New Method for Determining Azimuths of ELF Signals Associated with the Global Thunderstorm Activity and the Hunga Tonga Volcano Eruption

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1 New Method for Determining Azimuths of ELF Signals Associated with the 2 **Global Thunderstorm Activity and the Hunga Tonga Volcano Eruption** 3 4 J. Kubisz¹, M. Gołkowski², J. Mlynarczyk³, M. Ostrowski^{1†}, A. Michalec^{1†} 5 ¹ Astronomical Observatory, Jagiellonian University, Kraków, Poland. 6 ² Department of Electrical Engineering, University of Colorado Denver, Denver, USA. 7 ³ Institute of Electronics, AGH University of Science and Technology, Kraków, Poland. 8 9 Corresponding author: Michał Ostrowski (michal.ostrowski@uj.edu.pl) 10 † Emeritus. 11 12 **Key Points:** A new method for deriving wave arrival azimuths with parametric temporal filtering 13 14 of electromagnetic waves in the ELF band is introduced. 15 • A multitude of thunderstorms on Earth varying during the day at different azimuths are resolved. 16

The Hunga Tonga volcano eruption signals are diffracted by ≈10° when propagating
 in the Earth-ionosphere cavity over the polar regions.

20 Abstract

21 A new method is proposed for deriving Extremely Low Frequency (ELF) wave arrival azimuths using 22 the wide range of signal amplitudes, contrary to previously applied high amplitude impulses only. The 23 method is applied to observations from our new magnetic sensor in the Hylaty station with an18 bit 24 dynamic range and a 3 kHz sampling frequency. We analyzed a day of January 15th, 2022, to test the 25 procedure against the ability to extract ELF signals generated during the Hunga Tonga volcano 26 eruption. With complementary filtering of power line 50 Hz signatures, precise azimuth information 27 can be extracted for waves from a multitude of thunderstorms on Earth varying during the day at 28 different azimuths. A phenomenon of successive regular variation - decay or activation - of 29 thunderstorms activity with varying azimuth is observed, possibly due to passing over the solar 30 (day/night) terminator, and signatures of azimuth direction change during this passage can be noted. 31 We also show that the erupting Hunga Tonga volcano associated impulses dispersed due to a long 32 propagation path are clearly revealed in the azimuth distribution with analysis using parameters fitted 33 to measure slowly varying signals, but not for fast varying impulses. We show that the Hunga Tonga 34 related signals arrive from the azimuth $\approx 10^{\circ}$ smaller than the geographic great circle path. The

- 35 discrepancy is believed to be due to propagation through the polar region and in the vicinity of the
- 36 solar terminator.

37 **1.** Introduction

38

39 Electromagnetic fluctuations in the extremely low frequency (ELF) band, defined here as 0.03 – 1000

40 Hz, provide a unique source of geophysical information that has not been exploited in depth

41 (Nickolaenko, 1997; Price, 2016; Nickolaenko et al., 2002). Naturally occurring ELF waves include

42 Schumann resonances and ELF transients created by lightning, with often associated optical

43 phenomena of sprites and elves. These waves are transmitted in the Earth-ionosphere waveguide and

44 therefore provide a diagnostic on the lower ionosphere, which itself responds to solar changes and

45 space weather phenomena (*Gołkowski et al.*, 2018). Ground based ELF observations have also become

46 important support in identification of gravitational waves (*Coughlin et al.*, 2018).

47 Determining the arrival direction of natural emissions in the ELF/VLF bands has been of
 48 longstanding interest and is possible from a single receiver station if two or more components of the

49 propagating fields are observed (*Kemp*, 1971; *Jones and Kemp*, 1970; *Kemp and Jones*, 1971). In the

50 VLF band, the multimodal aspect of propagation in the Earth-ionosphere waveguide can yield

51 polarization error in direction finding, which means signals are often analyzed in the frequency

52 domain and efforts are made to quantify the polarization (*Golkowski and Inan*, 2008; *Hosseini et al.*,

53 2018). In lightning detection networks such as the Vaisala GLD360 system, azimuth of VLF transients

54 is determined in the time domain and polarization errors are mitigated by using only the first 200 µsec

55 of the lightning signal (*Said et al.*, 2010).

56 In the ELF band the propagation is unimodal and typically two orthogonal measurements of 57 the horizontal magnetic field are employed to find the arrival angle (*Nieckarz et al.*, 2011; *Füllekrug* 58 and Constable, 2000). Nevertheless, there can be errors in the emission source direction finding at 59 ELF claimed to be due to anisotropy of the ionosphere (Füllekrug and Sukhorukov, 1999) and 60 scattering from the sharp conductivity boundaries such as ocean/land boundaries and the solar 61 (day/night) terminator (Mlynarczyk et al., 2017; Nickolaenko et al. 2018, 2021; Schvets et al. 2022). 62 The impact of the ionospheric anisotropy on the signal propagation was discussed by Nickolaenko and 63 Sentman (2007) to be observed as characteristic variations of signal ellipticity with the frequency. 64 Techniques has been developed which seek to use two components of horizontal magnetic field and a 65 vertical electric field to improve accuracy (Jones and Kemp, 1970; Kemp and Jones, 1971). In all 66 cases of direction finding, operating over a larger bandwidth is known to reduce error (Strangeways

67 and Rycroft, 1980; Mlynarczyk et al., 2017; Wood and Inan, 2002, 2004).

