SUB-IONOSPHERIC VLF/LF WAVEGUIDE ELECTRIC FIELD INVESTIGATION FROM MW≥5.0 EARTHQUAKE EVENTS WITH MULTIPLE RECEIVERS IN EUROPE

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Electric field amplitude and phase measurements between narrowband VLF/LF transmitters and receivers in the sub-ionospheric waveguide are affected and altered by man-made and natural sources (Nina 2024; Boudjada et al., 2024a,b). In this study we investigate Mw ≥ 5.0 earthquakes (EQs) which occurred in Europe during the year 2024 based on data from the INFREP receiver network (Biagi et al., 2019; Moldovan et al., 2015; Galopeau et al., 2023). In the selected Mediterranean area with geographical longitude [-10°E, 40°E] and latitude [30°N, 50°N] the United States Geological Survey EQ catalog (USGS, 2025) provides 19 events with Mw≥5.0. For these EQs we apply the night-time amplitude method and consider variations in the terminator times (Hayakawa et al., 2010). The main radio links that cross the EQ prone areas are from transmitters localized in the southern part of Europe, including TBB (26.70 kHz, Bafa, Turkey), ITS (45.90 kHz, Niscemi, Sicily, Italy), and ICV (20.27 kHz, Tavolara, Italy). We find statistically significant electric field anomalies for various VLF/LF paths, particularly for events with higher magnitudes. The continuous VLF/LF electric field amplitude and phase datasets can be important parameters for real-time observations and services to assess seismic hazards and disturbing physical phenomena within the waveguide.

TRANSMITTER LIST & VLF/LF SYSTEM PARAMETERS

Receiver: Graz, IWF, Elettronika [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 1sec], [U 20sec], [E 60 sec]
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	Vijayanarayanam, 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	Dimona	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]

VLF/LF NETWORK, EUROPEAN PATHS, EQ M5+

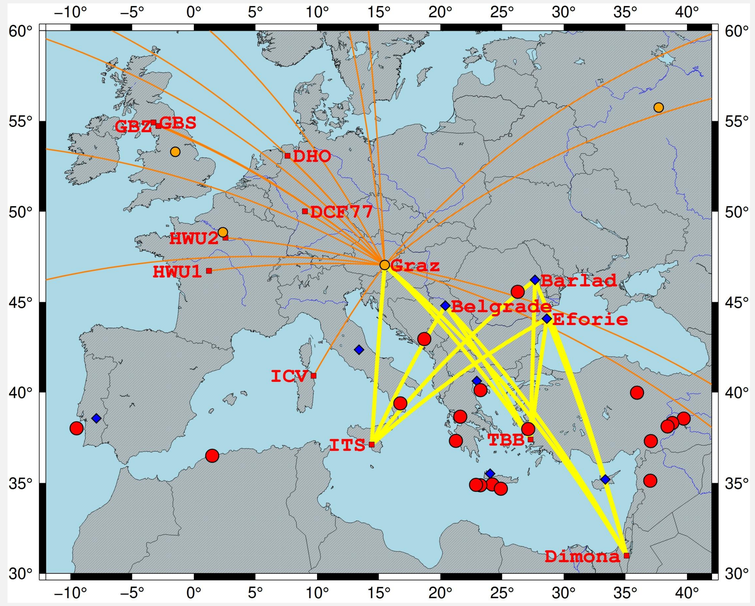

Table 2: System parameters and transmitters received at the VLF/LF Graz facility [1, 4, 6], settings in blue/green/red color, 3 major EQs event paths (yellow background). **Figure 1**: Great circle paths (orange & yellow lines) between VLF/LF transmitters and INFREP receivers (diamonds in blue color; orange circles for other UltraMSK systems [4]). Magnitude M5+ EQs 2024 (19 red dots) and the relevant paths related to the Dobrovolsky-Bowman relationship are indicated (yellow lines good S/N, remaining are control links and long-distance paths). Credit map: GMT

EARTHQUAKES M ≥ 5, 2024, MEDITERRANEAN & SOUTHERN EUROPE, DATA PROCESSING & RESULTS

We investigate VLF/LF electric field amplitudes from sub-ionospheric VLF/LF propagation paths in the geogr. range [30° ≤ lat ≤ 50°] / [-10° ≤ long ≤ 40°] in 2024. For this temporal, spatial and magnitude M ≥ 5.0 constraints the USGS EQ database [8] includes 19 EQs, the Dst-index considers external geomagnetic disturbances. All events (Tab. 1, Fig. 1) are selected, emphasis is according to VLF/LF path crossings and the Dobrovolsky-Bowman relationship, i.e., the radius of the effective precursor manifestation zone $\varrho = 10^{(0.43*M)}$ km and log(R) ≈ M/2 km. VLF/LF amplitude nighttime values are used (±2 hours around midnight), 1 Hz time 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 Özdere, Pazarcık (both Turkey), and Cașoca (Romania) events.

Table 1: Results for all M ≥ 5 earthquakes (Fig. 1, dots in red color) in 2024, Mediterranean and Southern Europe area (relevant events in orange).

Selected Earthquakes Magnitude M ≥ 5.0, USGS database, time span 01.01.2024 – 31.12.2024, long/lat range: [-10° – +40°]/[+30° – +50°], ρ (km) Dobrovolsky–Bowman radius							
No.	Date, Time	Lat (°), Lon (°), d (km)	M / ρ (km)	Location	Main path	Available paths for the event, time span ± 11 days around the earthquake	Result, Annotation
1	2024–01–12 03:51:05	+34.89, +22.89, 28.8	5.0 / 141	81 km WSW of Palaióchora, Greece	{TBB, Dimona}–GRZ	12 {ISR TBB NAU NAA JXN JJI ITS ICV GBZ GBS DHO DCF}–GRZ	Not OK: One day missing because of GRZ receiver failure, |Dst| = 24 nT (calm period)
2	2024–01–25 13:04:06	+38.12, +38.42, 16.2	5.0 / 141	19 km WNW of Sincik, Turkey	{TBB, Dimona}–GRZ	14 {ISR VTX TBB NAU NAA JXN JJI ITS ICV GWU GBZ GBS DHO DCF}–GRZ	NOK: |Dst| = 23 nT (calm period)
3	2024–01–27 05:19:19	+37.98, +27.12, 11.3	5.1 / 156	4 km S of Özdere, Turkey	{TBB, Dimona}–GRZ	13 {ISR TBB NAU NAA JXN JJI ITS ICV GWU GBZ GBS DHO DCF}–GRZ	OK: ISR: Post EQ > Pre EQ values with significance level 5%, TBB near 5% significance level, |Dst| = 23 nT (calm period), near TBB transmitter, Bafa, Turkey
4	2024–03–14 03:06:47	+42.95, +18.69, 16.1	5.4 / 210	20 km NW of Nikšić , Montenegro	{TBB, Dimona}–GRZ	14 {ISR VTX TBB NAU NAA JXN JJI ITS ICV GWU GBZ GBS DHO DCF}–GRZ	NOK: |Dst| = 128 nT (high disturbances)
5	2024–03–29 07:12:48	+37.32, +21.26, 26.9	5.8 / 312	34 km WNW of Filiatrá, Greece	{TBB, Dimona}–GRZ	11 {ISR TBB NAU NAA JJI ITS ICV GBZ GBS DHO DCF}–GRZ	NOK: |Dst| = 128 nT (high disturbances)
6	2024–04–18 15:11:25	+39.99, +35.95, 16.0	5.6 / 256	11 km W of Sulusaray, Turkey	{TBB, Dimona}–GRZ	Lack of receiver data for the event	|Dst| = 117 nT (high disturbances)
7	2024–07–21 04:01:26	+34.87, +23.24, 10.0	5.3 / 190	56 km SW of Palaióchora, Greece	{TBB, Dimona}–GRZ	12 {ISR TBB NAU NAA JJI ITS HWU GBZ GBS DHO DCF NRK}–GRZ	NOK:|Dst| = 50 nT
8	2024–08–01 19:43:20	+39.40, +16.75, 30.0	5.1/ 156	2 km S of Bocchigliero, Italy	ITS–GRZ	10 {ISR TBB NAU NAA JJI ITS GBZ DHO DCF NRK}–GRZ	NOK: |Dst| = 100 nT (high disturbances)
9	2024–08–07 08:23:52	+34.68, +24.90, 10.0	5.0 / 141	41 km S of Moíres, Greece	{TBB, Dimona}–GRZ	10 {ISR TBB NAU NAA JJI ITS GBZ DHO DCF NRK}–GRZ	NOK: |Dst| = 188 nT (high disturbances)
10	2024–08–12 20:55:59	+35.12, +37.02, 7.30	5.2 / 172	12 km NNW of As Salamīyah, Syria	{TBB, Dimona}–GRZ	10 {ISR TBB NAU NAA JJI ITS GBZ DHO DCF NRK}–GRZ	NOK: |Dst| = 188 nT (high disturbances)
11	2024–08–26 04:11:37	+38.02, –09.50, 6.60	5.0 / 141	56 km W of Sines, Portugal	No close–by paths	10 {ISR TBB NAU NAA JJI ITS ICV GBZ DHO DCF}–GRZ	NOK: |Dst| = 76 nT
12	2024–08–28 16:29:57	+34.91, +24.20, 54.8	5.1 / 156	13 km NE of Kastrí, Greece	{TBB, Dimona}–GRZ	10 {ISR TBB NAU NAA JJI ITS ICV GBZ DHO DCF}–GRZ	NOK: not significant, all paths out of 5% level, |Dst|= 76 nT
13	2024–09–07 06:31:10	+37.31, +37.06, 4.10	5.0 / 141	28 km SW of Pazarcık, Turkey	{TBB, Dimona}–GRZ	11 {ISR TBB NAU NAA JJI ITS ICV GBZ GBS DHO DCF NRK}–GRZ	OK: significant values for the TBB–GRZ path, |Dst|= 121 nT
14	2024–09–16 14:40:21	+45.57 +26.27, 133	5.2 / 232	8 km N of Cașoca, Romania	{TBB, Dimona}–GRZ	13 {ISR TBB NAU NAA JXN JJI ITS ICV GBZ GBS DHO DCF NRK}–GRZ	OK: sig. values for TBB–GRZ, major magnetic storm at 2024–09–12: |Dst|= 121 nT
15	2024–10–16 07:46:32	+38.31, +38.81, 10.0	6.0 / 380	19 km W of Doğanyol, Turkey	{TBB, Dimona}–GRZ	15 {ISR VTX TBB NAU NAA JXN JJI ITS ICV GWU GBZ GBS DHO DCF NRK}–GRZ	OK: but major magnetic storm at 2024–10–11: |Dst| = 333 nT (huge disturbances)
16	2024–11–03 17:03:52	+40.13, +23.25, 9.00	5.2 / 172	10 km SW of Néa Poteídaia, Greece	{TBB, Dimona}–GRZ	12 {ISR TBB NAU NAA JJI ITS ICV GBZ GBS DHO DCF NRK}–GRZ	OK/NOK: mixed results |Dst| = 89 nT
17	2024–11–08 14:04:01	+38.55, +39.73, 10.0	5.1 / 156	21 km SSW of Kovancılar, Turkey	{TBB, Dimona}–GRZ	12 {ISR TBB NAU NAA JJI ITS ICV GBZ GBS DHO DCF NRK}–GRZ	NOK: |Dst| = 89 nT
18	2024–12–16 00:09:46	+36.50, +1.49, 9.30	5.0 / 141	17 km ENE of Sidi Akkacha, Algeria	{ICV, ITS}–GRZ	14 {ISR TBB NAU NAA JXN JJI ITS ICV HWU GBZ GBS DHO DCF NRK}–GRZ	OK: no excitations for all paths, |Dst| = 40 nT
19	2024–12–21 16:29:52	+38.64, +21.61, 10.0	5.0 / 141	8 km ENE of Paravóla, Greece	{TBB, Dimona}–GRZ	14 {ISR TBB NAU NAA JXN JJI ITS ICV HWU GBZ GBS DHO DCF NRK}–GRZ	NOK: |Dst| = 40 nT

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SUMMARY

VLF/LF electric field variations (nighttime amplitude method; assumed significance level 5%) can be related to the Özdere, Pazarcık (both Turkey), and Cașoca (Romania) events. Strong geomagnetic disturbances (based on mag. storm Dst values) for particular EQs.

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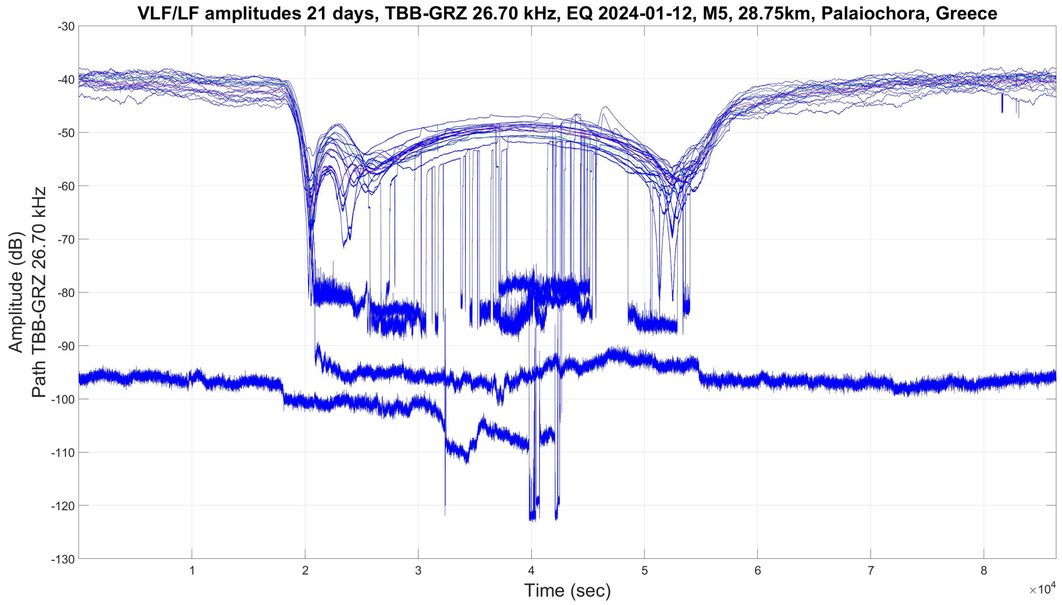
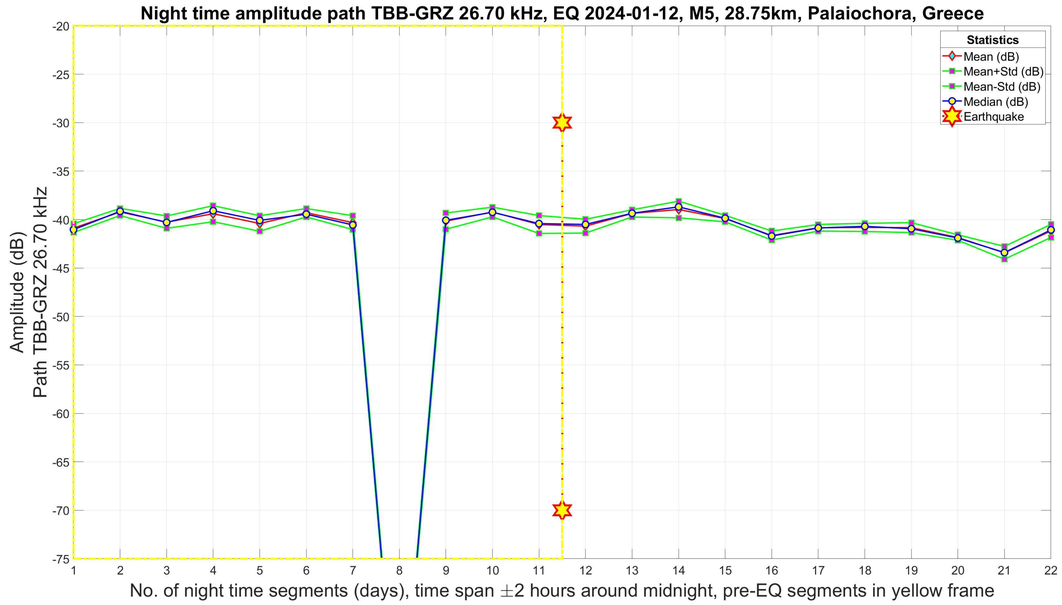
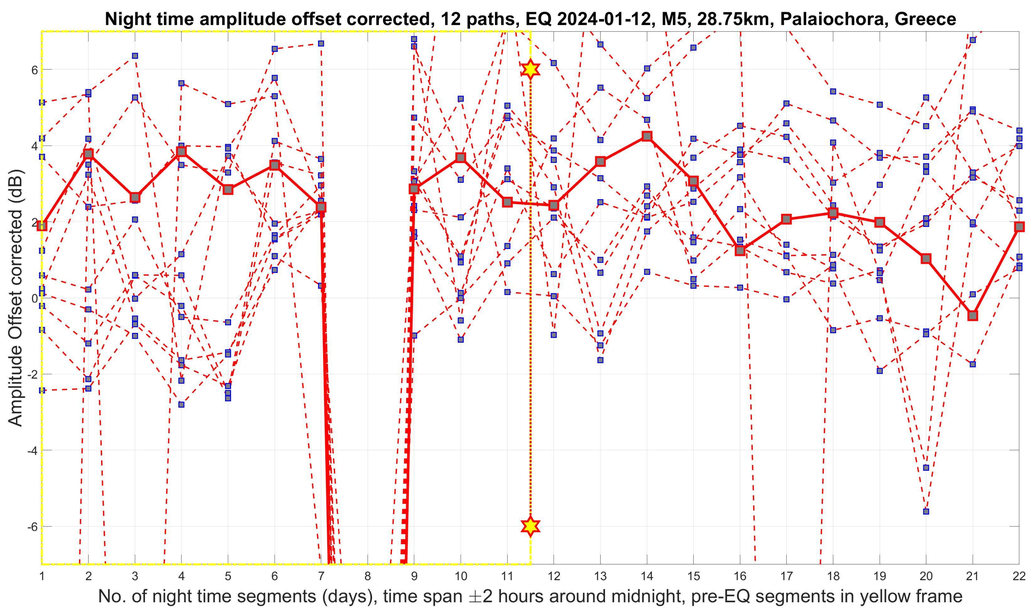
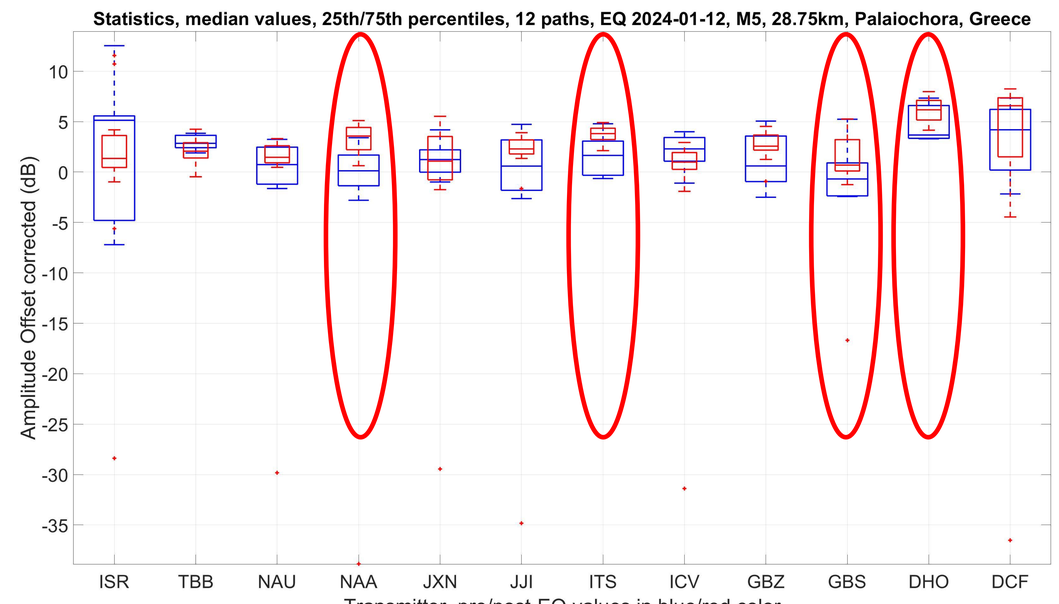
VLF/LF AMPLITUDE MEASUREMENTS, EARTHQUAKE 2024-01-12, MB 5 / 28.8 KM, PALAIÓCHORA, GREECE

- Top Left: VLF/LF amplitudes (2024-01-02 to 2024-01-22) for the 26.70 kHz TBB-GRZ path, spikes and transmitter switch off periods are omitted (one day missing, |Dst| = 24 nT, calm period)
- Bottom Left: Offset corrected nighttime (± 2h 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, for a sig. level of 5% the paths {NAA ITS GBS DHO}-GRZ show higher amplitude values after the EQ (nighttime method)









