ELF-transients detected in the broadband recordings at the Hylaty station in Poland

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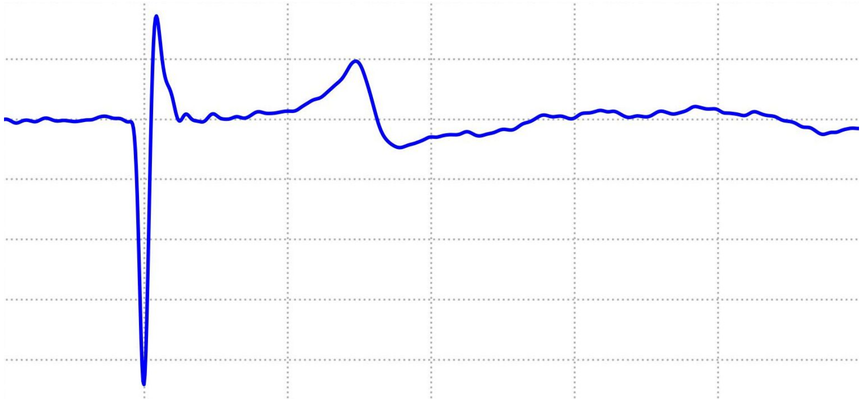

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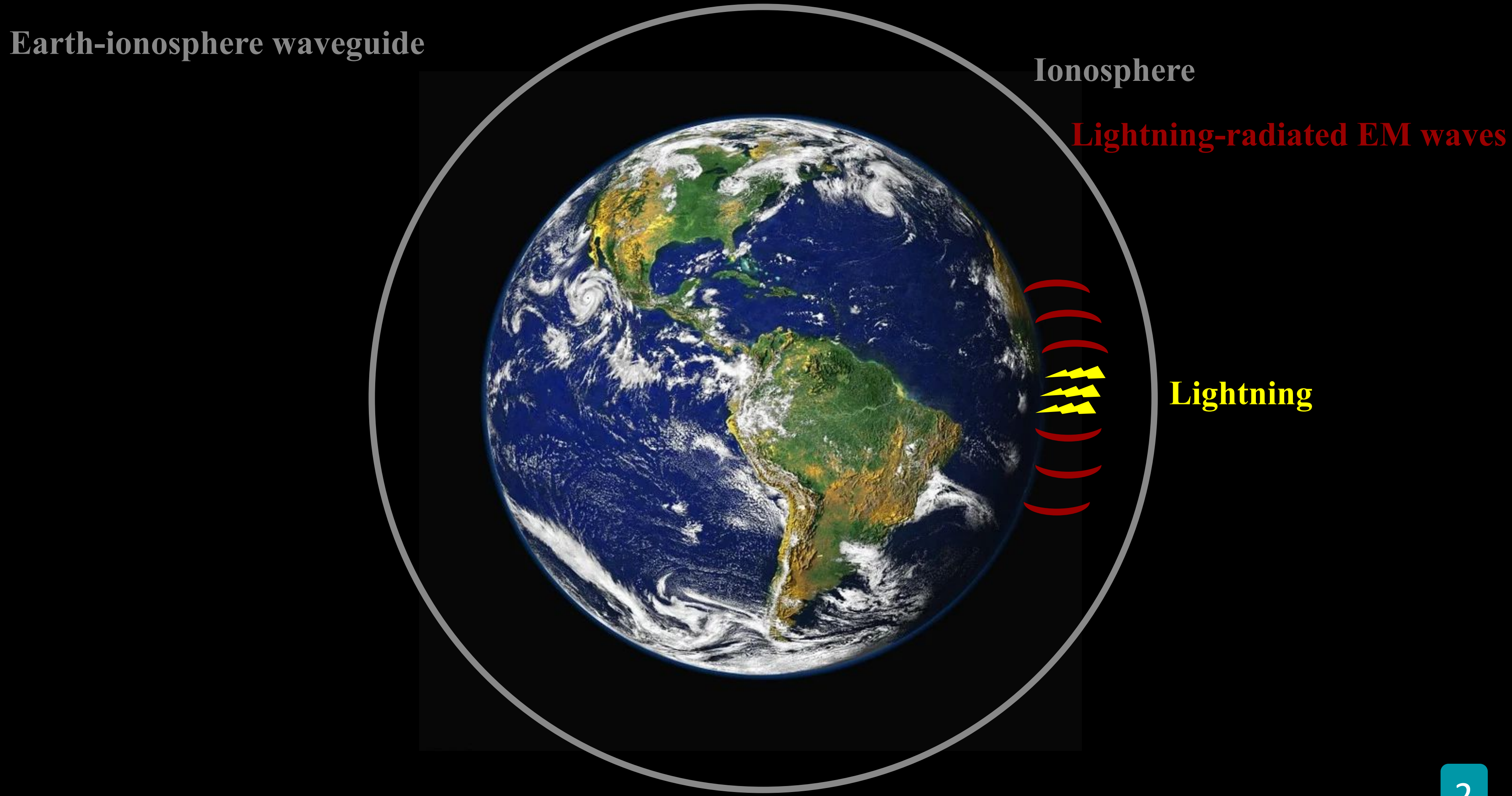
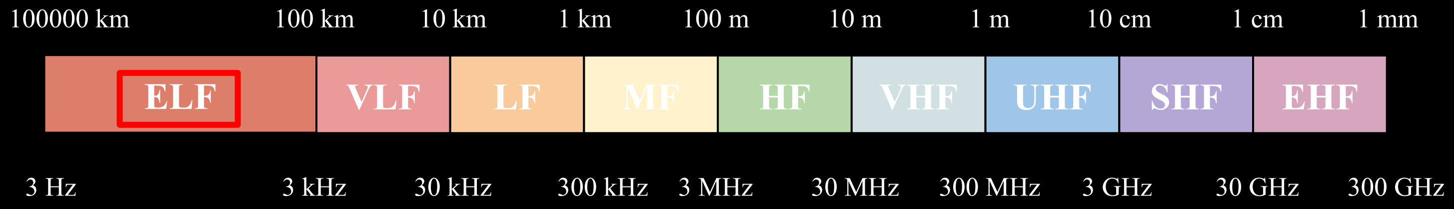
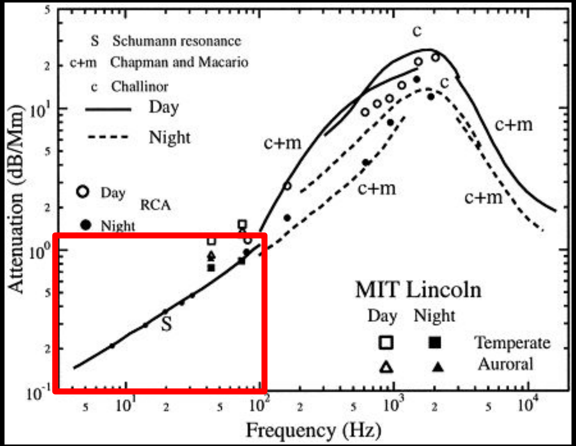

