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Expanding seismic surface waves measurements towards low periods with gravity measurements

Monika Wilde-Piórko
Institute of Geodesy and Cartography, 27 Jacka Kaczmarskiego St., 02-679 Warsaw, Poland
Tel.: +48 22 3291914, Fax: +48 22 3291950, E-mail: monika.wilde-piorko@igik.edu.pl
Przemysław Dykowski
Institute of Geodesy and Cartography, 27 Jacka Kaczmarskiego St., 02-679 Warsaw, Poland
Tel.: +48 22 3291914, Fax: +48 22 3291950, E-mail: przemyslaw.dykowski@igik.edu.pl
Marcin Polkowski
Faculty of Physics, University of Warsaw, 5 Pasteura St., 02-093 Warsaw, Poland
Tel.: +48 22 5532006, E-mail: marcin.polkowski@igf.fuw.edu.pl
Tomasz Olszak
Faculty of Geodesy and Cartography, Warsaw University of Technology, 1 Plac Politechniki, 00-661 Warsaw, Poland
Tel.: +48 22 2346042, Fax: +48 22 2341578, E-mail: tomasz.olszak@pw.edu.pl
Marek Grad
Faculty of Physics, University of Warsaw, 5 Pasteura St., 02-093 Warsaw, Poland
Tel.: + 48 22 5532007, E-mail: mgrad@mimuw.edu.pl
Jan Kryński
Institute of Geodesy and Cartography, 27 Jacka Kaczmarskiego St., 02-679 Warsaw, Poland
Tel.: +48 22 3291904, Fax: +48 22 3291950, E-mail: jan.krynski@igik.edu.pl
Marcin Sękowski
Institute of Geodesy and Cartography, 27 Jacka Kaczmarskiego St., 02-679 Warsaw, Poland
Tel.: +48 22 3291905, Fax: +48 22 3291950, E-mail: marcin.sekowski@igik.edu.pl
Andrzej Krankowski
Space Radio-Diagnostics Research Centre, University of Warmia and Mazury, 9 Prawochenskiego St., 10-719 Olsztyn, Poland
Tel.: +48 89 5233836, E-mail: kand@uwm.edu.pl
Marcin Rajner
Faculty of Geodesy and Cartography, Warsaw University of Technology, 1 Plac Politechniki, 00-661 Warsaw, Poland; currently at the Onsala Space Observatory, Chalmers University of Technology, Gothenburg, Sweden
Fax: +46 31 7725590, E-mail: marcin.rajner@pw.edu.pl

Abstract: Seismic events in gravity measurements are considered as disturbances and are usually removed from the records. However, the physical properties of tidal gravimetric instruments allow researchers to record seismic surface waves of very long periods. In the case of a superconducting gravimeter, periods of even up to 400 s can be determined. Simultaneous seismic and gravity records at the same locations allow the study of a wider response for incoming seismic waves by using two quite different instruments. For test purposes 4 seismometer-gravimeter pairs were temporarily deployed in Poland at three locations: Borowa Gora Geodetic-Geophysical Observatory (BG), Jozefoslaw Astro-Geodetic Observatory (JO), and Lamkowko Satellite Observatory (LA). During the test period from December 2016 to May 2017 several large teleseismic events were observed with well-formed surface waves. Group velocity dispersion curves for long surface waves, as well as periods of free oscillations are presented for selected events. The correlation of a broadband seismometer signal with different types of gravimetric sensors signals gives the opportunity to analyse gravimeter noise components, in the instrumental and micro-seismic domains.

Keywords: gravity, seismometer, earthquake, dispersion curve, surface waves

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1. Introduction

Seismic and gravity measurements are usually considered separately, although both are related to the same object — the Earth. Seismic events in gravity measurements are considered as disturbances and are usually removed from the gravity records. A variety of broadband seismometers allow the measurement of surface waves generated by earthquakes up to a period of 120–150 s, spring gravimeters make it possible to record longer waves (up to 250 s), while superconducting gravimeters can record surface waves up to 400 s. That fact creates an unique opportunity to study the structure of the Earth more deeply than by seismic instruments only, because surface waves of longer periods penetrate deeper structures of the Earth directly.