As described in more detail below, the novelty of the present approach is the use of a difference technique that intrinsically introduces selective temporal filtering that can be used to remove power line interference or target specific temporal signatures. Thus a significant amount of the measurement data can be applied for the azimuth determinations, contrary to previous studies focusing on large ELF impulses in the data (see, e.g., a recent description in Nickolaenko et al. 2023) For

- 73 illustration of the possibilities of the proposed novel approach, we analyze observations from the day
- of January 15th, 2022, when occurrence of the Hunga Tonga (HT) volcano eruption created a strong
- 75 compact ELF source (*Nickolaenko et al.,* 2022; Mezentsev *et al.,* 2022; Bor *et al.,* 2023; see also
- 76 Nickolaenko et al., 2023). We also present the capabilities of single site monitoring of global
- thunderstorm activity. In particular, at the figures one can note daily variations of the global
- thunderstorm activity, influenced by the Asian center at the azimuths ~90°, operating in the hours 6 -
- 10 h UT, shifting to the more powerful African center at the azimuths ~180° (12 18 h UT), and
- 80 shifting toward the South American center at the azimuths ~-90° (18 22 h UT). The derived azimuths
- 81 can be compared in detail with the list of selected reference azimuths from the Hylaty station
- 82 presented in the Table 1. When inspecting the figures below one should not forget that the presented
- 83 azimuth structures are significantly "filtered" by the parameters' sets selected in the applied azimuth
- 84 derivation and the procedure provides more or less symmetric distribution for the source azimuth + or
- 85 -180°.
- 86

87 Table 1. A list of selected reference geographic azimuths A, their respective anti-azimuths (indicated

- 88 with an asterisk) and distances from the Hylaty ELF station.
- 89

Place	A [°]	A [°]	Distance
	(0°< A< 180°)	(-180° <a<0°)< th=""><th>[Mm]</th></a<0°)<>	[Mm]
Hawaii, Honolulu	0.4	-179.6 *	12.2
Angola, Lubango	9.6 *	-170.4	7.2
Nigeria, Lagos	27.5 *	-152.5	5.1
Hunga Tonga	32.9	-147.1 *	16.4
Alps, Graz	38.4 *	-111.6	0.6
Japan, Honshu	48.4	-131.6 *	8.6
Russia, Moscow	48.7	-131.3 *	1.3
Guinea Bissau	52.8 *	-127.2	5.4
Brazil, Belem	57.6 *	-122.4	7.4
Uruguay, Montevideo	58.4 *	-121.6	12.1
Brazil, Recife	59.3 *	-120.7	8.4
Papua New Guinea, Port Moresby	68.7	-111.3 *	13.3
Hong Kong	73.8	-106.2 *	8.3
Philippines, Manila	74.1	-105.9 *	9.4
Alps, Chamonix	78.6 *	-101.4	1.2
Vietnam, Hanoi	80.6	-99.4 *	7.8
Portugal, Porto	81.6 *	-98.4	2.6
Brazil, Manaus (Amazon region)	82.3 *	-97.7	9.7
Borneo	88.9	-91.1 *	10.1
Bangladesh, Dhaka	89.8	-90.2 *	6.4
Indonesia, Jakarta	98.3	-81.7 *	10.1
Haiti, Port-au-Prince	102.8 *	-77.2	8.8
India, Mumbai	108.4	-71.6 *	5.6
Pakistan, Karachi	108.7	-71.3 *	4.7
US, Florida, Orlando	118.9 *	-61.1	8.6

Nicaragua, Managua	121.2 *	-67.9	10.3
US, Georgia, Atlanta	124.5 *	-55.5	8.3
Madagascar	155.1	-24.9 *	8.0
Kenya, Mombasa	159.0	-21.0 *	6.1
DR Kongo, Kisangani	176.4	-3.6 *	5.4

2. ELA11 magnetic sensor

94	We use data (a data copy available at DATA_HYLATY_ELA11_2022_01_15, 2022) from our novel
95	magnetic sensor ELA11 (Mlynarczyk et al., in preparation) with two perpendicular, NS and EW, active
96	antennas installed at the Hylaty station (49.2° N, 22.5° E). The new sensor has a high 18-bit ADC
97	resolution, enabling a much higher dynamic range than our ELA10 sensors deployed in the WERA
98	system (Kulak et al., 2014; <u>https://www.oa.uj.edu.pl/WERA</u>). It also features a sampling frequency of
99	3 kHz (3004.81 Hz precisely), which is over three times higher than that of the ELA10 sensor. The
100	increased dynamic range and higher bandwidth, as well as use of a Bessel anti-aliasing filter, enable
101	improved resolution of individual impulses in the registered signal and better characterization of the
102	temporal signal shape, as illustrated in Figure 1. The measured signal is provided by natural numbers
103	in the ELA11 sensor units, with 1 pT magnetic field change equivalent to 12.68 sensor units. When
104	analyzing the measured signal variations, one should keep in mind that the presented data have a zero
105	reference point near the middle of the measurement range and only presented magnetic field variations
106	have physical meaning.
107	The data analyzed in the present paper are available from an on-line repository (Kubisz 2023).
108	



