Cross-correlation analysis of seismic noise in Bulgaria - first results

Reneta Raykova[1], Liliya Dimitrova[2], Andrea Morelli[3]

[1] Faculty of Physics, Sofia University "St. Kl. Ohridski", rraykova@phys.uni-sofia.bg
[2] National Institute of Geophysics, Geodesy and Geography, Bulgarian Academy of Sciences, lidim@geophys.bas.bg
[3] Istituto Nazionale di Geofisica e Vulcanologia, Bologna branche, Italy, andrea.morelli@ingv.it

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1. Introduction

The velocity models of the Earth's structure were obtained studying propagation of seismic waves on various scales - along wave paths with different length (tens to thousands of kilometers) or by tomography on global, regional or local scale (Ritzwoller and Levshin, 1998; Brandmayr et al., 2010; Legendre et al., 2012). The main sources of seismic waves in these studies are moderate to strong earthquakes. The most used techniques are related to the surface waves and measurement of their dispersion, since it is indicative for the velocity structure along the wave path. The major difficulties are connected to the fact that earthquakes are spaced not evenly, they are concentrated in narrow zones between different tectonic units (with few exceptions of intraplate foci). Another obstacle is connected with the high level of the noise in the period range 1-15 *s*, that makes uncertain the measurements of dispersion curves in this period range. Additional limits are related to the scattering of short-period waves and uncertainties in seismic source parameters.

A new technique that has been developed at the beginning of this century, uses ambient seismic noise long-time correlation between two stations in order to obtain the signal that is determined mainly by the structure between these two stations (Campillo and Paul, 2003). Period range of the measured dispersion curves in this case depends mainly on the distance between two stations: as close are the stations as small are the obtained periods. Therefore period range of measurements depends only of availability of seismic stations with broad-band instruments.

The Bulgarian territory, as part of the Balkan Peninsula, has complex Earth structure. Shallow crustal structure has been investigated by several seismic surveys in the past century, summarized in Dachev (1988). Recent studies (Grad et al., 2010; Molinari and Morelli, 2011; Molinari et al., 2012) presented homogenized maps of crustal structure, interpolating available studies in Euro-Mediterranean region. Deeper structure has been obtained in several global and regional studies (Levshin et. al., 1998; Piromallo and Morelli, 2003) and few local studies (Botev et al., 1988; Raykova and Nikolova, 2007; Raykova and Panza, 2015). One of the reasons for a lack of resolution of the tomographic studies over the Bulgarian territory was the small number of seismic stations from the Bulgarian seismic network that were equipped mainly with short-period seismometers. The Bulgarian network has been modernized in 2005 and presently consists of 24 stations, and 15 of them have broad-band (BB) or very-broad-band (VBB) seismometers installed (Solakov et al., 2011).

This paper presents the first results of ambient noise cross-correlation of long time registrations from selected stations on the Bulgarian territory. Dispersion properties between each pair of stations have been evaluated and compared. This study is a base for further tomography and detailed velocity structure mapping of crustal structure in Bulgarian region.

Method

Surface wave ambient noise tomography has been successfully used in number of studies to model shallow crustal structures (e.g. Yang et al., 2007). The main part of the method consists of measuring the dispersion of empirical Green functions (EGFs) obtained from cross-correlation of time-series containing ambient noise. The main properties of the noise wavefields are random amplitude and phase of the waves and propagation in all possible directions. The Green function between two locations can be extracted from the diffuse wavefield with simple field-to-field correlation taken over sufficiently long time (Campillo and Paul, 2003). The amplitude in continuous seismic noise records is disregarded by one-bit transformation in order to not overweight the most energetic waves. Cross-correlation of two records is applied for long-time series divided in few hours. Signal processing techniques was described in Bensen et al. (2007). The resulting wavefield has characteristics of Rayleigh waves, i.e. long periods arrived before short periods. We employed the tool developed by H. Yao (Yao et al., 2006) that uses MATLAB package and seismograms in SAC format. The method estimates also the empirical Green's functions (EGFs) that are computed from the time derivative of the noise cross-correlation function (NCF). The Rayleigh wave dispersion curves were extracted by EGFs of each station pair employing the technique developed by H. Yao (Yao et al., 2005).

