Determination of Phase-Velocity Dispersion Curves of Rayleigh Surface Waves from Tidal Gravimetric Recordings of Earthquakes

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Abstract

This study presents the novel application of tidal gravimetric data in the determination of phase-velocity dispersion curves of Rayleigh surface waves. Tidal gravimeters are capable to detect surface waves of periods even up to 500-600 s, while a typical broad-band seismic sensor can detect them up to the periods of 200-300 s due to its mechanical limitation. The capability of using tidal gravimeters as long period seismometers has already been analyzed since the late '90s. These researches were mainly focused on the comparison of the power spectral density of noise level of gravimeters and seismometers and the analysis of normal modes of the largest earthquakes recorded by gravimeters. The first steps in the calculation of group velocity dispersion curves of Rayleigh surface waves were carried out lately. The Wiener deconvolution technique was used to calculate the phase-velocity dispersion curve by a two-stations method, from two pre-processed traces recorded in two different stations, located at the same great circle that the epicentre. The Incorporated Research Institutions for Seismology (IRIS) database were searched in terms of availability of at least 1 Hz data recorded by a co-located broad-band seismometer and tidal gravimeter. Additionally, the IRIS database provides the information about the transfer function of instruments, what is necessary in the two-stations method. Only, three sites met the above conditions: Black Forest, Membach and Rochfort, all located in Western and Central Europe. The compatibility of gravimetric and seismic data in the period range of 20-100 s are shown. Tidal gravimeters, because of their higher sensitivity, can better detect weaker earthquakes, which results in a higher number of recordings. However, to explore all advantages of gravimetric recordings of earthquakes, especially up to the periods of 500-600 s, above analysis must be applied to tidal gravimeters with higher inter-station distances and evaluated transfer functions. This work was done in the research project No. 2017/27/B/ST10/01600 financed from the funds of the Polish National Science Centre.

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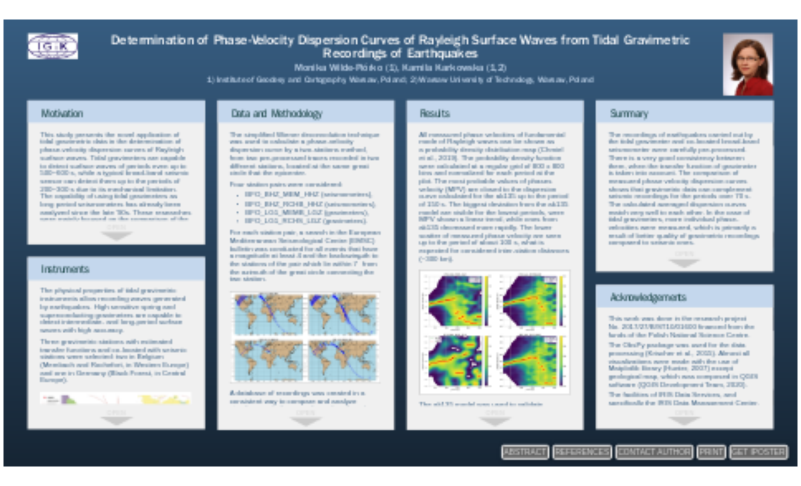

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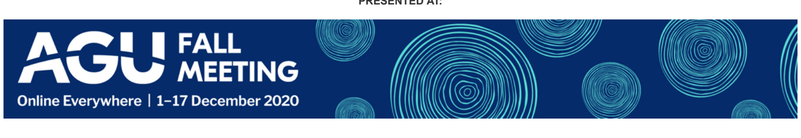