Earth-ionosphere waveguide
Ionosphere
Lightning-radiated EM waves
Lightning

Extremely low frequency (ELF) band

The radio spectrum

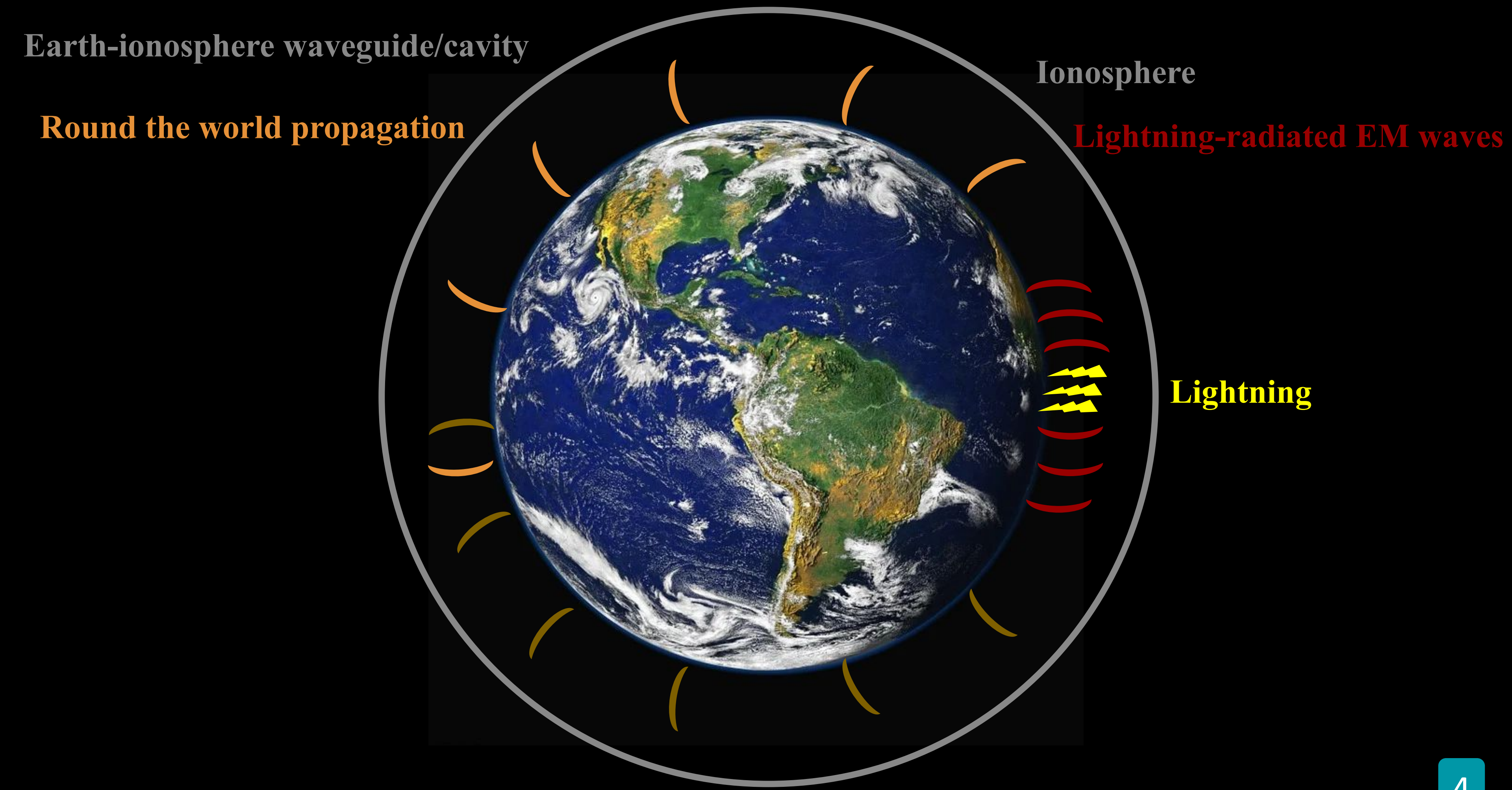




Attenuation of EM waves:

<1 dB/Mm (f<100Hz)

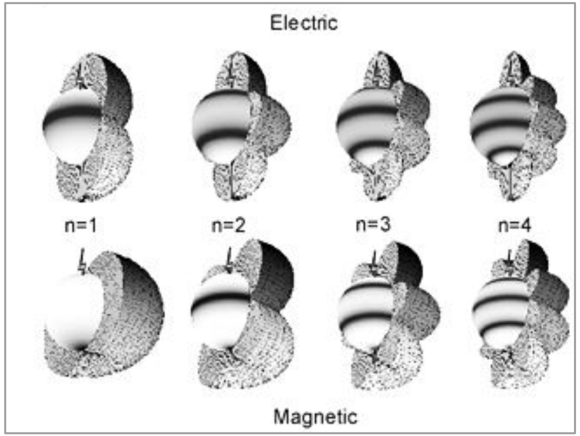
(from Barr et al., 2000)


Earth-ionosphere waveguide/cavity
Round the world propagation
Ionosphere
Lightning-radiated EM waves
Lightning

Schumann resonances (SRs)

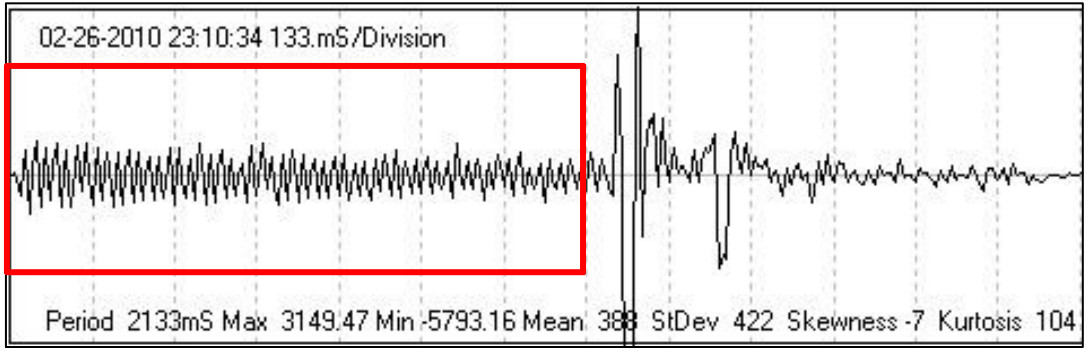
SRs are the **global electromagnetic resonances of the Earth-ionosphere cavity** with resonance frequencies at ~8, ~14, ~20, ~26 etc. Hz excited primarily by lightning-radiated electromagnetic waves.

Angular distribution of SR modes (Sentman, 1995).



