

 Open access • Journal Article • DOI:10.1002/2017RS006370

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

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Published on: 01 Oct 2017 - Radio Science (John Wiley & Sons, Ltd)

Topics: Radio wave, Angle of arrival, Radio propagation, Radio propagation model and Direction finding

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1 **The accuracy of radio direction finding in the Extremely Low Frequency range**

2

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10

11 **Key Points:**

- 12 • Using a newly installed broadband ELF receiver, we analyzed 1000 strong atmospheric
13 discharges at distances of up to 5000 km
- 14 • We identified the most important factors that influence the accuracy of radio direction
15 finding
- 16 • Our analytical radio wave propagation model allowed us to explain the obtained results.
17

18 Abstract

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

34 1 Introduction

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

43 In this study, we focus on the accuracy of direction finding using one receiver equipped
44 with two orthogonal magnetic antennas (induction coils). In a similar study published recently by
45 Bor *et al.* [2016], the authors analyzed the accuracy of direction finding using their ELF station
46 in Hungary. They identified the local anisotropic ground conductivity as the dominant factor of
47 error. Once identified, it can be minimized using an angle-dependent correction factor. We show
48 that in our case, the main factor influencing accuracy is the presence of the day-night terminator
49 zone and the signal-to-noise ratio. The obtained maximum error in the angle of arrival due to the
50 terminator zone was 12° , which is consistent with the residual bearing deviation found by an
51 early study with a very narrowband systems (4-16 Hz and 4-19 Hz; Füllekrug and Sukhorukov,
52 [1999]). However, the mean error in the direction finding and its standard deviation are
53 significantly smaller in our case. This could be related to much broader frequency range of our
54 receiver leading to a smaller influence of local anisotropies on direction finding. Lightning
55 location in the ELF range has also been studied at large distances. Boccippio *et al.* [1998]
56 analyzed 40 events observed from TRMM satellite at the distances of up to 20 Mm and found
57 that the mean ground range error was 2 Mm. Single-station Schumann resonance method has
58 also been used by Williams *et al.* [2007] for a sprite lighting at the distance of 16.6 Mm.
59 Williams *et al.* [2010] analyzed sprites lighting events from Africa detected by several ELF
60 stations worldwide. Mlynarczyk *et al.* [2015] analyzed strong lighting discharges at the distances
61 of up to 12 Mm using two ELF receivers, one located in Poland and the other in Colorado, USA.

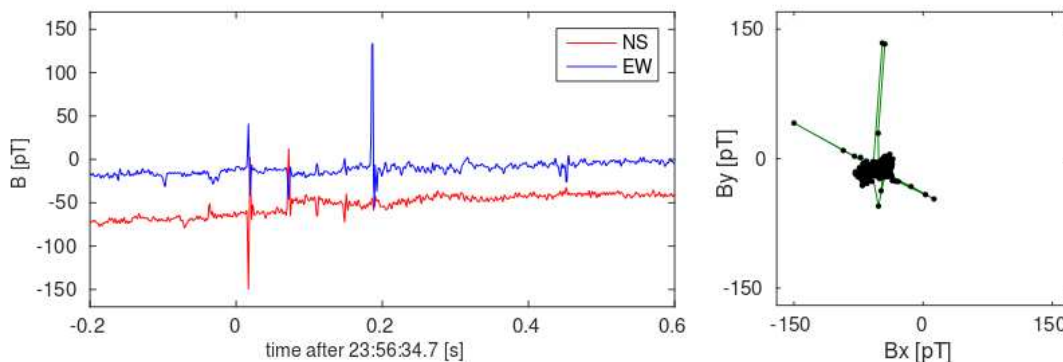
62 Some other studies related to lightning location that the reader might be interested in include
 63 *Reising et al.* [1996], and *Fullekrug and Constable* [2002],

64 In our study, we analyzed 1000 strong lightning discharges at distances of up to 5000 km
 65 from the receiver. To our knowledge, this is the first study of radio direction finding performed
 66 with a broadband ELF receiver (0.03-300 Hz) on such a large data set. The use of a broadband
 67 receiver allowed us to work with impulses that had high amplitude, limiting the influence of
 68 Schumann resonance background on the obtained results.