109 110

111 Figure 1. A (two panels at the top): An example 300 s (5 minutes') data stream in the receiver units 112 and the associated log-log Amplitude Spectrum Density [pT / SQRT(Hz)] in NS (red) and EW (green) antennas from January 15th, 2022, 0:00-0:05 UT, from the ELA11 magnetometer at the Hylaty 113 114 station; the same data and respective spectra are presented after electric power line filtering (see Sect. 115 3) with the bandstop filter (**B**, second row) and with the MA60 filter (**C**, third row); **D** (bottom): 116 Detailed data comparison for a short 1 s range of unfiltered data (left panel) and filtered data with both 117 the bandstop filter (middle panel) and the MA60 filter (right panel). Please, note different vertical 118 scales at the presented spectra.

120 **3. Derivation of ELF signal azimuths**

122 Let us consider a geographic azimuth A measured from the North toward the East direction and we 123 assume that the studied ELF waves have magnetic field component parallel to the Earth surface. We 124 derive the signal azimuth of arrival, A_{i} , using the registered signal changes in our NS and EW antennas 125 between time instants t_i and t_{i+n} from the expression:

126

121

$$tan\left(A_{(i, n)}\right) = -\Delta B_{NS(i, n)} / \Delta B_{EW(i, n)}$$
(1)

128

129 were $\Delta B_{(i,n)} = B_{(i+n)} - B_{(i)}$ is a difference between two signal measurements from a given magnetic 130 antenna, NS or EW. Let us stress that the sign "minus" in the above expression is required due to our 131 use of the measured $\Delta B_{\rm EW}$, not $\Delta B_{\rm WE}$. As pointed out above, the parameter *n* provides the time delay 132 between successive signal samples applied for the azimuth derivation. For example, n=1 corresponds 133 to two successive samples in the 3 kHz measurements, n=60 corresponds to a delay of 0.02 s, the 134 50Hz electric power line period, and n=3000 to a delay of 1 second. Depending on positive or 135 negative values of the derived $\Delta B_{(i,n)}$ we obtain the azimuths in the range (-180°, +180°). One should 136 stress that for a single impulse the proposed approach – applying signal changes between two selected 137 measurements instead of the full impulse amplitude – results in two azimuth values, A and $A \pm 180^{\circ}$, 138 derived respectively for its growing part and declining part. Below, we apply this procedure to all 139 successive measurements within the analyzed time range, applying the selected time delay *n* at each 140 "i".

141 In the applied digital electronics, the measurement values are given by natural numbers, and 142 with the applied 3 kHz sampling frequency, the derived differences between successive samples ΔB 143 are often represented by small natural numbers or even zero. Such small values in the numerator or 144 denominator of the right-hand side of Eq. (1) can drive the inverse tangent function to significant 145 maxima of derived azimuth distributions at (\pm) 0, 90° and 180° degrees, as well as several discrete 146 values $90^{\circ*}(j/k)$, where j and k are small natural numbers. Additionally, the electric power grid 147 associated signal at 50 Hz (see Figure 1) can introduce large scatter in the derived azimuth distribution 148 and its possible arrangement respective to local electric power lines. Thus, when selecting signals for 149 the azimuth derivation, we limit their magnitudes to pre-defined values for any given *n* by selecting 150 the minimum and maximum limits r_{\min} and r_{\max} for the signal change parameter r =SORT($\Delta B_{\rm EW}^2 + \Delta B_{\rm NS}^2$). Depending on the selected minimum and maximum values of this parameter 151 152 one can study azimuth values for different wave (impulse) amplitudes, using the full available data 153 above the level of electric power line signal variations, but not restricted to large individual magnetic 154 peaks only. One should remember that the proposed procedure generates azimuth values differing by 155 180° between the rising and falling parts of the individual impulse. The analogous azimuth changes

156 would be obtained for positive and negative discharges as well as for signals propagating directly from 157 the discharge location to the measuring station and the one reaching the station after propagation by 158 the longer path around the Earth. Thus, in the presented figures we use an azimuth scale from -180° to 159 $+180^{\circ}$ to present data resulting from Eq. 1, with expected symmetric A and $A \pm 180^{\circ}$ values generated in 160 this range by any single lightning generated impulse within the measurement range $r_{\min} < r < r_{\max}$. An 161 inspection of the derived azimuth distributions in the figures below reveals a clearly visible difference 162 between positive and negative azimuth distributions pointing to the existence of numerous temporally 163 asymmetric signals with some superimposed background fluctuations and possible deviations of the

164 impulse path from the geographic great circle.