EGU GENERAL ASSEMBLY, 14-19 APRIL 2024, VIENNA, AUSTRIA

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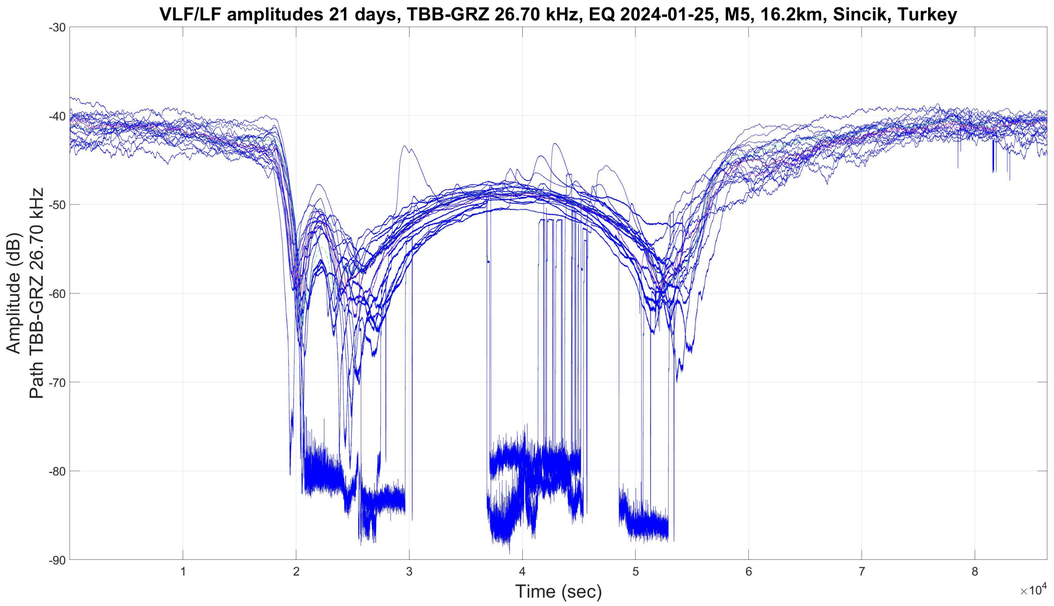
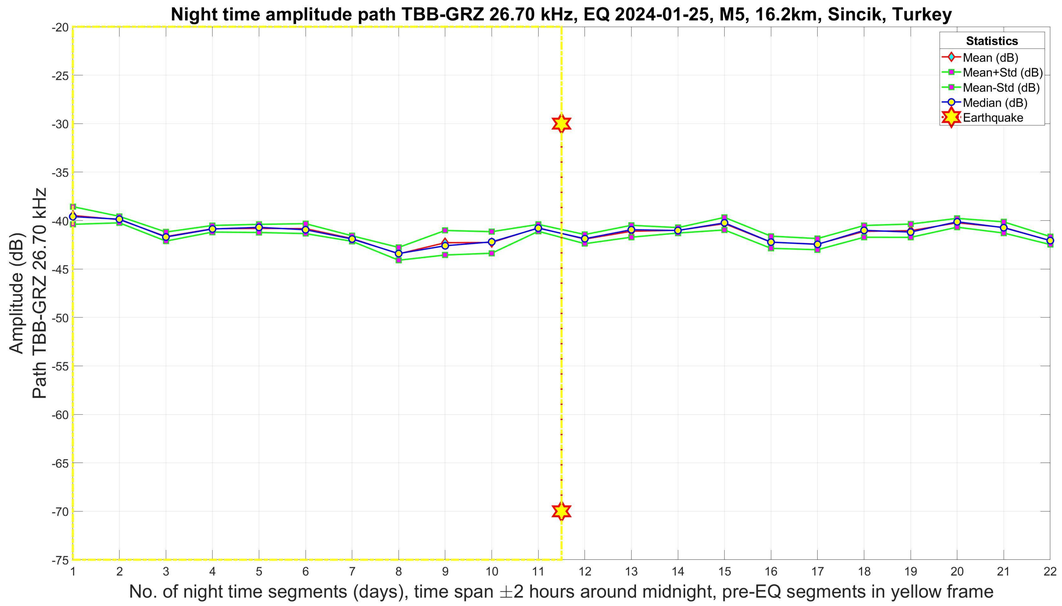
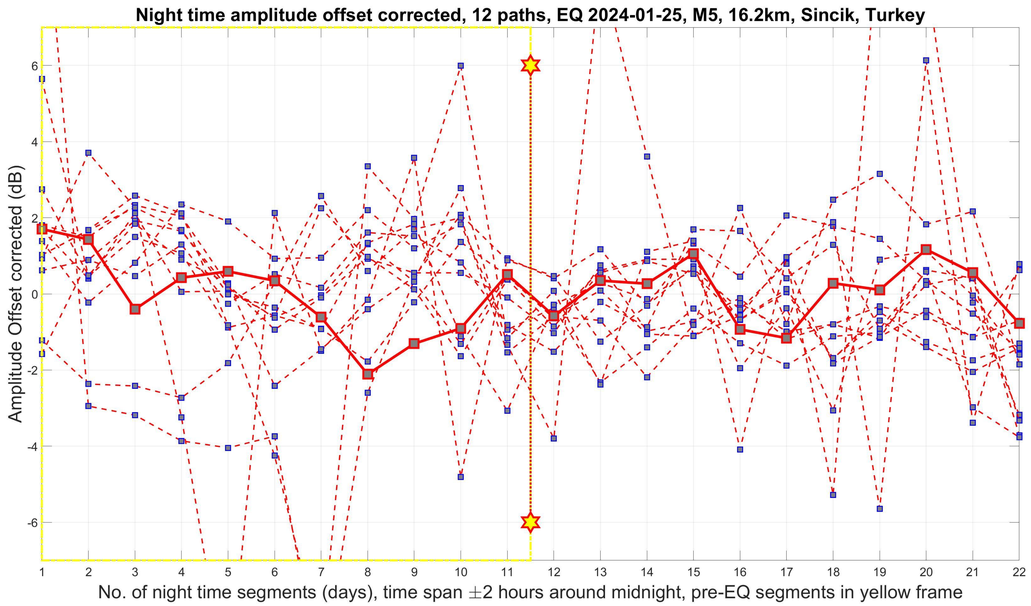
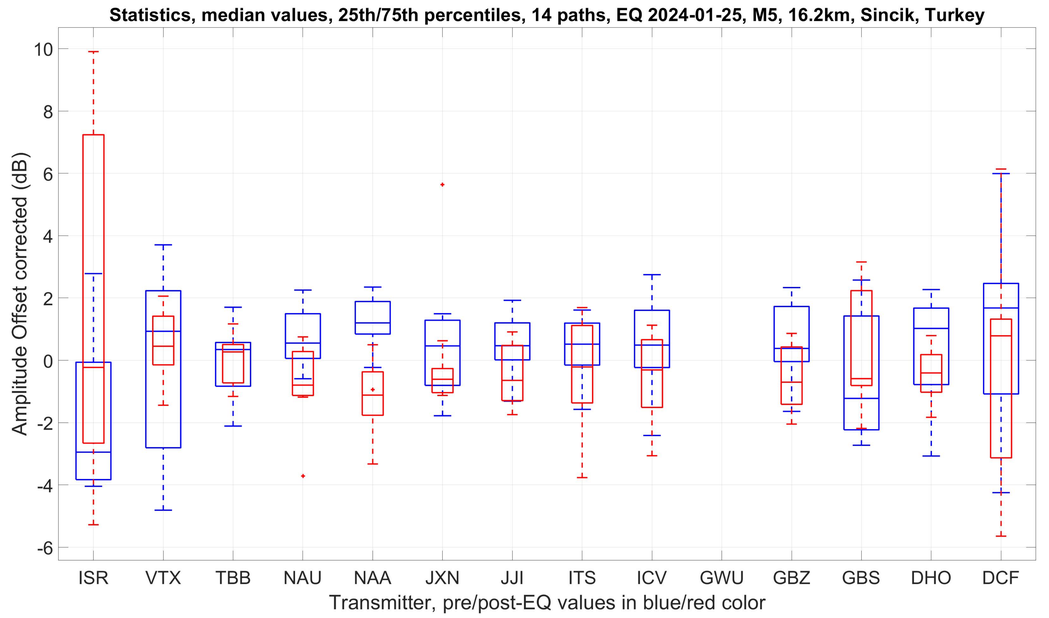
VLF/LF AMPLITUDE MEASUREMENTS, EARTHQUAKE 2024-01-25, MWW 5 / 16.2 KM, SINCIK, TURKEY

- Top Left: VLF/LF amplitudes (2024-01-15 to 2024-02-04) for the 26.70 kHz TBB-GRZ path, spikes and transmitter switch off periods are omitted (|Dst| = 23 nT, calm period)
- Bottom Left: Offset corrected nighttime (± 2h around midnight) amplitude values for the 14 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 14 paths, for a significance level of 5% no path shows higher amplitude values after the EQ (nighttime method)









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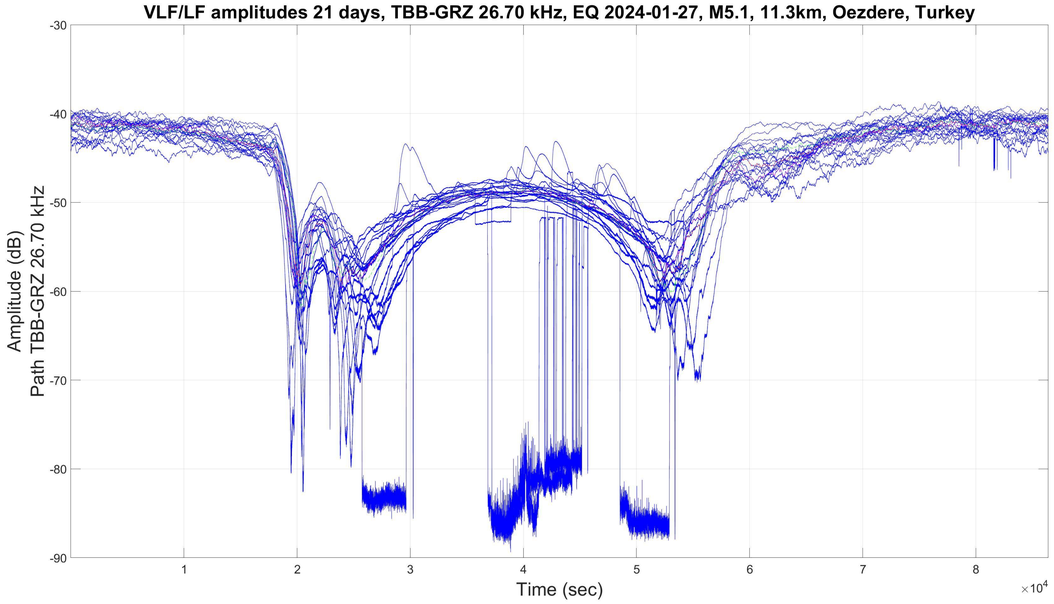
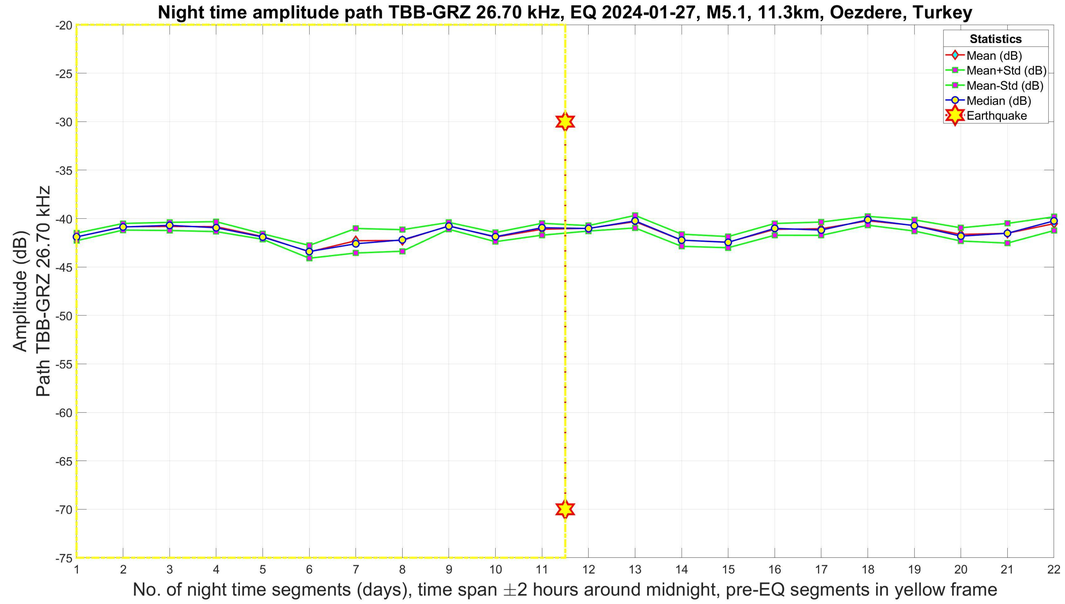
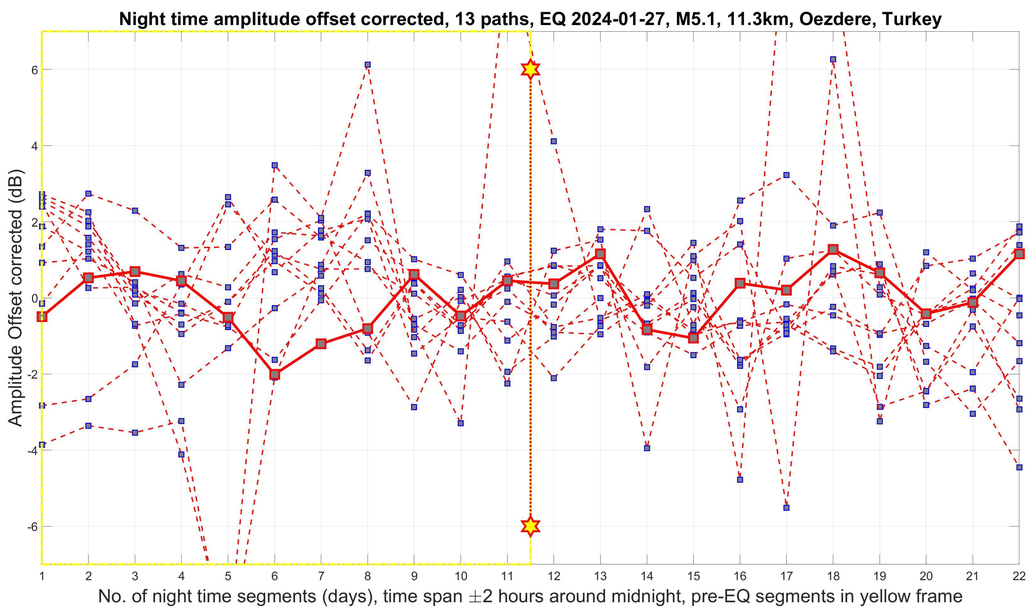
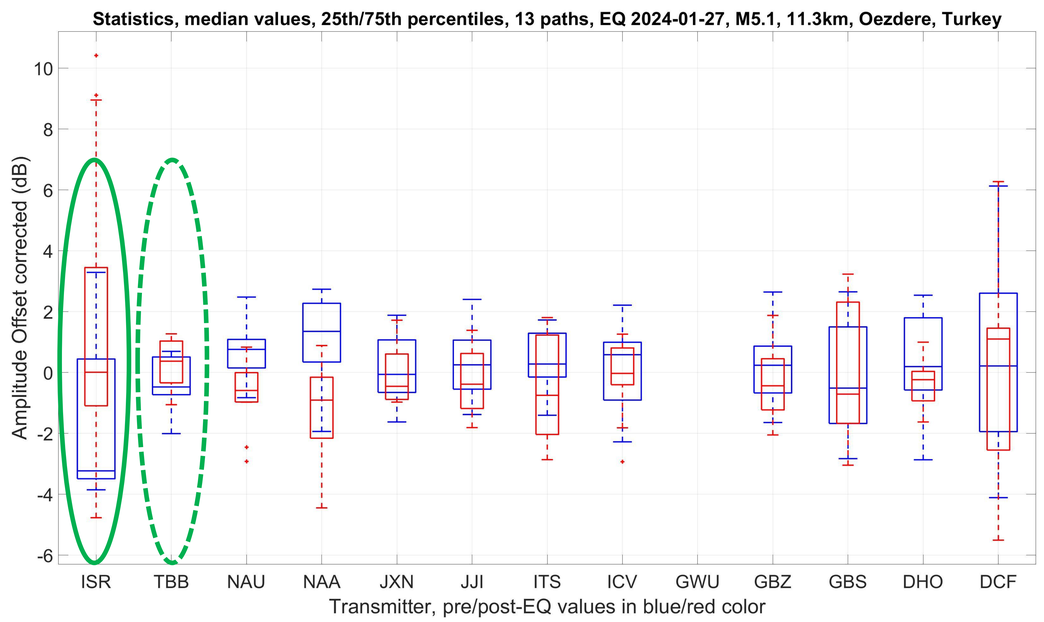
VLF/LF AMPLITUDE MEASUREMENTS, EARTHQUAKE 2024-01-27, MWW 5.1 / 11.3 KM, ÖZDERE, TURKEY

- Top Left: VLF/LF amplitudes (2024-01-17 to 2024-02-06) for the 26.70 kHz TBB-GRZ path, spikes and transmitter switch off periods are omitted (|Dst| = 23 nT, calm period)
- Bottom Left: Offset corrected nighttime (± 2h around midnight) amplitude values for the 13 paths
- Top Right: Nighttime amplitude values for the affected TBB-GRZ event path (crossing the Dobrovolsky-Bowman area/radius) , near TBB transmitter, Bafa, Turkey
- Bottom Right: Statistics (box plots) for the offset corrected 13 paths, for a significance level of 5% the event path Dimona-GRZ (approx. TBB-GRZ) shows higher amplitude values after the EQ









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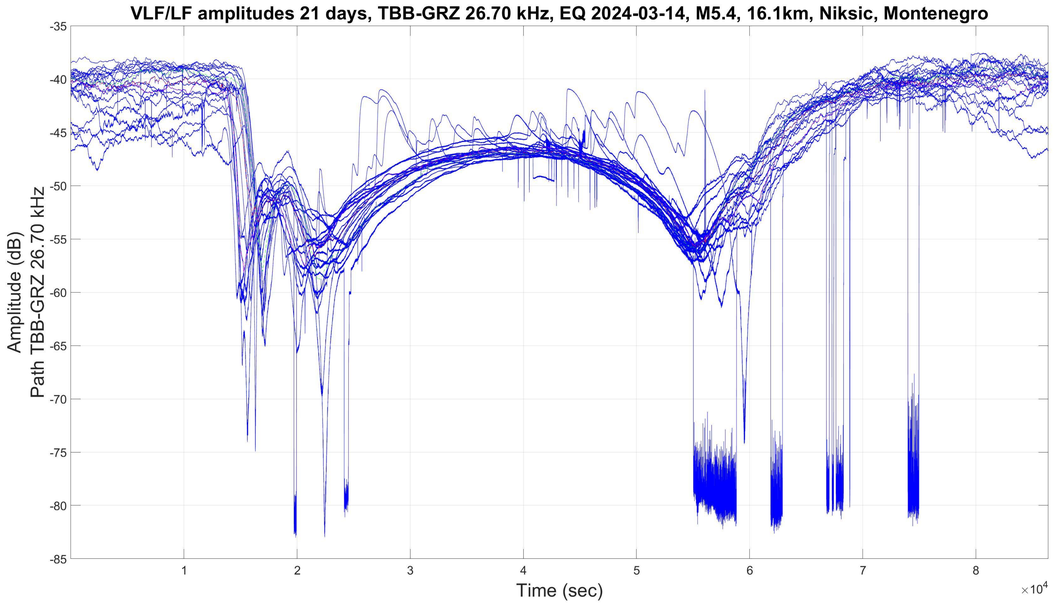
SUB-IONOSPHERIC VLF/LF WAVEGUIDE ELECTRIC FIELD INVESTIGATION FROM MW≥5.0 EARTHQUAKE EVENTS WITH MULTIPLE RECEIVERS IN EUROPE

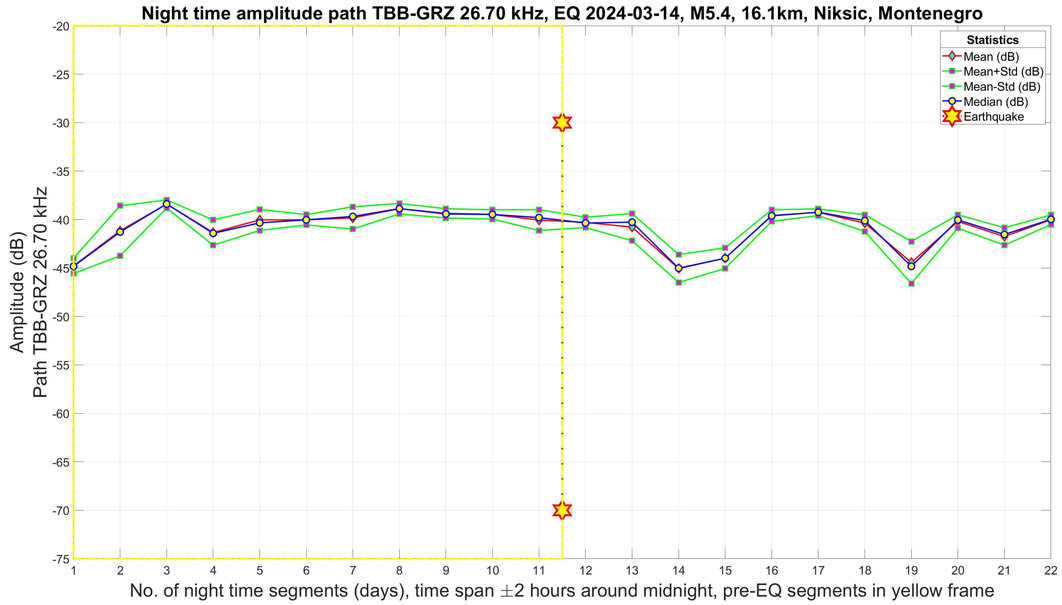
Hans U. Eichelberger[1], Mohammed Y. Boudjada[1], Aleksandra Nina[2], Bruno P. Besser[1], Daniel Wolbang[1], Maria Solovieva[3], Pier F. Biagi[4], Patrick H. M. Galopeau[5], Christoph Schirninger[6], Iren-Adelina Moldovan[7], Giovanni Nico[8], Manfred Stachel[1], Özer Aydogar[1], Cosima Muck[1], Josef Wilfinger[1], and Irmgard Jernej[1]