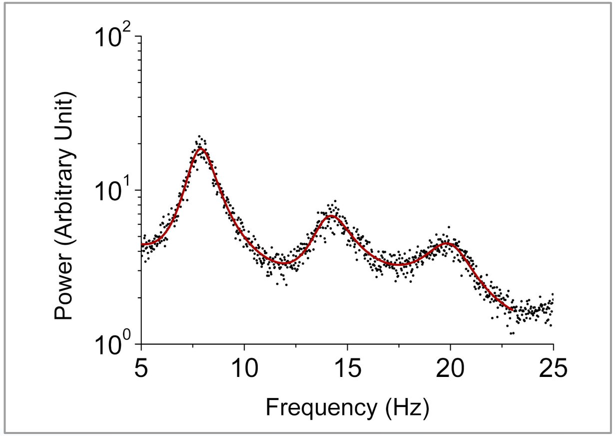
Q-burst/SR-transient/ELF-transient

"Background" field



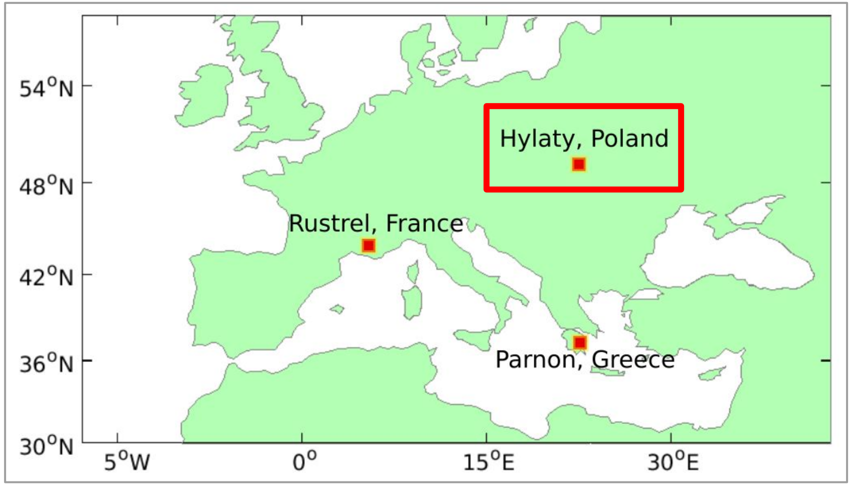
The appearance of a transient and the "background" field in a time series.

Power spectrum of the "background" field



Broadband ELF Radiolocation System (BERS)

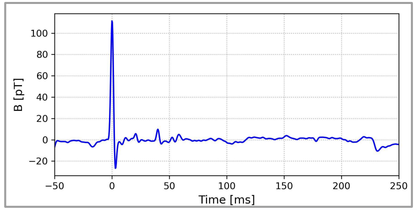
Operator	AGH University of Science and Technology
Equipement	Two magnetic antennas
Sampling frequency	3004.81 Hz
Antenna bandwidth	0.02 Hz to 1.1 kHz
Receiver energy bandwidth	900 Hz

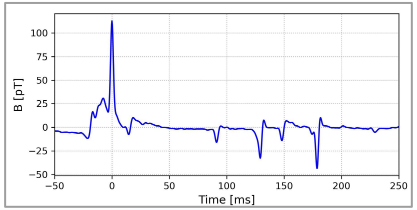


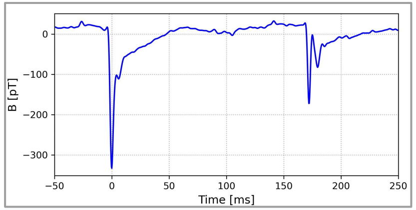
Location of the 3 measuring stations (same equipment).

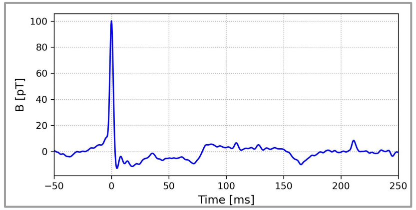
Krakow ELF Group: http://www.oa.uj.edu.pl/elf/

