https://doi.org/10.69646/aob241112

Terminator variations of VLF/LF amplitudes - observational techniques and case studies

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Abstract

The VLF/LF Earth-ionosphere waveguide enables the remote detection of important variabilities related to environmental and solar processes. Two case studies have been considered with medium and high solar activities, both recorded by Belgrade (Serbia) and Graz (Austria) stations. This study shows the existence of electric field amplitude wave phenomena with periods of ~500 sec during terminator times. Our findings underscore the importance of measurement networks for future surveys.

Introduction

Remote sensing of the lower ionosphere via very low frequency (VLF, f = 3-30 kHz) and low frequency (LF, f = 30-300 kHz) signals emitted by powerful transmitter stations and detected by ground-based facilities are crucial for the study of the Earth's environment, e.g., space weather studies, the coupling between atmosphere and ionosphere, and commercial applications. The radio waves from narrowband VLF/LF transmitters are confined within the Earth-ionosphere waveguide, between the Earth's surface (lower boundary) and the lower ionospheric layers (upper boundaries), i.e., D-layer (altitudes approx. 50-70 km) during daytime, E-layer (altitudes approx. 70-90 km) during night time, and during sunrise and sunset transitions. The ion production in the lower ionospheric D-region is dominated by solar Lyman-alpha (mainly [NO^+] and cluster ions), to a minor extend by EUV, UV, X-ray (solar flare events) on the species [O_2, N_2] and at lower altitudes by galactic cosmic rays [N_2, O_2]. The D-region electron density profiles show a solar zenith angle dependence as reported in several models (Nina et al., 2021; Friedrich et al., 2018; Mironova et al., 2015; and Wait and Spies, 1964).

VLF/LF observations recorded by Belgrade (Serbian) and Graz (Austria) Stations

In this study we consider two VLF/LF receivers, located in Belgrade (Serbia) and Graz (Austria) as displayed in Figure 1. Table 1 lists the transmitter signal detected by Belgrade and Graz facilities and the corresponding features: frequency, geographical coordinate, and the distances. The reception systems in Belgrade (Nina, 2024) and in Graz (Galopeau et al., 2023) are capable of measuring amplitudes and phases of electric fields with a high time resolution (sampling frequencies fs 1 sec). Electric fields are associated with transmitter signals propagating in the Earth-ionosphere waveguide. The selected paths shall have a distance far and close to the transmitter station to avoid near field evanescent modes and to enhance the signal-to-noise ratio.

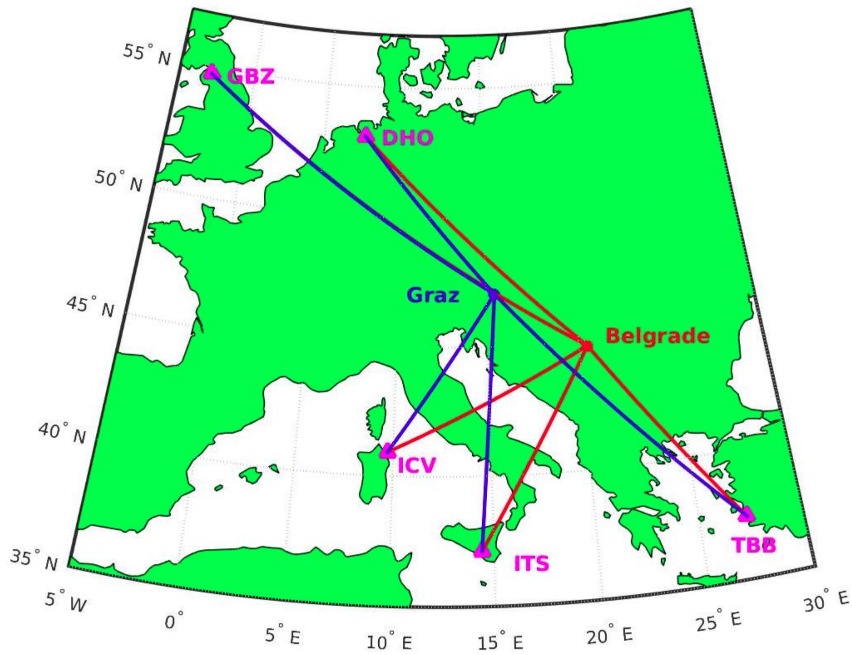

Fig. 1. Geographical locations of the five transmitter signals (i.e., DHO, GBZ, ICV, ITS and TBB) detected by VLF reception systems in Belgrade (Serbia) and Graz (Austria).