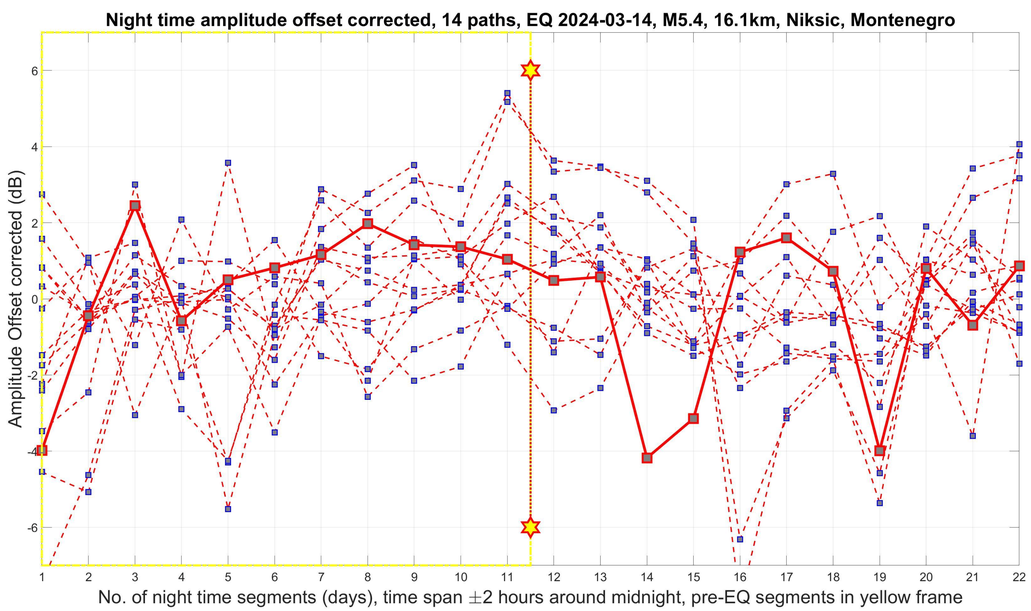
[1] Space Research Institute, Austrian Academy of Sciences, Graz, Austria, [2] Institute of Physics Belgrade, University of Belgrade, Belgrade, Serbia, [3] Schmidt Institute of Physics of the Earth, RAS, Moscow, Russia, [4] Department of Physics, University of Bari, Bari, Italy, [5] LATMOS-CNRS, UVSQ Université Paris-Saclay, Guyancourt, France, [6] Institute for Physics, University of Graz, Graz, Austria, [7] National Institute for Earth Physics, Magurele, Romania, [8] Institute of Applied Mathematics, Italian National Research Council, Bari, Italy

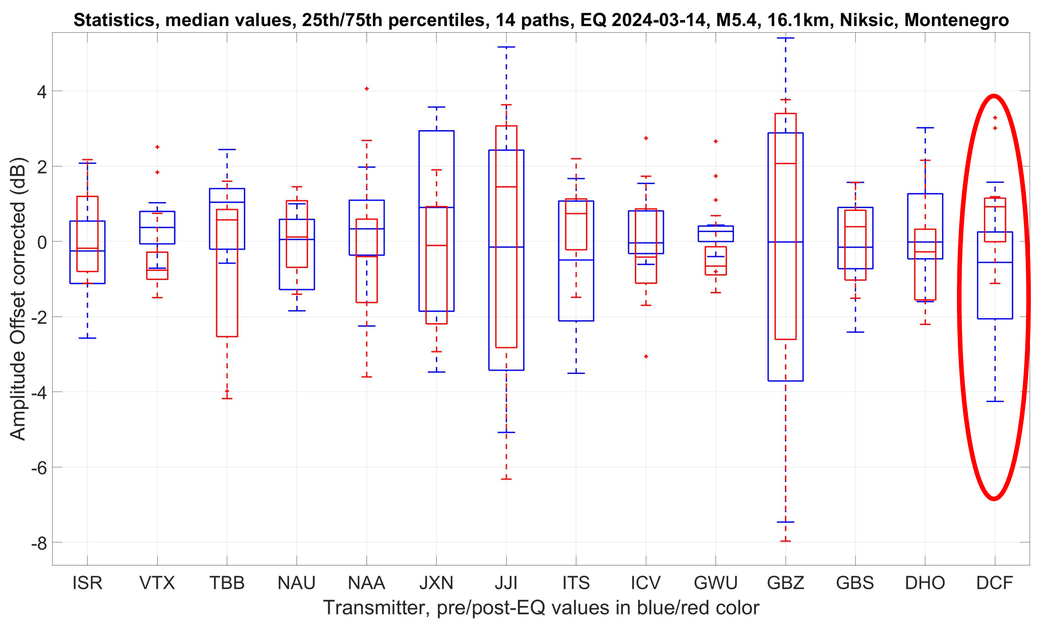
VLF/LF AMPLITUDE MEASUREMENTS, EARTHQUAKE 2024-03-14, MWW 5.4 / 16.1 KM, NIKŠIĆ , MONTENEGRO

- Top Left: VLF/LF amplitudes (2024-03-04 to 2024-03-24) for the 26.70 kHz TBB-GRZ path, spikes and transmitter switch off periods are omitted (|Dst| = 128 nT, high disturbances)
- Bottom Left: Offset corrected nighttime (± 2h around midnight) amplitude values for the 13 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 13 paths, for a significance level of 5% only the path DCF-GRZ shows higher amplitude values after the EQ (nighttime method)









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SUB-IONOSPHERIC VLF/LF WAVEGUIDE ELECTRIC FIELD INVESTIGATION FROM MW≥5.0 EARTHQUAKE EVENTS WITH MULTIPLE RECEIVERS IN EUROPE

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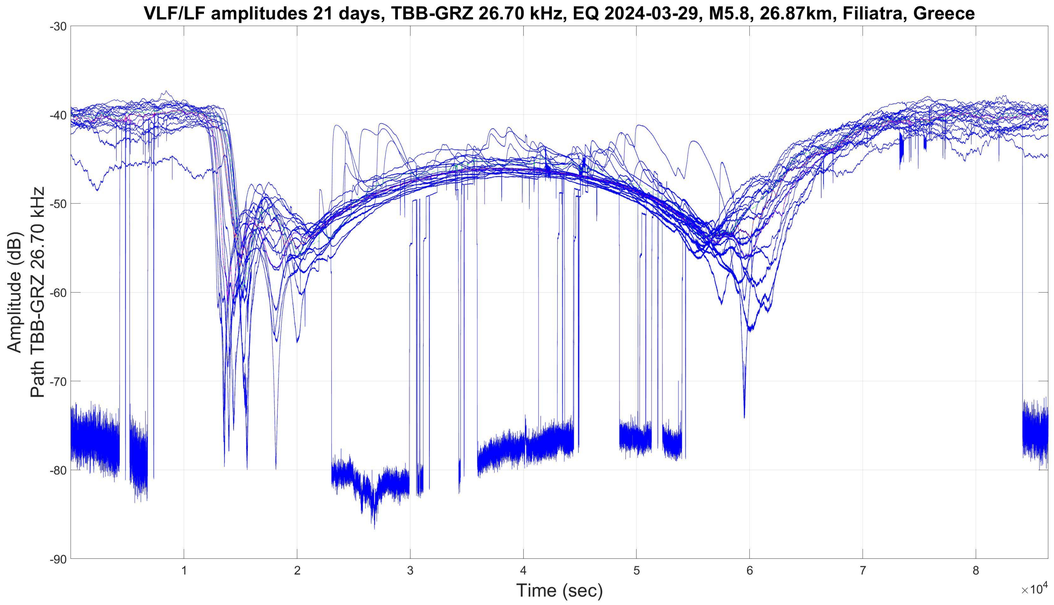
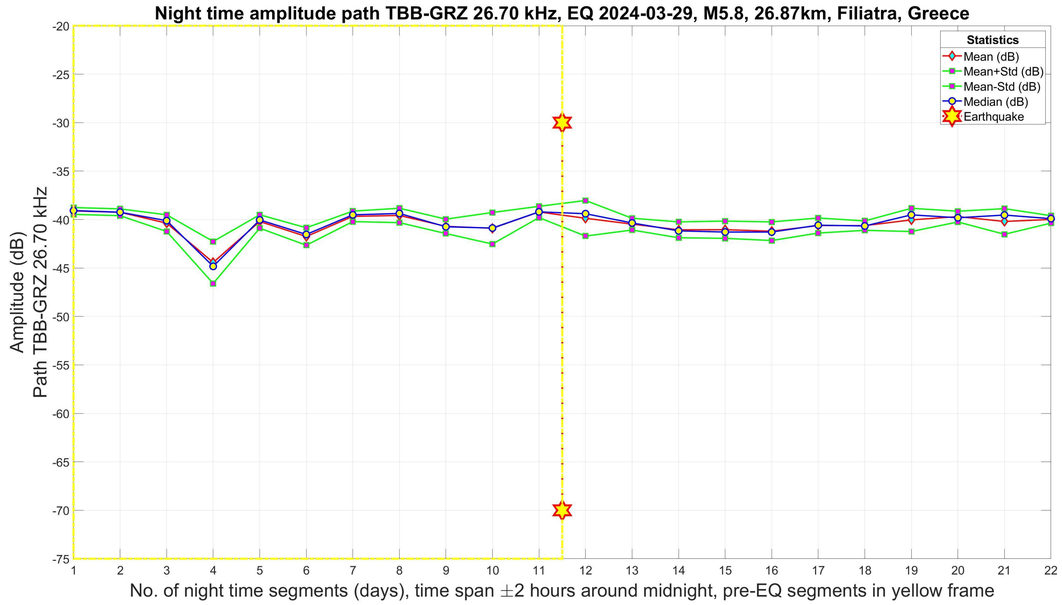
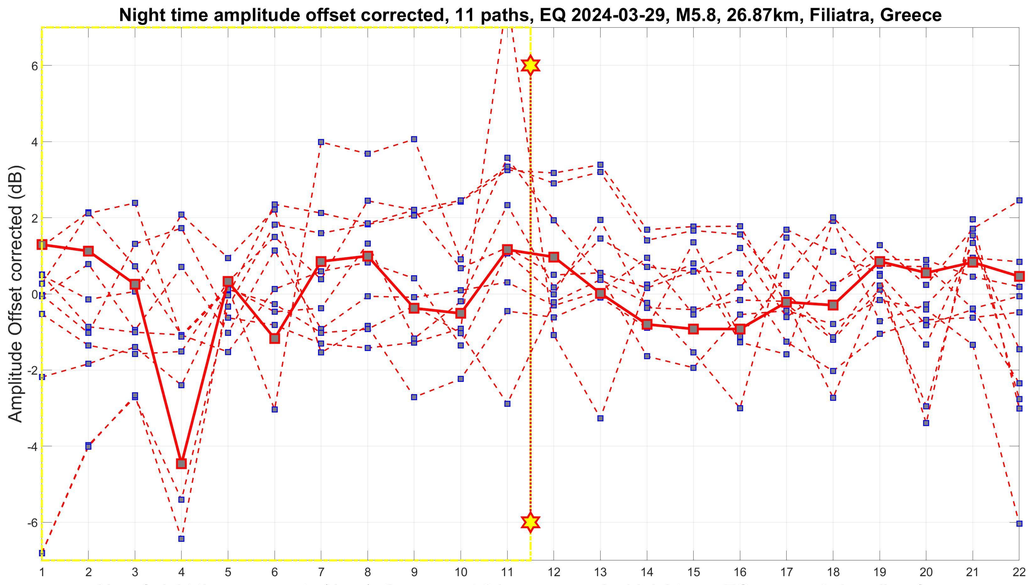
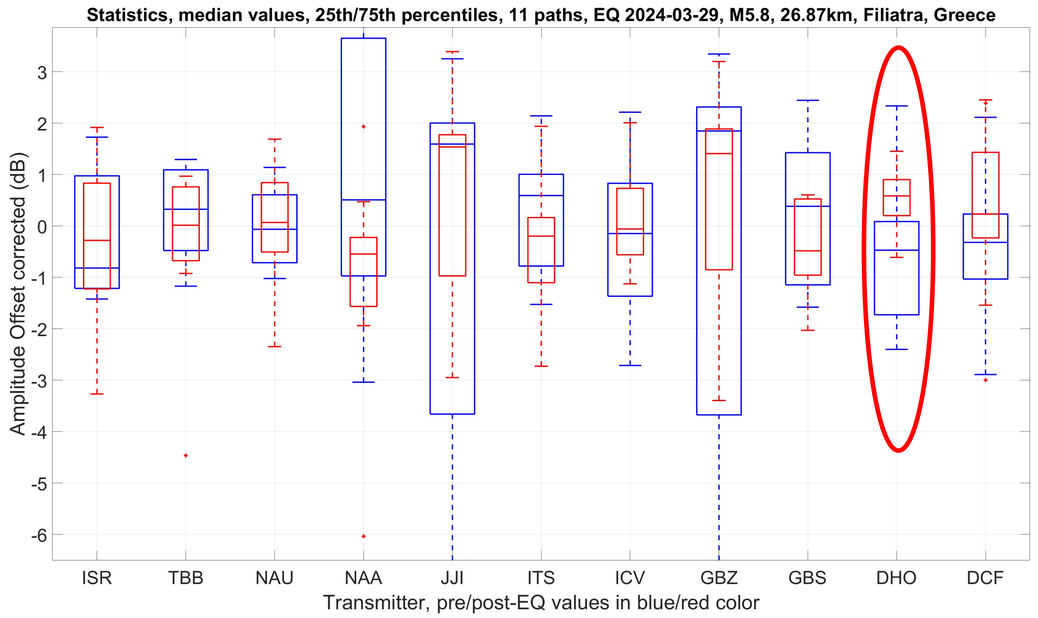
VLF/LF AMPLITUDE MEASUREMENTS, EARTHQUAKE 2024-03-29, MWW 5.8 / 26.9 KM, FILIATRÁ, GREECE

- Top Left: VLF/LF amplitudes (2024-03-19 to 2024-04-08) for the 26.70 kHz TBB-GRZ path, spikes and transmitter switch off periods are omitted (|Dst| = 128 nT, high disturbances)
- Bottom Left: Offset corrected nighttime (± 2h around midnight) amplitude values for the 11 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 11 paths, for a significance level of 5% only the path DHO-GRZ shows higher amplitude values after the EQ (nighttime method)









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SUB-IONOSPHERIC VLF/LF WAVEGUIDE ELECTRIC FIELD INVESTIGATION FROM MW≥5.0 EARTHQUAKE EVENTS WITH MULTIPLE RECEIVERS IN EUROPE

Hans U. Eichelberger[1], Mohammed Y. Boudjada[1], Aleksandra Nina[2], Bruno P. Besser[1], Daniel Wolbang[1], Maria Solovieva[3], Pier F. Biagi[4], Patrick H. M. Galopeau[5], Christoph Schirninger[6], Iren-Adelina Moldovan[7], Giovanni Nico[8], Manfred Stachel[1], Özer Aydogar[1], Cosima Muck[1], Josef Wilfinger[1], and Irmgard Jernej[1]

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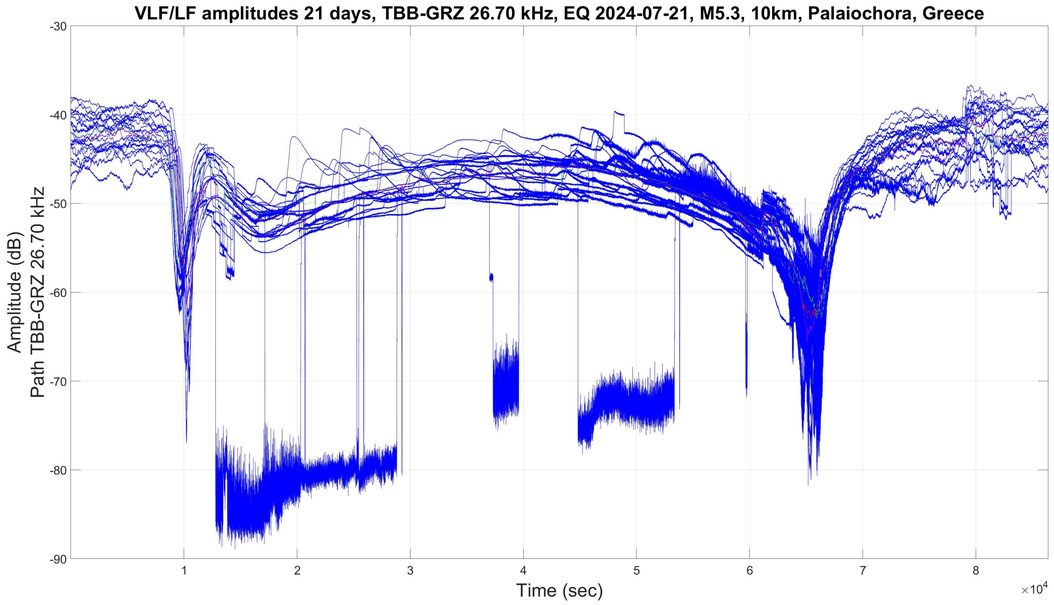
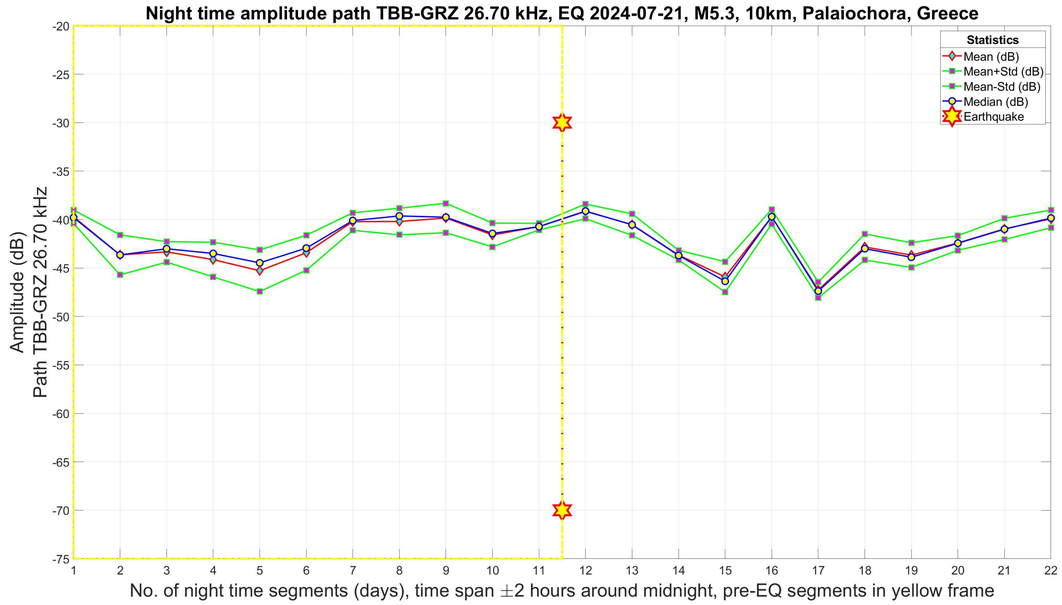
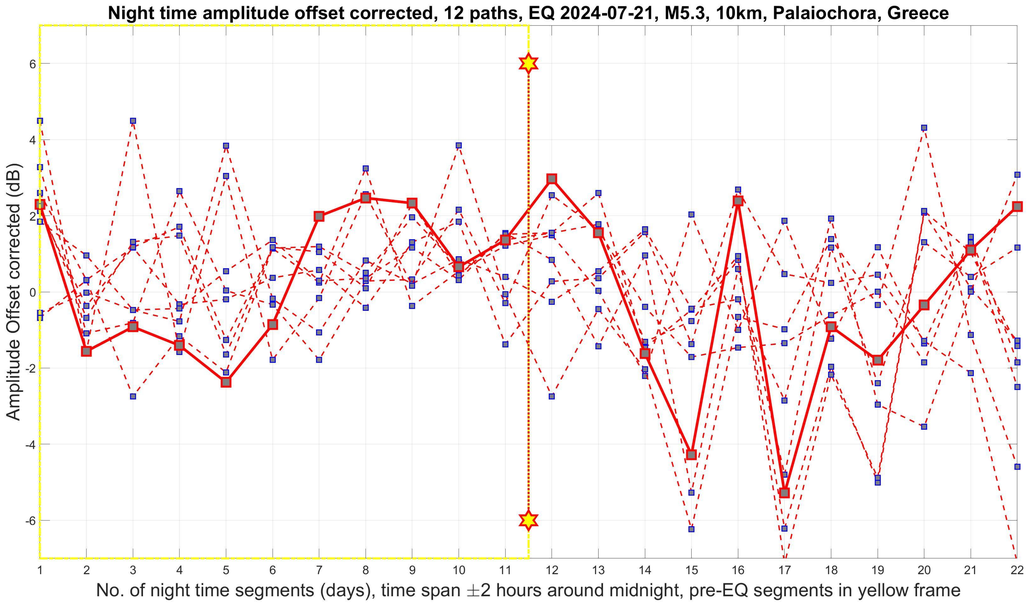
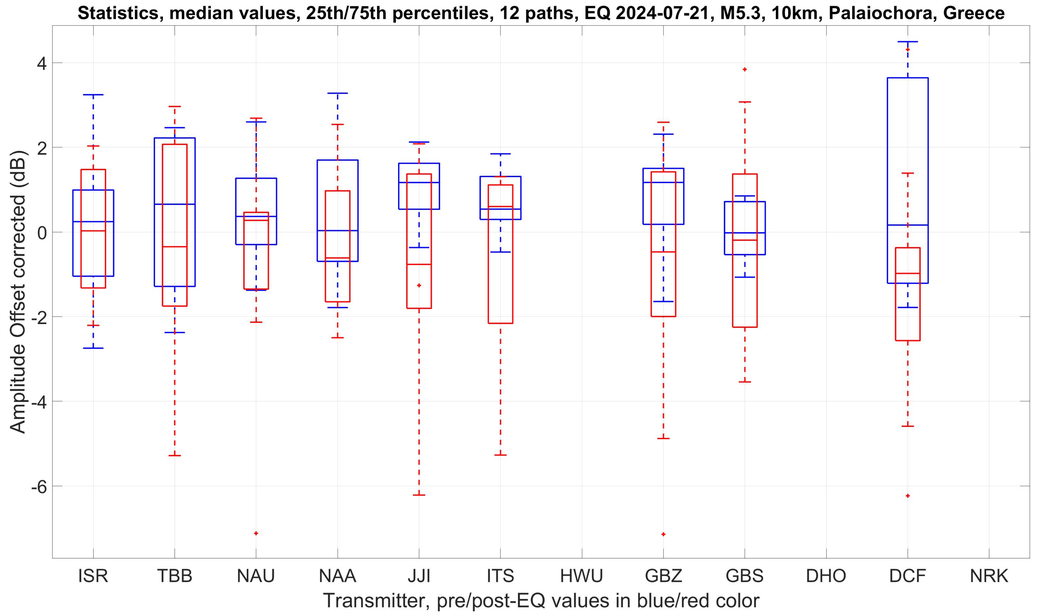
VLF/LF AMPLITUDE MEASUREMENTS, EARTHQUAKE 2024-07-21, MWW 5.3 / 10 KM, PALAIÓCHORA, GREECE

