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Hans Eichelberger, Mohammed Boudjada, Konrad Schwingenschuh, Bruno Besser, Daniel Wolbang, et al.. Investigation of VLF/LF electric field variations related to magnitude $M_w \geq 5.5$ earthquakes in the Mediterranean region for the year 2023. EGU General Assembly 2024, Apr 2024, Vienna, Austria. pp. EGU24-6001, 10.5194/egusphere-egu24-6001 . insu-04507069

HAL Id: insu-04507069

<https://insu.hal.science/insu-04507069v1>

Submitted on 5 Jun 2024

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INVESTIGATION OF VLF/LF ELECTRIC FIELD VARIATIONS RELATED TO MAGNITUDE $M_{w} \geq 5.5$ EARTHQUAKES IN THE MEDITERRANEAN REGION FOR THE YEAR 2023

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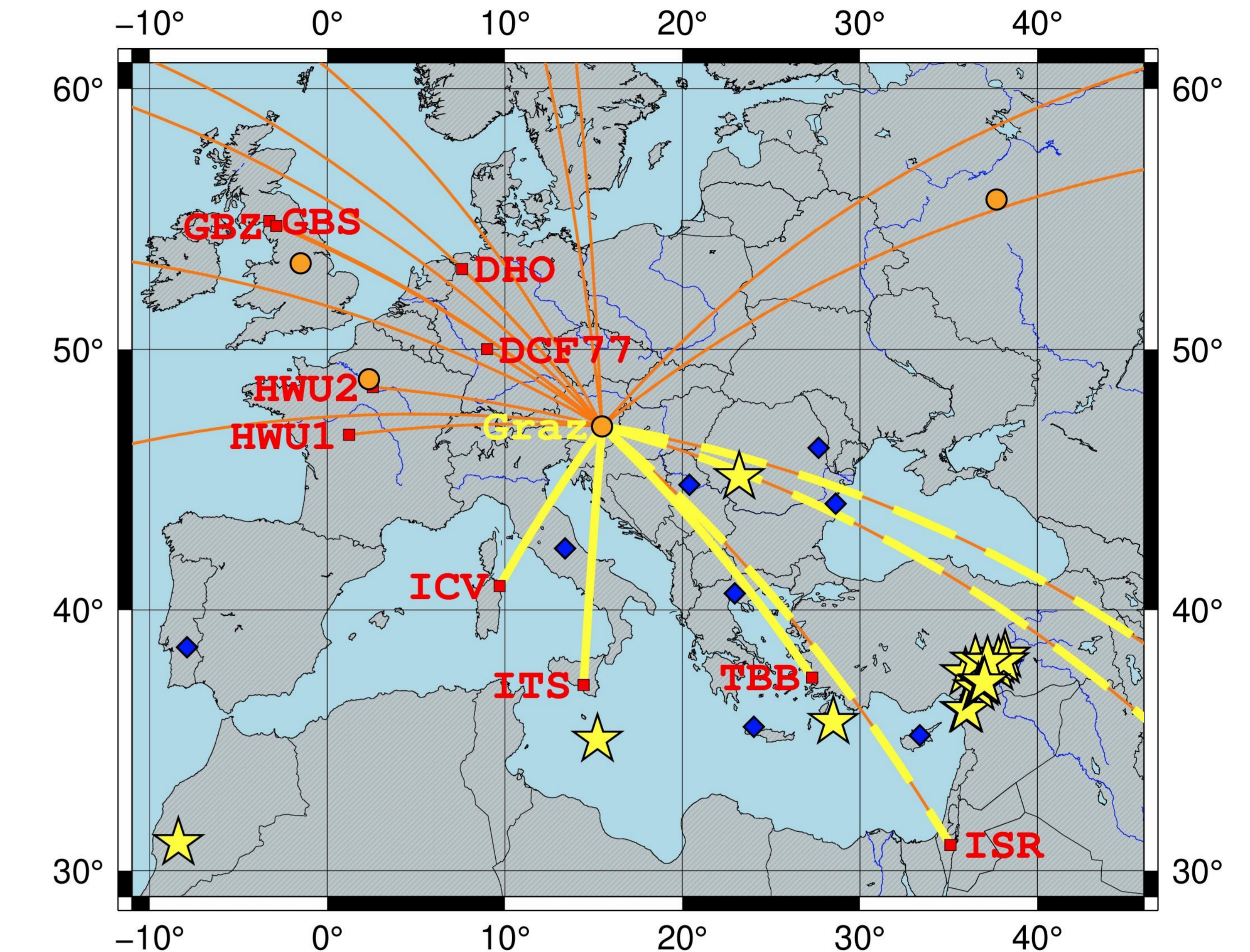
Strong natural hazards together with their societal impact are usually accompanied by multiple physical phenomena which can be an important information source about the underlying processes. In this study we statistically analyze the lithosphere-atmosphere-ionosphere couplings of magnitude $M_{w} \geq 5.5$ earthquakes (EQs) in the year 2023 with the aid of sub-ionospheric VLF/LF radio links. The electric field amplitude and phase measurements with a temporal resolution of one second are from the seismo-electromagnetic receiver facility in Graz (GRZ), Austria (Galopeau et al., 2023), which is part of the INFREP network. The spatial extend of the study area has the range $[-10^{\circ}E \leq \text{longitude} \leq 40^{\circ}E]$ and $[30^{\circ}N \leq \text{latitude} \leq 50^{\circ}N]$, in total are 17 EQs according to the United States Geological Survey (USGS) data base, among them the Turkey-Syria EQs (main shocks $M_{w} 7.8$ and $M_{w} 7.5$) and the Morocco $M_{w} 6.8$ EQ. We apply the night-time amplitude method (Hayakawa et al., 2010) for all available paths, of particular importance are the transmitter links TBB (26.70 kHz, Bafa, Turkey), ITS (45.90 kHz, Niscemi, Sicily, Italy), and ICV (20.27 kHz, Tavolara, Italy). Relevant crossings are determined by the size of the Dobrovolsky-Bowman relationship (Dobrovolsky et al., 1979; Bowman et al., 1998). A major finding is the statistically significant electric field variation of the TBB-GRZ link related to the Turkey-Syria EQ sequence. A physical interpretation is based on atmospheric gravity waves (AGWs) which could alter the E-layer in the lower ionosphere during nighttime and modulate the height of the waveguide cavity.

TRANSMITTER LIST & VLF/LF SYSTEM PARAMETERS

Receiver: Graz, IWF, Elektronika [E] and UltraMSK [U] system, geographic location N 47°2'40.38" E 15°28'47.68"					
No.	Acronym	Frequency (kHz)	GCP (km)	Transmitter, Systems [U 1s], [U 20s], [E 60s]	
1	JXN	16.40	2160	Aldra, Norway [U 1s] [U 20s]	
2	GWU	18.30	980	Le Blanc, Rosnay, St. Assise, France [U 1s]	
3	VTX	19.20 (17.00)	7240	Vijayanarayanan, India [U 1s] [U 20s]	
4	GBS	19.58	1570	Anthorn, UK [U 1s] [U 20s]	
5	NWC	19.80	12390	Exmouth, Western Australia [U 1s]	
6	ICV	20.27	820	Tavolara, Sardinia, Italy [U 1s] [U 20s] [E 60s]	
7	HWU	20.90 / 21.75	1080	Le Blanc, St. Assise, France [U 1s] [U 20s] [E 60s]	
8	NPM	21.40	12380	Lualualei, Hawaii, USA [U 1s] [U 20s]	
9	GBZ	22.10	1540	Skelton, UK [U 1s] [U 20s] [E 60s]	
10	JJI	22.20	9140	Ebino, Kyushu, Japan [U 1s]	
11	DHO	23.40	875	Rhauderfehn, Germany [U 1s] [U 20s] [E 60s]	
12	NAA	24.00	6110	Cutler, Maine, USA [U 1s] [U 20s]	
13	NLM	25.20	7820	LaMoure, North Dakota, USA [U 1s]	
14	TBB	26.70	1445	Bafa, Turkey [U 1s] [U 20s]	
15	ISR	29.70	2450	Dimona, Israel [U 1s]	
16	NRK	37.50	2975	Keflavik, Iceland [U 1s] [U 20s] [E 60s]	
17	JJY	40.00	9195	Mount Otakadoya, Honshu, Japan [U 1s]	
18	NAU	40.80	7985	Aguada, Puerto Rico, USA [U 1s]	
19	ITS	45.90	1105	Niscemi, Sicily, Italy [U 1s] [U 20s]	
20	DCF	77.50	580	Mainflingen, Germany [U 1s]	
21	RRO	153	790	Brasov, Romania [E 60s]	
22	TDF (EU1)	162 (183)	1010 (700)	Allouis, France (Felsberg-Berus, Luxembourg) [E 60s]	
23	CH1	198	1900	Berkaoui/Ouargia, Algeria [E 60s]	
24	RTL (MCO)	234 (216)	740 (820)	Beidweiler, Luxembourg (Roumoules, Monte Carlo) [E 60s]	
25	CZE	270	275	Topolna, Czech Republic [E 60s]	

Table 2: Transmitters received at the VLF/LF Graz facility, settings in blue/green/red color [1, 5, 6], major EQs event paths with yellow background. Figure 1: Great circle paths (orange & yellow lines) between VLF/LF transmitters and the Graz receiver (orange circle, UltraMSK systems [1, 5]), for INFREP (diamonds in blue color) see [6]. Magnitude $M_{5.5+}$ EQs (17 yellow stars) and the relevant paths related to the Dobrovolsky-Bowman relationship are indicated (yellow lines good S/N, yellow-dotted lines are {VTX, NWC, ISR}-GRZ long distance paths). Credit map: GMT

VLF/LF NETWORK, EUROPEAN PATHS, EQ $M_{5.5+}$



EARTHQUAKES $M \geq 5.5$, 2023, MEDITERRANEAN AREA, DATA PROCESSING & RESULTS

We investigate VLF/LF electric fields from sub-ionospheric VLF/LF propagation paths in the geo. lat/lon range $[30^{\circ} \leq \text{lat} \leq 50^{\circ}] / [-10^{\circ} \leq \text{long} \leq 40^{\circ}]$ in 2023. For this temporal, spatial and magnitude $M_{w} \geq 5.5$ constraints the USGS EQ database [9] includes 17 EQs, the Dst-index [10] considers external influences. All events (Tab. 1, Fig. 1) are selected, emphasis is according to VLF/LF path crossings and the Dobrovolsky-Bowman relationship [2, 3], i.e., the radius of the effective precursor manifestation zone $\rho = 10^{(0.43^*M)}$ km and $\log(R) \approx M/2$ km. VLF/LF amplitude nighttime values are used (± 2 hours around midnight) [7, 8], with 1 Hz resolution. The data are smoothed with a low-pass filter, the residuals are below 1 dB. Positive results (green color in Tab. 1), i.e., the link between measured VLF/LF electric fields and EQs, based on statistics from nighttime electric field amplitude variations with significance level 5%, are achieved for the big Kahramanmaraş EQ sequence and the Lárdos, Greece, event.

Table 1: Results for all $M \geq 5.5$ earthquakes (see Figure 1, stars in yellow color), time period 2023, Mediterranean area (2 OK, 2 mixed, 3 NOK).

Selected Earthquakes Magnitude $M \geq 5.5$, USGS database, time span 01.01.2023 - 31.12.2023, long/lat range: $[-10^{\circ} - +40^{\circ}] / [+30^{\circ} - +50^{\circ}]$							
No.	Date, Time	Lat (°) / Lon (°) / Depth (km)	Mag / ρ (km)	Location	Main path	Control paths	Result, Annotation
1	2023-01-25 12:37:05	+35.709 / +28.497 / 29.6	5.9 / 344	Lárdos, Greece	TBB-GRZ	11 {ISR, NAA, JJI, ITS, ICV, GWU, GBZ, GBS, DHO, DCF, NRK}-GRZ	OK: Post EQ > Pre EQ values with significance level 5%, min(Dst) = -57 nT
2	2023-02-06 01:17:34	+37.226 / +37.014 / 10.0	7.8 / 2260	Kahramanmaraş EQs sequ.	TBB-GRZ	08 {NAA, ITS, ICV, HWU, GWU, GBZ, GBS, DHO}-GRZ	OK: Post EQ > Pre EQ values with significance level 5%
3	2023-02-06 01:26:51	+37.225 / +37.000 / 10.0	6.7 / 760	Nurdağı, Turkey	TBB-GRZ		magnetic storm starts late in the period at 2023-02-15: min(Dst) = -72 nT
4	2023-02-06 01:28:16	+37.189 / +36.893 / 9.80	5.6 / 255	Nurdağı, Turkey	TBB-GRZ		
5	2023-02-06 01:36:27	+36.992 / +36.683 / 10.0	5.4 / 210	Turkey-Syria border	TBB-GRZ		
6	2023-02-06 10:24:49	+38.0101 / +37.196 / 7.43	7.5 / 1679	Kahramanmaraş EQs sequ.	TBB-GRZ	08 {NAA, ITS, ICV, HWU, GWU, GBZ, GBS, DHO}-GRZ	
7	2023-02-06 10:26:46	+38.032 / +38.099 / 10.0	6.0 / 380	Çelikhán, Turkey	TBB-GRZ		
8	2023-02-06 10:35:58	+38.025 / +37.802 / 10.0	5.8 / 312	Doğuşehir, Turkey	TBB-GRZ		
9	2023-02-06 10:51:31	+38.248 / +38.185 / 10.0	5.7 / 283	Yeşilyurt, Turkey	TBB-GRZ		
10	2023-02-06 12:02:11	+38.058 / +36.511 / 8.52	6.0 / 380	Göksun, Turkey	TBB-GRZ		
11	2023-02-07 03:13:13	+37.764 / +37.731 / 10.0	5.5 / 232	Gölbasi, Turkey	TBB-GRZ		
12	2023-02-14 13:16:51	+45.100 / +23.201 / 10.0	5.6 / 255	Leleşti, Romania	TBB-GRZ	14 {ISR, VTX, NWC, NAA, JJI, ITS, ICV, HWU, GWU, GBZ, GBS, DHO, DCF, NRK}-GRZ	Not OK: not significant, all paths out of 5% level, min(Dst) = -72 nT
13	2023-02-20 17:04:30	+36.162 / +36.025 / 16.0	6.3 / 512	Uzunbağ, Turkey	TBB-GRZ	14 {ISR, VTX, NWC, NAA, JJI, ITS, ICV, HWU, GWU, GBZ, GBS, DHO, DCF, NRK}-GRZ	OK/NOK: Mixed results; significant values for the ISR-GRZ path
14	2023-02-20 17:07:36	+36.159 / +35.935 / 10.0	5.5 / 232	Uzunbağ, Turkey	TBB-GRZ		Major magnetic storm at 2023-02-26: min(Dst) = -132 nT
15	2023-04-21 22:19:49	+35.026 / +15.219 / 13.8	5.5 / 232	Birzebbuga, Malta	ITS-GRZ	08 {TBB, NAA, ICV, GBZ, GBS, DHO, DCF, NRK}-GRZ	OK/NOK: Mixed results; major mag. storm at 2023-04-23: min(Dst) = -213 nT
16	2023-07-25 05:44:51	+37.579 / +35.948 / 13.1	5.5 / 232	Kozan, Turkey	TBB-GRZ	09 {NAA, ITS, ICV, HWU, GBZ, GBS, DHO, DCF, NRK}-GRZ	NOK: Several magnetic storms: min(Dst) = -59 nT
17	2023-09-08 22:11:01	+31.058 / -08.385 / 19.0	6.8 / 839	Al Haouz, Morocco	{ITS, ICV}-GRZ	06 {JJI, HWU, GBZ, GBS, DHO, NRK}-GRZ	NOK: Receiver systematics and out of Dobrovolsky-Bowman area; ICV-Morocco EQ = 1958 km, ITS-Morocco EQ = 2204 km, two major magnetic storms: min(Dst) = -79 nT

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- World Data Center for Geomagnetism, Kyoto, database <https://wdc.kugi.kyoto-u.ac.jp/> as of April 2024.

