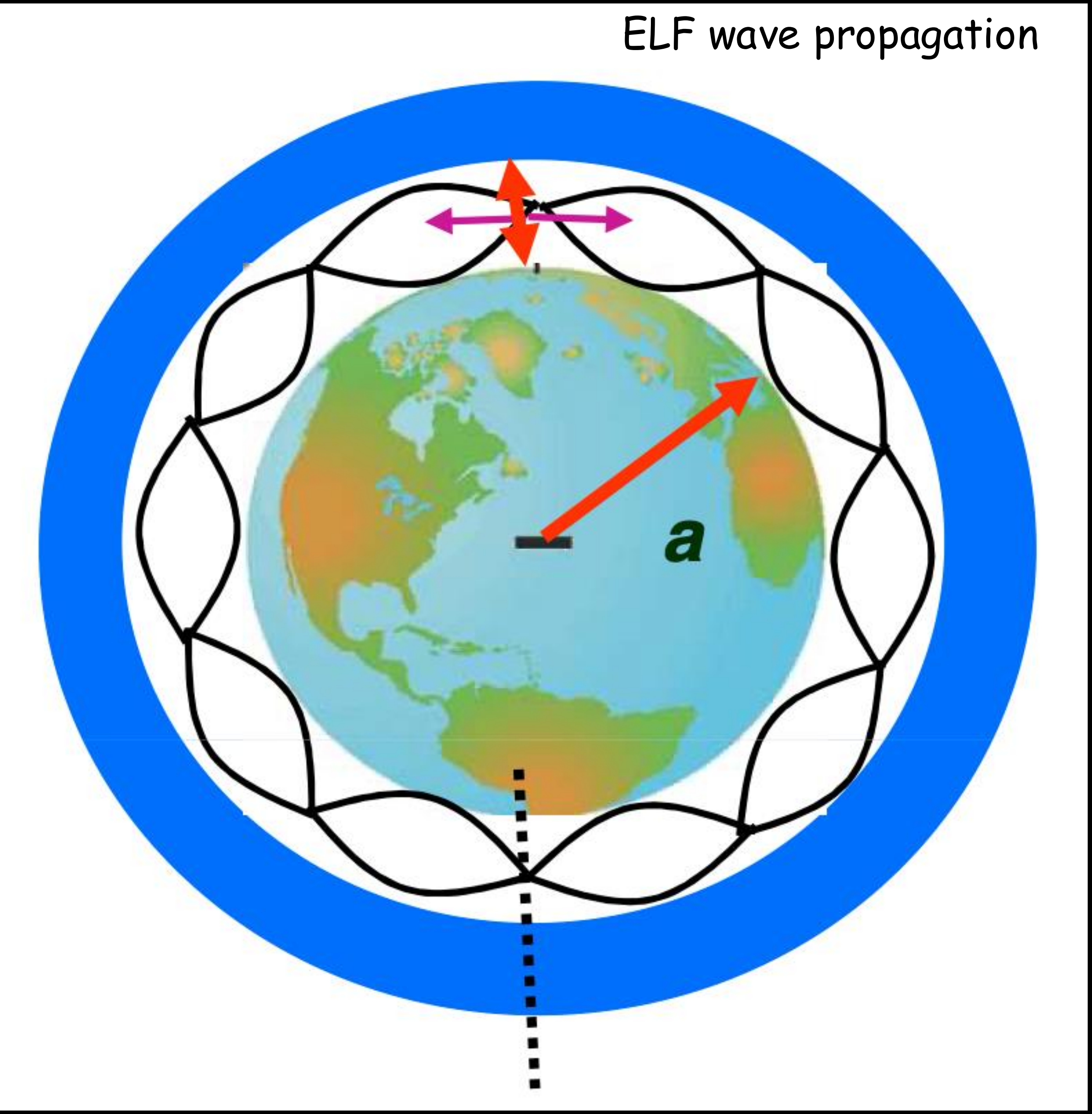
ELF study of positive WWLLN discharges

M. Ostrowski

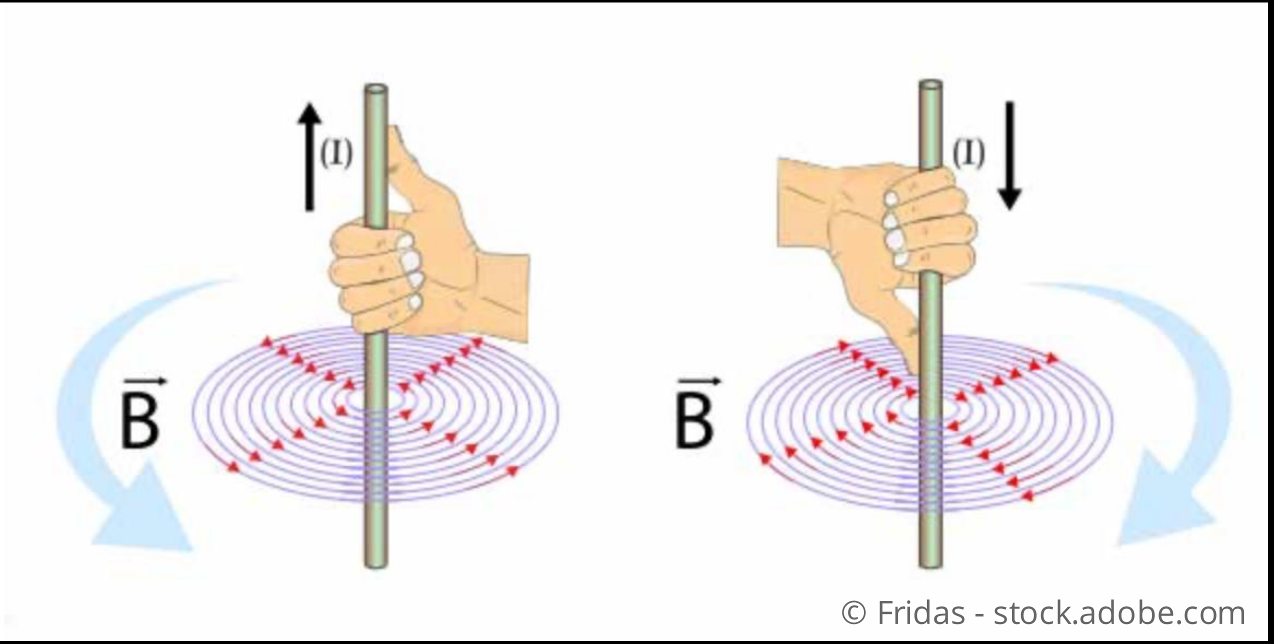
Jagiellonian University
Kraków

Collaborators: Z. Nieckarz, J. Lichtenberger, M. Gołkowski, J. Mlynarczyk, J. Kubisz, A. Michalec