- Top Left: VLF/LF amplitudes (2024-07-11 to 2024-07-31) for the 26.70 kHz TBB-GRZ path, spikes and transmitter switch off periods are omitted (|Dst| = 50 nT)
- Bottom Left: Offset corrected nighttime (± 2h 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, for a significance level of 5% no event path shows higher amplitude values after the EQ (nighttime method)









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SUB-IONOSPHERIC VLF/LF WAVEGUIDE ELECTRIC FIELD INVESTIGATION FROM MW≥5.0 EARTHQUAKE EVENTS WITH MULTIPLE RECEIVERS IN EUROPE

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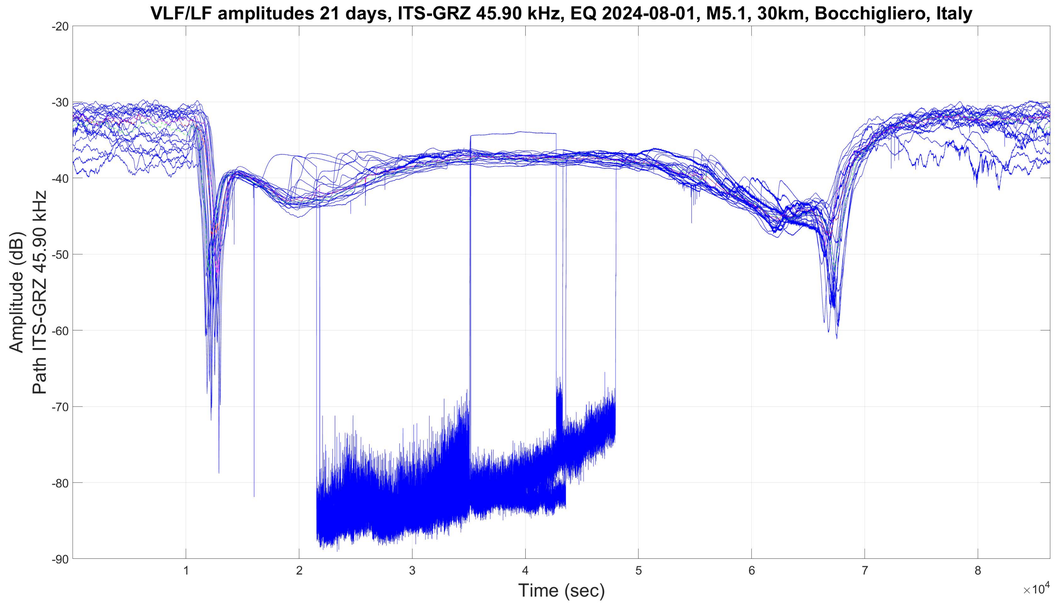
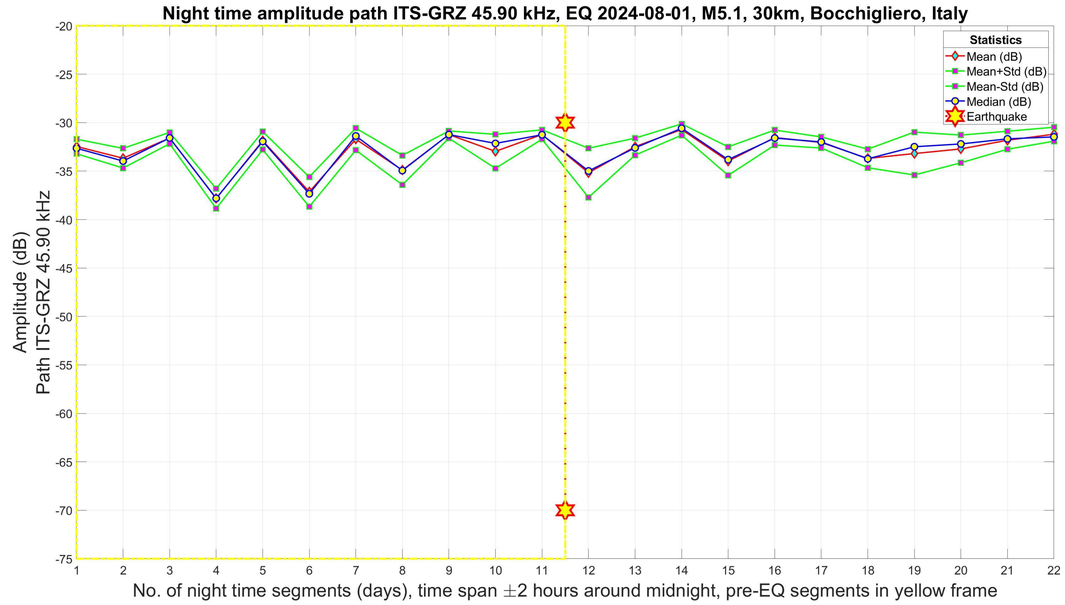
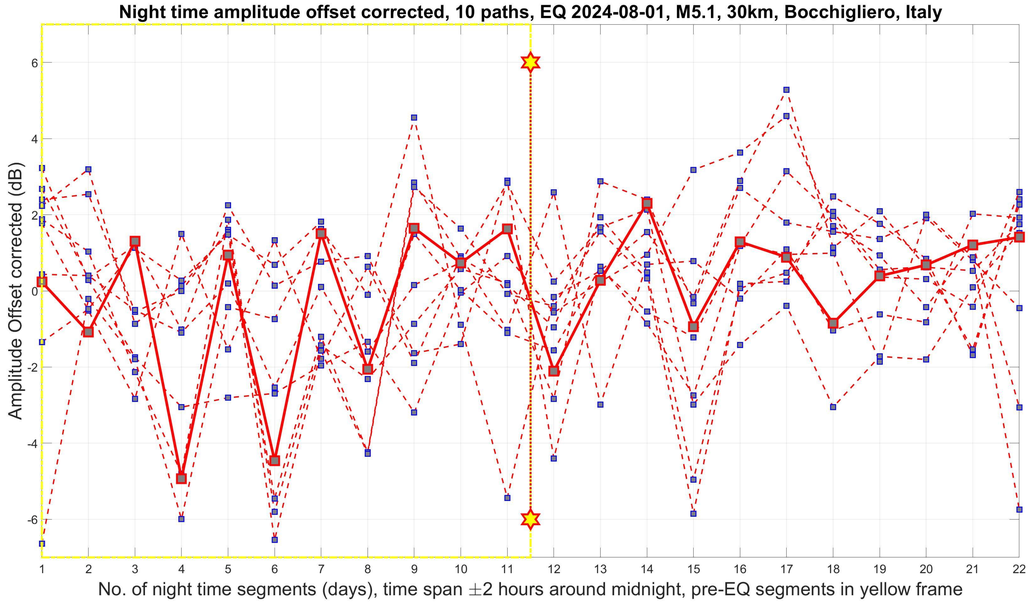
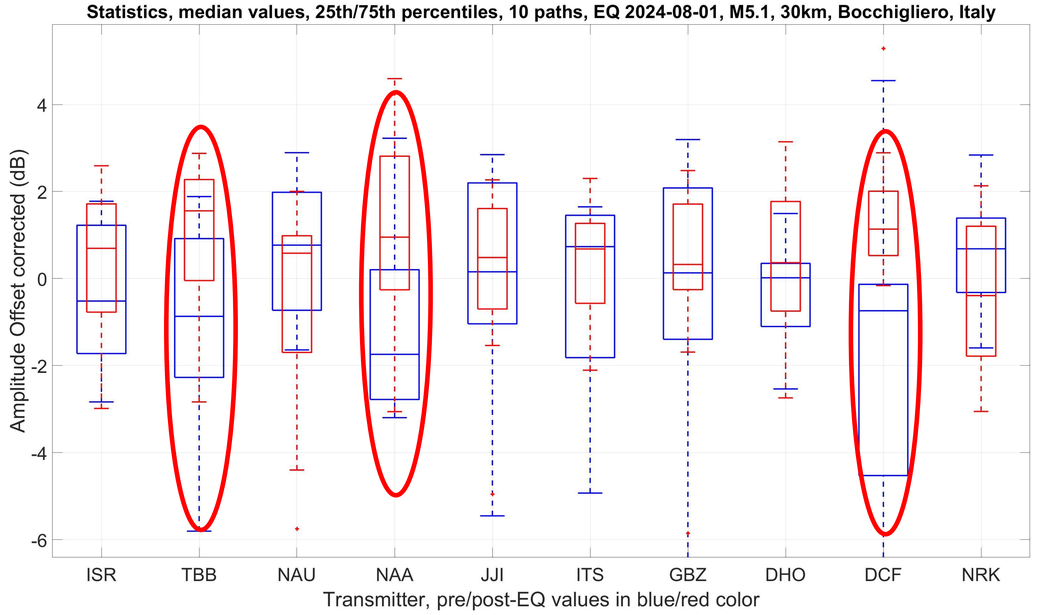
VLF/LF AMPLITUDE MEASUREMENTS, EARTHQUAKE 2024-08-01, MWW 5.1 / 30 KM, BOCCHIGLIERO, ITALY

- Top Left: VLF/LF amplitudes (2024-07-22 to 2024-08-11) for the 45.90 kHz ITS-GRZ path, spikes and transmitter switch off periods are omitted (|Dst| = 100 nT, high disturbances)
- Bottom Left: Offset corrected nighttime (± 2h 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 paths {TBB NAA DCF}-GRZ show higher amplitude values after the EQ (nighttime method)









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SUB-IONOSPHERIC VLF/LF WAVEGUIDE ELECTRIC FIELD INVESTIGATION FROM MW≥5.0 EARTHQUAKE EVENTS WITH MULTIPLE RECEIVERS IN EUROPE

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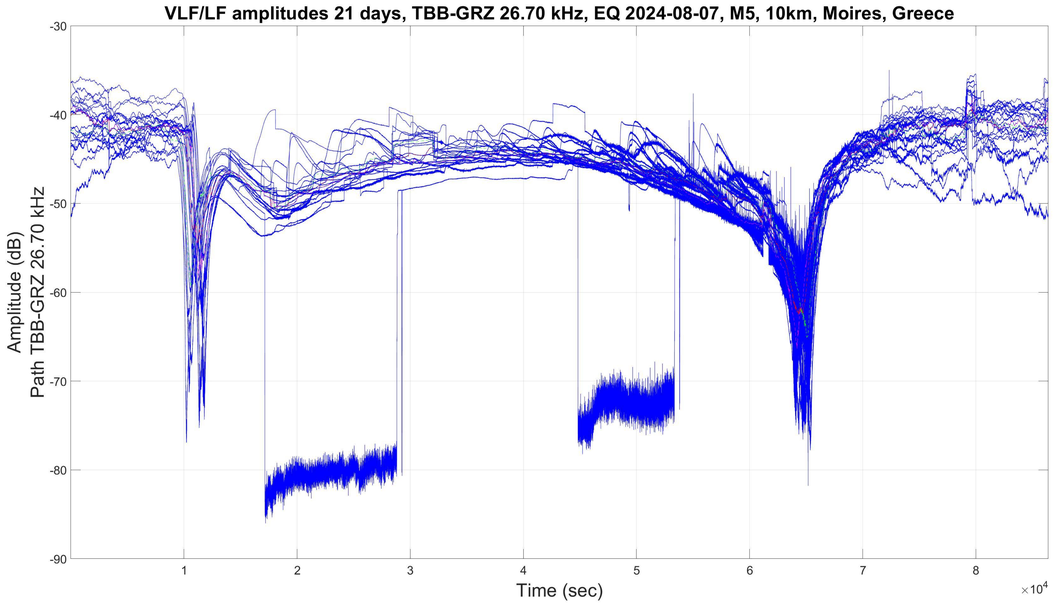
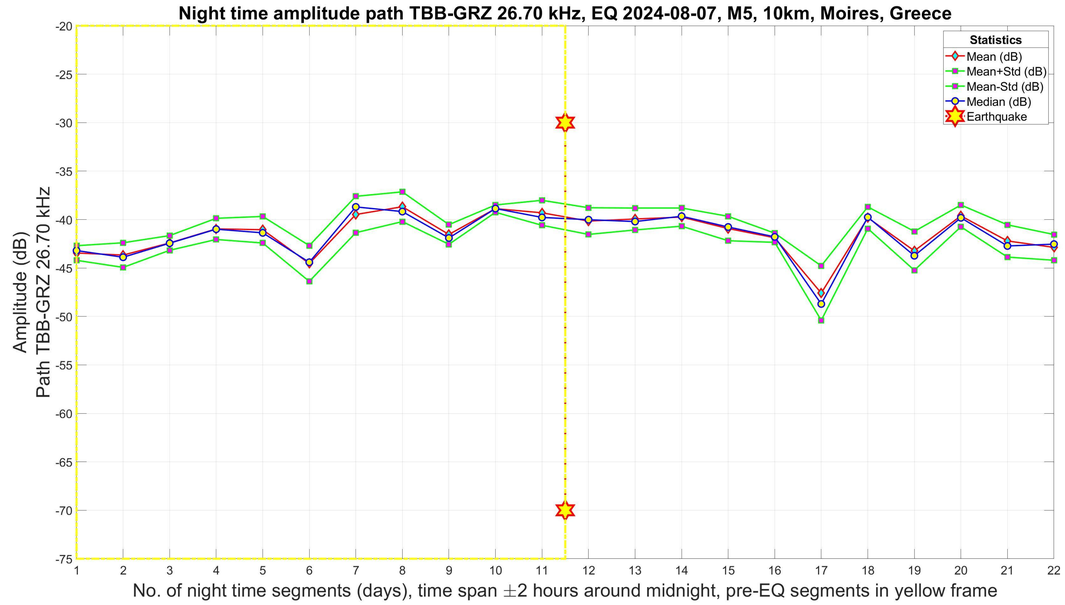
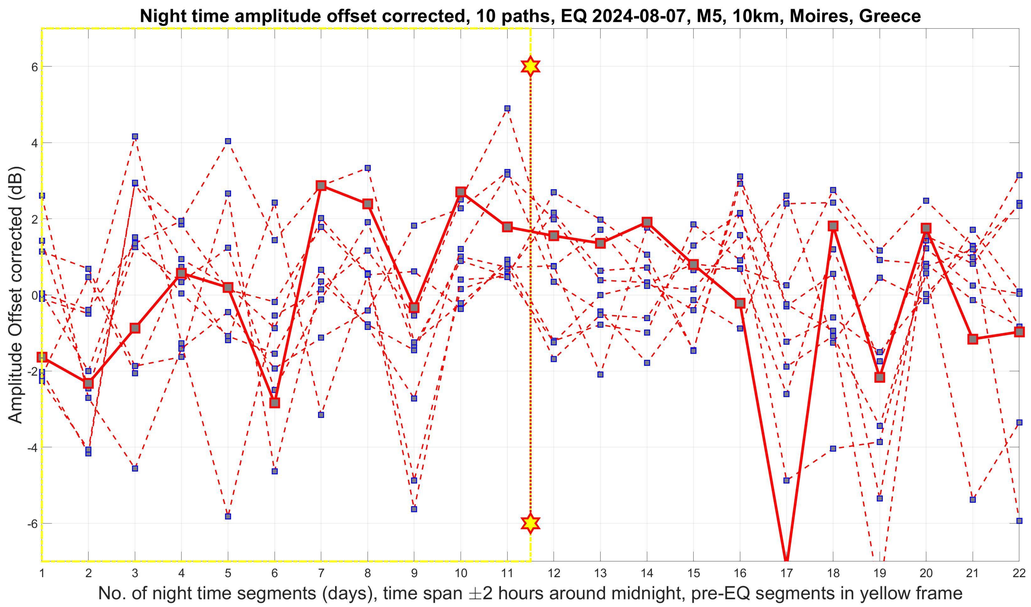
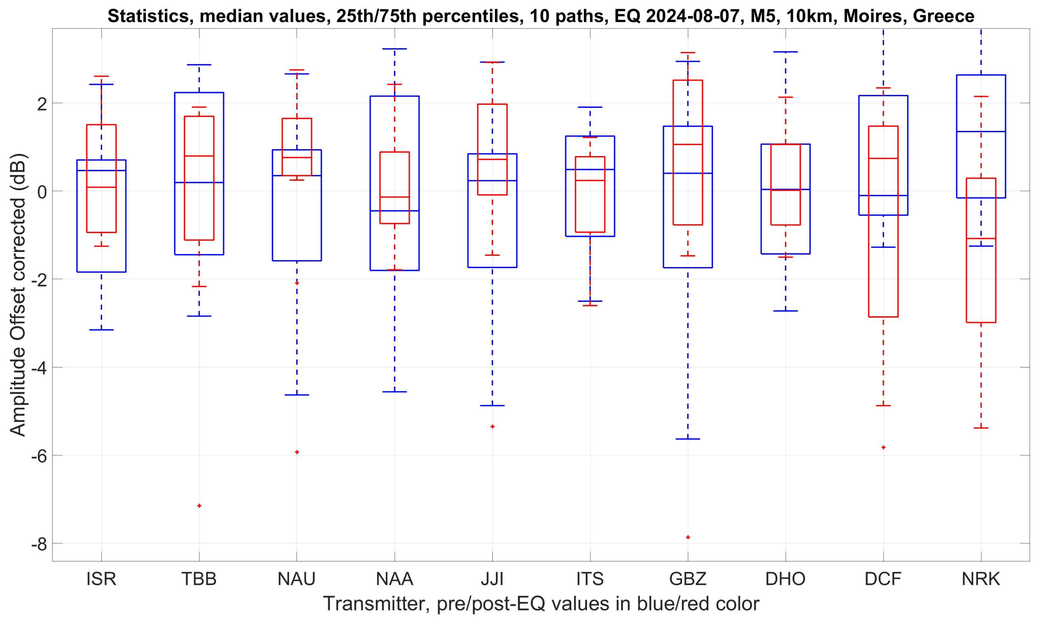
VLF/LF AMPLITUDE MEASUREMENTS, EARTHQUAKE 2024-08-07, MWW 5 / 10 KM, MOÍRES, GREECE

- Top Left: VLF/LF amplitudes (2024-07-28 to 2024-08-17) for the 26.70 kHz TBB-GRZ path, spikes and transmitter switch off periods are omitted (|Dst| = 188 nT, high disturbances)
- Bottom Left: Offset corrected nighttime (± 2h 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% no event path shows higher amplitude values after the EQ (nighttime method)









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SUB-IONOSPHERIC VLF/LF WAVEGUIDE ELECTRIC FIELD INVESTIGATION FROM MW≥5.0 EARTHQUAKE EVENTS WITH MULTIPLE RECEIVERS IN EUROPE