SUMMARY

VLF/LF electric field variations (nighttime amplitude method; assumed significance level 5%) can be related to the 2023 Turkey-Syria earthquakes ($M_{7.8}$, $M_{7.5}$) and the Lárdos, Greece ($M_{5.9}$) event.



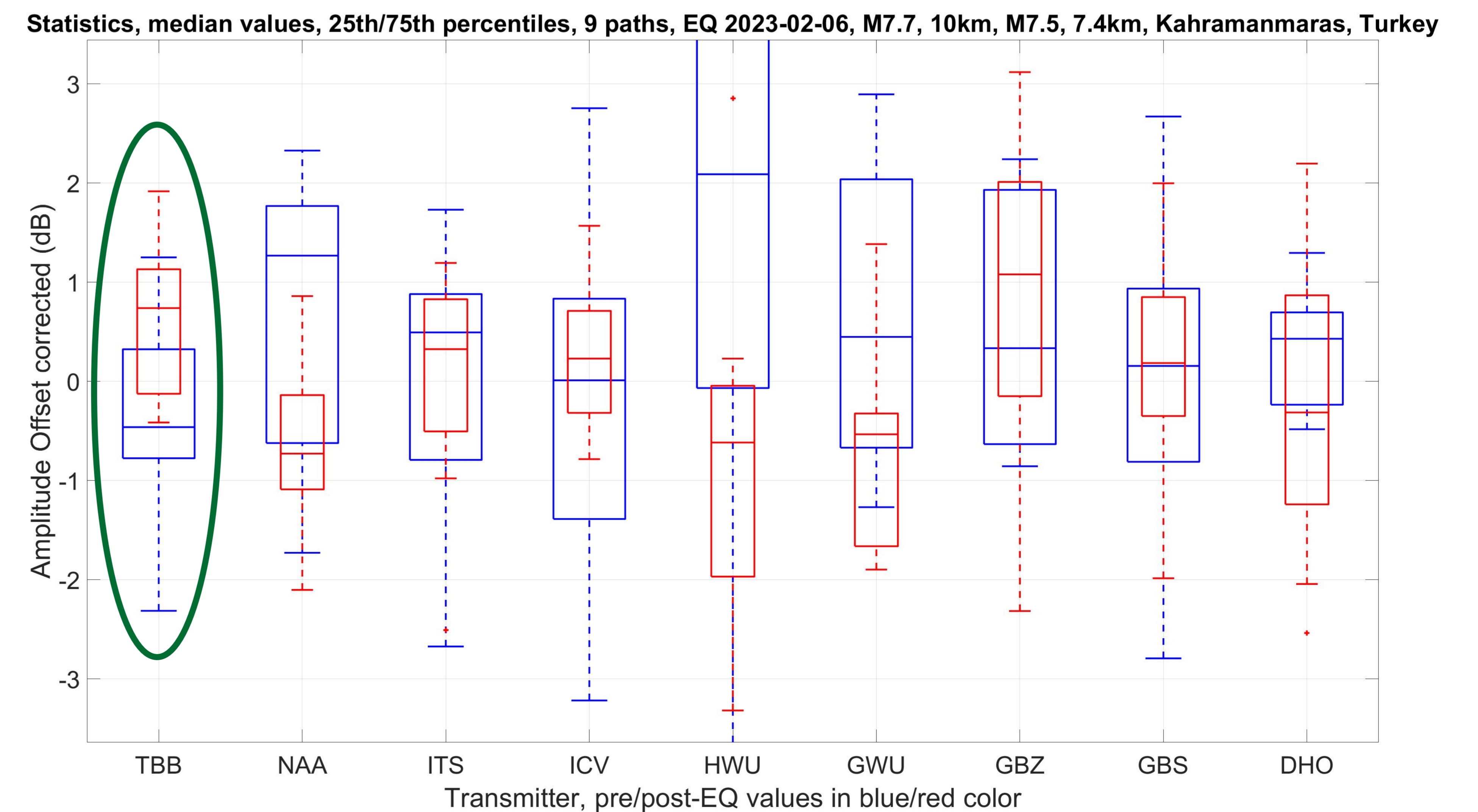
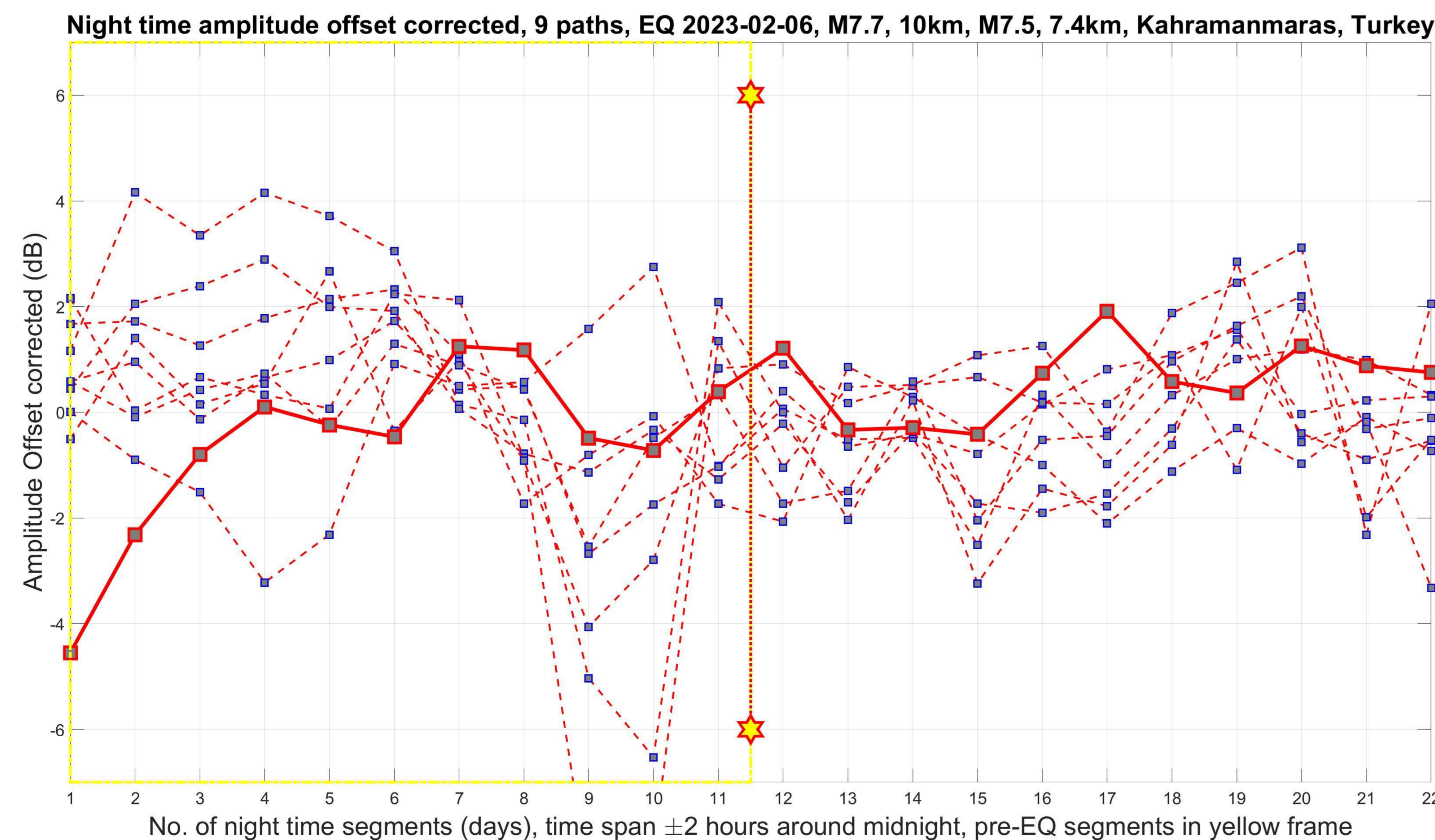
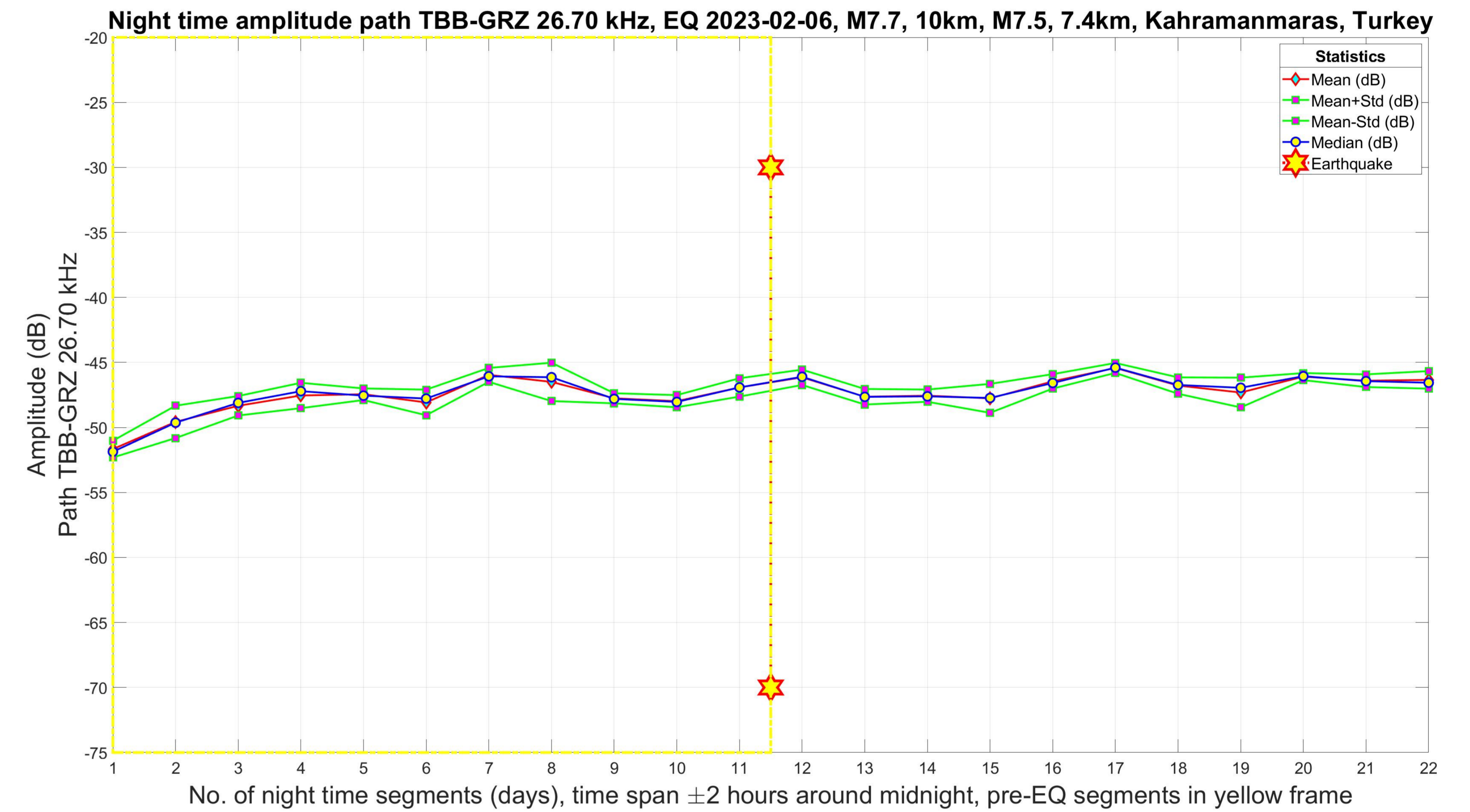
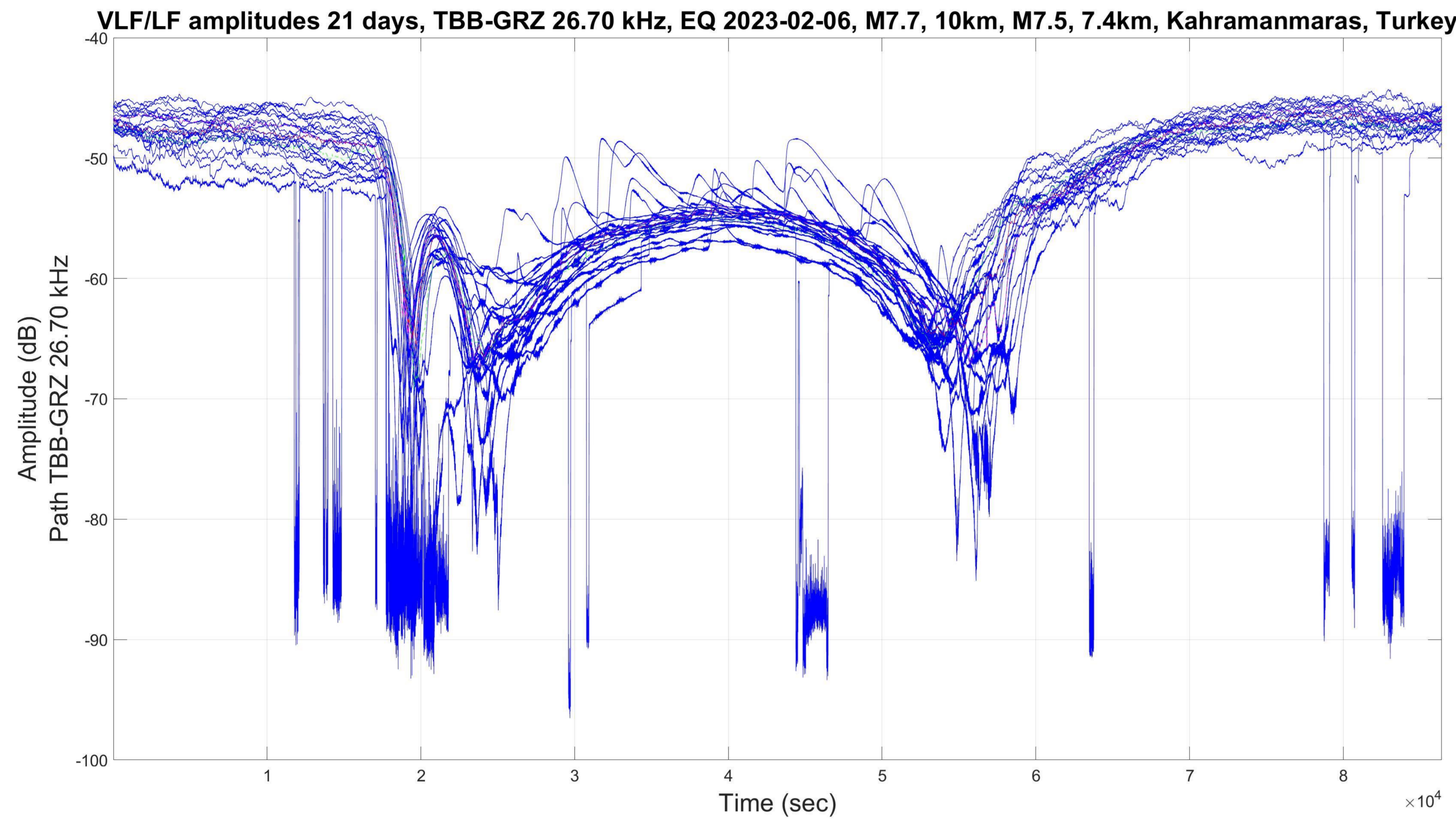
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VLF/LF AMPLITUDE MEAS., EARTHQUAKES 2023-02-06, M7.8 10 KM / M7.5 7.4 KM, KAHRAMANMARAS EARTHQUAKE SEQUENCE, TURKEY

