The Accuracy of Radio Direction Finding in the Extremely Low Frequency Range

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Abstract In this work, we study the accuracy of direction finding in the extremely low frequency (ELF) range using a newly installed broadband receiver equipped with two active magnetic antennas. The main natural source of ELF radio waves is lightning. In this work, we analyzed 1000 atmospheric discharges at distances of up to 5000 km from the receiver. We identified the most important factors influencing the accuracy of the angle of arrival: the deviation of the radio waves propagating through the day-night terminator zone and the signal-to-noise ratio resulting from local electromagnetic noise and Schumann resonance background. The obtained results clearly show that the accuracy of estimating the direction of arrival is very high (an average error of 0.1° with the standard deviation of 2.3°) when the signal-to-noise ratio is large (the amplitude of the magnetic field component above 100 pT), except for short periods in the local morning and evening, when the day-night terminator is present on the propagation path of the direct wave. For the day-night propagation paths, the refraction angle was larger than the incidence angle, and for the night-day propagation paths, the refraction angle was smaller than the incidence angle, which is consistent with theory. Using our analytical ELF radio propagation model allowed us to explain the obtained results.

1. Introduction

In this work, we analyze data from our new ELF receiver equipped with two magnetic antennas, which was set up in Patagonia in southern Argentina. The station was built using our most recent generation of ELF equipment (Kulak et al., 2014). It features a frequency bandwidth of 0.03 to 300 Hz. It is part of our ongoing project, called the World ELF Radiolocation Array, the intention of which is to locate the strongest atmospheric discharges occurring anywhere on Earth. One station enables us to find the direction of arrival of the signal. Two stations would allow us to determine the location of the source. The third station would make it possible to increase the accuracy of the location and to determine the polarity of the source.

In this study, we focus on the accuracy of direction finding using one receiver equipped with two orthogonal magnetic antennas (induction coils). In a similar study published recently by Bór et al. (2016), the authors analyzed the accuracy of direction finding using their ELF station in Hungary. They identified the local anisotropic ground conductivity as the dominant factor of error. Once identified, it can be minimized using an angle-dependent correction factor. We show that in our case, the main factor influencing accuracy is the presence of the day-night terminator zone and the signal-to-noise ratio. The obtained maximum error in the angle of arrival due to the terminator zone was 12°, which is consistent with the residual bearing deviation found by an early study with a very narrowband systems (4–16 Hz and 4–19 Hz; Füllekrug & Sukhorukov, 1999). However, the mean error in the direction finding and its standard deviation are significantly smaller in our case. This could be related to much broader frequency range of our receiver leading to a smaller influence of local anisotropies on direction finding. Lightning location in the ELF range has also been studied at large distances. Boccippio et al. (1998) analyzed 40 events observed from Tropical Rainfall Measuring Mission satellite at the distances of up to 20 Mm and found that the mean ground range error was 2 Mm. Single-station Schumann resonance method has also been used by Williams et al. (2007) for a sprite lighting at the distance of 16.6 Mm. Williams et al. (2010) analyzed sprites lighting events from Africa detected by several ELF stations worldwide. Mlynarczyk et al. (2016) analyzed strong lightning discharges at the distances of up to 12 Mm using two ELF receivers, one located in Poland and the other in Colorado, USA. Some other studies related to lightning location that the reader might be interested in include Reising et al. (1996) and Füllekrug and Constable (2000). In our study, we analyzed 1000 strong lightning discharges at distances of up to 5000 km from the receiver. To our knowledge, this is the first study of radio direction finding performed with a broadband ELF receiver.
(0.03–300 Hz) on such a large data set. The use of a broadband receiver allowed us to work with impulses that had high amplitude, limiting the influence of Schumann resonance background on the obtained results.

2. Data and Methods

Two orthogonal magnetic antennas enable us to infer the angle of arrival (AoA) of the recorded signal. There are several factors that influence its accuracy. The first one is the accuracy of antenna alignment toward the geographic north and east. We set up the antennas using a liquid-filled compass with a sighting mechanism for precise bearing and the International Geomagnetic Reference Field model (Thébault et al., 2015) to correct for the magnetic declination. To increase the precision of bearing we used long cords fixed to ground stakes, which we aligned with the geographical north-south and east-west directions and with the two antennas. We recheck the alignment using another liquid-filled compass and an electronic compass. We also checked the length of hypotenuse of a triangle formed by the stakes and cords. This way both the correct direction and the 90° angle between the two antennas were checked. However, the accuracy of this procedure is still limited; we did not expect it to be better than about ±1°. Another factor that can influence the angle of arrival inferred from the signal is the local ground conductivity (Bór et al., 2016). The accuracy of direction finding is also strongly influenced by the Schumann resonance background. To limit its influence, for this analysis we chose the signals that had the amplitude of at least 100 pT. Due to very low attenuation of ELF waves and a wide bandwidth of our receiver, we typically record a few hundred discharges per hour which meet this criterion. In this study, we excluded sources located farther than 5000 km from the receiver in order to exclude any additional effects that might be related to long-range propagation, rather than the direction finding itself.