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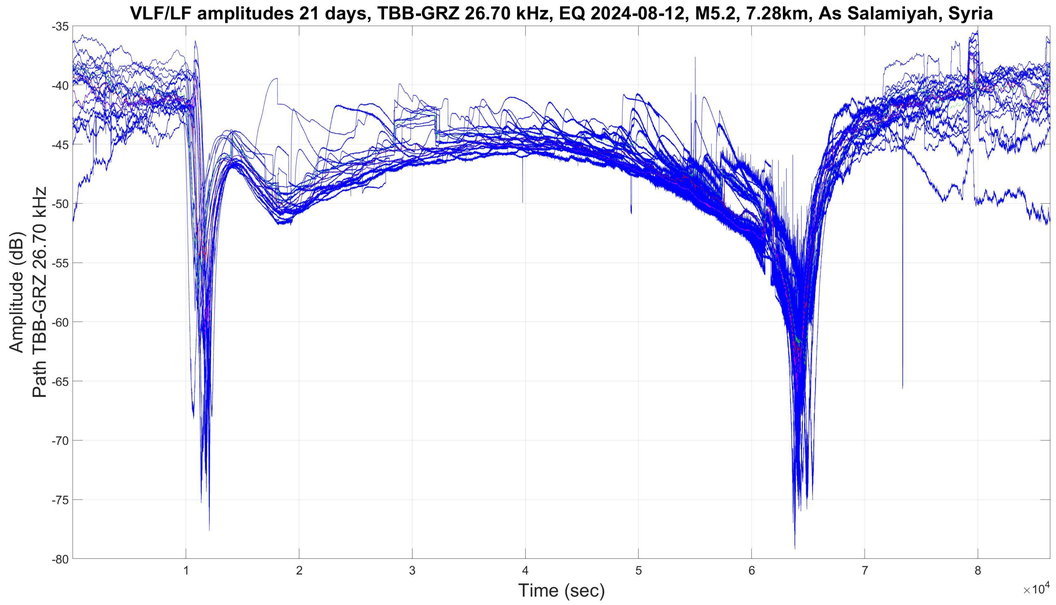
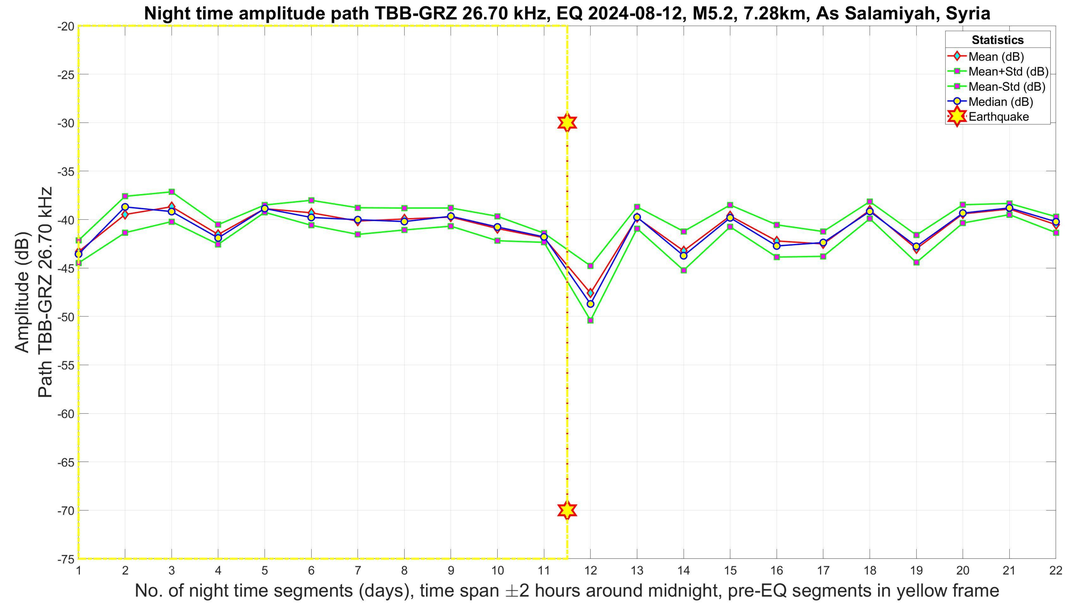
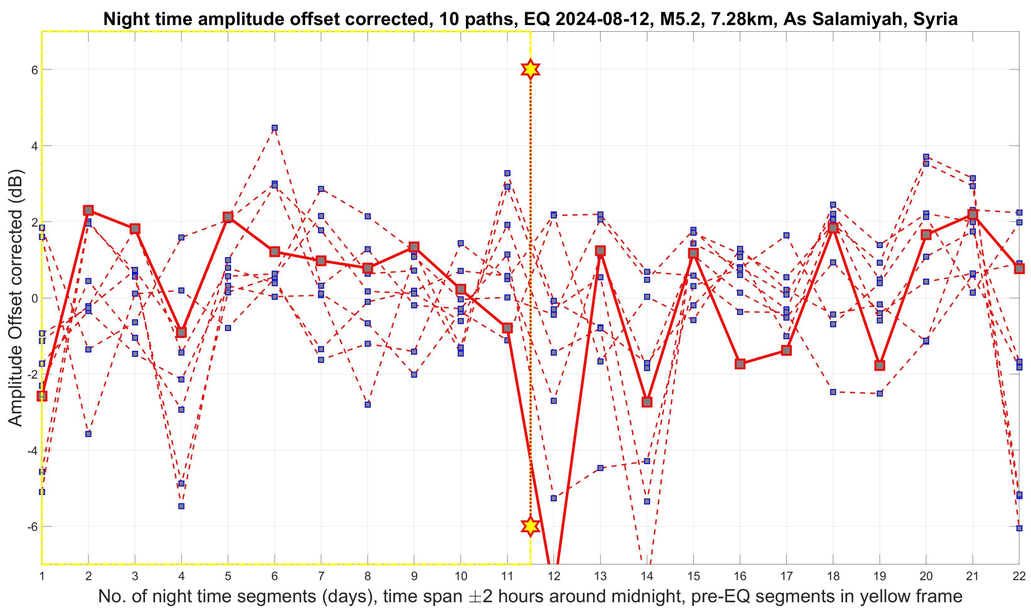
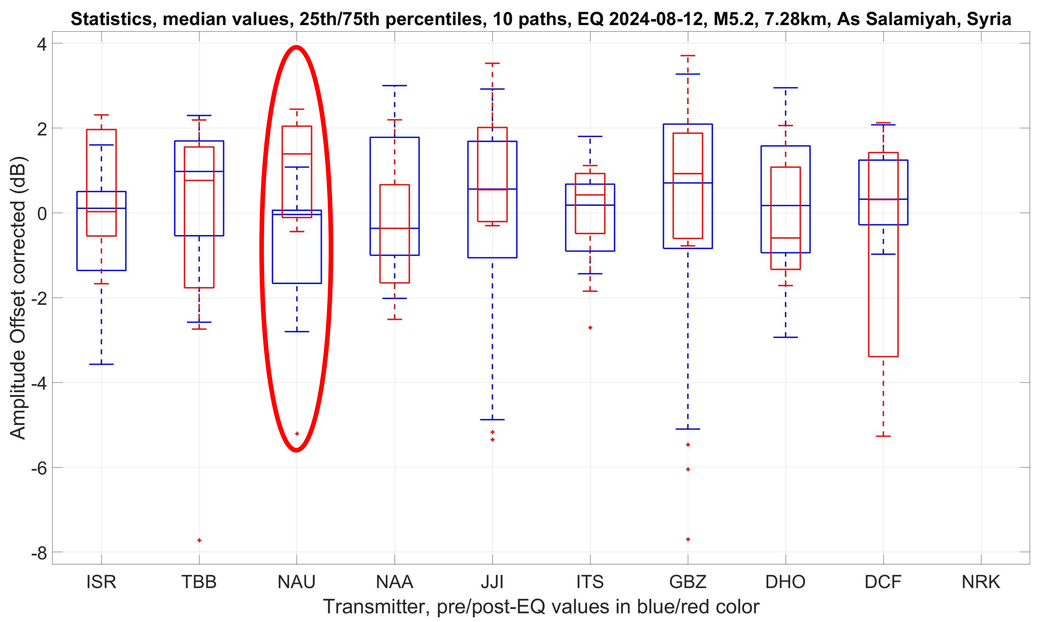
VLF/LF AMPLITUDE MEASUREMENTS, EARTHQUAKE 2024-08-12, MWW 5.2 / 7.3 KM, AS SALAMĪYAH, SYRIA

- Top Left: VLF/LF amplitudes (2024-08-02 to 2024-08-22) for the 26.70 kHz TBB-GRZ path, spikes and transmitter switch off periods are omitted (|Dst| = 188 nT, high disturbances)
- Bottom Left: Offset corrected nighttime (± 2h 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 NAU-GRZ shows higher amplitude values after the EQ (nighttime method)









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SUB-IONOSPHERIC VLF/LF WAVEGUIDE ELECTRIC FIELD INVESTIGATION FROM MW≥5.0 EARTHQUAKE EVENTS WITH MULTIPLE RECEIVERS IN EUROPE

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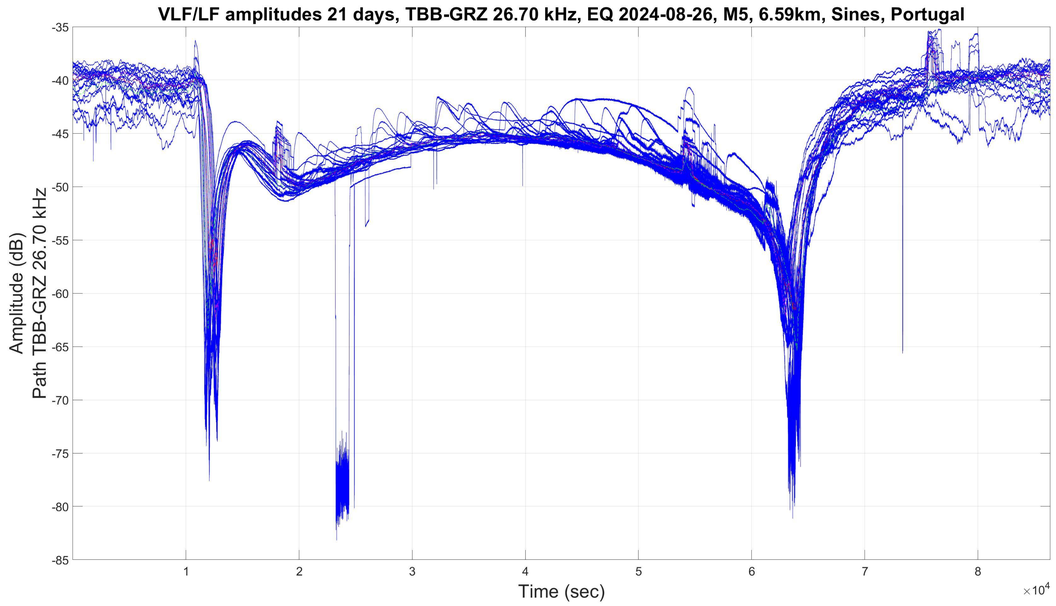
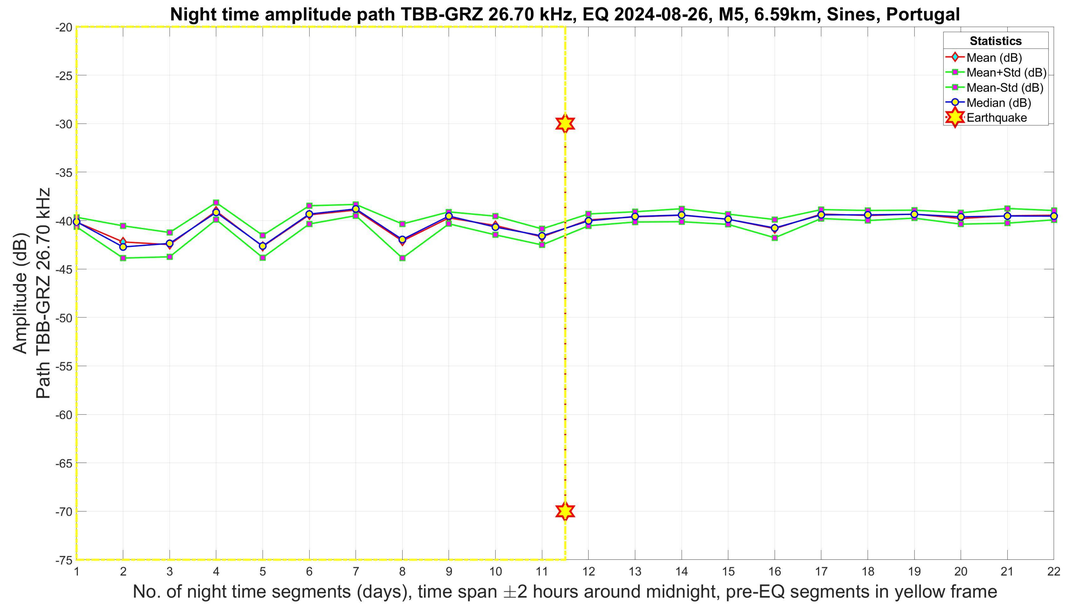
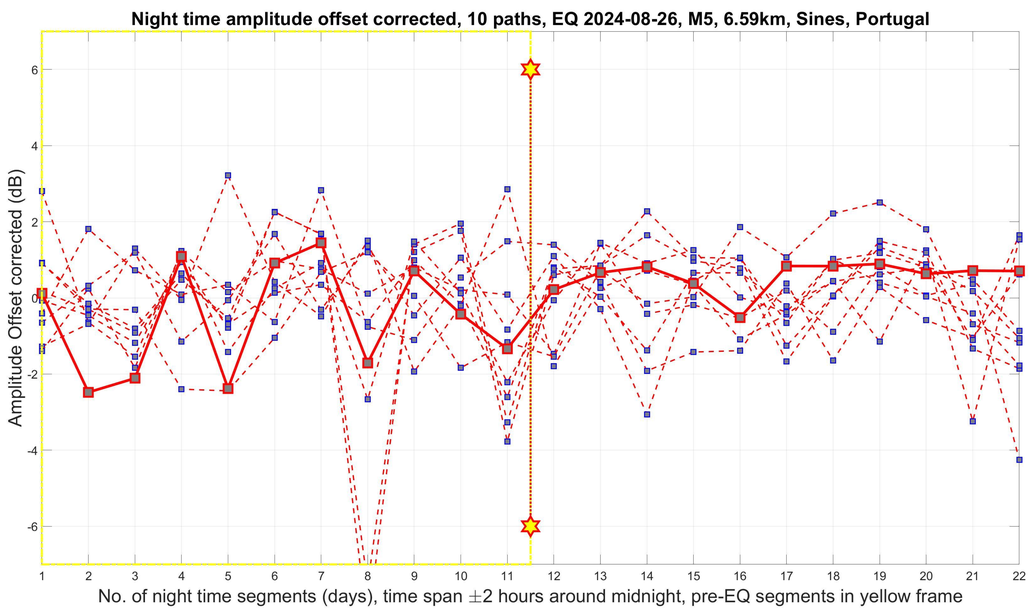
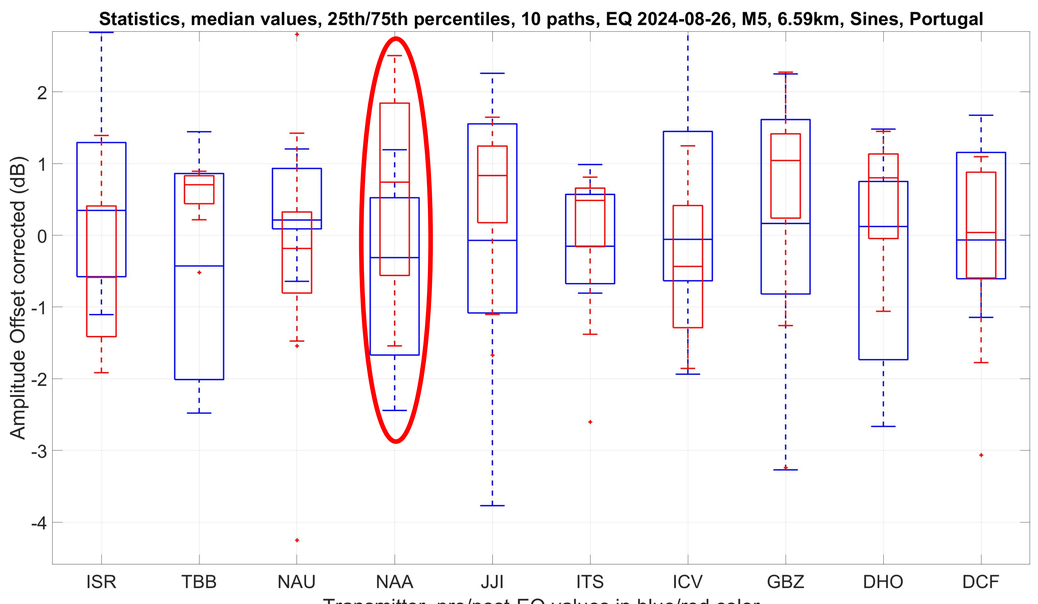
VLF/LF AMPLITUDE MEASUREMENTS, EARTHQUAKE 2024-08-26, MWR 5 / 6.6 KM, SINES, PORTUGAL

- Top Left: VLF/LF amplitudes (2024-08-16 to 2024-09-05) for the 26.70 kHz TBB-GRZ path, spikes and transmitter switch off periods are omitted (|Dst| = 76 nT)
- Bottom Left: Offset corrected nighttime (± 2h 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 NAA-GRZ shows higher amplitude values after the EQ (nighttime method)









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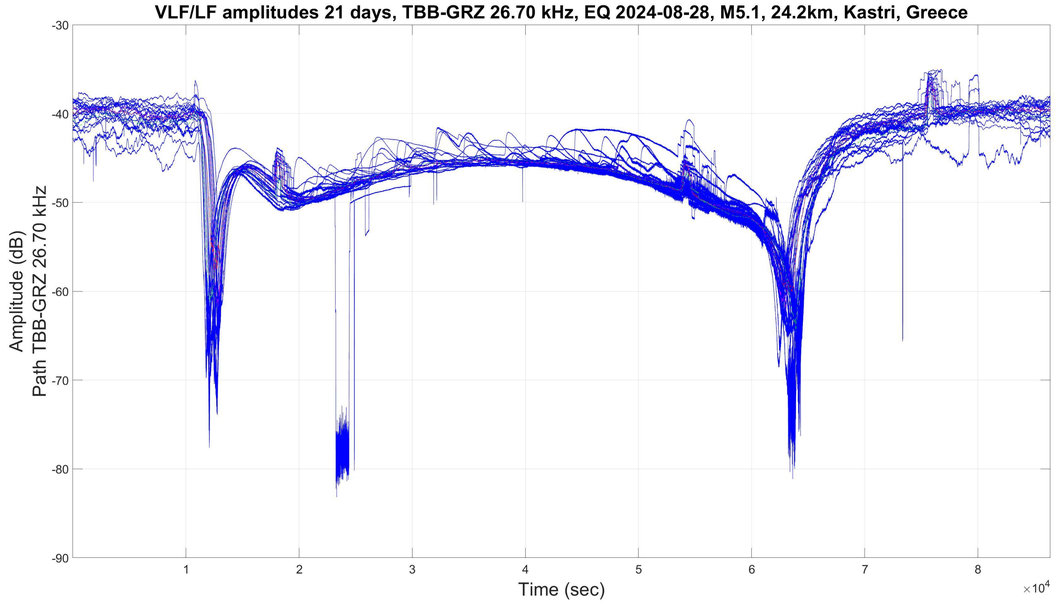
SUB-IONOSPHERIC VLF/LF WAVEGUIDE ELECTRIC FIELD INVESTIGATION FROM MW≥5.0 EARTHQUAKE EVENTS WITH MULTIPLE RECEIVERS IN EUROPE

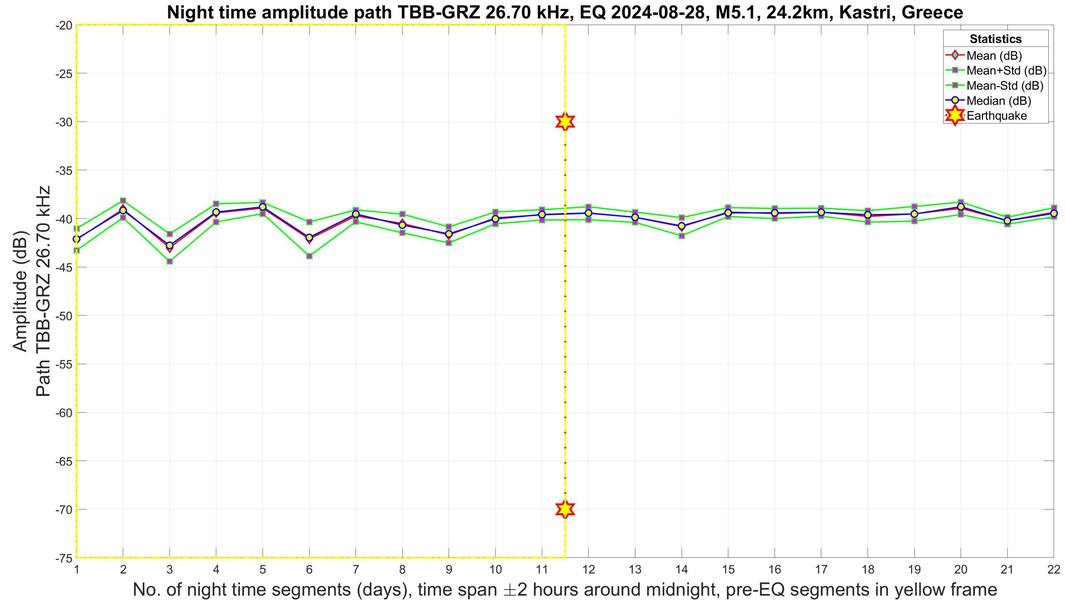
Hans U. Eichelberger[1], Mohammed Y. Boudjada[1], Aleksandra Nina[2], Bruno P. Besser[1], Daniel Wolbang[1], Maria Solovieva[3], Pier F. Biagi[4], Patrick H. M. Galopeau[5], Christoph Schirninger[6], Iren-Adelina Moldovan[7], Giovanni Nico[8], Manfred Stachel[1], Özer Aydogar[1], Cosima Muck[1], Josef Wilfinger[1], and Irmgard Jernej[1]

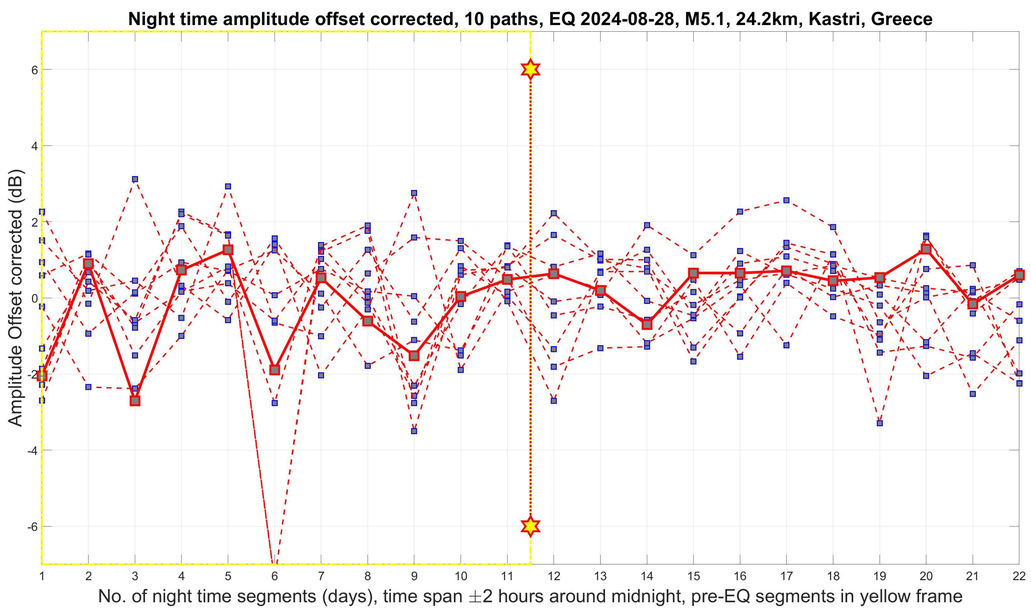
[1] Space Research Institute, Austrian Academy of Sciences, Graz, Austria, [2] Institute of Physics Belgrade, University of Belgrade, Belgrade, Serbia, [3] Schmidt Institute of Physics of the Earth, RAS, Moscow, Russia, [4] Department of Physics, University of Bari, Bari, Italy, [5] LATMOS-CNRS, UVSQ Université Paris-Saclay, Guyancourt, France, [6] Institute for Physics, University of Graz, Graz, Austria, [7] National Institute for Earth Physics, Magurele, Romania, [8] Institute of Applied Mathematics, Italian National Research Council, Bari, Italy

