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Hans Eichelberger, Mohammed Boudjada, Konrad Schwingenschuh, Bruno Besser, Daniel Wolbang, et al.. Sub-ionospheric VLF/LF waveguide variations related to magnitude $M > 5$ earthquakes in the eastern Mediterranean area. EGU23, the 25th EGU General Assembly, Apr 2023, Vienna, Austria. pp. EGU-8521, 10.5194/egusphere-egu23-8521 . insu-04486976

HAL Id: insu-04486976

<https://insu.hal.science/insu-04486976v1>

Submitted on 3 Jun 2024

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SUB-IONOSPHERIC VLF/LF WAVEGUIDE VARIATIONS RELATED TO MAGNITUDE M>5 EARTHQUAKES IN THE EASTERN MEDITERRANEAN AREA

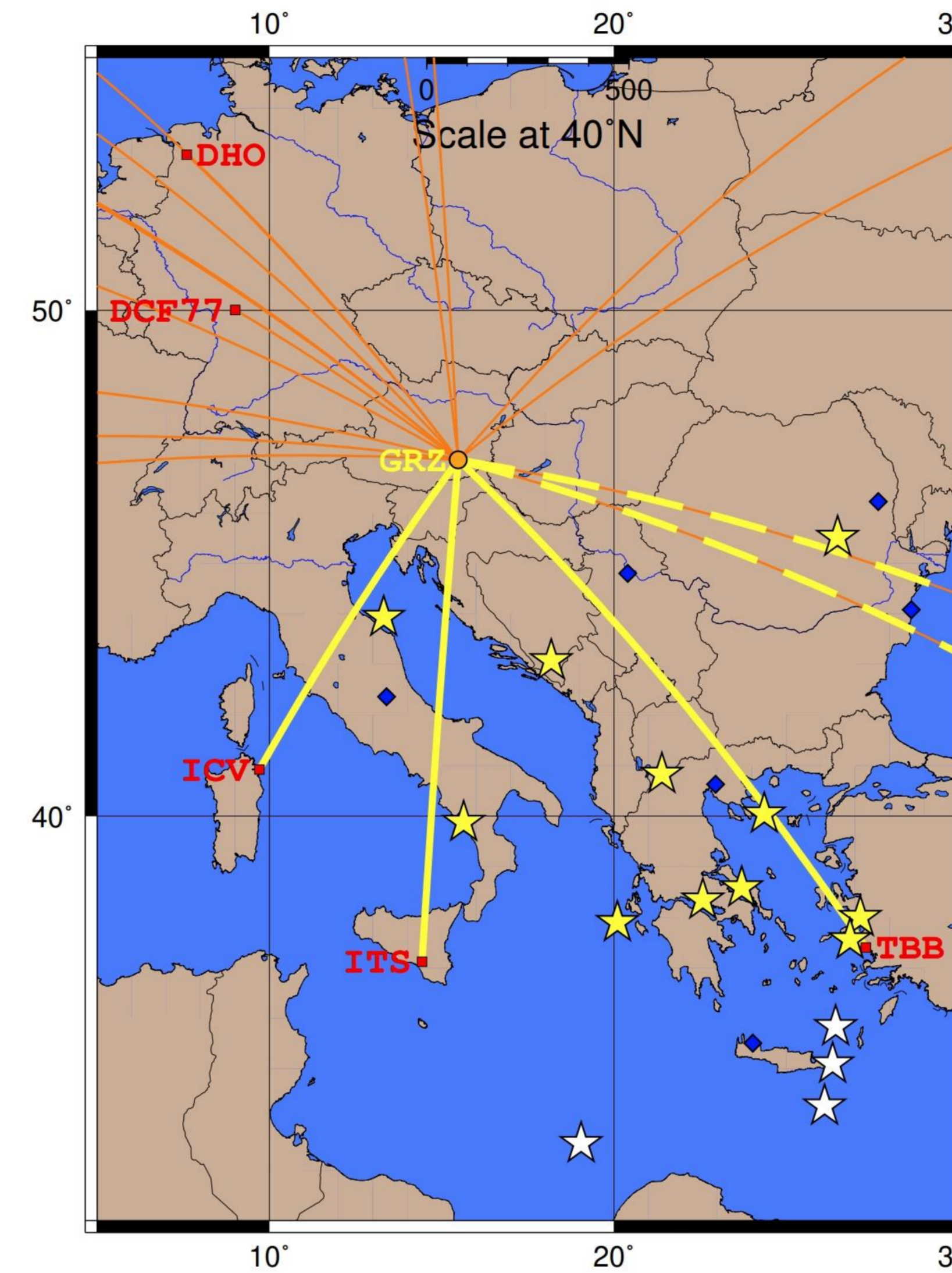
Hans Eichelberger¹, Mohammed Y. Boudjada¹, Konrad Schwingenschuh¹, Bruno P. Besser¹, Daniel Wolbang¹, Maria Solovieva², Pier Francesco Biagi³, Patrick Galopeau⁴, Ghulam Jaffer⁵, Özer Aydogar¹, Christoph Schirninger¹, Cosima Muck¹, Irmgard Jernej¹, and Werner Magnes¹

¹ Space Research Institute, Austrian Academy of Sciences, Graz, Austria, ² Schmidt Institute of Physics of the Earth, RAS, Moscow, Russia, ³ Department of Physics, University of Bari, Bari, Italy, ⁴ LATMOS-CNRS, UVSQ Université Paris-Saclay, Guyancourt, France, ⁵ SpaSys, SnT - Interdisciplinary Centre for Security, Reliability and Trust, University of Luxembourg, Luxembourg

In this study we examine earthquakes with magnitude $M \geq 5$ in the year 2022 where the epicenters are crossed by sub-ionospheric narrowband VLF/LF radio links. The study regions are Italy, Aegean area, and the Balkan Peninsula. Ideal suited for this task are paths from the transmitters TBB (26.70 kHz, Bafa, Turkey), ITS (45.90 kHz, Niscemi, Sicily, Italy), and ICV (20.27 kHz, Tavolara, Italy) to the seismo-electromagnetic receiver facility GRZ (Graz, Austria). The receiver is part of a wider network, this gives the opportunity to have multiple simultaneous crossings of an earthquake event. We investigate electric field amplitude variations in the time span a few days around the main shock, in particular we apply the so-called night-time amplitude method. All electric field data sets have 1 sec temporal resolution. A crucial point is a certain threshold magnitude to obtain statistically significant results, but to firm up the results additional complementary investigations are necessary. In summary, VLF/LF investigations of strong earthquakes show the complex interplay between the lithospheric events and electric field amplitude waveguide variations, multi-parametric observations in a network could be a tool to derive robust results.

VLF/LF NETWORK, SOUTH EUROPEAN PATHS

Figure 1: Great circle paths (orange & yellow lines) between VLF/LF transmitter and Graz receiver (orange circle, UltraMSK system [3]), for the INFREP system (diamonds in blue color) see [4]. Magnitude $M > 5$ earthquakes (15 white & yellow stars) and the relevant paths (ITS-GRZ, TBB-GRZ, and ICV-GRZ) related to Dobrovolsky-Bowman relationship are indicated (yellow lines good S/N, yellow-dotted lines are VTX-GRZ and NWC-GRZ long distance paths). Credit map: GMT



TRANSMITTER, VLF/LF SYSTEM PARAMETERS

| Receiver: Graz, IWF, Elektronika [E] and UltraMSK [U] system, N 47°2'40.38" O 15°28'47.68" | | | | |
|--|-----------|-----------------|------------|---|
| No. | Acronym | Frequency (kHz) | GCP (km) | Transmitter, Systems [U 1sec], [U 20sec], [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 | Vijayanarayananam, 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 | NRK | 37.50 | 2975 | Keflavik, Iceland [U 1s] [U 20s] [E 60s] |
| 16 | JJY | 40.00 | 9195 | Mount Otakadoya, Honshu, Japan [U 1s] |
| 17 | NAU | 40.80 | 7985 | Aguada, Puerto Rico, USA [U 1s] |
| 18 | ITS | 45.90 | 1105 | Niscemi, Sicily, Italy [U 1s] [U 20s] |
| 19 | DCF | 77.50 | 580 | Mainflingen, Germany [U 1s] |
| 20 | RRO | 153 | 790 | Brasov, Romania [E 60s] |
| 21 | TDF (EU1) | 162 (183) | 1010 (700) | Allouis, France (Felsberg-Berus, Luxembourg) [E 60s] |
| 22 | CHI | 198 | 1900 | Berkaoui/Ouargia, Algeria [E 60s] |
| 23 | RTL (MCO) | 234 (216) | 740 (820) | Beidweiler, Luxembourg (Roumoules, Monte Carlo) [E 60s] |
| 24 | CZE | 270 | 275 | Topolna, Czech Republic [E 60s] |

Table 2: Transmitter received at the VLF/LF Graz facility, current settings in blue/green color, see [3, 4], event paths in yellow color.

EARTHQUAKES $M \geq 5$, 2022, EASTERN MEDITERRANEAN AREA, DATA PROCESSING & RESULTS

We investigate VLF/LF electric fields from sub-ionospheric VLF/LF propagation paths in the geographic lat/lon range $[30^\circ \leq \text{lat} \leq 50^\circ]$ / $[10^\circ \leq \text{long} \leq 30^\circ]$, i.e., an Eastern Mediterranean area, in the year 2022. For this temporal, spatial and moment magnitude $M_w \geq 5$ the USGS earthquake database [7] gives 15 EQs. All events (Tab. 1, Fig. 1) are selected, emphasis is according to VLF/LF path crossings and the size of the Dobrovolsky-Bowman relationship [1, 2] (the radius of the effective precursor manifestation zone $\rho = 10^{(0.43^*M)}$ km and $\log(R) \approx M/2$ km). Four events are out of a crossing area (Fig. 1, white stars and Tab. 1, no. 12-15). The VLF/LF amplitude data have 1 Hz temporal resolution, nighttime values are used (± 2 hours around midnight), see [5, 6]. The values 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 field and EQ, based on statistics from nighttime electric field amplitude variations with significance level 5%, are mainly achieved for $M \geq 5.5$ earthquakes.

| Selected Earthquakes Magnitude $M \geq 5$, USGS database, time span 01.01.2022 – 31.12.2022, long/lat range: $[10^\circ-30^\circ]/[30^\circ-50^\circ]$ | | | | | | | |
|---|---------------------|--------------------------------|-------------------|---------------------------|---------------|--|---|
| No. | Date, Time | Lat (°) / Lon (°) / Depth (km) | Mag / ρ (km) | Location | Main path | Control paths | Result, Annotation |
| 1 | 2022-01-09 21:43:47 | +40.827 / +21.392 / 13.4 | 5.5 / 232 | Flórina, Greece | TBB-GRZ | 6 {NAA,ICV,GWU,GBZ,GBS,NRK}-GRZ | Not OK: not significant, all paths out of 5% level |
| 2 | 2022-01-16 11:48:05 | +40.041 / +24.361 / 7.0 | 5.5 / 232 | Karyes, Greece | TBB-GRZ | 8 {NAA,JJI,ICV,GWU,GBZ,GBS,DHO,NRK}-GRZ | Not OK: not significant, except ICV |
| 3 | 2022-04-22 21:07:48 | +43.074 / +18.180 / 10.0 | 5.7 / 282 | Ljubinjce, Bos. & Herzeg. | ITS-GRZ | 9 {TBB,NAA,JJI,ICV,HWU,GBZ,DHO,DCF,NRK}-GRZ | OK: Post EQ > Pre EQ values with significance level 5% |
| 4 | 2022-08-14 03:24:22 | +37.995 / +27.151 / 11.7 | 5.0 / 141 | Özdere, Turkey | TBB-GRZ | 8 {NAA,ITS,HWU,GBZ,GBS,DHO,DCF,NRK}-GRZ | Not OK: not significant |
| 5 | 2022-08-31 10:10:11 | +37.553 / +26.852 / 10.9 | 5.4 / 210 | Megálo Chorió, Greece | TBB-GRZ | 9 {NAA,JJI,ITS,HWU,GBZ,GBS,DHO,DCF,NRK}-GRZ | Not OK: not significant, except NAA, GBZ, DHO |
| 6 | 2022-09-08 07:36:23 | +37.894 / +20.099 / 10.5 | 5.5 / 232 | Lixouri, Greece | {TBB,ITS}-GRZ | 6 {NAA,HWU,GBZ,GBS,DHO,NRK}-GRZ | OK / not OK: Post EQ > Pre EQ values with sig. level 5% |
| 7 | 2022-10-08 22:02:28 | +38.339 / +22.579 / 19.8 | 5.3 / 190 | Antikyra, Greece | TBB-GRZ | 9 {NAA,JXN,JJI,ITS,ICV,GBZ,GBS,DHO,NRK}-GRZ | OK: Post EQ > Pre EQ values with significance level 5% |
| 8 | 2022-10-31 21:42:50 | +39.877 / +15.640 / 271 | 5.5 / 232 | Tortora Marina, Italy | ITS-GRZ | 9 {TBB,NAA,JJI,ICV,GWU,GBZ,GBS,DHO,NRK}-GRZ | Not OK: not significant, except GBS |
| 9 | 2022-11-03 04:50:25 | +45.512 / +26.490 / 153 | 5.1 / 156 | Gura Teghii, Romania | TBB-GRZ | 9 {NAA,JJI,ITS,ICV,GWU,GBZ,GBS,DHO,NRK}-GRZ | Not OK: not significant, except GBS; out of Dob-Bow area |
| 10 | 2022-11-09 06:07:26 | +43.932 / +13.315 / 8.0 | 5.6 / 256 | Central Italy, Italy | {ITS,ICV}-GRZ | 9 {TBB,NAA,JJI,HWU,GWU,GBZ,GBS,DHO,NRK}-GRZ | Not OK: not significant, except TBB; ITS, ICV close to OK |
| 11 | 2022-12-28 12:24:20 | +38.581 / +23.709 / 10.3 | 5.0 / 141 | Psachná, Greece | TBB-GRZ | 9 {NAA,JJI,IST,ICV,GWU,GBZ,GBS,DHO,NRK}-GRZ | Not OK: not significant, except NAA, GBS, NRK |
| 12 | 2022-08-12 21:31:50 | +33.524 / +19.044 / 18.2 | 5.2 / 172 | Tukrah, Libya | {TBB,ITS}-GRZ | 7 {NAA,JJI,HWU,GBZ,GBS,DHO,NRK}-GRZ | No crossing link, not in Dobrovolsky-Bowman area |
| 13 | 2022-09-03 04:13:10 | +35.097 / +26.347 / 8.8 | 5.3 / 190 | Palekastro, Greece | TBB-GRZ | 10 {NAA,JXN,JJI,ITS,HWU,GBZ,GBS,DHO,DCF,NRK}-GRZ | No crossing link, not in Dobrovolsky-Bowman area |
| 14 | 2022-10-02 04:04:01 | +34.266 / +26.114 / 10.0 | 5.4 / 210 | Ierápetra, Greece | TBB-GRZ | 10 {NAA,JXN,JJI,ITS,ICV,GBZ,GBS,DHO,DCF,NRK}-GRZ | No crossing link, not in Dobrovolsky-Bowman area |
| 15 | 2022-11-20 23:24:58 | +35.836 / +26.412 / 63.0 | 5.5 / 232 | Crete, Greece | TBB-GRZ | | Receiver out of service during the EQ epoch |

Table 1: Results for all $M \geq 5$ earthquakes (see Figure 1, stars in yellow and white color), time period 2022, Eastern Mediterranean area.

REFERENCES

- Dobrovolsky, I.P., Zubkov, S.I., and Miachkin, V.I., *Estimation of the size of earthquake preparation zones*, PAGEOPH 117, 1025–1044, 1979. <https://doi.org/10.1007/BF00876083>
- Bowman, D.D., Ouilon, G., Sammis, C.G., Sornette, A., and Sornette, D., *An observational test of the critical earthquake concept*, JGR Solid Earth, 103, B10, 24359–24372, 1998. <https://doi.org/10.1029/98JB00792>
- Schwingenschuh, K., et al., *The Graz seismo-electromagnetic VLF facility*, NHESS, 11, 1121–1127, 2011. <https://doi.org/10.5194/nhess-11-1121-2011>
- Biagi, P.F., et al., *The INFREP Network: Present Situation and Recent Results*, OJER, 8, 101–115, 2019. <https://doi.org/10.4236/ojer.2019.82007> Website www.infrep-network.eu
- Rozhnoi, A., et al., *Middle latitude LF (40 kHz) phase variations associated with earthquakes for quiet and disturbed geomagnetic conditions*, Phys. Chem. Earth, Parts A/B/C, 29, 4–9, 589–598, 2004. <https://doi.org/10.1016/j.pce.2003.08.061>
- Rozhnoi, A., et al., *Anomalies in VLF radio signals prior the Abruzzo earthquake ($M=6.3$) on 6 April 2009*, NHESS, 9, 1727–1732, 2009. <https://doi.org/10.5194/nhess-9-1727-2009>
- United States Geological Survey (USGS) earthquake catalog, database and website <https://earthquake.usgs.gov/> as of April 2023.

SUMMARY

VLF/LF electric field variations (nighttime amplitude method; assumed significance level 5%) could be related to $M \geq 5.5$ (threshold) earthquakes. Multi-parametric observations shall complement the VLF/LF method to achieve robust results.



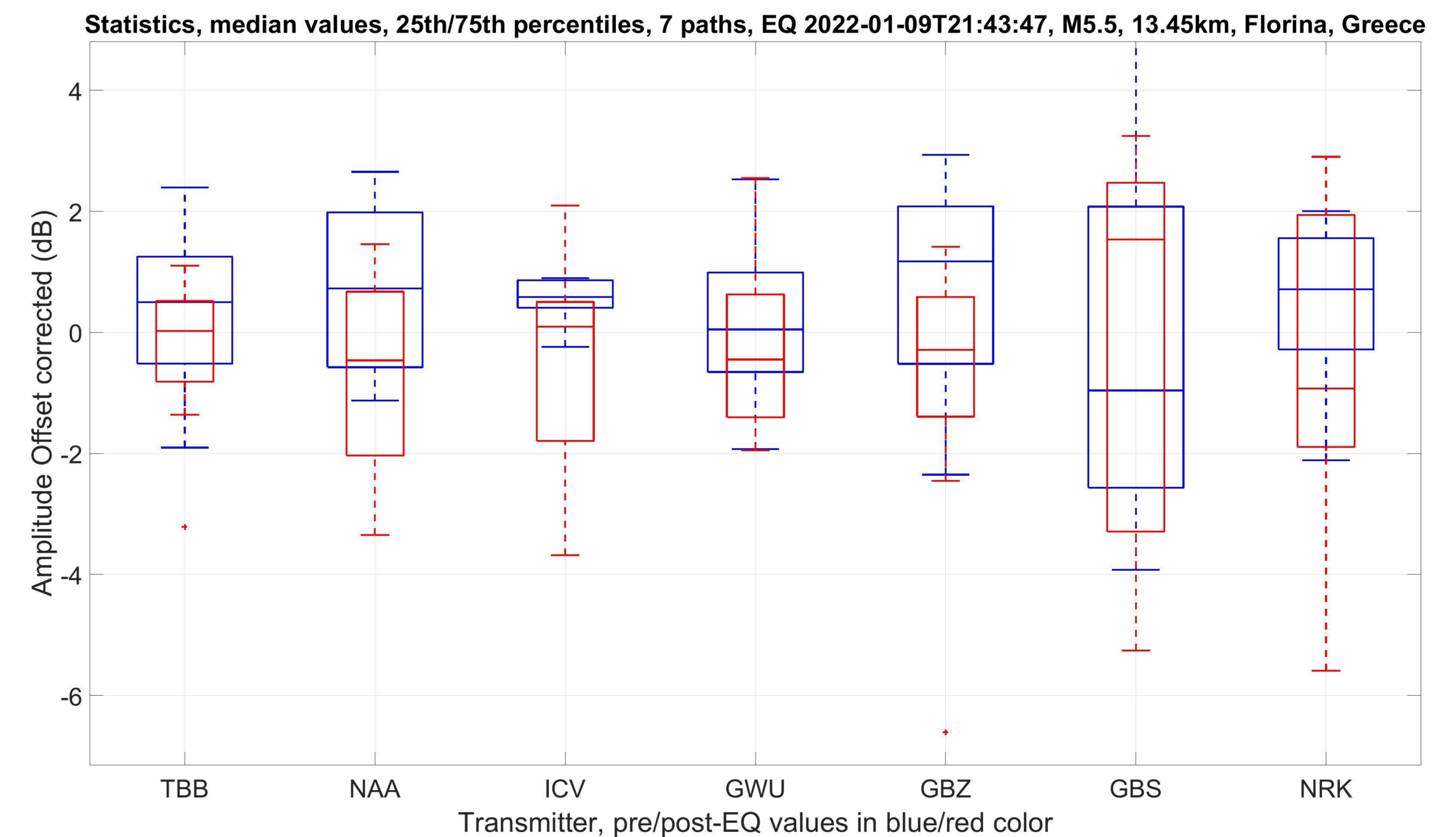
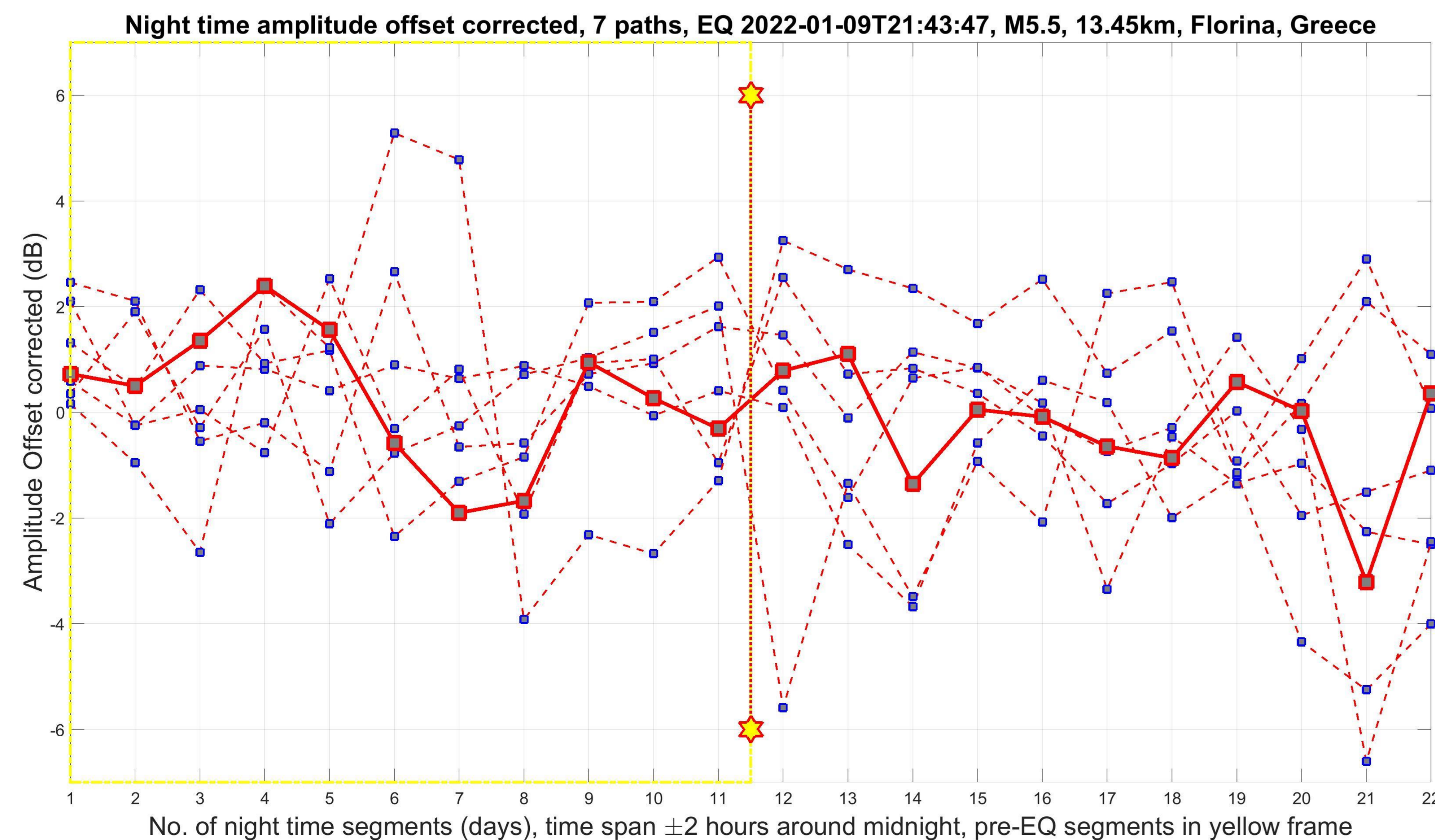
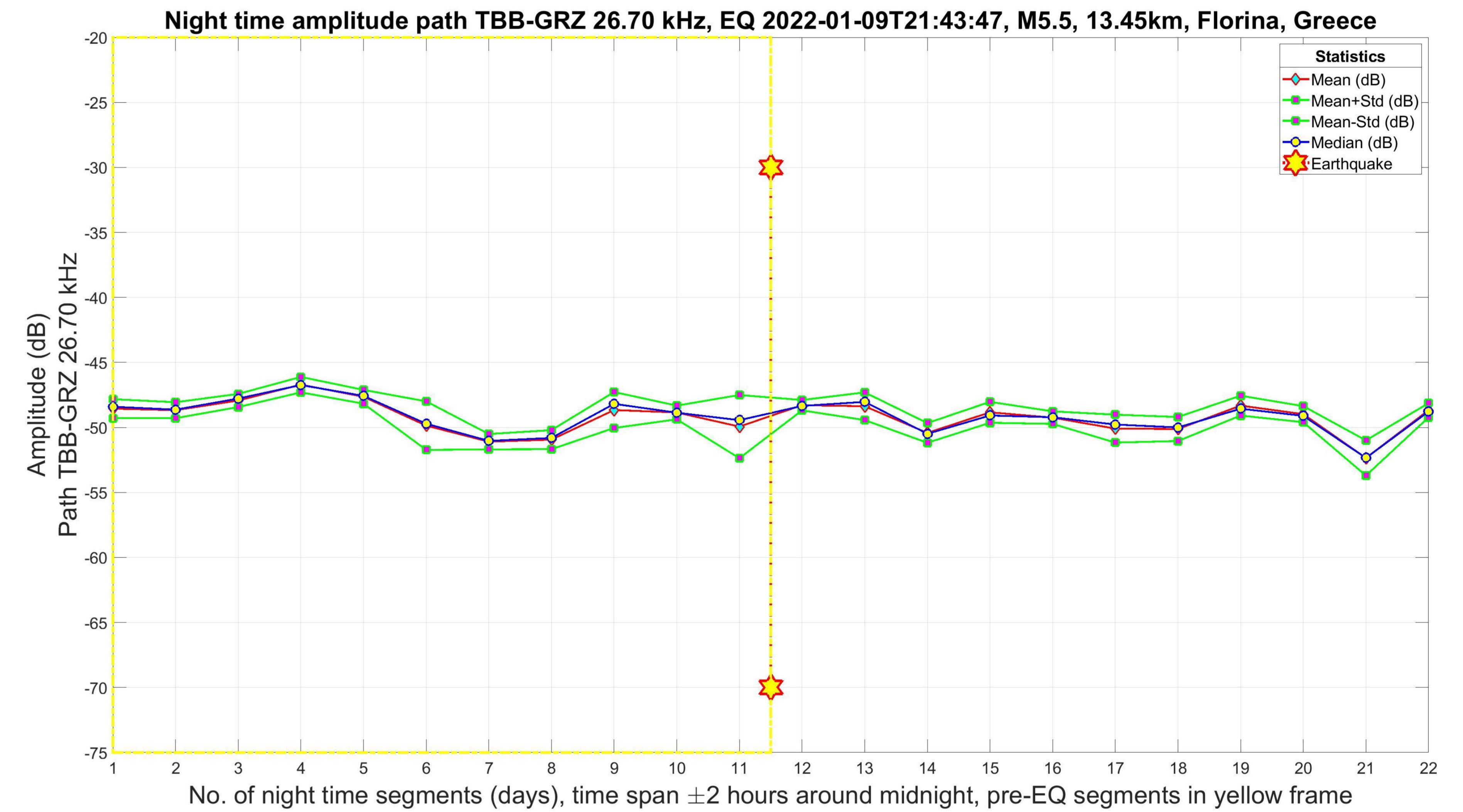
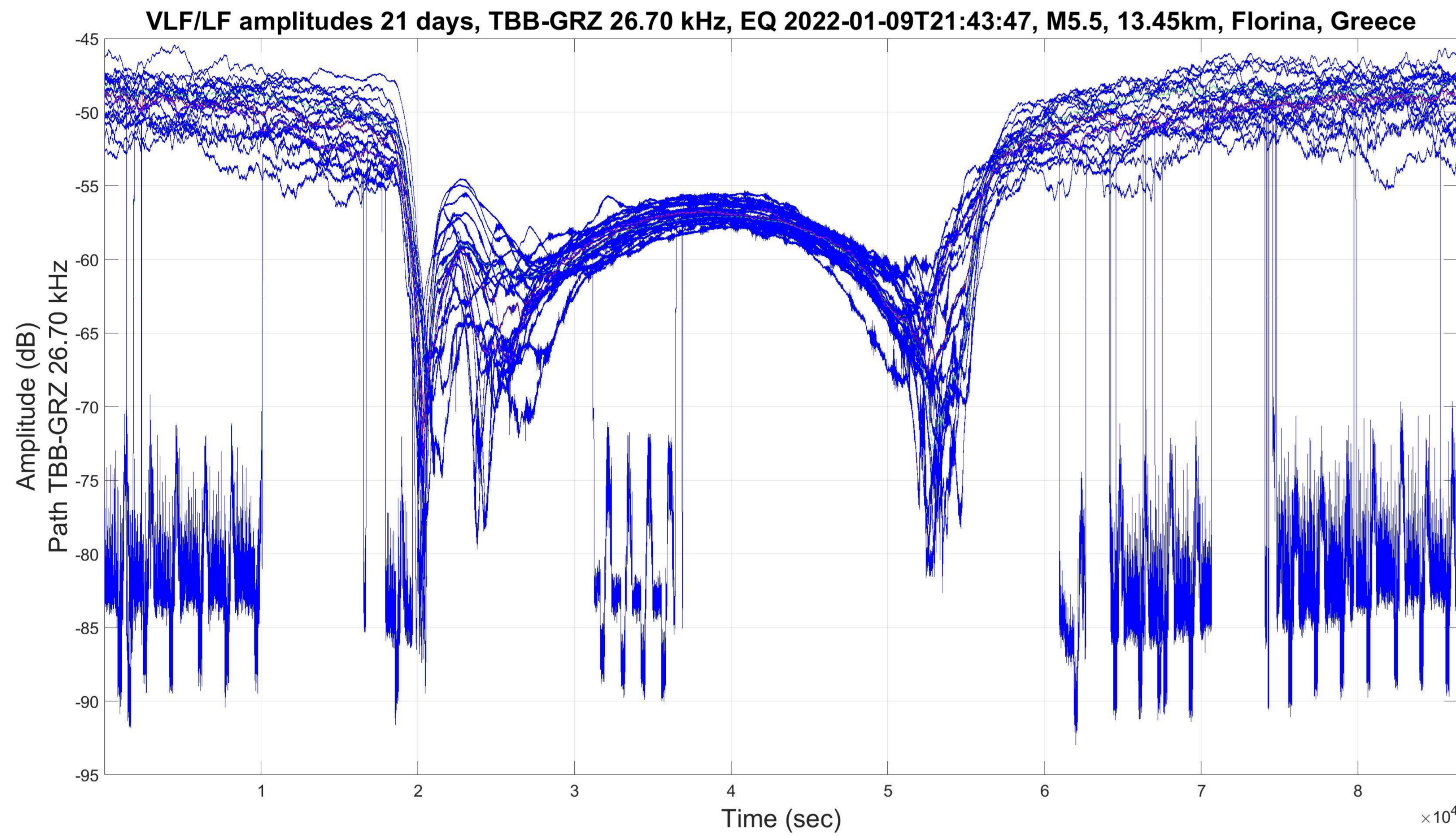
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VLF/LF AMPLITUDE MEASUREMENTS, EARTHQUAKE 2022-01-09, M5.5, 13.45 KM, FLÓRINA, GREECE