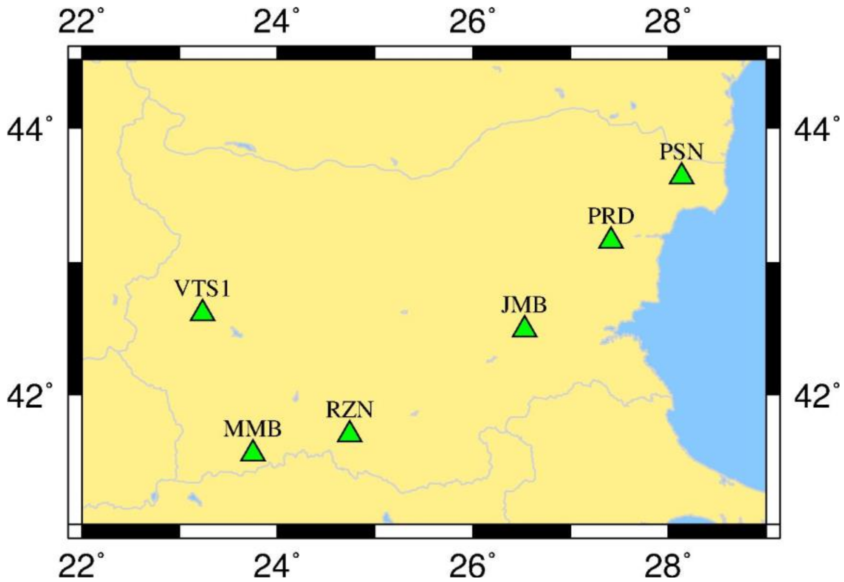

Fig. 1. Map of the Bulgarian territory and seismic stations used in cross-correlation

Data

We used the one-year (2015) continuous seismic data recorded by six stations belonging to the Bulgarian seismic network (Fig. 1). The stations are equipped with BB or VBB seismometers and they are: VTS1 (CMG3ESP seismometer), MMB (STS2 seismometer), JMB, PRD, PSN and RZN (CMG40T seismometer). The power spectral density (PSD) functions of the ambient noise at the selected stations have been estimated in previous studies (Dimitrova, 2009; Dimitrova and Nikolova, 2011). Comparison of the mode PSD functions of the six stations to the Low Noise Model (NLNM) (Peterson, 1993) in the period range above 5 s shows that the VTS station is the quietest one. The stations MMB and RZN have a little bit higher noise level and the stations PSN, PRD and JMB have significant noise caused mainly by the proximity to the Black Sea. The interstation distance varies between 79 and 428 *km*. We used only the vertical component data and they were converted from miniSEED and datalessSEED files to one-day-SAC records. Instrument response was applied to original records, mean value and eventual trends were removed. Preliminary band-pass filter in the period range 5-50 *s* or 2-100 *s* was applied. The initial records were resampled from 100 to 5 samples per seconds. The NCF and EGFs were estimated for one-hour segments.

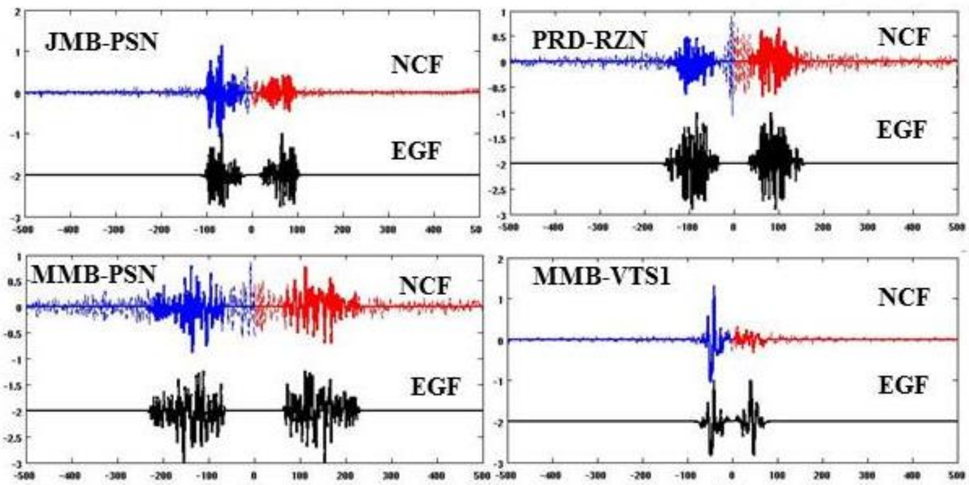

Fig. 2. NCFs and EGFs for station pairs JMB-PSN, PRD-RZN, MMB.PSN and MMB-VTS1 (blue lines). Red lines denoted the correlated signals from reverse pairs

Results

NCFs were calculated in period interval 5-30 *s* due to the BB seismometers installed in 4 of the stations used. Additionally, the NCF of station pair MMB-VTS1 were calculated in the period interval 2-100 *s*. Initially, NCFs were calculated for 3-month records, but this period was not long enough to obtain clear dispersion signals. We obtained much better results using one-year records and therefor longer is the correlated period, clearer are the extracted dispersion curves. Fig. 2 shows NCF and relevant EGF for several pair of stations. Theoretically, NCF between station1-station2 and station2-station1 should be the same. In practice, very often the two NCF are different because of relatively sharp non-horizontal layer borders. Instead of this, the calculated EGFs are rather similar. The EGFs were used to measure the group velocity dispersion curve between each pair of station for 15 wave paths. Most of the obtained dispersion curves are rather smooth, but there are several contradictionary signals. NCFs of several station pairs contain also clear first mode of Rayleigh waves together with the fundamental mode. Two examples of dispersion measurements are shown in Fig. 3 for the station pairs PRD-PSN (79 *km*) and MMB-PSN (428 *km*). The used software visualizes the points from selected dispersion curve with good signal-to-noise ratio (red points, red line), set to the value of 3. The maximum period T (*s*) of dispersion curve is related to the interstation distance L (*km*) by the equation $L>CT$, where C is the phase velocity in *km/s*. The correlated signal between station MMB and PSN contains also first mode of the Rayleigh waves.