- Top Left: VLF/LF amplitudes (2023-01-27 to 2023-02-16) for the 26.70 kHz TBB-GRZ path, spikes and transmitter switch off periods are omitted
- Bottom Left: Offset corrected nighttime (± 2 h around midnight) amplitude values for the 9 paths
- Top Right: Nighttime amplitude values for the affected TBB-GRZ event path (crossing the Dobrovolsky-Bowman area/radius)
- Bottom Right: Statistics (box plots) for the offset corrected 9 paths, **for a significance level of 5% only the event path TBB-GRZ shows higher amplitude values after the EQ (nighttime method)**





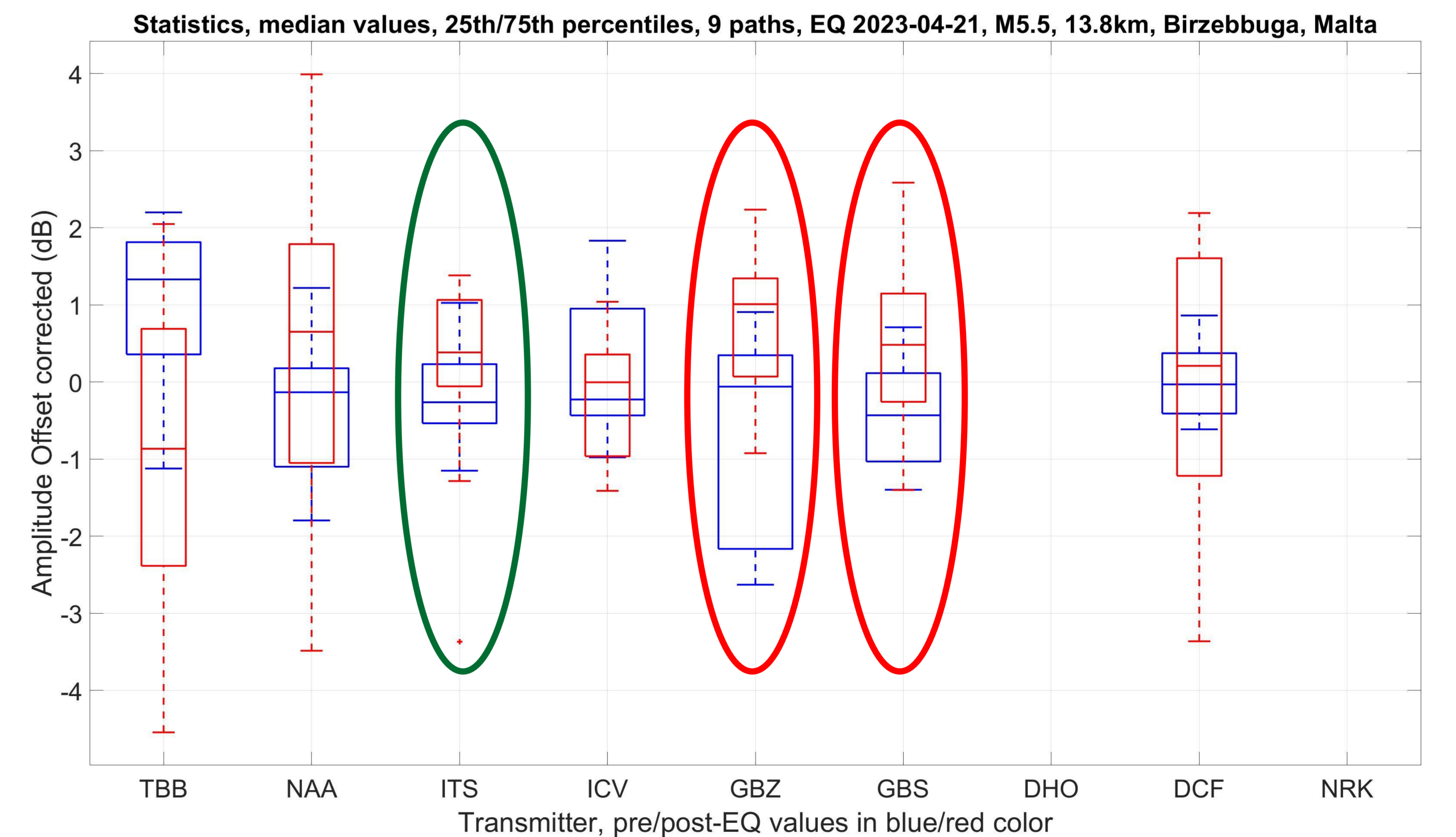
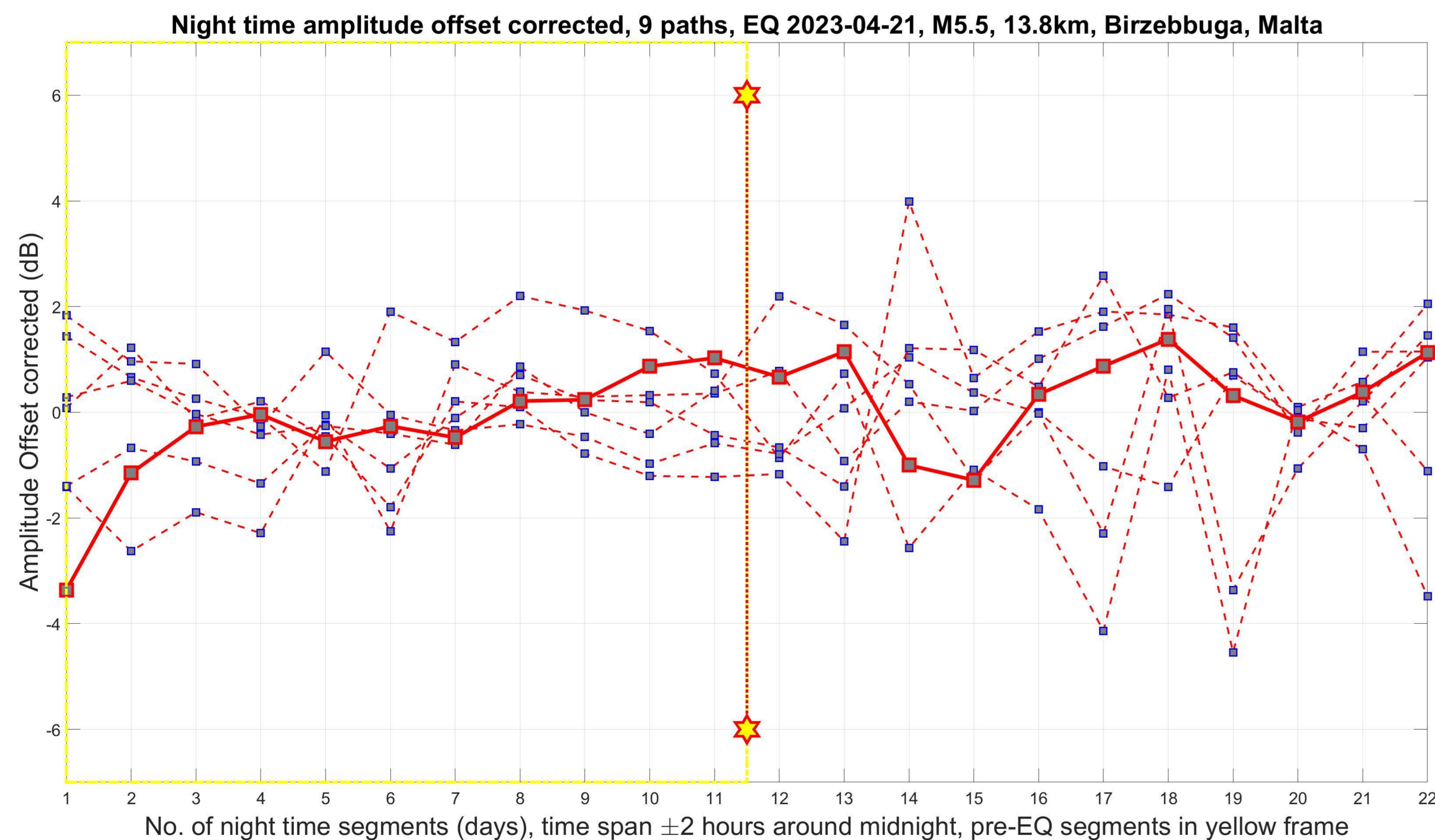
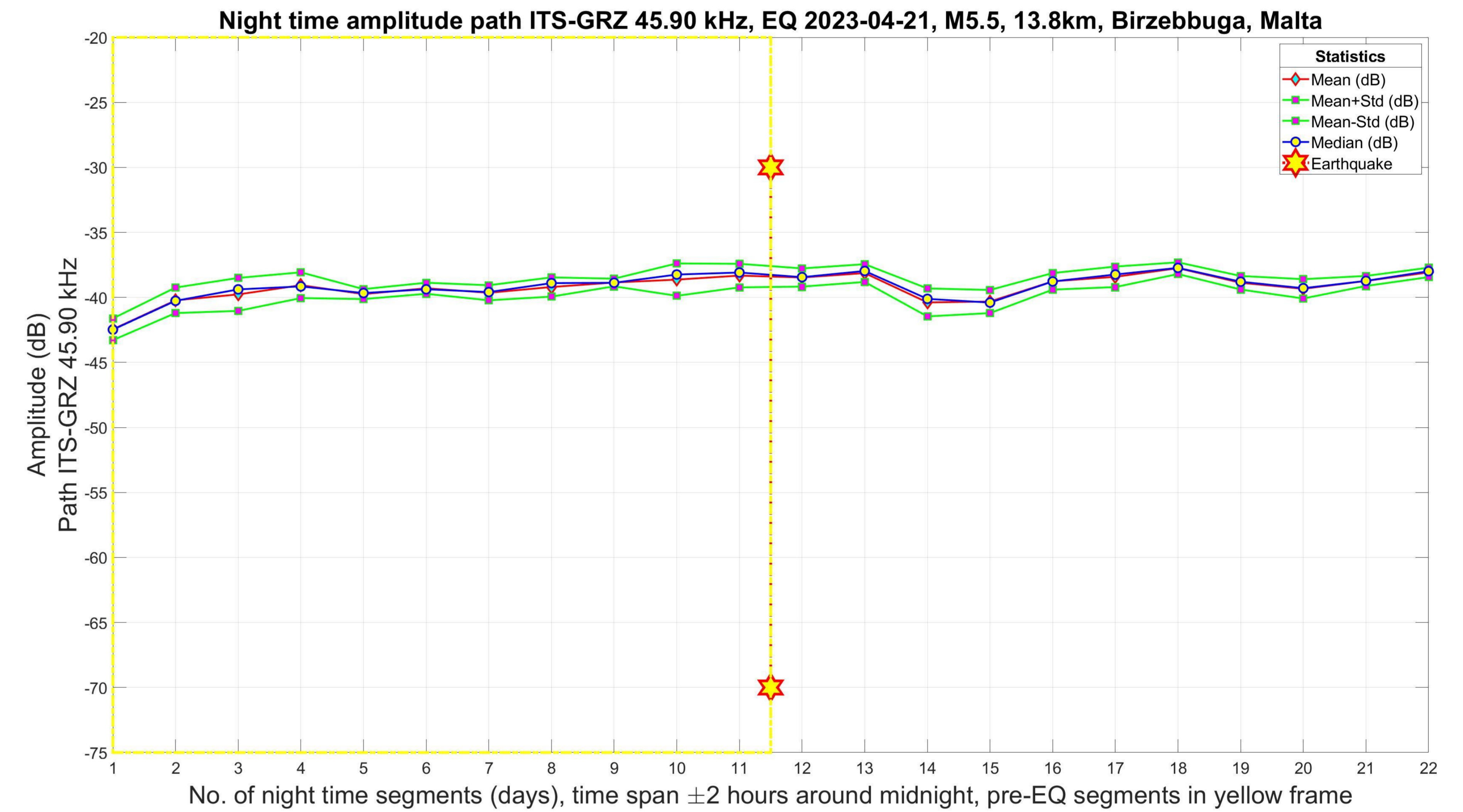
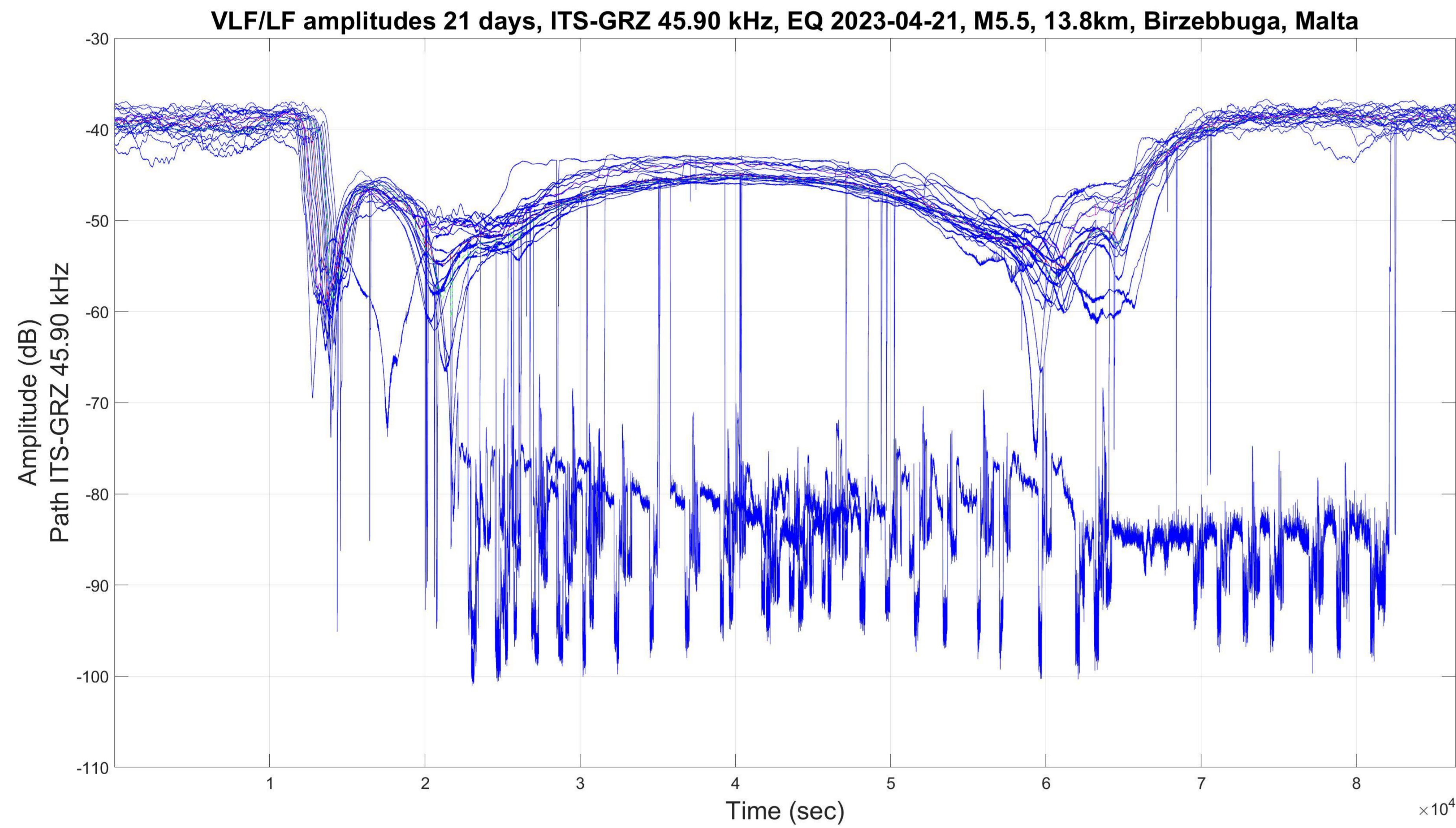
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VLF/LF AMPLITUDE MEASUREMENTS, EARTHQUAKE 2023-04-21, M5.5 13.8 KM, BIRŽEBBUĠA, MALTA

