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

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In this study we examine earthquakes with magnitude M ≥ 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, Nisemi, 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 VLF-LF waveguide 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 have shown the complex interplay between the lithosphere's 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 INFRF 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

**EARTHQUAKES M ≥ 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° ≤ lat ≤ 50°] / [10° ≤ long ≤ 30°], i.e., an Eastern Mediterranean area, in the year 2022. For this temporal, spatial and moment magnitude M ≥ 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 ε = 104.4356 km and log(R) = 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 (yellow color in Tab. 1), i.e., the link between VLF/LF electric field and EQ, based on statistics from night-time electric field amplitude variations with significance level 5%, are mainly achieved for M ≥ 5.5 earthquakes.

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

**REFERENCES**


**SUMMARY**

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

Table 1: Results for all M ≥ 5 earthquakes (see Figure 1, stars in yellow and white color). time period 2022, Eastern Mediterranean area.
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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 (±2h 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

[Graphs showing VLF/LF amplitudes and statistics for the earthquake event]
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 (±2h 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)
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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 (±2h 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 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 (+2h 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

Night time amplitude path TBB-GRZ 26.70 kHz, EQ 2022-08-14T03:24:22, M5, 11.7 km, Oezdere, Turkey

Statistics, median values, 25th/75th percentiles, 9 paths, EQ 2022-08-14T03:24:22, M5, 11.7 km, Oezdere, Turkey
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 (± 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%, NAA-GRZ, GBZ-GRZ and DHO-GRZ show higher amplitude values after the EQ
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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 (± 2h 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

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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 (± 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 TBB-GRZ shows higher amplitude values after the EQ (nighttime method)
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 (±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 path GBS-GRZ shows higher amplitude values after the EQ (nighttime method)
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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 (±2h 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)

VLF/LF amplitudes 21 days, TBB-GRZ 26.70 kHz, EQ 2022-11-03T04:50:25, M5.1, 153.2km, Gura Teghii, Romania

Night time amplitude path TBB-GRZ 26.70 kHz, EQ 2022-11-03T04:50:25, M5.1, 153.2km, Gura Teghii, Romania

Statistics, median values, 25th/75th percentiles, 10 paths, EQ 2022-11-03T04:50:25, M5.1, 153.2km, Gura Teghii, Romania

Transmitter, pre/post-EQ values in blue/red color
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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 (± 2h 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)

VLF/LF amplitudes 16 days, ITS-GRZ 45.90 kHz, EQ 2022-11-09T06:07:26, M5.6, 8km, Central Italy, Italy

Night time amplitude path ITS-GRZ 45.90 kHz, EQ 2022-11-09T06:07:26, M5.6, 8km, Central Italy, Italy

Night time amplitude offset corrected, 11 paths, EQ 2022-11-09T06:07:26, M5.6, 8km, Central Italy, Italy

Statistics, median values, 25th/75th percentiles, 11 paths, EQ 2022-11-09T06:07:26, M5.6, 8km, Central Italy, Italy
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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 (±2h 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

![VLF/LF amplitudes 21 days, TBB-GRZ 26.70 kHz, EQ 2022-12-28T12:24:20, M5, 10.3km, Psachna, Greece](image1)

![Night time amplitude path TBB-GRZ 26.70 kHz, EQ 2022-12-28T12:24:20, M5, 10.3km, Psachna, Greece](image2)

![Night time amplitude offset corrected, 10 paths, EQ 2022-12-28T12:24:20, M5, 10.3km, Psachna, Greece](image3)

![Statistics, median values, 25th/75th percentiles, 10 paths, EQ 2022-12-28T12:24:20, M5, 10.3km, Psachna, Greece](image4)
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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 (± 2h 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)
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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 (±2h 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)
VLF/LF AMPLITUDE MEASUREMENTS, EARTHQUAKE 2022-10-02, M5.4, 10 KM, IERÄPETRA, 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 (±2h 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