69 2 Data and Methods

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

89 Most atmospheric discharges take the form of short impulses (Figure 1).



90
 91 **Fig. 1.** Atmospheric discharges recorded by two orthogonal magnetic antennas, north-south (NS)
 92 and east-west (EW) on 28 March 2016 (left panel). NS versus EW component for the same time
 93 segment (right panel).

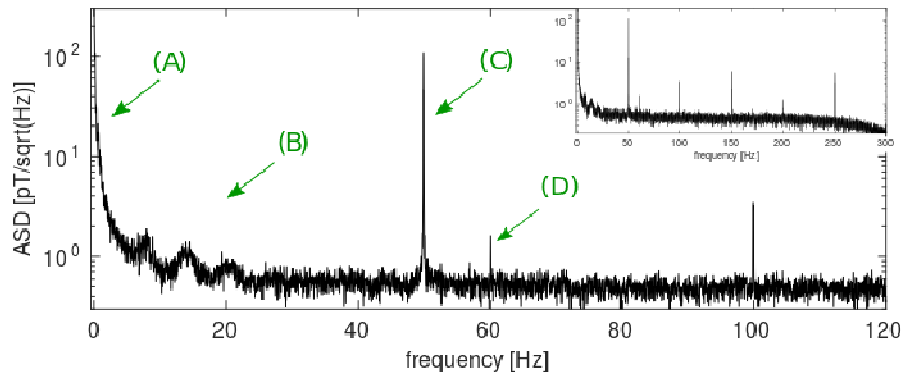
94 The simplest way to infer the angle of arrival is to take the ratio of the peak amplitudes
 95 recorded by the two magnetic antennas and calculate the inverse tangent. Another method would

96 be to perform digital antenna rotation in software until the maximum is found in one channel and
 97 zero in the other channel, but this method is more difficult to automate. We will illustrate this in
 98 section 3.

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

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

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



118

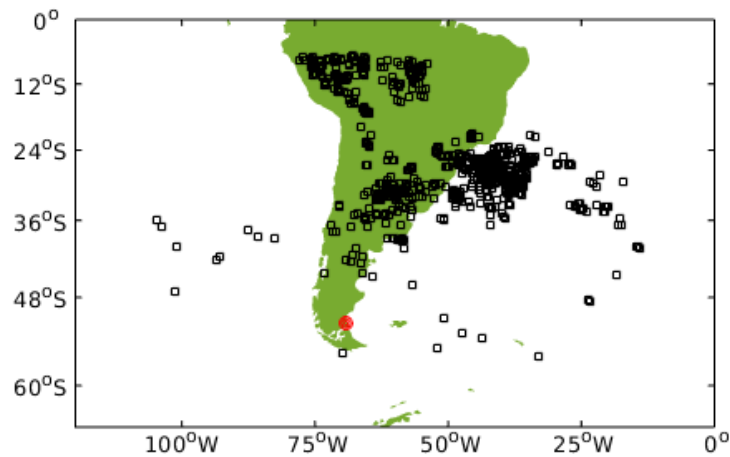
119 **Fig. 2.** A typical spectrum obtained from a five-minute recording (27 March 2016, 2:15 UT).
 120 Three factors limiting the direction finding accuracy can be seen: **(A)** 1/f noise (increase in
 121 geophysical and instrumental noise as the frequency decreases); **(B)** Schumann Resonance
 122 background (three maxima can be clearly seen: around 8, 14 and 20 Hz); **(C)** power line noise at
 123 50 Hz; **(D)** sporadically present 60 Hz power line noise. **(top right corner)** Spectrum view up to
 124 300 Hz, with clearly visible power line harmonic frequencies at 100, 150, 200 and 250 Hz.