Table 1. Great circle path (GCP) distances between Belgrade or Graz reception systems and VLF/LF transmitters (see Figure 1) with fully developed waveguide modes and sufficient S/N ratio.

	ICV 20.27 kHz 09.71 E 40.92 N	DHO 23.40 kHz 07.60 E 53.08 N	TBB 26.70 kHz 27.31 E 37.40 N	GBZ 22.10 kHz 02.87 W 54.73 N	ITS 45.90 kHz 14.43 E 37.12 N
Belgrade 20.40 E 44.80 N	973 km general overview	1310 km single case study	1005 km general overview	1993 km general overview	989 km single case study
Graz 15.48 E 47.04 N	820 km general overview	875 km single case study	1445 km general overview	1541 km general overview	1105 km single case study

Case study of transmitter amplitude variations at terminator times

In this Section we consider amplitude variations around the terminators, i.e., during the transition from E- to D-layer (sunrise) and vice versa (sunset). Regular patterns are due to solar Lyman-alpha modulations connected with wave excitations where additional external influences could occur due to solar flares or internal sources via the atmosphere and the ionosphere, e.g., atmospheric gravity waves (AGWs). For the two days of the study the composite solar Lyman-alpha irradiance is 8.48732 mW/m^2 (3. May 2024, 12 UTC) and with 9.99519 mW/m^2 higher for the 5. Aug 2024, 12 UTC (these data were accessed via the LASP Interactive Solar Irradiance Data center, LISIRD).

a) Case study of DHO VLF transmitter signal with medium solar flare activity (3. May 2024)

The top panel of Figure 2 shows the amplitude variations recorded on 3. May 2024 during a medium solar flare activity. Sunrise and sunset data (civil time) are indicated by a vertical red color line for Belgrade and black one for Graz. We find that both DHO signals exhibit similar fluctuations during the day observation. However, a difference of intensity level of about 10 dB is found when combining Graz and Belgrade observations as clearly seen in Figure 2. The time resolution for Belgrade observations is one minute (red line in top panel of Figure 2), and for Graz is one second (blue line in top panel of Figure 2) and one minute (green line in top panel of Figure 2). It is important to note that Belgrade data have been slightly adjusted (offsets) to enable visual comparison.