- Top Left: VLF/LF amplitudes (2021-12-30 to 2022-01-19) 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 7 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 7 paths, **no significant variations (5% level) according to the nighttime method**



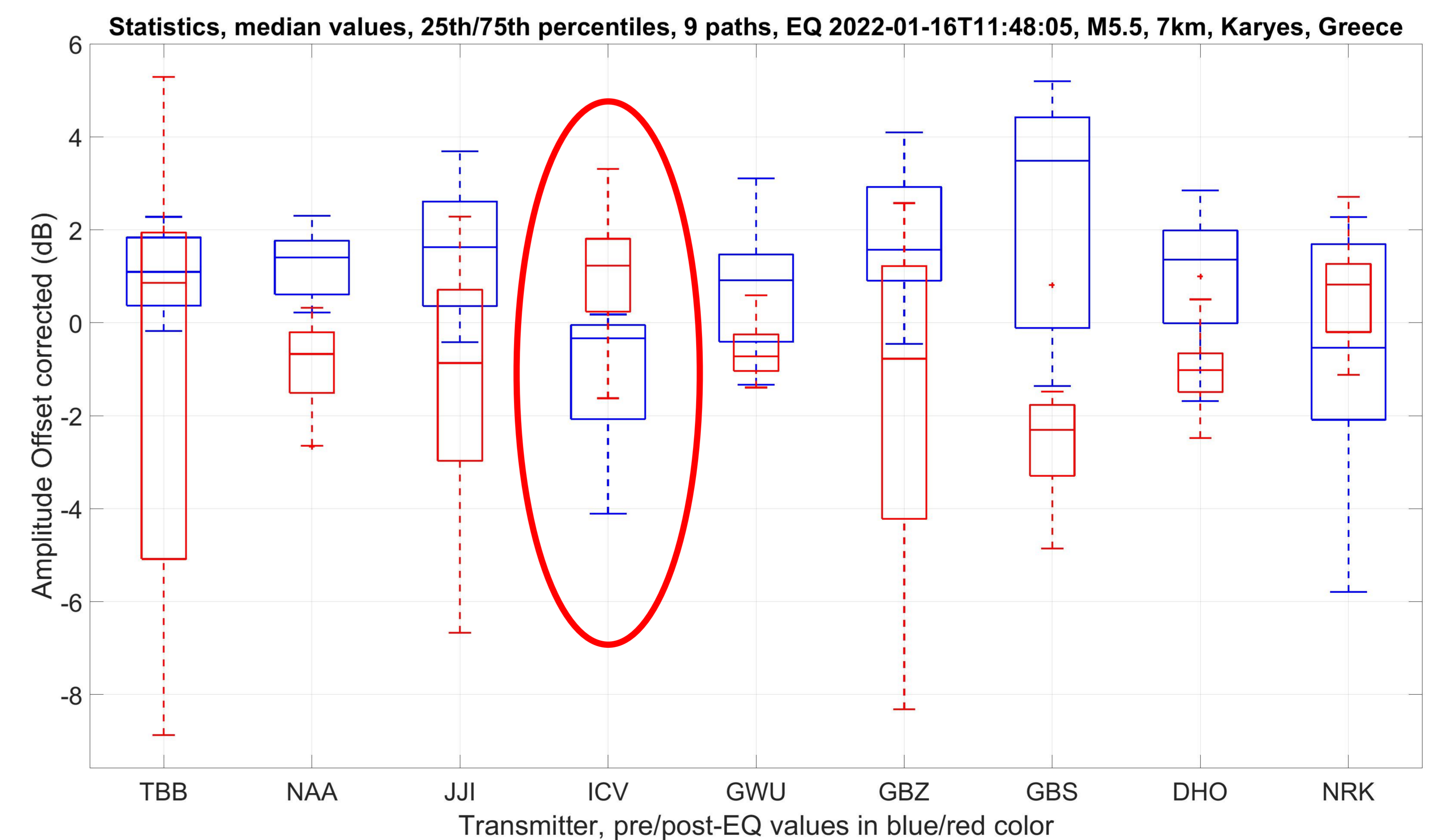
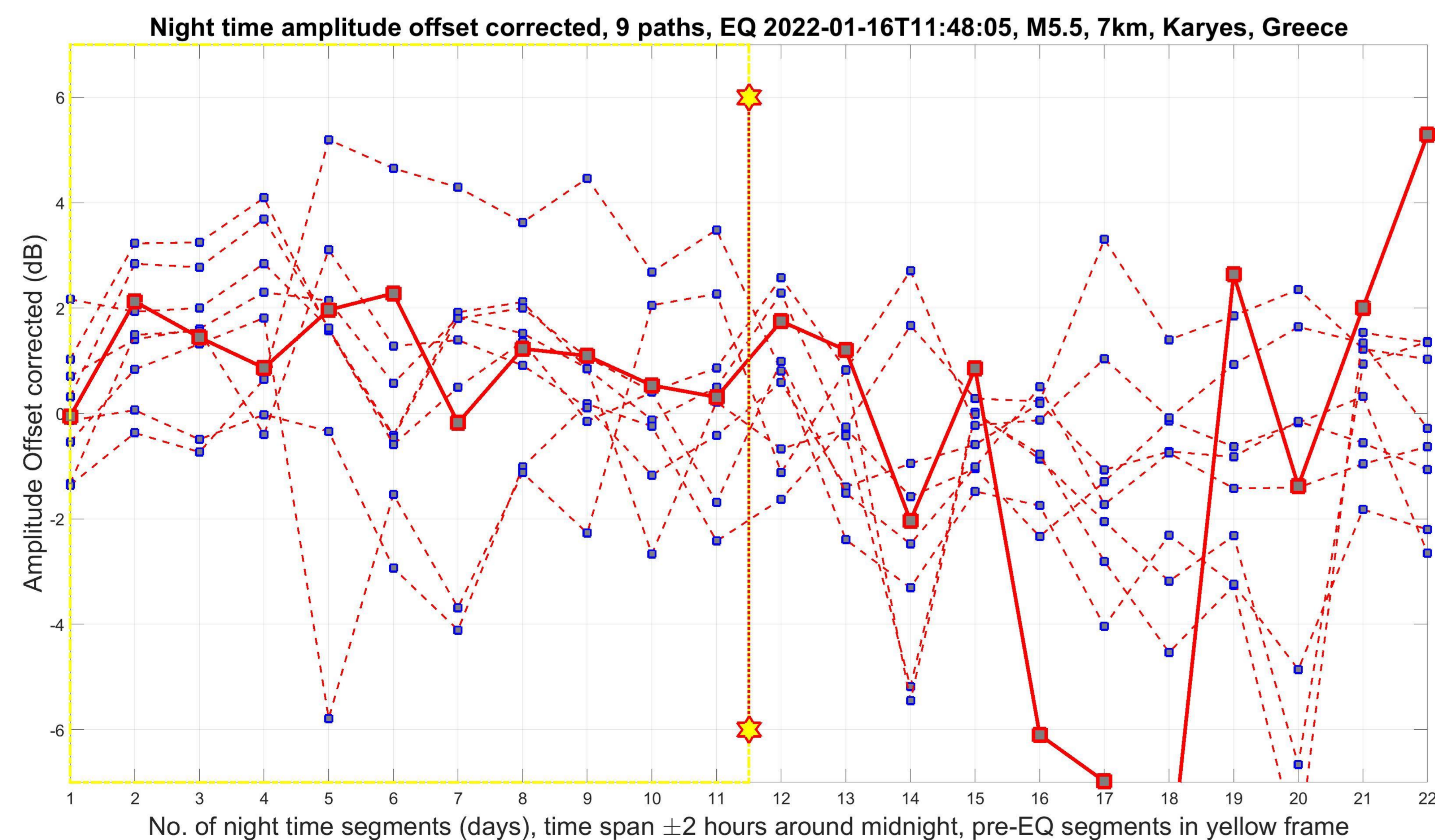
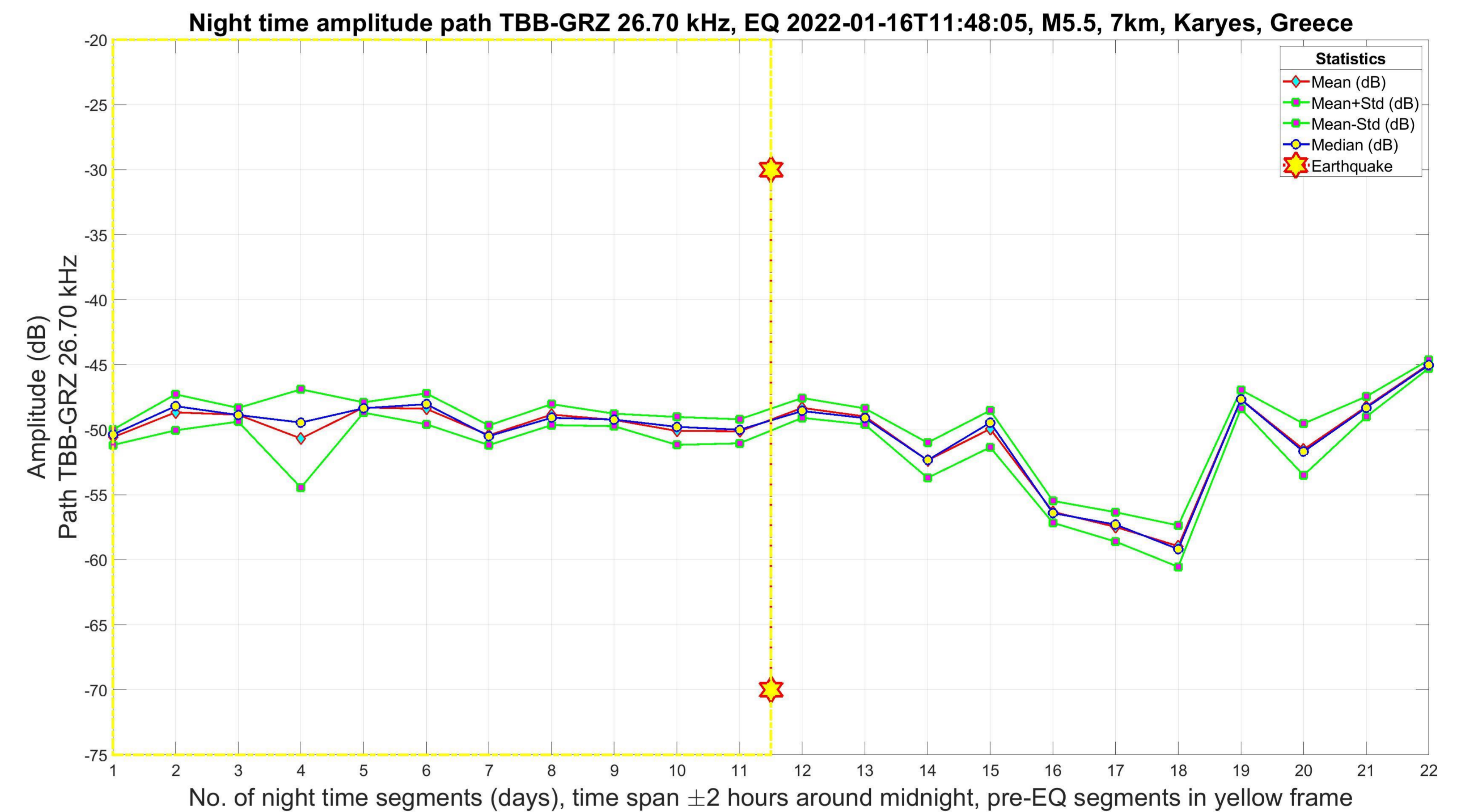
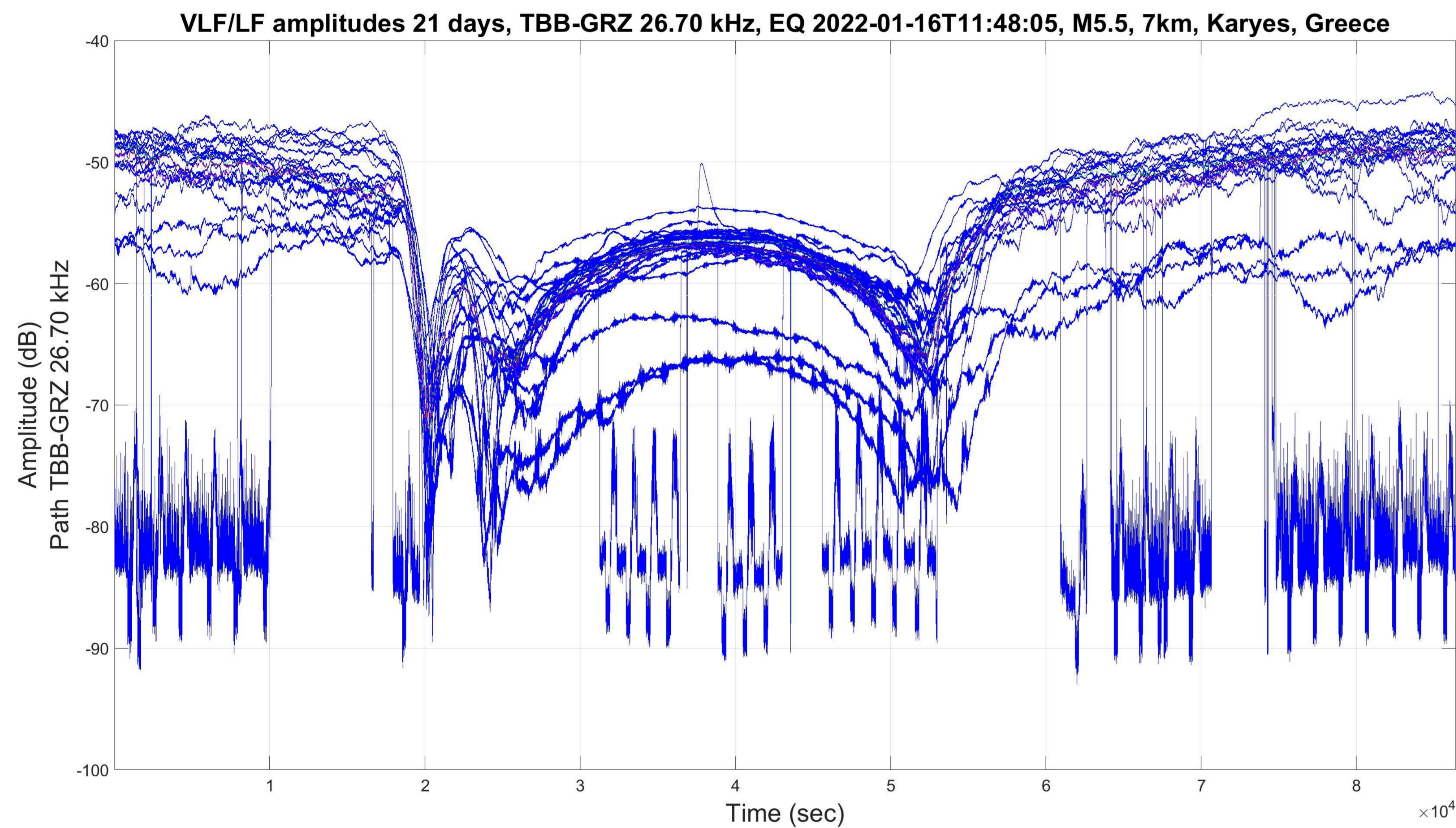
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VLF/LF AMPLITUDE MEASUREMENTS, EARTHQUAKE 2022-01-16, M5.5, 7 KM, KARYES, GREECE

- Top Left: VLF/LF amplitudes (2022-01-06 to 2022-01-26) for the 26.70 kHz TBB-GRZ path, spikes and transmitter switch off periods are omitted, **variations in the electric fields (power issue)**
- 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 ICV-GRZ shows higher amplitude values after the EQ (nighttime method)**



SUB-IONOSPHERIC VLF/LF WAVEGUIDE VARIATIONS RELATED TO MAGNITUDE M>5 EARTHQUAKES IN THE EASTERN MEDITERRANEAN AREA

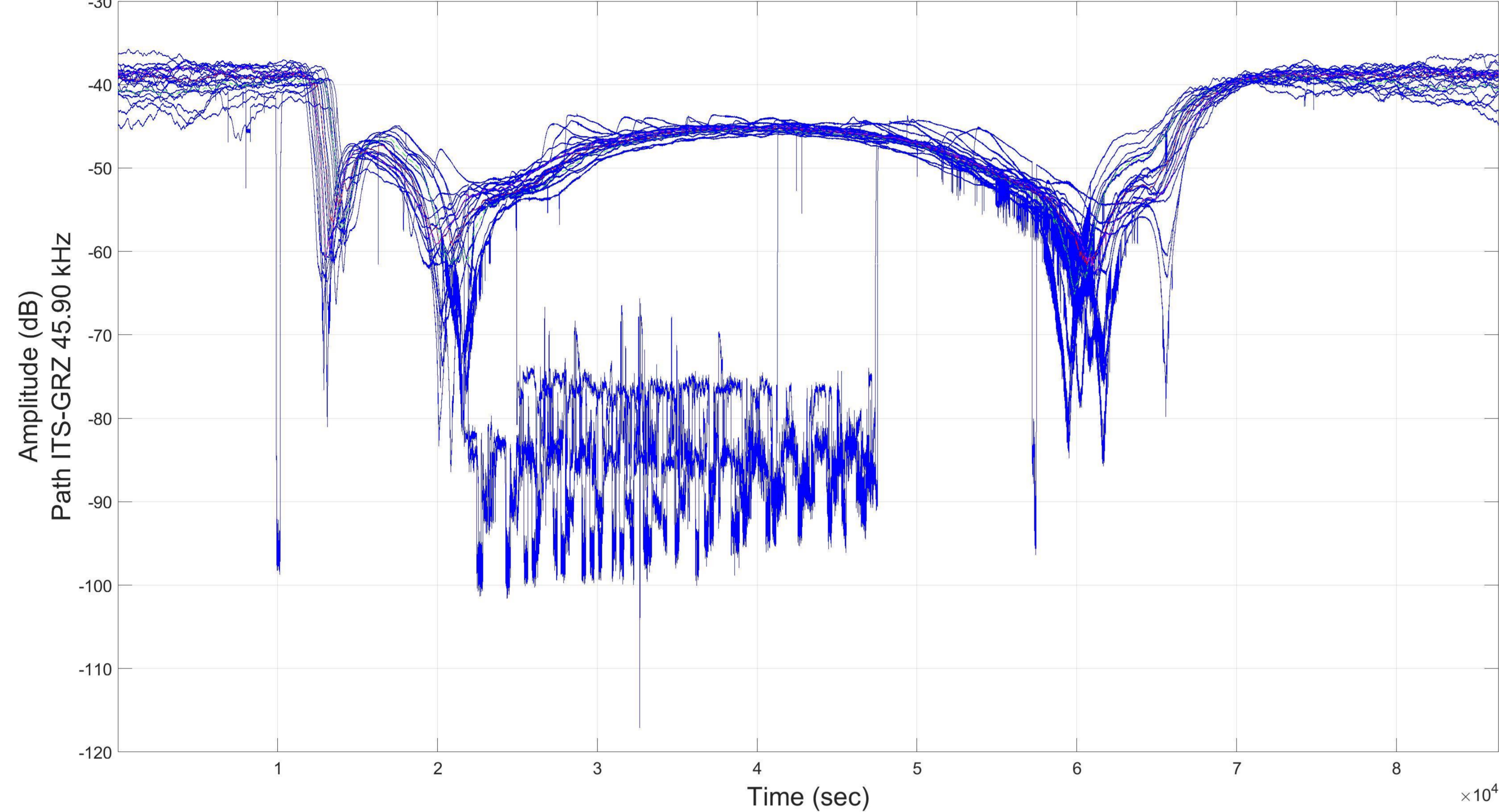
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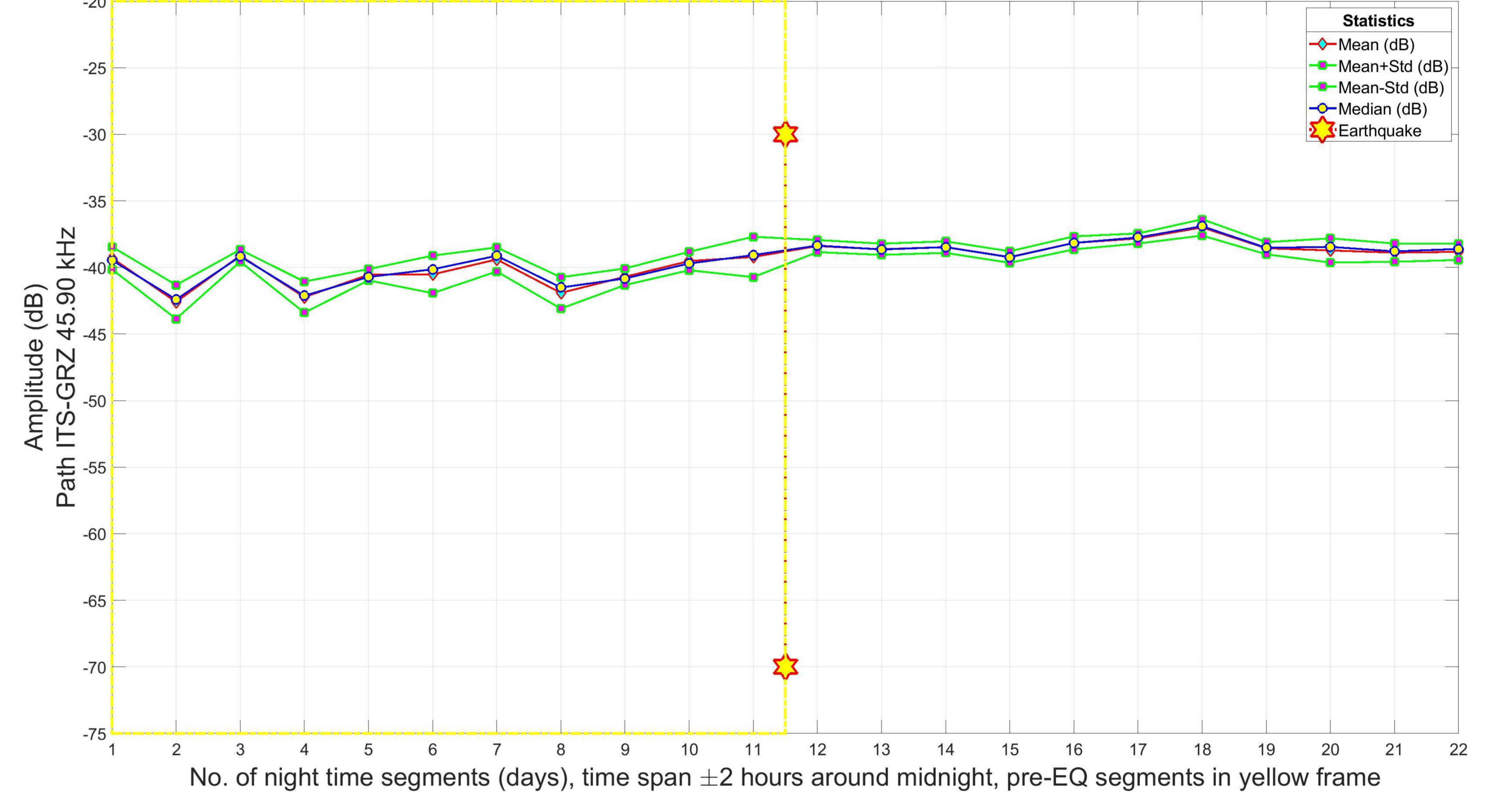
VLF/LF AMPLITUDE MEASUREMENTS, EARTHQUAKE 2022-04-22, M5.7, 10 KM, LJUBINJE, BOSNIA AND HERZEGOVINA

- Top Left: VLF/LF amplitudes (2022-04-12 to 2022-05-02) 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 10 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 10 paths, **for a significance level of 5% only the event path ITS-GRZ shows higher amplitude values after the EQ (nighttime method)**