The seismic normal modes excited by large earthquakes have been intensively investigated with gravimeters since the 1990s (e.g. Richert et al., 1995, Hinderer et al., 2015). Typically, in tidal studies periods of 6–24 hours are analysed, while the normal mode range is 1–54 minutes. Banka and Crossley (1999) have performed a noise study of different instrument-site combinations, superconducting gravimeters and seismometers, in the frequency range of 0.05–20 mHz to test the suitability of gravimeters in providing useful information to seismology. The superconducting gravimeter can also be used to detect co-seismic effects that accompany a large earthquake (Imanishi et al., 2004) and to monitor the accumulation of gravity changes in locked areas and stress release by earthquakes (Imanishi et al., 2007). The intention of the authors was to apply the analysis of surface waves, common in seismology, to gravity records of earthquakes to study the structure of the Earth's interior. The present paper shows how to analyse simultaneous seismic and gravity records, carried out at the same locations, in order to study long period surface waves generated by the earthquakes and their dispersion in a period range of 26–1000 s (1–38 mHz).

2. Data

Seismic and gravity records were simultaneously conducted in three geodetic observatories (Fig. 1a; Table 1). Three REF-TEK 151B-120 seismometers were paired with two types of LaCoste&Romberg (LCR) spring gravimeters (ET and model G) at all those observatories.

Additionally one REF-TEK 151B-120 seismometer was co-located on the same pillar with the iGrav-027 superconducting gravimeter at the BG location (Fig. 1b). The LCR G-1036 has been operating at the BG Observatory since February 2012 (Dykowski and Sekowski, 2014). The LCR G-986 gravimeter was specially installed at the LA Observatory by the Warsaw University of Technology (WUT). The LCR ET-26 gravimeter has been

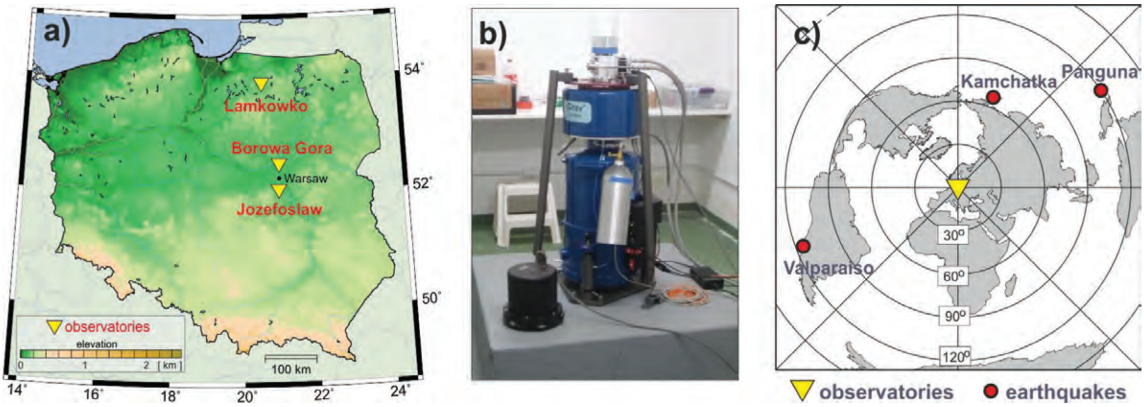

Fig. 1. (**a**) Location of observatories (yellow triangle); (**b**) picture of the iGrav-027 superconducting gravimeter (blue instrument) and the REF-TEK Observer 151B-120 seismometer (black instrument) during the operation time; (**c**) location of epicentres of analysed earthquakes (from USGS/NEIC Catalogue), the equidistant projection shows the true distances and backazimuths of the epicentres with respect to the Borowa Gora Observatory (BG)

operating at the JO location since 2002 (Bogusz, 2002) and the iGrav-027 superconducting gravimeter at the BG location since May 2016 (Sekowski et al., 2016). A summary of the instrumentation specification is presented in Table 2.