165 The raw unfiltered data has a strong signature of the local electric power line at 50 Hz, which 166 makes azimuth determination more difficult for small impulses. Specifically, from a visual inspection 167 of the raw data (see Fig. 1D) we find that *r* values below $r_{50\text{Hz}} \sim 100$ (or ~8 pT in physical units) are not 168 usable for the azimuth derivation when processing our raw data. To get around this limitation, we 169 propose two optional approaches to extract azimuth information from the low amplitude signal

170 fluctuations:

171 — by selecting the electric grid frequency *n*=60 (or its multiples) in Eq. 1 one removes significant part
172 of the electric power line perturbations in the analysis (cf. Mitchell 1976) by using measurements in
173 the same phase of this perturbing signal. However, the existing irregularities in the electric network
174 signal shapes (see Figure 1D) still leave a noticeable scatter in the derived azimuths, and of course we

175 lose the freedom to use different values of n in the analysis. Below, we positively tested the validity of

176 such an approach (called also an *inter-period subtraction*) by comparing the azimuth distributions

177 derived with small $r_{\text{max}} < r_{50\text{Hz}}$ with the ones for the larger impulses above the electric grid

178 fluctuations.

179 — by filtering the 50 Hz component and its harmonics from the data one removes a significant part of 180 its contribution to the analyzed signal. The situation is more complicated however, because the power 181 line signal is subject to various fluctuations and any filtering procedure also perturbs the background 182 ELF noise to be analyzed. Thus, it is essential to carefully evaluate possible 50 Hz filtering impact on 183 the derived azimuths, which may significantly vary depending on the filtering method and the *n*, r_{min} 184 and r_{max} parameters selected in the analysis. Below we will discuss application of two significantly 185 different filtering procedures.

186 The first approach uses a third-order bandstop Butterworth filter (henceforth: "the bandstop 187 filter") which enables removal of the 50 Hz line fluctuations and its harmonic frequencies if they have 188 significant amplitudes. A great advantage of a software filter over a hardware filter is that its center 189 frequency and bandwidth can be adjusted to the processed signal, to minimize the distortions (see, e.g. 190 Mlynarczyk et al. 2017). For studying short data samples (like the 5-minute or shorter time samples 191 considered in our measurements) or individual strong impulses we typically use a filter with a

192 bandwidth of only 0.3 Hz at 50 Hz and 150 Hz (the precise central frequency is measured for each 193 date file). Since the filter bandwidth is very narrow, it has little influence on the amplitude of lightning 194 associated impulses. If 250 Hz and higher harmonic frequencies have a significant amplitude, one can 195 filter them as well, but it is rarely necessary. The filter bandwidth at these higher harmonic frequencies 196 is a little larger (we increment it by 0.2 Hz at each consecutive harmonic frequency). A slightly less 197 intricate application of this filter is applied below where we analyze long 24h measurements, with 198 present significant variations of the 50 Hz line: its intensity and central frequency, as well as the line 199 width and more extended low intensity wings. For such cases we decided to use a uniform in all 200 measurements, wider filter bandwidth of 1 Hz at the 50 Hz line as well as at its all registered harmonic 201 frequencies. Thus, small observed variations of the line central frequency do not influence the 202 filtering, but we note that the 50 Hz line wings as measured at our site sometimes extend off the 203 applied 1 Hz exclusion bandwidth. Therefore, the remaining signal from the wings can still be left in 204 the data after filtering, possibly perturbing low amplitude wave measurements. The raw ELA11 data 205 are compared with the filtered data resulting from application of the above-described filter in Figure 206 1B and D.

207 A significantly different, second filtering procedure uses the moving average (MA60) filter, 208 perhaps one of the most widely used FIR filters, here with averaging over the electric grid period of 209 0.02 s (i.e. over 60 successive measurement points). The filter fully removes the 50 Hz line and all its 210 higher harmonic frequencies up to the considered here upper limit of 1500 Hz. In this case the 211 procedure provides a low band pass filtering, significantly damping high frequency impulses, but 212 preserving relatively undisturbed the low frequency ELF fluctuations. To see the effect, our raw data 213 are compared below with the filtered ones in Figure 1C and D, showing that besides the 50 Hz 214 periodic signal the filtering procedure removes (or significantly damps) all naturally occurring strong 215 spikes.

216 Thus, when applying any of these 50 Hz filtering procedures, or not applying filtering at all, 217 one should be careful in interpretation of the azimuths derived from the respective data for any set of 218 the analysis parameters r_{\min} , r_{\max} and n. When possible, e.g., from a nearby/strong thunderstorms, one 219 can compare the derived signal azimuth distributions with the one derived from the large impulses at 220 $r > r_{50 \text{Hz}}$. Also, the azimuth continuity of the signal from a single thunderstorm center, with its 221 expected varying daily intensity and scatter, confirm reality and characterize accuracy of the measured 222 azimuths. The studies, without considering powerful sources of ELF electromagnetic waves with 223 known location (like the volcano eruption) or impulses from individual discharges registered in the 224 VLF networks (e.g., WWLN or Vaisala) are not suitable to directly extract information about eventual 225 systematic wave diffraction and respective azimuth modification along the signal path in the Earth-226 ionosphere cavity. However, such extended detailed analysis, involving studies of EM impulses from