MOTIVATION

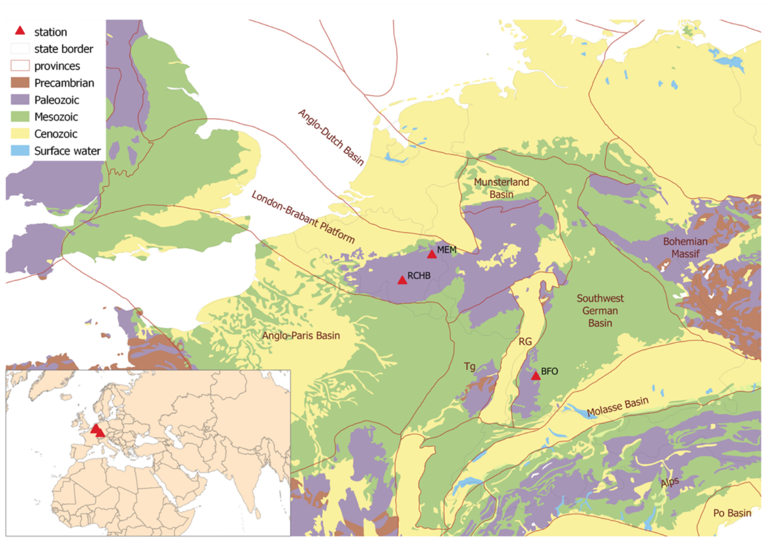
This study presents the novel application of tidal gravimetric data in the determination of phase-velocity dispersion curves of Rayleigh surface waves. Tidal gravimeters are capable to detect surface waves of periods even up to 500−600 s, while a typical broad-band seismic sensor can detect them up to the periods of 200−300 s due to its mechanical limitation. The capability of using tidal gravimeters as long period seismometers has already been analyzed since the late '90s. These researches were mainly focused on the comparison of the power spectral density of noise level of gravimeters and seismometers and the analysis of normal modes of the largest earthquakes recorded by gravimeters. The first steps in the calculation of group-velocity dispersion curves of Rayleigh surface waves recorded by tidal gravimeters were carried out lately (Wilde-Piorko et al., 2017).

In the presented research, data recorded by co-located tidal gravimeters and broad-band seismometers (only vertical component) were analyzed to confirm the high ability of tidal gravimeters to record earthquakes in intermediate- and long-period seismic range. Values of phase-velocities of fundamental-mode of Rayleigh waves recorded by the tidal gravimeters and co-located seismometers were measured and compared.

INSTRUMENTS

The physical properties of tidal gravimetric instruments allow recording waves generated by earthquakes. High sensitive spring and superconducting gravimeters are capable to detect intermediate- and long-period surface waves with high accuracy.

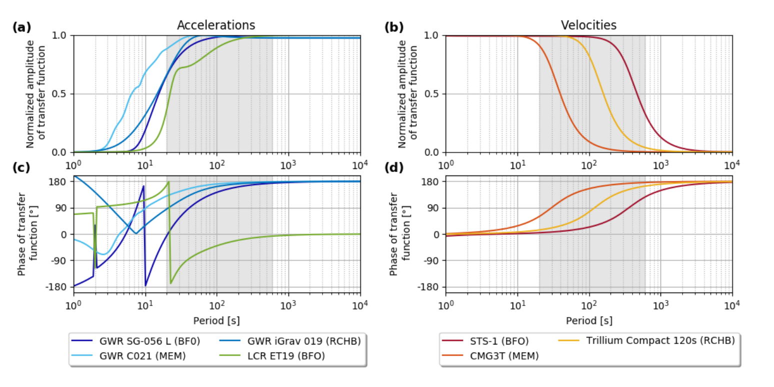
Three gravimetric stations with estimated transfer functions and co-located with seismic stations were selected: two in Belgium (Membach and Rochefort, in Western Europe) and one in Germany (Black Forest, in Central Europe).



Selected observatories upload their gravimetric and seismic data to IRIS database, which facilitates the process of downloading the data and instrument's transfer function. Each selected station provides data recorded by a superconducting gravimeter (SG) and a broad-band (BB) seismometer. Although the Black Forest Observatory is equipped with a dual-sphere SGs, only data from the lower sphere (L) has been analyzed.

Observatories	Data resources	Analyzed data	Gravimeter	Seismometer
Black Forest (Germany)	IRIS	07.2013-09.2019	GWR SG-056 L	STS-1
Membach (Belgium)	IRIS	07.2013-09.2019	GWR C021	CMG3T
Rochefort (Belgium)	IRIS	06.2017-09.2019	GWR iGrav 019	Trillium Compact 120s

In the analyzed period range (grey shaded area in below figure), the amplitude and phase of seismic waves recorded by gravimetric and seismic stations are distorted, so their transfer functions must be included in the data pre-processing for a proper comparison of signals recorded by different instruments.