Example waveforms







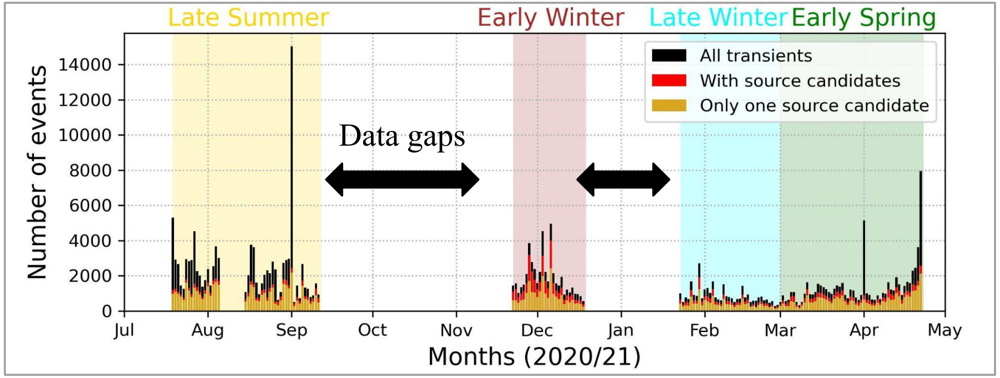


Research concept

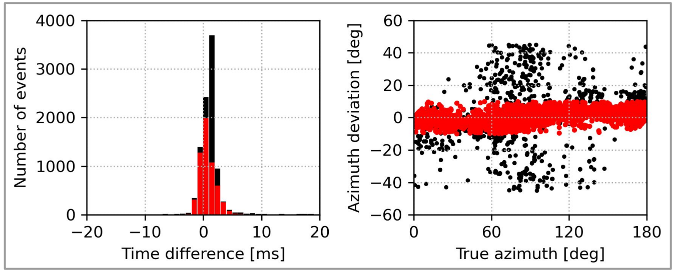
We developed an algorithm that identifies ELF-transients in the broadband recordings at Hylaty, Poland **and finds their most probable source lightning stroke** in the lightning database of the WWLLN based on the technique described by Bór et al. (2022).

Main steps of the process:

- Filter data
- Find transients (B>100 pT)
- Merge transients within 80 ms
- Determine ELF azimuth based on ellipse fitting
- Save source candidates that fulfill the following criteria:
  - |ELF azimuth - True azimuth| < 10°
  - 180 Mm/s < v < 320 Mm/s



The daily number of ELF-transients detected in the studied time interval.



Source lightning stroke identification based on the expected arrival time and azimuth (Early Winter events). Red color marks the accepted events.

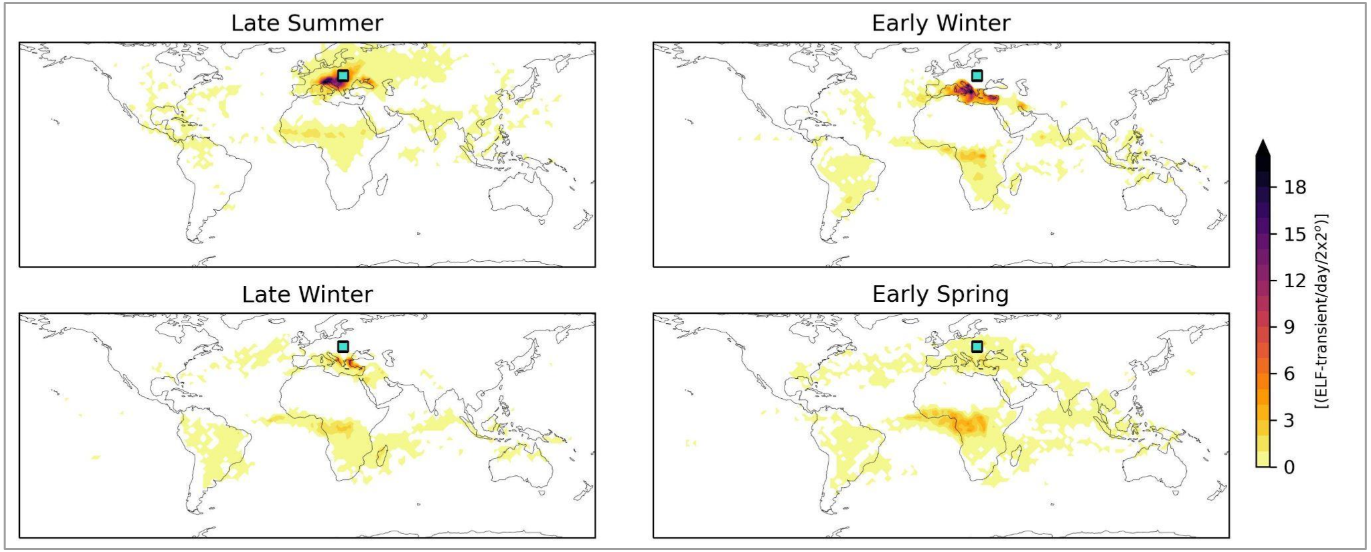
<u>All transients</u>: 266434

<u>With source candidates</u>: 157179 (59%)