227 individual lightning discharges registered by the WWLLN VLF network, lays outside the scope of the

- 228 present paper, with exception of the signal azimuth verification for the Hunga Tonga volcano eruption.
 229 One should note that the applied filtering procedures introduce unphysical perturbed signal in
 230 the very beginning of each filtered 300s data stream. Therefore, in this work we simply removed the
 231 initial 2.6s of the data where such artifacts are observed from all analyzed filtered data samples.
- Another option that one can use is to append the last part of the previous data file to the data range for
- 233 filtering and removing it afterwards.
- 234

235 4. Azimuths of ELF electromagnetic waves registered in the Hylaty station

236

237 To illustrate the range of possibilities of the proposed ELF signal azimuth analysis applied to the

ELA11 receiver measurements we selected the day of January 15th, 2022 (0-24 h UT). We processed

the data to extract information on natural ELF wave fields anisotropies and additionally, to check

240 constraints on revealing the ELF signature associated with the HT volcano eruption (Nickolaenko et

241 al., 2022; Bor et al., 2023). The eruption signatures in the time range 4:15-5:50 UT for the main

eruption and in the time range 8:35-9:30 UT for the next weaker one, are visible in our data, as

243 presented in the 24-hour dynamic spectrum evolution at Figure 2. The discussed below azimuth

244 distributions provide an additional tool to extract the HT electromagnetic signal from a background

thunderstorms' noise superimposed in the plot.

Before inspecting the daily evolution of spectrum and azimuth let us explain that to reveal variations in all considered frequency and amplitude ranges we performed fine tuning of the presented values to the plot color scale by using two numerical factors, the first was multiplying the data while the second was subtracted from the data. Thus, in Figure 2 one can analyze nearly all spectra in the full range of 1-165 Hz, clearly revealing also the secondary HT eruption signatures, on the expense that strong HT signal is presented as white, being unresolved above the applied color scale.



Figure 2. Evolution of the ELF signal power spectrum in the EW antenna on January 15th, 2022, from 0 till 24 UT. Each vertical line shows a successive 75-second spectrum in the frequency range up to 257 165 Hz. We used the Hann window in computations to minimize nearby thunderstorms' noise in the 258 plot. The HT eruption signatures are clearly visible for frequencies less than 50 Hz at 4:15-5:50 UT 259 and a somewhat weaker eruption from 8:35 till 9:30 UT.

260

261 In Figure 2 one can note continuous horizontal stripes of at least seven Schumann resonances, 262 a 50 Hz power line, and its harmonic at 150 Hz, also a weak 60 Hz line and the 82 Hz (possibly a 263 Russian submarine communication) line switching on at 10 UT. One can also notice a decrease in 264 power of higher frequency components in the spectra (steepening of the spectrum) from approximately 265 5 till 16 UT (darker colors at higher frequencies). Strong succession of impulsive signals generated 266 during the HT main eruption occurs during the HT primary eruption and again but slightly less 267 pronounced during the secondary. The analogous, but less pronounced HT related features are also 268 visible in the (not presented) power spectrum evolution plot for the NS antenna, as expected for the 269 HT azimuth (see below).

270 Now, let us analyze a daily (Jan. 15th, 2022) evolution of ELF signal azimuths derived as 271 explained above in Section 3. One should remember that differences of the considered source 272 distances lead to modification of intensity and dispersion of individual impulses. Below, we

- 273 demonstrate how selection of parameters n, r_{min} and r_{max} enables one to extract azimuths for particular
- 274 ELF signals and thunderstorm regions. In the plots, we originally searched for signatures of the HT
- eruption near its geographic azimuth $A_{\rm HT} = 32.8^{\circ}$ and $A_{\rm HT} 180^{\circ} = -147.2^{\circ}$ to learn that it is significantly
- shifted to $\approx 20^{\circ}$ and -160° , respectively. The distance to the erupting volcano is significant, D = 16400
- km, so we expected and confirmed in the measurements below that the volcano originated signals are
- 278 subject to significant dispersion even for the direct path propagation.



Figure 3. Azimuth daily evolution and distributions of derived azimuths during 75 s time bins

283 beginning in selected times, derived with the raw data for *n*=60. We present plots for A (two panels at

284 the top) ($r_{min}=10$, $r_{max}=30$) and 5:10:00 UT; **B** (4 panels in rows 2 and 3) ($r_{min}=200$, $r_{max}=300$) and

285 5:10:00 UT, 9:00:00 UT and 21:00:00 UT; and C (4 panels at the bottom, rows 4 and 5) (r_{min} =500,

 r_{max} =5000) and 5:10:00 UT, 9:00:00 UT and 21:30 UT. At vertical axes of the azimuth distributions,

287 we present the number of measurements per one-degree azimuth range. Note vertical scale changes