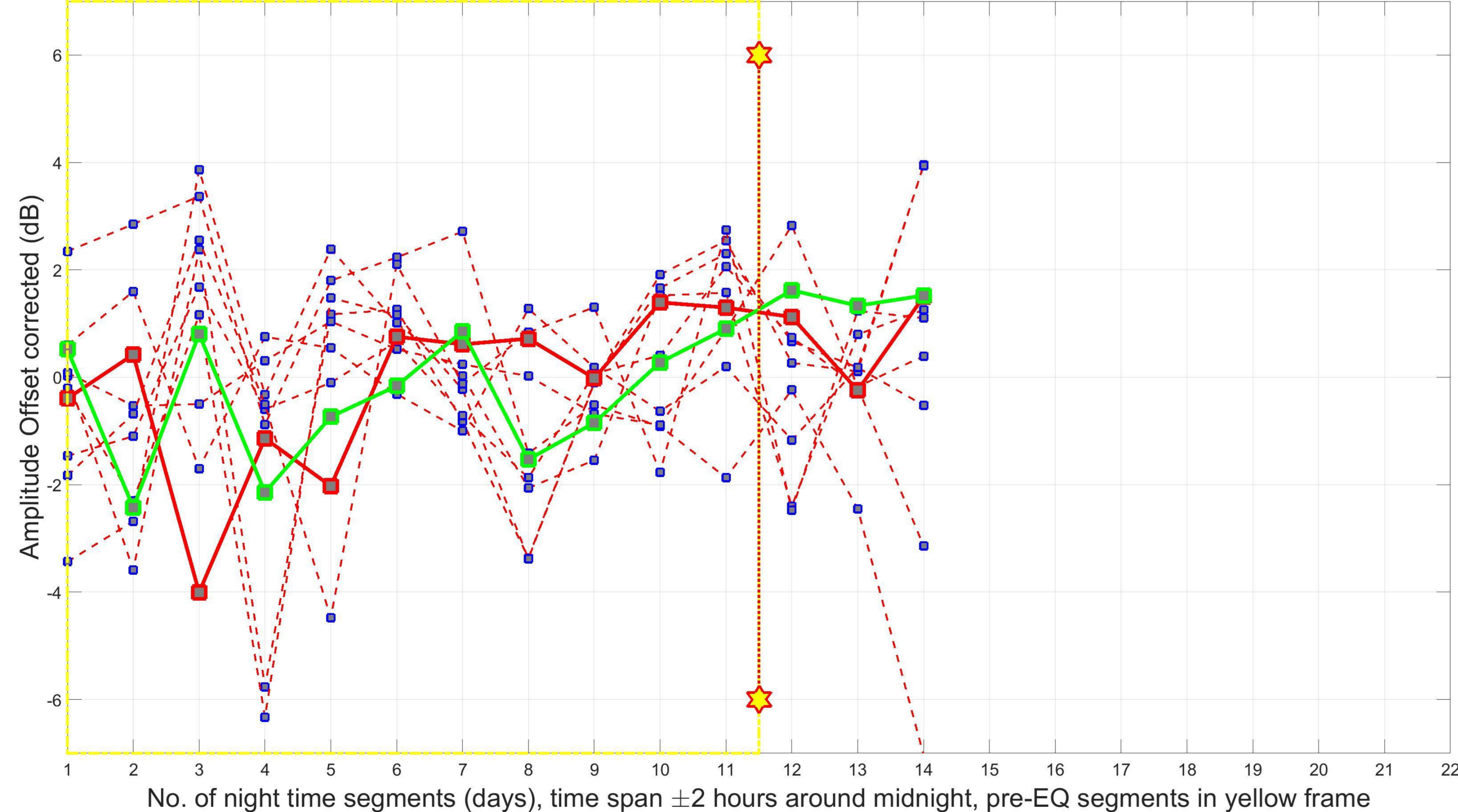
VLF/LF amplitudes 21 days, ITS-GRZ 45.90 kHz, EQ 2022-04-22T21:07:48, M5.7, 10km, Ljubinje, Bosnia and Herzegovina



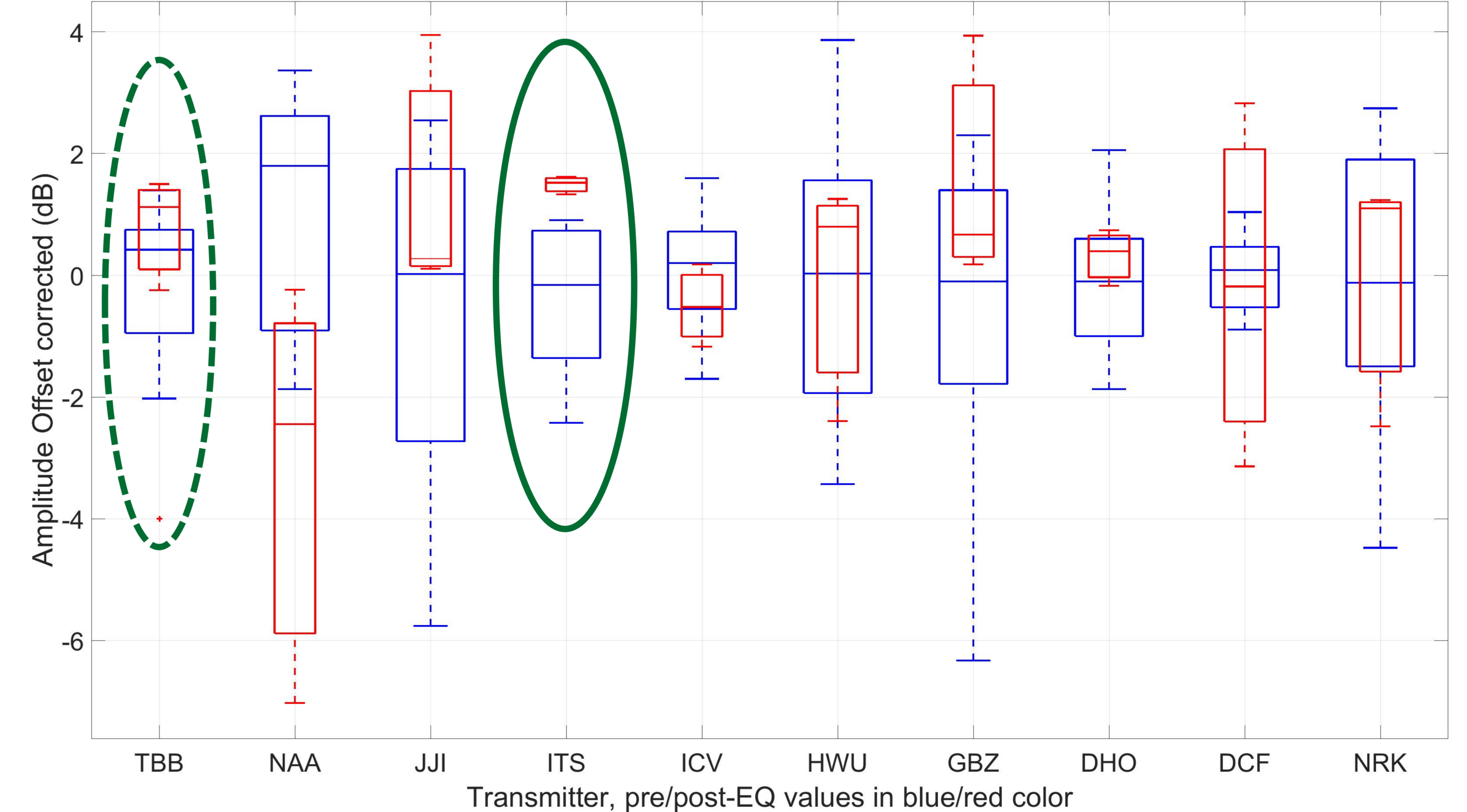
Night time amplitude path ITS-GRZ 45.90 kHz, EQ 2022-04-22T21:07:48, M5.7, 10km, Ljubinje, Bosnia and Herzegovina



Night time amplitude offset corrected, 10 paths, EQ 2022-04-22T21:07:48, M5.7, 10km, Ljubinje, Bosnia and Herzegovina



Statistics, median values, 25th/75th percentiles, 10 paths, EQ 2022-04-22T21:07:48, M5.7, 10km, Ljubinje, Bosnia and Herzegovina



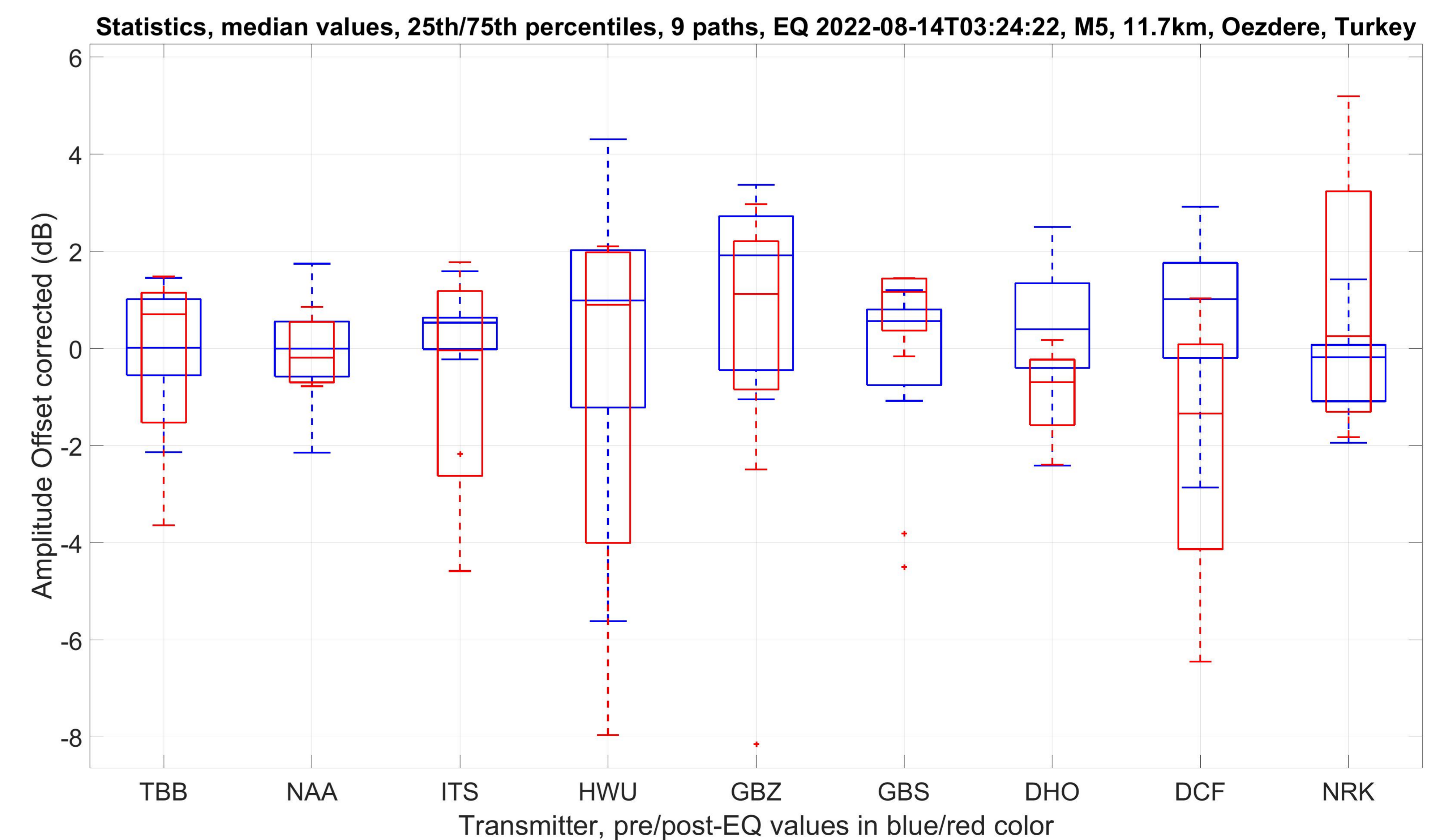
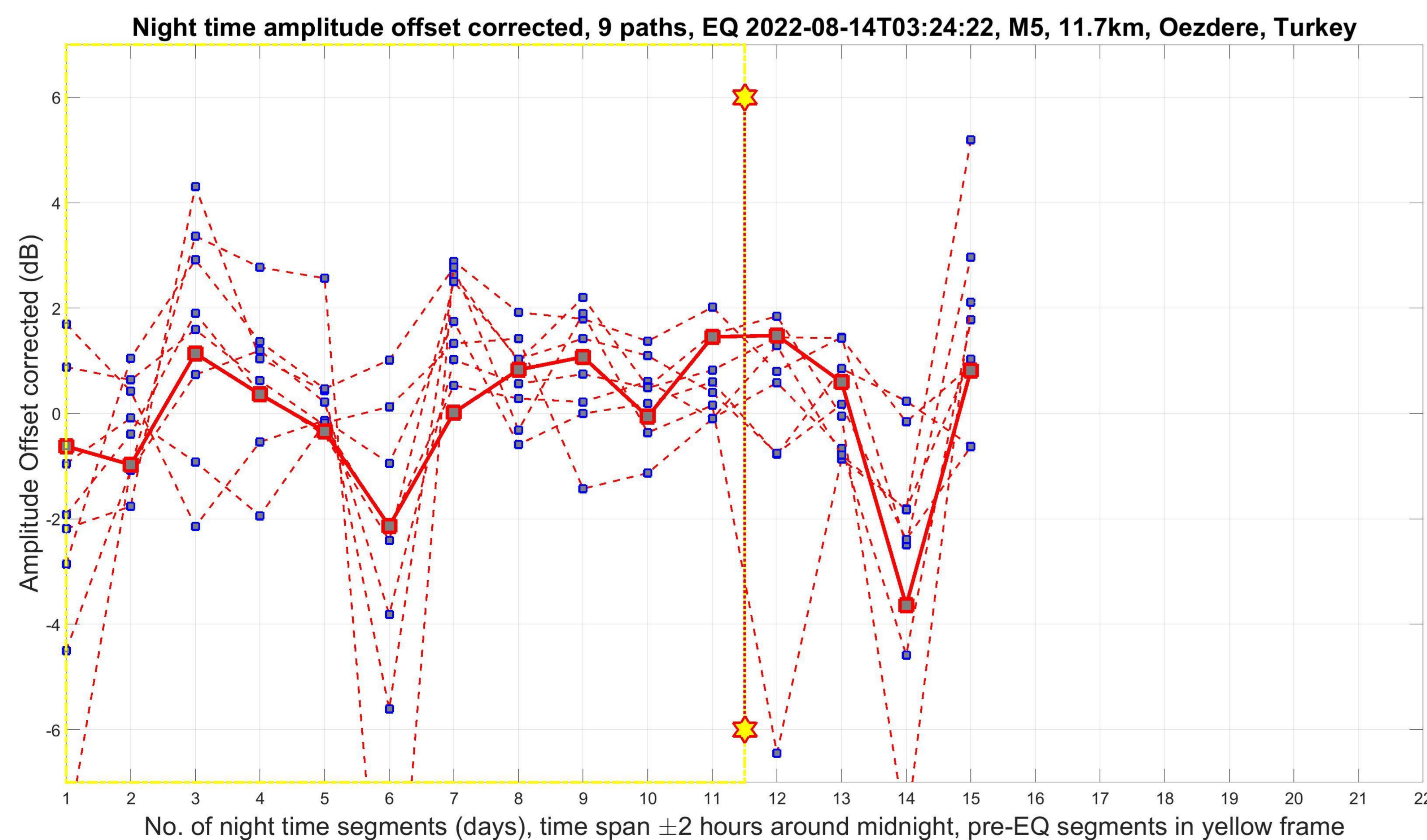
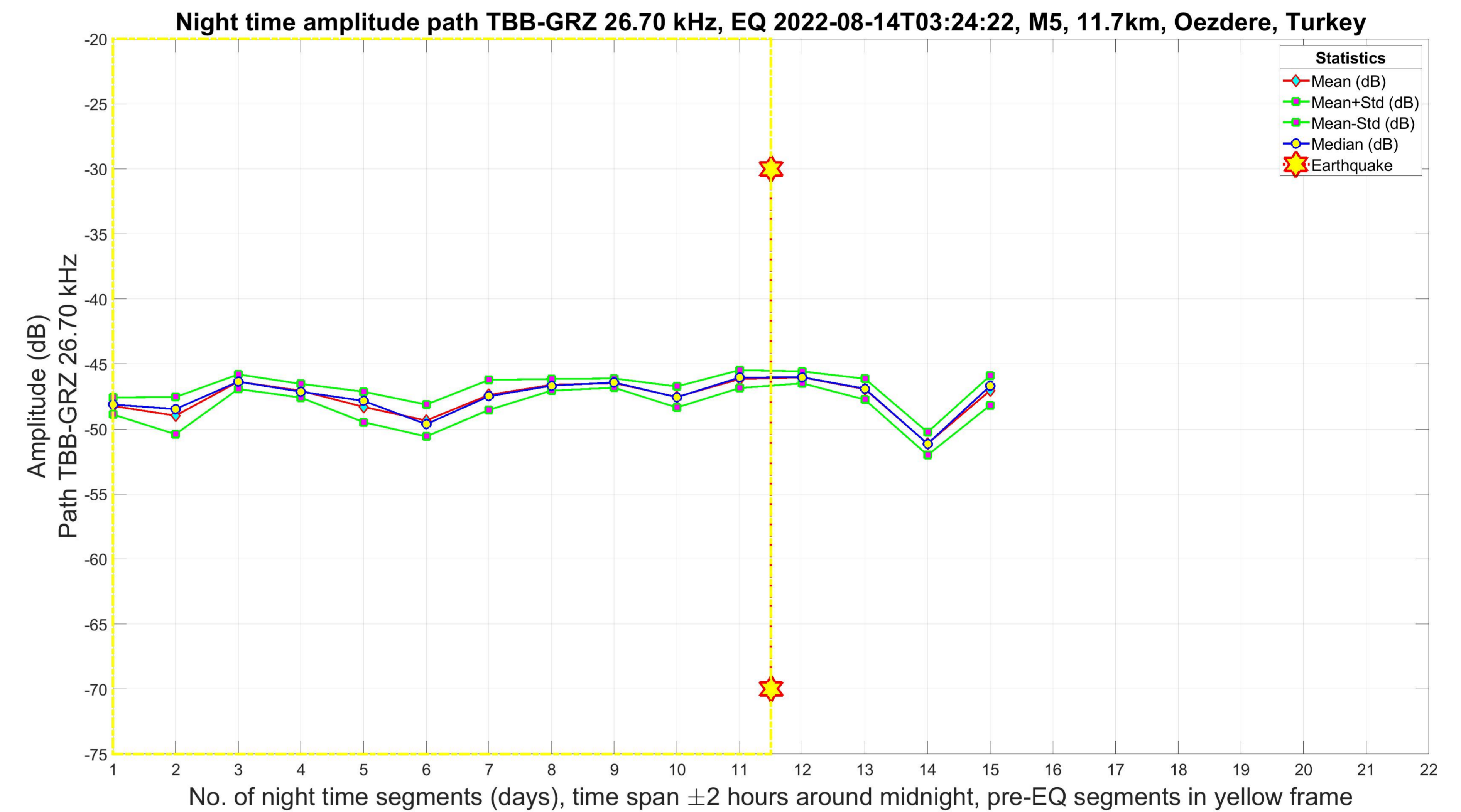
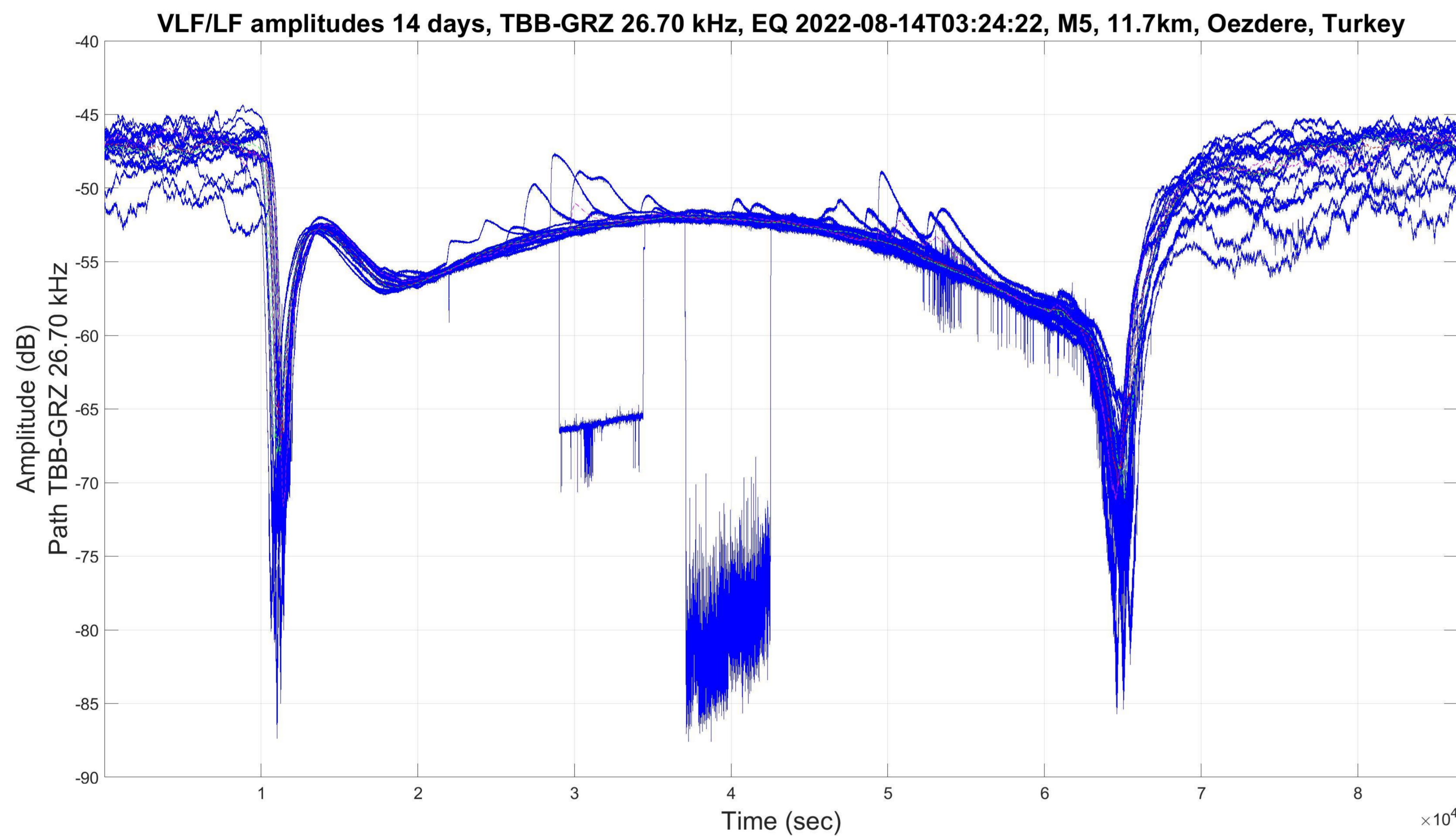
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VLF/LF AMPLITUDE MEASUREMENTS, EARTHQUAKE 2022-08-14, M5.0, 11.7 KM, ÖZDERE, TURKEY

- Top Left: VLF/LF amplitudes (2022-08-04 to 2022-08-17) 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, **no significant variations (5% level) according to the nighttime method**