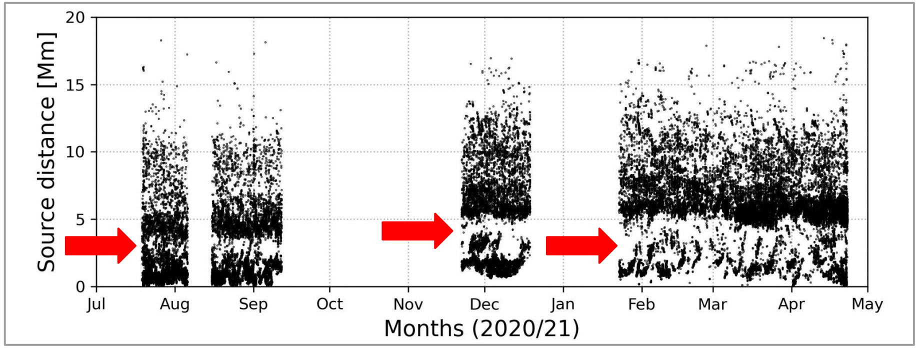
<u>Only one source candidated</u>: **115555 (43 %)**

Results

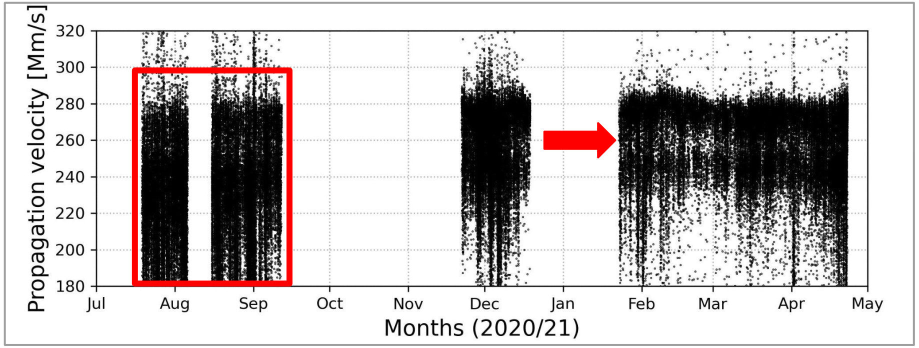
There is a clear seasonal trend in the distribution of source lightning strokes (as expected) and also in the propagation velocity of the transient signals.



Global distribution of source lightning strokes in different seasons.

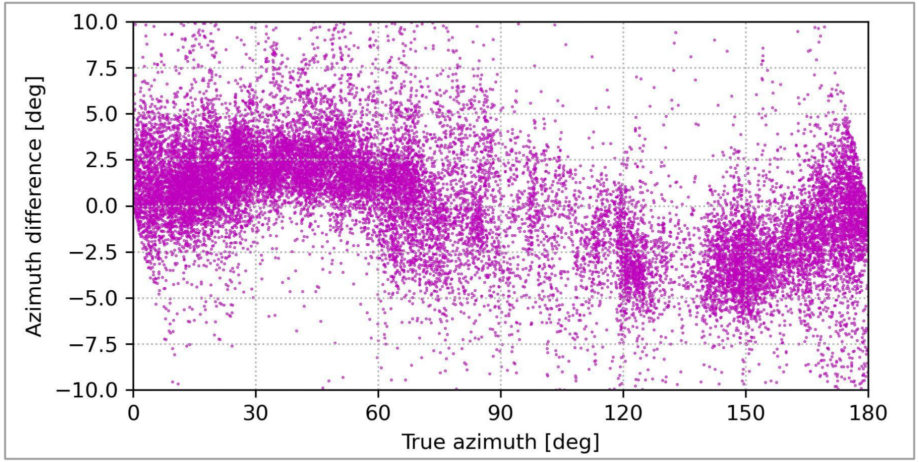


Source lightning stroke distances from the Hylaty station.

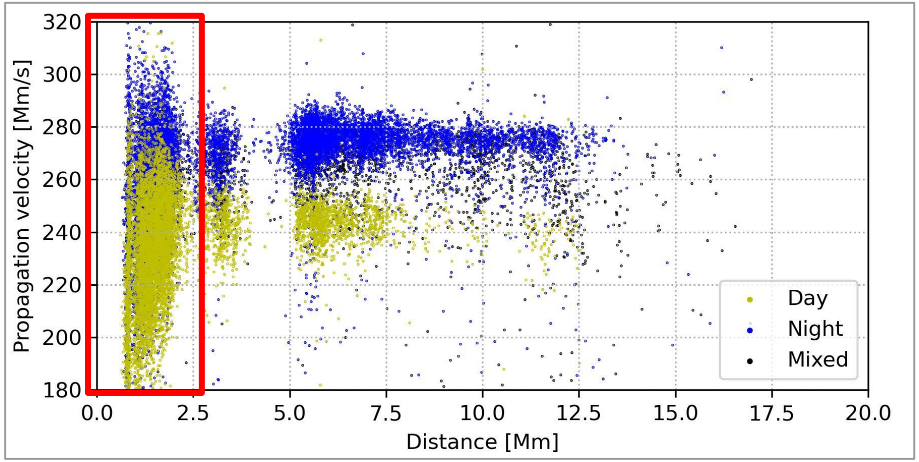


Propagation velocities.