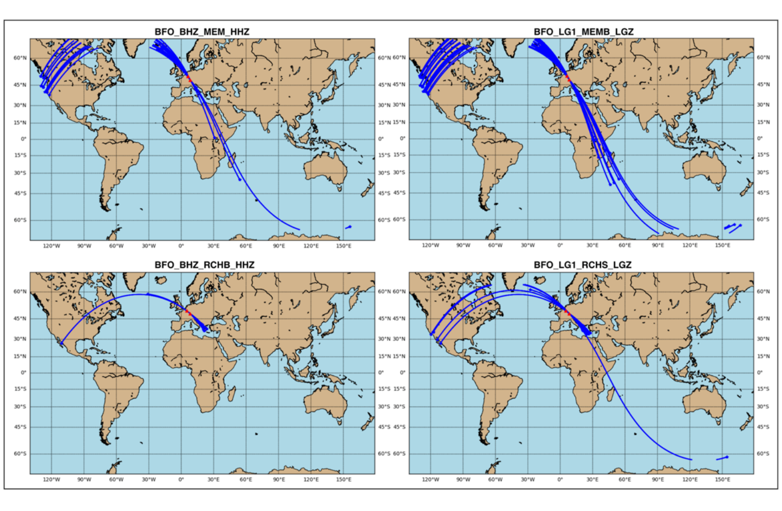
DATA AND METHODOLOGY

The simplified Wiener deconvolution technique was used to calculate a phase-velocity dispersion curve by a two-stations method, from two pre-processed traces recorded in two different stations, located at the same great circle that the epicenter.

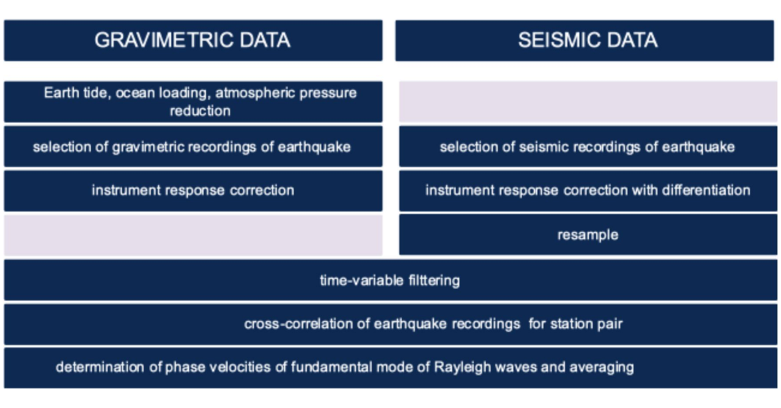
Four station pairs were considered:

- BFO_BHZ_MEM_HHZ (seismometers),
- BFO_BHZ_RCHB_HHZ (seismometers),
- BFO_LG1_MEMB_LGZ (gravimeters),
- BFO_LG1_RCHS_LGZ (gravimeters).

For each station pair, a search in the European Mediterranean Seismological Centre (EMSC) bulletin was conducted for all events that have a magnitude at least 4 and the backazimuth to the stations of the pair which lie within 7° from the azimuth of the great circle connecting the two station.



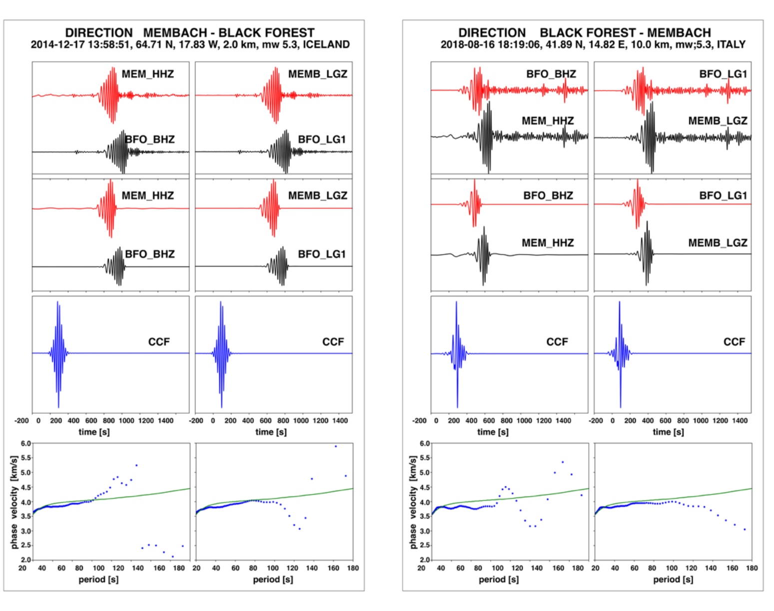
A database of recordings was created in a consistent way to compare and analyze simultaneously the recordings of earthquakes from gravimeters and seismometers. For gravimetric data, the effects of Earth tides (Tamura (1987) potential catalogue and tidal parameter sets from WDD Earth model), ocean tidal loading (FES04), atmospheric pressure (standard coefficient of −3.0 nm/s2/hPa) and polar motion were subtracted from monthly gravimetric signals (residuals were calculated by TSoft program of Van Camp and Vauterin (2005)). After that, the instrument response (transfer function) was removed from the selected event trace together with detrending, tapering and filtering of the signal. A zero-phase bandpass Butterworth filter with corner frequencies of 20 and 320 s was applied. For seismic data, the instrument response (transfer function) was removed together with detrending, tapering, filtering and differentiating of the signal. Finally, the seismic data was resampled to 1 Hz the same as it is for gravimetric data.