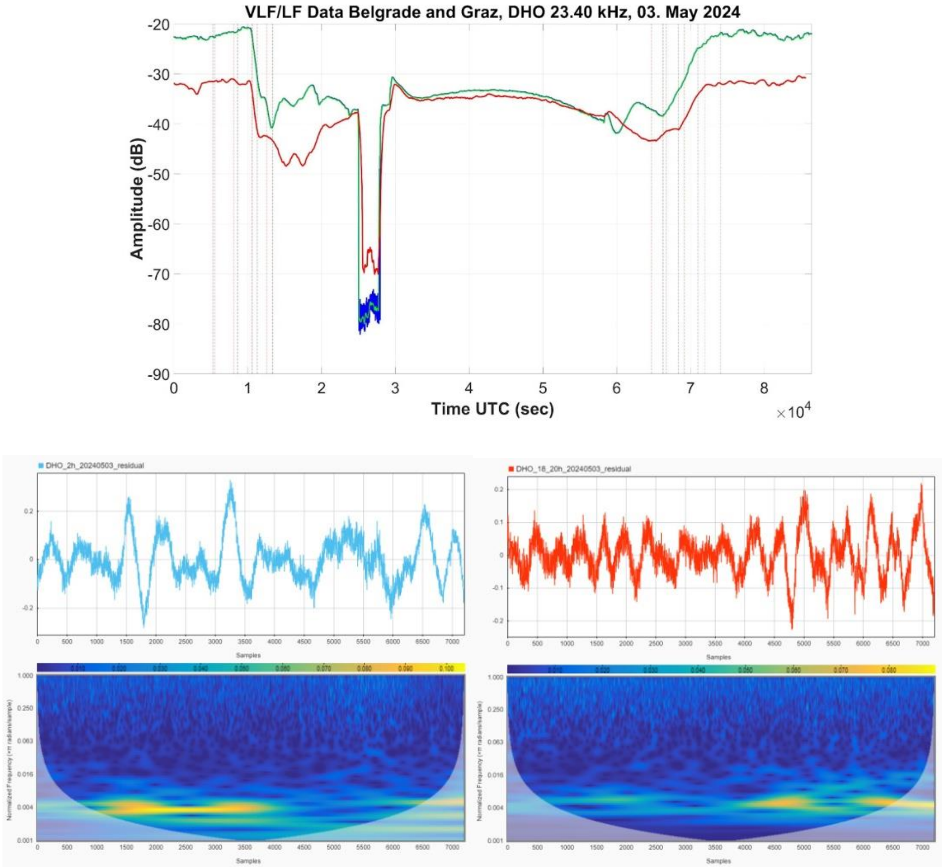

Fig. 2. Top panel: VLF DHO 23.40 kHz transmitter amplitude signal recorded on 3. May 2024, at Belgrade (red line) and Graz (blue line) reception stations. The bottom panels display the residual (bottom above panels) and the wavelet spectrum (bottom below panels).

The residuals shown in the bottom upper panels of Figure 2 are the difference between the DHO measured amplitude signal and the smoothed DHO amplitude using Savitzky-Golay filter. Those residuals are considered two hours before and after sunrise (bottom upper left panel of Figure 2) and sunset (bottom upper right panel of Figure 2) terminators. We find clear minima at terminators related to the ionospheric layers, i.e., D- and E-layers. Those residual minima appear when considering the wavelet spectrum of DHO signal as displayed in the bottom lower left panel for the sunrise and in the bottom lower right panel for the sunset terminators. We note the presence of wave activities with periods of about 500 seconds occurring at terminator times.

b) Case study of ITS VLF transmitter signal with high solar flare activity (5. August 2024)

