EARTH FREE OSCILLATION MEASUREMENTS WITH LCR-ET 26 SPRING GRAVIMETER

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Abstract

After strong earthquakes the Earth oscillates with spheroidal and toroidal modes. The former cause gravity changes which can be detected with sensitive instruments. For this purpose we used continuous gravity measurements with LaCoste&Romberg Earth Tide spring gravimeter from Józefosław Observatory. Spectral analyses of records show significant peaks in normal mode frequencies. This peaks are above noise level and their eigenfrequencies are in good agreement with seismic theories. We show here some examples of free oscillations registration after particular earthquakes and stacking method as well. Some remarks concerning noise level in gravity measurements and data treatment are also given.

1 Introduction

It is well known that studying of free oscillation provides information and constraints of Earth's interior (Gilbert and Dziewoński, 1975; Resovsky and Ritzwoller, 1998; Park et al., 2005). In this works not only seismometers can be applied. The gravimeters are also used and are superior in the low-frequency band.

In this study we used tidal gravity measurements collected with *LC&R Earth Tide no. 26* spring gravimeter at Józefosław Observatory (Bogusz, 2002). This gravimeter serves in tidal and geodynamical studies (Rajner, 2010). In this paper we discuss sub-seismic and normal mode band where Earth free oscillations have their eigenfrequencies. Analysis of records after strong earthquakes shows that whole spectrum of spheroidal fundamental modes is exited and and their frequencies are in very good agreement with theoretical ones computed on the basis of Earth models.

It should be pointed out that nowadays the superconducting gravimeters are far superior than spring type instruments especially in low frequency band where the gravest modes are observed (Widmer-Schnidrig, 2003). Nevertheless spring gravimeters still can challenge them in subseismic band (Richer et al., 1995).

2 Data treatment

Classical tidal gravity analysis treats earthquake data as a serious disturbance which has to be corrected or removed in preprocessing stage. Moreover after removing outliers the data is usually decimated to hourly samples which is common procedure as there are no any significant tidal components with periods shorter then few hours. Consecutive we dispose all information in periods shorter than few hours.

In order to investigate in frequency band with periods from several minutes to hour we took raw data which are recorded every one minute. This data is 400s window length moving averaged. Consecutively we refer to this data as filtered data. Before spectral analysis we subtracted solid Earth tides from data. This was done with the previously determined gravimetric factors and phases for main tidal constituents (Rajner, 2010). This procedure removes also ocean tidal loading. For the pressure correction single admittance factor from tidal analysis (-3.45 $nm \cdot s^{-2} \cdot hPa^{-1}$) was used along with local barometric records.

2.1 Noise level

The Józefosław is located in Warsaw suburb area, near the fast growing settlement. This fact is well observed in quality of our records in terms of environmental noise. One could see in the spectrogram of gravity residuals (Fig. 1) long-term increase of noise with seasonal fluctuation. Barlik et al. (2010) gave some insight in noise level in Józefosław. They analysed detided and depressured gravity measurements in time-domain. This approach showed significant variation of noise in seasonal and daily time scale. The former is probably of geophysical origin (pelagic storms) and the latter is caused by intensive urbanization. More qualitative evaluation of the noise level is shown as power spectral densities (PSD) of whole multi-year data set in comparison to New Low Noise Model (NLNM) introduced by Peterson (1993). This model reflects the lowest noise from whole network of seismometers and is frequently used as reference level in instrument and site dependent noise evaluation. Fig. 2 shows very high noise level in data. We do not see any significant improvements in residuals after subtracting synthetic tides and pressure effect (diminishing of diurnal and semidiurnal tidal peaks is the only distinct change). This indicate that dominant source of noise in short-period spectrum is not connected with atmosphere. On the right graph we show PSD in normal mode band from long data set with PSD of one of the quiets day. This huge difference proves that this increased noise is due to anthropogenic origin. From comparison of PSD with NLNM one can conclude that Józefosław is very noisy site. We should mention that gravimeters, when located in quiet sites, are slightly above or even below NLNM, especially in low-frequency normal mode band (Banka and Crossley, 1999; Rosat et al., 2004).

