ELF seminar 26 November 2025 on-line

On the impact of ground electric conductivity on ELF measurements

First insights

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Overview

There is a systematic deviation in azimuth determination of sources (strong lightnings) between estimations based on ELF signals and on lightning detection networks like WWLLN. We aim at a quantitative explanation.

I) Introduction

II) The magnetotelluric perspective

III) Hylaty measurements

IV) Open questions & outlook

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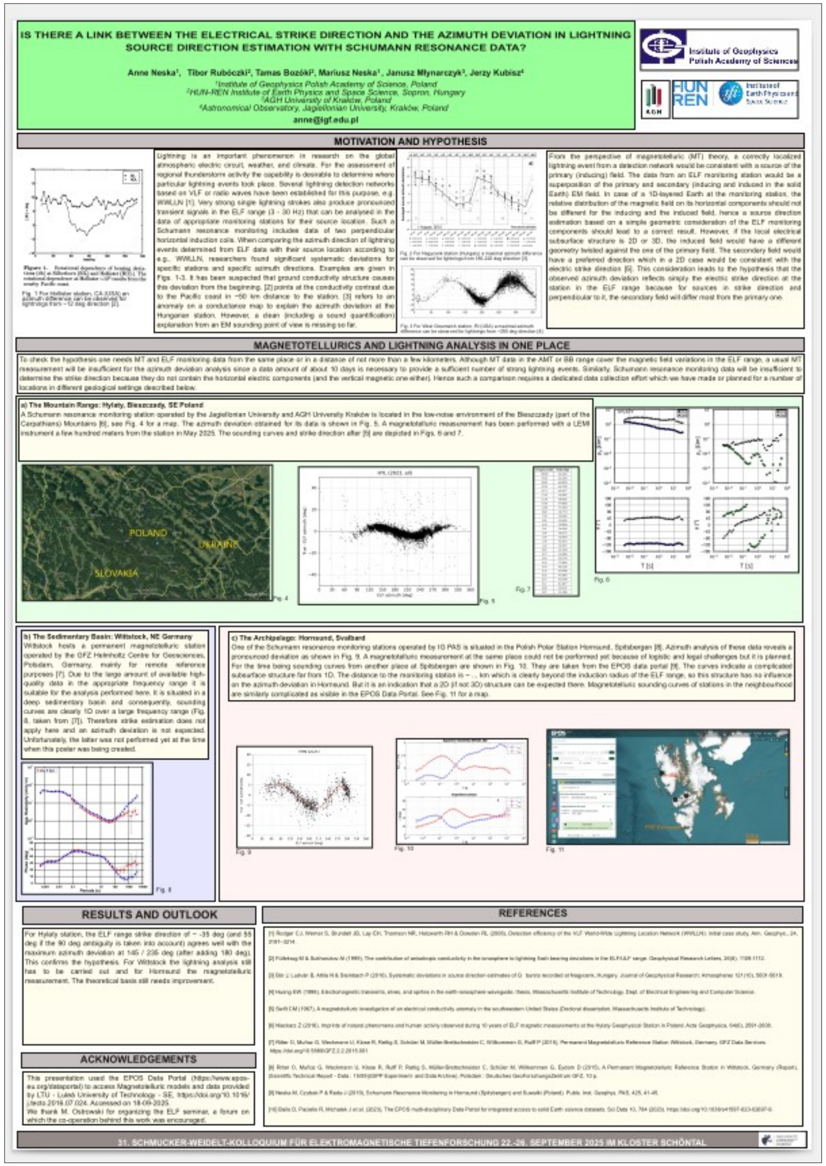
Introduction 1: Status of work

- Poster presentation on the „31. Schmucker-Weidelt-Kolloquium für Elektromagnetische Tiefenforschung”, 22.-26. September 2025, Kloster Schöntal, Germany

- Co-operation between experts in magnetotellurics, ELF monitoring, and lightning utilization from Hungary and Poland



Introduction 2: History, people, communities

Ulrich Schmucker
1930-2008

Professorship in Geophysics
Göttingen 1971-1995

A significant part of the people traditionally gathering during the aforementioned colloquium are students of him (among them Heinrich Brasse, head of the FU Berlin working group during my time there) and their students.