- Top Left: VLF/LF amplitudes (2023-04-11 to 2023-05-01) for the 45.90 kHz ITS-GRZ path, spikes and transmitter switch off periods are omitted
- Bottom Left: Offset corrected nighttime (± 2 h around midnight) amplitude values for the 9 paths
- Top Right: Nighttime amplitude values for the affected ITS-GRZ event path (crossing the Dobrovolsky-Bowman area/radius)
- Bottom Right: Statistics (box plots) for the offset corrected 9 paths (7 continuous), for a sig. level of 5% the event paths ITS-GRZ, GBZ-GRZ, GBS-GRZ show higher amplitude values after the EQ



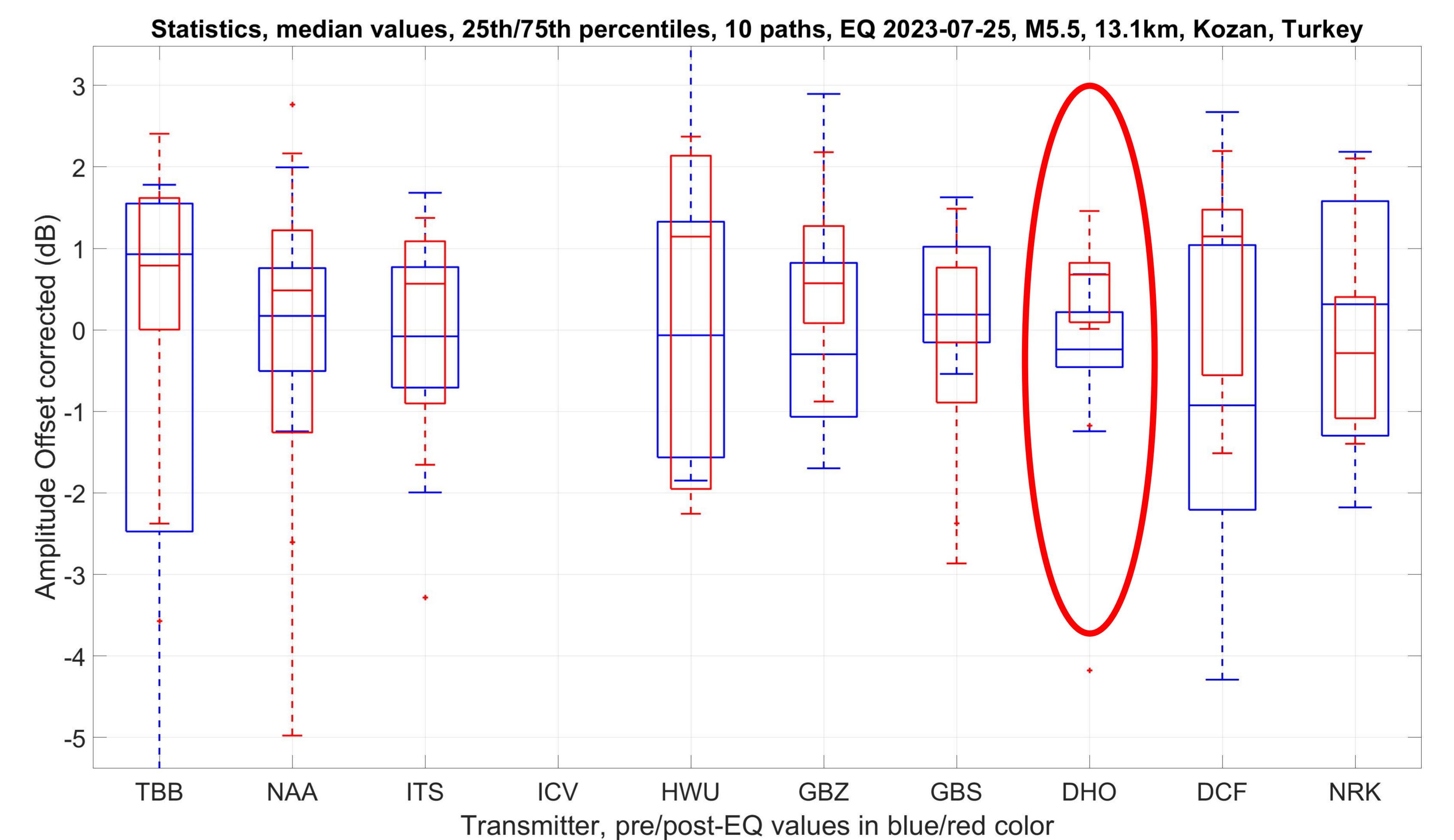
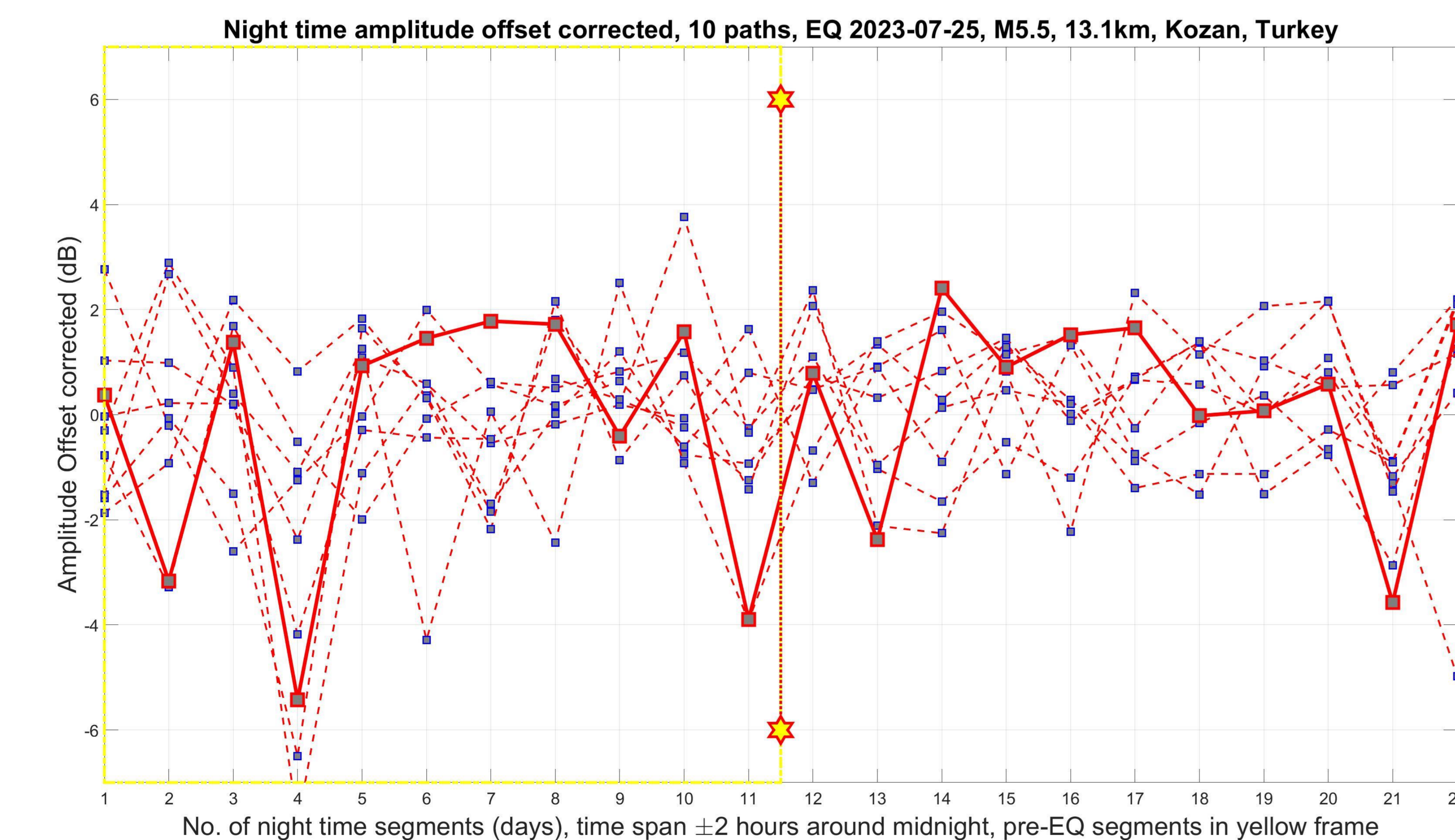
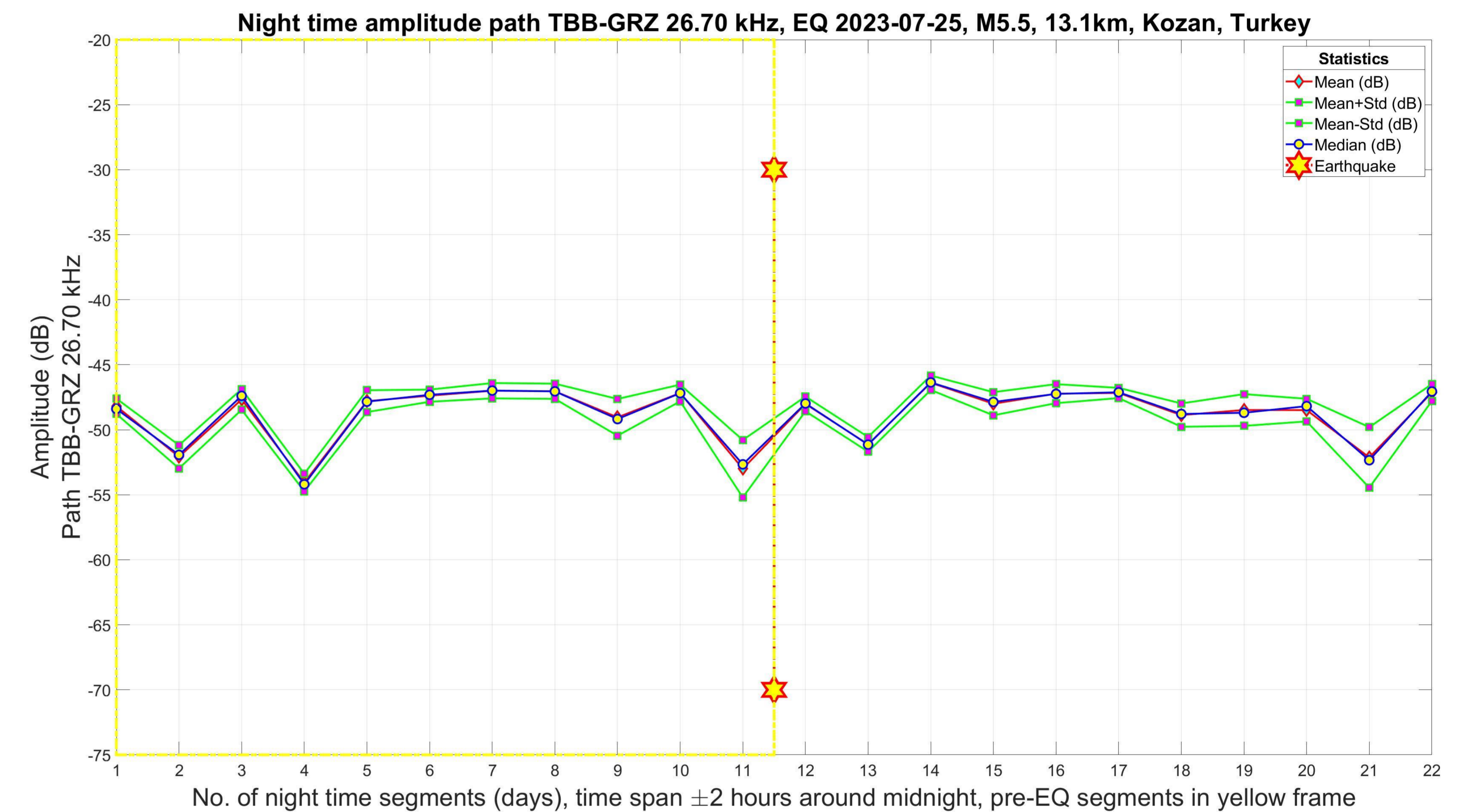
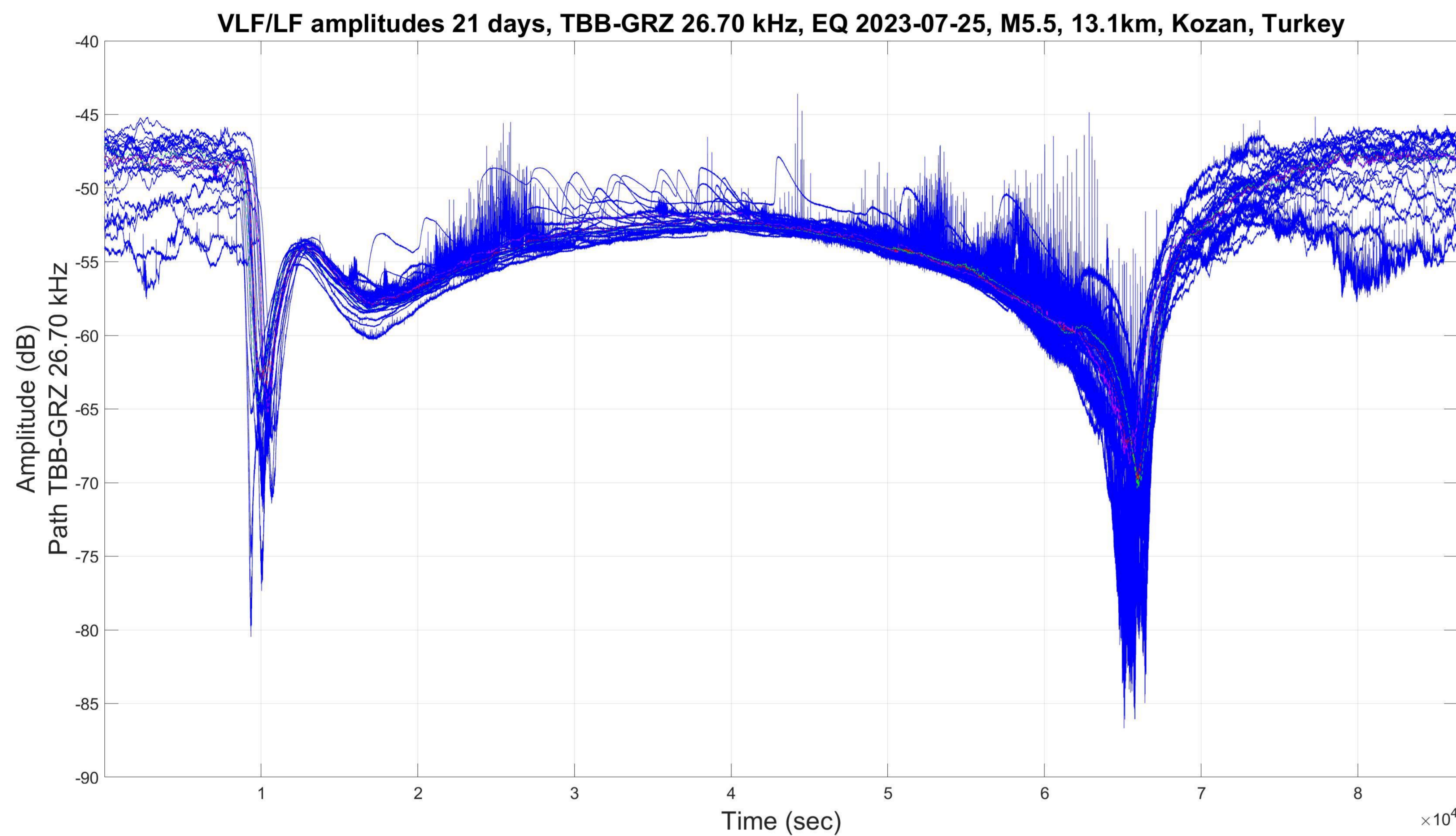
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VLF/LF AMPLITUDE MEASUREMENTS, EARTHQUAKE 2023-07-25, M5.5 13.12 KM, KOZAN, TURKEY