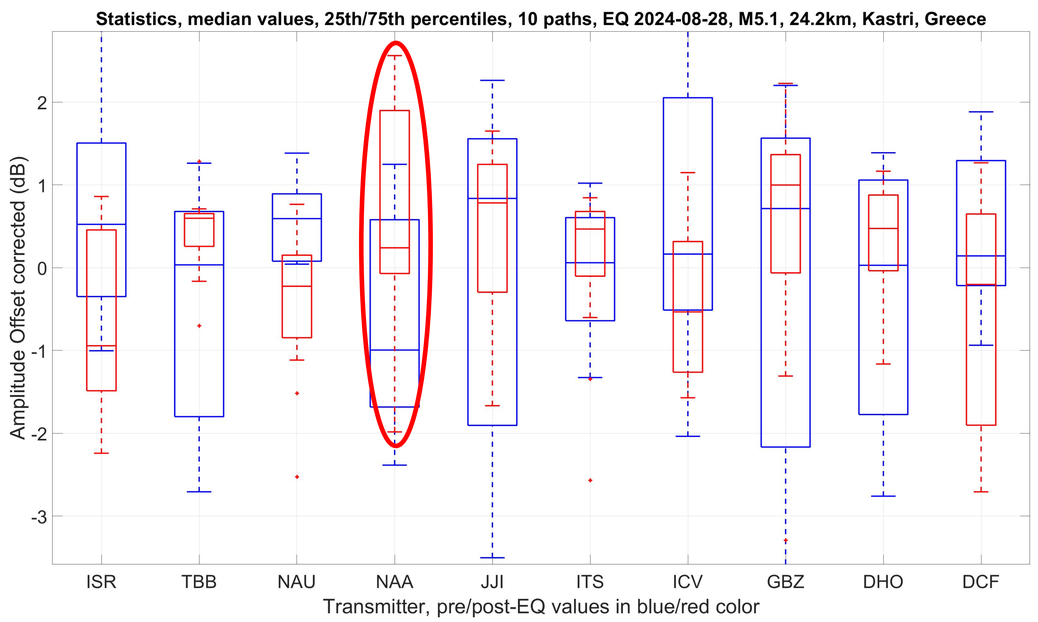
VLF/LF AMPLITUDE MEASUREMENTS, EARTHQUAKE 2024-08-28, MWW 5.1 / 54.8 KM, KASTRÍ, GREECE

- Top Left: VLF/LF amplitudes (2024-08-18 to 2024-09-07) for the 26.70 kHz TBB-GRZ path, spikes and transmitter switch off periods are omitted (|Dst| = 76 nT)
- Bottom Left: Offset corrected nighttime (± 2h 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 NAA-GRZ shows higher amplitude values after the EQ (nighttime method)









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SUB-IONOSPHERIC VLF/LF WAVEGUIDE ELECTRIC FIELD INVESTIGATION FROM MW≥5.0 EARTHQUAKE EVENTS WITH MULTIPLE RECEIVERS IN EUROPE

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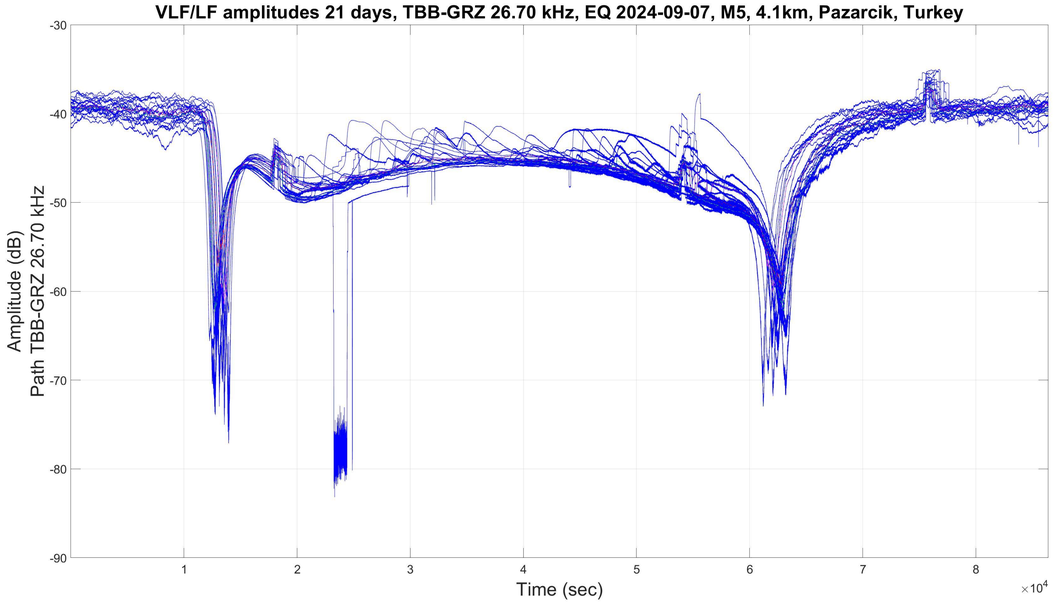
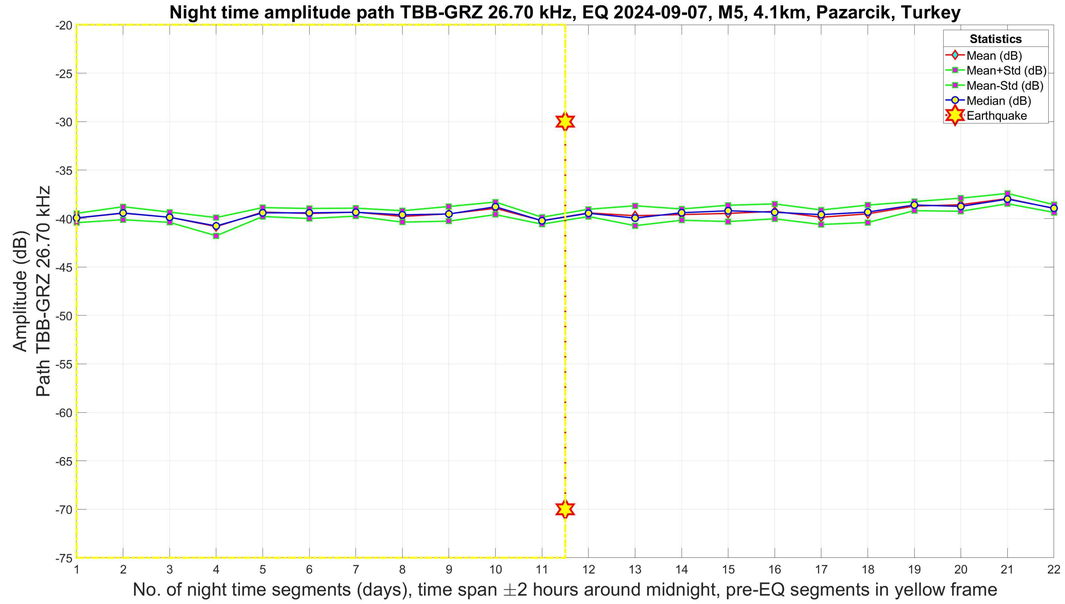
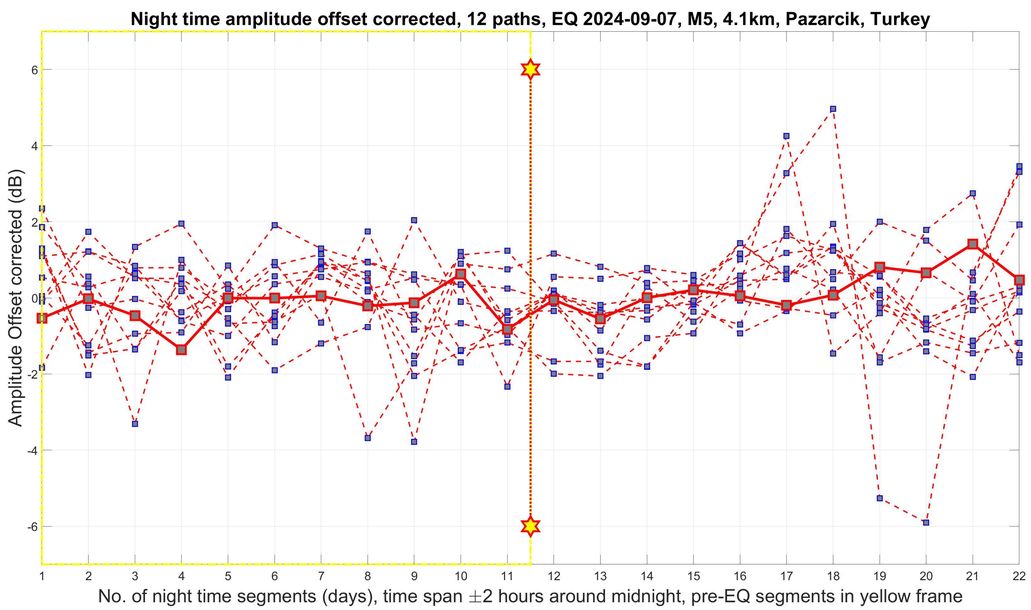
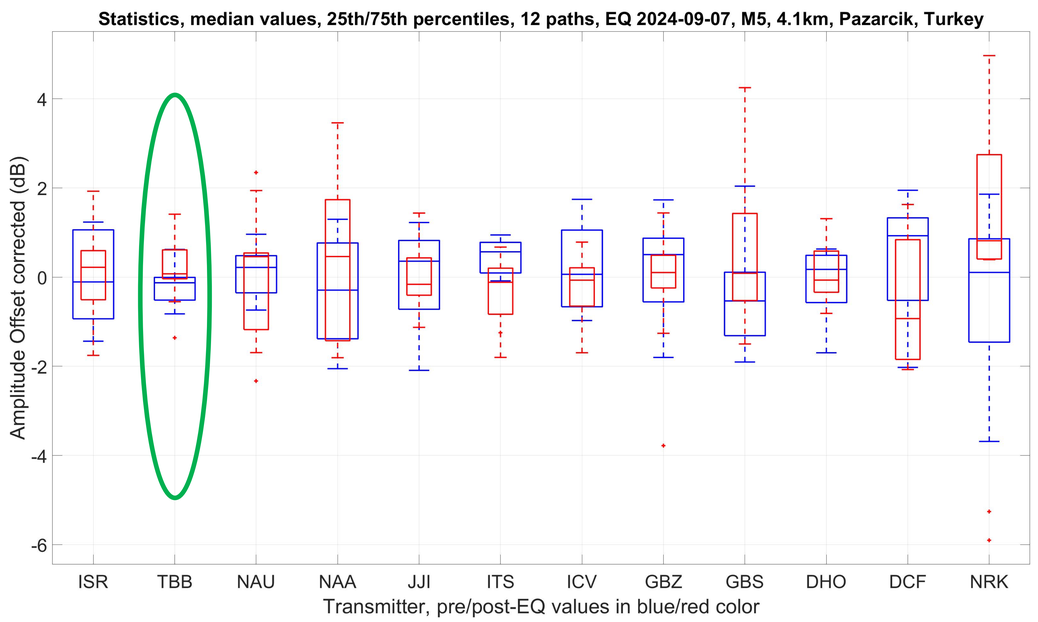
VLF/LF AMPLITUDE MEASUREMENTS, EARTHQUAKE 2024-09-07, MWW 5 / 4.1 KM, PAZARCIK, TURKEY

- Top Left: VLF/LF amplitudes (2024-08-28 to 2024-09-17) for the 26.70 kHz TBB-GRZ path, spikes and transmitter switch off periods are omitted (|Dst| = 121 nT, high disturbances)
- Bottom Left: Offset corrected nighttime (± 2h 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, 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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SUB-IONOSPHERIC VLF/LF WAVEGUIDE ELECTRIC FIELD INVESTIGATION FROM MW≥5.0 EARTHQUAKE EVENTS WITH MULTIPLE RECEIVERS IN EUROPE

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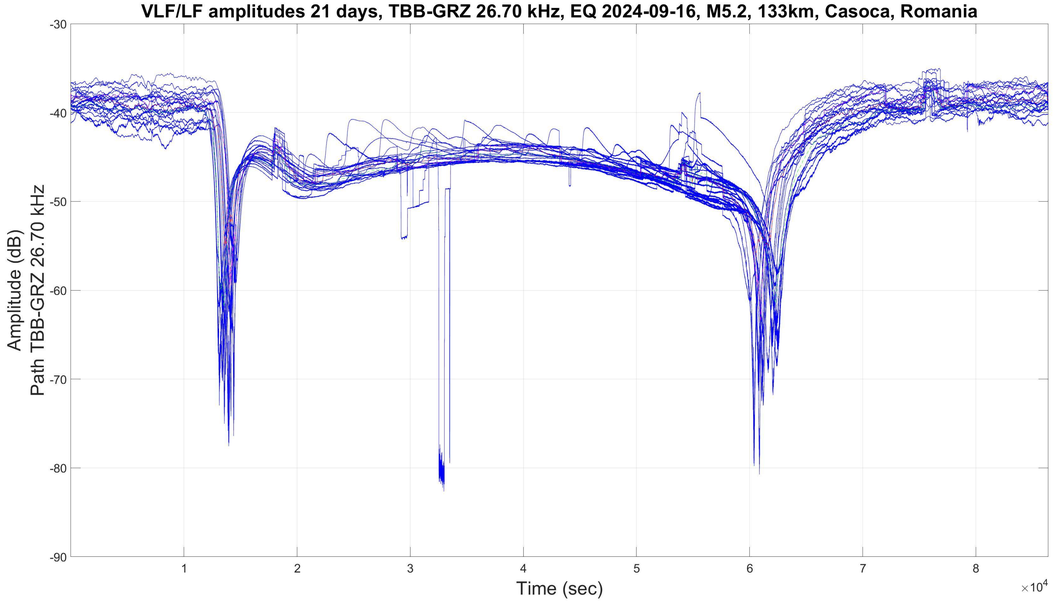
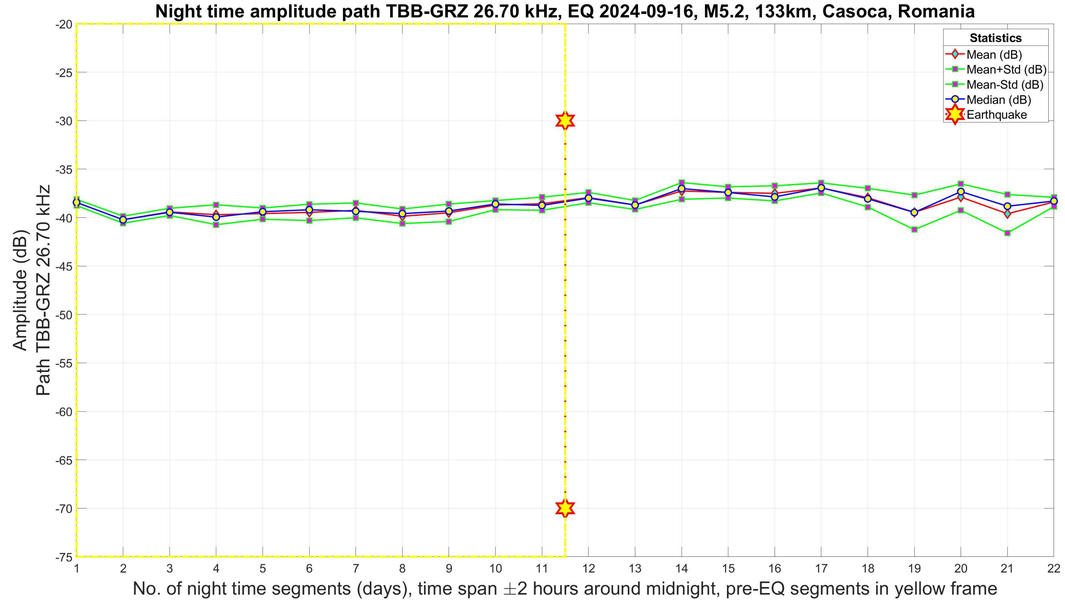
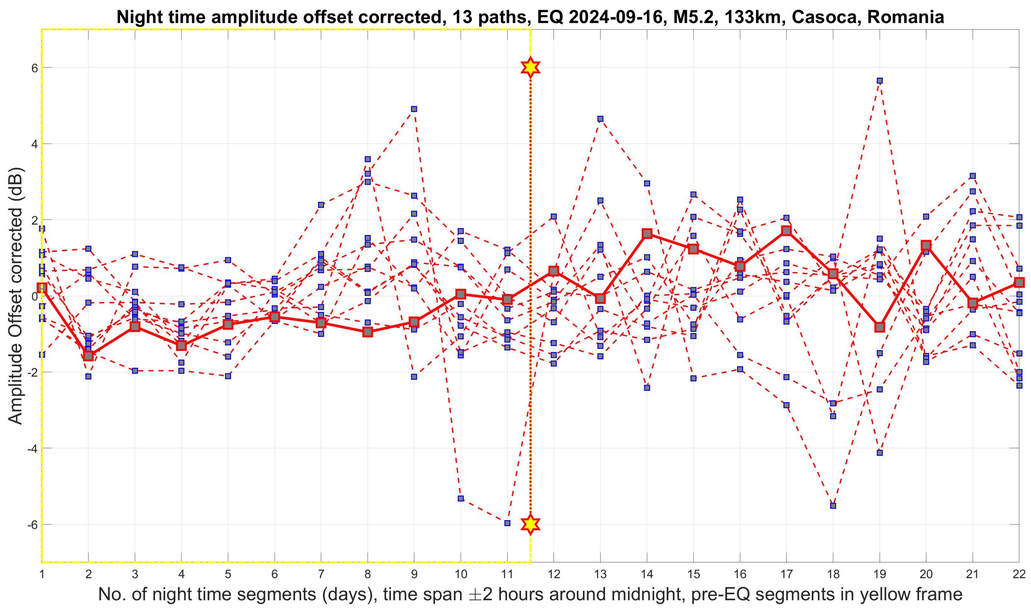
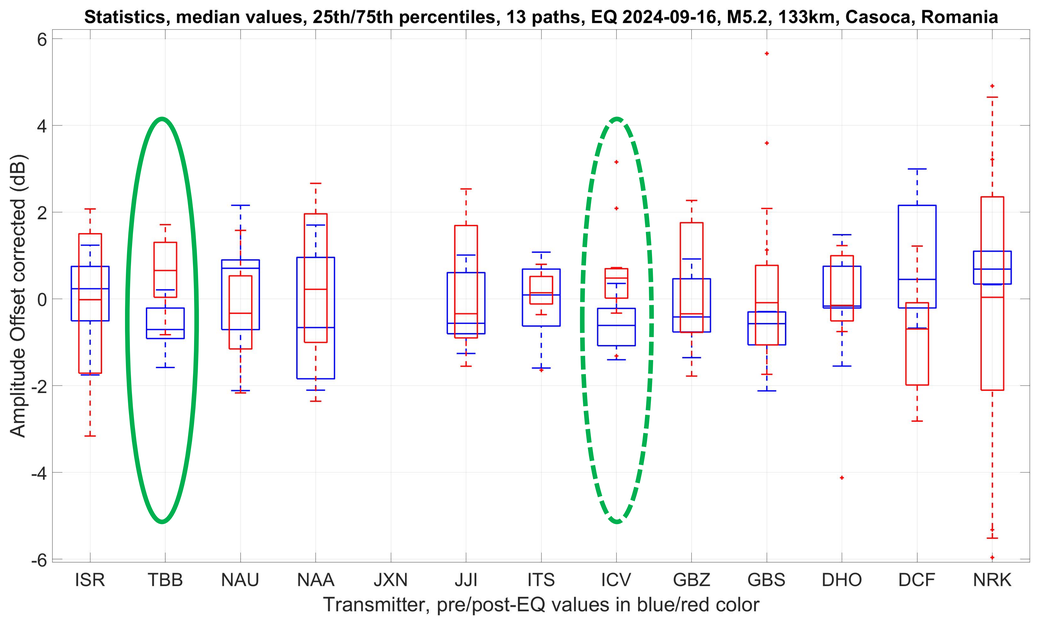
VLF/LF AMPLITUDE MEASUREMENTS, EARTHQUAKE 2024-09-16, MWW 5.2 / 133 KM, CAȘOCA, ROMANIA

- Top Left: VLF/LF amplitudes (2024-09-06 to 2024-09-26) for the 26.70 kHz TBB-GRZ path, spikes and transmitter switch off periods are omitted (|Dst| = 121 nT, high disturbances)
- Bottom Left: Offset corrected nighttime (± 2h around midnight) amplitude values for the 13 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 13 paths, for a significance level of 5% only the paths {TBB ICV}-GRZ show higher amplitude values after the EQ (nighttime method)









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SUB-IONOSPHERIC VLF/LF WAVEGUIDE ELECTRIC FIELD INVESTIGATION FROM MW≥5.0 EARTHQUAKE EVENTS WITH MULTIPLE RECEIVERS IN EUROPE