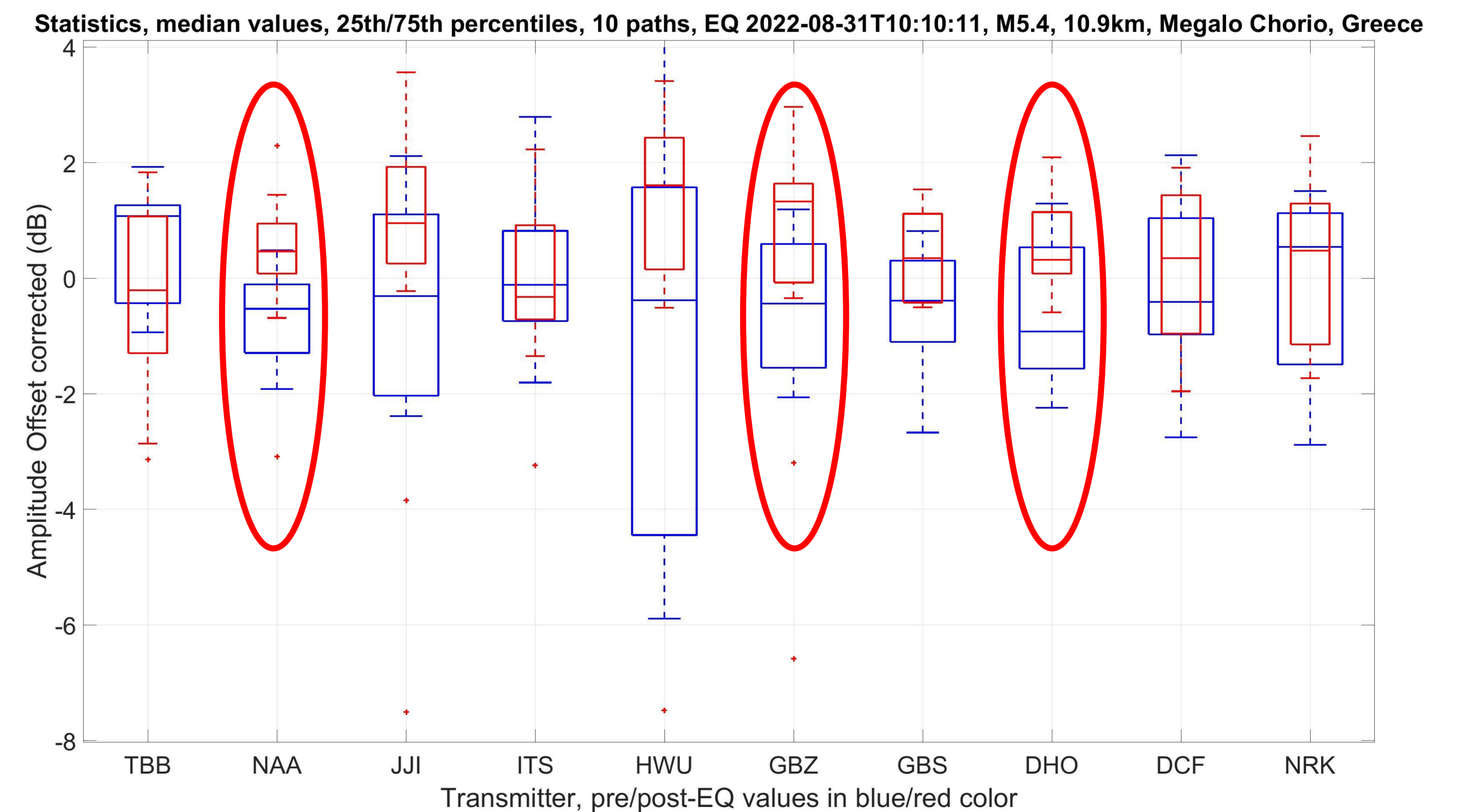
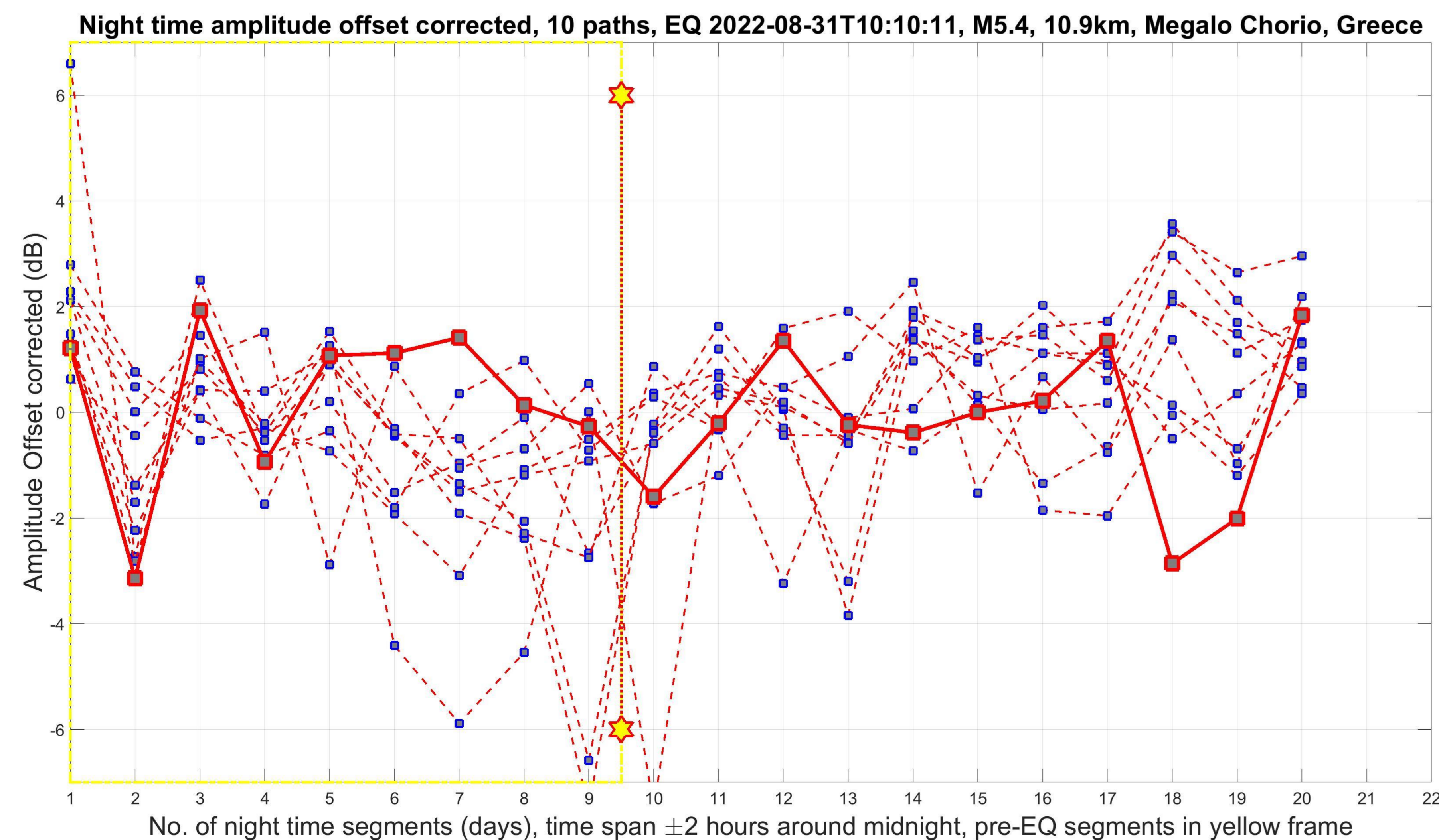
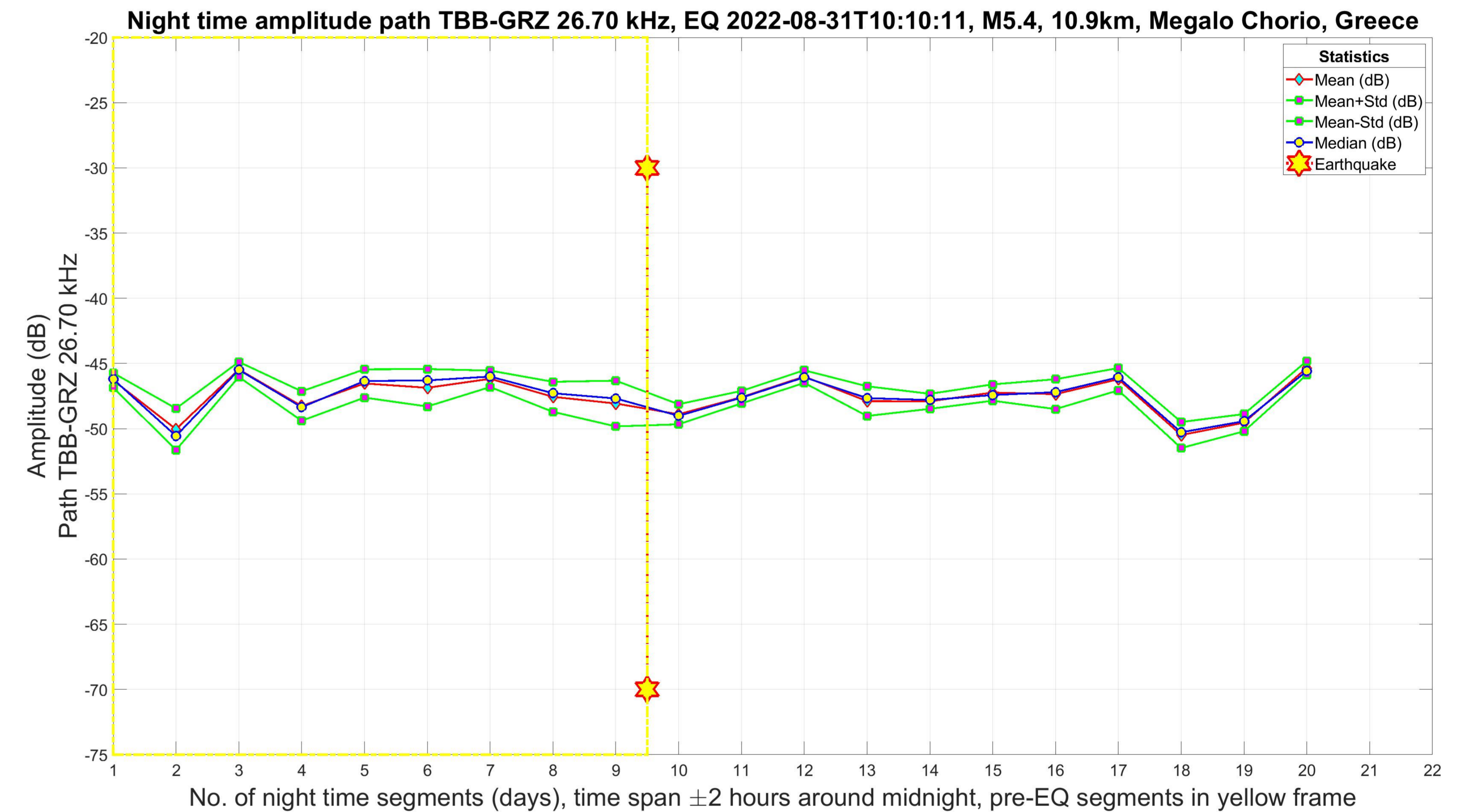
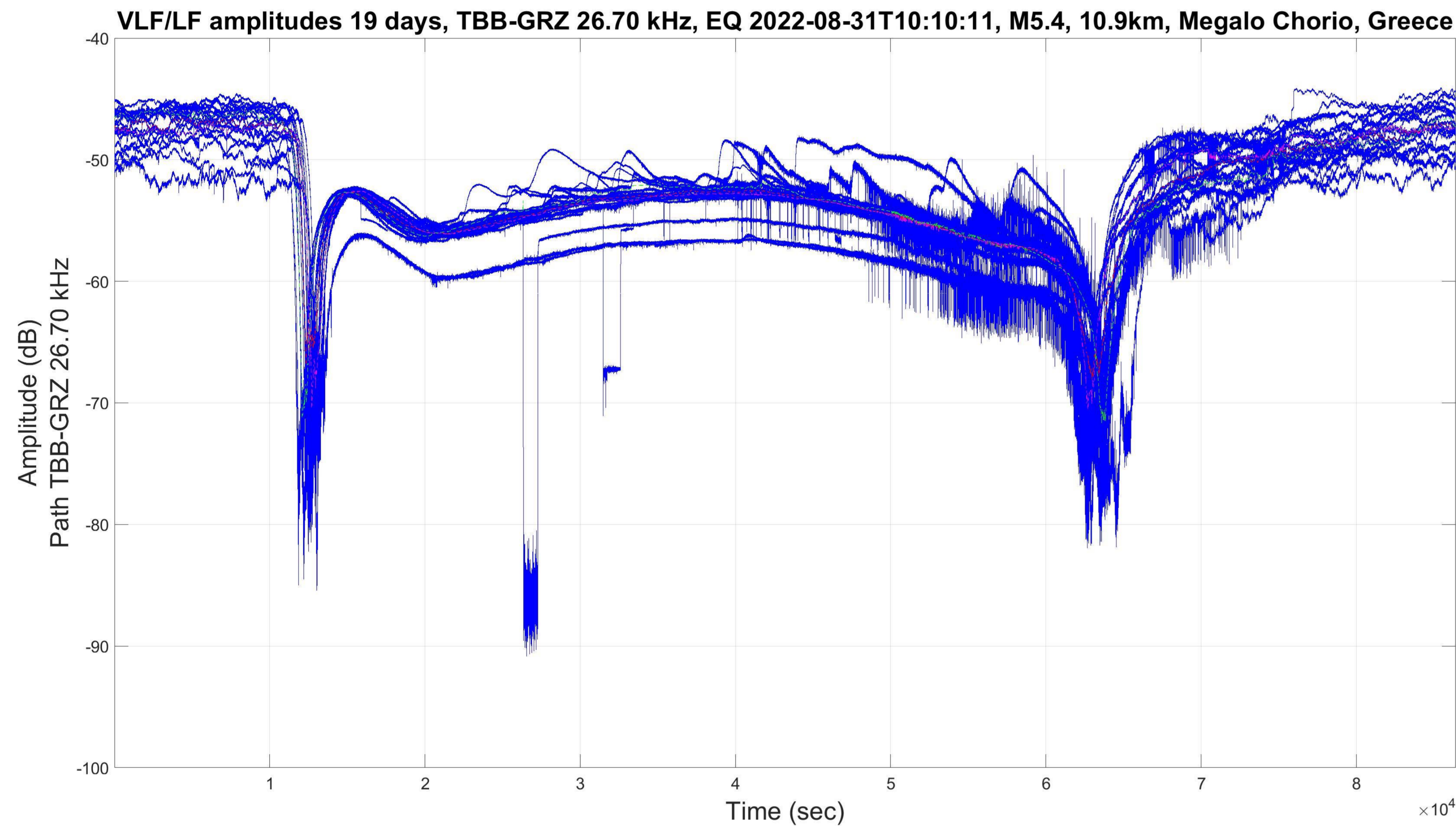
SUB-IONOSPHERIC VLF/LF WAVEGUIDE VARIATIONS RELATED TO MAGNITUDE M>5 EARTHQUAKES IN THE EASTERN MEDITERRANEAN AREA

Hans Eichelberger¹, Mohammed Y. Boudjada¹, Konrad Schwingenschuh¹, Bruno P. Besser¹, Daniel Wolbang¹, Maria Solovieva², Pier Francesco Biagi³, Patrick Galopeau⁴, Ghulam Jaffer⁵, Özer Aydogar¹, Christoph Schirninger¹, Cosima Muck¹, Irmgard Jernej¹, and Werner Magnes¹

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VLF/LF AMPLITUDE MEASUREMENTS, EARTHQUAKE 2022-08-31, M5.4, 10.9 KM, MEGÁLO CHORIÓ, GREECE

- Top Left: VLF/LF amplitudes (2022-08-23 to 2022-09-10) for the 26.70 kHz TBB-GRZ path, spikes and transmitter switch off periods are omitted, **variations in the electric field values**
- 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, **for a significance level of 5%, NAA-GRZ, GBZ-GRZ and DHO-GRZ show higher amplitude values after the EQ**



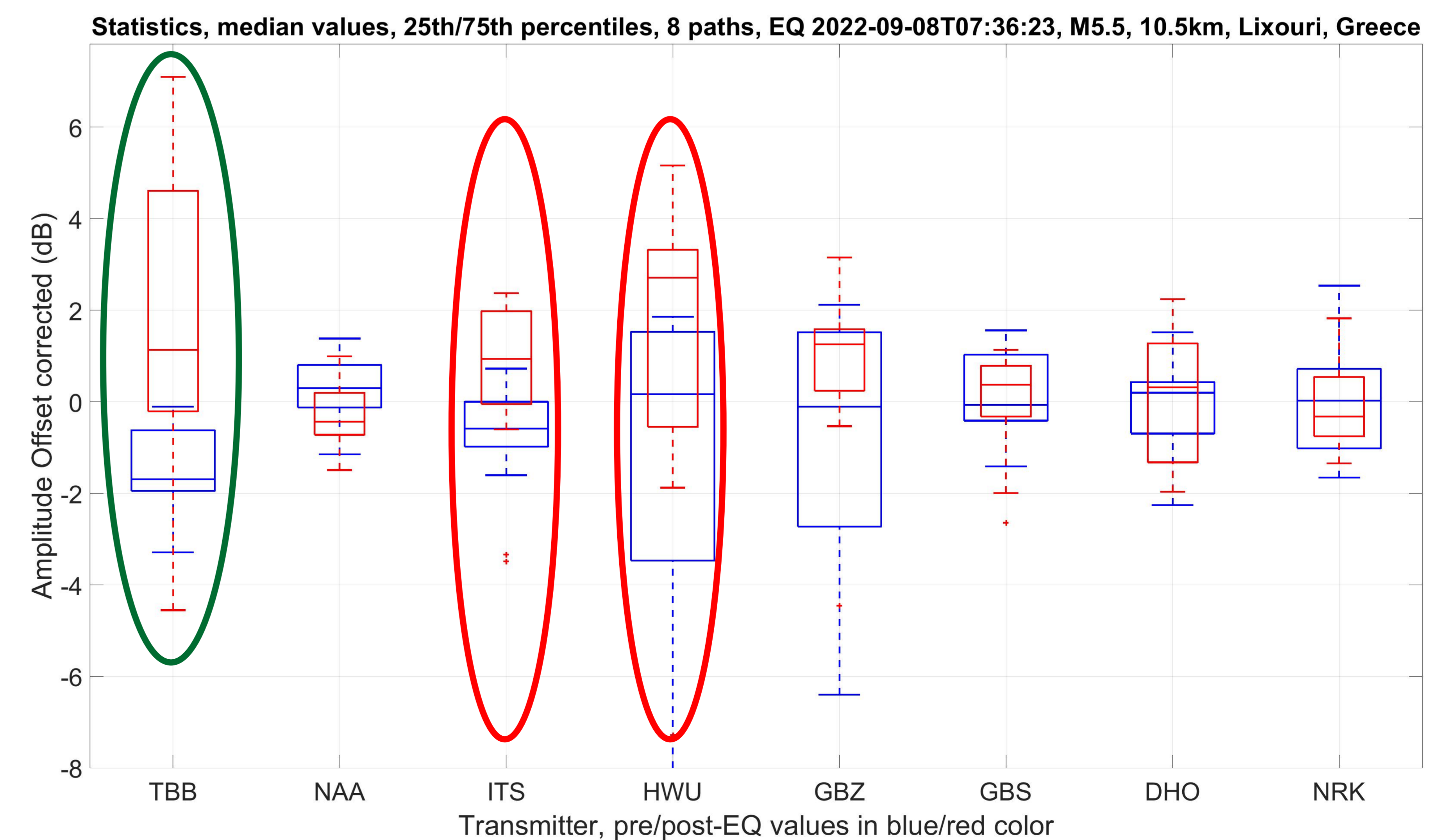
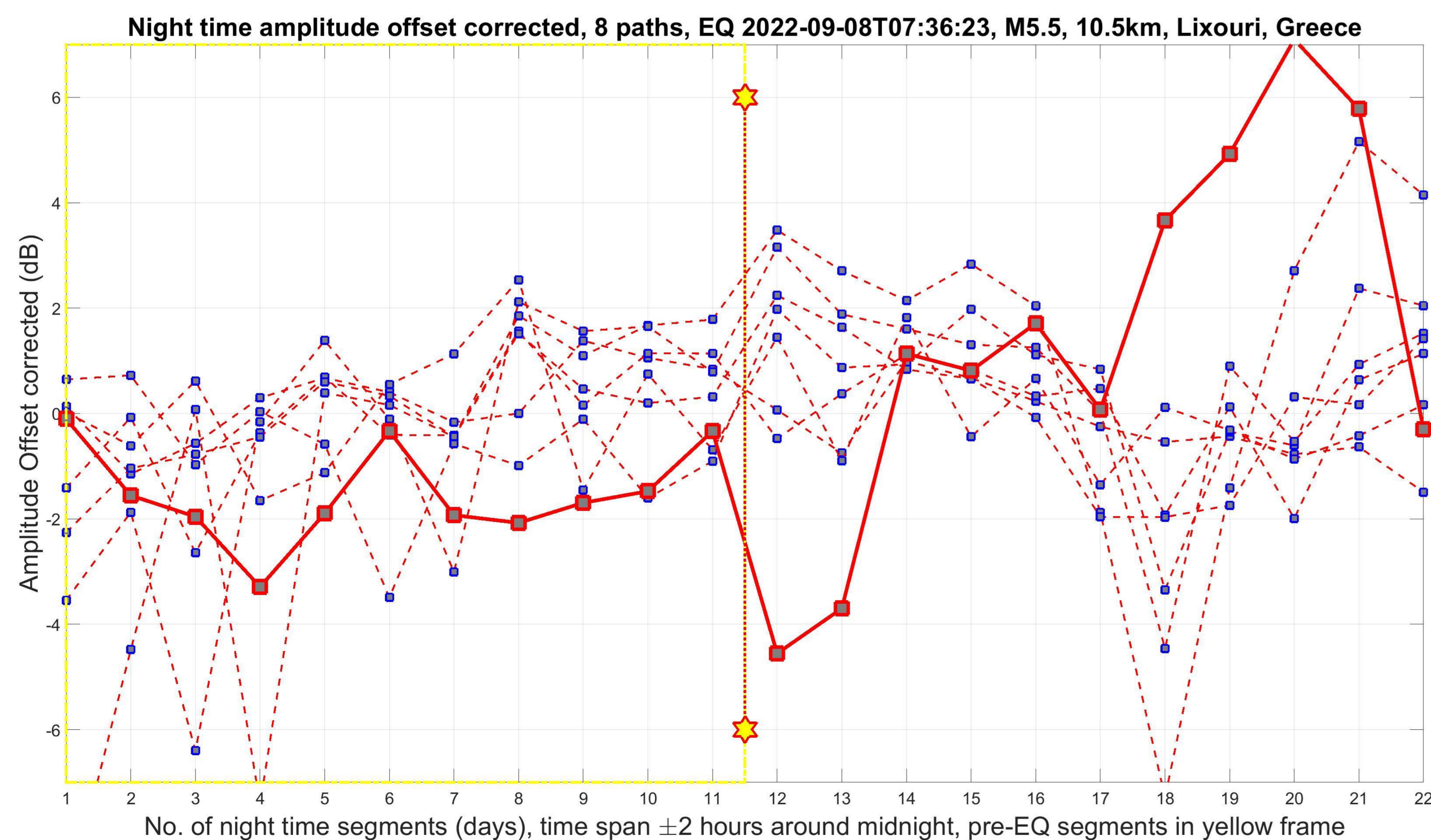
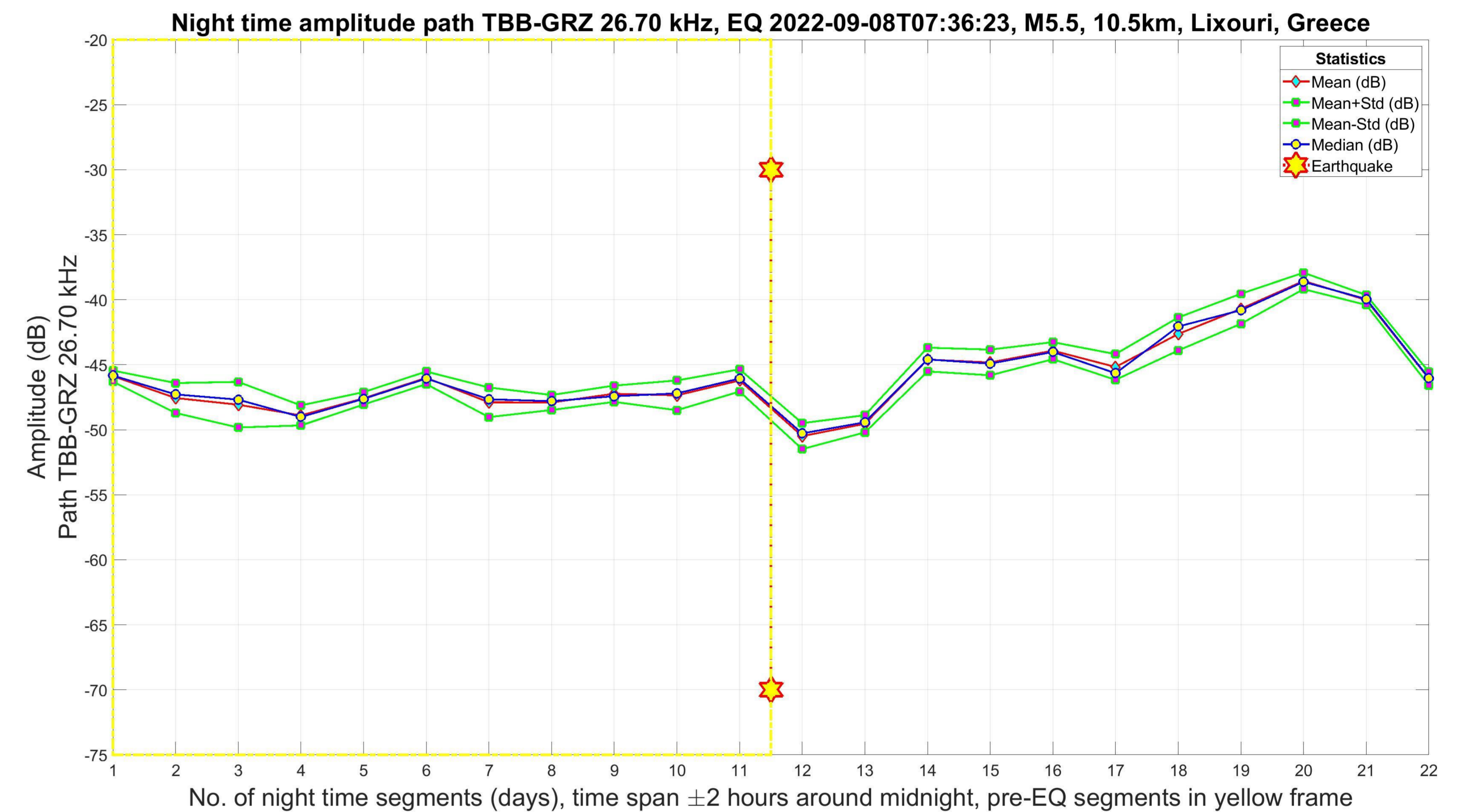
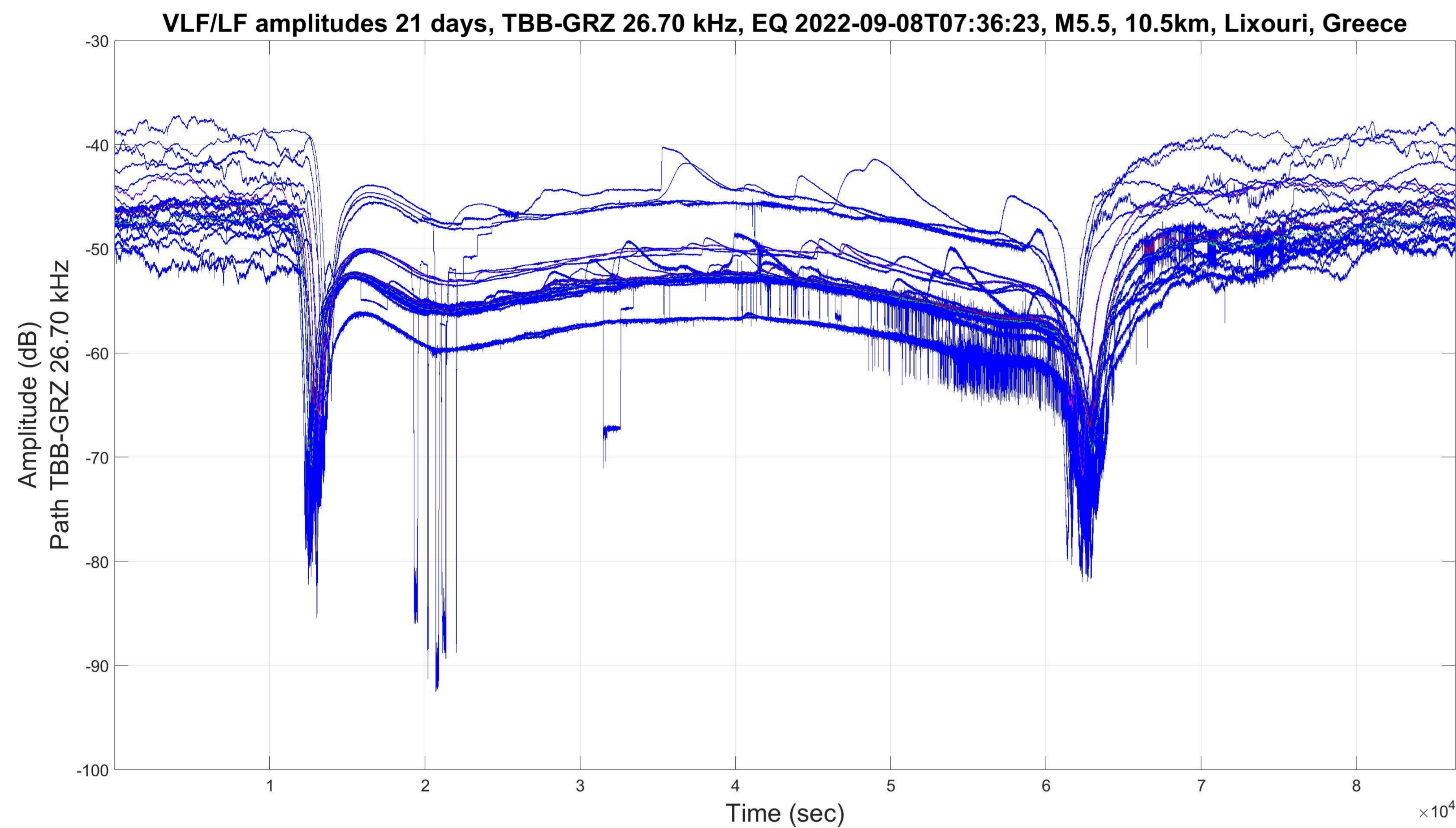
SUB-IONOSPHERIC VLF/LF WAVEGUIDE VARIATIONS RELATED TO MAGNITUDE M>5 EARTHQUAKES IN THE EASTERN MEDITERRANEAN AREA

Hans Eichelberger¹, Mohammed Y. Boudjada¹, Konrad Schwingenschuh¹, Bruno P. Besser¹, Daniel Wolbang¹, Maria Solovieva², Pier Francesco Biagi³, Patrick Galopeau⁴, Ghulam Jaffer⁵, Özer Aydogar¹, Christoph Schirninger¹, Cosima Muck¹, Irmgard Jernej¹, and Werner Magnes¹

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VLF/LF AMPLITUDE MEASUREMENTS, EARTHQUAKE 2022-09-08, M5.5, 10.5 KM, LIXOURI, GREECE

- Top Left: VLF/LF amplitudes (2022-08-29 to 2022-09-18) for the 26.70 kHz TBB-GRZ path, spikes and transmitter switch off periods are omitted, **variations in the electric field values**
- Bottom Left: Offset corrected nighttime (± 2 h around midnight) amplitude values for the 8 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 8 paths, **for a significance level of 5% the event paths TBB-GRZ, ITS-GRZ, HWU-GRZ show higher amplitude values after the EQ**