Table 1. Location of geodetic observatories

Observatories	Latitude [°]	Longitude [°]
Borowa Gora (BG)	52.4756 N	21.0359 E
Jozefoslaw (JO)	52.0978 N	21.0323 E
Lamkowko (LA)	53.8909 N	20.6710 E

Table 2. Type of gravimeter and seismometer used and their sampling rate

Location	Gravimeter	Seismometer
BG	iGrav-027/1 Hz	151B-120 B-941/100 Hz
BG	LCR G-1036/1.8 Hz	151B-120 B-953/100 Hz
JO	LCR ET-26/1 Hz	151B-120 B-954/100 Hz
LA	LCR G-0986/1.8 Hz	151B-120 B-904/100 Hz

During the test period from December 2016 to May 2017 several large teleseismic events were observed with well-formed surface waves. The recordings of three teleseismic earthquakes are analysed in the present paper. The location of their epicentres is shown in Fig. 1c while the information about origin time and coordinates, in Table 3. A few important issues due to variety of instrumentation used have been noted. First of all, there are different sampling rates of seismometers (100 Hz) and gravimeters (1 Hz or 1.8 Hz), different sensitivity levels and readout resolution of instruments. Some gravimeters also have a limited dynamic measurement range, which is clearly visible for the very sensitive iGrav-027. All seismometers and the iGrav-027 gravimeter were synchronized with GPS time, LCR G-1036 and ET-26 were synchronized via internet time, and G-986 had no time synchronization. Although there are papers about transfer function determination (e.g. Van Camp et al., 2000), there is no fully unified procedure for the evaluation of phase shifts in seismic frequencies for all gravity instrumentation.

Table 3. Origin time and coordinates of teleseismic earthquakes according to USGS/NEIC PDE Catalogue analysed in the study. Distances and backazimuths are calculated with respect to the Borowa Gora Observatory (BG)

Earthquake	Kamchatka	Valparaiso	Panguna
Date	2017-03-29	2017-04-24	2017-01-22
Time (UTC)	04:09:24.19	21:38:30.82	04:30:22
Latitude [°]	56.940 N	3.038 S	6.246 S
Longitude [°]	162.786 E	72.062 W	155.172 E
Depth [km]	17	28	135
Magnitude	6.6	6.9	7.9
Distance [km]	7384.97	13036.83	13405.81
Backazimuth [°]	21.66	250.79	55.75

3. Spectrograms of earthquakes

Gravimeter and seismometer recordings of surface waves need to be correctly pre-processed for further analyses. Gravimeter data were elaborated with the use of the TSoft software package (Van Camp and Vauterin, 2005) for the analysis of the time series and Earth tides. Data were unified to 1 s sampling intervals, and gaps below 10 s were filled by interpolation. Raw gravity records were corrected for the Earth tides using the Tamura potential catalogue (Tamura, 1987) with tidal parameters for the inelastic non-hydrostatic Earth model WDD (Dehant et al., 1999), ocean tidal loading (FES04) and barometric pressure with a standard coefficient of -3.0 nm/s^2/hPa. The remaining signal was high pass filtered with the cut off frequency at 6 cpd which removed all residual tidal and drift signals.

Seismometer data were detrended, the transfer function of the instrument was removed, the signal was differentiated to obtain acceleration units, and filtered with a zero-phase bandpass Butterworth filter with corner frequencies 0.001 Hz and 0.5 Hz. Finally, it was resampled to a 1 s sampling interval.

Initially the prepared data were evaluated with a noise analysis for site and instrument quality control checks. Figure 2 shows the smoothed vertical component of noise spectra at the BG location calculated for the iGrav-027 superconducting gravimeter, the LCR G-1036 spring gravimeter and the

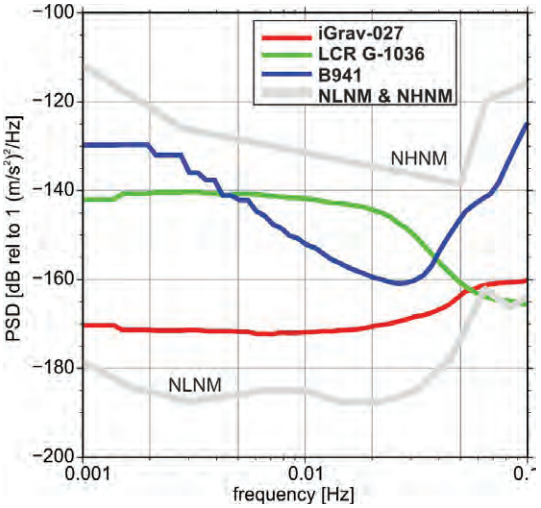

Fig. 2. Smoothed noise spectra of vertical component for all instruments at the BG location calculated by a routine used by McNamara et al. (2004) for five quiet days. The New Low (NLNM) and High (NHNM) Noise Models marked by a grey line are also shown for reference (Peterson, 1993)