Results



ELF azimuth - True azimuth as a function of the True azimuth (early winter events).



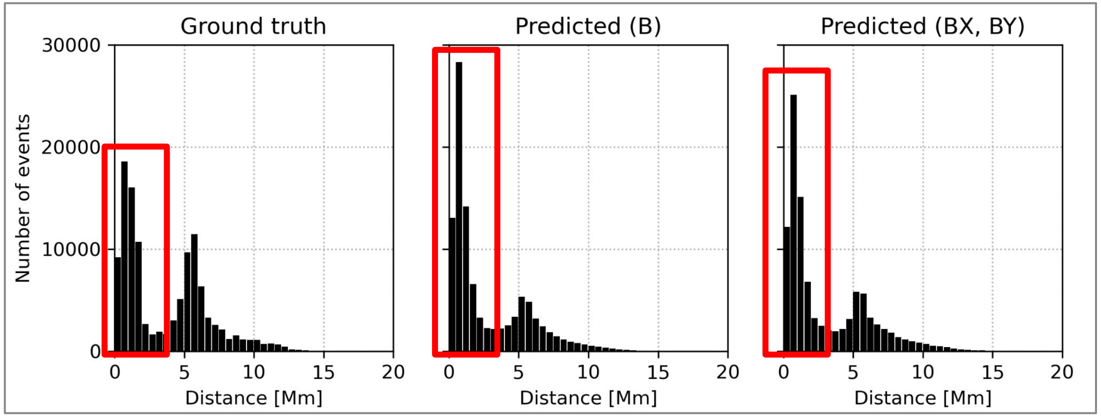
Propagation velocities as a function of source distance (early winter events). The colors indicate whether the propagation path is under fully day (yellow), fully night (blue) or mixed day-night (black) conditions.

ELF azimuths differ systematically from true azimuths obtained from WWLLN lightning locations. This effect could be related to the **anisotropic conductivity in the Earth's crust below the station** as suggested by Bór et al. (2016)

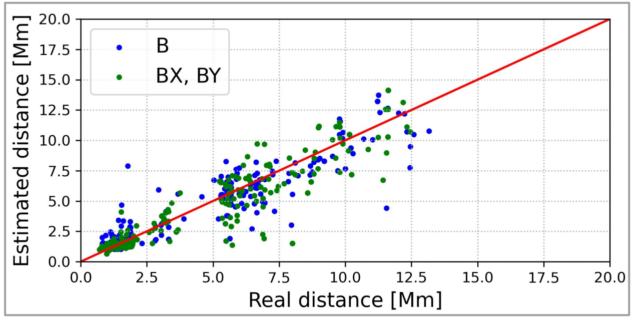
Propagation velocities are markedly higher for ELF-transients propagating on the nightside. The significant spread for nearby events is likely due to the timing and location **inaccuracy of the WWLLN database** (confirmed by comparison with LINET data for a subset of lightning strokes).

Machine learning model

A **classic convolutional network** (5 convolutional layers with 64,128,256,512,512 filters) + 3 fully-connected layers with 64, 32, 1 neurons has been applied to solve the **regression problem of estimating the source distances based solely on the ELF waveforms**.



The distance distribution for events where we could find the source lightning stroke in the WWLLN database (left, training set) and those events where we couldn't (middle and right). In the latter case the source distances are estimated by the neural network based on a single waveform (middle) and based on the two perpendicular field components (right).



Estimated vs. real source distances for the validation dataset.

The average accuracy of the distance provided by the neural network is 700 km (18%), which is a very good result considering the wavelength range of ELF waves (10 000 km at 3 Hz, 1000 km at 300 Hz). The source distance estimates also support the conclusion that the WWLLN-based source lightning stroke determination does not work well for nearby events.

Summary

- ELF-transients were identified along with their most probable source lightning stroke (based on the WWLLN database) **in a nearly one-year period**, from July 2020 to April 2021. The obtained dataset was used to train a **convolutional neural network** to determine the distance of the source lightning stroke based solely on the ELF waveforms.
- The following preliminary results have been achieved so far:
    - There is a clear **seasonal trend** in the distribution of source lightning strokes.
    - ELF azimuths differ systematically from true source azimuths, possibly due to **anisotropic ground conductivity** under the station.
    - The propagation velocities differ significantly when the **propagation path is on the dayside or on the nightside** of the Earth.
    - **The timing and location (in)accuracy of WWLLN** has a large impact on the identification of the lightning source and on the inferred propagation velocities especially for events near the ELF recording station.
    - The average accuracy of the distance provided by the neural network is **700 km**.