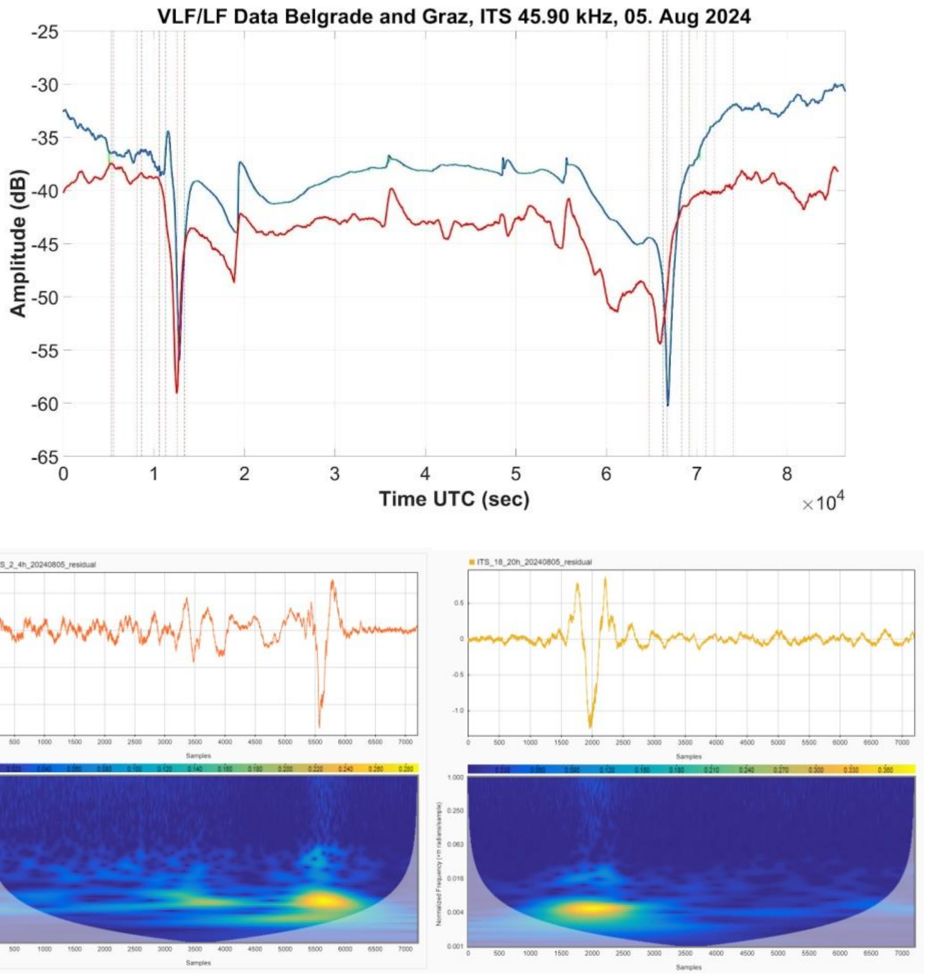

Fig. 3. Top panel: Top panel: VLF ITS 45.90 kHz transmitter amplitude signal recorded on 5. August 2024, at Belgrade (red line) and Graz (blue line) reception stations. The bottom panels display the residual (bottom upper panels) and the wavelet spectrum (bottom lower panels).

The top panel of Figure 3 displays the amplitude variations of ITS transmitter signal recorded on 5. August 2024 during a high solar flare activity. Vertical red and black color lines indicate, respectively, the sunrise and sunset terminators for Belgrade and for Graz. Like in the case of the event of 3. May 2024 the Belgrade data have been slightly adjusted (offsets) to enable visual comparison. Also, the time resolutions used for the data processing of Belgarde and Graz observations are similar to those considered in Figure 2. Generally, ITS amplitude variations at Belgrade and Graz are found similar but exhibit a difference of 10 dB during the day and the night observations. The high solar activity is due to two X-class solar flares, accompanied by several M-class flares, recorded by GOES satellite in the wavelength range 0.1-0.8 nm. The first X-class flare occurs at about 13:40 UT (49200 sec) with a flux equal to $1.73*10^{-4}$ W/m^2, and the second one happens at about 15:20 UT (55200 sec) with a flux equal to $1.17*10^{-4}$ W/m^2.

The residuals shown in the bottom upper panel of Figure 3 are also considered two hours before and after sunrise (bottom upper left panel of Figure 3) and sunset (bottom upper right panel of Figure 3) terminators. We see clearly a pronounced and important minima at terminators when compared to the previous event (i.e., 3. May 2024). The increase of the residual minima is directly related to the solar flare effects on the ionospheric layers particularly at terminators. The wavelet spectrum of ITS signals show similar fluctuation as displayed in the bottom lower left panel of Figure 3 for the sunrise and in the bottom lower right panel of Figure 3 for the sunset terminators. In this case we note the existence of wave activities with periods of about 500 seconds occurring at terminator times, and also minor ones with periods in the order of 125 second.

Conclusions

The electric field amplitude data from the two receivers coincide very well and show the benefit of combined investigations of same VLF/LF links at different sites. During the terminator times wave activities with periods of ~500 sec could be measured, additional excitations occur for the more disturbed day 5. August 2024. In general, a high sample rate enables the detection of different types of variations and characterisation of noise parameters in the Earth-ionosphere waveguide.

Acknowledgments: The authors acknowledge the support provided by the Austrian Federal Ministry of Education, Science and Research (BMBWF) (project no. RS 22/2024), and the Ministry of Science, Technological Development and Innovation of the Republic of Serbia (project 337-00-216/2023-05/188). The authors acknowledge funding provided by the Institute of Physics Belgrade through the grant by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia.

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