151-120 B941 seismometer following the routine used by McNamara et al. (2004). For the analysis five quiet full days (24 hours) were selected: two in December 2016, two in February 2017 and one in April 2017. The signals were analysed in two-hours time segments overlapping by 50%. The mean power spectral density (PSD) values were finally averaged over a full octave at each central frequency while the one smooth PSD value on the frequency axis was measured every 1/8 of an octave. The iGrav-027 superconducting gravimeter shows the lowest noise level as compared with the New Low Noise Model (Peterson, 1993), while the noise level of LCR G-1036 sprint gravimeter and the 151-120 B941 seismometer are a little higher, but still below the New High Noise Model (Peterson, 1993).

Spectrograms of the M6.9 Valparaiso earthquake for selected instruments are shown in Fig. 3. All records including the seismometer were normalized with the maximum range of the event. The seismometer can distinguish a seismic signal slightly above its capabilities, e.g. up to a period of 150 s

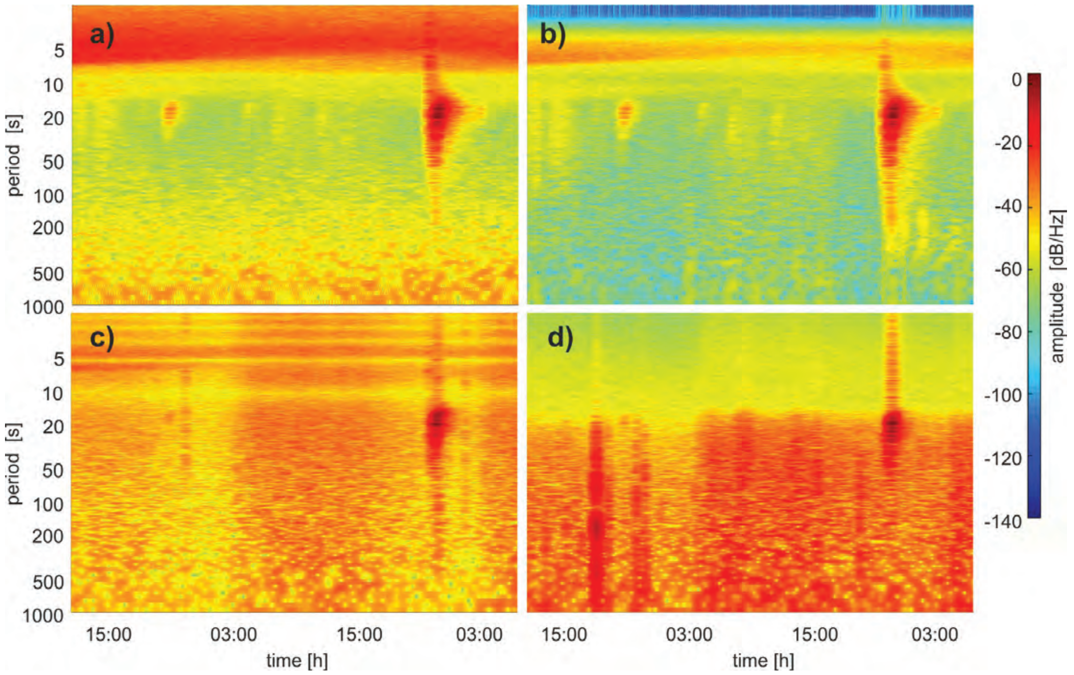

Fig. 3. Spectrograms of the M6.9 Valparaiso earthquake: (**a**) seismic station B941 (BG); (**b**) superconducting gravimeter iGrav-027 (BG); (**c**) spring gravimeter LCR G-986 (LA); (**d**) spring gravimeter LCR ET-26 (JO). Each record was normalized with the maximum amplitude range of the event

(Fig. 3a). An excellent signal-to-noise ratio of the iGrav-027 recordings up to the period of 1000 s can be observed and a seismic signal can be recognized up to periods of 300–400 s (Fig. 3b). The spectrograms of spring gravimeters (Fig. 3c,d) are more noisy than those for the seismometer and the iGrav-027. The ET-26 gravimeter is located very close to urban areas, and the G-986 and G-1036 gravimeters exhibit worse sensitivity and readout resolution.