125 All the discharges were identified using data from the WLLN lightning detection
 126 network [Rodger *et al.*, 2006] and taking into account the time of arrival (ToA). The reported
 127 location was used as a reference for determining the error in the angle of arrival (AoA). We
 128 defined this error as the difference between the azimuth inferred from the location reported by
 129 WLLN and the azimuth obtained from the ELF data. The WLLN network operates in the

130 Very Low Frequency (VLF, 3-30 kHz) band, and its ultimate aim is to provide location of cloud-
 131 to-ground (CG) discharges with mean location accuracy below 10 km [Rodger *et al.*, 2006]. As
 132 of 2012 [Hutchins *et al.*, 2012], WWLLN consisted of 60 stations distributed around the world.
 133 The detection efficiency was estimated to be of about 11% for cloud-to-ground (CG) strokes and
 134 above 30% for higher peak current flashes over the Continental United States. The WWLLN
 135 located 61% of strokes with the accuracy of below 5 km [Hutchins *et al.*, 2012].

136 3 Results and discussion

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



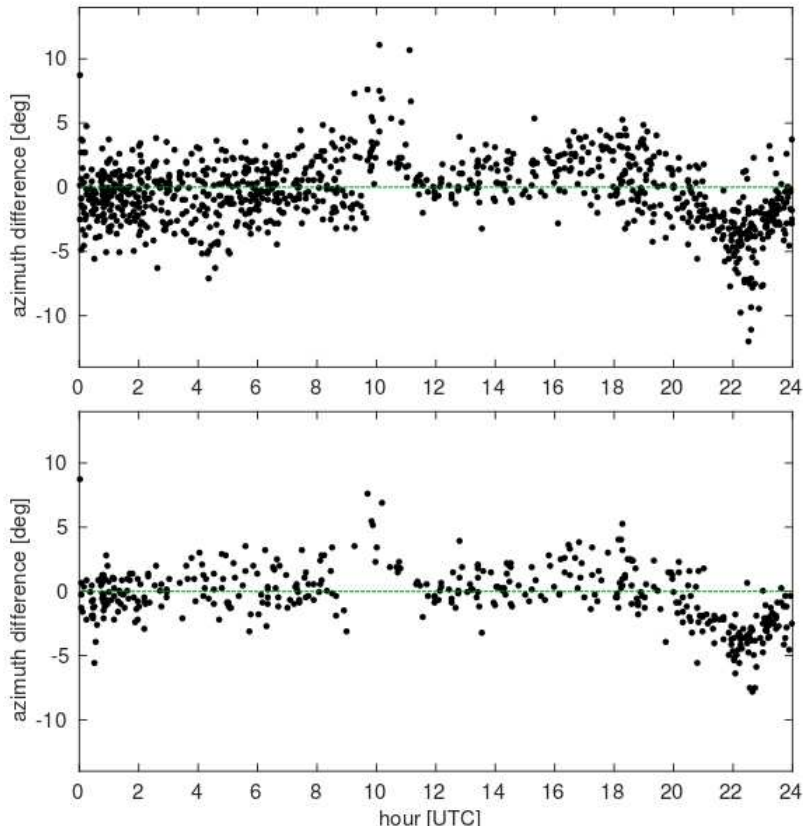
142 **Fig. 3.** Location of the lightning discharges considered in this study (black squares; provided by
 143 WWLLN) and location of the Patagonia ELF station (red circle). (Data visualized using M_Map
 144 mapping package.)
 145

146 Figure 4 presents the error in the direction of arrival at various hours of the day for
 147 discharges at distances of up to 3500 km (top panel) and 5000 km (bottom panel).

148 We can see two periods during the day where the error is clearly higher. These are
 149 periods during which the day-night terminator is above South America. Figure 5 shows the
 150 terminator's location at 10:00 and 22:00 UTC.