Earth-Ionosphere resonance cavity

Lightning generated ELF impulses
can propagate around the Earth

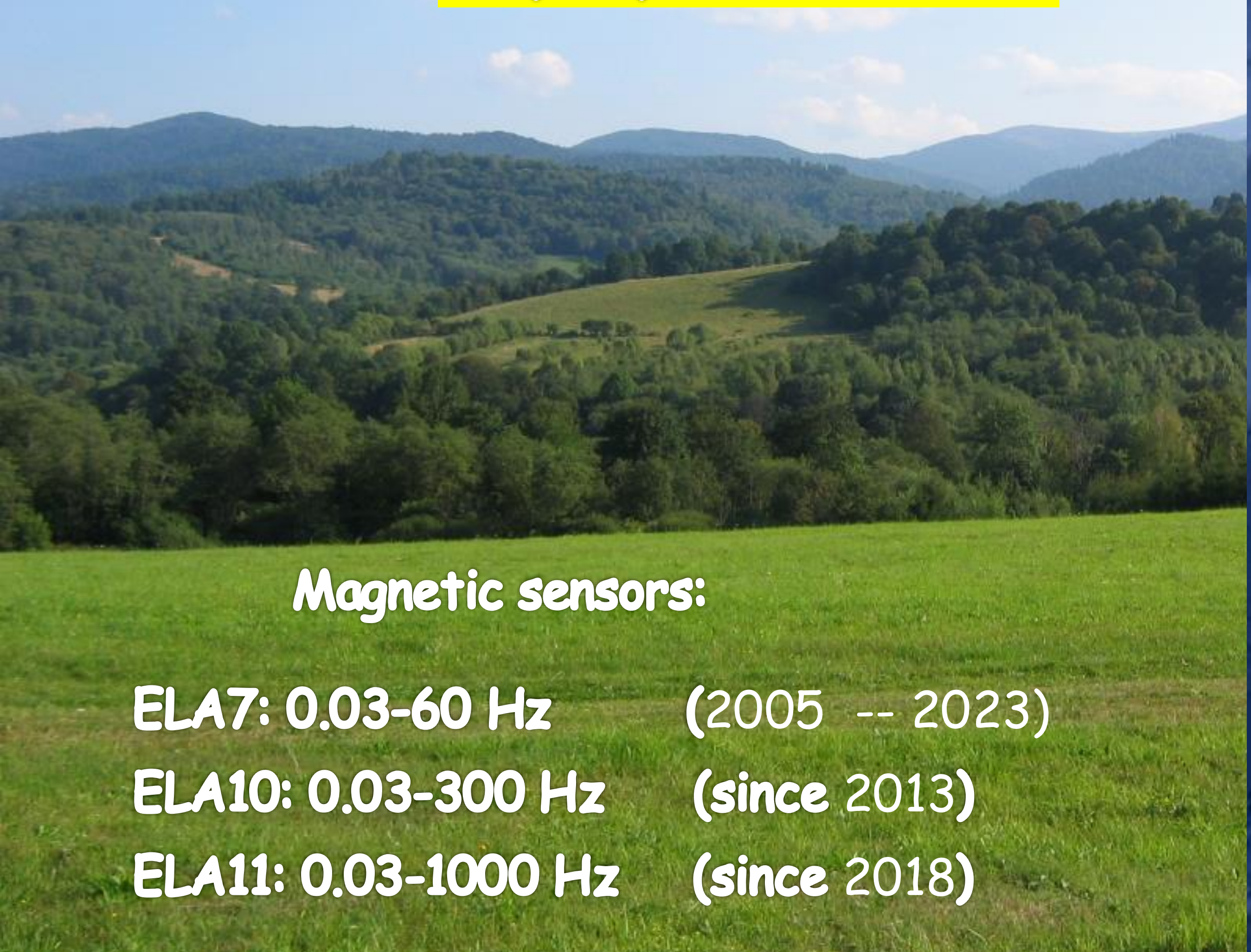


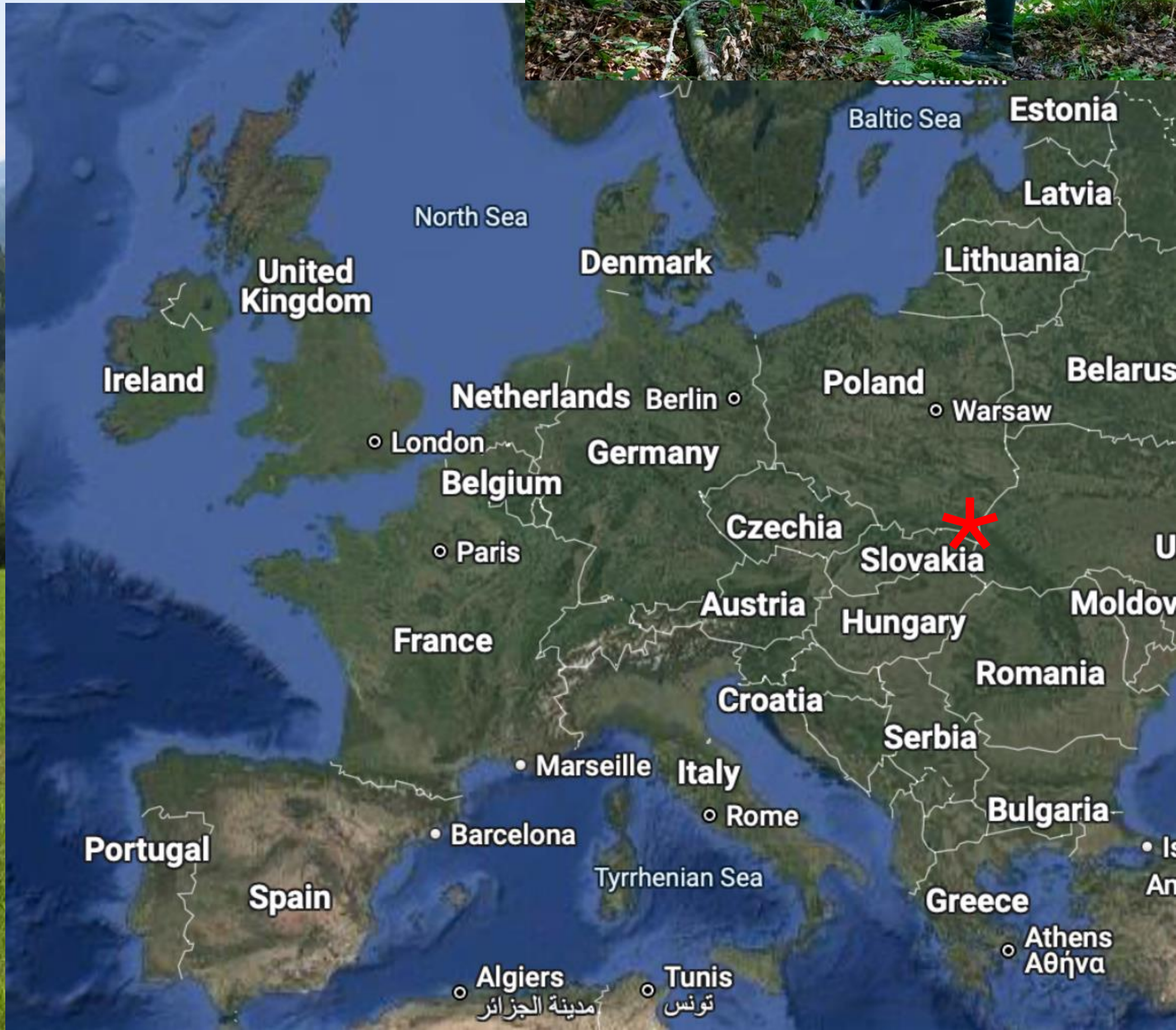
Knowing the propagating impulse origin site
one can recognize ELF magnetic impulses
from positive and negative vertical currents.

Bieszczady Mountains

very low EM pollution

http://www.oa.uj.edu.pl/elf/





"Hylaty" ELF Station

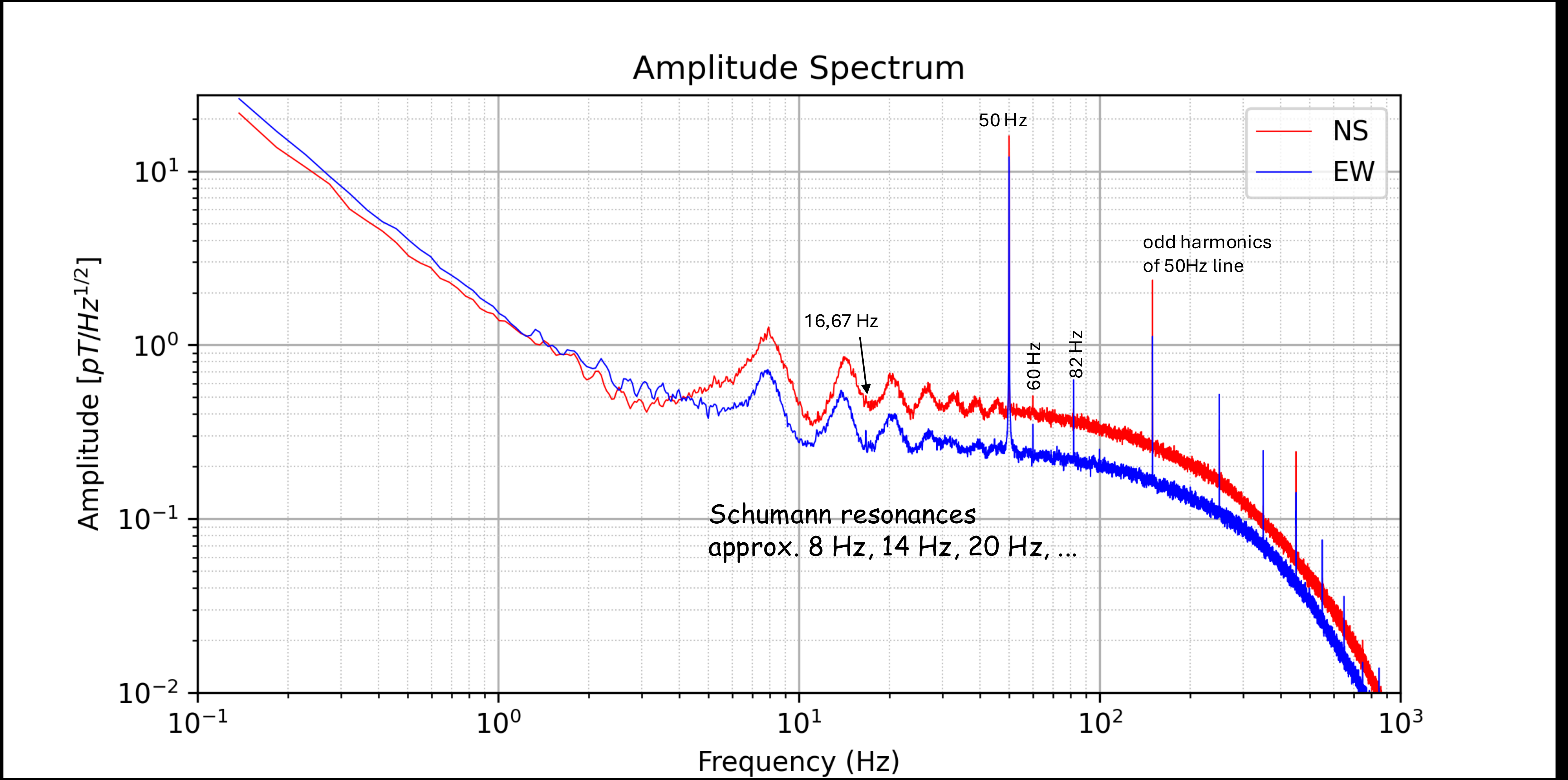
Magnetic sensors:

ELA7: 0.03-60 Hz (2005 -- 2023)

ELA10: 0.03-300 Hz (since 2013)

ELA11: 0.03-1000 Hz (since 2018)

ELF spectrum of ELA11 data (1h, night)



ELF impulses

Long-distance propagation influenced by

- velocity dispersion and wave damping;
- refraction processes due to ionospheric nonuniformities;
- changing ionosphere parameters along the propagation path (day and night).