Prof. Schmucker also was the supervisor of Martin Füllekrug's PhD thesis on Schumann resonances.

Introduction 3: Literature

Hollister, CA

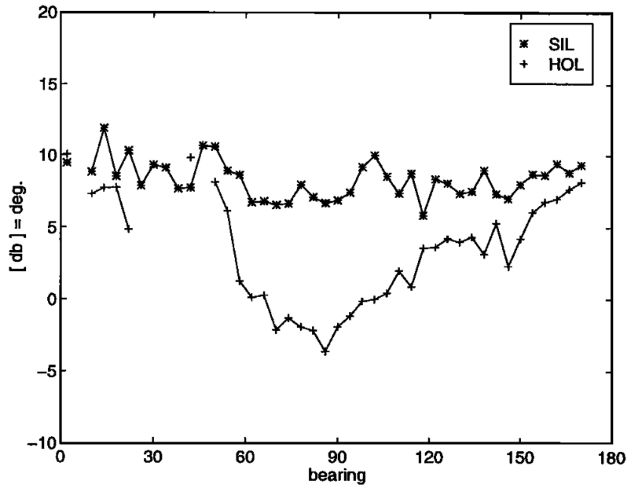
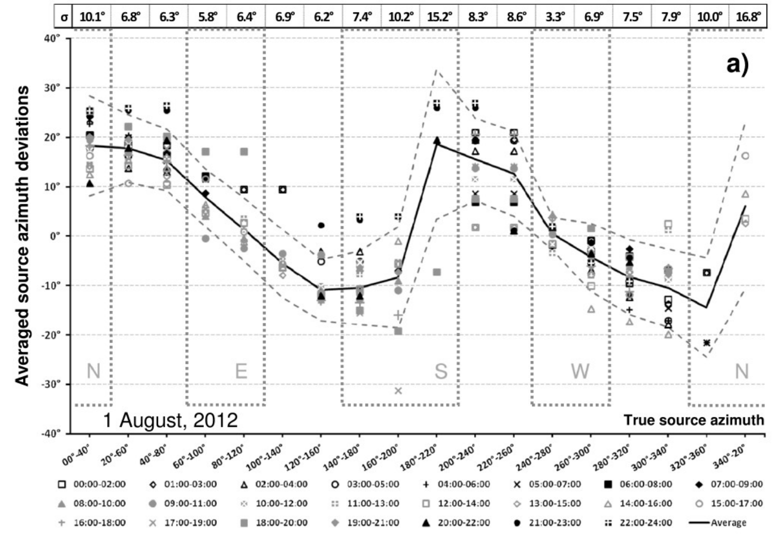


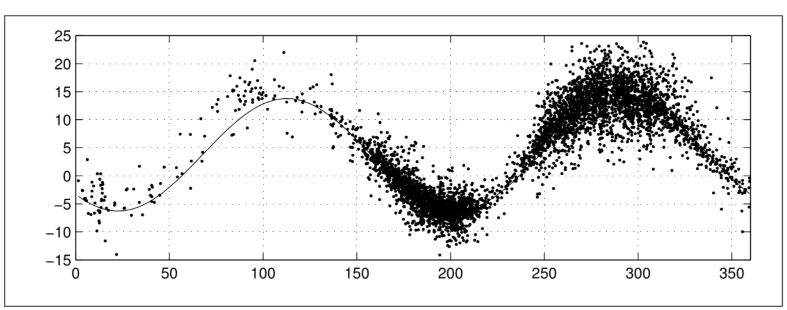
Figure 1. Rotational dependence of bearing deviations (db) at Silberborn (SIL) and Hollister (HOL). The rotational dependence at Hollister ~12° results from the nearby Pacific coast.