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

155



156

157 **Fig. 4.** The error in the azimuth estimation from the ELF recording based on the location
 158 reported by the WWLLN lighting detection network. **(top)** Discharges at distances of up to 3500
 159 km. **(bottom)** The entire data set considered in this study (distances of up to 5000 km). Two
 160 periods during the day where the error is clearly higher coincide with the presence of day-night
 161 terminator above South America (see Figure 5).

162



163

164 **Fig. 5.** Day and night zones and the location of the day-night terminator (astronomical, nautical
 165 and civil shown in various shades of gray, from darker to lighter, respectively) at 10 UT (left
 166 panel) and 22 UT (right panel) on April 5, 2016. The red circle shows the receiver location. Day
 167 and night maps courtesy of www.timeanddate.com.

168

169 To understand these results, we assume a sharp boundary between the day and night
 170 zones and use the Snell's law [Davis, 1990, p. 73]. The phase velocities in the day and night time
 171 zones are related to the sines of the angles of incidence θ_1 and refraction θ_2 :

$$172 \quad v_{night} \sin \theta_1 = v_{day} \sin \theta_2. \quad (1)$$

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

174 The phase velocity in the Earth-ionosphere waveguide can be calculated from [Mushtak and
 175 Williams, 2002]

$$176 \quad v(f) = \frac{c}{\text{Re} \bar{S}(f)}, \quad (2)$$

177 where \bar{S} is the dimensionless frequency dependent complex propagation parameter, which is
 178 related to the wave number \bar{k} by the equation [Kulak et al., 2013]:

$$179 \quad \bar{S} = \frac{c}{\omega} \bar{k}. \quad (3)$$

180 The propagation parameter \bar{S} can be calculated from [Mushtak and Williams, 2002]

$$181 \quad \bar{S}(f)^2 = \frac{\bar{h}_m(f)}{\bar{h}_e(f)}, \quad (4)$$

182 where \bar{h}_m and \bar{h}_e are the complex magnetic and electric altitudes of the Earth-ionosphere
 183 waveguide, and they are frequency dependent [Kulak and Mlynarczyk, 2013].

184 From our ELF propagation model [Kulak and Mlynarczyk, 2013], we obtained the
 185 complex altitudes and then calculated the phase velocities for the day and night propagation
 186 paths. Since the deviation of the trajectory was based on the peak amplitude comparison, we
 187 were interested in the phase velocity at the frequency close to the upper cut-off frequency of the
 188 receiver. We got the following values at 300 Hz:

$$189 \quad v_{day} = 0.823 c \quad (4)$$

$$190 \quad v_{night} = 0.944 c \quad (5)$$

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

$$196 \quad \sin \theta_1 = v_{day} \sin \theta_2 / v_{night} = 0.856,$$

197 which gives the incidence angle $\theta_1 = 59^\circ$. Once θ_1 and θ_2 are known, we can calculate the error
 198 in the direction of arrival based on the geometry of the propagation path (as seen in Fig. 6)

$$199 \quad \Delta = Az_{Source} - Az_{ELF} = 10.5^\circ$$

200 The obtained error in the direction of arrival is positive, which means that the azimuth to the
 201 source location Az_{Source} is larger than the azimuth inferred from the ELF data Az_{ELF} . Taking a
 202 very small refraction angle, for example 10° , which means that the angle of arrival is 80° , we
 203 obtain the incidence angle of 8.7° and the error in the angle of arrival