Quality of recordings of surface waves was checked manually for each station based on the signal-to-noise ratio (SNR > 2) and the below events were selected.

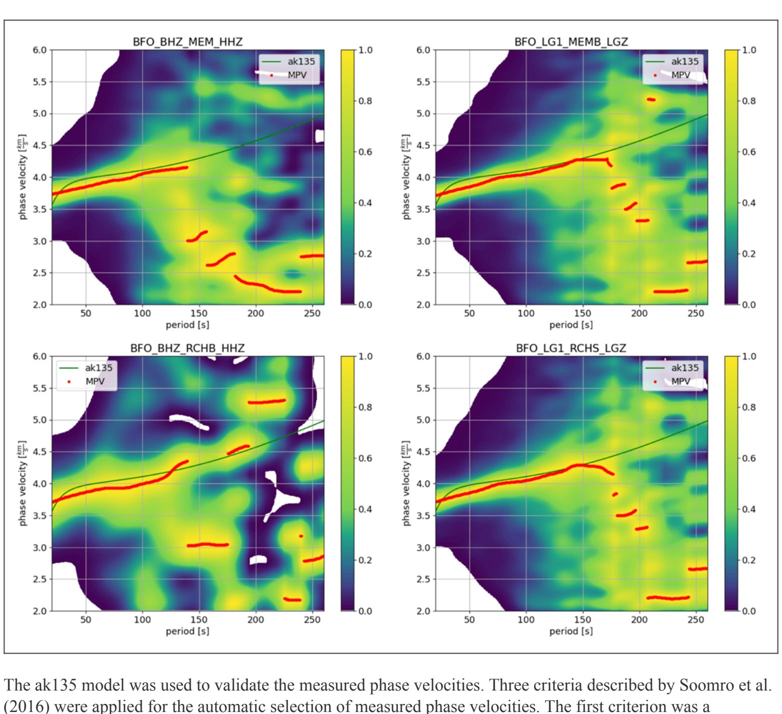
Station pair	Interstation distance [km]	Distance [km]	Magnitude of event	Depth of event [km]	Number of events
BFO_BHZ – MEM_HHZ	302.0 – 304.3	980 – 17755	4.3 – 6.9	1 – 20	58
BFO_LG1 – MEMB_LGZ	302.0 – 304.3	813 – 18252	4.0 – 6.9	1 – 57	127
BFO-BHZ – RCHB_HHZ	302.3 – 303.7	1168 – 9722	4.9 – 6.8	1 – 20	10
BFO_LG1 – RCHS_LGZ	301.3 – 303.7	1275 – 17427	4.1 – 6.4	1 – 103	48

Next, the selected traces was windowed by Time Variable Filtering (TVF) to remove all effects of noise, higher modes and undesirable perturbations (Cara, 1973). A reference dispersion curve was calculated for the ak135 model, and TVF was performed with a parameter alpha = 5. The phase difference of the fundamental modes was determined from the cross-correlation of the fundamental mode waveforms in a frequency domain (Meier et al., 2004). The desired 2π branch was chosen with the help of the reference dispersion curve.