4. Surface waves

Surface waves generated by large earthquakes can travel a long distance from the source to the receiver. They can interfere producing free oscillations of the Earth. The dispersion of surface waves is a well-known phenomenon; waves with different periods can travel with different group and phase velocities due to the Earth's structure.

4.1 Free oscillation detection

The power spectrum on residual 1 s sampled of the iGrav-027 gravimeter record was calculated from the period of 72 h after the M7.9 Panguna earthquake (Fig. 1c and Table 3). The instrument shows very good agreement with the selected spheroidal normal modes compared to the PREM model (Dziewonski and Anderson, 1981). The frequency range from 0.2 to 3.0 mHz is presented in Fig. 4. The vertical axis range is 0.13 nm/s^2 (13 nGal) with the noise level of 0.01 nm/s^2 (1 nGal). Selected associated modes are presented on the top of the graph with a grey vertical line representing the model frequency. The analysis of the above earthquake was also performed for the LCR gravimeters, but their records were too noisy for detection of normal modes. However, the LCR ET-26 had proved itself for this purpose in the past for earthquakes of larger magnitude (Rajner and Rogowski, 2011).

4.2 Non-constant relative resolution filtering

A classical method of Fourier transform based on multiple filtering is applied to analyse the dispersive records of the M6.6 Kamchatka earthquake (Fig. 1c and Table 3). Non-constant relative resolution filtering with the filter coefficient linearly dependent on a period was used (Dziewonski et al., 1969; Kolínský et al., 2011). Periods from 26 to 1000 s with 123 Gaussian filters were analysed. All monochromatic signals were normalized to their maximum amplitudes. Wave trains of near monochromatic signals of the iGrav-027 are clearly visible above the period of 200 s; while those of the seismometer disappear above the period of 160 s (Fig. 5).

4.3 Dispersion curves of group velocity

As symmetric Gaussian filters were applied to a generally asymmetric spectrum, the frequencies which prevail in the filtered spectra do not match the central frequencies of the filter. This was solved

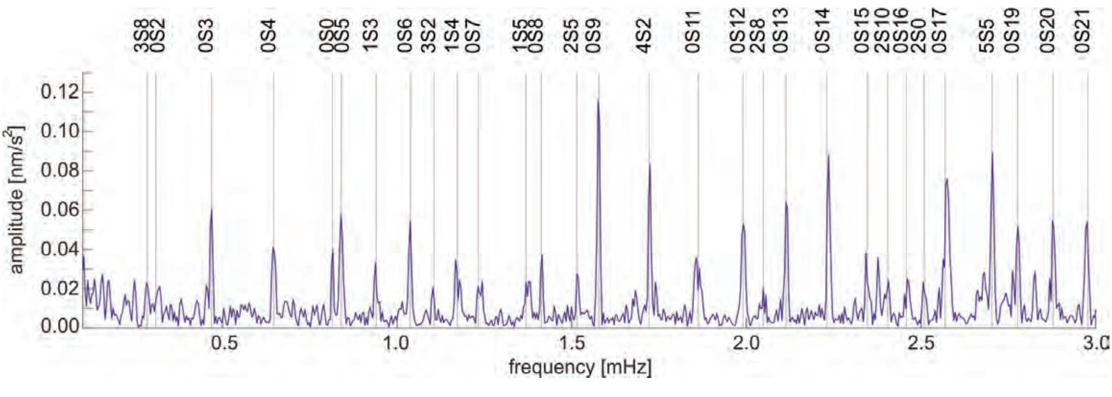

Fig. 4. Spheroidal modes detected by the iGrav-027 gravimeter after the M7.9 Panguna earthquake. Selected mode names (on the top) together with their theoretical frequencies (vertical lines) calculated from the PREM model (Dziewonski and Anderson, 1981) are also shown