Most atmospheric discharges take the form of short impulses (Figure 1). The simplest way to infer the angle of arrival is to take the ratio of the peak amplitudes recorded by the two magnetic antennas and calculate the inverse tangent. Another method would be to perform digital antenna rotation in software until the maximum is found in one channel and zero in the other channel, but this method is more difficult to automate. We will illustrate this in section 3.

Figure 2 shows a typical spectrum recorded by our ELF receiver, in which we identified three main sources that have negative influence on the accuracy of direction finding: power line noise, Schumann resonance background, and 1/f noise. The Schumann resonance background exhibits diurnal, seasonal, and geographical variabilities due to its dependence from the intensity and location of storm centers. Therefore, the signal-to-noise ratio will also exhibit such variability (Huang et al., 1999).

The accuracy of direction finding can be improved significantly by reducing 1/f noise, which includes both geophysical and instrumental contributions. Therefore, we used a high-pass filter with a
The chosen cutoff frequency is a trade-off between the accuracy of direction finding and ELF waveform distortions that a high-pass filter can cause. We also removed the 50 Hz power line noise and its third harmonic. We used a third-order bandstop digital Butterworth filter with the bandwidth of 0.4 Hz. Interestingly enough, a 60 Hz power line noise is sometimes visible in our spectra (see Figure 2), even though the closest 60 Hz power grid system is located about 2500 km away.

The sampling rate of the station is 887.784 Hz. In order to find more accurately the peak amplitude, we resample the signal at 5 times the original sample rate. Resampling consists in inserting additional samples between each of the original samples (Proakis & Manolakis, 2007, section 6), and it can be treated as an interpolation. The obtained waveform is smoother and the peak amplitude (as well as the timing) can be read with better precision.

All the discharges were identified using data from the World-Wide Lightning Location Network (WWLLN) lightning detection network (Rodger et al., 2006) and taking into account the time of arrival. The reported location was used as a reference for determining the error in the angle of arrival (AoA). We defined this error as the difference between the azimuth inferred from the location reported by WWLLN and the azimuth obtained from the ELF data. The WWLLN network operates in the very low frequency (VLF; 3–30 kHz) band, and its ultimate aim is to provide location of cloud-to-ground (CG) discharges with mean location accuracy below 10 km (Rodger et al., 2006). As of 2012 (Hutchins et al., 2012), WWLLN consisted of 60 stations distributed around the world. The detection efficiency was estimated to be of about 11% for cloud-to-ground (CG) strokes and above 30% for higher peak current flashes over the continental United States. The WWLLN located 61% of strokes with the accuracy of below 5 km (Hutchins et al., 2012).

### 3. Results and Discussion

We analyzed 1000 impulses with an amplitude of above 100 pT and which originated from cloud-to-ground discharges detected by WWLLN between 27 March and 6 April 2017. To obtain such long data span we set the WWLLN energy threshold to 50 kJ. This allowed us to reduce the number of empty angles (directions without any lightning). Figure 3 shows the location of the discharges.

Figure 4 presents the error in the direction of arrival at various hours of the day for discharges at distances of up to 3500 km (top plot) and 5000 km (bottom plot). We can see two periods during the day where the error is clearly higher. These are periods during which the day-night terminator is above South America. Figure 5 shows the terminator’s location at 10:00 and 22:00 UTC.

At around 10:00 UTC the error was positive, which means that the azimuth calculated from the WWLLN data was larger than the azimuth estimated from the ELF recording. At around 22:00 UTC the error was mostly negative, which means that the azimuth obtained from the WWLLN data was smaller than the azimuth inferred from the ELF signal.

To understand these results, we assume a sharp boundary between the day and night zones and use the Snell’s law (Davis, 1990, p. 73).
The phase velocities in the day and nighttime zones are related to the sines of the angles of incidence $\theta_1$ and refraction $\theta_2$:

$$v_{\text{night}} \sin \theta_1 = v_{\text{day}} \sin \theta_2.$$  \hspace{1cm} (1)

The refraction principle on the day-night path is illustrated in Figure 6.