(see also our recent papers Kubisz et al. 2024; Ostrowski et al. 2024; Nieckarz et al. 2025)

The global VLF monitoring programs of lightning discharges, like WWLLN, enable studies of generated ELF impulse propagation.

The present study proves possibility of mass detection of ELF impulses from lightnings detected by WWLLN.

We use the ELA11 sensor installed in the Hylaty Station in Poland.

3 kHz; the effective frequency range from 0.03 to ~1000 Hz.

ELF data analysis – data preparation

Each **5 minutes' data set** from the ELA11 sensor is analyzed separately .

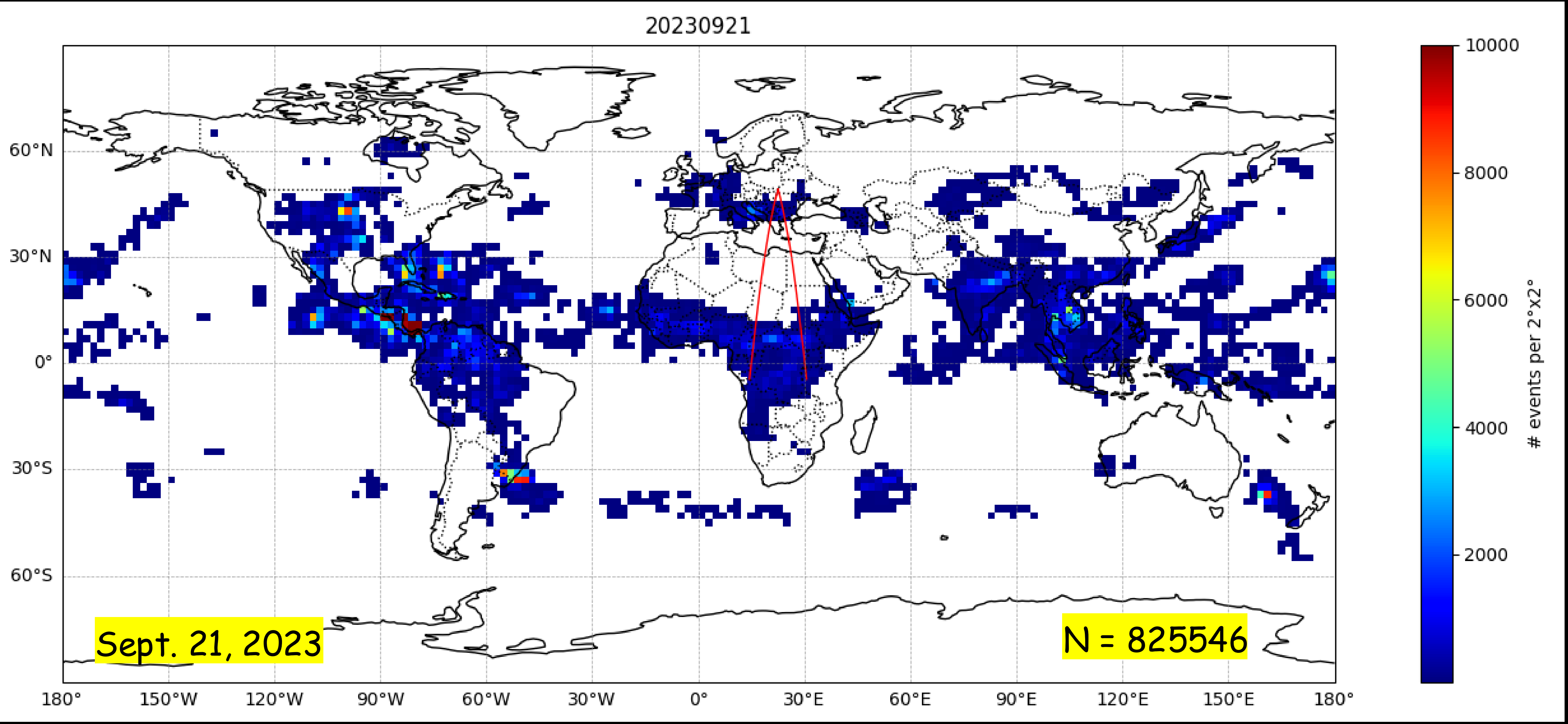
The low frequency (< 1 Hz) fluctuations and the electric grid signal are subtracted from NS and EW signals with consecutive use of 3 filters:

- a high pass forth order Butterworth filter with the cutoff frequency f=1Hz
- the fourth order Butterworth filter in the power grid frequency (f_{min}=49 Hz, f_{max}=51 Hz)
- and its third harmonic (f_{min}=149 Hz, f_{max}=151 Hz).

Average NS and EW signals are subtracted from each magnetic channel.

With such data we identify impulses related to WWLLN discharges basing on expected arrival times.