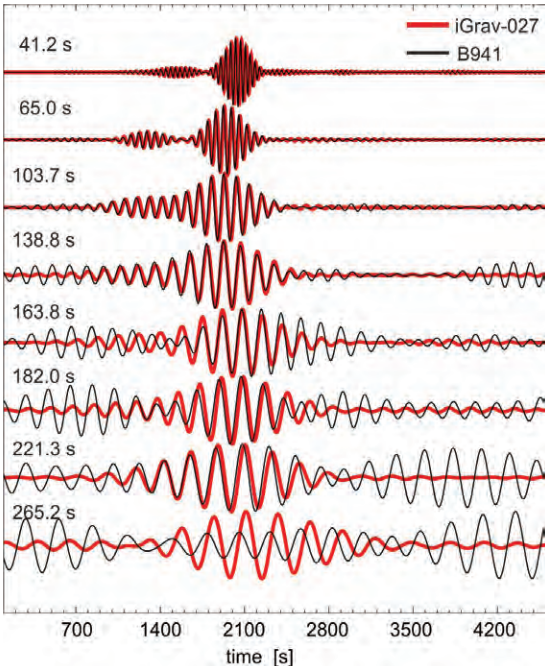

Fig. 5. Near monochromatic complex signal of the M6.6 Kamchatka earthquake recorded by the B941 seismometer (thin black line) and the iGrav-027 superconducting gravimeter (red line). Eight Gaussian filters of the central period given on the left were selected for this figure from more than one hundred filters used

by estimating the instantaneous frequency which was computed using the analytical signal corresponding to each filtered quasi-monochromatic signal (Levshin et al., 1989). The modulus of the analytical signal represents an envelope of the filtered signal. Normalized amplitudes of these envelopes of the M6.6 Kamchatka earthquake recorded by the B941 seismometer and the iGrav-027 gravimeter are shown by colour scale in Fig. 6. The loss of signal integrity above the period of 250 s for the B941 is clearly visible, while in the case of the iGrav-027 it continues up to the period of 400 s. Amplitudes of these envelopes were used to estimate the travel time of monochromatic signals for the fundamental mode. Kolínský et al. (2011) proposed to search the dispersion ridge of the fundamental mode by the criterion of continuity — among all ridges found in the spectrogram, the desired fundamental mode was selected to present a smooth curve regardless of the amplitudes.

After the selection of wave-groups corresponding to the fundamental mode, each of these harmonic signals was truncated by a window centred at the envelope maximum with cosine taper on both window sides. The group velocities were calculated dividing the epicentral distance by travel-time of selected envelope maxima for each period (Fig. 7). Group velocities of all gravimeters and seismometers match very well up to the period of 100 s. Above the period of 100 s, calculated group velocities are very scattered. Generally, for surface waves with longer periods the group velocity should increase, because generally seismic velocities increase with depth. Group velocities lower than 3.5 km/s for periods above 160 s should not be considered as reliable. Probably, also values received for the B904 and B953 for periods above 300 s are not valid, because that period range is far away from the resolution power of the REF-TEK seismometers.

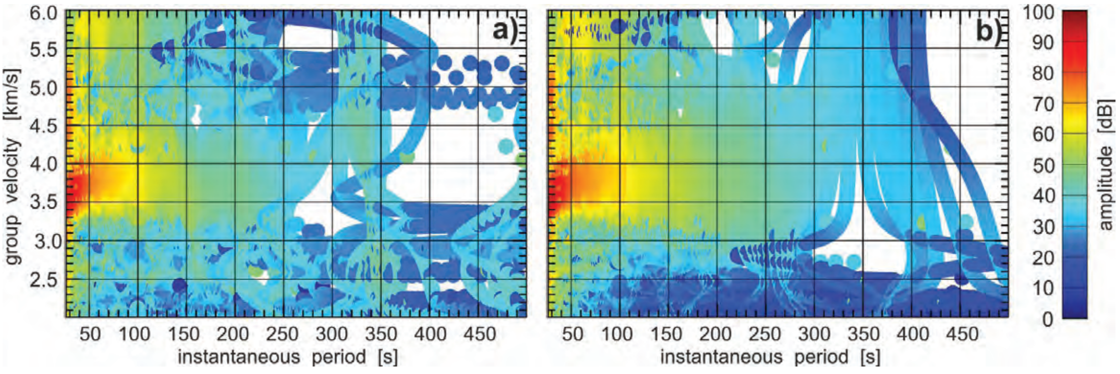

Fig. 6. Spectrogram of the M6.6 Kamchatka earthquake recorded by the B941 seismometer (**a**) and the iGrav-027 (**b**)