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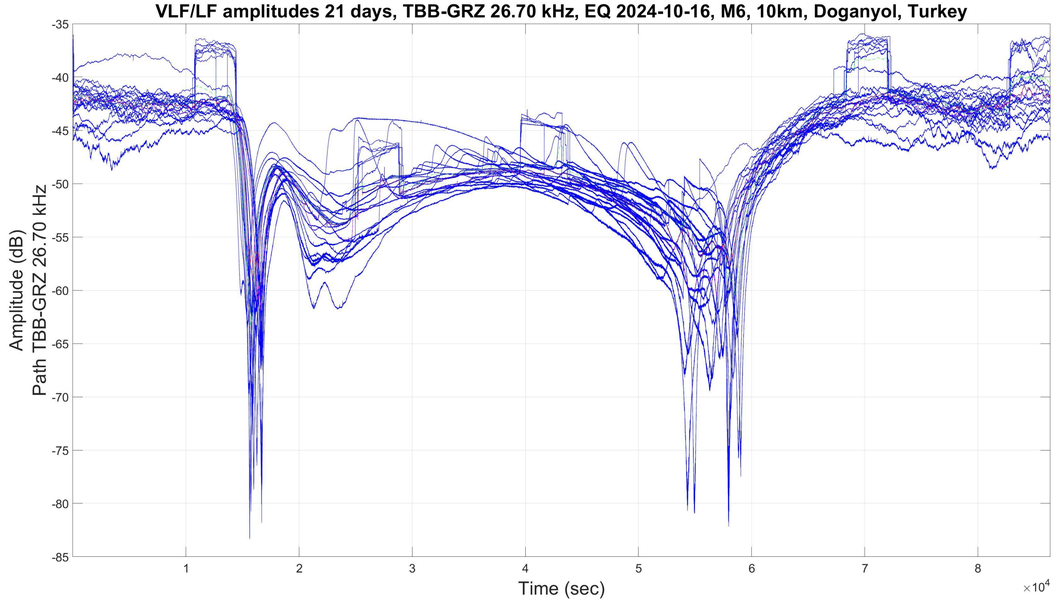
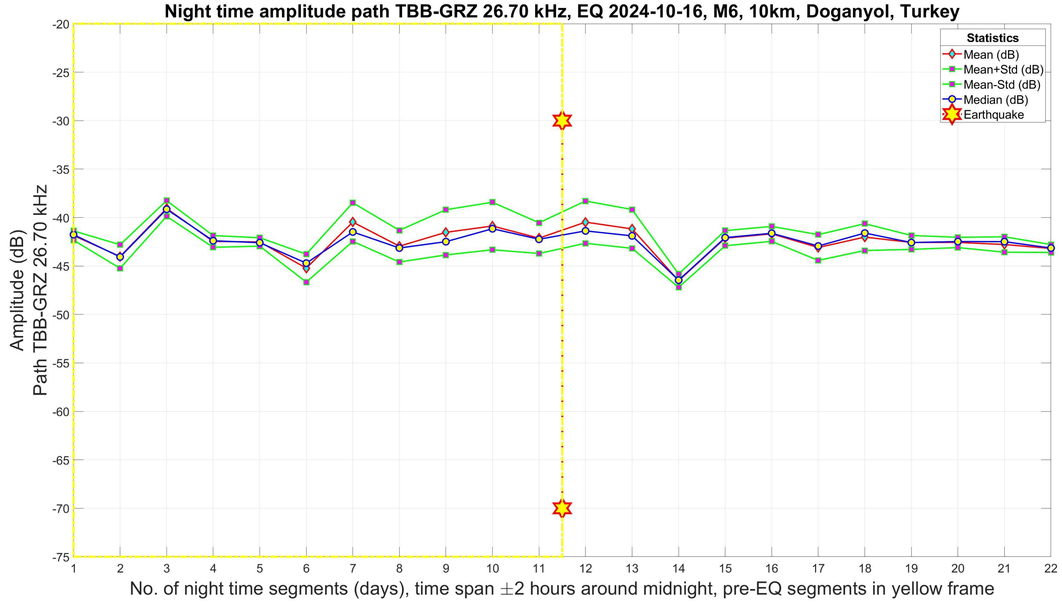
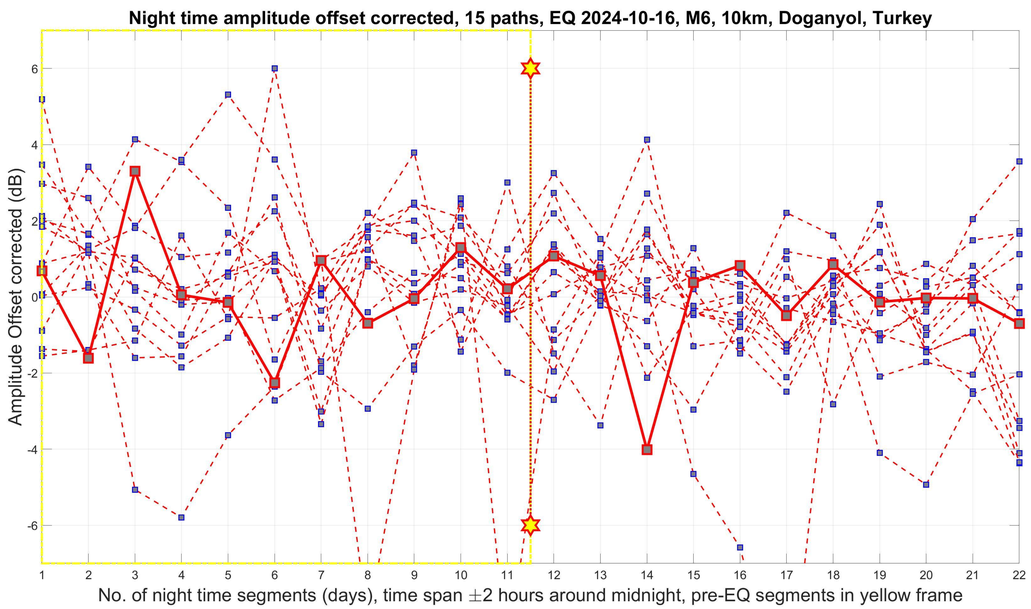
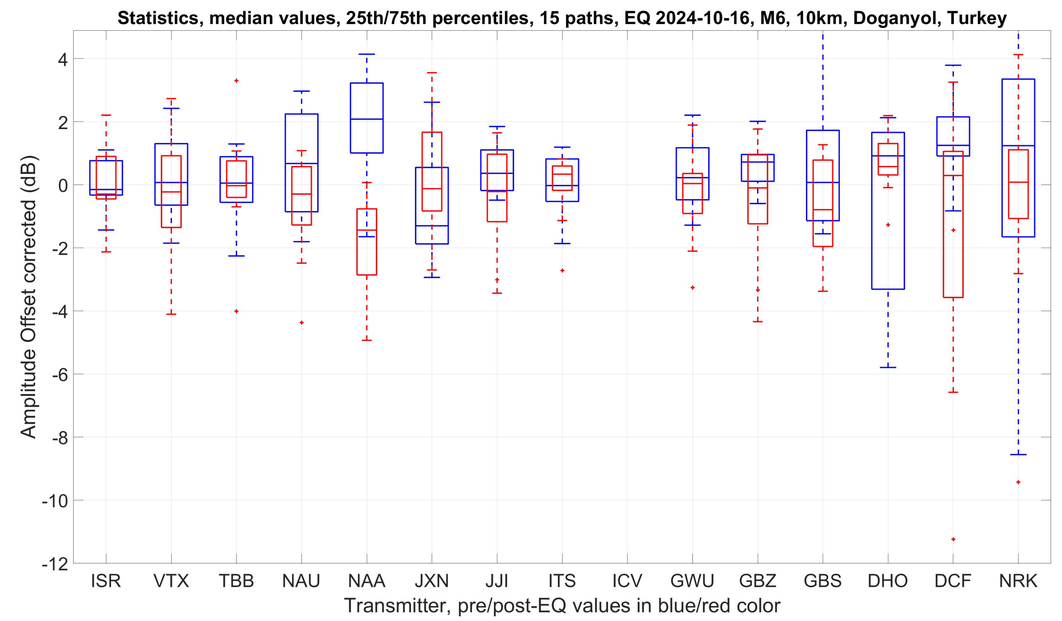
VLF/LF AMPLITUDE MEASUREMENTS, EARTHQUAKE 2024-10-16, MWW 6 / 10 KM, DOĞANYOL, TURKEY

- Top Left: VLF/LF amplitudes (2024-10-06 to 2024-10-26) for the 26.70 kHz TBB-GRZ path, spikes and transmitter switch off periods are omitted (|Dst| = 333 nT, huge disturbances)
- Bottom Left: Offset corrected nighttime (± 2h 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 significance level of 5% no event path shows higher amplitude values after the EQ (nighttime method)









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SUB-IONOSPHERIC VLF/LF WAVEGUIDE ELECTRIC FIELD INVESTIGATION FROM MW≥5.0 EARTHQUAKE EVENTS WITH MULTIPLE RECEIVERS IN EUROPE

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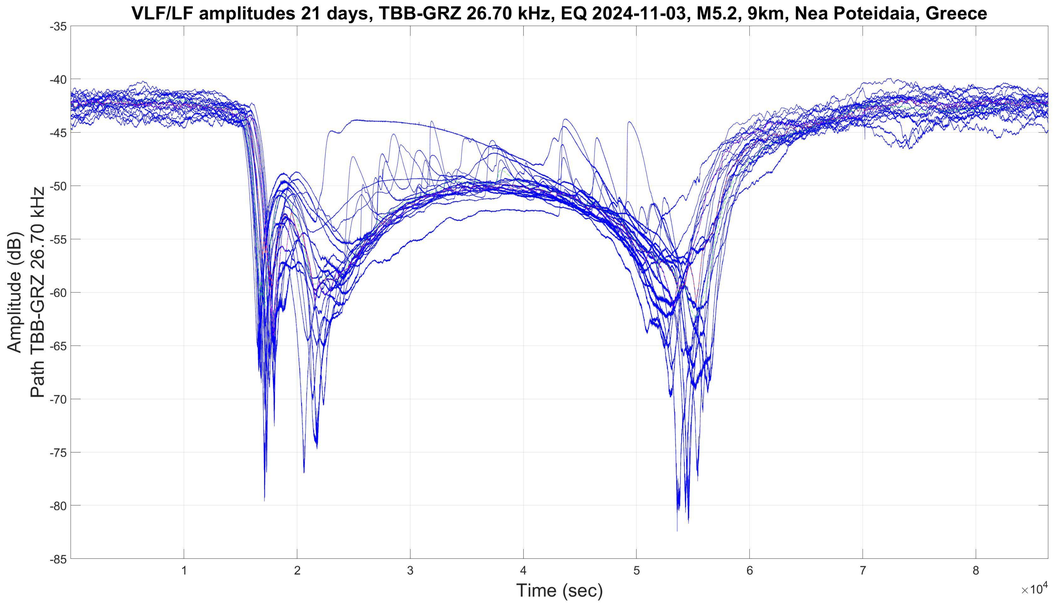
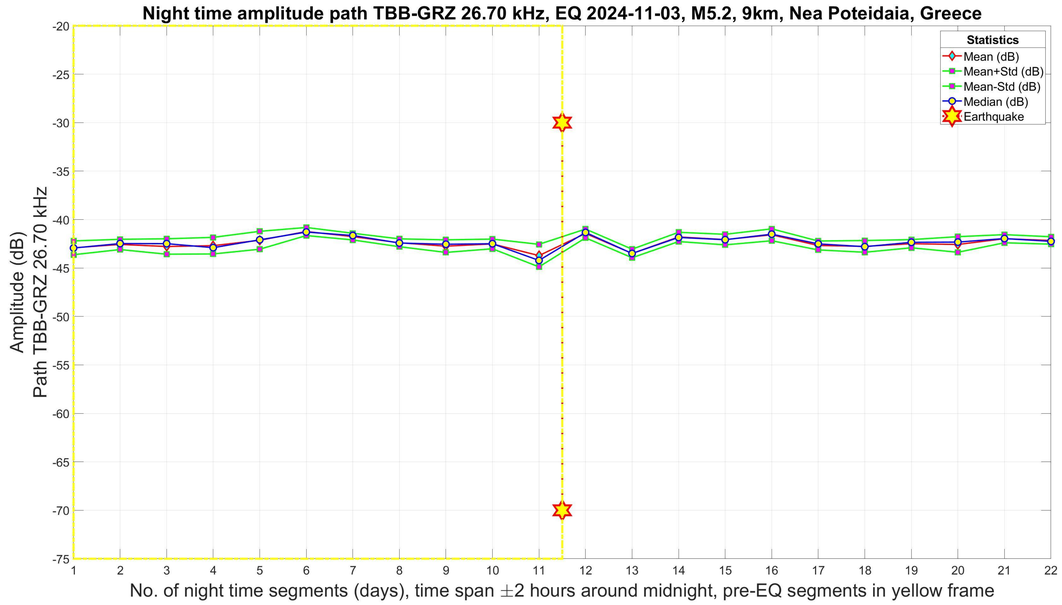
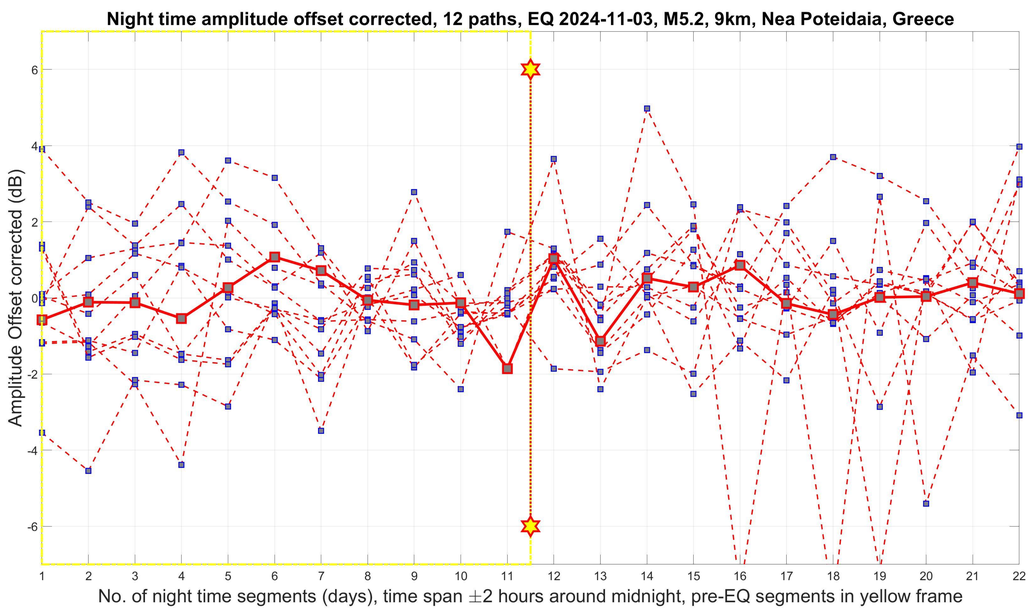
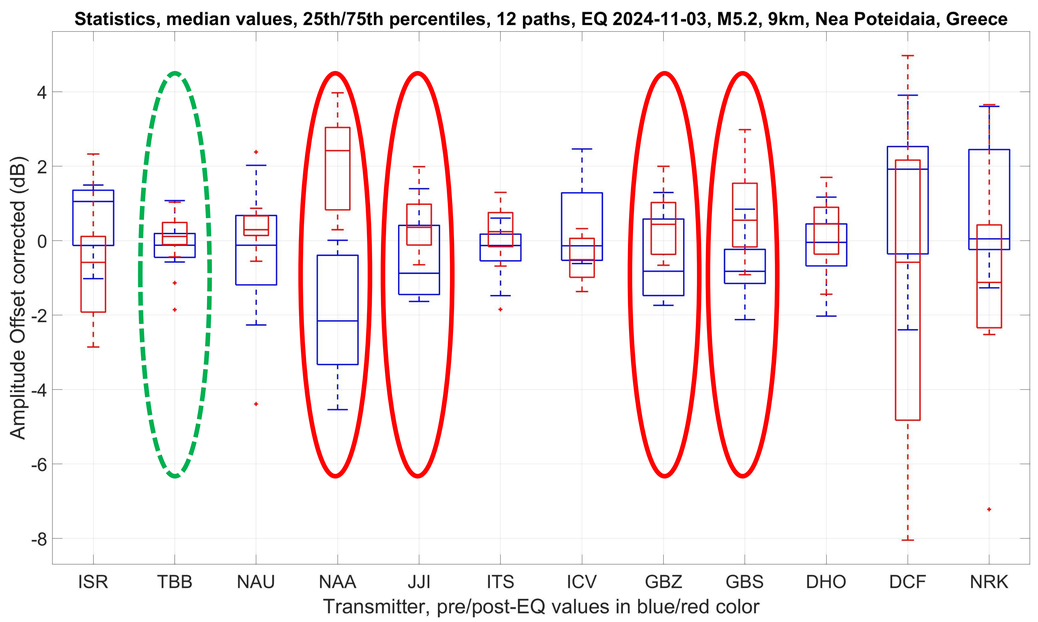
VLF/LF AMPLITUDE MEASUREMENTS, EARTHQUAKE 2024-11-03, MWW 5.2 / 9 KM, NÉA POTEÍDAIA, GREECE

- Top Left: VLF/LF amplitudes (2024-10-24 to 2024-11-13) for the 26.70 kHz TBB-GRZ path, spikes and transmitter switch off periods are omitted (|Dst| = 89 nT)
- Bottom Left: Offset corrected nighttime (± 2h 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, for a significance level of 5% the paths {NAA JJI GBZ GBS}-GRZ show higher ampl. values after the EQ (nighttime method)









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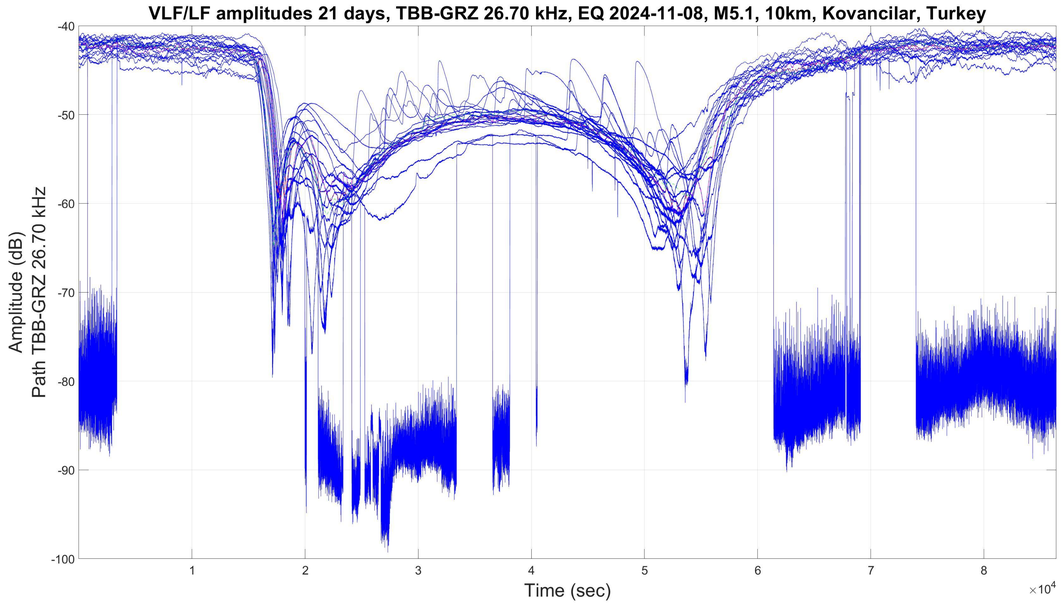
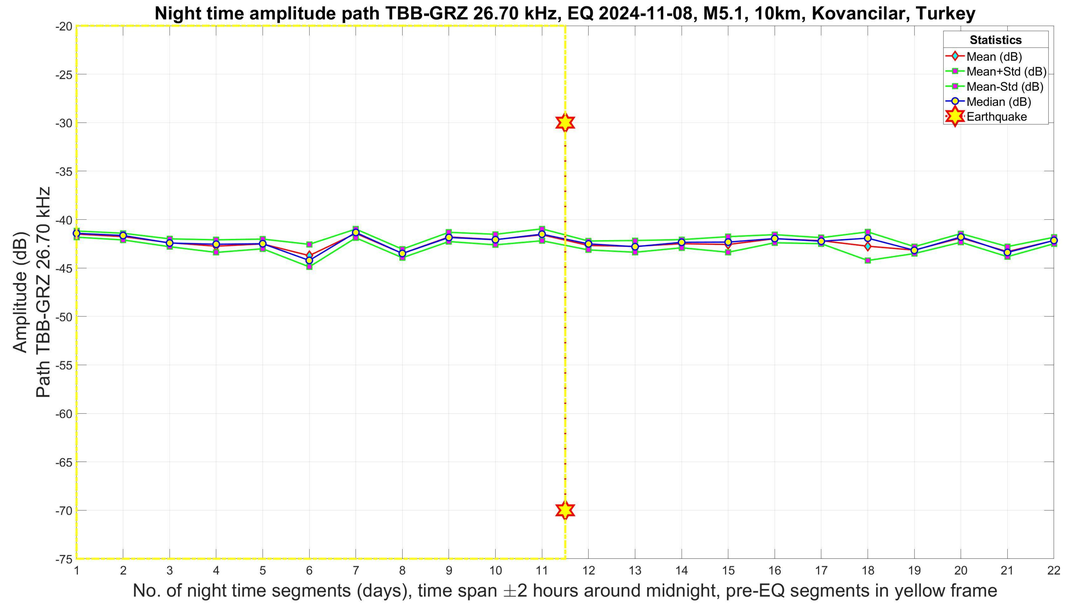
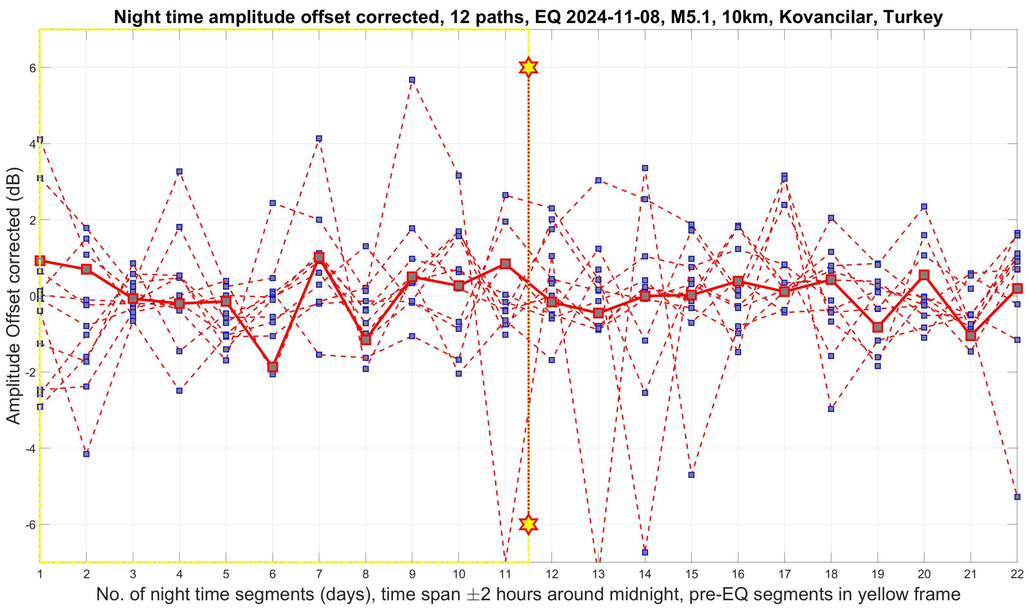
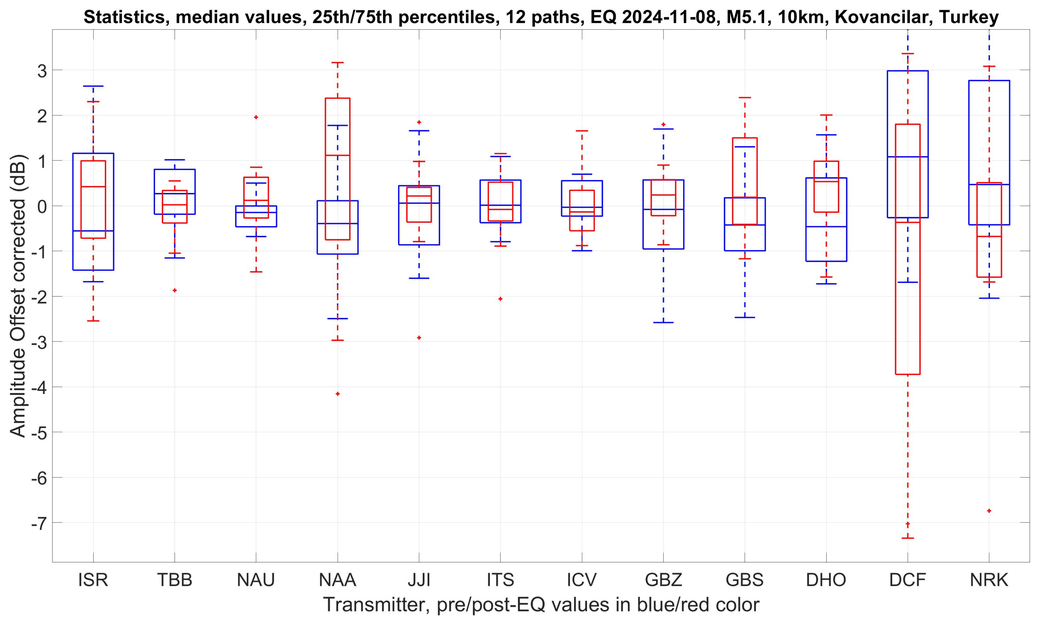
VLF/LF AMPLITUDE MEASUREMENTS, EARTHQUAKE 2024-11-08, MWR 5.1 / 10 KM, KOVANCILAR, TURKEY