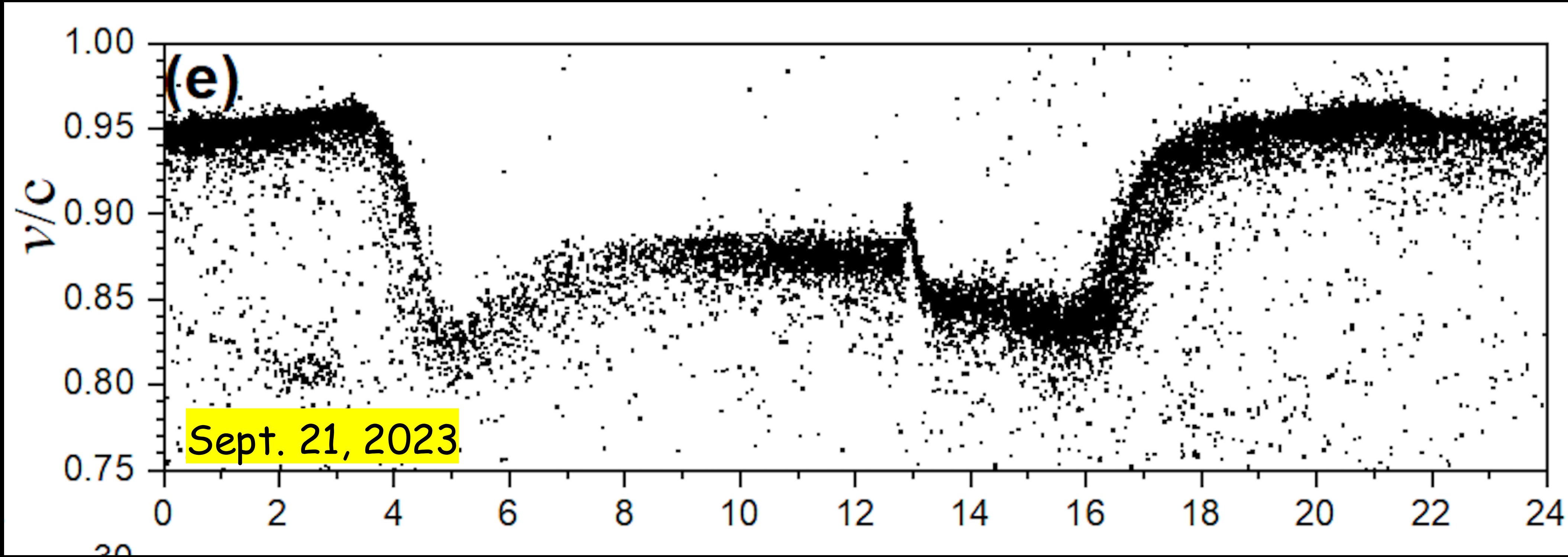
WWLLN lightning strokes in 2°x2° bins



Red lines have 6000 km lengths and show the azimuth range 170<A<190

ELF propagation velocities of WWLLN impulses from Africa

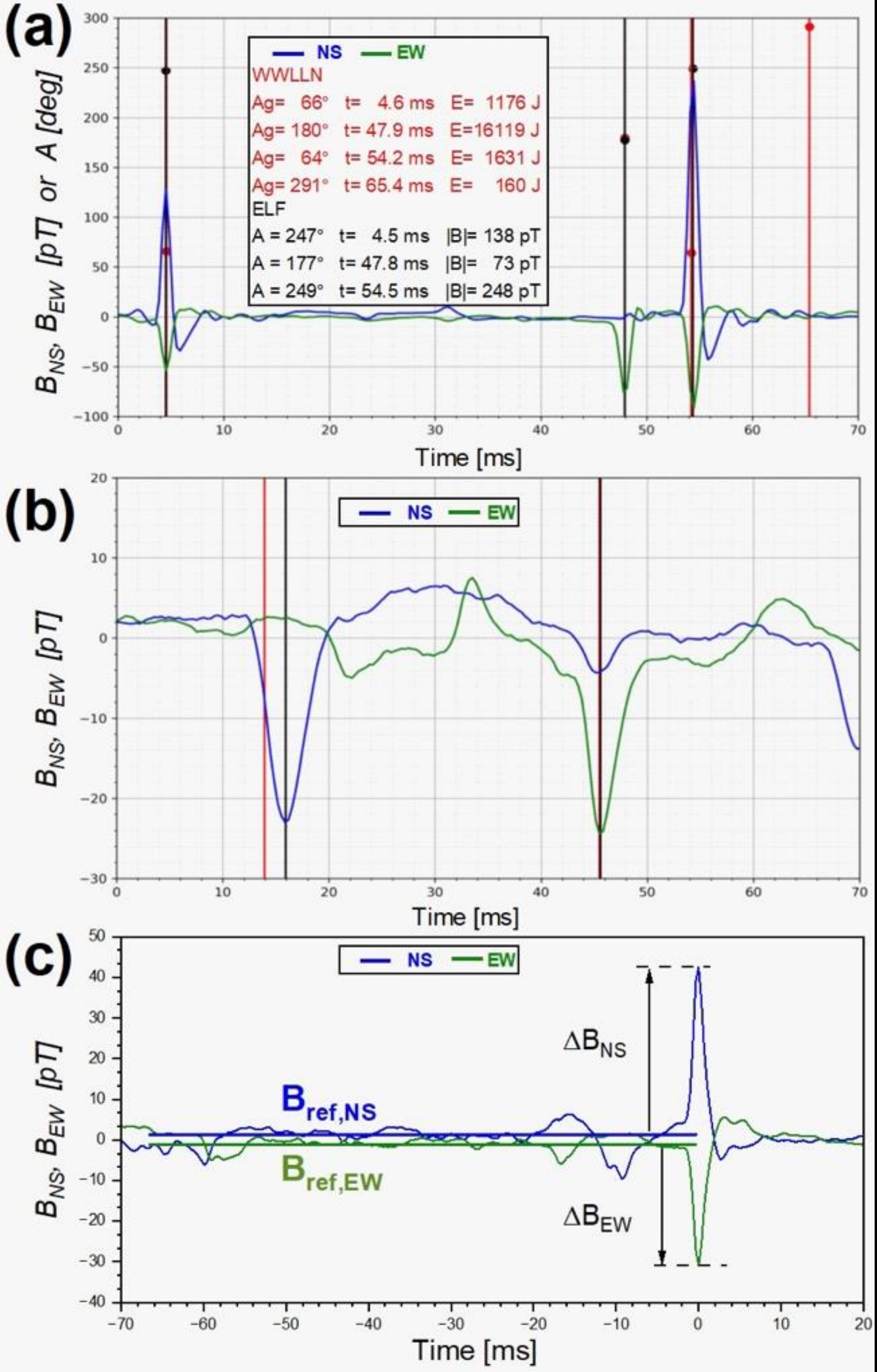
(from Nieckarz et al. 2025)



To derive reference (~minimum) propagation times for the ELF impulses we use the velocities: 0.95c in the night and 0.88c during the day

The internal time delay of the ELA11 magnetic sensor is measured to be 1,85 ms.

WWLLN discharge impulses in ELF



(a) High amplitude impulses

(b) Medium amplitude impulses

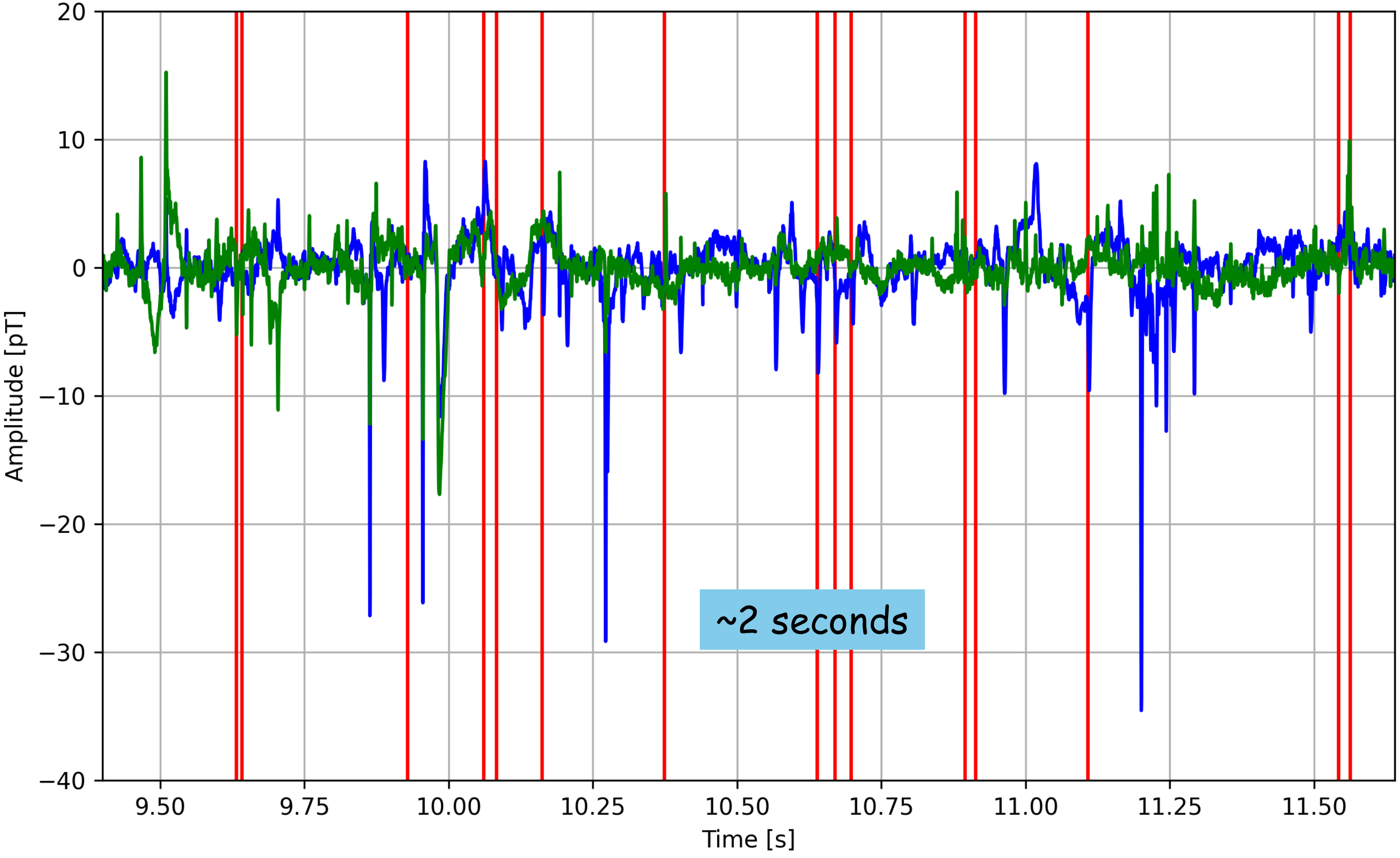
$$\Delta B = SQRT(\Delta B_{EW}{}^2 + \Delta B_{NS}{}^2)$$

$$A = ATAN\ (\Delta B_{NS} / \Delta B_{WE})$$

(c) The magnetic impulse module ΔB and azimuth A derivation respectively to background reference levels.

WWLLN related ELF impulses in the ELA11 data

A precise evaluation of the impulse arrival time is essential for its' identification



Energy of the lightning discharge E[J] .

The WWLLN data – originally including the time and location of the detected lightning strokes – have been appended with estimations of the energy of the lightning discharge (Hutchins et al., 2012b).

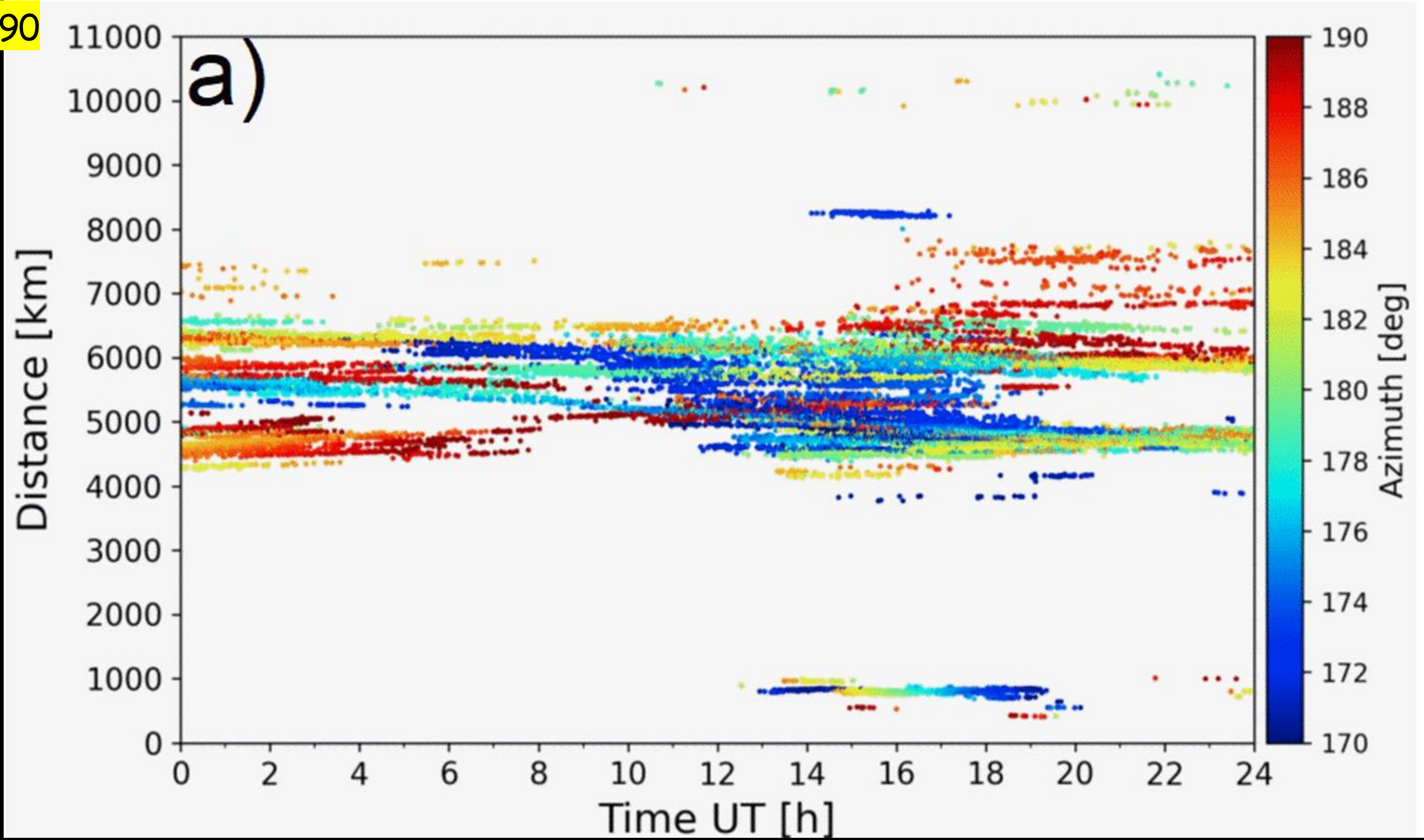
The energy estimation is based on a complex procedure using a (few) calibrated receiver(s) and the LWPC code (Ferguson, 1998) to model the wave attenuation and then a 'bootstrapping technique' to transfer the calibration to other, non-calibrated WWLLN stations.