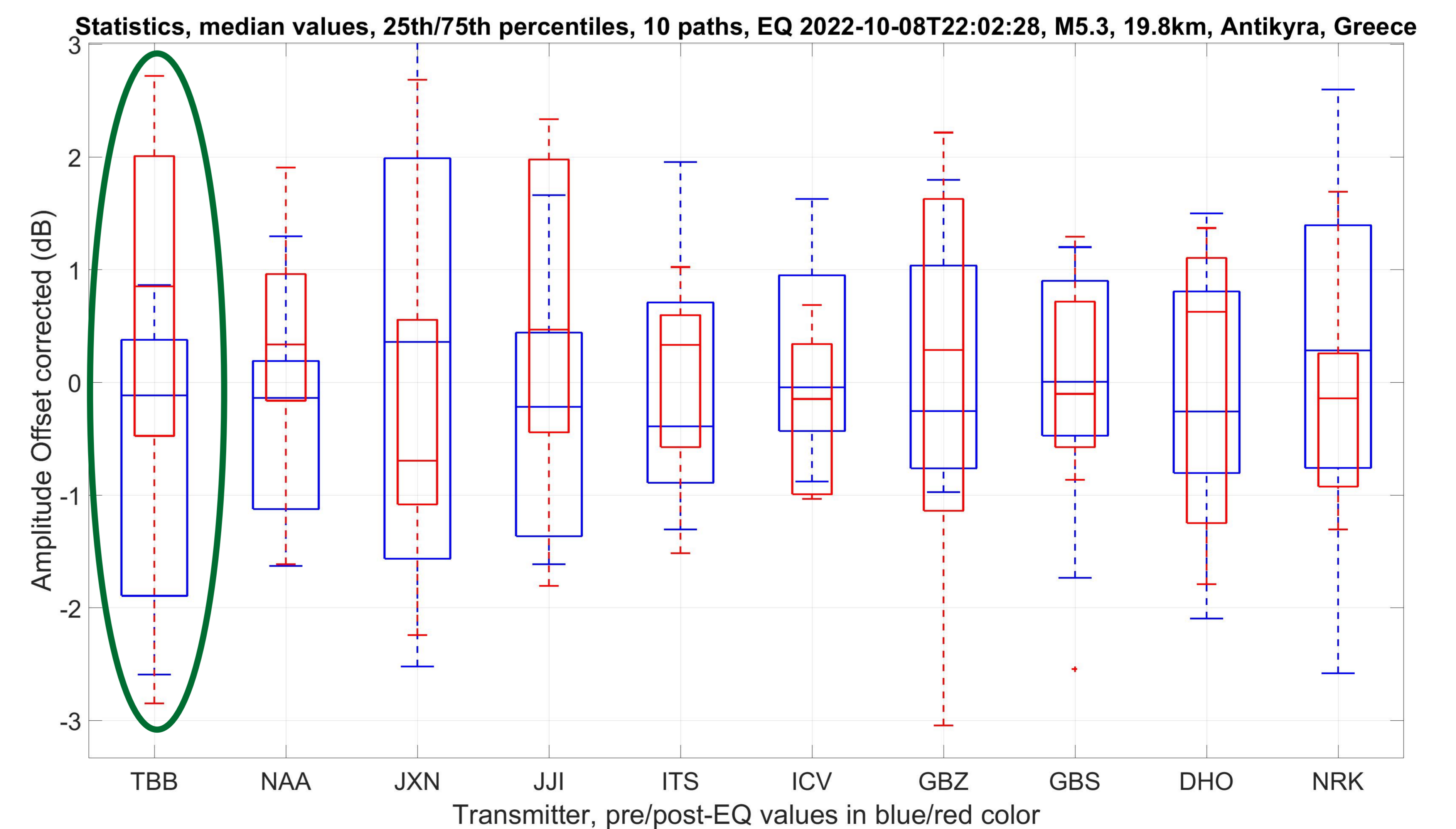
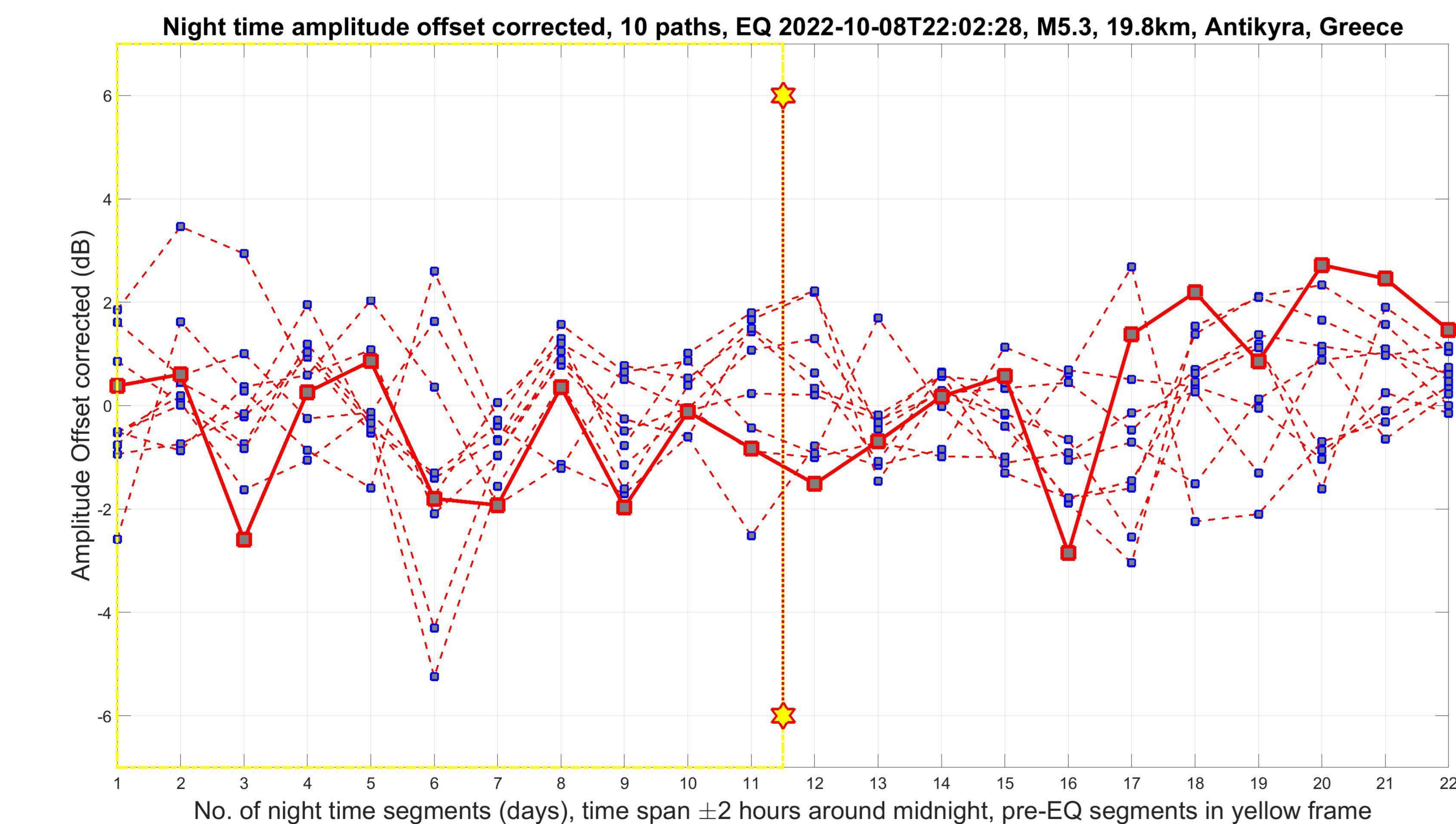
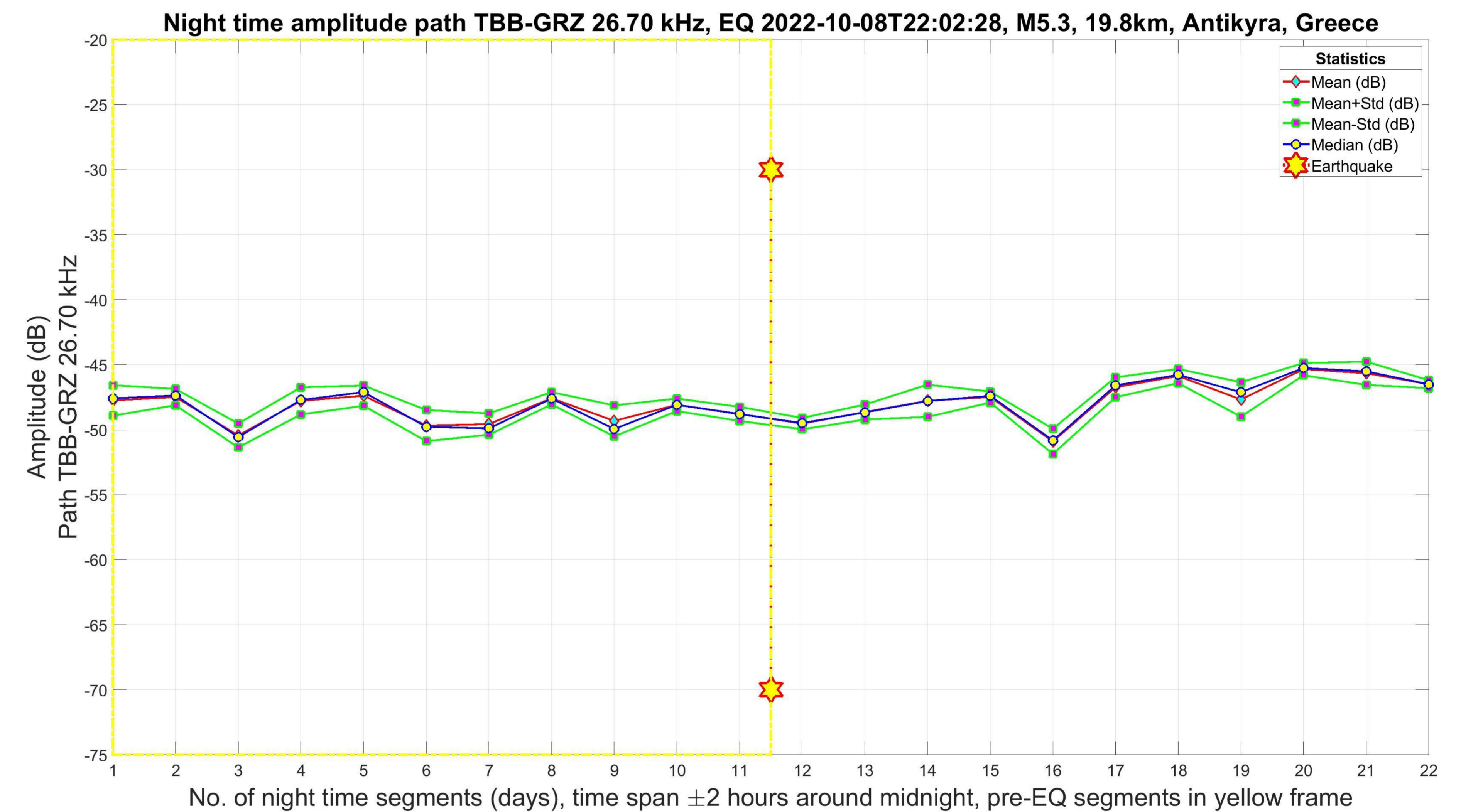
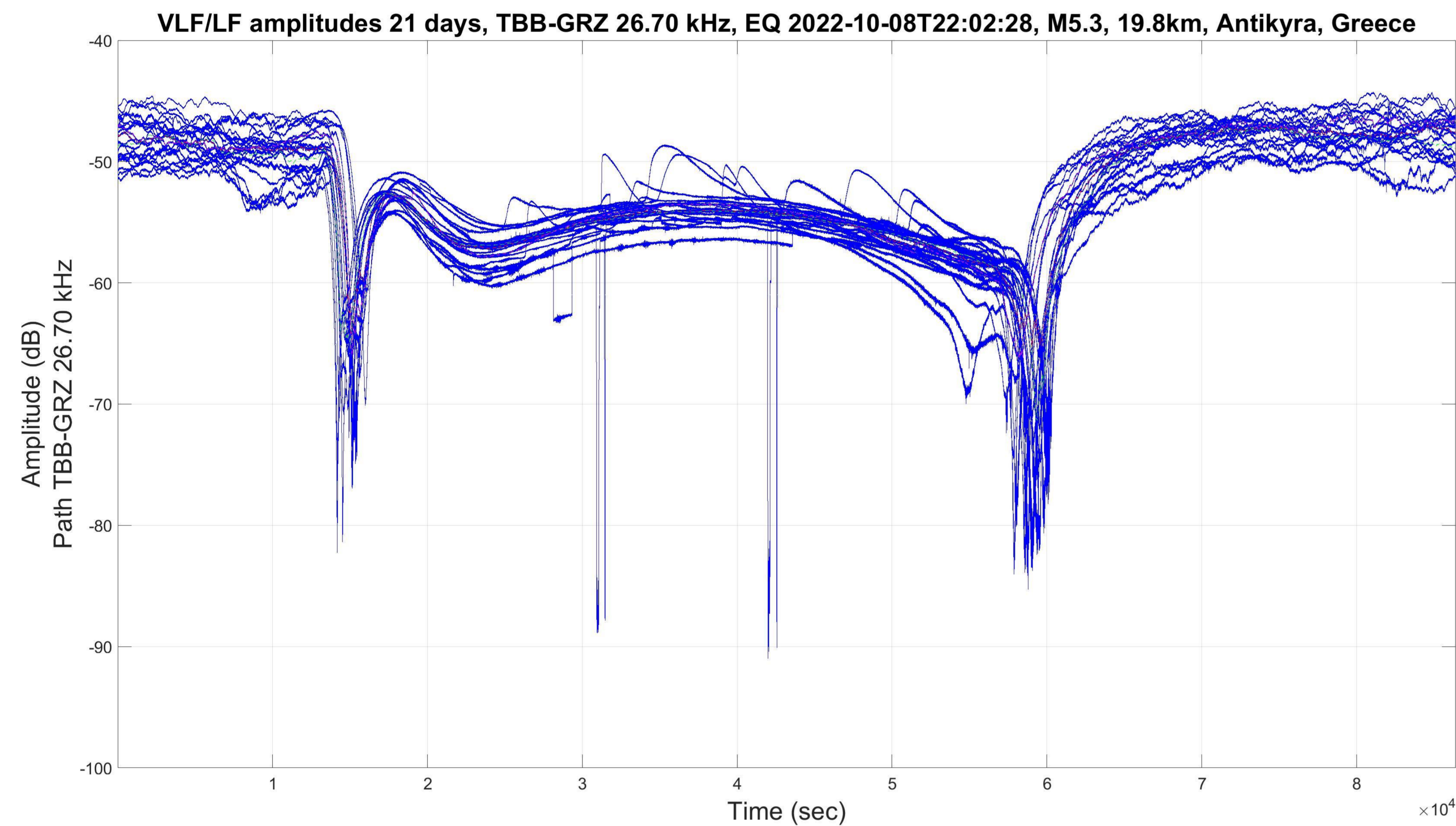
SUB-IONOSPHERIC VLF/LF WAVEGUIDE VARIATIONS RELATED TO MAGNITUDE M>5 EARTHQUAKES IN THE EASTERN MEDITERRANEAN AREA

Hans Eichelberger¹, Mohammed Y. Boudjada¹, Konrad Schwingenschuh¹, Bruno P. Besser¹, Daniel Wolbang¹, Maria Solovieva², Pier Francesco Biagi³, Patrick Galopeau⁴, Ghulam Jaffer⁵, Özer Aydogar¹, Christoph Schirninger¹, Cosima Muck¹, Irmgard Jernej¹, and Werner Magnes¹

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VLF/LF AMPLITUDE MEASUREMENTS, EARTHQUAKE 2022-10-08, M5.3, 19.8 KM, ANTIKYRA, GREECE

- Top Left: VLF/LF amplitudes (2022-09-28 to 2022-10-18) 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, **for a significance level of 5% only the event path TBB-GRZ shows higher amplitude values after the EQ (nighttime method)**



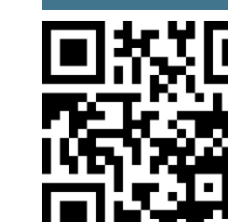
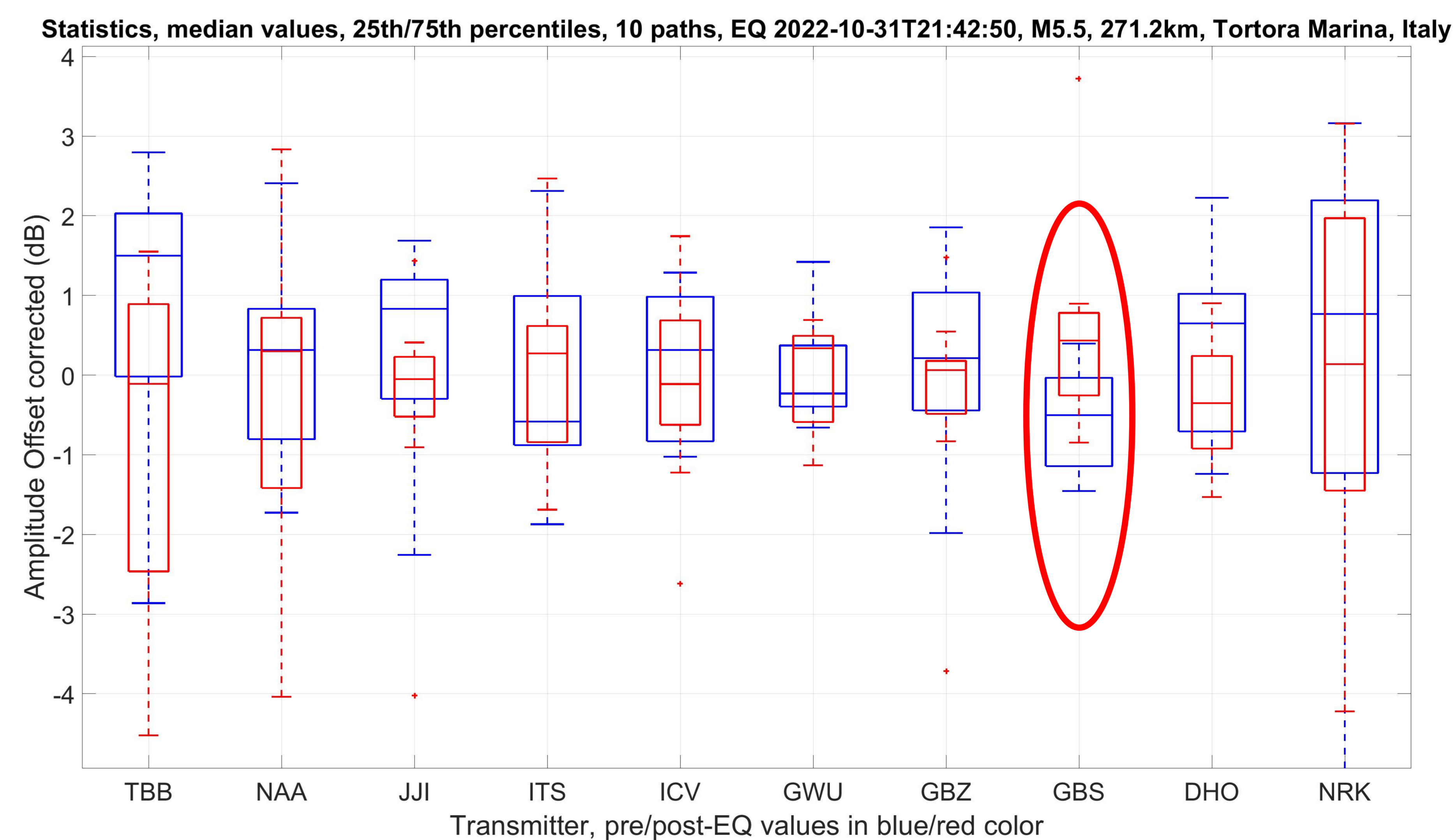
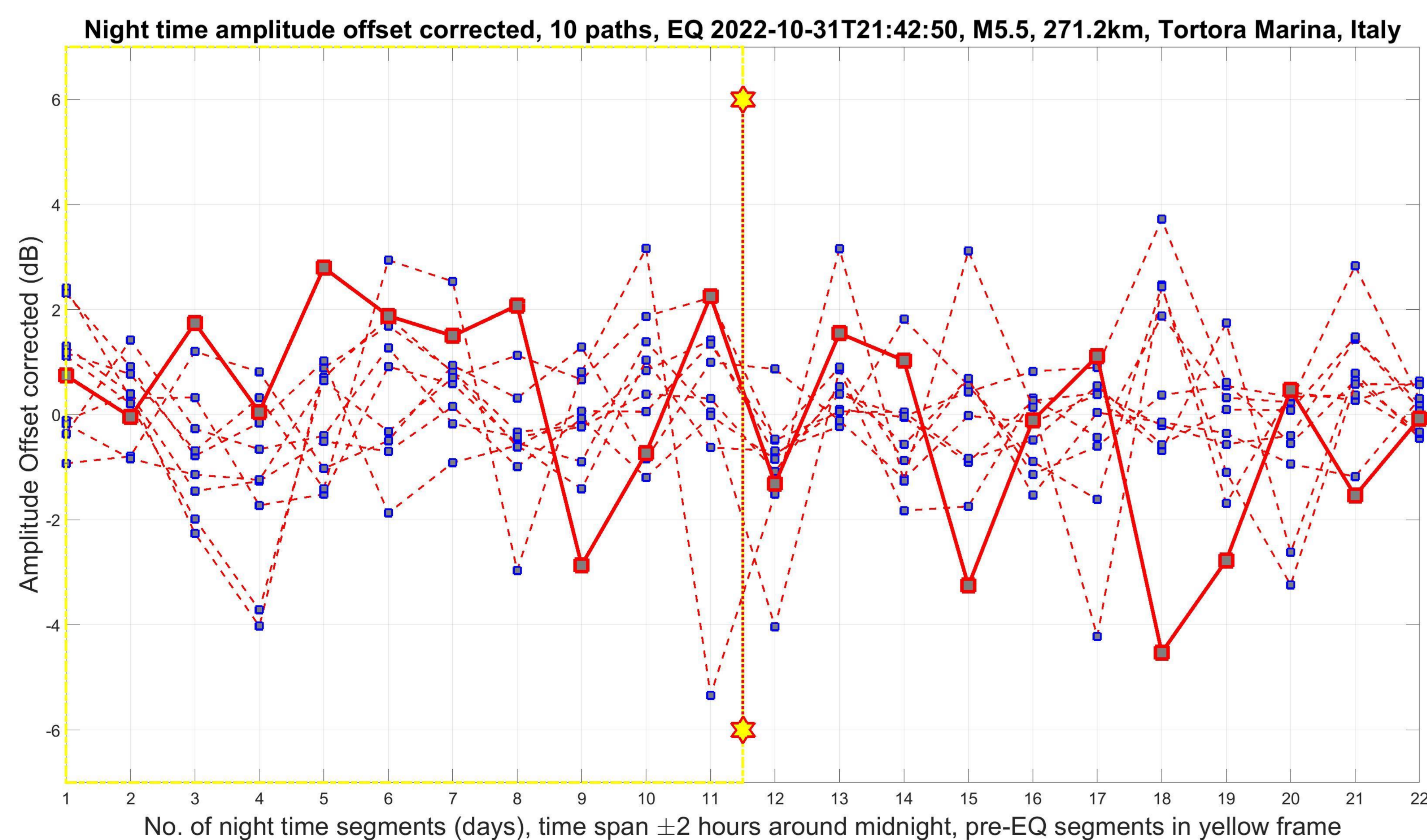
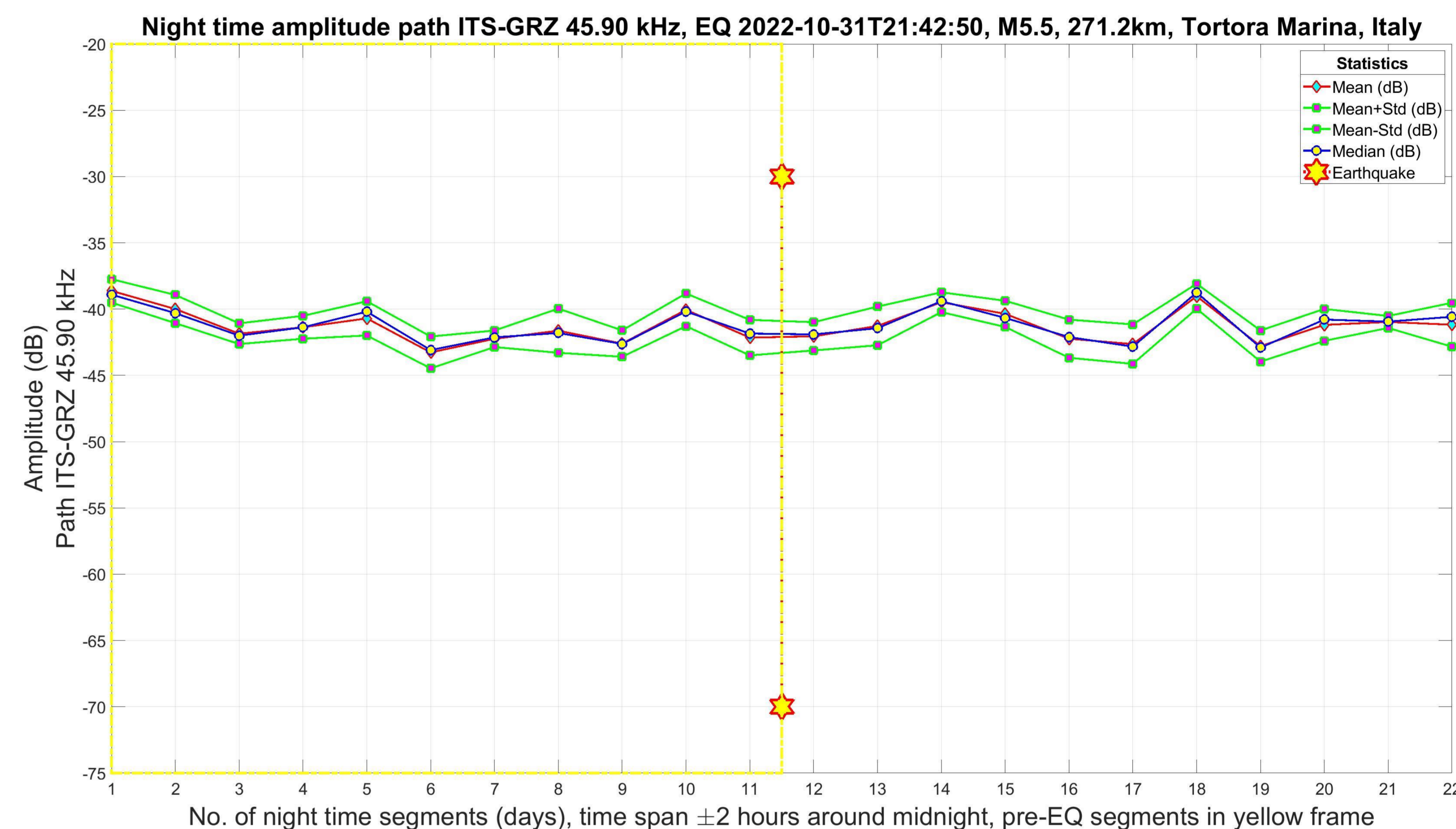
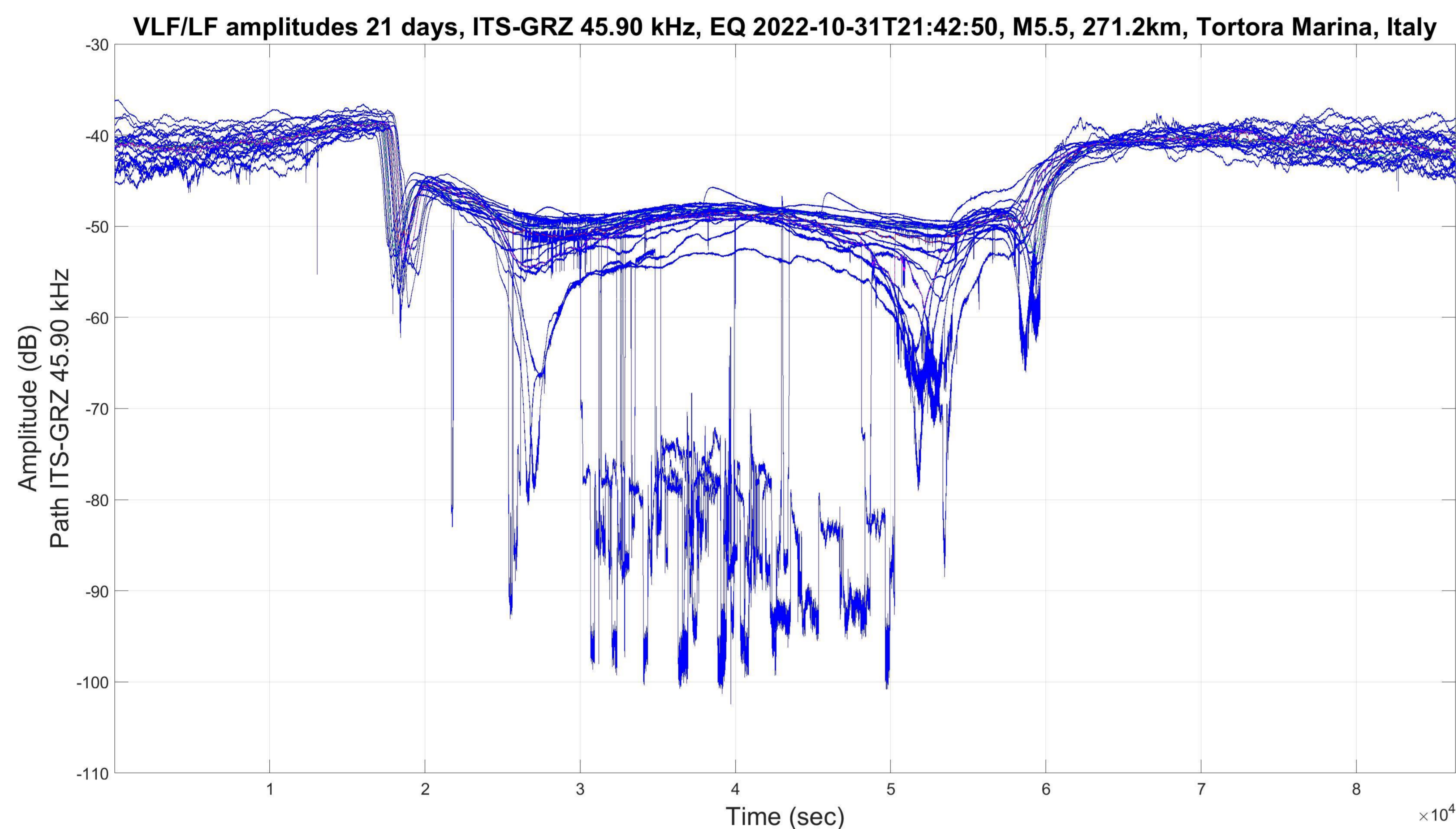
SUB-IONOSPHERIC VLF/LF WAVEGUIDE VARIATIONS RELATED TO MAGNITUDE M>5 EARTHQUAKES IN THE EASTERN MEDITERRANEAN AREA