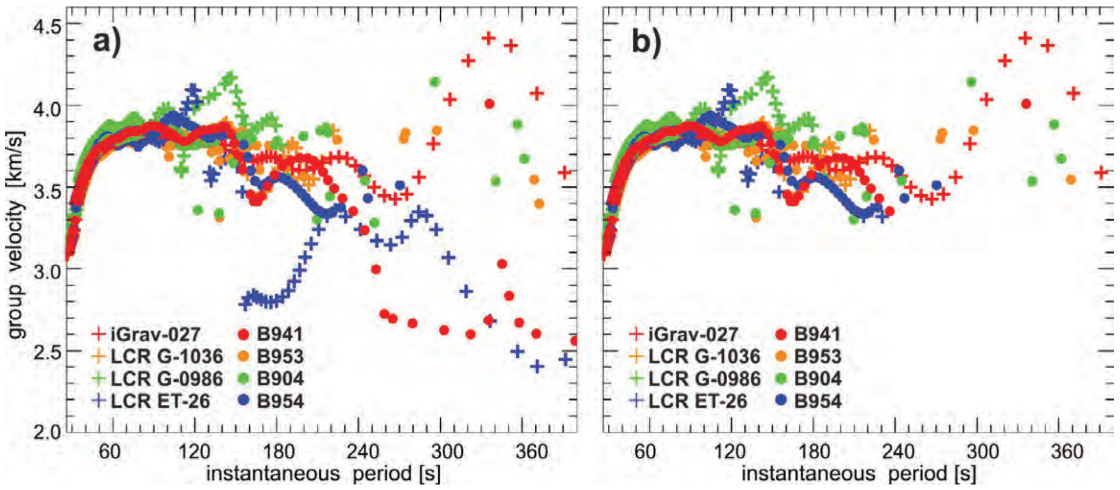

Fig. 7. (**a**) Dispersion curves of group velocities of the M6.6 Kamchatka earthquake. (**b**) Group velocities lower than 3.5 km/s for periods above 160 s should not be considered as reliable, so they are removed from the diagram

The open question is the validation of values of group velocities above the period of 300 s calculated from recordings of the iGrav-027 gravimeter. The analysis of more earthquakes is necessary to resolve this problem.

5. Conclusions

The presented seismic analysis of surface waves recorded by the gravimeters shows great potential. The standard procedure of pre-processing of the gravity signal used in Earth tides analysis is adequate to receive gravity records of earthquakes to which the standard seismic analysis can be applied. However, the remaining gravity signal should be high pass filtered with the cut off frequency at 6 cpd to remove all residual tidal and drift signals. The superconducting gravimeter iGrav-027 shows excellent consistency with the seismometer within the frequency range of a seismometer (up to 120 s periods). What is more, the iGrav-027 shows great potential for analysing periods above 120 s. Spring gravimeters also proved good consistency with the seismometer, yet their recordings need further analysis. Particularly the knowledge of the transfer function and/or a less noisy location can help to properly access their usefulness for seismic analysis. Generally, transfer functions for gravimeters are desirable to improve their usefulness for seismic analysis and gravimeter to seismometer comparisons.