Due to this complex procedure, the accuracy of the estimated energy can be relatively low.

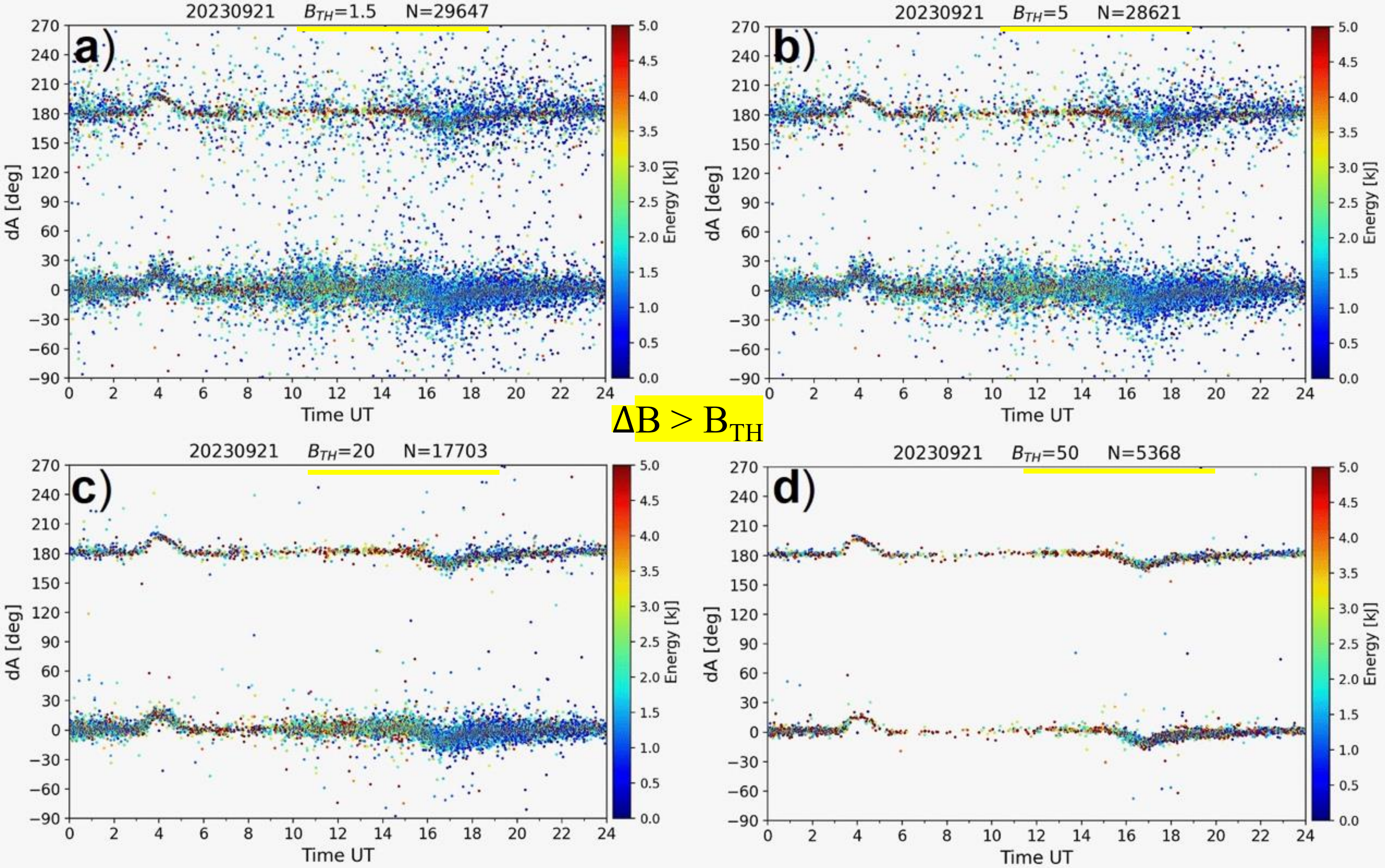
Africa, Sept. 21, 2023

WWLLN discharges

170 < A < 190



For Africa we consider either a distance range 4000-9000 km or a limited range 5000-6000 km