References

- Bór, J., Ludván, B., Attila, N., and Steinbach, P. (2016): Systematic deviations in source direction estimates of Q-bursts recorded at Nagycenk, Hungary. *J. Geophys. Res. Atmos.*, **121**, 5601–5619. https://doi.org/10.1002/2015JD024712

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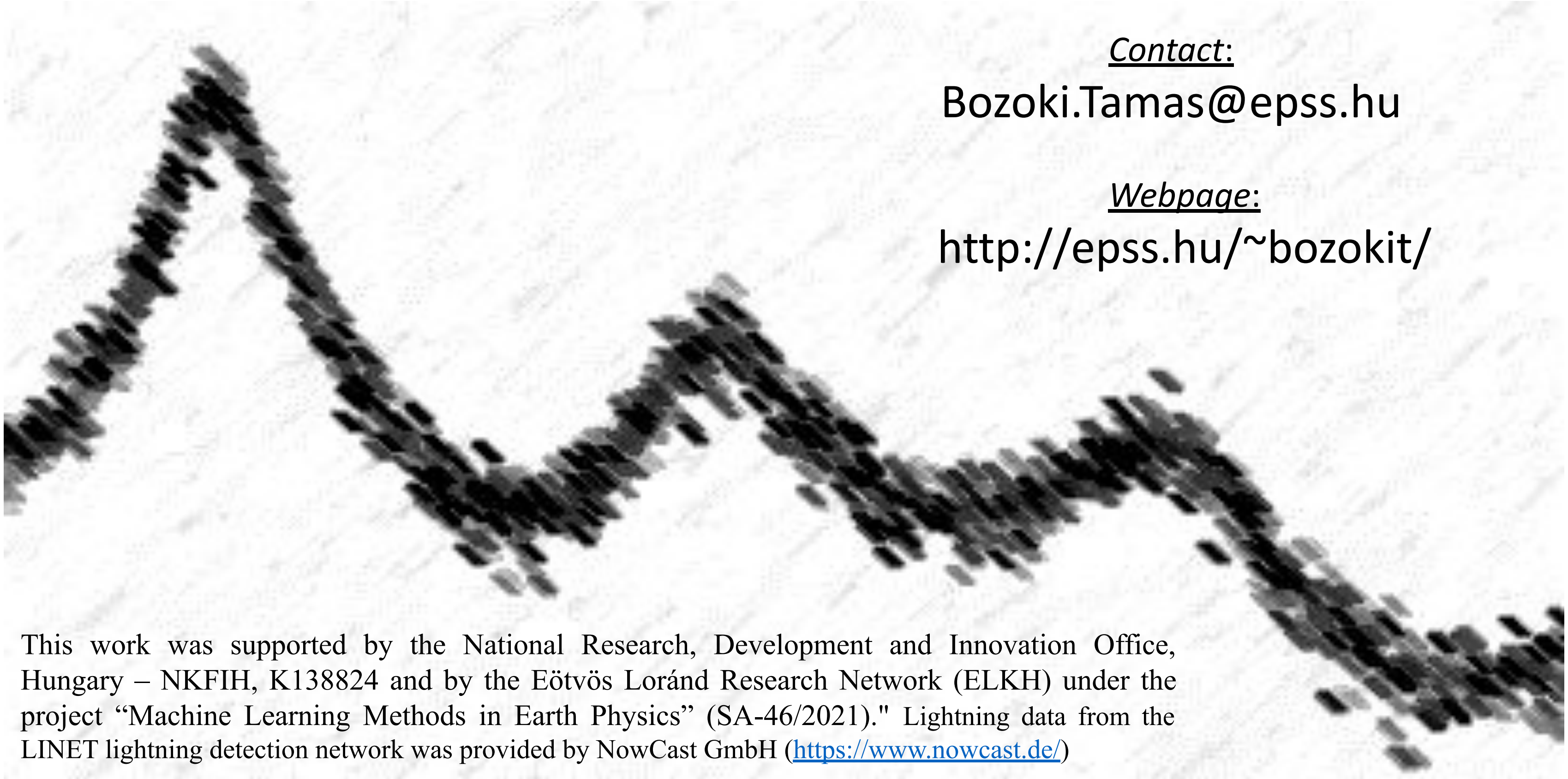
- Füllekrug, M. and Sukhorukov, A.I. (1999). The contribution of anisotropic conductivity in the ionosphere to lightning flash bearing deviations in the ELF/ULF range. *Geophysical Research Letters*, **26**(8), 1109-1112. https://doi.org/10.1029/1999GL900174

Thank you for your attention!



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