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Rejestracje długookresowych powierzchniowych fal sejsmicznych za pomocą grawimetrów pływowych

Monika Wilde-Piórko
Instytut Geodezji i Kartografii, ul. Jacka Kaczmarskiego 27, 02-679, Warszawa
Tel.: +48 22 3291914, Fax: +48 22 3291950, E-mail: monika.wilde-piorko@igik.edu.pl
Przemysław Dykowski
Instytut Geodezji i Kartografii, ul. Jacka Kaczmarskiego 27, 02-679, Warszawa
Tel.: +48 22 3291914, Fax: +48 22 3291950, E-mail: przemyslaw.dykowski@igik.edu.pl
Marcin Polkowski
Wydział Fizyki, Uniwersytet Warszawski, ul. Pasteura 5, 02-093, Warszawa
Tel.: +48 22 5532006, E-mail: marcin.polkowski@igf.fuw.edu.pl
Tomasz Olszak
Wydział Geodezji i Kartografii, Politechnika Warszawska, Plac Politechniki 1, 00-661, Warszawa
Tel.: +48 22 2346042, Fax: +48 22 2341578, E-mail: tomasz.olszak@pw.edu.pl
Marek Grad
Wydział Fizyki, Uniwersytet Warszawski, ul. Pasteura 5, 02-093, Warszawa
Tel.: + 48 22 5532007, E-mail: mgrad@mimuw.edu.pl
Jan Kryński
Instytut Geodezji i Kartografii, ul. Jacka Kaczmarskiego 27, 02-679, Warszawa
Tel.: +48 22 3291904, Fax: +48 22 3291950, E-mail: jan.krynski@igik.edu.pl
Marcin Sękowski
Instytut Geodezji i Kartografii, ul. Jacka Kaczmarskiego 27, 02-679, Warszawa
Tel.: +48 22 3291905, Fax: +48 22 3291950, E-mail: marcin.sekowski@igik.edu.pl
Andrzej Krankowski
Centrum Diagnostyki Radiowej Środowiska Kosmicznego, Uniwersytet Warmińsko-Mazurski, ul. Prawocheńskiego 9, 10-719, Olsztyn
Tel.: +48 89 5233836, E-mail: kand@uwm.edu.pl
Marcin Rajner
Wydział Geodezji i Kartografii, Politechnika Warszawska, Plac Politechniki 1, 00-661, Warszawa;
obecnie w Onsala Space Observatory, Chalmers University of Technology, Gothenburg, Szwecja
Fax: +46 31 7725590, E-mail: marcin.rajner@pw.edu.pl

Streszczenie: Zjawiska sejsmiczne w pomiarach grawimetrycznych są traktowane jako zakłócenia i zwykle ich efekty są usuwane z zapisów grawimetrycznych. Jednakże, grawimetry dzięki swojej konstrukcji umożliwiają rejestrację sejsmicznych fal powierzchniowych o bardzo długich okresach. W przypadku grawimetru nadprzewodnikowego, możliwe jest zaobserwowanie fal powierzchniowych, generowanych przez trzęsienia ziemi, o okresach nawet do 400 s. Przeprowadzenie równoczesnych rejestracji sejsmicznych i grawimetrycznych instrumentami zlokalizowanymi w tym samym miejscu, powinno umożliwić przeanalizowanie szerszego zakresu częstości sygnału sejsmicznego niż w przypadku użycia tylko jednego typu instrumentu. W celu sprawdzenia prawdziwości powyższego stwierdzenia, 4 pary instrumentów: sejsmometrów i grawimetrów zostały zainstalowane w Polsce w trzech lokalizacjach, w Obserwatorium Geodezyjno-Geofizycznym Borowa Góra (BG), Obserwatorium Astronomiczno-Geodezyjnym Józefosław (JO) oraz Obserwatorium Satelitarnym Lamkówko (LA). W czasie projektu pilotażowego, trwającego od grudnia 2016 do maja 2017 roku, zarejestrowano kilka dużych trzęsień ziemi z dobrze wykształconymi falami powierzchniowymi. W pracy zaprezentowano krzywe dyspersji grupowych prędkości fal powierzchniowych, jak również okresy oscylacji swobodnych dla wybranych zjawisk. Korelacja szerokopasmowego sygnału sejsmicznego z sygnałem zarejestrowanym przez różnego typu grawimetry umożliwi analizę szumu grawimetrycznego w zakresie częstości pływowych instrumentów, jak i w zakresie mikrosejsmicznym.

Słowa kluczowe: grawimetr, sejsmometr, trzęsienie ziemi, krzywa dyspersji, fale powierzchniowe