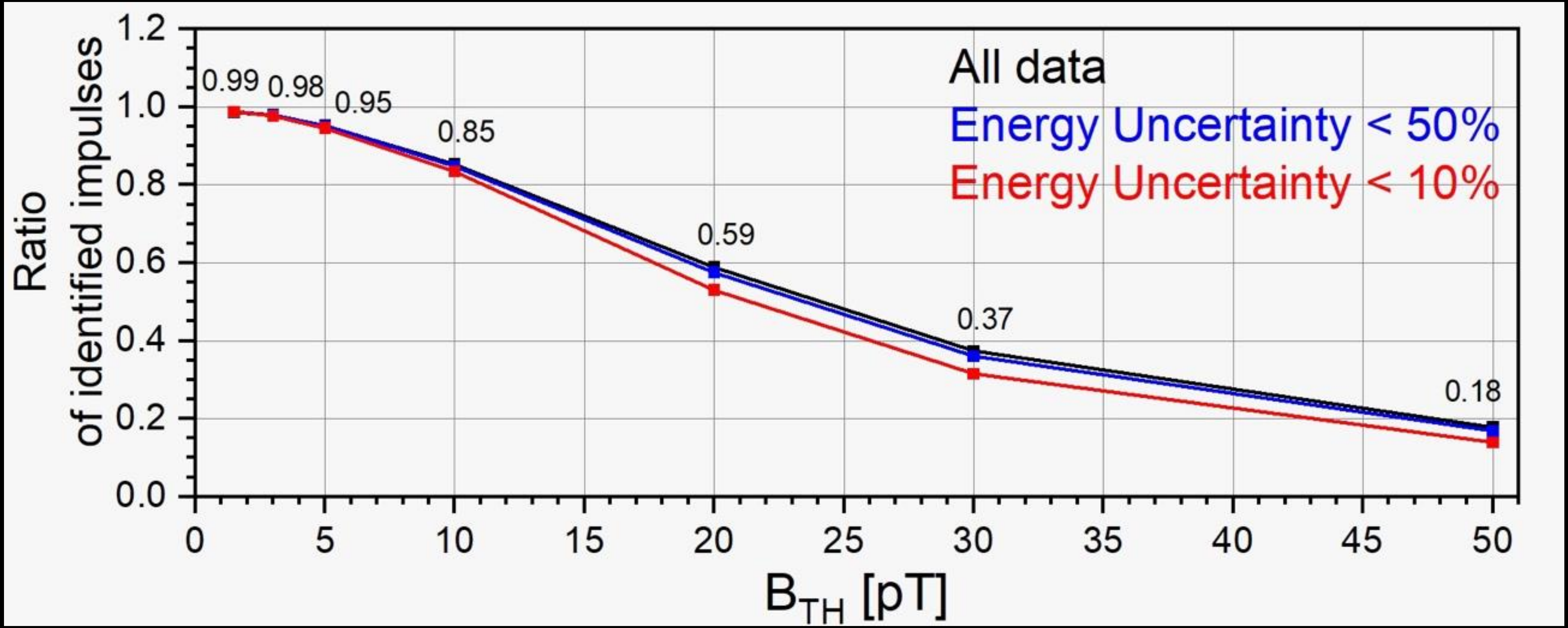
$dA = A_g - A$

30052 WWLLN discharges

B_{TH} [pT] detection threshold

A ratio of ELF identified impulses vs. ALL WWLLN detections

for different accuracies of the VLF energy evaluation

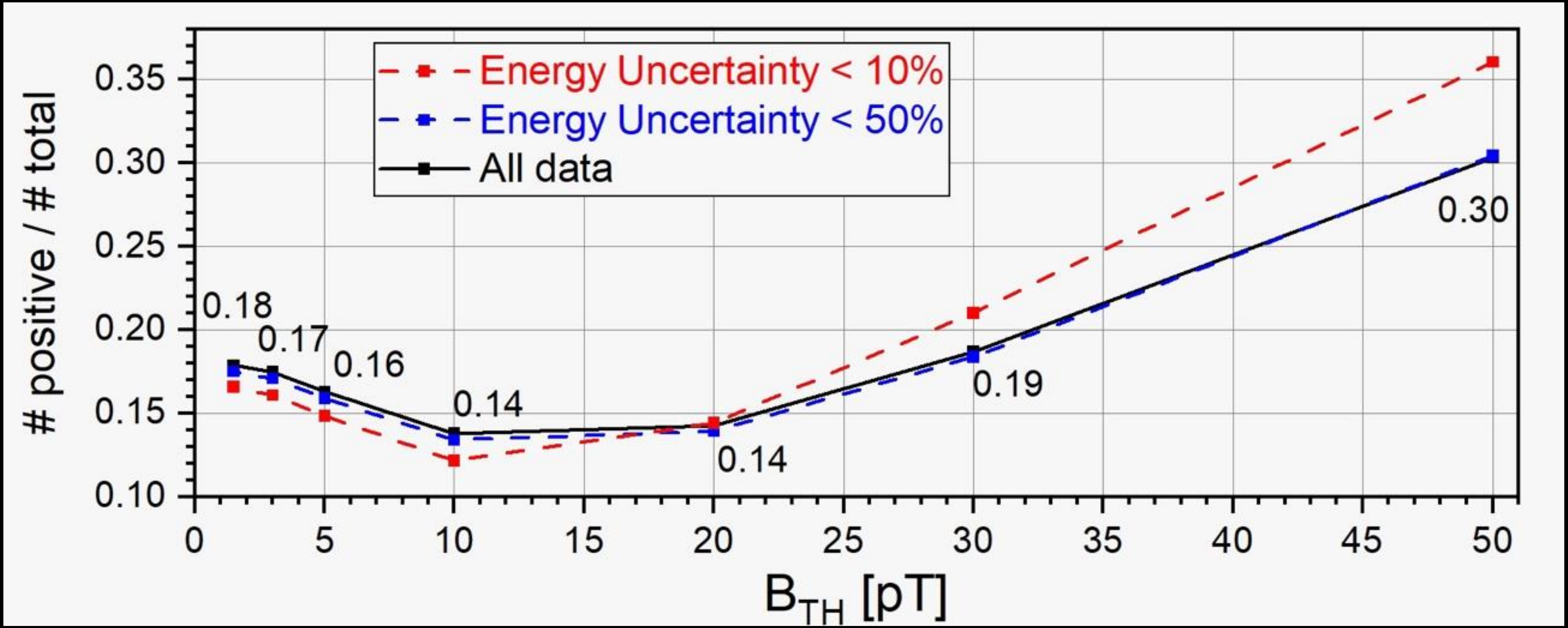


B_{TH} [pT] = 1,5 , 3 , 5 , 10 , 20 , 30 , 50

A ratio of POSITIVE divided by ALL identified ELF impulses for WWLLN detections

for different accuracies of the VLF energy evaluation

|dA| < 45° or |dA-180°| < 45°

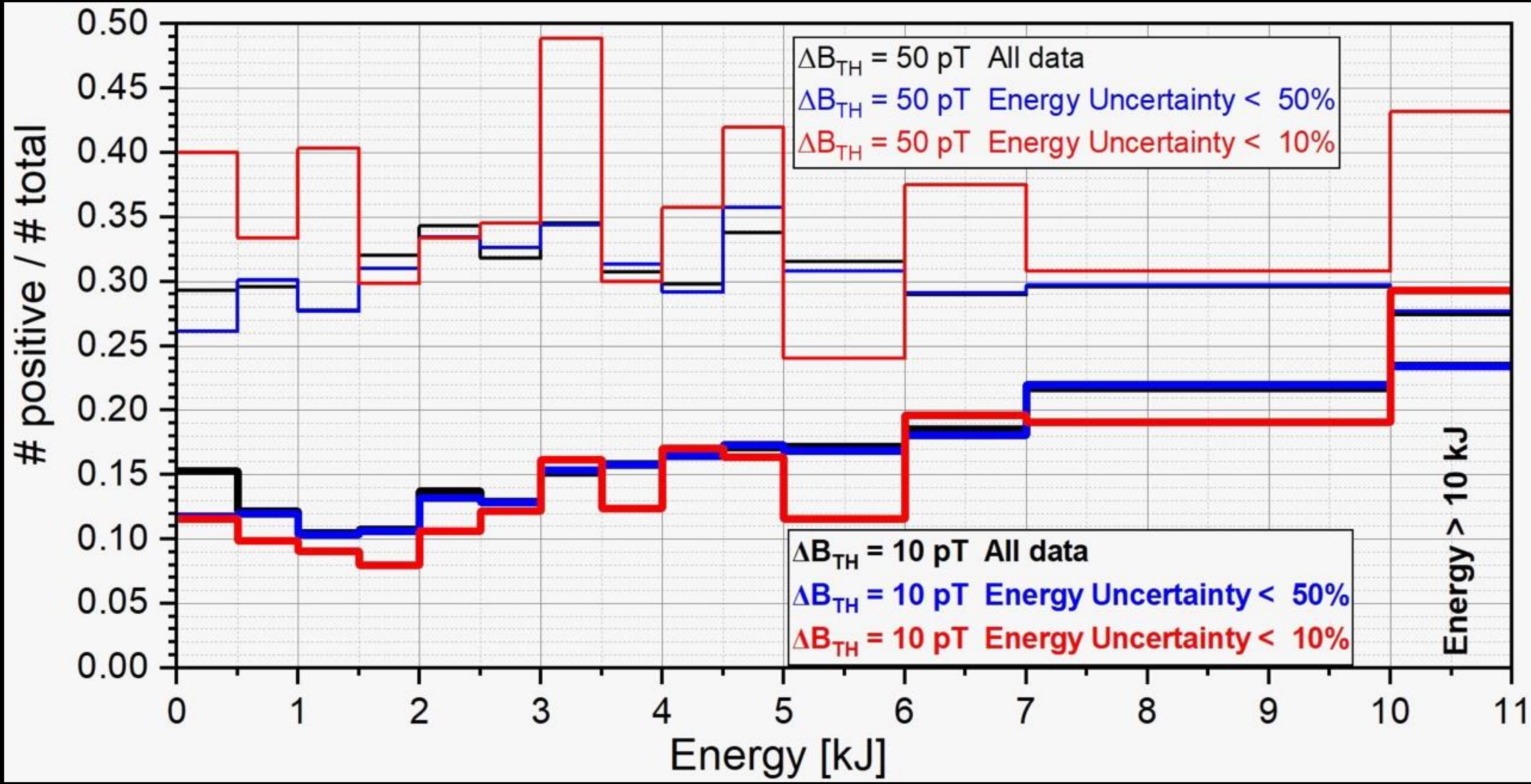


B_{TH} [pT] = 1,5 , 3 , 5 , 10 , 20 , 30 , 50

The ratio of POSITIVE divided by ALL identified impulses

in selected VLF energy ranges

|dA| < 45° or |dA-180°| < 45°



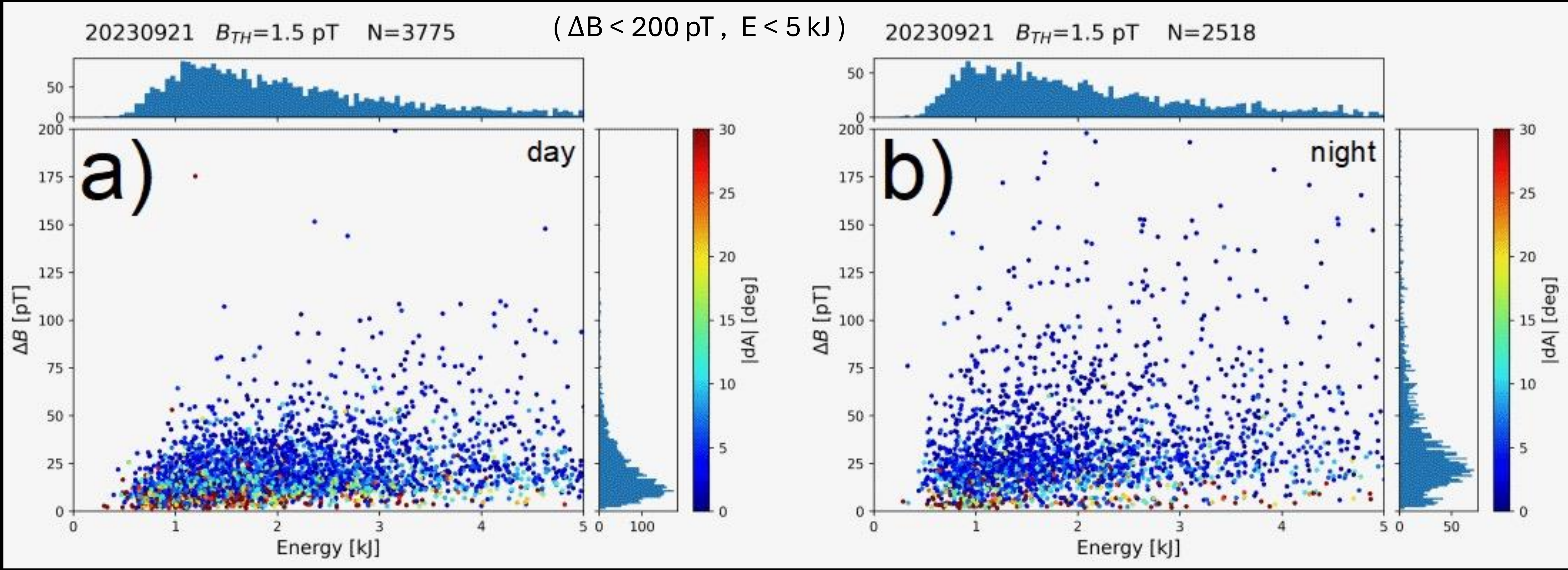
?