- Top Left: VLF/LF amplitudes (2024-10-29 to 2024-11-18) for the 26.70 kHz TBB-GRZ path, spikes and transmitter switch off periods are omitted (|Dst| = 89 nT)
- Bottom Left: Offset corrected nighttime (± 2h 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, for a significance level of 5% no event path shows higher amplitude values after the EQ (nighttime method)









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SUB-IONOSPHERIC VLF/LF WAVEGUIDE ELECTRIC FIELD INVESTIGATION FROM MW≥5.0 EARTHQUAKE EVENTS WITH MULTIPLE RECEIVERS IN EUROPE

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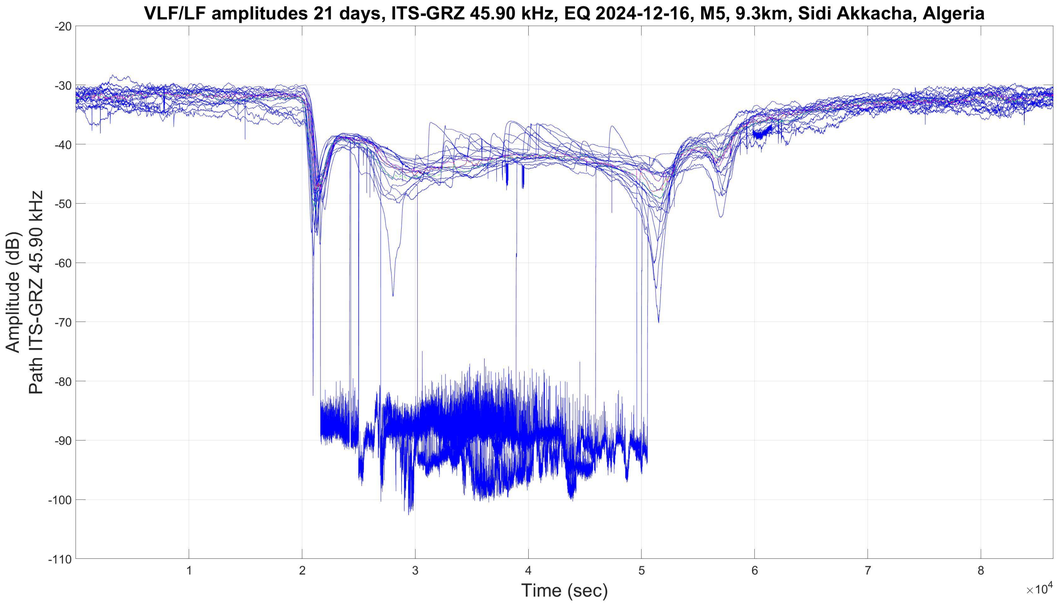
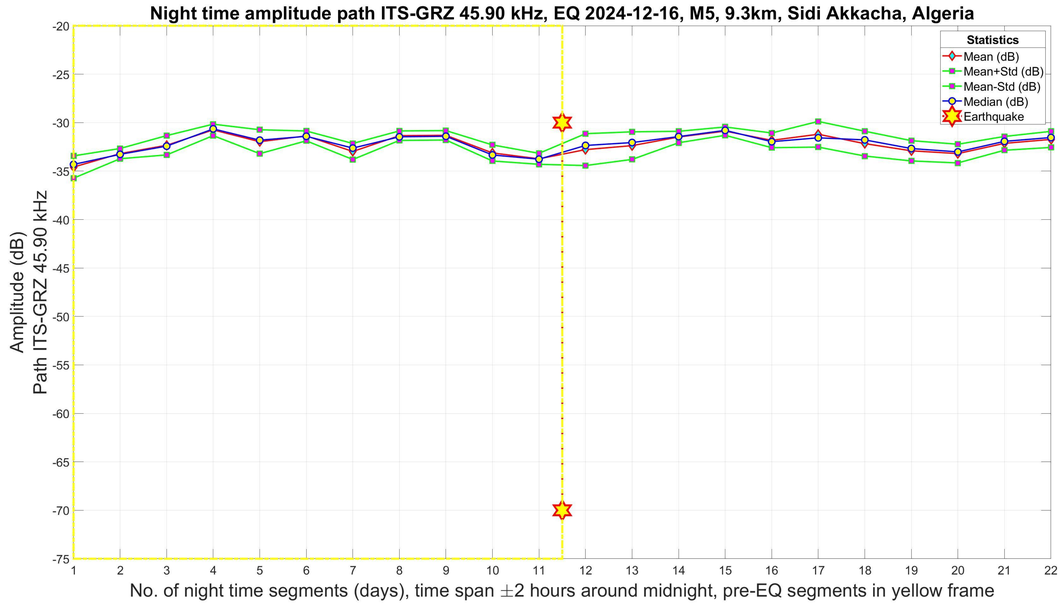
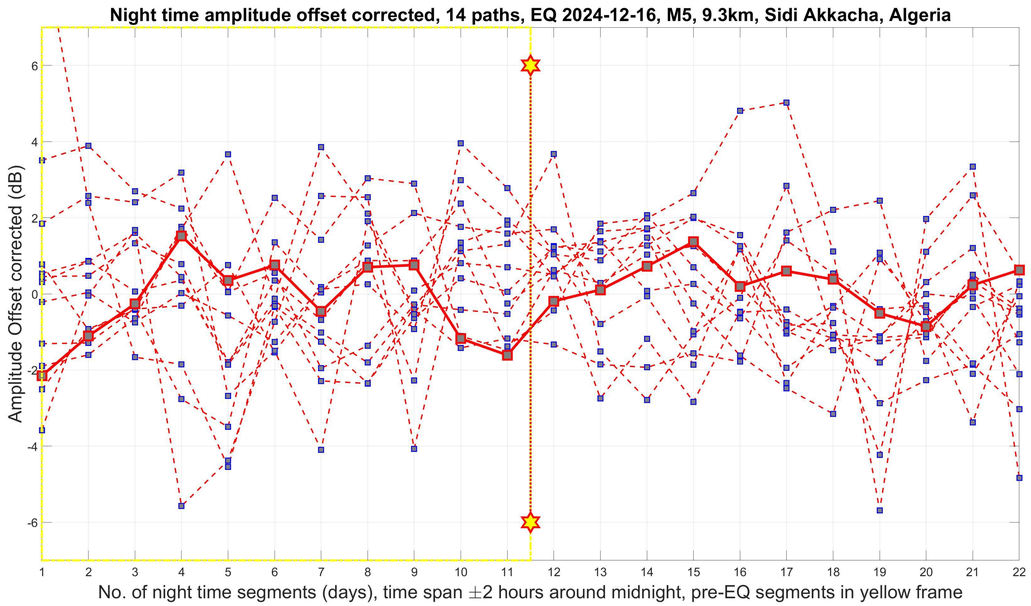
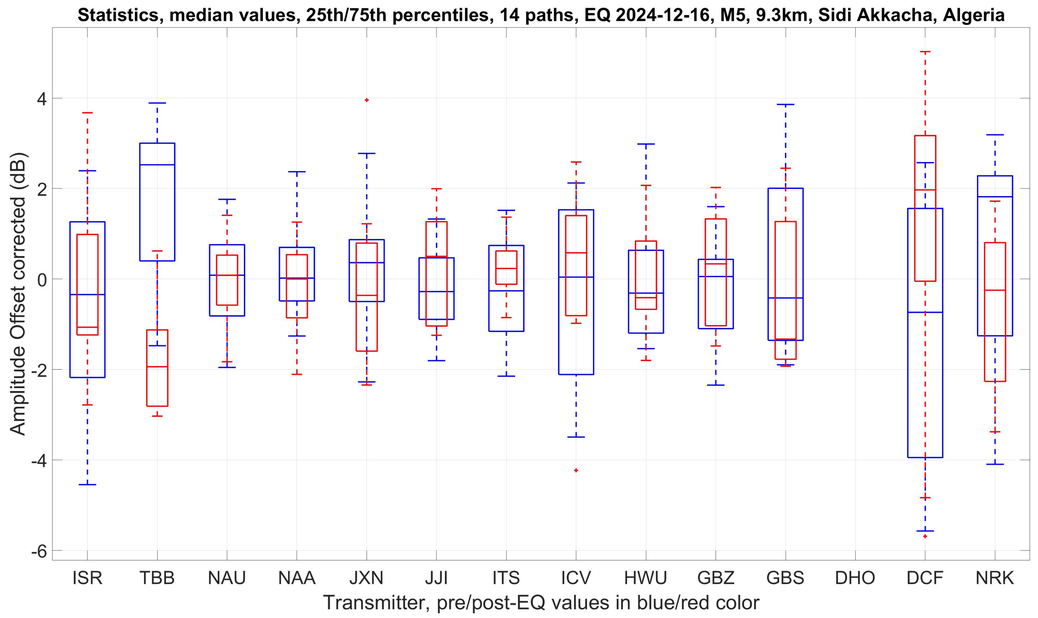
VLF/LF AMPLITUDE MEASUREMENTS, EARTHQUAKE 2024-12-16, MB 5 / 9.3 KM, SIDI AKKACHA, ALGERIA

- Top Left: VLF/LF amplitudes (2024-12-05 to 2024-12-25) for the 45.90 kHz ITS-GRZ path, spikes and transmitter switch off periods are omitted (|Dst| = 40 nT)
- Bottom Left: Offset corrected nighttime (± 2h around midnight) amplitude values for the 14 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 14 paths, for a significance level of 5% no path (no DB-crossings) shows higher amplitude values after the EQ (nighttime method)









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SUB-IONOSPHERIC VLF/LF WAVEGUIDE ELECTRIC FIELD INVESTIGATION FROM MW≥5.0 EARTHQUAKE EVENTS WITH MULTIPLE RECEIVERS IN EUROPE

Hans U. Eichelberger[1], Mohammed Y. Boudjada[1], Aleksandra Nina[2], Bruno P. Besser[1], Daniel Wolbang[1], Maria Solovieva[3], Pier F. Biagi[4], Patrick H. M. Galopeau[5], Christoph Schirninger[6], Iren-Adelina Moldovan[7], Giovanni Nico[8], Manfred Stachel[1], Özer Aydogar[1], Cosima Muck[1], Josef Wilfinger[1], and Irmgard Jernej[1]

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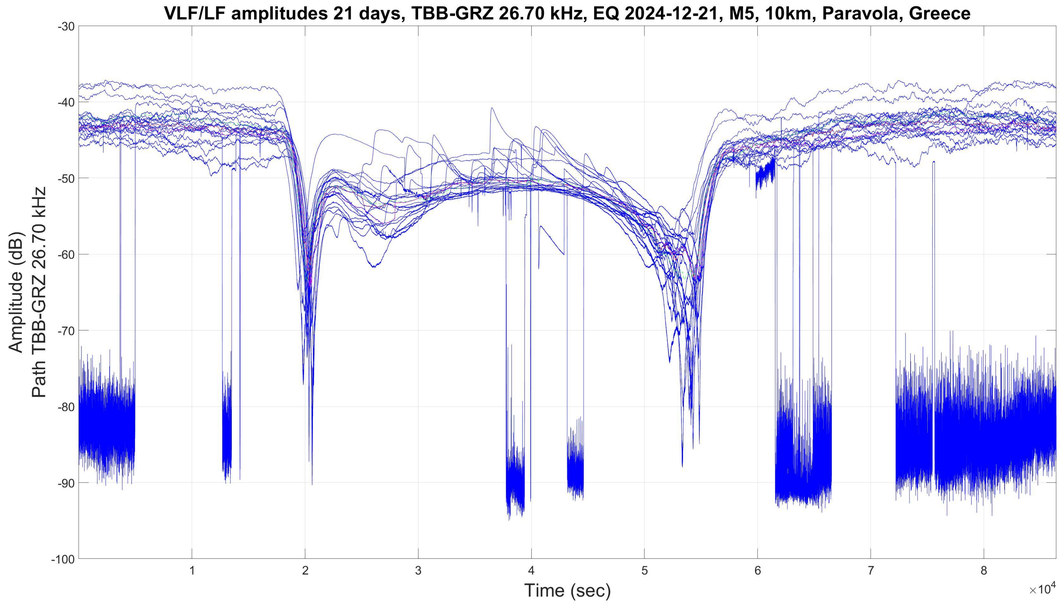
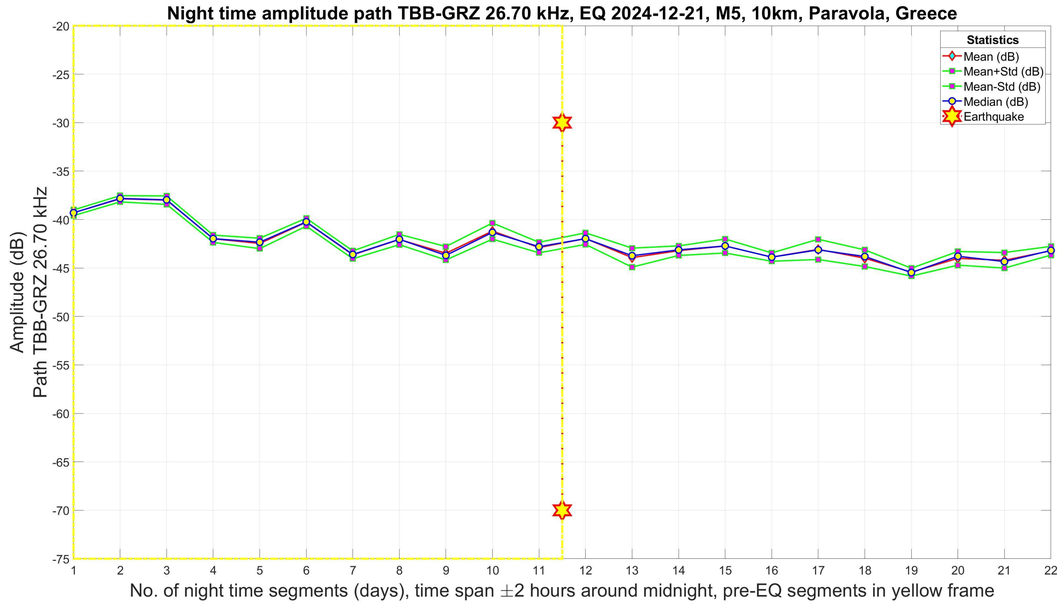
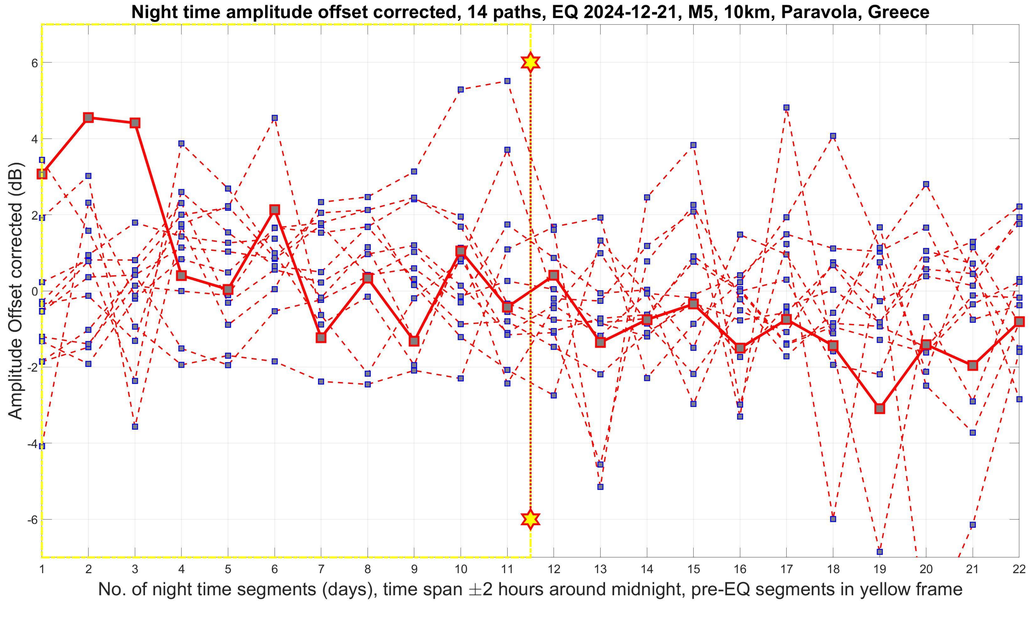
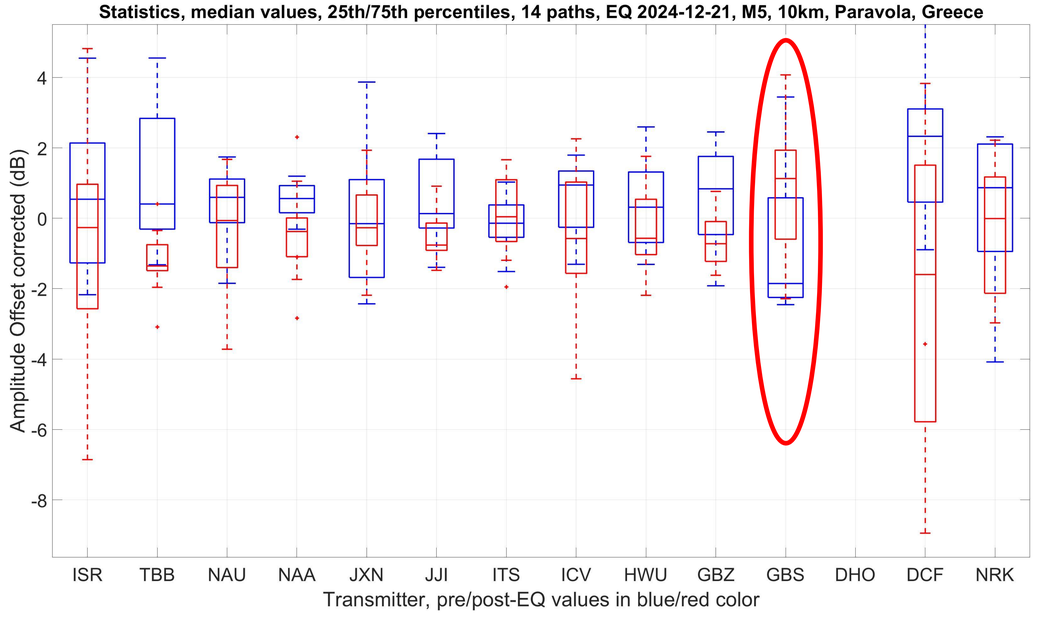
VLF/LF AMPLITUDE MEASUREMENTS, EARTHQUAKE 2024-12-21, MWR 5 / 10 KM, PARAVÓLA, GREECE

- Top Left: VLF/LF amplitudes (2024-12-11 to 2024-12-31) for the 26.70 kHz TBB-GRZ path, spikes and transmitter switch off periods are omitted (|Dst| = 40 nT)
- Bottom Left: Offset corrected nighttime (± 2h around midnight) amplitude values for the 14 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 14 paths, for a significance level of 5% only the event path GBS-GRZ shows higher amplitude values after the EQ (nighttime method)









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