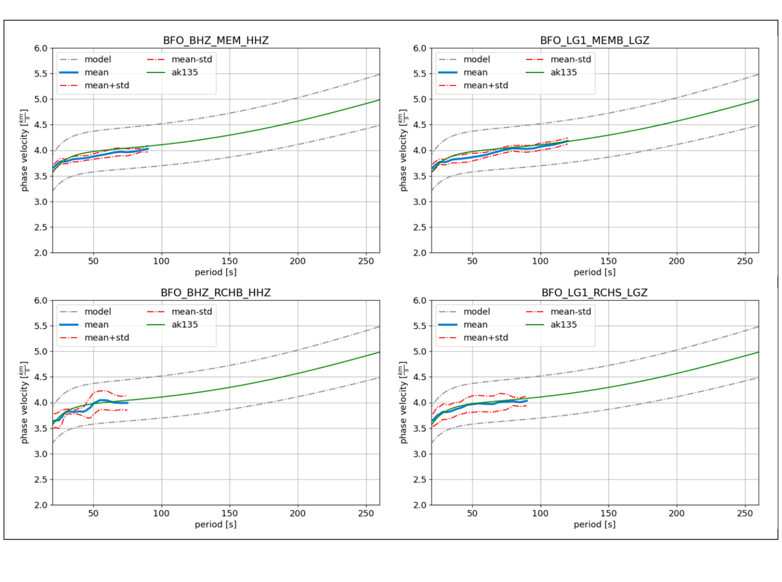


RESULTS

All measured phase velocities of fundamental mode of Rayleigh waves can be shown as a probability density distribution map (Chmiel et al., 2019). The probability density functions were calculated at a regular grid of 800 x 800 bins and normalized for each period in the plot. The most probable values of phase velocity (MPV) are closed to the dispersion curve calculated for the ak135 up to the period of 110 s. The biggest deviation from the ak135 model are visible for the lowest periods, were MPV shown a linear trend, while ones from ak135 decreased more rapidly. The lower number of measured phase velocity are seen up to the period of about 100 s, what is expected for considered inter-station distances (~300 km).



The ak135 model was used to validate the measured phase velocities. Three criteria described by Soomro et al. (2016) were applied for the automatic selection of measured phase velocities. The first criterion was a background model criterion, which is defined by the difference of the estimated phase-velocity and value from the aforementioned background model for each single frequency. The second criterion is based on smoothness consideration where the difference of slope of measured and reference curves are taken into consideration. The third criterion – the longest segment of dispersion curve was used to avoid too short segments. Averaged dispersion curves for all instruments were calculated from individual phase velocity dispersion curves by the estimation of the mean value of phase velocity for respective periods together with its standard deviation. The mean dispersion curves measured based on the gravimetric data clearly can be determined for higher periods than ones measured from the seismic data.



SUMMARY

The recordings of earthquakes carried out by the tidal gravimeter and co-located broad-band seismometer were carefully pre-processed. There is a very good consistency between them, when the transfer function of gravimeter is taken into account. The comparison of measured phase velocity dispersion curves shows that gravimetric data can complement seismic recordings for the periods over 70 s. The calculated averaged dispersion curves match very well to each other. In the case of tidal gravimeters, more individual phase-velocities were measured, which is primarily a result of better quality of gravimetric recordings compared to seismic ones.

It can be concluded that recordings surface waves by tidal gravimeters are very reliable and tidal gravimeters show the potential of using them in typical seismological studies. However, to explore all advantages of gravimetric recordings of earthquakes, especially up to the periods of 500-600 s, above analysis must be applied to tidal gravimeters with higher inter-station distances and evaluated transfer functions.

ACKNOWLEDGEMENTS

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The ObsPy package was used for the data processing (Krischer et al., 2015). Almost all visualizations were made with the use of Matplotlib library (Hunter, 2007) except geological map, which was composed in QGIS software (QGIS Development Team, 2020).

The facilities of IRIS Data Services, and specifically the IRIS Data Management Center, were used for access to waveforms (seismic data and gravimetric data from the Black Forest, Membach and Rochefort stations), related metadata, and/or derived products used in this study. IRIS Data Services are funded through the Seismological Facilities for the Advancement of Geoscience and EarthScope (SAGE) Proposal of the National Science Foundation under Cooperative Agreement EAR-1261681.

The list of earthquakes was downloaded from the European Mediterranean Seismological Centre bulletin (https://www.emsc-csem.org/Earthquake/).

ABSTRACT

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