- Top Left: VLF/LF amplitudes (2023-07-15 to 2023-08-04) for the 26.70 kHz TBB-GRZ path, spikes and transmitter switch off periods are omitted
- Bottom Left: Offset corrected nighttime (± 2 h around midnight) amplitude values for the 10 paths
- Top Right: Nighttime amplitude values for the affected TBB-GRZ event path (crossing the Dobrovolsky-Bowman area/radius)
- Bottom Right: Statistics (box plots) for the offset corrected 10 paths (9 continuous), for a significance level of 5% the control path DHO-GRZ show higher amplitude values after the EQ





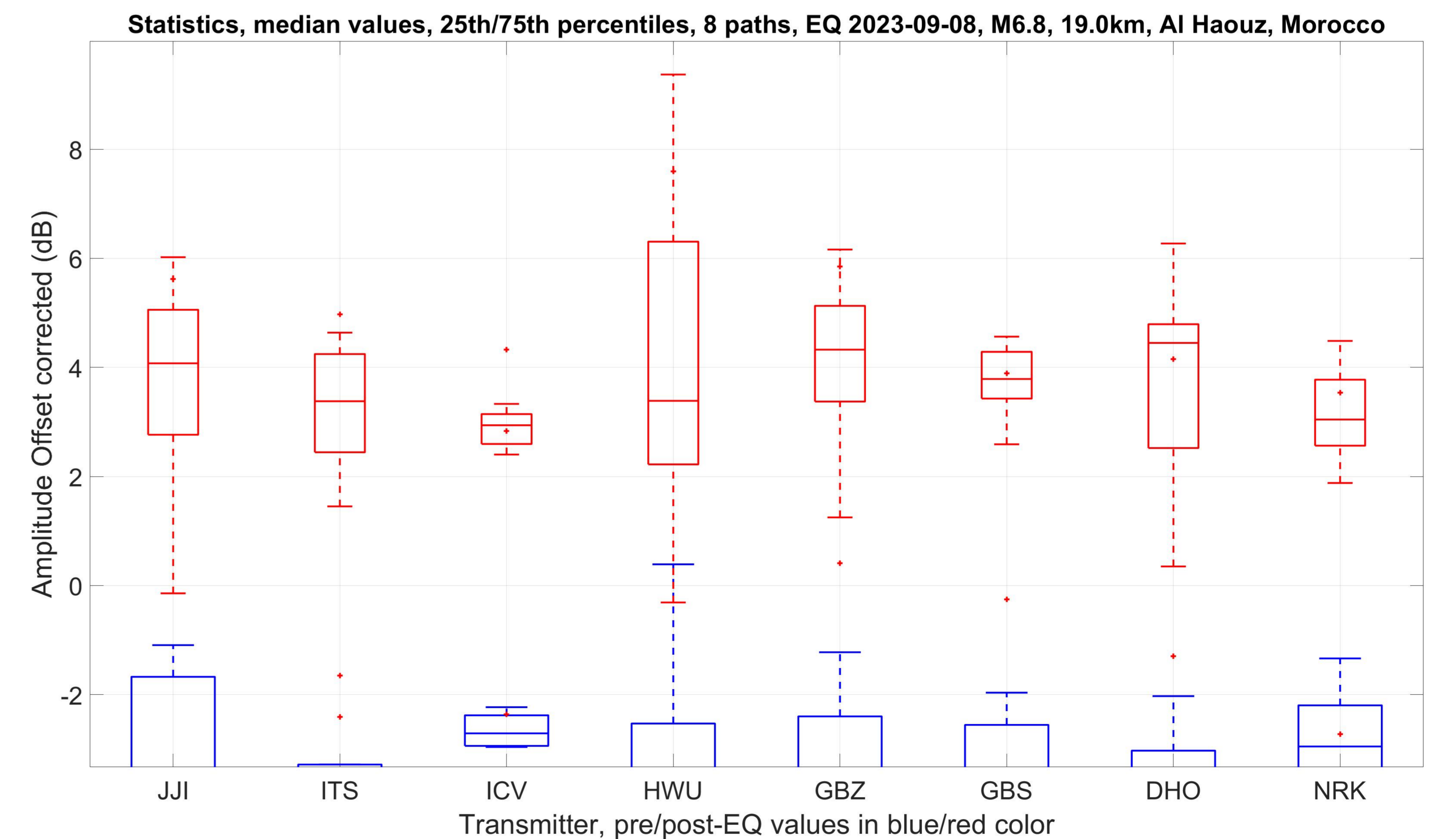
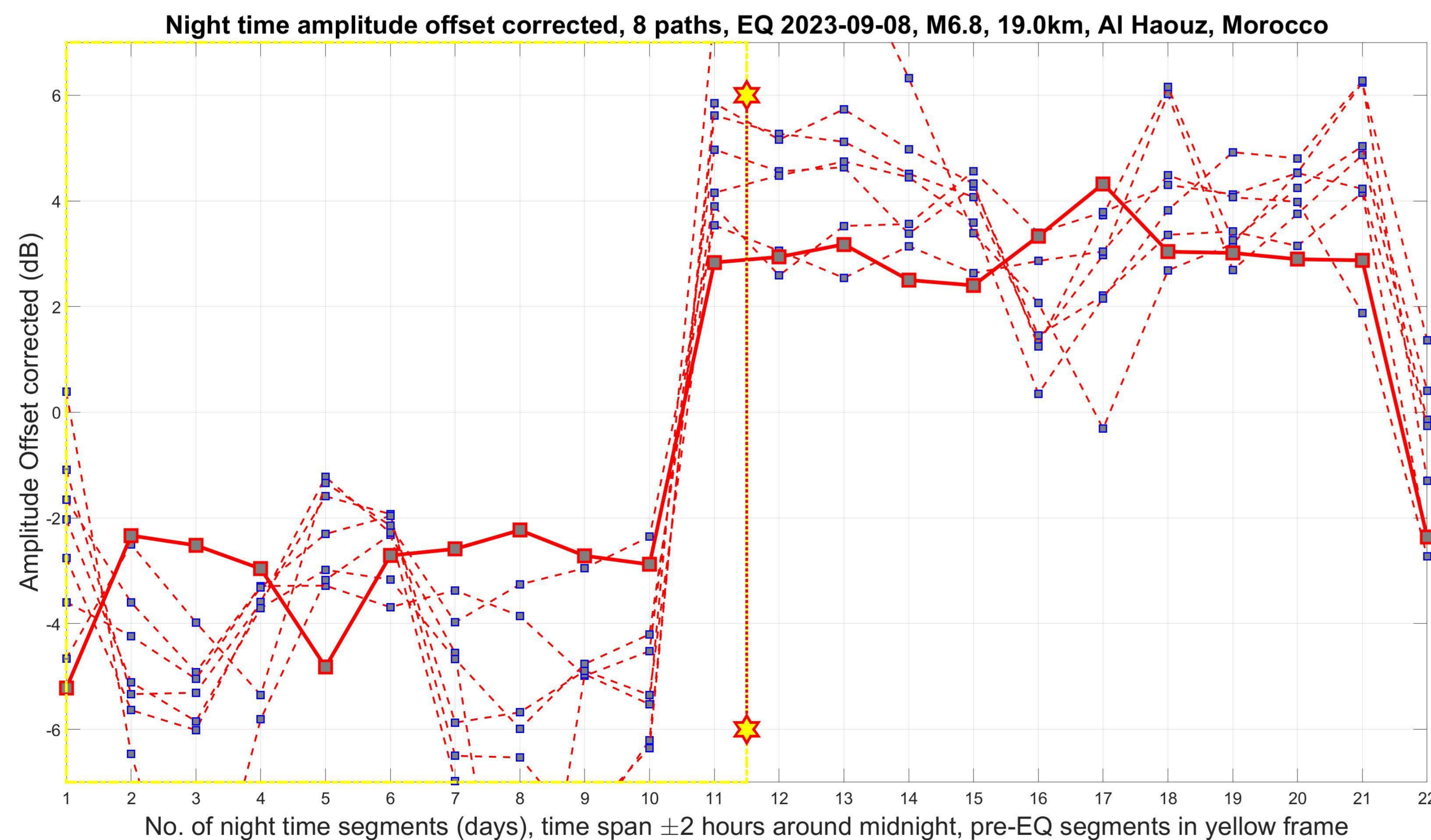
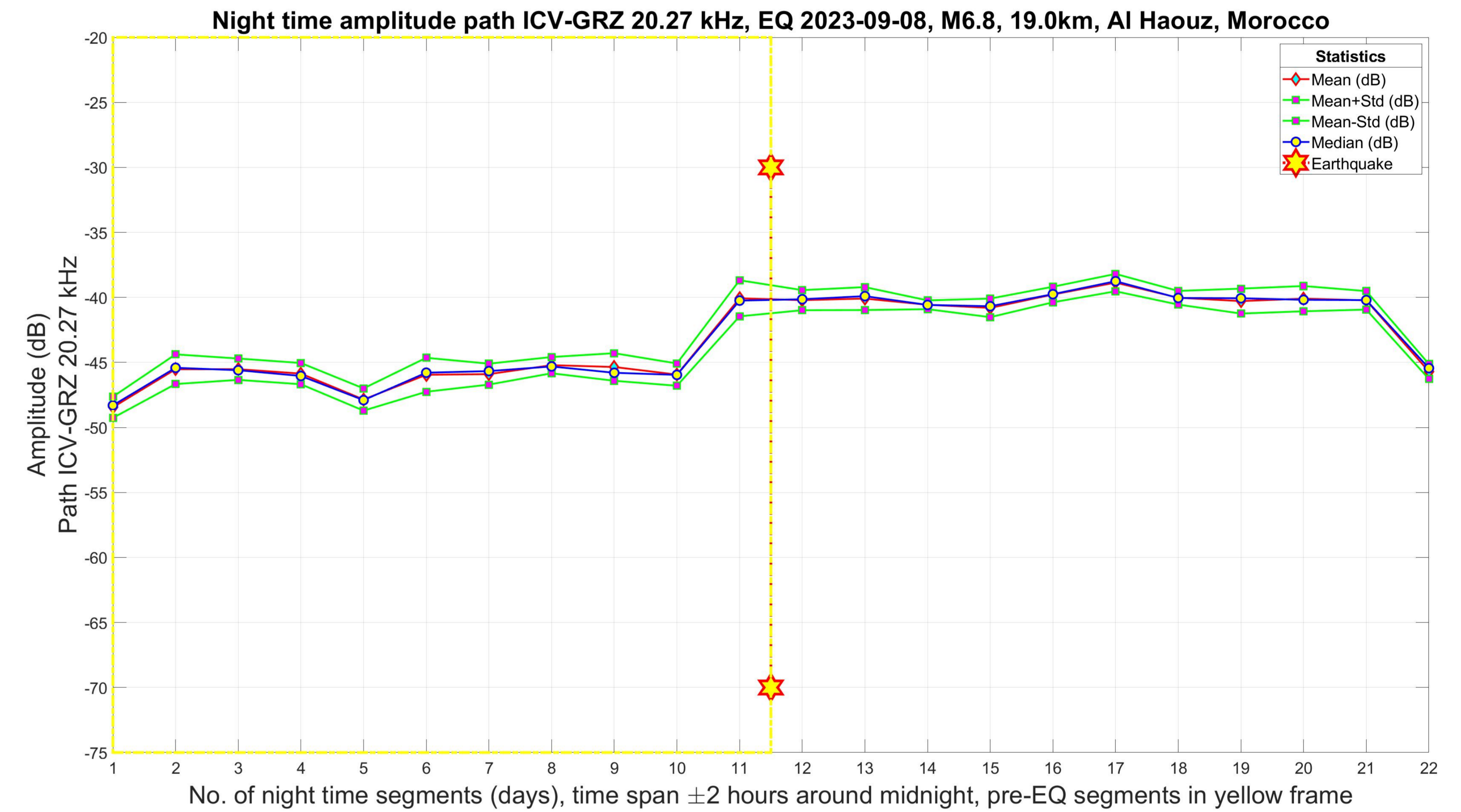
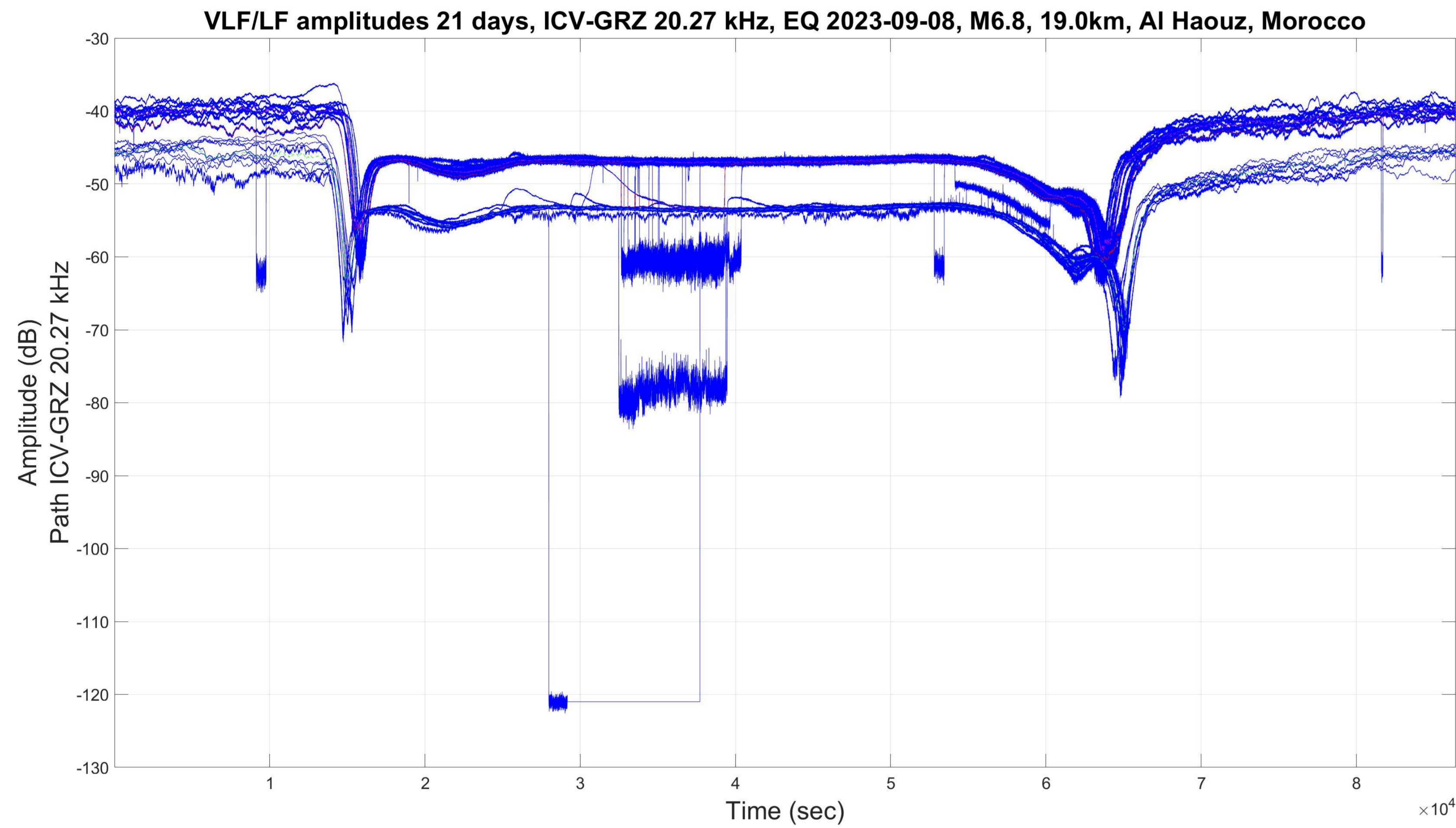
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Hans Eichelberger¹, Mohammed Y. Boudjada¹, Konrad Schwingenschuh¹, Bruno P. Besser¹, Daniel Wolbang¹, Maria Solovieva², Pier F. Biagi³, Patrick H. M. Galopeau⁴, Ghulam Jaffer⁵, Christoph Schirninger⁶, Aleksandra Nina⁷, Gordana Jovanovic⁸, Giovanni Nico⁹, Manfred Stachel¹, Özer Aydogar¹, Cosima Muck¹, Josef Wilfinger¹, Irmgard Jernej¹, and Werner Magnes¹

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VLF/LF AMPLITUDE MEASUREMENTS, EARTHQUAKE 2023-09-08, M6.8 19 KM, AL HAOUZ, MOROCCO

- Top Left: VLF/LF amplitudes (2023-08-29 to 2023-09-18) for the 20.27 kHz ICV-GRZ path, spikes and transmitter switch off periods are omitted
- Bottom Left: Offset corrected nighttime (± 2 h around midnight) amplitude values for the 8 paths
- Top Right: Nighttime amplitude values for the possibly affected ICV-GRZ event path
- Bottom Right: Statistics (box plots) for the offset corrected 8 paths, **systematic variation (antenna relocation) and not in the Dobrovolsky-Bowman area, nighttime ampl. method not reliable**