Füllekrug M & Sukhorukov AI (1999), The contribution of anisotropic conductivity in the ionosphere to lightning flash bearing deviations in the ELF/ULF range. Geophysical Research Letters, 26(8), 1109-1112

Nagycenk



Bór J, Ludván B, Attila N & Steinbach P (2016), Systematic deviations in source direction estimates of Q-bursts recorded at Nagycenk, Hungary. Journal of Geophysical Research: Atmospheres 121(10), 5601-5619



Rhode Island

Huang EW (1998), Electromagnetic transients, elves, and sprites in the earth-ionosphere waveguide, thesis, Massachusetts Institute of Technology, Dept. of Electrical Engineering and Computer Science

Magnetotellurics 1: overview

- Aim / target: Probing the solid earth for electrical conductivity and its distribution in the subsurface for interpretation in terms of tectonics, geology, exploration

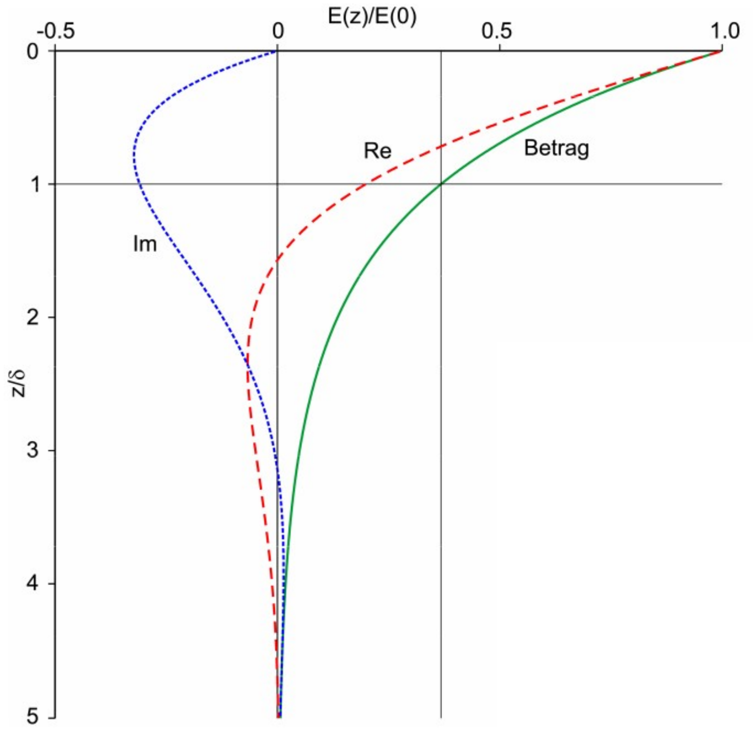
- Measurement: at (array / profile of) station(s) at surface or seafloor above the region of interest. A station measures variations of two perpendicular horizontal components of both the electric and the magnetic field

- Source signal: naturally occurring electromagnetic fields

- Frequency range: ~100 kHz – 10000 s, depends on desired depth range

- Principle: electromagnetic induction, skin effect

Magnetotellurics 2: The skin depth δ



$$\delta[km] \approx \frac{1}{2}\sqrt{\frac{\rho[\Omega m]}{f[Hz]}}$$

ρ - resistivity of the subsurface (homogeneous halfspace)

f - frequency

At the skin depth the electric or magnetic field strength (E or B) in a conductor of resistivity ρ has decayed to 1/*e* of its value at surface, *e* being Euler’s number

Using the Hollister-Pacific Ocean distance of 50 km and an approximate frequency of 10 Hz for the SR range with this formula would infer a ground resistivity of 100,000 Ωm, which is unrealistically high for a region with active tectonics

Magnetotellurics 3: The impedance tensor, apparent resistivity, and phase

The impedance tensor Z contains the four transfer functions between the two electric and the two magnetic field components measured at a magnetotelluric station. Transfer functions are complex-valued and are functions of frequency ω