- 288 between the presented azimuth distribution plots.
- 289

290 Let us start with the raw unfiltered data. Here to subtract the 50 Hz line contribution from the 291 data we either select n=60 ($\Delta t_{50Hz} = 0.02$ s) to compare ELF signal changes in the same phase of the 292 electric power line signal or we select only high amplitude $(r > r_{50Hz})$ impulses/waves for any selected 293 n. When analyzing the results in the first considered case for n=60 we see that preferential values of r 294 are comparable or above the electric line fluctuations, as the tests with $r_{\text{max}} < r_{50\text{Hz}}$ show a significant 295 random smoothing of the azimuth distribution as seen in Figure 3A. In a period of the high intensity 296 HT eruption most of r measurements for n=60 are above r_{max} selected for this plot and thus excluded 297 from the plot, leading to a vertical dip in the azimuth distribution measurement (cf. Mezentsev et al., 298 2022). On the other hand, a clear HT signal dominating the azimuth distribution during the eruption 299 (4:15 - 5:50 UT and near 9:00 UT) is visible in Figure 3B, where results for r a few times larger than 300 $r_{50\text{Hz}}$ (still with n=60) are presented. Outside of the eruption times, the thunderstorm activity produces 301 in this analysis quite diffuse, not well resolved structures. To reach high directional resolution of the 302 incoming waves one must select $r_{\min} \gg r_{50Hz}$, as presented in Figure 2C. Then, both the HT primary 303 and secondary eruption signatures are clearly visible, but also several separate azimuth ranges of 304 thunderstorm activity, varying during the day, can be clearly resolved outside the HT eruption periods. 305 In conclusion, use of n=60 to subtract the electric grid background seems to be fully effective only for 306 large amplitude signals, while irregularities of the electric grid signal presented in Figure 1D (left plot) 307 introduce significant scatter in azimuths derivations for smaller r.

From inspection of Figures 3B and C one should note, however, that the mean measured HT signal azimuth from our Hylaty ELF station appears to be near 20°, which is more than 10 degrees smaller than the HT geographic azimuth, $A_{\rm HT}$ = 32.8°. An azimuthal deviation of similar magnitude from the true geographic azimuth for ELF measurements was also noted by Füllekrug and Sukhorukov (1999) to occur when the waves propagated near the high conductivity of the Pacific Ocean.

313 Mlynarczyk et al. (2017) found that azimuthal deviations can be caused by diffraction from the solar

314 terminator nonuniformity. Following those past studies, we interpret the presently measured difference

- 315 as resulting from the signal deflection at ionospheric nonuniformities in the northern and southern
- 316 polar regions as well as at the solar terminator. In this context it is worthy to note that the terminator

- 317 was passing over the Hylaty station in time of the volcano main eruption and the HT signal direct path 318 to the station was close to the terminator in the polar region. In principle, also a contribution from the 319 powerful African thunderstorm center at $A < 20^{\circ}$ could contribute to this distribution shift, but we note a 320 fortunate significant calming of this signal (see Figure 4 and Figure 5 below) in the beginning of the 321 HT eruptive activity what makes such an explanation doubtful.
- 322 One can also minimize the influence of electric grid signal at the derived azimuth distribution 323 at any other selected n by considering values of r much higher than the ones in the grid signal. One 324 should note here that a change of the grid signal from its minimum to maximum occurs at a time scale 325 of $\frac{1}{4}\Delta t_{50Hz}$ (or n=15) and thus effective grid signal variations for n<15 may be significantly smaller 326 that the full amplitude r_{50Hz} . Thus, let us consider the case with n=3 (a time step of 1 ms) and the 327 required large signal changes with $r_{min}=300$. At the resulting azimuth distribution presented on Figure 328 4 one can note quite efficient azimuth resolution in the plot. However, we also note that the HT signal 329 signature completely disappears from the plot. In fact, such an effect is expected for signals from a 330 distant source since the impulses diminish their amplitudes and experience significant dispersion 331 during propagation, contributing to the ELF signal with smaller r, outside the parameter range selected 332 for this derivation. Removal of the HT contribution from the azimuth distribution reveals interesting 333 structures on the remaining plot. In the analyzed winter day, a significant ~12h range of low 334 thunderstorm activity appears on the plot, between ca. 5 UT and 16:30 UT for thunderstorm centers 335 close to azimuths 0° and $\pm 180^{\circ}$, while regularly shifting with time for growing azimuths, with the 336 quiescence range roughly 6 UT-18 UT at 45° but extending only up to ~14 UT at the azimuth stripe 337 visible above 90°. Following earlier publications we interpret this regular structure in the studied 338 winter day at the Northern hemisphere as switching-off of the thunderstorm activity at successive 339 azimuths by the propagating solar terminator. A similar but somewhat less regular process of azimuth 340 dependent switching-on of the thunderstorm activity appears in the evening (see also Figure 5 below). 341 Let us also note that careful inspection (also in the studies of filtered data below) of the considered 342 thunderstorm switching-off ranges suggest existence of small upturns to higher azimuths before the 343 quiescence phase (cf. Shvets et al. 2022). If real, such behavior could indicate the effect of the signal 344 diffraction at the terminator passing over the given thunderstorm site. One more important feature is 345 present in these azimuth data with absent HT signatures. An active thunderstorm center with the 346 measured azimuth close to $A_{\rm HT}$ =32.8° (and -147.2°) initiated its activity before the HT main eruption 347 (Figure 4B) and was continuing activity during the main eruption phase, as we observed in the 348 respective azimuth distributions before and during the main eruption. Thus, it is important to know 349 that this signal from the HT geographic azimuth is not the volcano eruption signature, but a 350 superimposed thunderstorm activity. 351