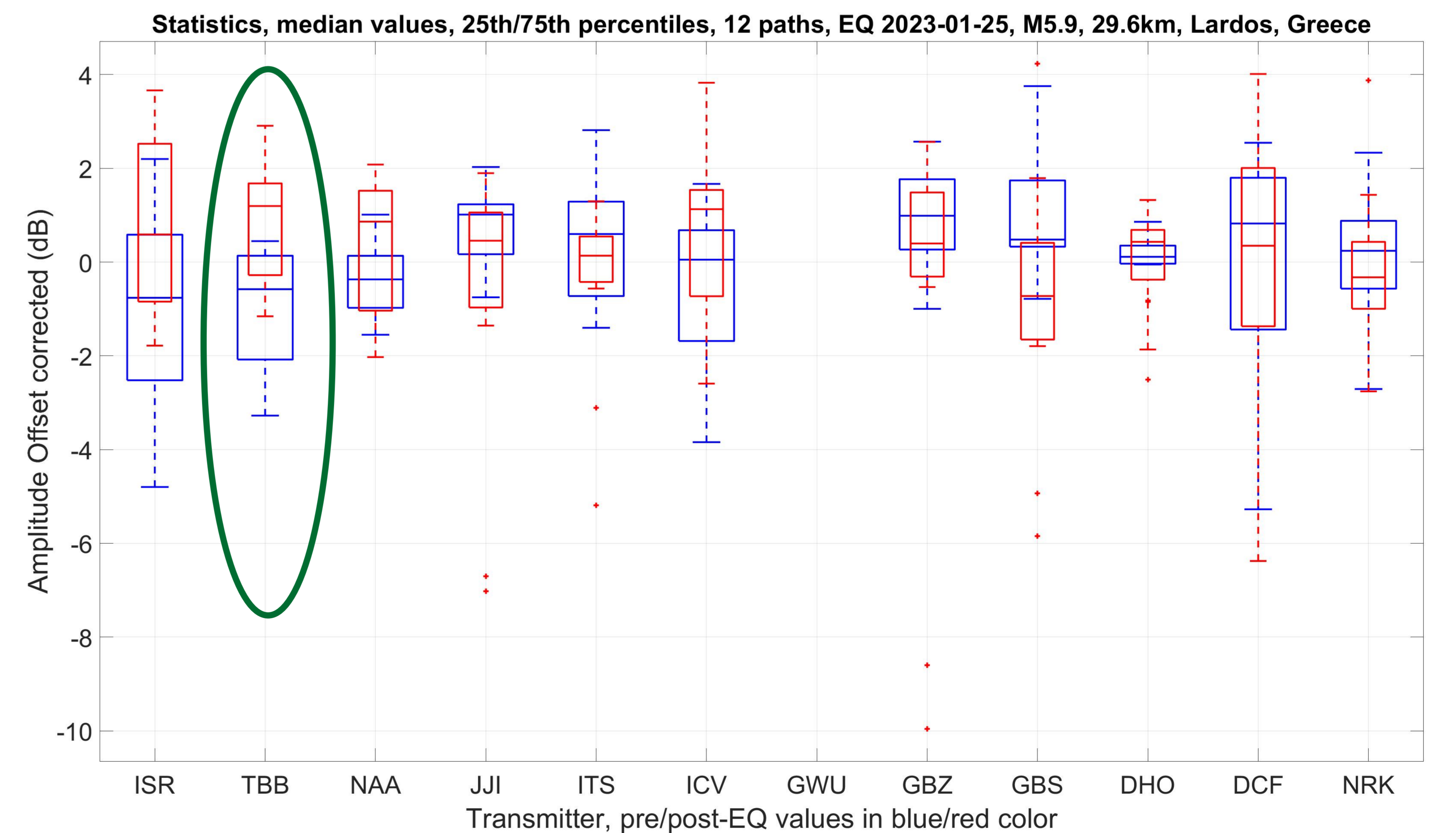
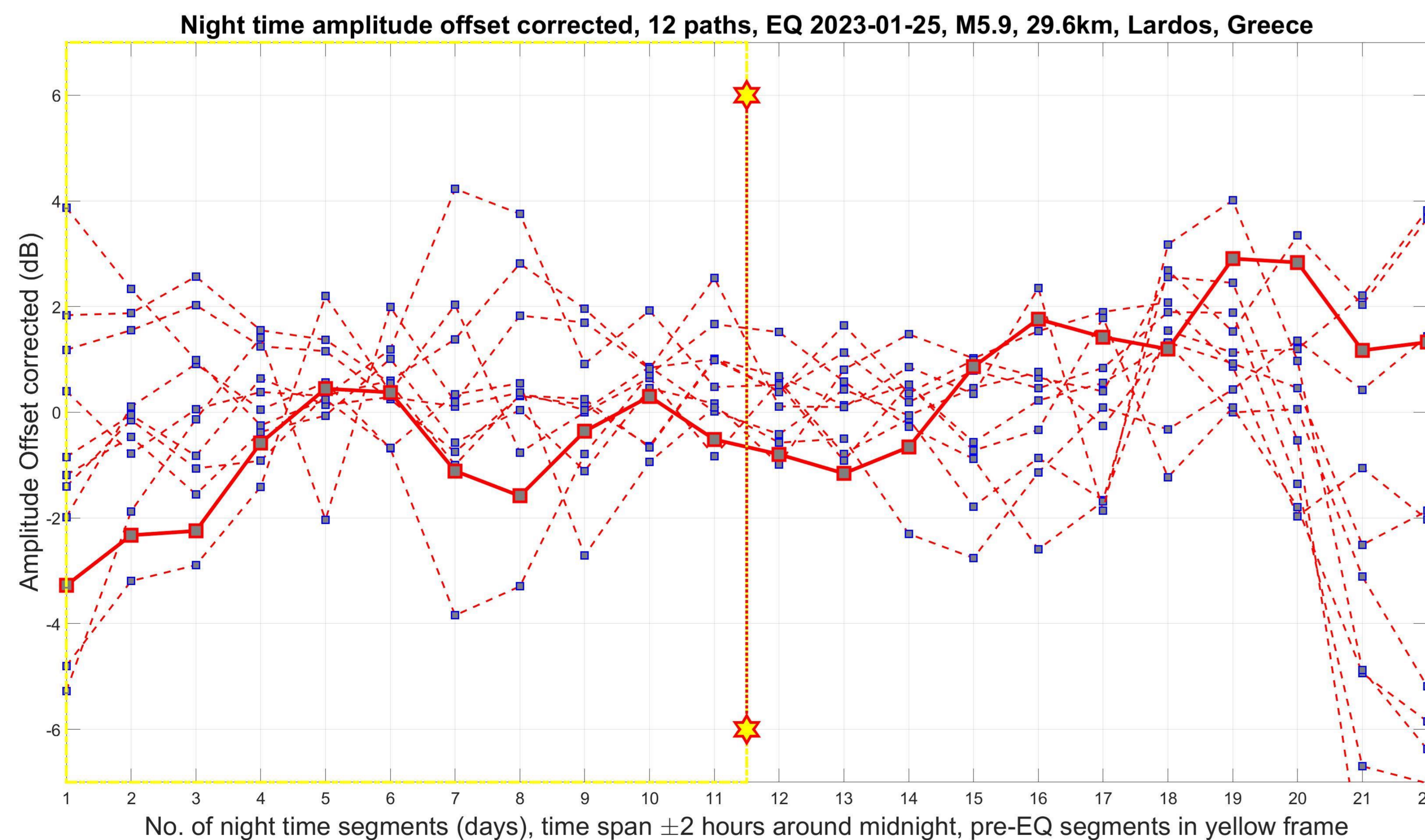
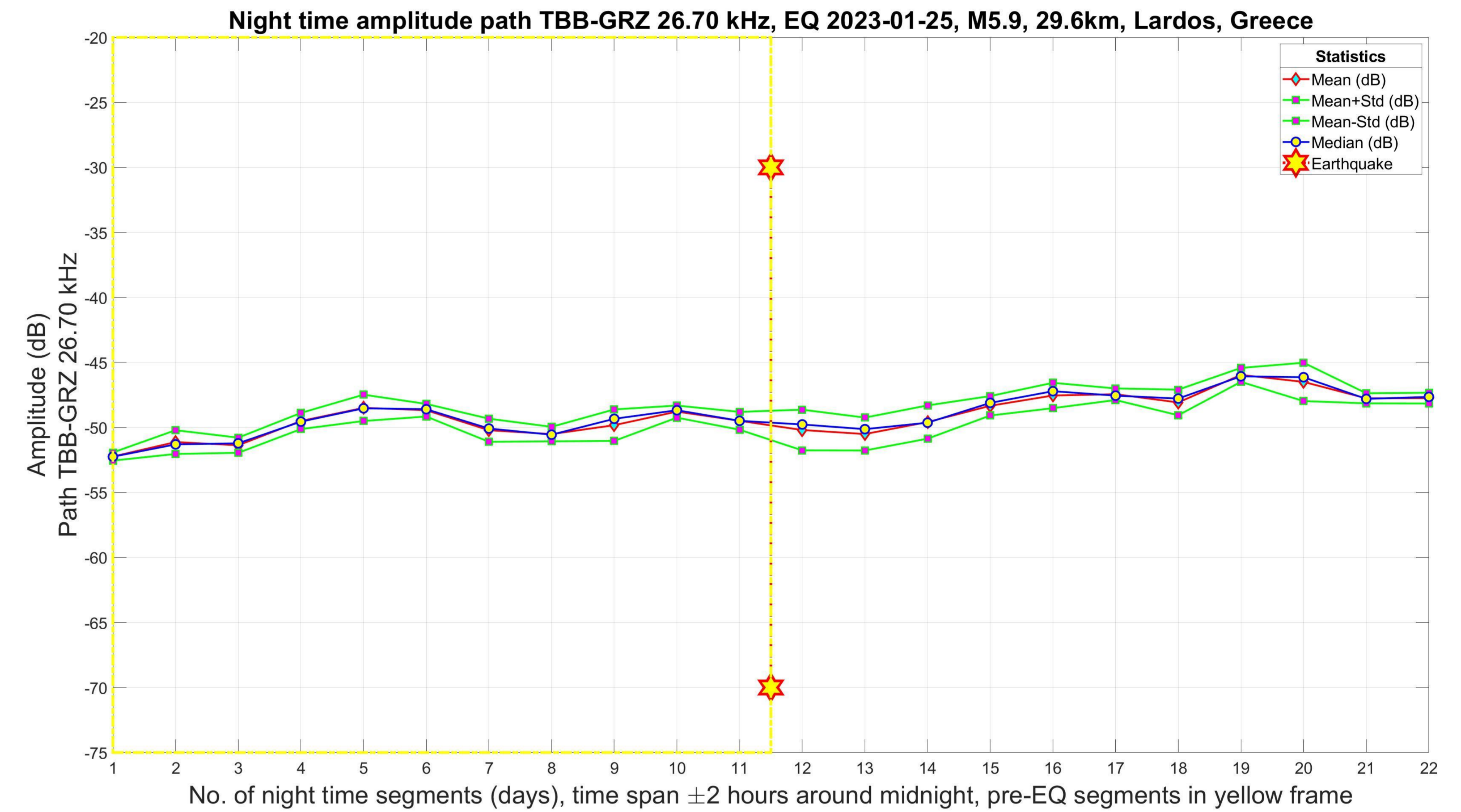
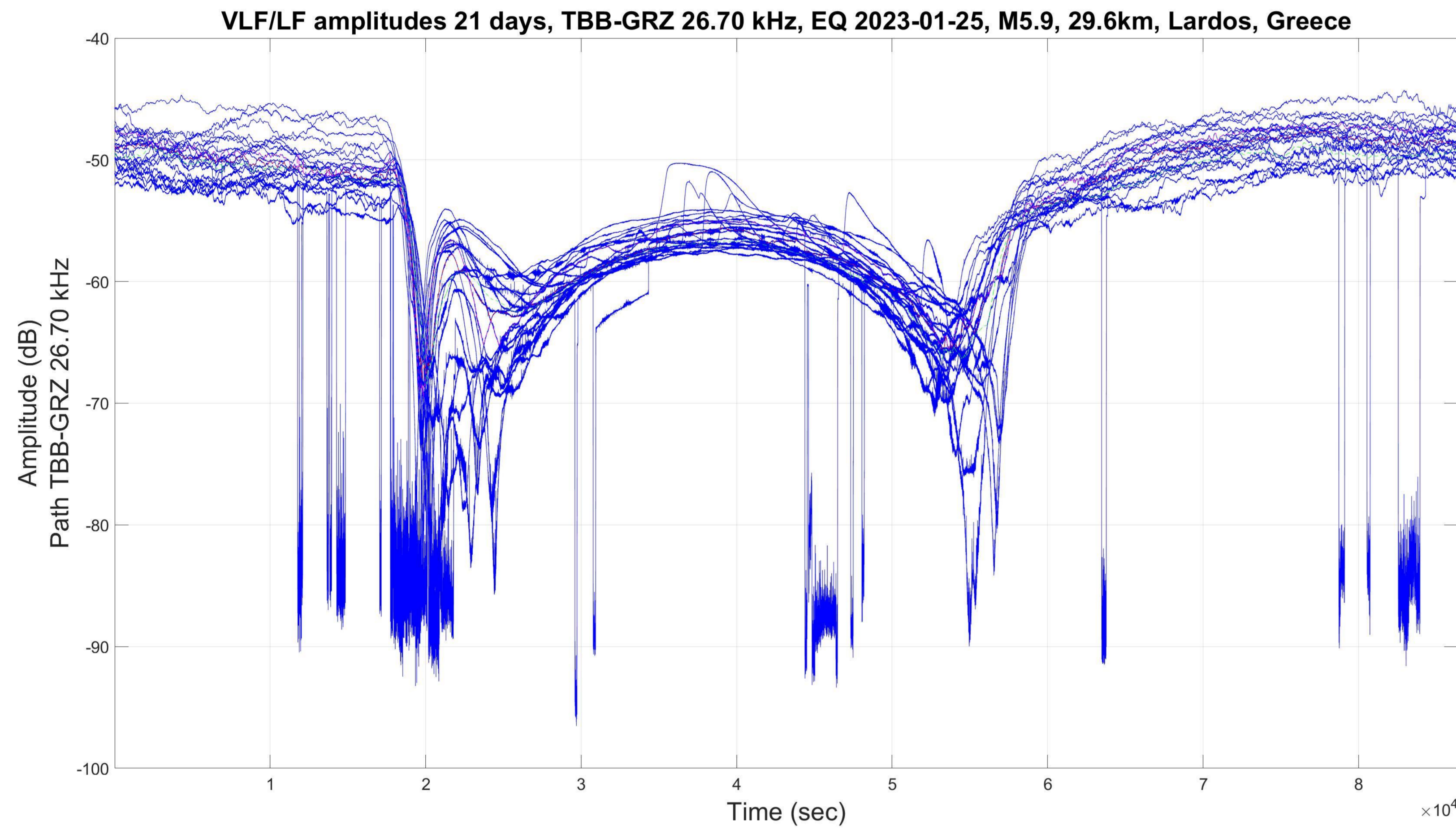
INVESTIGATION OF VLF/LF ELECTRIC FIELD VARIATIONS RELATED TO MAGNITUDE $MW \geq 5.5$ EARTHQUAKES IN THE MEDITERRANEAN REGION FOR THE YEAR 2023

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VLF/LF AMPLITUDE MEASUREMENTS, EARTHQUAKE 2023-01-25, M5.9 29.6 KM, LÁRDOS, GREECE

- Top Left: VLF/LF amplitudes (2023-01-15 to 2023-02-04) for the 26.70 kHz TBB-GRZ path, spikes and transmitter switch off periods are omitted
- Bottom Left: Offset corrected nighttime (± 2 h around midnight) amplitude values for the 12 paths
- Top Right: Nighttime amplitude values for the affected TBB-GRZ event path (crossing the Dobrovolsky-Bowman area/radius)
- Bottom Right: Statistics (box plots) for the offset corrected 12 paths (11 continuous), **for sig. level of 5% only the event path TBB-GRZ shows higher amp. values after the EQ (nighttime method)**