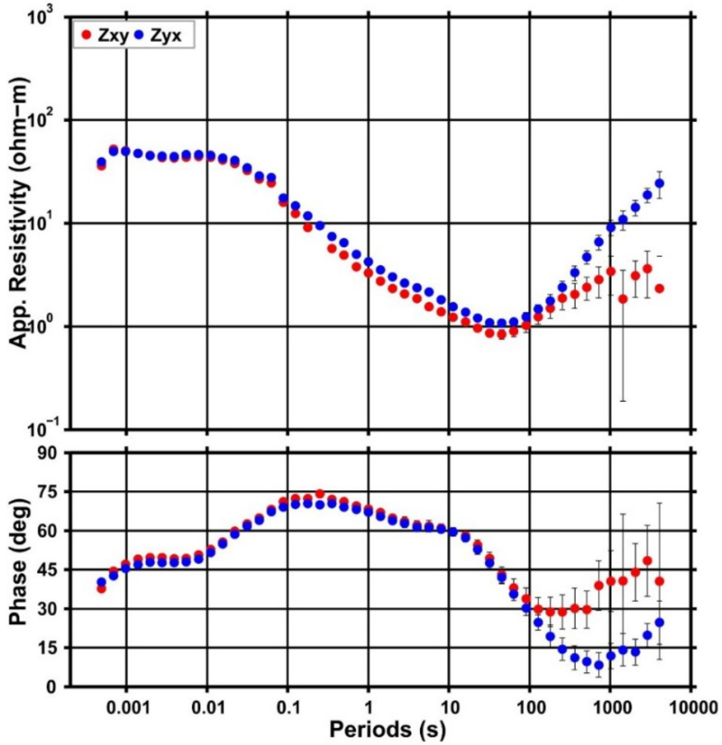
$$\vec{E}(\omega) = \underline{\underline{Z}}(\omega)\vec{B}(\omega) \qquad \begin{pmatrix} E_x \\ E_y \end{pmatrix} = \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix} \begin{pmatrix} B_x \\ B_y \end{pmatrix}$$

Impedances are depicted as apparent resistivities ρ_a and phases φ

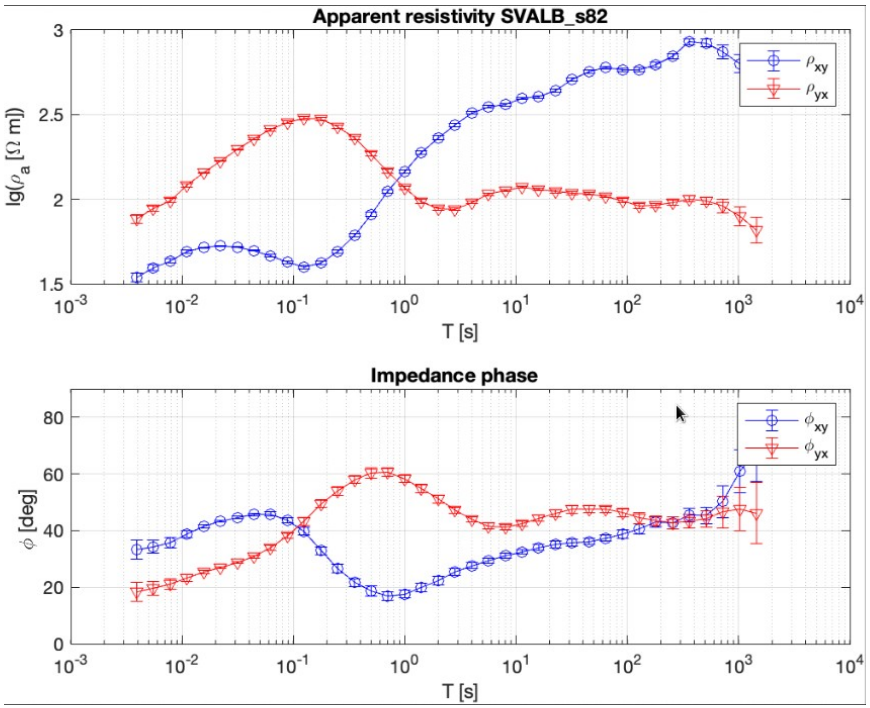
$$\rho_a = 0.2\, |Z_{xy}|/f, \qquad \varphi = \arctan\left(\mathrm{Im}(Z_{xy})/\mathrm{Re}(Z_{xy})\right).$$