Hans Eichelberger¹, Mohammed Y. Boudjada¹, Konrad Schwingenschuh¹, Bruno P. Besser¹, Daniel Wolbang¹, Maria Solovieva², Pier Francesco Biagi³, Patrick Galopeau⁴, Ghulam Jaffer⁵, Özer Aydogar¹, Christoph Schirninger¹, Cosima Muck¹, Irmgard Jernej¹, and Werner Magnes¹

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VLF/LF AMPLITUDE MEASUREMENTS, EARTHQUAKE 2022-10-31, M5.5, 271.2 KM, TORTORA MARINA, ITALY

- Top Left: VLF/LF amplitudes (2022-10-21 to 2022-11-10) 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 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, **for a significance level of 5% the path GBS-GRZ shows higher amplitude values after the EQ (nighttime method)**



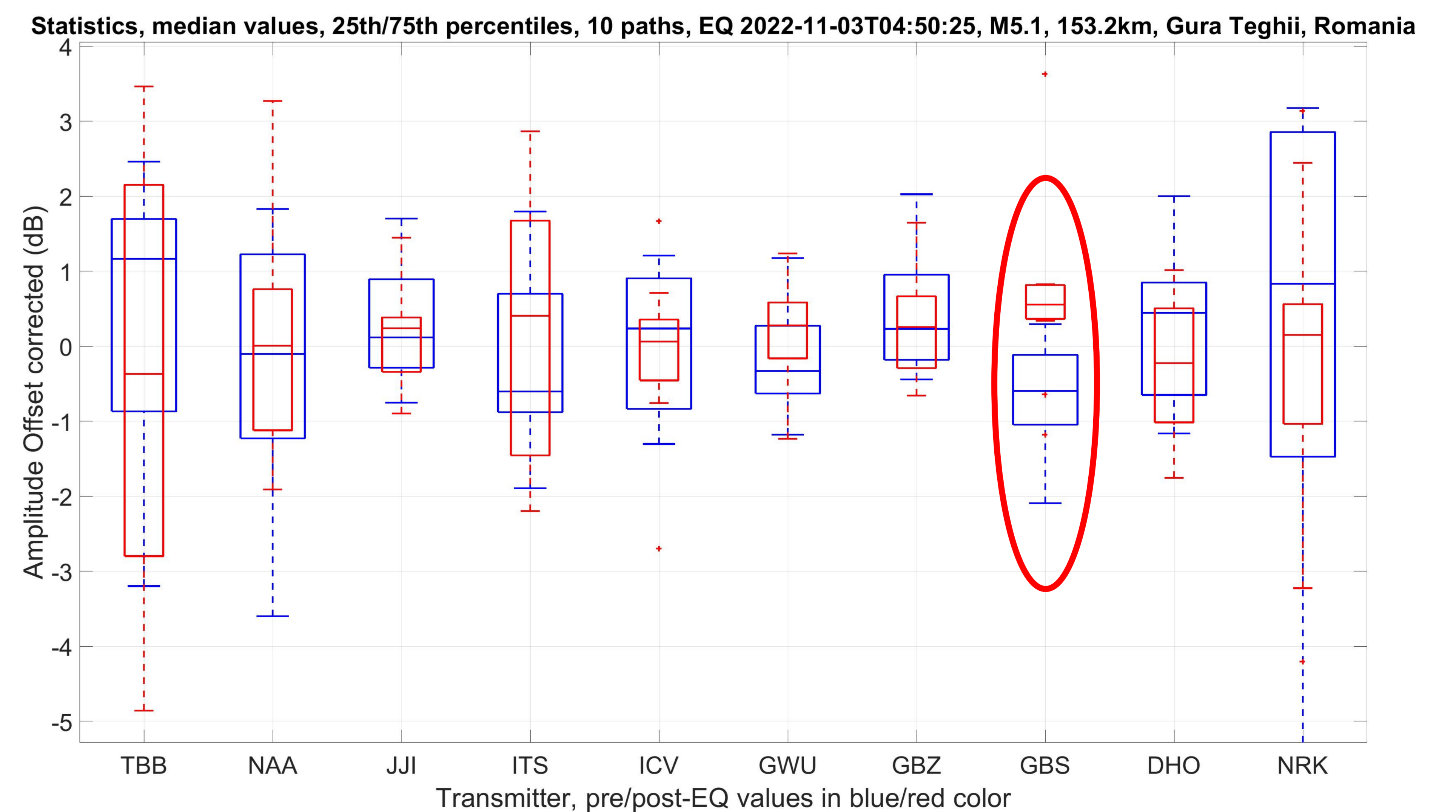
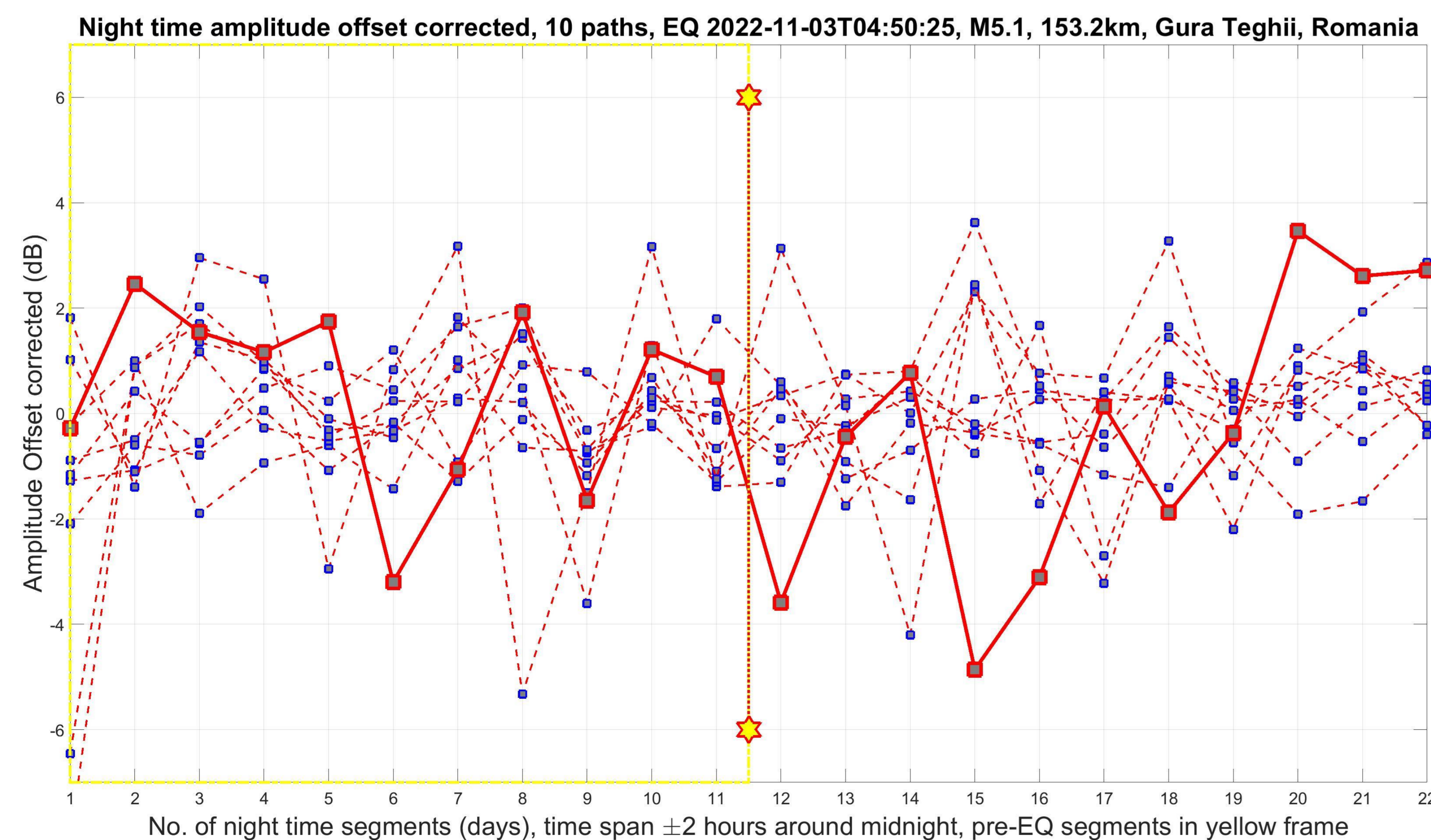
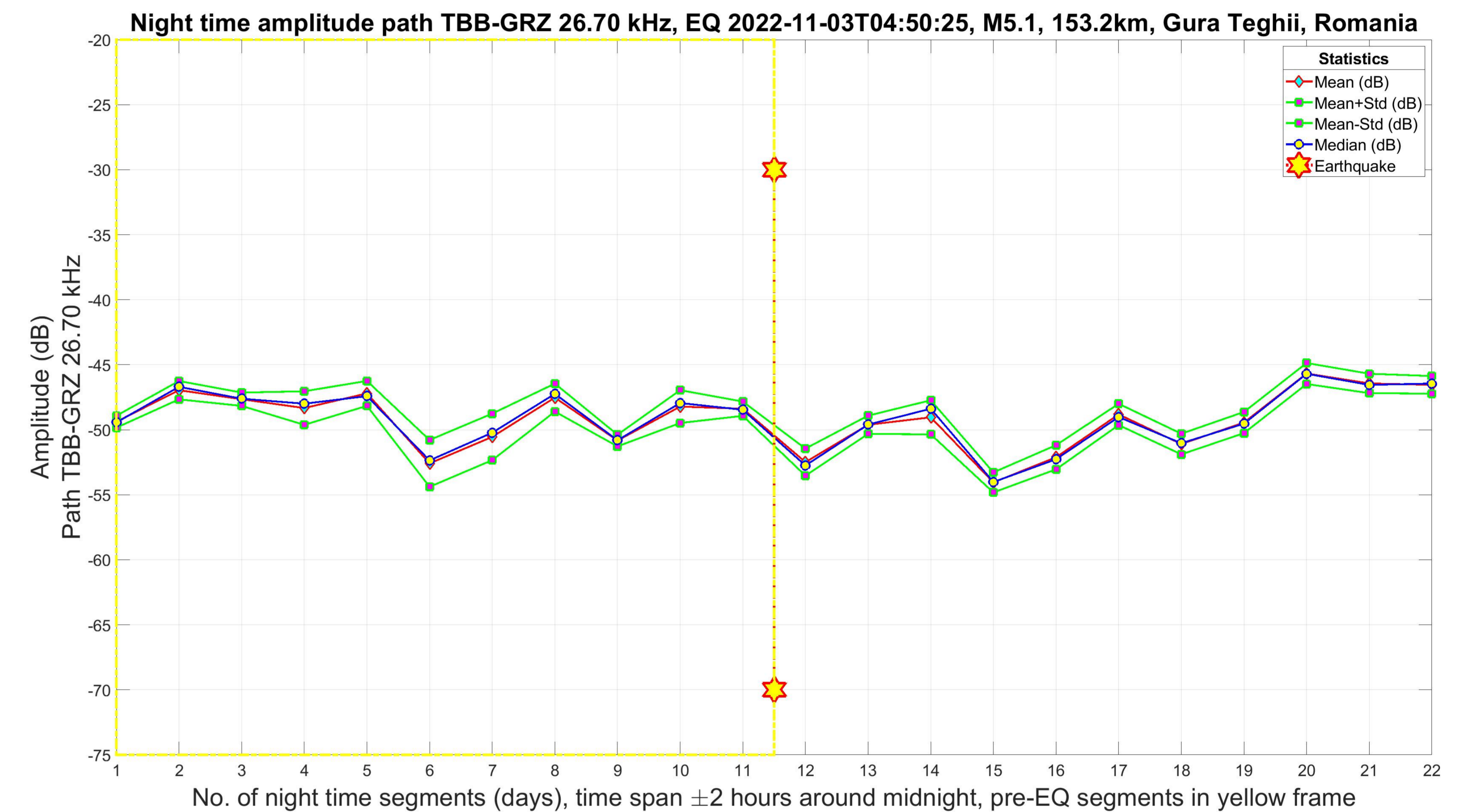
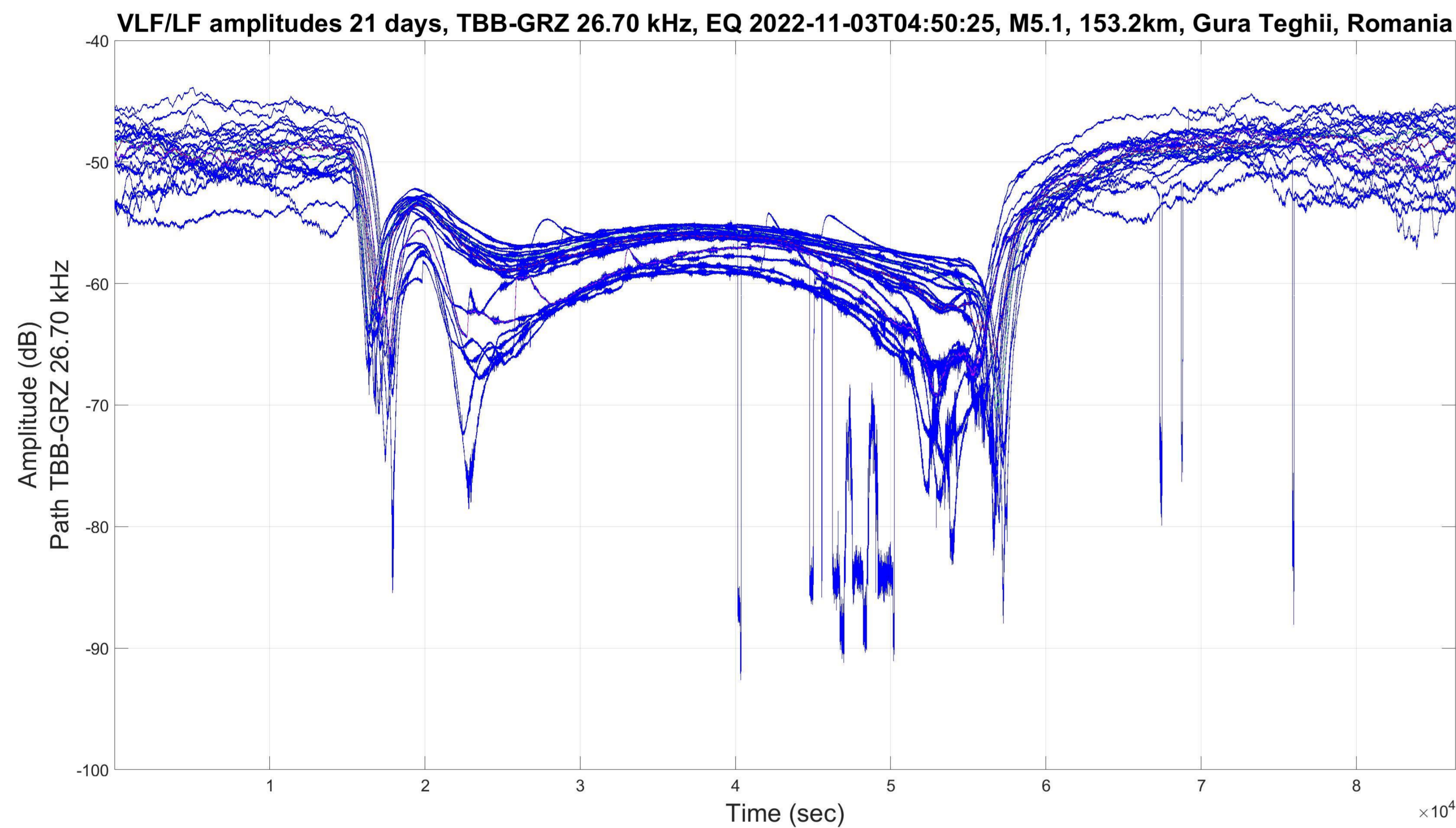
SUB-IONOSPHERIC VLF/LF WAVEGUIDE VARIATIONS RELATED TO MAGNITUDE M>5 EARTHQUAKES IN THE EASTERN MEDITERRANEAN AREA

Hans Eichelberger¹, Mohammed Y. Boudjada¹, Konrad Schwingenschuh¹, Bruno P. Besser¹, Daniel Wolbang¹, Maria Solovieva², Pier Francesco Biagi³, Patrick Galopeau⁴, Ghulam Jaffer⁵, Özer Aydogar¹, Christoph Schirninger¹, Cosima Muck¹, Irmgard Jernej¹, and Werner Magnes¹

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VLF/LF AMPLITUDE MEASUREMENTS, EARTHQUAKE 2022-11-03, M5.1, 153.2 KM, GURA THEGII, ROMANIA

- Top Left: VLF/LF amplitudes (2022-10-21 to 2022-11-10) 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 TBB-GRZ path (no crossing of the Dobrovolsky-Bowman area/radius), VTX-GRZ and NWC-GRZ are long distance links
- Bottom Right: Statistics (box plots) for the offset corrected 10 paths, for a significance level of 5% the path GBS-GRZ shows higher amplitude values after the EQ (nighttime method)



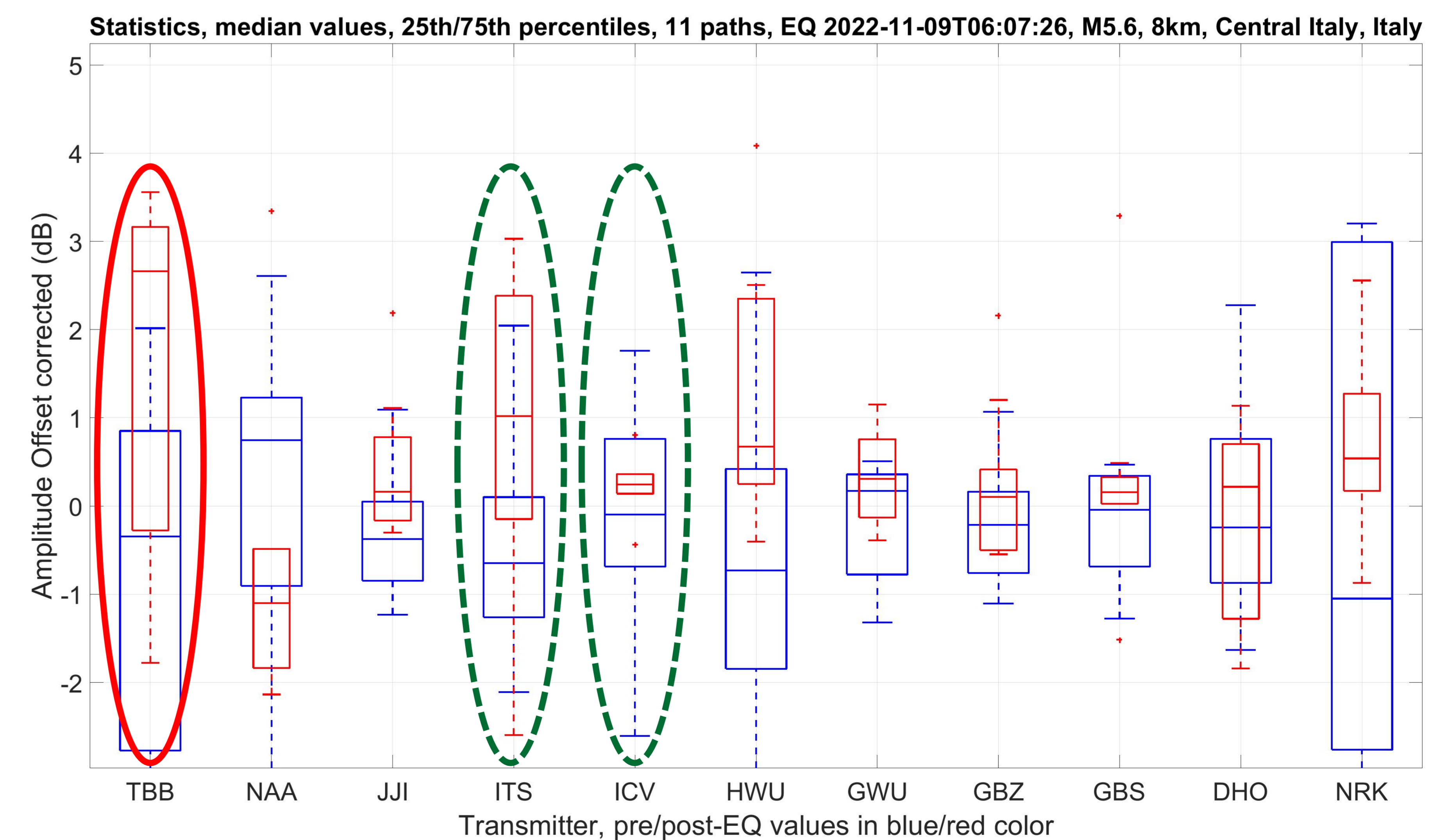
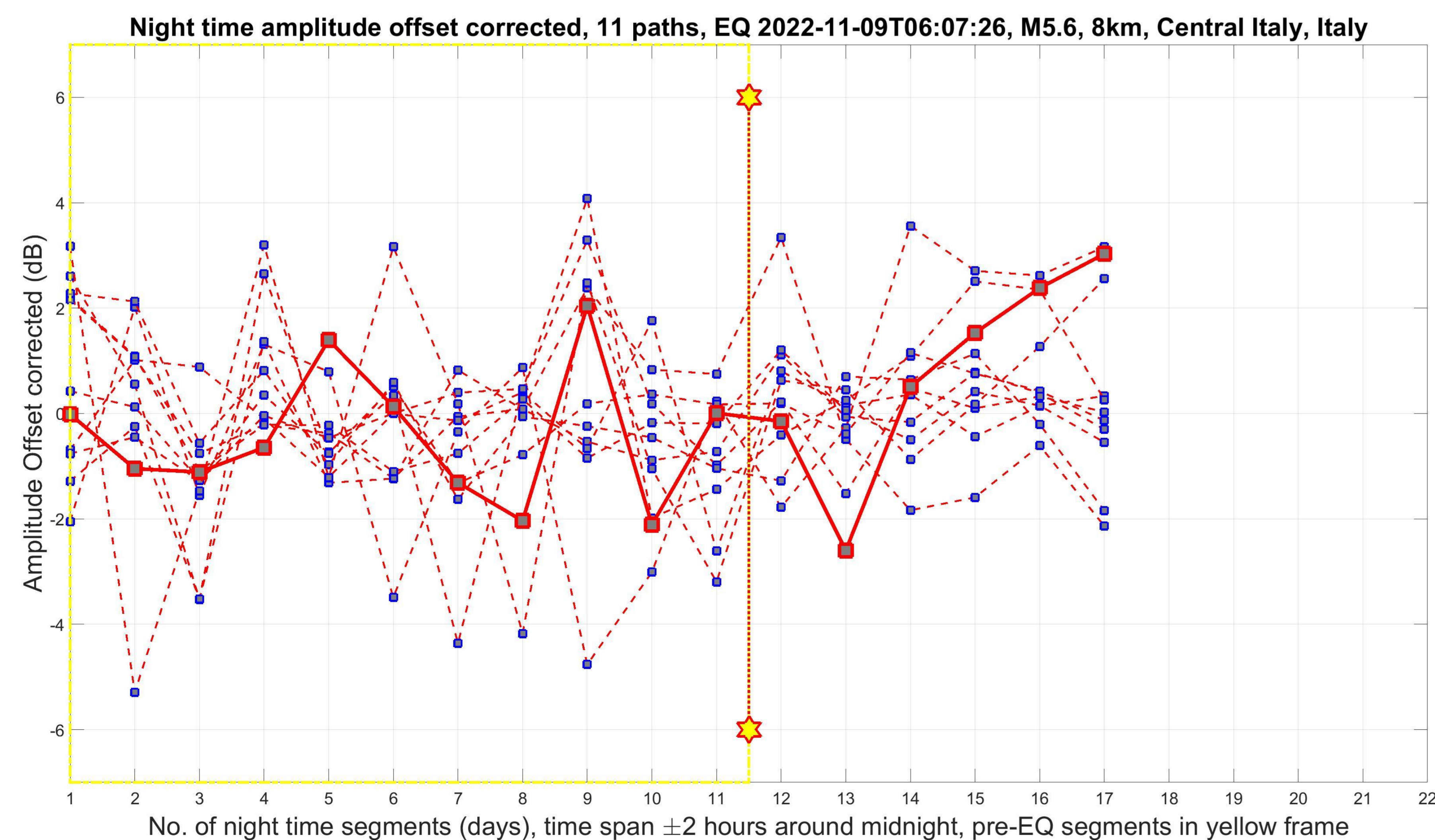
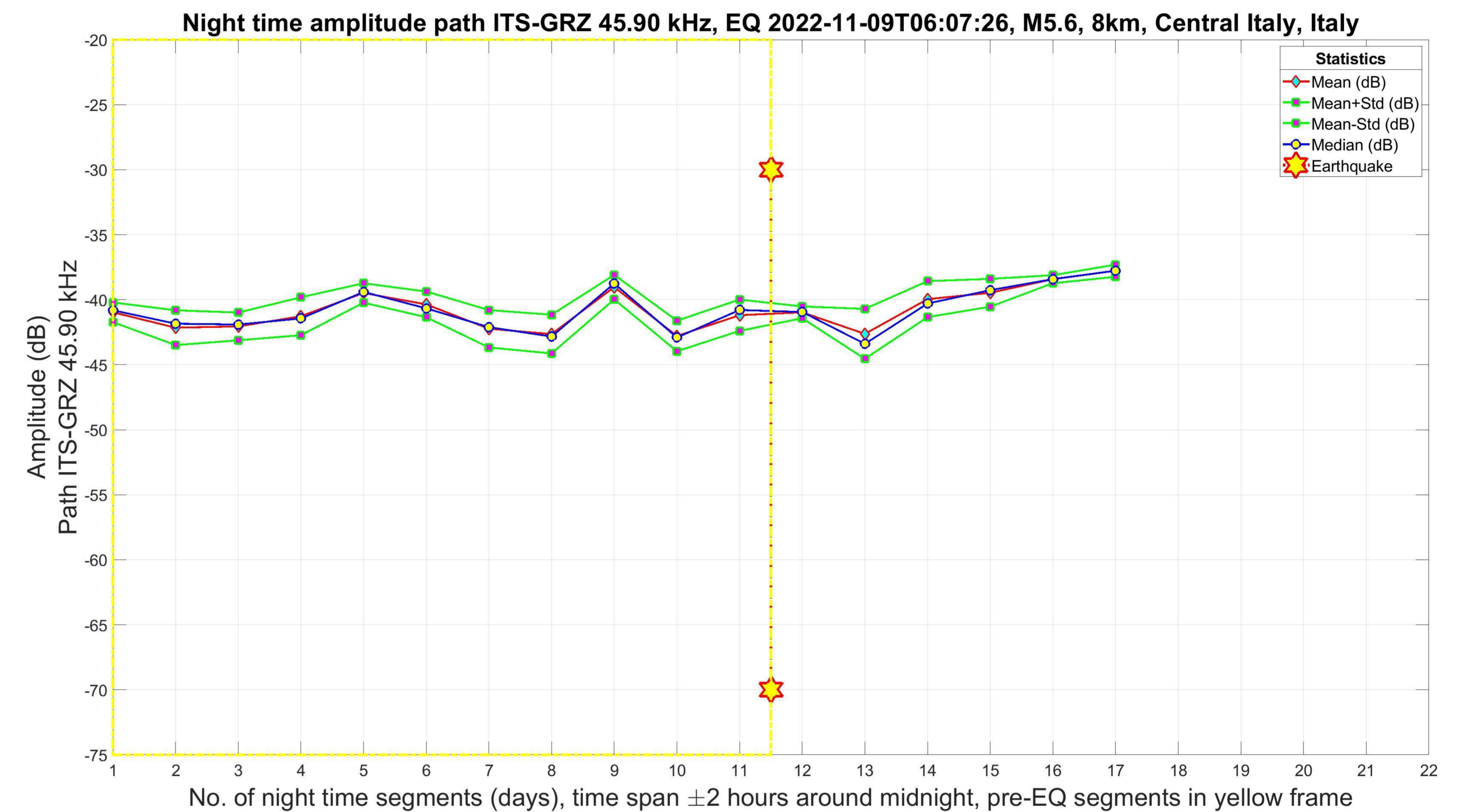
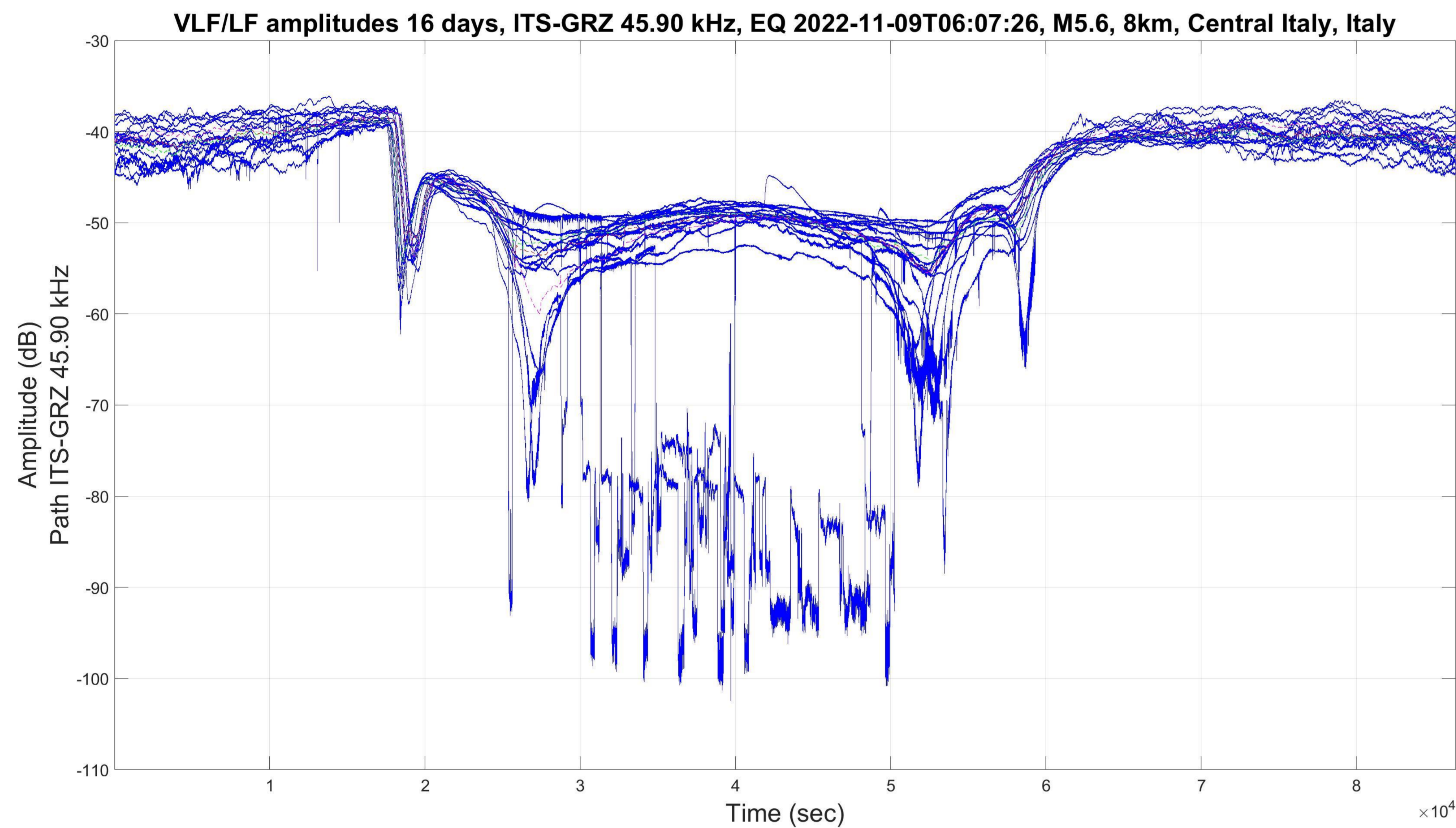
SUB-IONOSPHERIC VLF/LF WAVEGUIDE VARIATIONS RELATED TO MAGNITUDE M>5 EARTHQUAKES IN THE EASTERN MEDITERRANEAN AREA