$$204 \quad \Delta = Az_{Source} - Az_{ELF} = 0.65^\circ$$

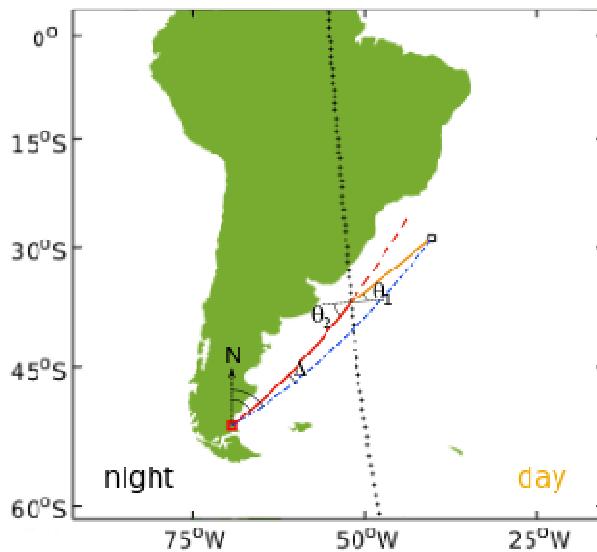
205 Taking the refraction angle of 45° , we obtain the incidence angle of 38.1° and the error in the
 206 angle of arrival

$$207 \quad \Delta = Az_{Source} - Az_{ELF} = 3.5^\circ$$

208 For the propagation from the night side to the dayside, we obtain negative values. For
 209 example, for the angle of arrival of 45° , we obtain the incidence angle of 54.2° and the error in
 210 the angle of arrival

$$211 \quad \Delta = Az_{Source} - Az_{ELF} = -4.6^\circ$$

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



217

218 **Fig. 6.** Illustration of refraction principle on a day-night path. The discharge is located on the
 219 dayside (black square) and the receiver is on the night side (red square). The propagation path
 220 between the source and the boundary is shown by the orange line. At the day-night boundary the
 221 direction changes due to refraction and follows the red line. Therefore, the direction of arrival
 222 inferred from the ELF signal is consistent with the red line, which is the source of error.

223

224 Table 1 shows the average error in the direction of arrival and its standard deviation for the
 225 whole data set, as well as for two subsets. In the first subset of data, we excluded discharges
 226 occurring at distances longer than 3500 km. In the second subset, we excluded two hours in the
 227 local morning and evening, when the day-night terminator has the largest influence on the radio
 228 wave propagation. The residual error is very small, which proves that the antennas were
 229 positioned accurately (at the distance of 5000 km, the mean error of 0.4° is equivalent to about 32
 230 km, and 0.1° is equivalent to about 8 km).

231

232 **Table 1.** Average error and standard deviation obtained by the comparison between the direction
 233 of arrival based on WWLLN and that calculated from the ELF recordings.

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

234

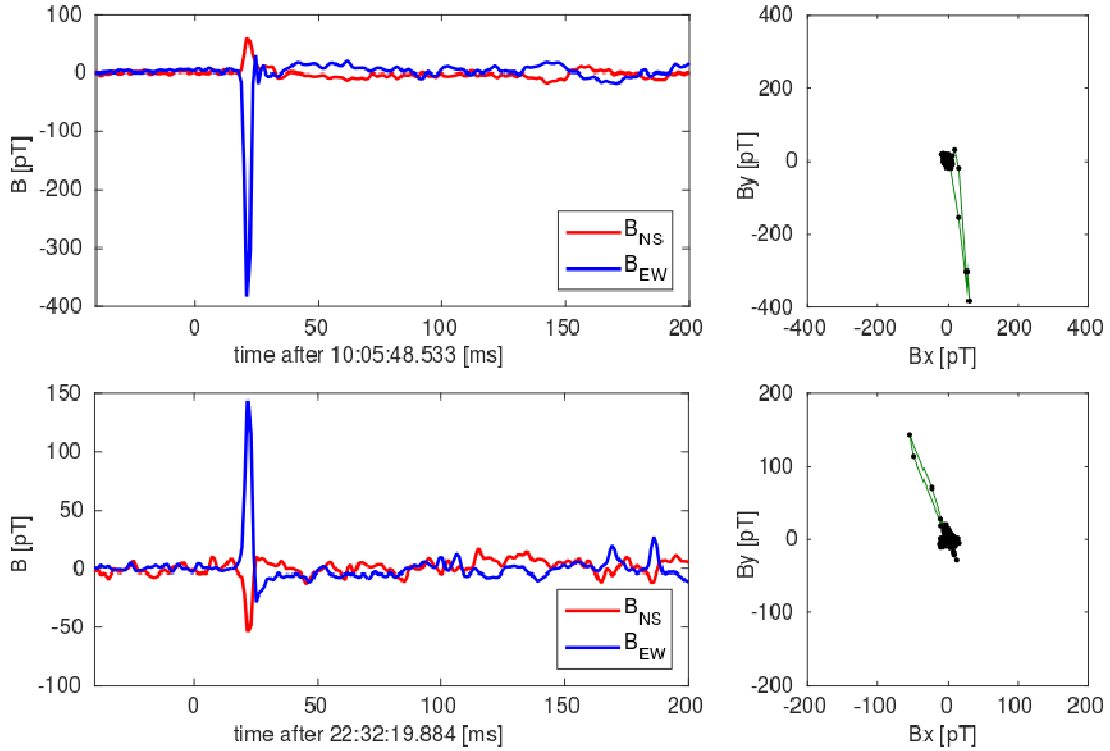
235 Figure 7 shows the impulses with the largest positive (top) and negative (bottom) errors
 236 in the calculated direction of arrival. It can be seen that the signal-to-noise ratio was good in both
 237 cases. Therefore, we can conclude that the main contribution to the error was from propagation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