The phase velocity in the Earth-ionosphere waveguide can be calculated from (Mushtak & Williams, 2002)

$$v(f) = \frac{c}{\text{Re}S(f)},$$  \hspace{1cm} (2)

where $S$ is the dimensionless frequency-dependent complex propagation parameter, which is related to the wave number $k$ by the equation (Kulak, Młynarczyk, & Kozakiewicz, 2013):

$$S = \frac{c}{\omega k}.$$  \hspace{1cm} (3)

The propagation parameter $S$ can be calculated from (Mushtak & Williams, 2002)

$$S(f)^2 = \frac{\bar{h}_m(f)}{\bar{h}_e(f)},$$  \hspace{1cm} (4)

where $\bar{h}_m$ and $\bar{h}_e$ are the complex magnetic and electric altitudes of the Earth-ionosphere waveguide, and they are frequency dependent (Kulak & Młynarczyk, 2013).

From our ELF propagation model (Kulak & Młynarczyk, 2013), we obtained the complex altitudes and then calculated the phase velocities for the day and night propagation paths. Since the deviation of the trajectory was based on the peak amplitude comparison, we were interested in the phase velocity at the frequency close to the upper cutoff frequency of the receiver. We got the following values at 300 Hz:

$$v_{\text{day}} = 0.823c, \quad v_{\text{night}} = 0.944c.$$  \hspace{1cm} (5)

First, we analyze the radio wave propagation from the dayside to the nightside (Figure 6). Let us assume a long propagation distance, for example, $d = 4800$ km, and a large refraction angle, $\theta_2 = 80^\circ$, which should generate a large error. The angle of arrival at the ELF receiver location for this case is about $10^\circ$ (assuming for simplicity that the terminator is a sharp boundary along the meridian located in the middle of the propagation path). Using equation (1) we obtain

$$\sin \theta_1 = \frac{v_{\text{day}} \sin \theta_2}{v_{\text{night}}} = 0.856,$$

which gives the incidence angle $\theta_1 = 59^\circ$. Once $\theta_1$ and $\theta_2$ are known, we can calculate the error in the direction of arrival based on the geometry of the propagation path (as seen in Figure 6):

$$\Delta = A\theta_{\text{source}} - A\theta_{\text{ELF}} = 10.5^\circ.$$

The obtained error in the direction of arrival is positive, which means that the azimuth to the source location $A\theta_{\text{source}}$ is larger.
than the azimuth inferred from the ELF data $\theta_{\text{ELF}}$. Taking a very small refraction angle, for example 10°, which means that the angle of arrival is 80°, we obtain the incidence angle of $8.7^\circ$ and the error in the angle of arrival

$$\Delta = \theta_{\text{source}} - \theta_{\text{ELF}} = 0.65^\circ.$$ 

Taking the refraction angle of 45°, we obtain the incidence angle of $38.1^\circ$ and the error in the angle of arrival

$$\Delta = \theta_{\text{source}} - \theta_{\text{ELF}} = 3.5^\circ.$$ 

For the propagation from the nightside to the dayside, we obtain negative values. For example, for the angle of arrival of 45°, we obtain the incidence angle of $54.2^\circ$ and the error in the angle of arrival

$$\Delta = \theta_{\text{source}} - \theta_{\text{ELF}} = -4.6^\circ.$$ 

The obtained results provide a very good explanation for the errors shown in Figure 4. Since most discharges were located north-east of the receiver location, the radio waves propagated mostly on the day-night paths around 10 UT, generating positive errors, and mostly on the night-day paths around 22 UT, causing negative errors. As a result, the average error obtained with the whole data set is very small.

### Table 1

| Maximum distance from the source | Average error in the angle of arrival (AoA) | Standard deviation | Comments |
|----------------------------------|--------------------------------------------|--------------------|----------|
| 5000 km                          | $-0.4^\circ$                                | 2.6°               | 1000 discharges |
| 3500 km                          | $-0.4^\circ$                                | 2.3°               | 429 discharges |
| 5000 km                          | $-0.1^\circ$                                | 2.1°               | 850 discharges; excluding 2 h with the largest influence of the terminator in the morning and in the evening |

Figure 7. Signals with the largest positive and negative errors in the angle of arrival. (top) Positive cloud-to-ground discharge recorded at 10:06 UT on 30 March 2016. (bottom) Negative cloud-to-ground discharge recorded at 22:30 on 5 April 2016. The time axis is relative to the time reported by WWLLN. The ELF propagation delay was not subtracted yet.
Table 1 shows the average error in the direction of arrival and its standard deviation for the whole data set, as well as for two subsets. In the first subset of data, we excluded discharges occurring at distances longer than 3500 km. In the second subset, we excluded 2 h in the local morning and evening, when the day-night terminator has the largest influence on the radio wave propagation. The residual error is very small, which proves that the antennas were positioned accurately (at the distance of 5000 km, the mean error of 0.4° is equivalent to about 32 km, and 0.1° is equivalent to about 8 km).