Hans Eichelberger¹, Mohammed Y. Boudjada¹, Konrad Schwingenschuh¹, Bruno P. Besser¹, Daniel Wolbang¹, Maria Solovieva², Pier Francesco Biagi³, Patrick Galopeau⁴, Ghulam Jaffer⁵, Özer Aydogar¹, Christoph Schirninger¹, Cosima Muck¹, Irmgard Jernej¹, and Werner Magnes¹

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VLF/LF AMPLITUDE MEASUREMENTS, EARTHQUAKE 2022-11-09, M5.6, 8 KM, CENTRAL ITALY, ITALY

- Top Left: VLF/LF amplitudes (2022-10-30 to 2022-11-14) 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 11 paths
- Top Right: Nighttime amplitude values for the affected ITS-GRZ (and ICV-GRZ, not shown) event path (crossing the Dobrovolsky-Bowman area/radius; EQ in the wedge of the two links)
- Bottom Right: Statistics (box plots) for the offset corrected 11 paths, **for a significance level of 5% the path TBB-GRZ shows higher amplitude values after the EQ (nighttime method)**



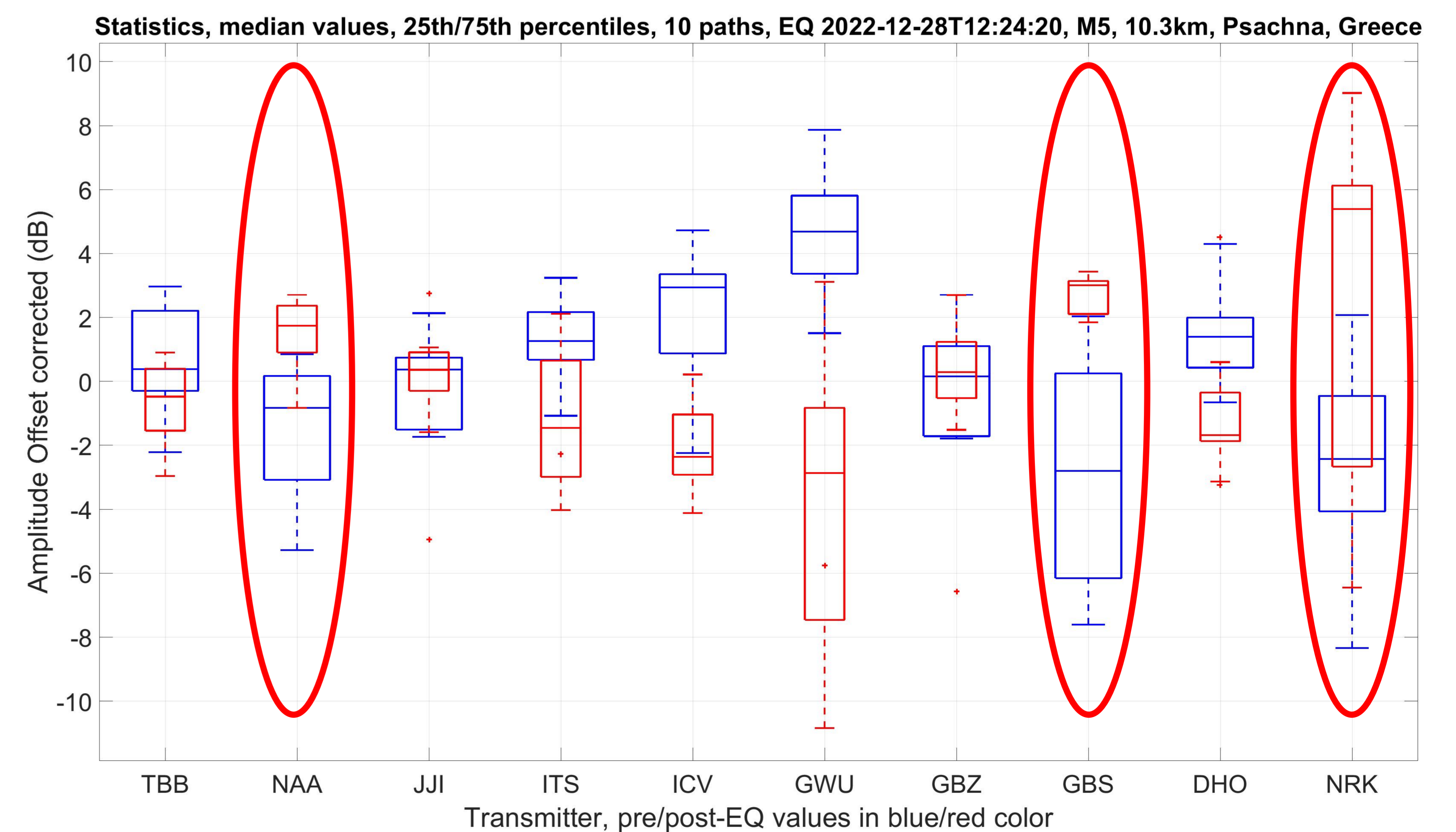
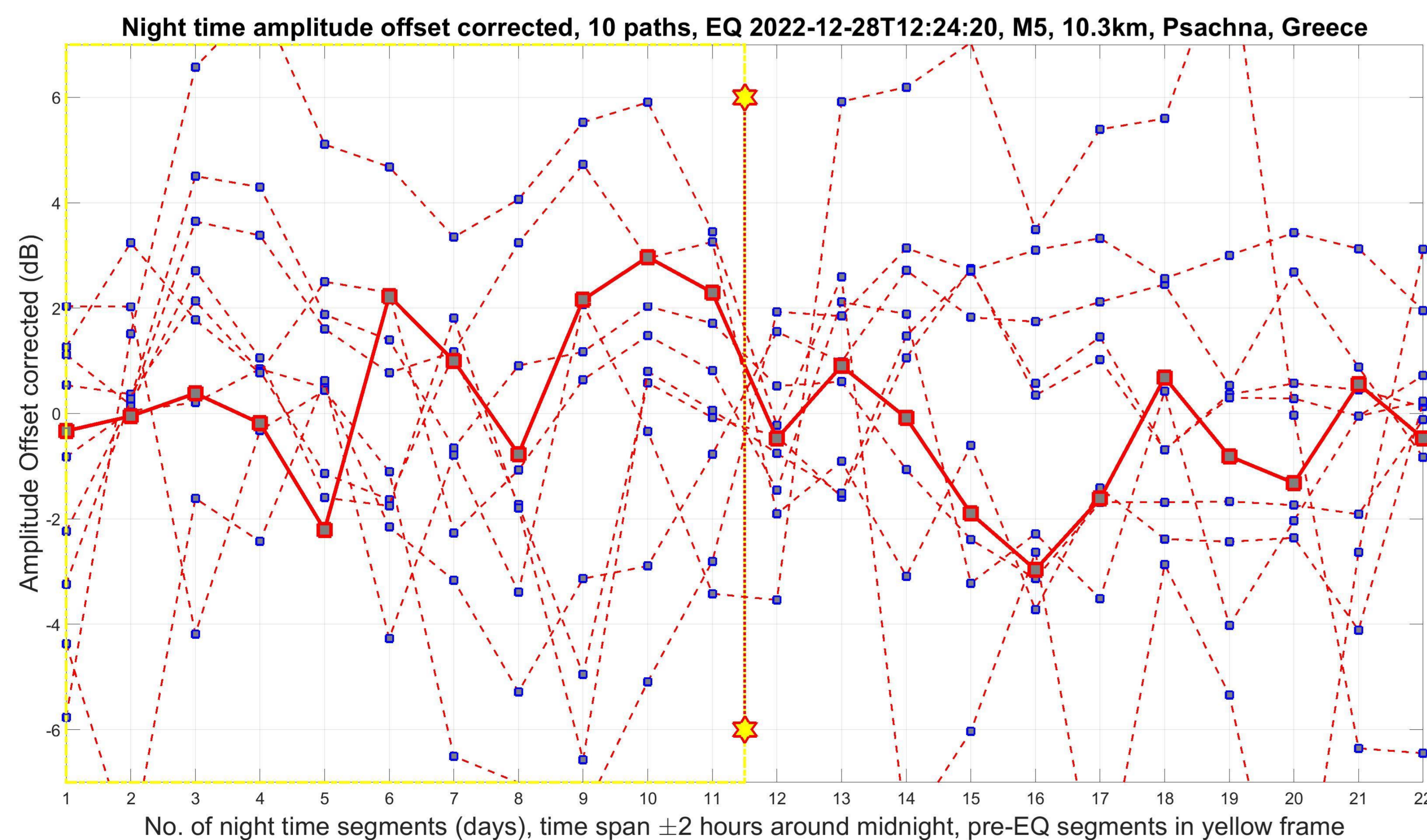
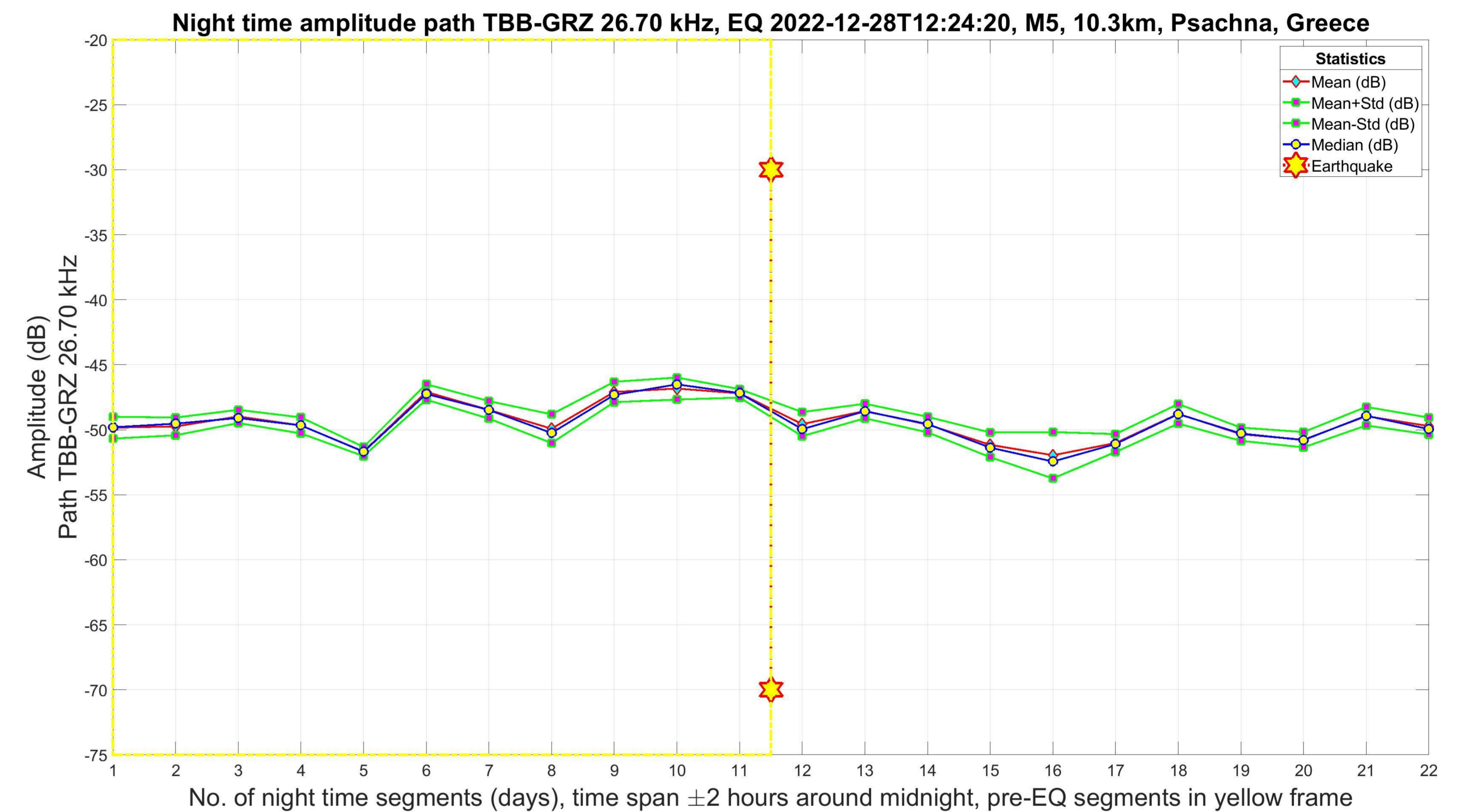
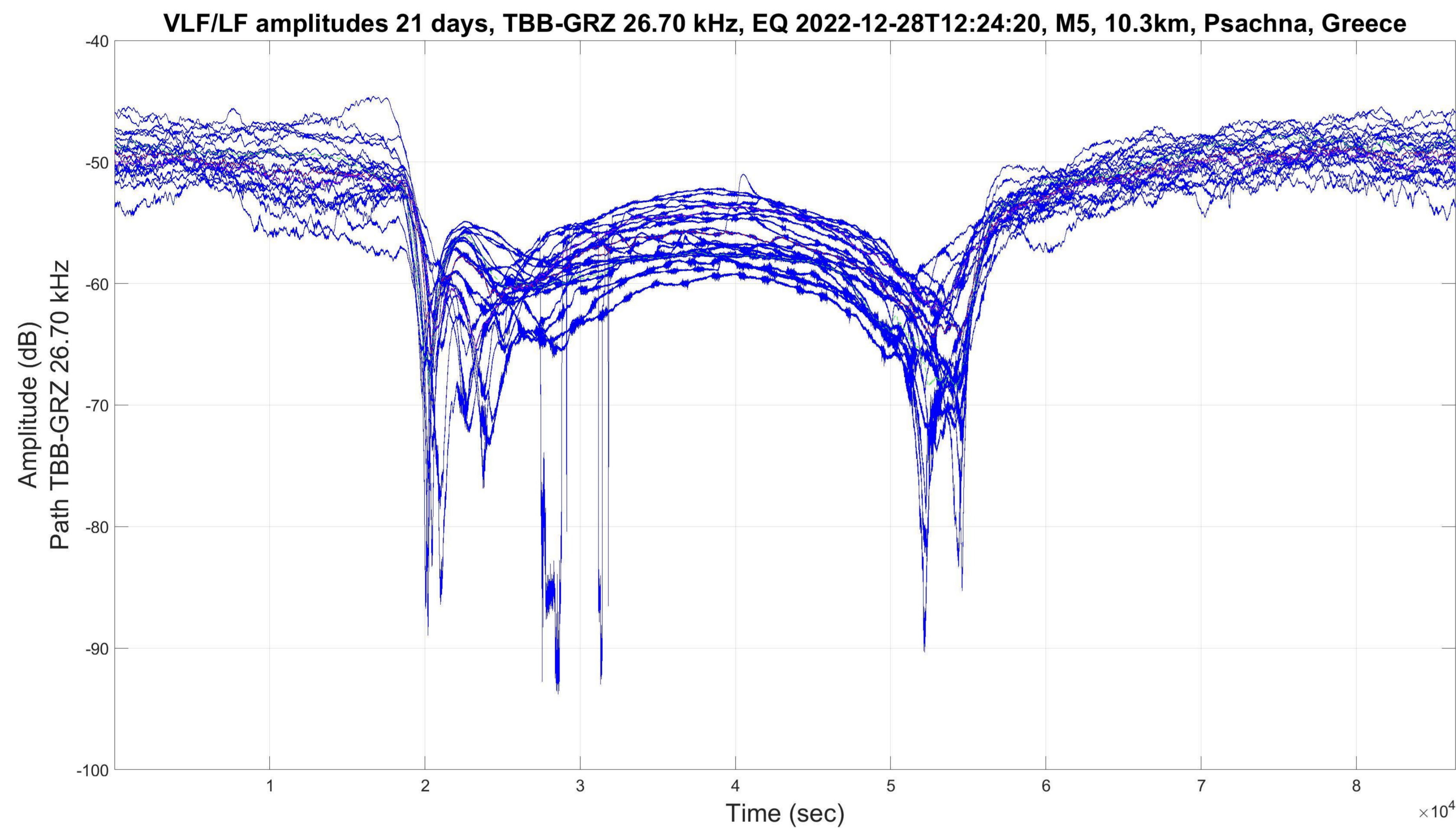
SUB-IONOSPHERIC VLF/LF WAVEGUIDE VARIATIONS RELATED TO MAGNITUDE M>5 EARTHQUAKES IN THE EASTERN MEDITERRANEAN AREA

Hans Eichelberger¹, Mohammed Y. Boudjada¹, Konrad Schwingenschuh¹, Bruno P. Besser¹, Daniel Wolbang¹, Maria Solovieva², Pier Francesco Biagi³, Patrick Galopeau⁴, Ghulam Jaffer⁵, Özer Aydogar¹, Christoph Schirninger¹, Cosima Muck¹, Irmgard Jernej¹, and Werner Magnes¹

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VLF/LF AMPLITUDE MEASUREMENTS, EARTHQUAKE 2022-11-09, M5.0, 10.3 KM, PSACHNÁ, GREECE

- Top Left: VLF/LF amplitudes (2022-12-18 to 2023-01-07) 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, **in general high variations**
- 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, **for a significance level of 5% the paths NAA-GRZ, GBS-GRZ, and NRK-GRZ show higher amplitude values after the EQ**