239 Since the discharge location is known and the signal was recorded by horizontal magnetic
 240 antennas, the knowledge of the phase relationship between the coils and use of Ampere's Law
 241 enable us to infer the polarity of the vertical current source. In the first case (top panel in Figure
 242 7), the source had a positive polarity (a positive cloud-to-ground discharge, +CG). In the second
 243 case (bottom panel in Fig. 7), the source had a negative polarity (negative cloud-to-ground
 244 discharge).

245 Both impulses shown in Figure 7 are delayed by about 21 ms from the timing reported by
 246 WWLLN. The reason for this is the propagation delay and the receiver delay. Our propagation
 247 model [Kulak and Mlynarczyk, 2013] and method [Mlynarczyk et al., 2015] allow us to
 248 reconstruct the current moment waveform at the source location. The timing at the source should
 249 agree with the WWLLN reported time. We illustrate this for the impulse shown in the top panel
 250 in Figure 7.

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

258



259

260 **Fig. 7.** Signals with the largest positive and negative errors in the angle of arrival. **(top)** Positive
 261 cloud-to-ground discharge recorded at 10:06 UT on 30 March 2016. **(bottom)** Negative cloud-
 262 to-ground discharge recorded at 22:30 on 5 April 2016. The time axis is relative to the time
 263 reported by WWLLN. The ELF propagation delay was not subtracted yet.

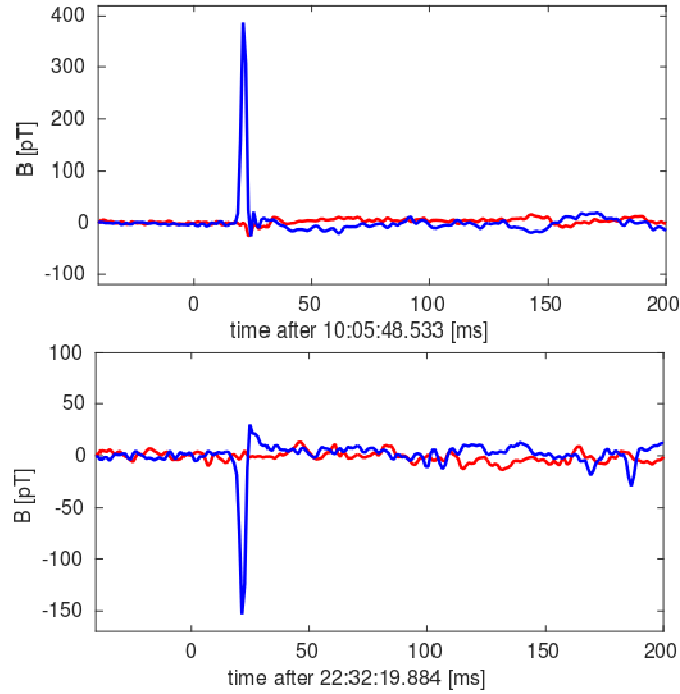
264 To obtain the current moment waveform at the source, we have to find the relationship
 265 between the magnetic field component of the electromagnetic wave and the spectral density of
 266 the source current moment $\bar{s}(f)$. Such a relationship can be found, for example, in *Porrat et al.*
 267 [2001], *Mushtak and Williams* [2002], *Fullekrug et al.* [2006], and *Kulak et al.* [2013]. In this
 268 work we use the latter. It was obtained by an analytical solution to Maxwell equations for a
 269 vertical electric dipole placed in the Earth-ionosphere waveguide. The magnetic field component
 270 of electromagnetic wave recorded at the distance r is given by:

$$271 \quad \bar{B}(r, f) \approx -i \frac{\pi \mu_0 f}{2 h_m(f) v(f)} H_1^{(2)} \left(2\pi r \frac{f}{v(f)} \right) e^{-\alpha(f) r} \bar{s}(f) \bar{g}(f) \quad [\text{T}] \quad (6)$$

272 where f is the frequency, $i = \sqrt{-1}$, μ_0 is the permeability of free space, $h_m(f)$ is the magnetic
 273 height of the Earth-ionosphere waveguide, $v(f)$ is the phase velocity, $H_1^{(2)}$ is the Hankel
 274 function of the second kind and first order, $\alpha(f)$ is the attenuation rate, $\bar{g}(f)$ is the transfer
 275 function of the receiver.

276

277



278

279 **Fig. 8.** Azimuthal magnetic field component (blue plot) obtained from the recorded signals
 280 shown in Fig. 7, by digitally rotating the antennas towards the direction of arrival. As a result,
 281 the impulse polarity is the same as the discharge polarity (that is positive for the discharge shown
 282 in top panel and negative for the discharge in the bottom panel).

283

284 Processing the signal in the frequency domain, we obtain $\bar{s}(f)$ from (6). Then we return it to the
 285 time domain using the inverse discrete Fourier transform (IDFT), obtaining the current moment
 286 waveform $s(t)$. We can write it in the following way:

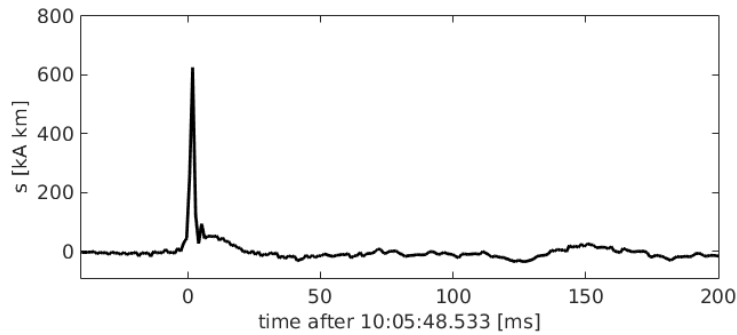
$$287 \quad \bar{s}(f) \approx \frac{\bar{B}(r, f)}{-i \frac{\pi \mu_0 f}{2h_m(f)v(f)} \phi(r) H_1^{(2)}\left(2\pi r \frac{f}{v(f)}\right) e^{-\alpha(f)r} \bar{g}(f)}; \quad s(t) = IDFT[\bar{s}(f)] \quad (7)$$

288 Since both the radio wave propagation and the receiver are included in the equation, the delay
 289 that they introduce is automatically subtracted.

290 Figure 9 shows the reconstructed current moment waveform. It can be seen that the time
 291 at the source agrees with WWLLN reported time. The delay of the signal in this case was 19 ms.