Figure 4. Comparing daily ELF signal azimuth distributions derived with n=3, $r_{min}=300$ and $r_{max}=3000$ for A. the raw data (left); and B. the data with 50 Hz line filtered using the bandstop filter (right). Existing slight differences between the plots are hardly visible.

357 Now, let us consider another suggested option for removing effects of 50 Hz line fluctuations 358 from the analysis by removing the power line periodic signal and its harmonics with filtering 359 procedures discussed in Section 3. Let us start with applying the bandstop filter. The resulting daily 360 varying distribution of signal azimuths derived from such filtered data is presented in Figure 4B, 361 where we selected for presentation quickly varying high amplitude impulses analyzed with $r_{min}=300$ 362 and n=3. In this case the filtering procedure allows for tiny but visible improving azimuth resolution as 363 compared to the unfiltered data in Figure 4A. In effect we reveal and can track during the day 364 numerous thunderstorm centers at different azimuths with slightly improved resolution. One should 365 note that, as mentioned above, some thunderstorm activity appears also close to the HT geographic 366 azimuth of $\approx 33^{\circ}$ long before the volcano first eruption and the accompanied signal is continuously 367 observed also during the HT main eruption, which is not visible in this plot with small n and $r_{\min} >>$ 368 $r_{50\text{Hz}}$ Thus, we interpret here the respective maximum $\approx 33^{\circ}$ in the azimuths' distribution during the 369 eruption as the projected local thunderstorm activity, not related to the HT. On the other hand, by 370 selecting r_{\min} and r_{\max} below the value of r_{50Hz} one can clearly reveal the signal with azimuths from the 371 HT first and second eruptions, but with a large scatter. It shows that the applied filtering procedure 372 cleans nicely the individual high amplitude impulses but is not able to do the same for the low 373 amplitude fluctuations in the data. At this figure (Fig. 4) one may note the previously discussed 374 azimuth dependent switching-off of the thunderstorm activity in the morning, finishing in a few cases 375 with the azimuth distributions' upturns.





Figure 5. Comparing daily ELF signal azimuth distributions derived with n=1 for the data with filtered 50 Hz line using **A**. the bandstop filter for $r_{min}=300$ and $r_{max}=3000$ (upper left); **B**. the MA60 filter for $r_{min}=6$ and $r_{max}=30$ (upper right) and **C**. the bandstop filter for $r_{min}=6$ and $r_{max}=30$ (bottom).

383 A quite different output is obtained when using the MA60 filter. In effect, as presented on 384 Figure 1C, D, the impulses with steep rising and declining slopes are removed or at least highly 385 attenuated in the filtered data. Thus, only the slowly varying or low amplitude signals are available for 386 the analysis with a selected *n* below 60. Let us perform azimuth analysis in such data with $r_{\text{max}} < r_{50\text{Hz}}$. 387 Example distributions resulting for n=1, $r_{min}=6$ and $r_{max}=30$ are compared in Figure 5 with the results 388 for the data cleaned using the bandstop filter. It is important to note that the characteristic azimuth 389 stripes from thunderstorms visible in this figure for the MA60 filter (Figure 5B) coincide with the 390 azimuths derived from high amplitude impulses using the bandstop filter (Figure 4B and 5A) as well 391 as the ones without any filtering for $r_{\rm min} >> r_{50\rm Hz}$ (Figure 4A). Thus, somehow to our surprise the 392 MA60 filtered data presented in Figure 1D preserved the azimuth information in the slowly varying 393 signal, including clear signatures from the HT eruption at $A \approx 20^{\circ}$. It is contrary to slowly varying 394 signals in the bandstop filtered data providing highly dispersed azimuth distributions in Figure 5C. 395 One should note that the HT azimuth distribution derived in this analysis matches well to the ones 396 derived from both the bandstop filtered data and, from the raw data, when using large amplitude 397 signals with larger *n*. This fact confirmed consistency of all considered approaches and in the same 398 time reality of the obtained azimuths.

399 Another interesting case in this analysis can be studying ultra-low frequency magnetospheric 400 PC fluctuations (see e.g. Kivelson, M.G. and Russell, C.T. 1995), studied earlier in the Hylaty station 401 by Nieckarz (2016) and Nieckarz & Michałek (2020). To illustrate this possibility, we selected a large n=3000 and -- from the data inspection -- we choose $r_{min}=10^3$ and $r_{max}=10^4$ for the analysis to obtain 402 403 results presented in Figure 6. It is interesting to note that the registered long wave azimuths are well 404 constraint to some discrete directions, forming a regular time pattern and revealing clear differences in 405 the observed trends between waves propagating in the early and late hours of the day, and in the daytime. We note that on Jan. 15th, 2022, there is lack of such high amplitude waves in time periods of 406 407 5-7 UT and 17-18:30 UT, close to the sunrise and the sunset in the Hylaty station (where the local time 408 = UT + 1h in winter). The measurements of large amplitude short spikes create more diffuse 409 "background" stripes of colored points at the plot, around azimuths of nearby thunderstorms.