Figure 7 shows the impulses with the largest positive (top) and negative (bottom) errors in the calculated direction of arrival. It can be seen that the signal-to-noise ratio was good in both cases. Therefore, we can conclude that the main contribution to the error came from propagation through the day-night terminator zone.

Since the discharge location is known and the signal was recorded by horizontal magnetic antennas, the knowledge of the phase relationship between the coils and use of Ampere’s law enable us to infer the polarity of the vertical current source. In the first case (top plot of Figure 7), the source had a positive polarity (a positive cloud-to-ground discharge, +CG). In the second case (bottom plot of Figure 7), the source had a negative polarity (negative cloud-to-ground discharge).

Both impulses shown in Figure 7 are delayed by about 21 ms from the timing reported by WWLLN. The reason for this is the propagation delay and the receiver delay. Our propagation model (Kulak & Mlynarczyk, 2013) and method (Mlynarczyk et al., 2015) allow us to reconstruct the current moment waveform at the source location. The timing at the source should agree with the WWLLN reported time. We illustrate this for the impulse shown in the top plot of Figure 7.

The first step consists of digital antenna rotation (Mlynarczyk et al., 2015). Figure 8 shows the impulse after antenna rotation by 8.8°, which is the angle of arrival found by the comparison of peak amplitudes in both channels. As a result, the antennas are digitally aligned to the direction of arrival (one is parallel and the other perpendicular). Therefore, the blue plot represents the azimuthal magnetic field component. The other antenna is orthogonal, so the amplitude in the other channel is zero during the peak (or close to zero due to noise). The same procedure can be applied to the second impulse.

To obtain the current moment waveform at the source, we have to find the relationship between the magnetic field component of the electromagnetic wave and the spectral density of the source current moment $3(f)$. Such a relationship can be found, for example, in Porrat et al. (2001), Mushtak and Williams (2002), Füllekrug et al. (2006), and Kulak et al. (2013). In this work we use the latter. It was obtained by an analytical solution to Maxwell equations for a vertical electric dipole placed in the Earth-ionosphere waveguide. The magnetic field component of electromagnetic wave recorded at the distance $r$ is given by

$$B(r,f) = -i \frac{\pi \mu_0 f}{2h_m(f) \nu(f)} H^{(2)}_f \left(2\pi r \frac{f}{\nu(f)} \right) e^{-i\varsigma(f) f} \cdot \nu(f) \cdot \frac{3(f) g(f)}{T} \cdot [T], \quad (6)$$

where $f$ is the frequency, $i = \sqrt{-1}$, $\mu_0$ is the permeability of free space, $h_m(f)$ is the magnetic height of the Earth-ionosphere
The error in the calculated direction of arrival versus the peak amplitude of the signal. (top) The entire data set. (bottom) Distances of up to 3500 km.

Figure 10. The error in the calculated direction of arrival versus the peak amplitude of the signal. (top) The entire data set. (bottom) Distances of up to 3500 km.

4. Summary and Conclusions

In this paper, we studied ELF radio wave propagation at distances of up to 5000 km. We analyzed 1000 strong lightning discharges. We calculated the angle of arrival at our ELF station and compared it with the azimuth obtained from the WWLLN lightning location network, which works in the VLF band. We clearly identified two factors that most influence the accuracy of the angle of arrival inferred from our ELF receiver: the signal-to-noise ratio and the presence of the day-night terminator.

The accuracy of the direction of arrival was high when the signal-to-noise ratio was large and the day-night terminator was not present on the propagation path (mean error of 0.1°). During short periods in local morning and evening hours, when the terminator was present, the error in the direction of arrival was clearly higher. The maximum error due to propagation through the day-night terminator zone was 12° but the average error was much smaller (1.9°). It was mostly positive in the morning (the azimuth to the location of the source was larger than the azimuth to the apparent location inferred from the ELF data) and negative in the evening. This translated into larger refraction angles than incidence angles for the day-night propagation paths, and smaller refraction angles than incident angles for the night-day propagation paths. Some basic propagation formulas and our analytical ELF radio wave propagation model allowed us to understand the obtained results.

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