Magnetotellurics 4: Sounding curves and dimensionality

Wittstock, NE Germany: 1D



North Svalbard: not 1D



Period T [s] = 1/f [Hz], main diagonal impedances xx and yy not shown

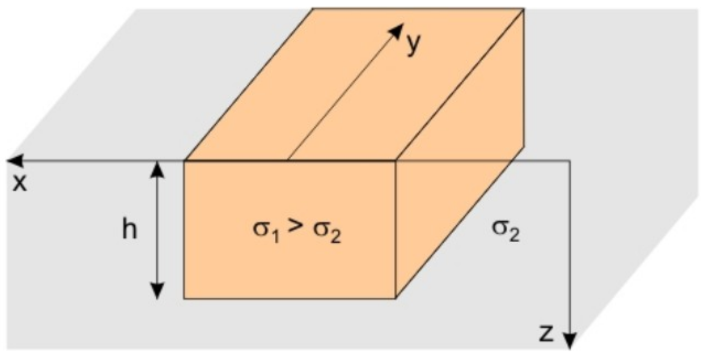
Dimensionality

1D (horizontally layered structure): Zxy = -Zyx, Zxx = Zyy = 0

2D (structure independent of one horizontal direction, e.g., y): Zxy ≠ Zyx, Zxx = Zyy = 0

3D no constraints on impedance elements

Magnetotellurics 5: The strike direction



In the 2D case a direction (here: y) exists in which the conductivity structure does not change.

Conductivity $\sigma = 1/\rho$

This direction is called the electrical strike and can be found by rotating the impedance tensor by an angle α_s that minimizes Z_{xx} and Z_{yy}:

$$\alpha_s = \frac{1}{4}\arctan\left\{\frac{2\,\mathrm{Re}\left(\left(Z_{xx}-Z_{yy}\right)^{*}\left(Z_{xy}-Z_{yx}\right)\right)}{\left|Z_{xx}-Z_{yy}\right|^{2}-\left|Z_{xy}+Z_{yx}\right|^{2}}\right\}$$

where * denotes the complex conjugate.

Remark: Disambiguity of 90° in α_s. Final decision by induction arrow or geology.

Magnetotellurics 6: suggestions

If you want to confirm that subsurface conductivity causes the azimuth deviation in lightning location estimation, make a magnetotelluric (MT) measurement at the ELF station, determine the strike direction for the ELF range (> 3 Hz), and check if it coincides with the direction where the deviation is maximum.

- Consideration: A lightning source in strike direction will have an electric field in strike direction which will drive the maximum possible current in the earth. Accordingly, the secondary magnetic field of this current will maximally distort the primary (originating from the lightning) magnetic field.

- Frequency range: The MT measurement must be of broad-band (BB) type which, in contrast to the long-period ones, includes the ELF range. This requires appropriate instrumentation (induction coil instead of fluxgate magnetometers).