ELF impulse amplitudes vs. WWLLN discharge energy

5000 km < Distance < 6000 km.

day hours 6 - 15 UT

night hours 0 - 3 UT and 19 - 24 UT



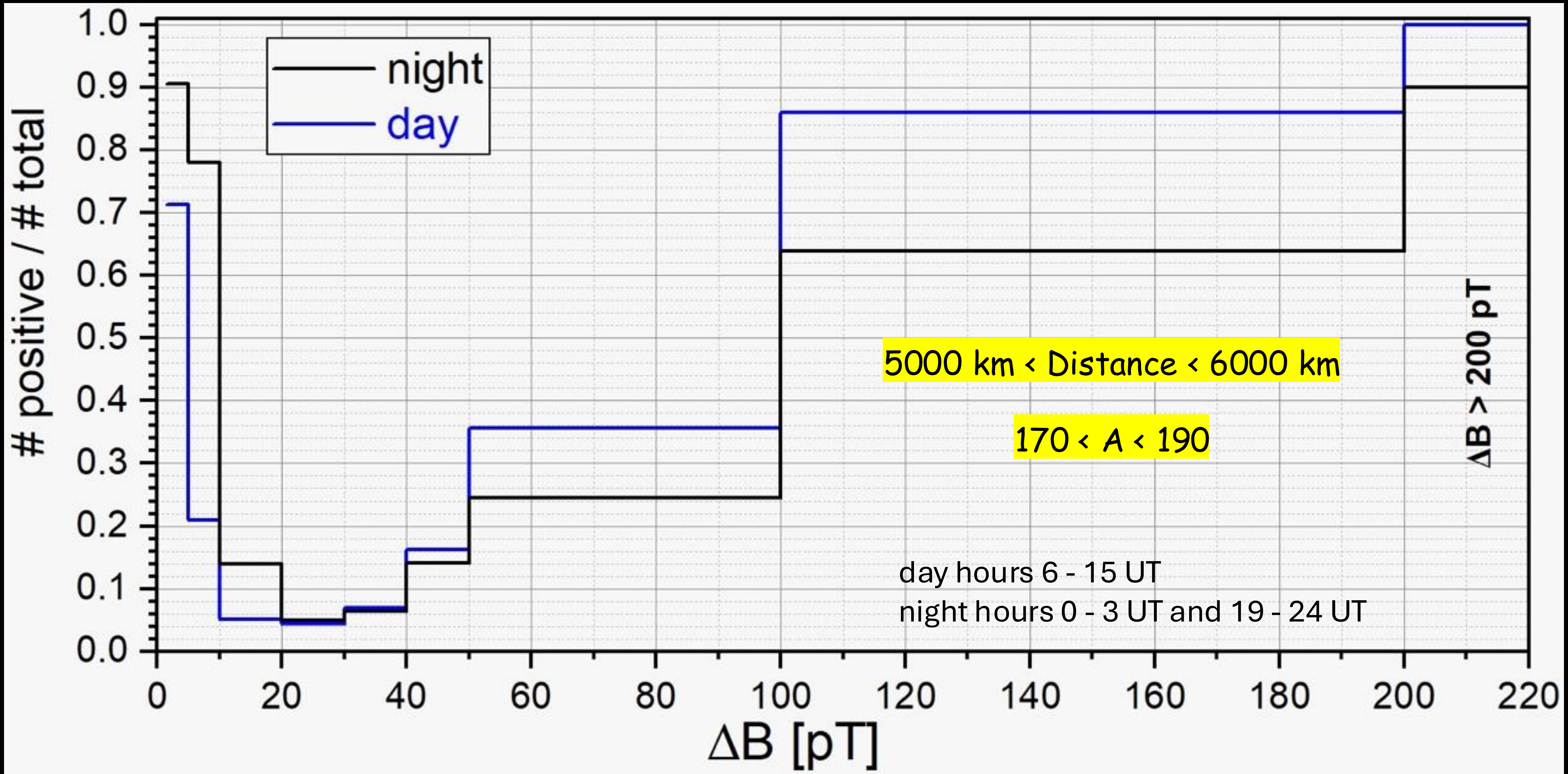
A colour scale for |dA| - all |dA| or |dA-180| > 30 are as 30

Weak (if any) correlation between ΔB and E . Is there a separate component for small ΔB ?