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414 while red/yellow points in the background are created by short large lightning spikes in the data.

415

416 **5. Conclusions**

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In the present study we show that with high quality ELF measurements, like our data from the ELA11

- 419 sensor, one can separate ELF signals emitted from numerous thunderstorm regions distributed along
- 420 the Earth. This very fact indicates that in many time instants signals from individual thunderstorm

regions dominate the measurements. It is contrary to our original expectation that in the majority of
observations – with the exception of large impulses - one would register a superposition of signals
from sources from a wide range of azimuths

424 To analyze azimuths of the registered ELF signals we proposed a new simple, but powerful 425 method comparing signal changes in two perpendicular magnetic antennas, as presented in Section 3. 426 By selecting 3 parameters in this method, the maximum and minimum signal changes, r_{max} and r_{min} , 427 and the time scale for these changes characterized with n, one can study waves/impulses with different 428 frequencies and amplitudes, to take into account the modification (dispersion) of the signal shape 429 during its propagation in the earth-ionosphere cavity. Thus, by selecting different sets of (r_{max}, r_{min}, n) 430 one can study different aspects of the thunderstorms' distribution and its varying activity. The derived 431 azimuths are more precise after one remove interference from the electric grid.

432 In the case of analyzing the signal changes smaller or comparable to the ones from the 50 Hz 433 electric power line perturbations, significant scatter is observed in the derived azimuth distribution. A 434 possibility to take into account such periodic perturbations is to measure the natural ELF signal 435 changes in the same phase of the electric power line signal, by selecting n=60 in our data for the 436 respective time delay between measurements. However, as one could see in Figure 1D, the power line 437 signal registered in our Hylaty station is not as regular as we would wish to have and accuracy 438 improvement of azimuth resolution for small measured amplitudes r appears to be quite moderate. On 439 the other hand, the analysis resolves separate thunderstorm directions for large impulses. Overall, 440 usage of n=60 falls short of the main intended goal of enabling study of azimuth information of small 441 amplitude ELF impulses.

To deal with this problem we tested the filtering of the 50 Hz signal from the data with two significantly different filtering procedures. The bandstop filtering appears excellent in "cleaning" steep impulses/spikes in the ELF signal and providing a significant improvement for derived azimuths. The procedure decreases dispersion of azimuths derived for high amplitude impulses and it enables reasonable thunderstorm direction resolution using even smaller spikes. Unfortunately, the small amplitude waves in such filtered signal do not show clear azimuth separation, possibly due to remaining perturbations left from the wide and thus not fully removed wings of the 50 Hz line.

449 When inspecting Figure 1D, at first glance the results of the applied low pass MA60 filter does 450 not give much hope for extracting detailed directional information about numerous thunderstorms. 451 However, despite the removal/deformation of the quickly varying impulses, this signal still contains 452 quite precise information about waves propagating from many different azimuths, also when analyzing 453 low amplitude signal changes with $r \ll r_{50Hz}$. Apparently, short impulses in both antennas are corrected 454 in the same proportion, without a noticeable change of the azimuth values resulting from equation 1. 455 Studying of such low amplitude or slowly varying signals is essential in identifying emissions from 456 distant sources, with impulses smoothed due to large dispersions.

457 A fortunate (for ELF research!) strong and extended in time point-like electromagnetic 458 emission from the HT eruption allowed us to analyze the propagation of ELF waves along a trajectory 459 crossing the Earth polar region and to test our azimuth derivation method for extracting a particular 460 source signal from the general electromagnetic activity in the earth-ionosphere cavity. The long >16461 Mm direct propagation path introduces significant dispersion into the volcano lightnings' generated 462 spikes. In effect, the HT azimuth signal is clearly visible when limiting analysis to the slowly varying 463 signals, while analysis of high amplitude and fast changing impulses does not show any clear HT 464 signature. Moreover, in this last case one can monitor in the azimuth distribution evolution map the 465 thunderstorm signals from directions close to the HT geographic azimuth, which are overshadowed in 466 the lower amplitude measurements by a dominating HT contribution. The analysis also shows the 467 research potential of azimuths distribution studies, by allowing a robust identification of the weaker 468 secondary HT eruption. The method allows for precise measurement of the significant (>10°) HT ELF 469 signal azimuth deviation from the geographic azimuth due to wave deflection in the polar region 470 and/or the waves propagation near the solar terminator, in the process discussed earlier by Mlynarczyk

- 471 et al. (2017).
- 472

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483 **Open research**

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485 The data analyzed in the present paper are available from an on-line repository (Kubisz 2023).

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487 **References**

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