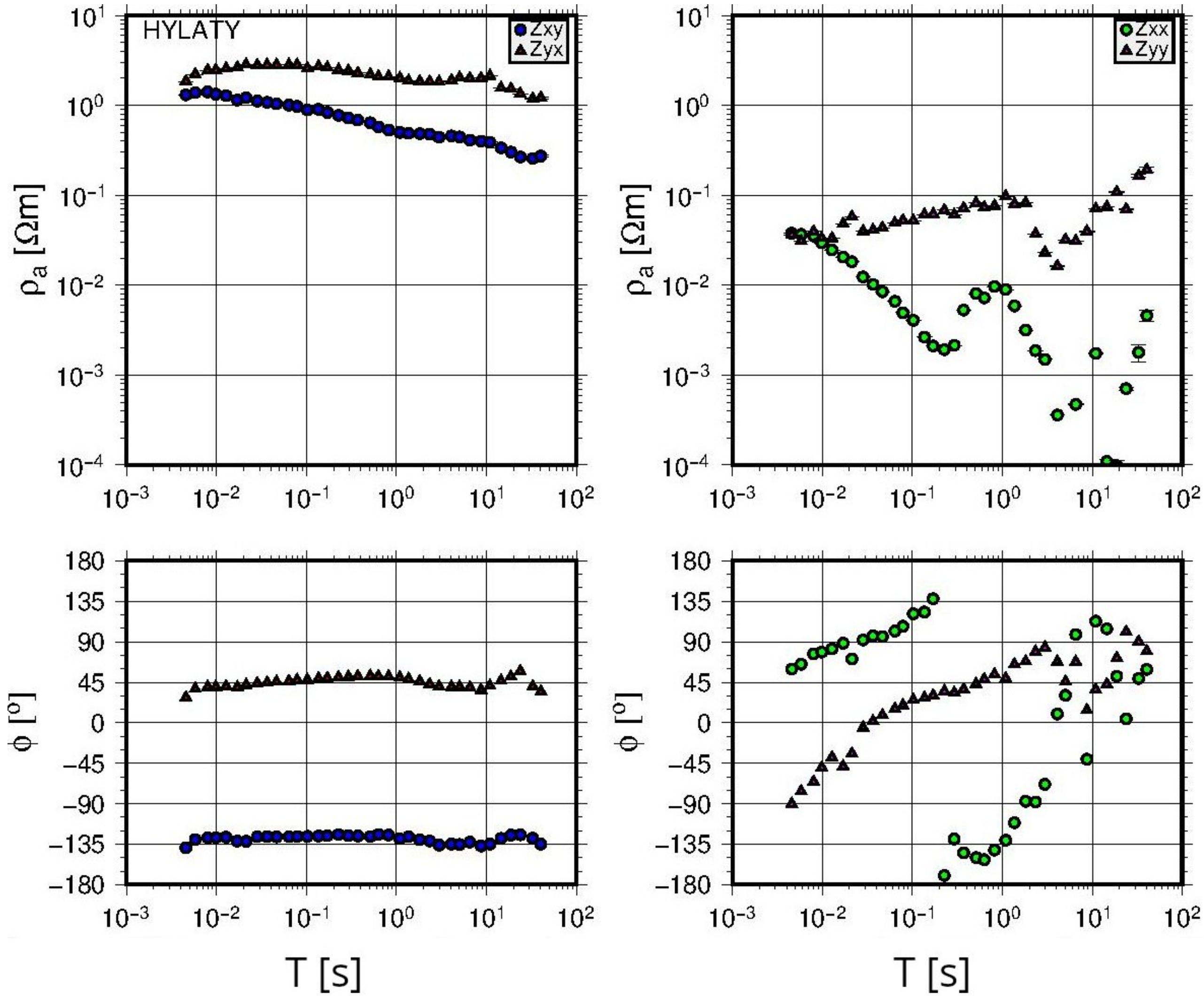
- The distance between ELF monitoring and BB-MT station should be within ~1km to warrant that the ELF range signal at both sites covers the same subsurface structure (overlapping lateral skin „depth”).

- Note that usually the duration of a BB-MT measurement / deployment is ~1 day.

Hylaty 1: campaign

- 19-21 May 2025, Bieszczady Mountains, by the group on the photo
- Magnetotellurics by Tibor Rubóczki & colleagues with a BB instrument manufactured by LEMI
- ELF data from Hylaty monitoring station operated by Krakow group (Janusz Młynarczyk, Jerzy Kubisz), azimuth deviation analysis by Tamás Bozóki
- Distance between both stations < 100 m

Hylaty 2: sounding curves & strike direction



Frequency [Hz]	Strike [deg]
100.00	-44.3222
76.92	-42.4316
58.82	-44.8959
47.62	-44.3769
35.71	-40.1077
27.03	-39.4565
21.28	-38.9201
15.63	-37.8920
12.66	-37.4704
9.80	-36.7774
7.30	-36.0362
5.85	-35.6592
4.34	-35.0804
3.41	-34.4500
2.69	-34.6272
1.95	-32.8183
1.59	-33.2613
1.22	-31.6571
0.92	-32.3294
0.73	-32.4696
0.55	-33.5719
0.43	-37.9666
0.34	-40.2236
0.24	-43.6940
0.20	-43.3083
0.15	-41.6790
0.11	-41.4077
0.09	-35.9237
0.07	-32.1366