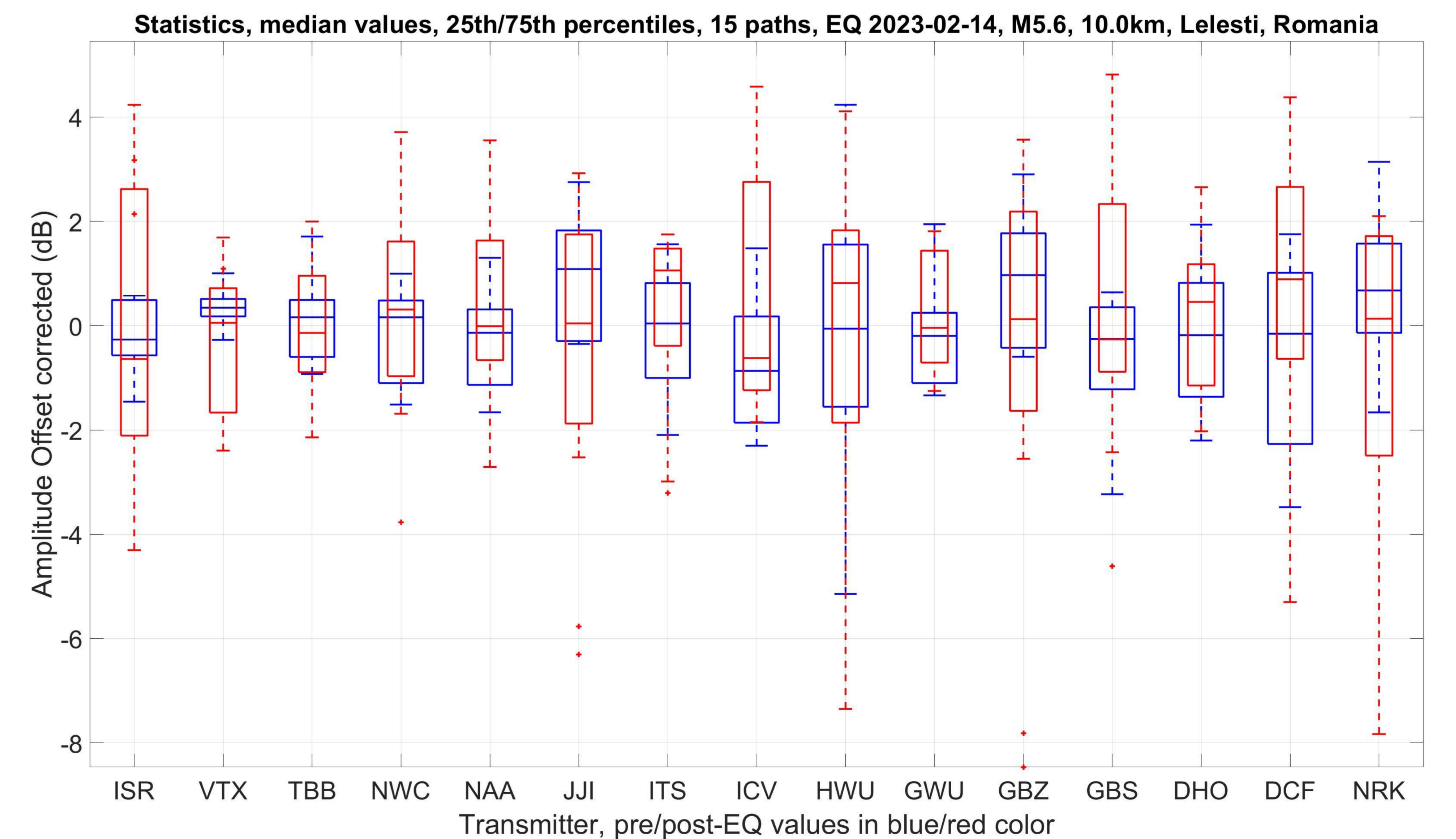
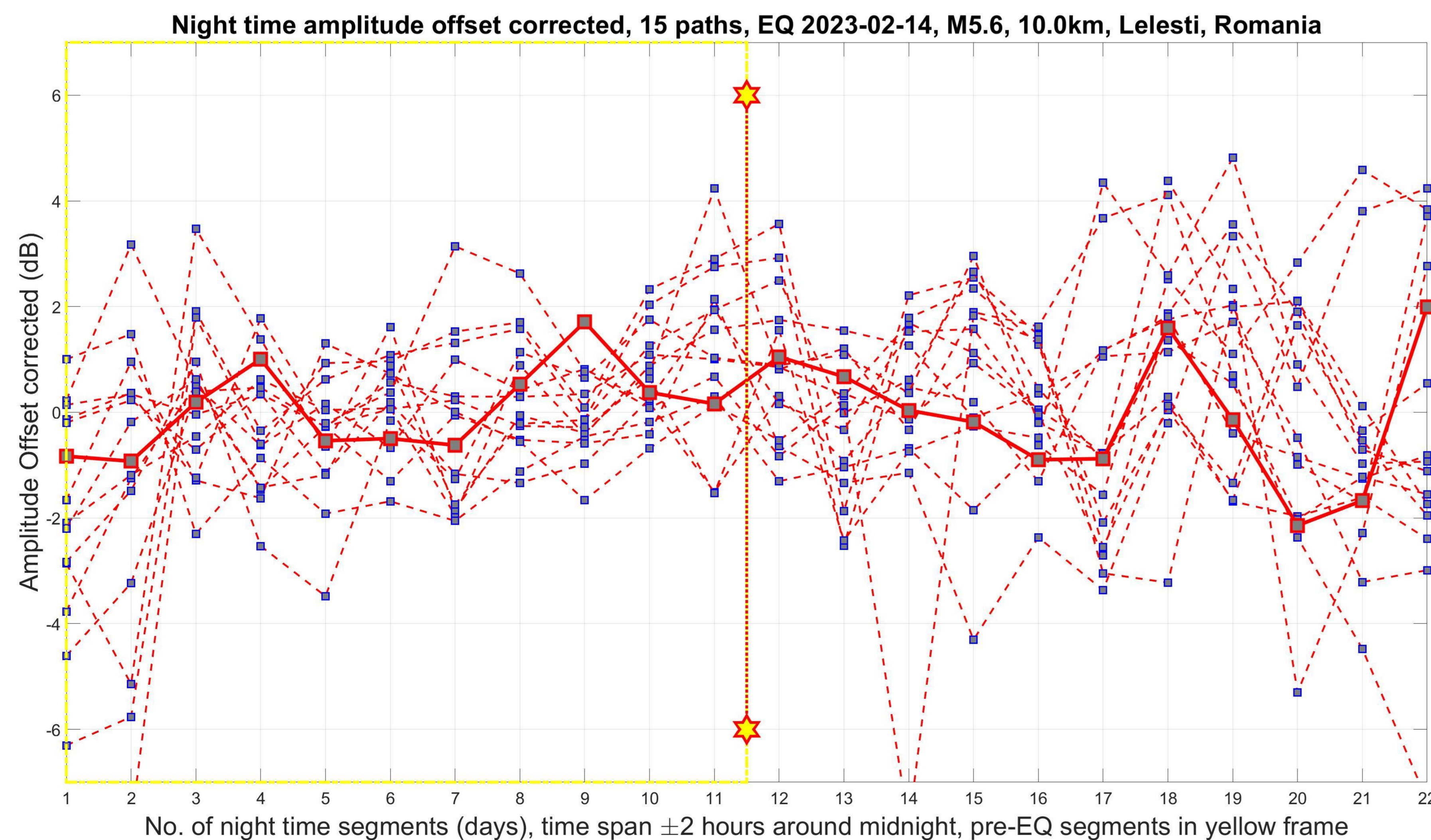
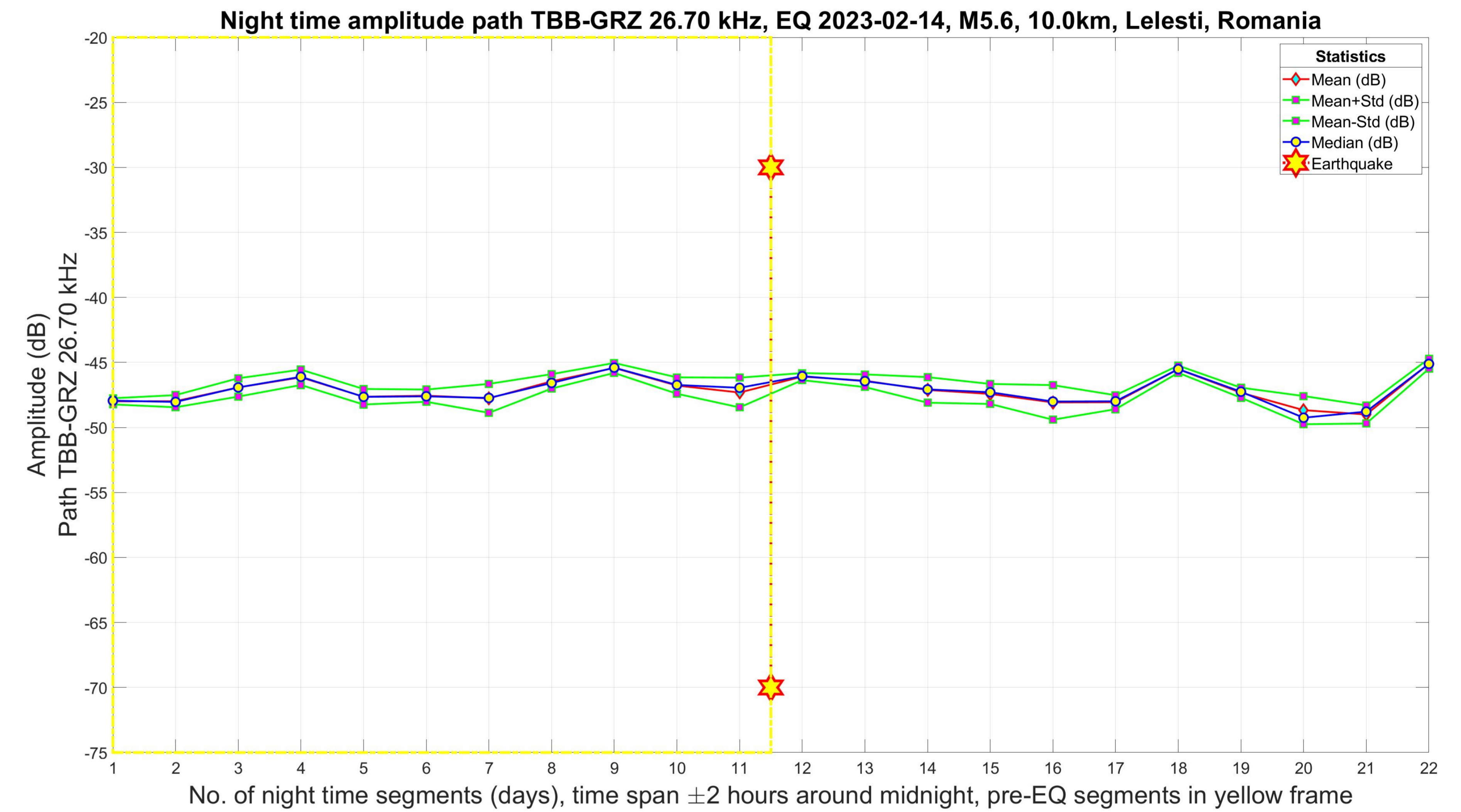
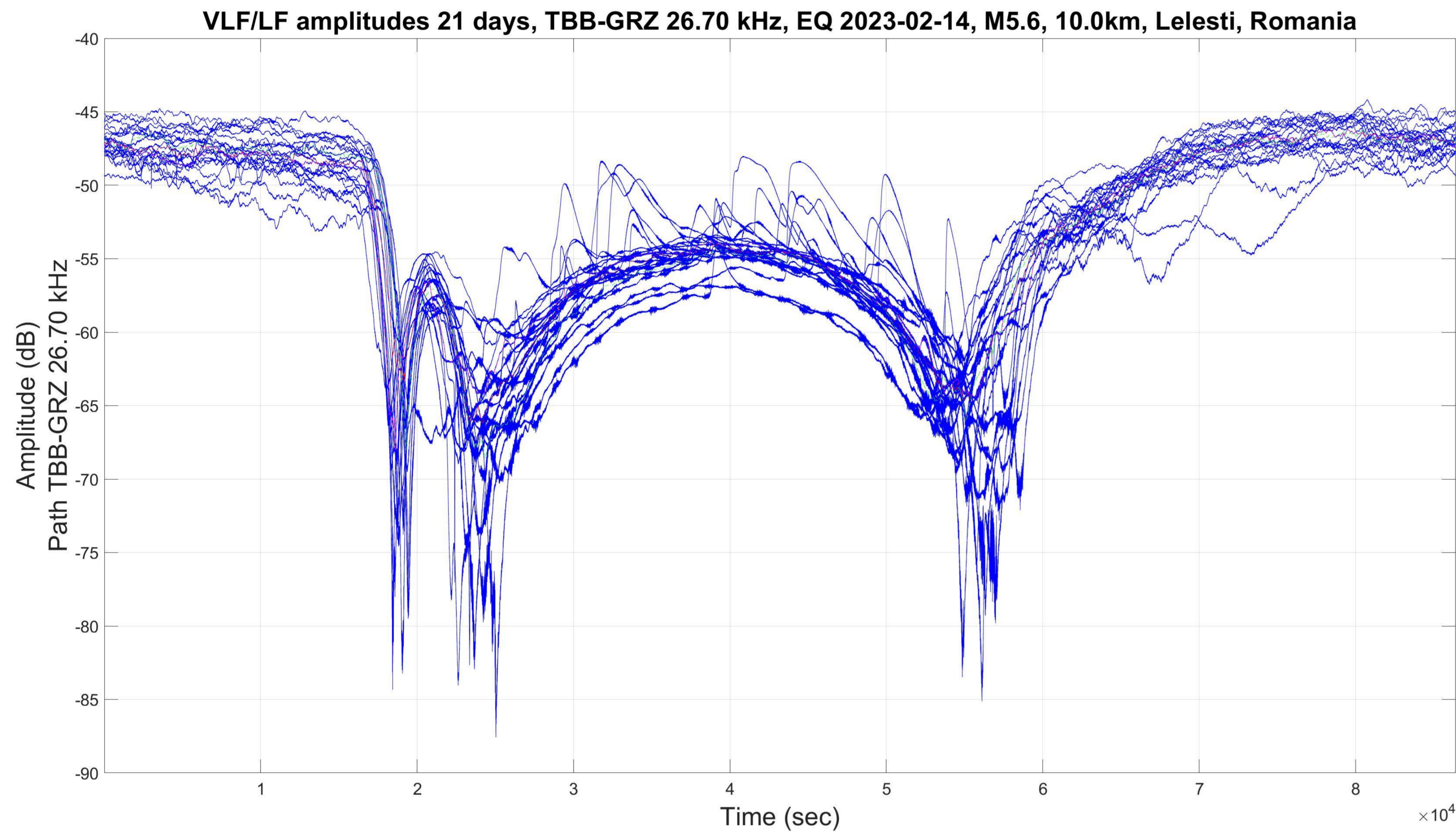
INVESTIGATION OF VLF/LF ELECTRIC FIELD VARIATIONS RELATED TO MAGNITUDE $MW \geq 5.5$ EARTHQUAKES IN THE MEDITERRANEAN REGION FOR THE YEAR 2023

Hans Eichelberger¹, Mohammed Y. Boudjada¹, Konrad Schwingenschuh¹, Bruno P. Besser¹, Daniel Wolbang¹, Maria Solovieva², Pier F. Biagi³, Patrick H. M. Galopeau⁴, Ghulam Jaffer⁵, Christoph Schirninger⁶, Aleksandra Nina⁷, Gordana Jovanovic⁸, Giovanni Nico⁹, Manfred Stachel¹, Özer Aydogar¹, Cosima Muck¹, Josef Wilfinger¹, Irmgard Jernej¹, and Werner Magnes¹

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VLF/LF AMPLITUDE MEASUREMENTS, EARTHQUAKE 2023-02-14, M5.6 10 KM, LELEȘTI, ROMANIA

- Top Left: VLF/LF amplitudes (2023-02-04 to 2023-02-24) for the 26.70 kHz TBB-GRZ path, spikes and transmitter switch off periods are omitted
- Bottom Left: Offset corrected nighttime (± 2 h around midnight) amplitude values for the 15 paths
- Top Right: Nighttime amplitude values for the affected TBB-GRZ event path (crossing the Dobrovolsky-Bowman area/radius)
- Bottom Right: Statistics (box plots) for the offset corrected 15 paths, **no significant variations (5% level) according to the nighttime method**