292 Returning to the analysis of the whole data set, we will show another factor with an
 293 influence on the direction finding in the ELF range. As shown in Figure 10, the signal amplitude
 294 has a very high influence on the accuracy of the angle of arrival. This is because it determines
 295 the signal-to-noise ratio. This is especially clear when sources at distances greater than 3500 km
 296 are excluded, which limits the number of cases for which the wave had to propagate through the
 297 terminator zone, from the dayside to the night side.

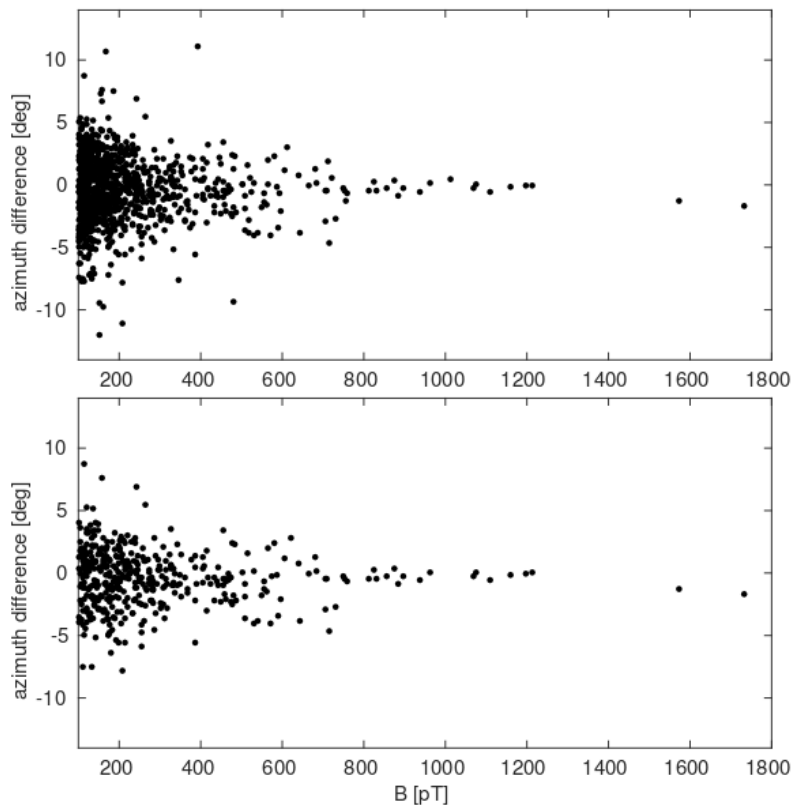
298



299

300

Fig. 9. Current moment waveform of the discharge shown in top panel of Figure 4.



301

Fig. 10. The error in the calculated direction of arrival versus the peak amplitude of the signal.

302

(top) The entire data set. **(bottom)** Distances of up to 3500 km.

303

304 305 **4 Summary and conclusions**

306 In this paper, we studied ELF radio wave propagation at distances of up to 5000 km. We
 307 analyzed 1000 strong lightning discharges. We calculated the angle of arrival at our ELF station
 308 and compared it with the azimuth obtained from the WWLLN lightning location network, which
 309 works in the VLF band. We clearly identified two factors that most influence the accuracy of the

310 angle of arrival inferred from our ELF receiver: the signal-to-noise ratio (SNR) and the presence
311 of the day-night terminator.

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

323

324 **Acknowledgments**

325 The authors would like to thank Dr. Eduardo J. Quel, Dr. Gabriela Nicora, Jonathan Quiroga and Nahuel Diaz for
326 making the setup of the ELF station possible, as well as the members of the Krakow ELF team for their contribution
327 to the ELF station setup and measurements. The authors wish to thank the World Wide Lightning Location Network
328 (<http://wwlln.net>), a collaboration among over 50 universities and institutions, for providing the lightning location
329 data used in this paper. The authors would also want to thank the reviewers for useful comments and suggestions.
330 This work has been supported by the National Science Center under Grant 2015/19/B/ST10/01055. The data used to
331 produce the results in this paper are available upon request from the corresponding author.

332

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