave is affected by traveling over mountainous terrain, resulting in location errors.

Finally, the lightning locations were recomputed for the reference speed of 0.998 c and the propagation speed of c after eliminating the sferics measured by the CWP station. Figure 14 shows that the timing error of the CWP station causes it to fail to improve the location accuracy and even results in negative improvement. When removing the CWP station, the percentage of the negative improvement is obviously reduced, and lightning locations mainly have positive optimization with an average value of 7.18 km. More matched lightning events are found, and the average relative position deviation is further reduced to 4.11 km and the median to 2.32 km, while the effective ratio is increased to 76%. This shows that the presence of the terrain compromises the positioning performance of the long-range network by introducing timing error, and removing the sensor, which is under the effect of the terrain, could effectively improve the location accuracy. The terrain envelope method presented by Li et al. [29] might be an available method and is used to compensate the extra time delay by elongating the propagation paths. The performance of this method in our long-range lightning detection network is left to be assessed in future work.
5.2. Relationship of the Propagation Speed versus Distance

It is found in Section 3 that the traveling speed of the ground wave is less than c, so setting a slower propagation speed is expected to have a better improvement in location accuracy. However, the best positioning performance was obtained with a faster propagation speed than the reference speed. Figure 15 illustrates that for the sources within 1600 km, most are closer to the reference location after correction by using the propagation speed of 0.998 c, which is less than c. However, with the increase of the propagation distance, using the propagation speed of c would result in less deviation. From Equation (5), \( v \) increases might be due to the increase of \( \Delta t^\text{delay}_i \). It means that the peak time delay is overcompensated.

![Figure 15. Percentage of the propagation speed that results in less deviation.](image)

Our simulation of the ground wave did not consider the reflection of the ionosphere. However, at a great distance, the propagation distance difference between the ground wave and the sky wave is decreased, so the peak from the ground wave contains some contribution from the sky wave [45], as shown in Figure 16. The peak of the actual ground wave lags behind that of the received wave, for the sky wave catches up with the ground wave. Moreover, the relative peak time delay between the ground wave and the received wave increases with distance. In this paper, the relative time delay is defined by the time difference between the peak time of the ground wave and the arrival time of the reference speed, while when compensating the peak time delay, the peak arrival time is picked by the received wave rather than the real ground wave. This causes the overcompensation of the peak time delay over a long range, whereby a faster propagation speed would be set to counteract the potential effects.

In this paper, the ground was assumed to be homogeneous, and the ground conductivity was set to be 0.01 S/m. It is demonstrated to be effective because the location accuracy is greatly improved by using the relationship of the relative time delay versus propagation distance obtained in Section 3 to compensate for the peak time delay of the ground wave. However, the relationship is different from the actual, which causes negative positioning performance in some cases. Ground waves may propagate over land, fresh water, seawater, and interspersions thereof. Propagation effects that varied among propagation paths with complex conductivity cause the peak time of pulses to be nonuniformly delayed. Schueler and Thomson [46] considered the different conductivity of the stratified ground using a stratified ground model and the method of least squares to estimate ground conductivity, time delay, stratum thickness, source location and station gain. It was found that the lightning location goodness of fit was significantly improved. The peak time delay of the ground wave under the effect of the complex conductivity will be considered to further
improve the location accuracy in the future. In addition, the average ground conductivity within our network detection range will be measured by the characteristics of ground wave pulses.

![Figure 16](image)

**Figure 16.** Division of the waveform bank (red solid line) into actual ground wave (blue solid line) and sky wave (green solid line). The red dashed line and blue dashed line represent the peak arrival time of the waveform bank and the actual ground wave, respectively. (a) Waveforms received at 1000 km. (b) Waveforms received at 2000 km.

### 5.3. Thresholds of Time Difference and Spatial Difference

The relative location accuracy is sensitive to the time difference and spatial difference thresholds. After a preliminary comparison of the different time and spatial difference thresholds, it is found that there is very little corrected lightning data with spatial differences beyond 100 km when the time threshold is set to 0.5 ms. As shown in Figure 17a, more than 60% of lightning strokes have spatial differences between our long-range lightning detection network and the ADTD of less than 5 km, and nearly 85% of them have less than 30 km. It means that it is available to choose the spatial threshold as 30 km to estimate the relative location accuracy. Figure 17b further demonstrates the mean and median relative position deviation with different spatial thresholds. The mean deviation increases, as expected, since it is influenced by the larger deviation values, while all the median deviations are less than 3.5 km. It can be mentioned that the long-range lightning detection network has good position performance after the correction method by compensating ground wave propagation delay.
Figure 17. (a) Distribution and cumulative percentage of spatial difference between two lightning datasets with the time threshold of 0.5 ms. (b) The mean and median relative position deviation histogram of corrected lightning data with increasing spatial difference thresholds.

6. Conclusions

In this paper, a propagation correction method is presented to improve the location accuracy of long-range LLS by compensating the peak time of lightning-radiated VLF ground waves. The improvement of the relative location accuracy and location offsets of the long-range lightning detection network are evaluated by comparing with ADTD datasets. Using the combination of $0.998 \cdot c$ for the reference speed and $c$ for the propagation speed in the positioning process, both the positioning efficiency and location accuracy are better than the equivalent propagation velocity method. After applying propagation correction, the average relative accuracy improved from 7.74 km to 4.32 km, and the median relative accuracy improved from 7.28 km to 2.46 km. The average westwards offset drops from 2.05 km to 0.93 km, and the average southwards offset drops from 1.19 km to 0.63 km. The residual offsets are likely relative to the distribution of the network. In addition, the existence of terrain over the propagation paths affects the location accuracy as well. Removing the sensor, which is greatly under the effect of the terrain, could further improve the location accuracy. The mean relative location accuracy is further improved to 4.11 km and the median to 2.32 km. The delay of the arrival time of lightning electromagnetic waves is not negligible because of the propagation effects, which would cause the location accuracy to be worse. The propagation correction method presented in the manuscript can be applied in other lightning networks that receive lightning signals that propagate over hundreds of kilometers, especially other long-range networks, to improve the positioning performance.
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Abbreviations

ALT Aletai
CD Chengdu
CF Chifeng
CH Conghua
CWP Caiwopu
GY Guiyang
JQ Jiuquan
KS Kashi
LS Lasa
NJ Nanjing
QM Qiemu
TY Taiyuan
WH Wuhan
WZ Wenzhou
XM Xiamen
XSBN Xishuangbanna
XW Xuwen
YC Yinchuan

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