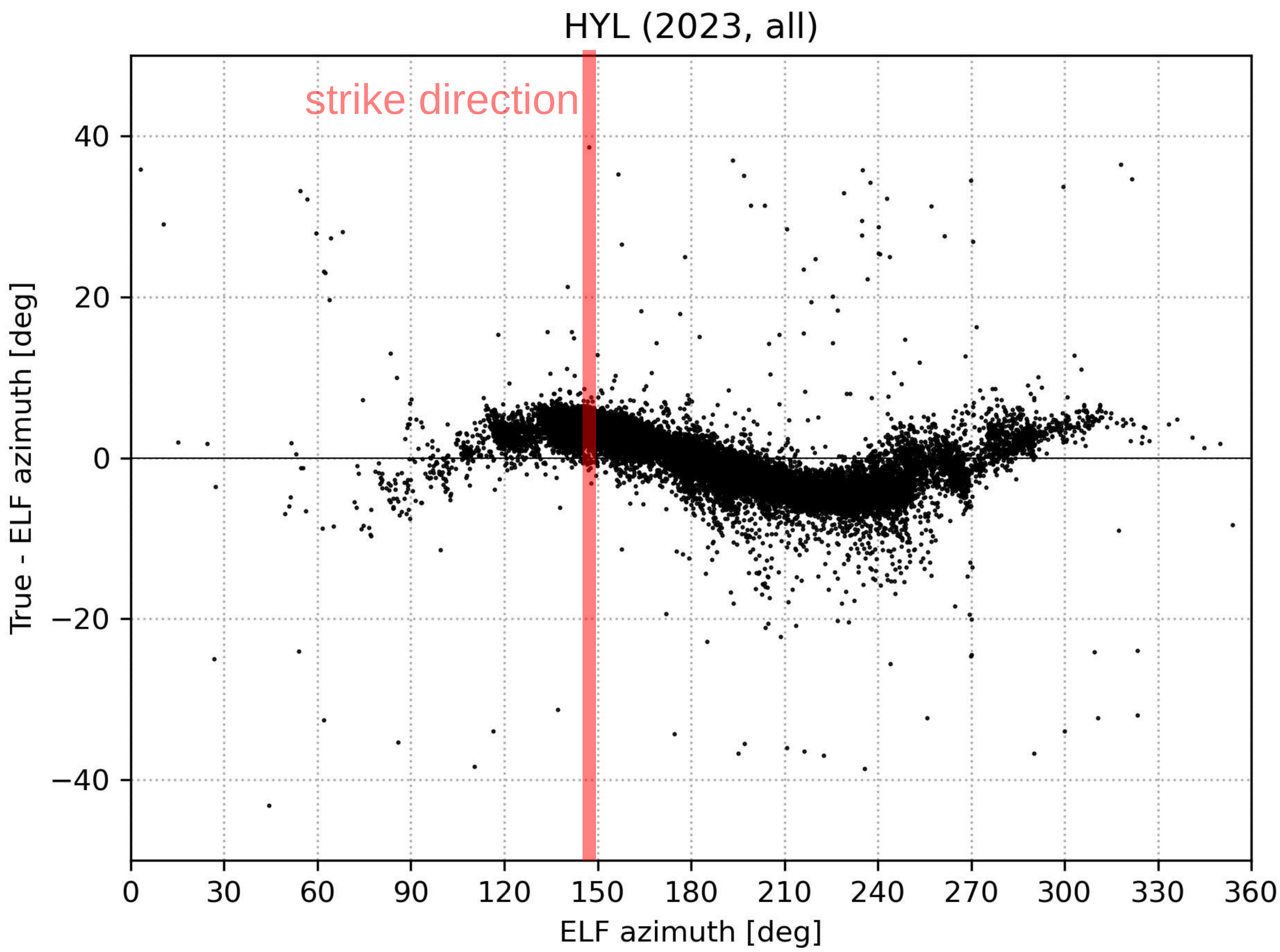
The strike direction in the ELF range is ~ -39°.

Since MT-North usually is geomagnetic and declination in the region is 7°, the „geographic” strike is -32° or -32° + 180° = 148°.

Hylaty 3: azimuth deviation

The maximum deviation is at ~140°.

This is at least not contradictory to the initial assumption.



Open questions & outlook

Theory

- Understand behaviour of the TM mode and reason for the negative azimuth deviation
- Think of another way to display the result (polar diagram?)

Practice

- More data. Tamás did azimuth deviation analysis for plenty of stations but there are problems with availability of appropriate MT data and with understanding statistic and systematic errors (scatter and offsets)

Thank you.