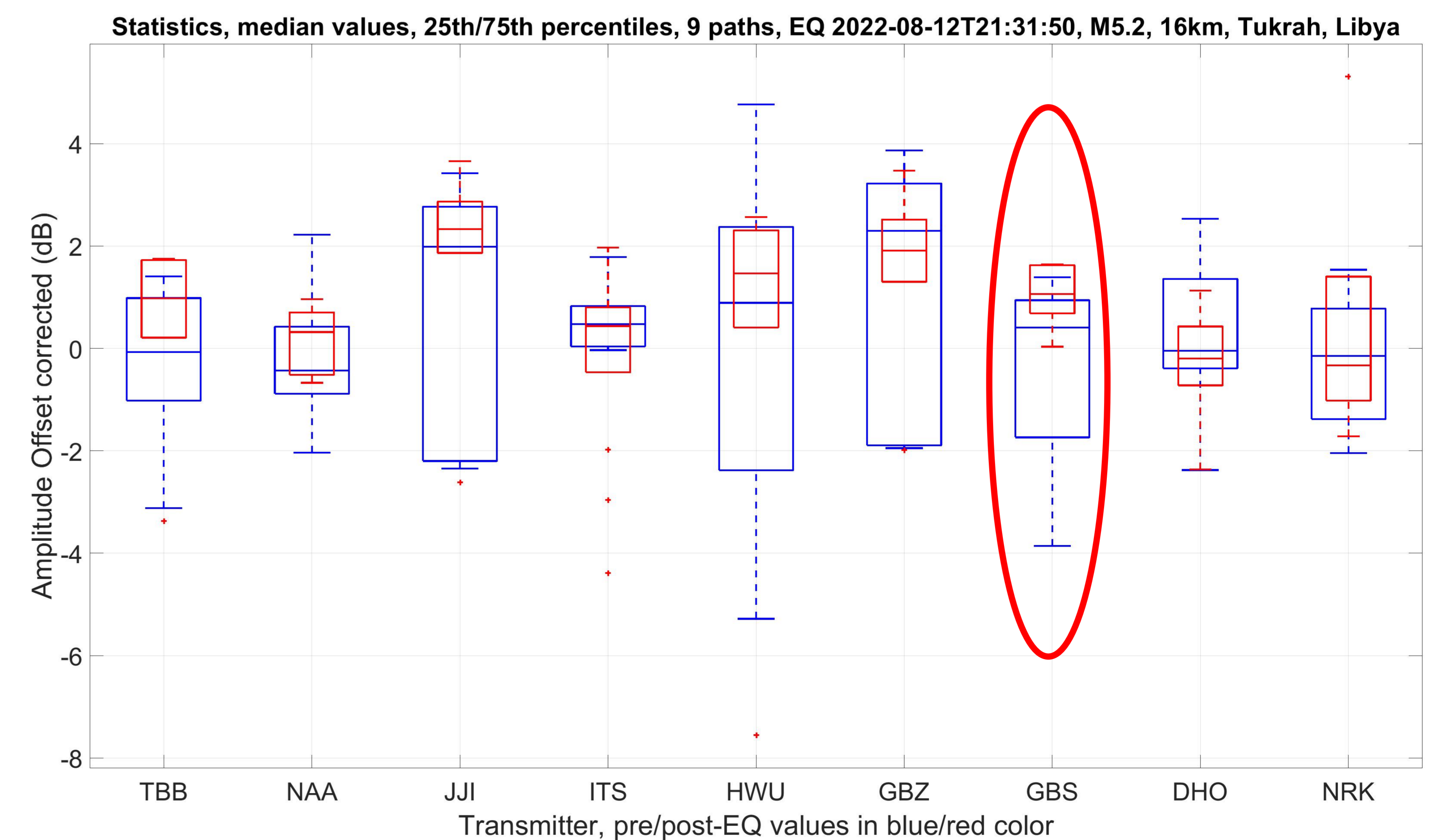
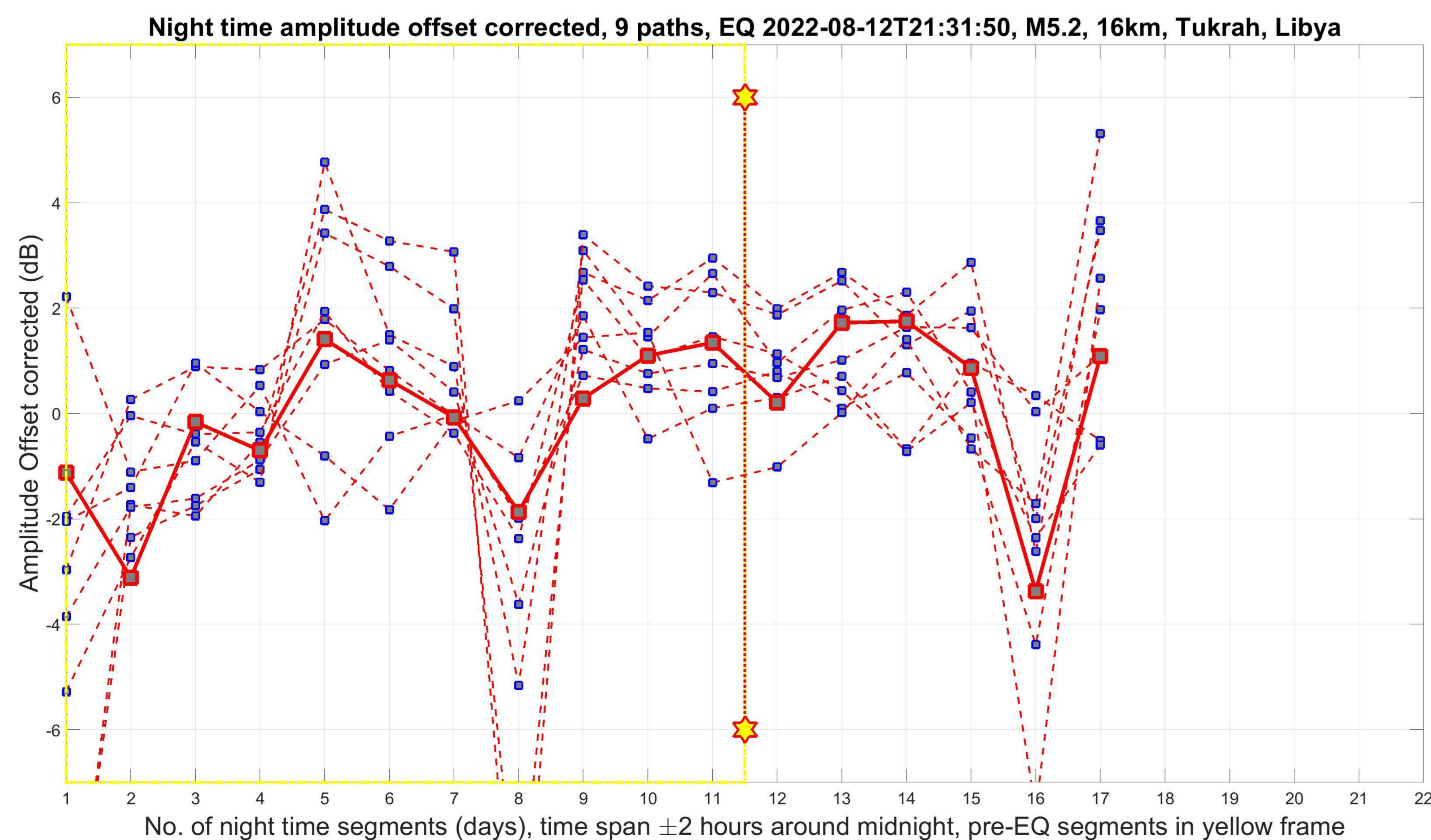
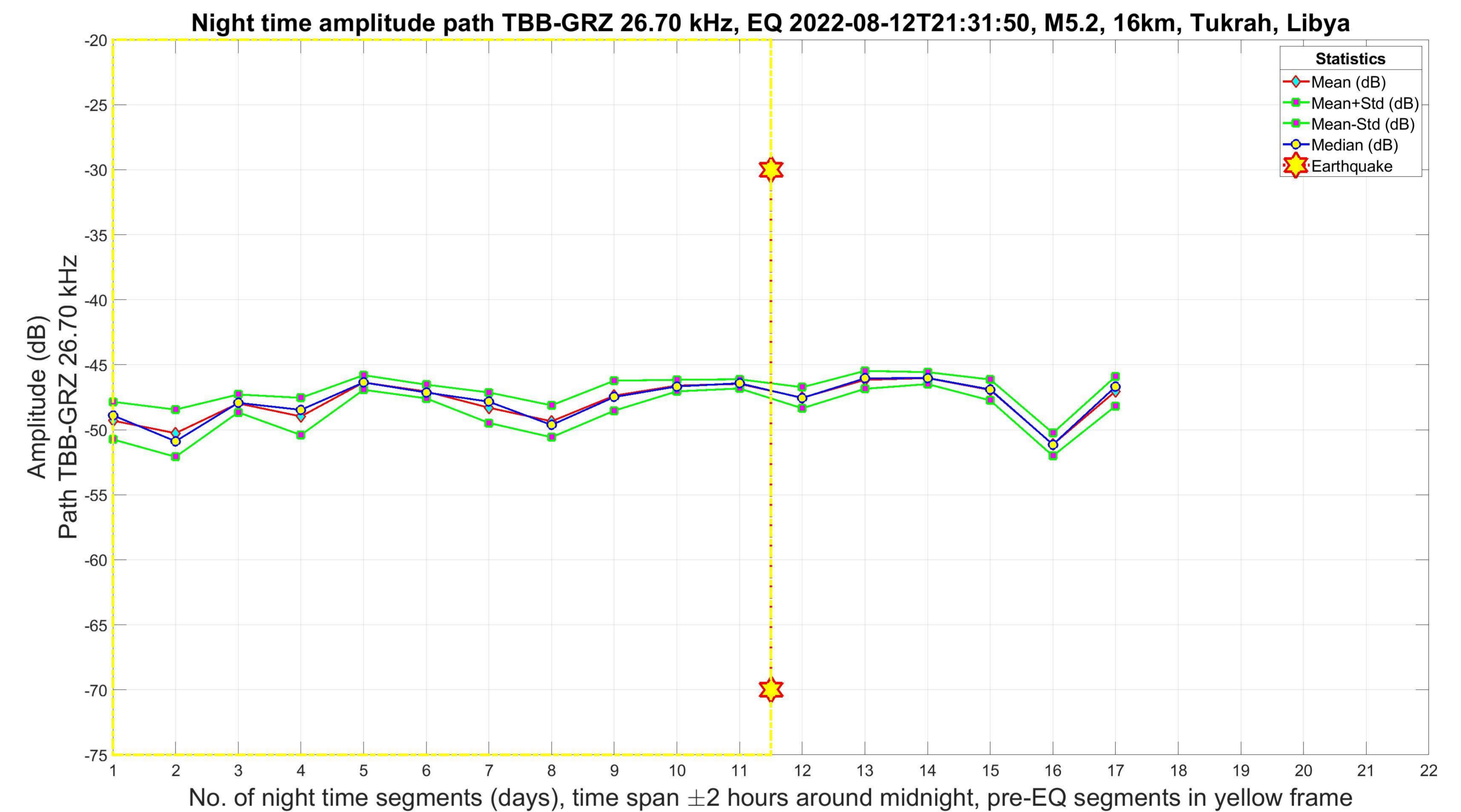
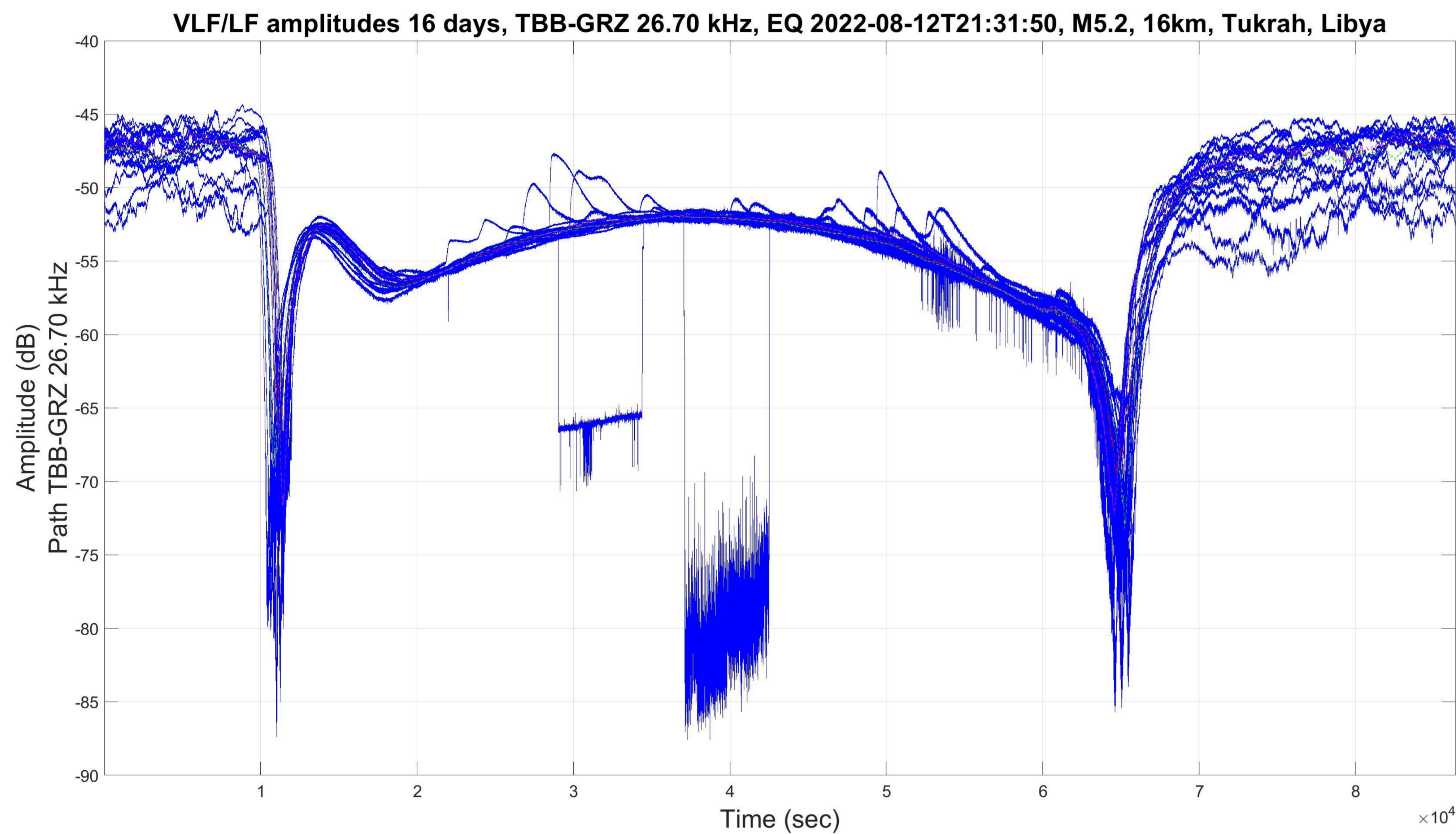
SUB-IONOSPHERIC VLF/LF WAVEGUIDE VARIATIONS RELATED TO MAGNITUDE M>5 EARTHQUAKES IN THE EASTERN MEDITERRANEAN AREA

Hans Eichelberger¹, Mohammed Y. Boudjada¹, Konrad Schwingenschuh¹, Bruno P. Besser¹, Daniel Wolbang¹, Maria Solovieva², Pier Francesco Biagi³, Patrick Galopeau⁴, Ghulam Jaffer⁵, Özer Aydogar¹, Christoph Schirninger¹, Cosima Muck¹, Irmgard Jernej¹, and Werner Magnes¹

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VLF/LF AMPLITUDE MEASUREMENTS, EARTHQUAKE 2022-08-12, M5.2, 16 KM, TUKRAH, LIBYA

- Top Left: VLF/LF amplitudes (2022-08-02 to 2022-08-17) 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 TBB-GRZ path (no crossing of the Dobrovolsky-Bowman area/radius)
- Bottom Right: Statistics (box plots) for the offset corrected 9 paths, for a significance level of 5% the path GBS-GRZ shows higher amplitude values after the EQ (nighttime method)



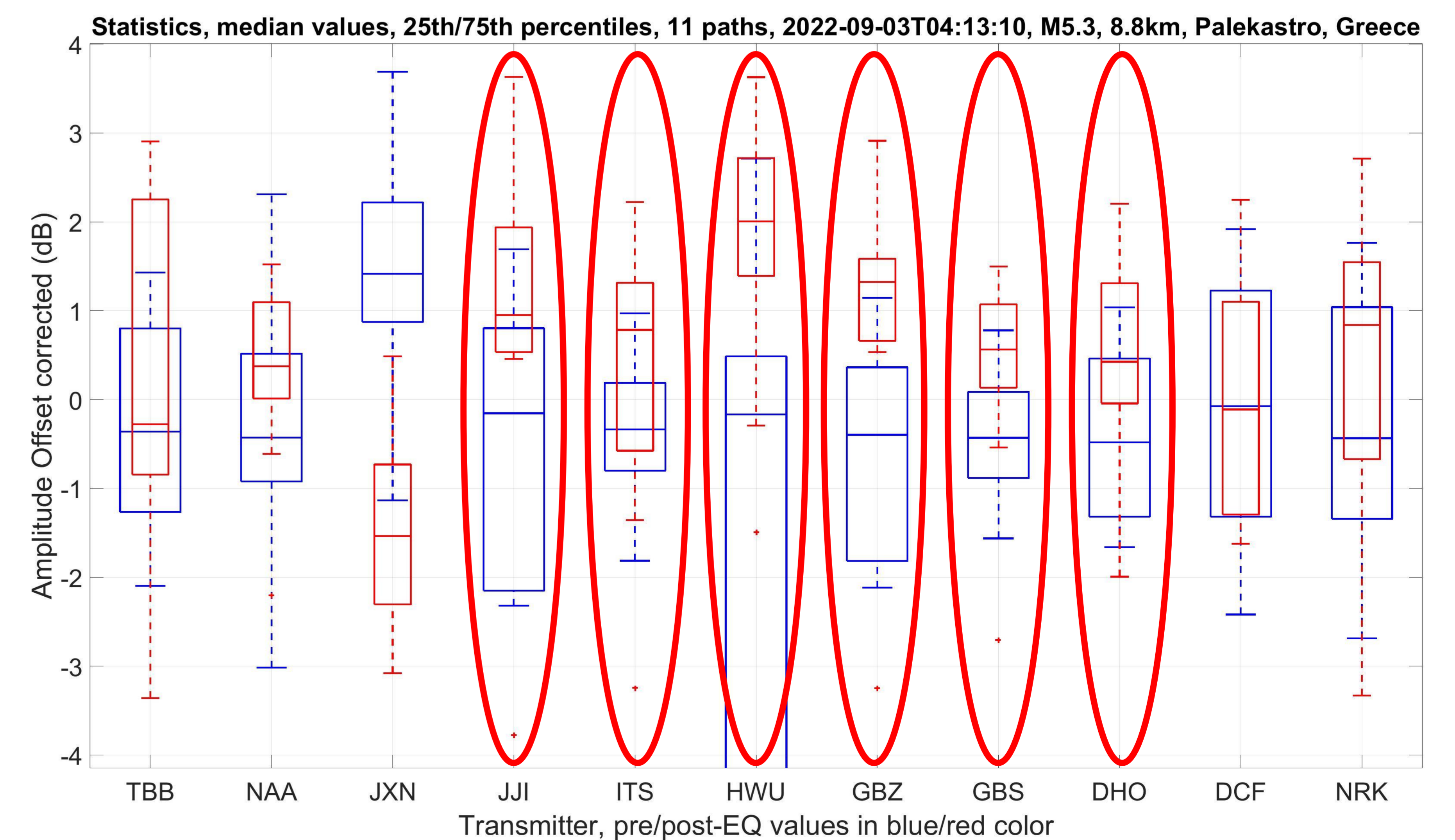
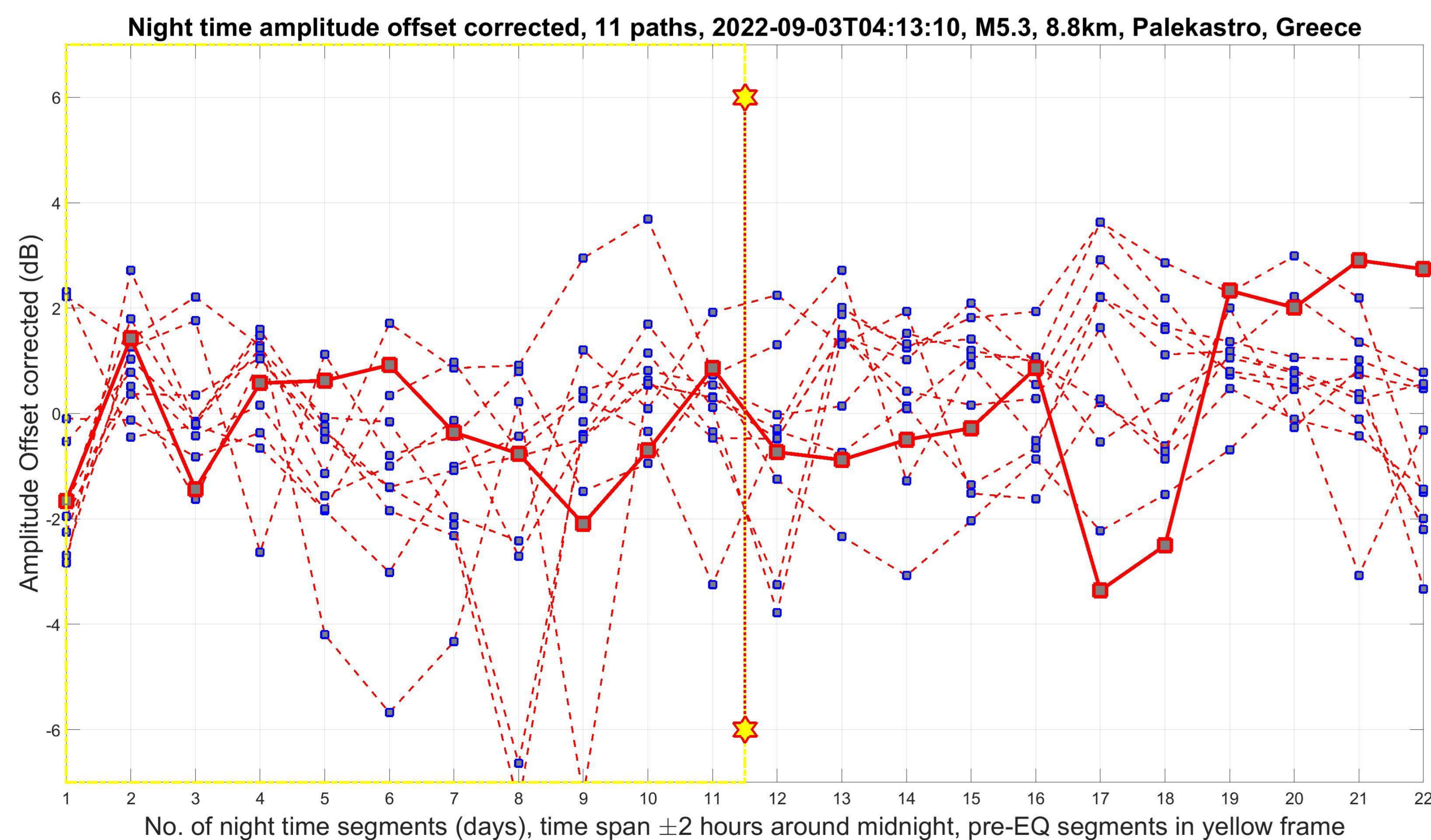
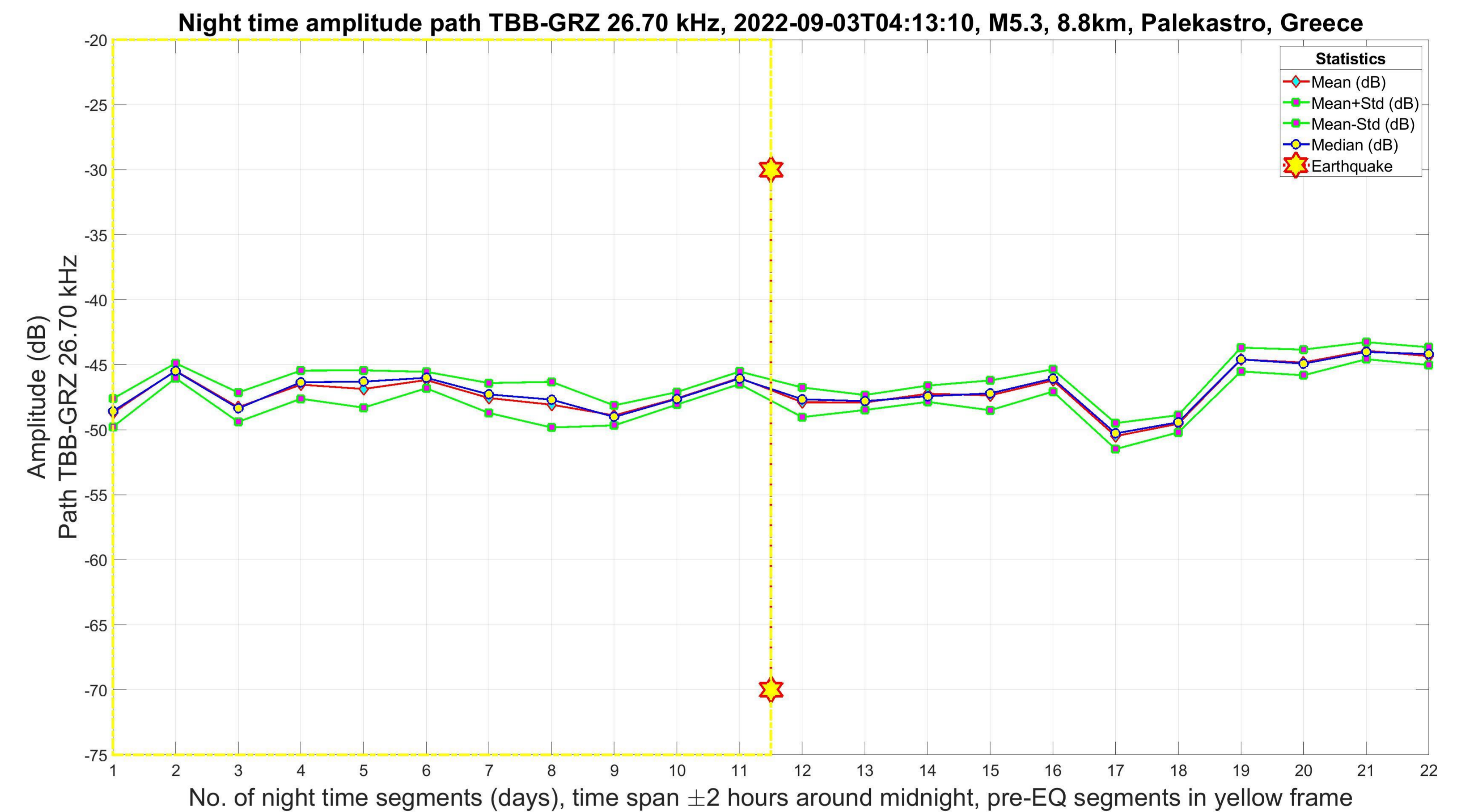
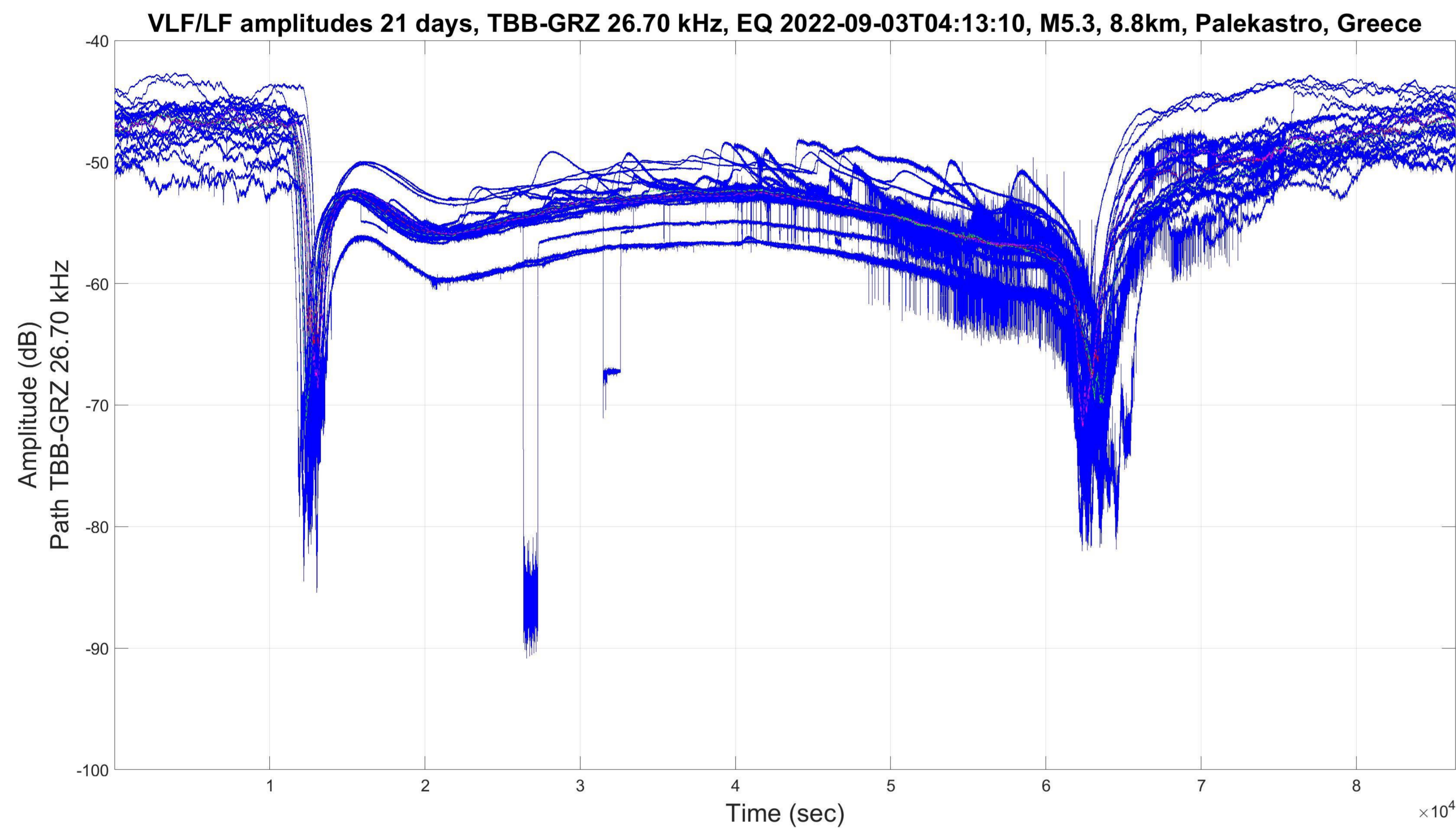
SUB-IONOSPHERIC VLF/LF WAVEGUIDE VARIATIONS RELATED TO MAGNITUDE M>5 EARTHQUAKES IN THE EASTERN MEDITERRANEAN AREA

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VLF/LF AMPLITUDE MEASUREMENTS, EARTHQUAKE 2022-09-03, M5.3, 8.8 KM, PALEKASTRO, GREECE

- Top Left: VLF/LF amplitudes (2022-08-24 to 2022-09-13) for the 26.70 kHz TBB-GRZ path, spikes and transmitter switch off periods are omitted, **variations in the electric field values**
- Bottom Left: Offset corrected nighttime (± 2 h around midnight) amplitude values for the 11 paths
- Top Right: Nighttime amplitude values for the TBB-GRZ path (**no crossing of the Dobrovolsky-Bowman area/radius**)
- Bottom Right: Statistics (box plots) for the offset corrected 11 paths, **for a significance level of 5% 6 paths show higher amplitude values after the EQ (nighttime method)**



SUB-IONOSPHERIC VLF/LF WAVEGUIDE VARIATIONS RELATED TO MAGNITUDE M>5 EARTHQUAKES IN THE EASTERN MEDITERRANEAN AREA

Hans Eichelberger¹, Mohammed Y. Boudjada¹, Konrad Schwingenschuh¹, Bruno P. Besser¹, Daniel Wolbang¹, Maria Solovieva², Pier Francesco Biagi³, Patrick Galopeau⁴, Ghulam Jaffer⁵, Özer Aydogar¹, Christoph Schirninger¹, Cosima Muck¹, Irmgard Jernej¹, and Werner Magnes¹

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VLF/LF AMPLITUDE MEASUREMENTS, EARTHQUAKE 2022-10-02, M5.4, 10 KM, IERÁPETRA, GREECE

- Top Left: VLF/LF amplitudes (2022-09-22 to 2022-10-12) 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 11 paths
- Top Right: Nighttime amplitude values for the TBB-GRZ path (no crossing of the Dobrovolsky-Bowman area/radius)
- Bottom Right: Statistics (box plots) for the offset corrected 11 paths, no significant variations (5% level) according to the nighttime method