INVESTIGATION OF VLF/LF ELECTRIC FIELD VARIATIONS RELATED TO MAGNITUDE $MW \geq 5.5$ EARTHQUAKES IN THE MEDITERRANEAN REGION FOR THE YEAR 2023

Hans Eichelberger¹, Mohammed Y. Boudjada¹, Konrad Schwingenschuh¹, Bruno P. Besser¹, Daniel Wolbang¹, Maria Solovieva², Pier F. Biagi³, Patrick H. M. Galopeau⁴, Ghulam Jaffer⁵, Christoph Schirninger⁶, Aleksandra Nina⁷, Gordana Jovanovic⁸, Giovanni Nico⁹, Manfred Stachel¹, Özer Aydogar¹, Cosima Muck¹, Josef Wilfinger¹, Irmgard Jernej¹, and Werner Magnes¹

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VLF/LF AMPLITUDE MEASUREMENTS, EARTHQUAKES 2023-02-20, M6.3 16 KM & M5.5 10 KM, UZUNBAĞ, TURKEY

- Top Left: VLF/LF amplitudes (2023-02-10 to 2023-03-02) for the 26.70 kHz TBB-GRZ path, spikes and transmitter switch off periods are omitted
- Bottom Left: Offset corrected nighttime (± 2 h around midnight) amplitude values for the 15 paths
- Top Right: Nighttime amplitude values for the affected TBB-GRZ event path (crossing the Dobrovolsky-Bowman area/radius)
- Bottom Right: Statistics (box plots) for the offset corrected 15 paths, **for a sig. level of 5% the paths ISR-GRZ, NAA-GRZ, ICV-GRZ show higher amplitude values after the EQ, TBB-GRZ almost**