The ratio of POSITIVE divided by ALL identified impulses

in selected ELF amplitude ranges

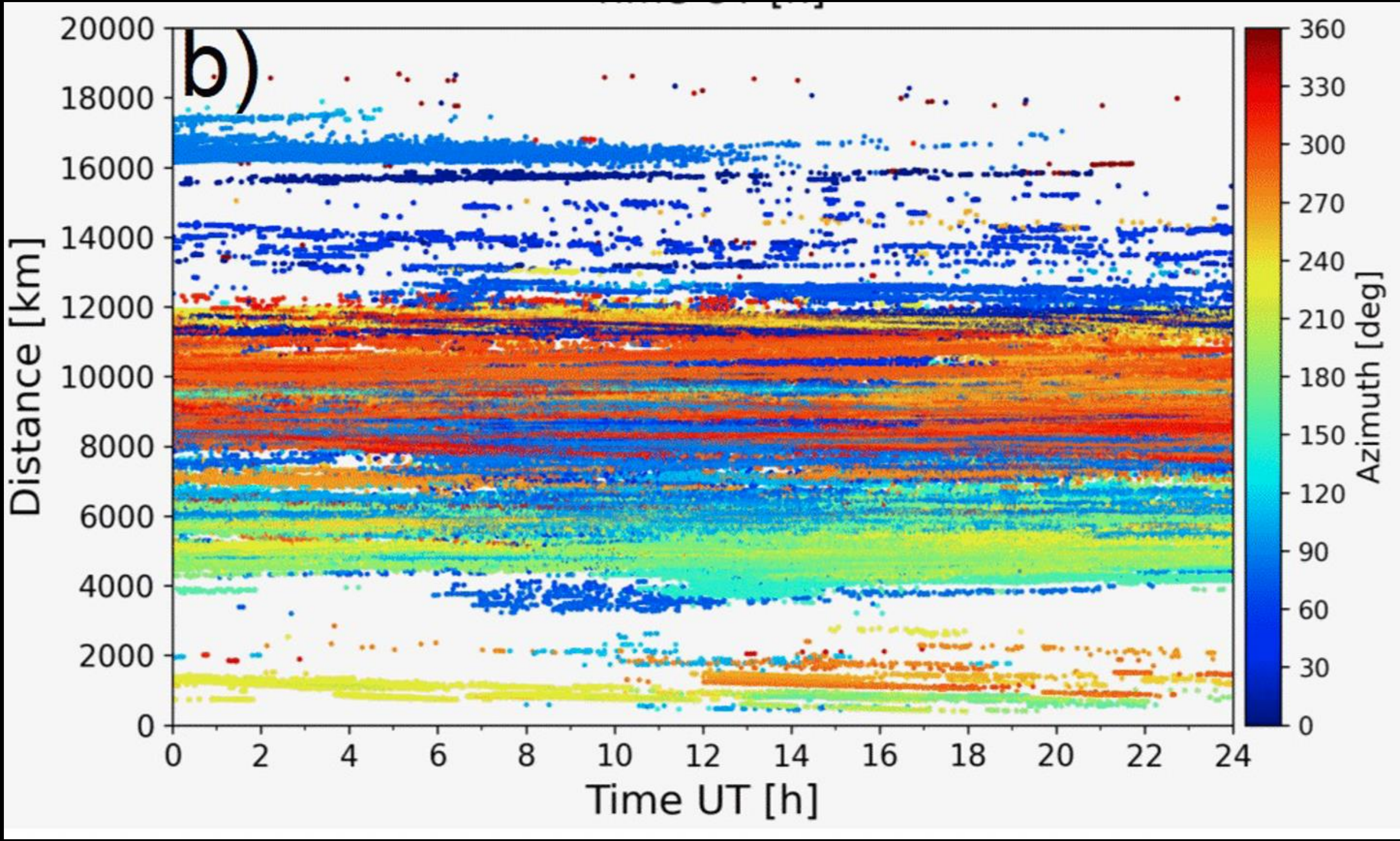
|dA| < 30° or |dA-180°| < 30°

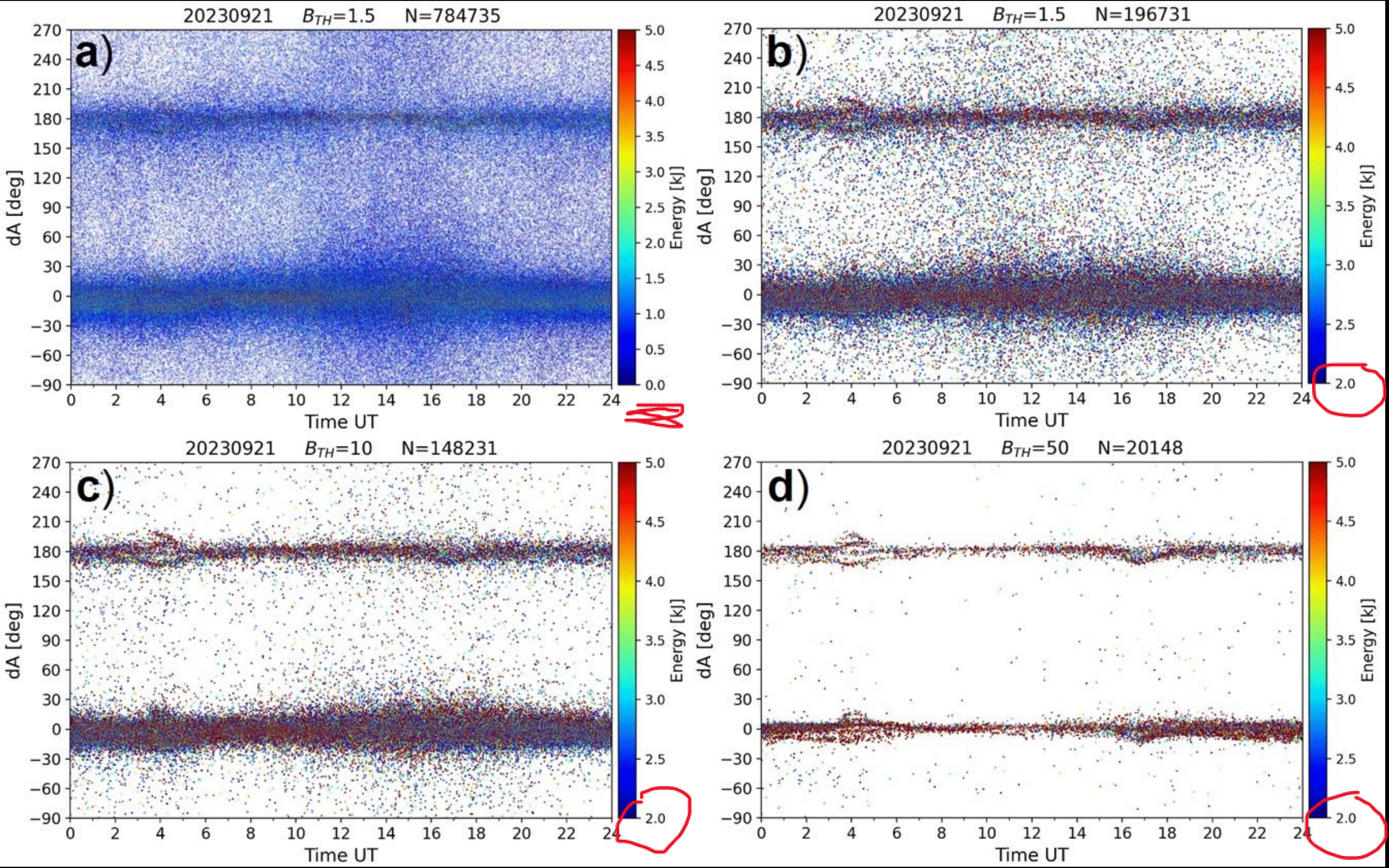


Africa ($170° < A_g < 190°$; 5000 km < distance < 6000 km)						
Amplitude range [pT]	N^+(day)	N^-(day)	$N^+/(N^-+N^+)$ (day)	N^+(night)	N^-(night)	$N^+/(N^-+N^+)$ (night)
1,5 - 5	92	37	0,713	67	7	0,905
5-10	114	431	0,209	113	32	0,779
10 - 20	66	1222	0,051	81	502	0,139
20 - 30	31	675	0,044	34	645	0,050
30 - 40	27	358	0,070	27	398	0,064
40 - 50	31	160	0,162	32	196	0,140
50 - 100	74	134	0,356	117	361	0,245
100 - 200	55	9	0,859	92	52	0,639
above 200	8	0	1,000	36	4	0,900

Whole Earth, Sept. 21, 2023

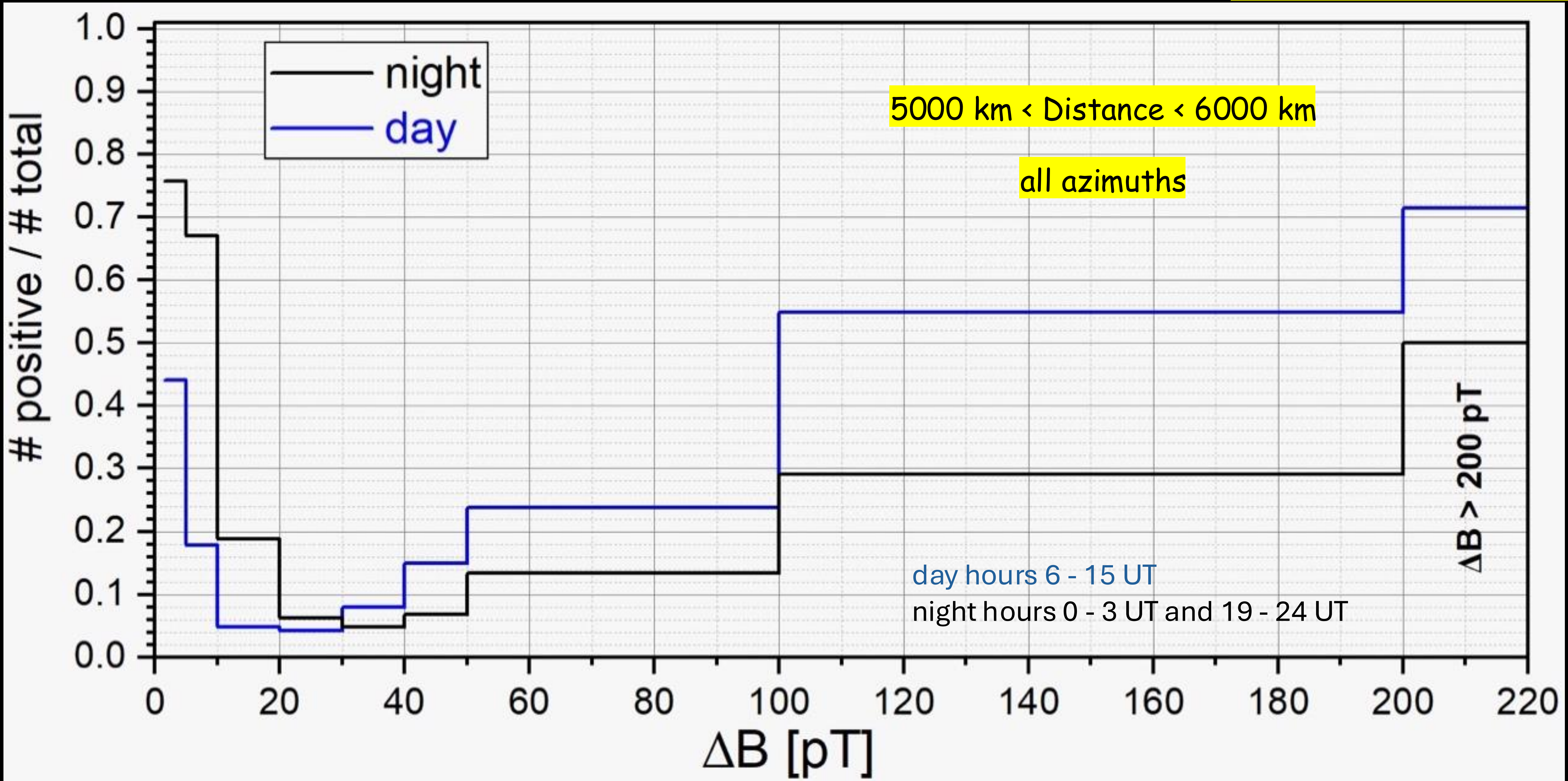
N = 825546




20230921 B_{TH}=1.5 N=784735
a)
20230921 B_{TH}=1.5 N=196731
b)
20230921 B_{TH}=10 N=148231
c)
20230921 B_{TH}=50 N=20148
d)
dA [deg]
Time UT
Energy [kJ]

The positive ratio in selected ELF amplitude ranges

|dA| < 30° or |dA-180°| < 30°



Whole Earth ($0° < A_g < 360°$; 5000 km < distance < 6000 km)						
Amplitude range [pT]	N^+(day)	N^-(day)	$N^+/(N^-+N^+)$ (day)	N^+(night)	N^-(night)	$N^+/(N^-+N^+)$ (night)
1,5 - 5	319	406	0,440	280	90	0,757
5-10	426	1963	0,178	579	285	0,670
10 - 20	284	5623	0,048	460	1986	0,188
20 - 30	129	2867	0,043	169	2541	0,062
30 - 40	127	1463	0,080	89	1741	0,049
40 - 50	123	697	0,150	83	1144	0,068
50 - 100	263	843	0,238	299	1944	0,133
100 - 200	101	83	0,549	207	505	0,291
above 200	10	4	0,714	74	74	0,500

Results of this study:

The **automatic procedure** for identification of WWLLN discharges in the ELF measurements.

We analyzed the data from Africa and from the whole globe **identifying positive discharges**

The **VLF** energy evaluations are **weakly correlated** with impulse amplitudes at **ELF** frequencies.

A **significant increase** of the ratio of positive discharges for highest amplitude impulses.

An unexpected **low amplitude component** with dominance of positive discharges

=> Possible **systematic effect** of the impulse identification procedure (?)

Paper in preparation:

Z. Nieckarz, M. Ostrowski, M. Gołkowski, J. Lichtenberger, J. Mlynarczyk, J. Kubisz, A. Michalec

Study of positive lightning discharges in WWLLN data using extremely low frequency electromagnetic wave measurements