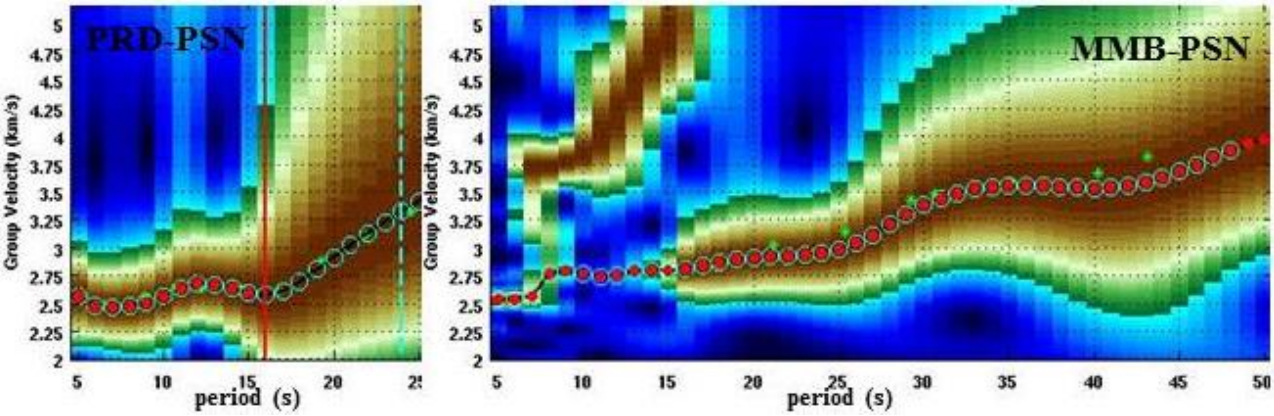

Fig. 3. Dispersion curves for pairs PRD-PSN and MMB-PSN.

Distribution, almost linear, of five of the stations used permits to follow the dispersion curves dependence from the interstation distances. Dispersion curves for short interstation distances have pronounced signal at short periods. However, the signal for short periods is almost missing for the longest distances because of attenuation of short-period waves. The shape of the obtained dispersion curves is similar for four combinations: PSN-PRD (79 *km*), PSN-JMB, PSN-RZN, and PSN-MMB (429 *km*). Comparing dispersion curves measured for similar interstation distances, we notice some characteristic pattern. For example, group velocity of waves with periods up to 20 *s* is greater than 2.75 *km/s* for MMB-VTS (high mountain area, elevation ~ 2500 *m* or higher, distance 126 *km*) and lower than 2.75 *km/s* for JMB-PRD (elevation up to 1000 *m*, distance 103 *km*) that indicate high velocity structure between MMB and VTS in respect to structure between JMB and PRD.

Conclusions

Recently, the seismic ambient noise cross-correlation technique is widely-used to study the shallow Earth's structure. The first NCFs obtained by one-year records from 6 stations belonging to Bulgarian seismic network are rather stable, with few exceptions. The measured dispersion curves are indicative for the velocity structure between related stations. Planned work will extend the time interval of the seismic records, utilizing two- or three-years records in order to minimize the effect of earthquakes (Yanovskaya et al., 2016). Further study will include all Bulgarian stations with BB and VBB sensors as well as the available stations from neighboring countries in order to have good data coverage of the Bulgarian territory. Furtherly, tomography and inversion techniques will be employed to obtain shallow crustal structure in Bulgarian region.

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Крос-корелационен анализ на сеизмичен шум в България - първи резултати

Ренета Райков, Лилия Димитрова, Андреа Морели

Настоящата работа представя първите резултати от крос-корелационния анализ на сеизмичен шум в България. Избрани са 6 станции от Българската сеизмична мрежа с широколентови сеизмометри. Използван е едногодишен непрекъснат запис за 2015 година, като корелационните функции се изчисляват за едночасови интервали. Получени са 15 корелационни функции, които са анализирани с честотно-времеви анализ с цел определяне на дисперсионната крива от всеки сигнал. Получените дисперсионни криви са ясно изразени, с няколко изключения, като за сигнала от някои двойки станции се наблюдава и добре изразена първа мода на вълните на Рейли. Бъдещата работа включва анализ на данните от всички български станции с широколентови приемници, както и данни от близки станции от околните държави. Събраните данни ще бъдат използвани за томография на земната кора в района на България.