The large noise is the most important delimitation when studying phenomena in subseismic frequency band. Anyway we show in subsequent paragraphs the despite of this disadvantages free oscillation still can be observed above noise floor.

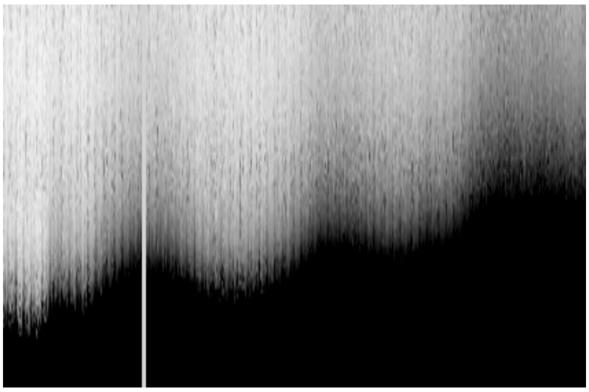

Fig. 1. Spectrogram of residuals of gravity measurements. Horizontal axis is time-span of 3.5 years (2006-2010) and vertical axis is frequency: 0-8 mHz.

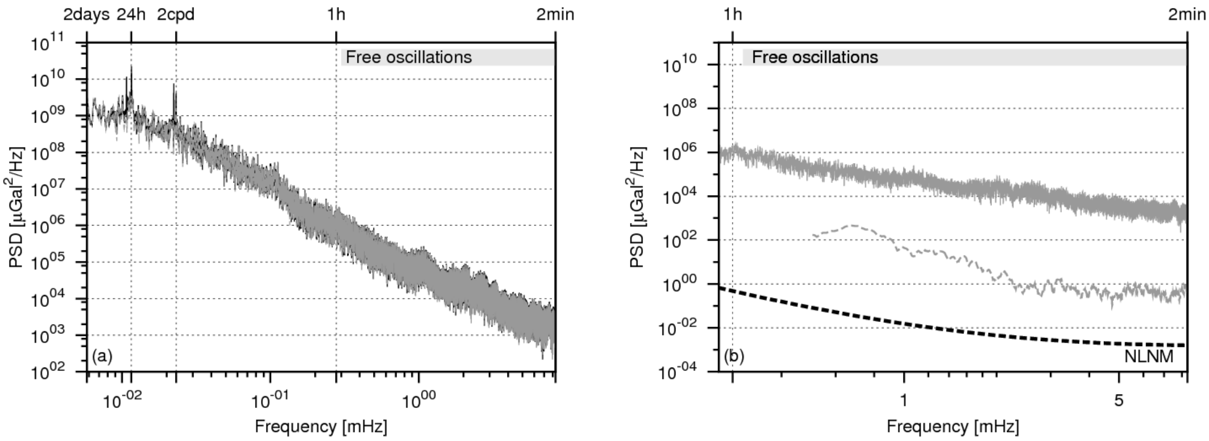

Fig. 2. (a) PSD of filtered gravity results (black) and residuals (de-tided and de-pressured time series, gray). (b) Blow-up of left figure with PSD of one very quiet day along NLNM. The free oscillation band is marked with horizontal bar.

3 Free oscillations

The main source of excitation of the Earth free oscillation are the strong earthquakes. A few examples are given in Fig. 3. During this event we see large amplitude of gravity variation. The motion of the Earth can be written as a sum of decaying harmonic (Masters and Widmer, 1995),

$$u(t) = \sum_k A_k \cos(\omega_k t + \phi_k) \cdot e^{-\frac{\omega_k t}{2Q_k}},$$

where A, ω, ϕ is amplitude, frequency and phase respectively and Q_k is “quality factor” of k-th constituent. This oscillation can be observed with horizontal and vertical seismometers as well as with gravimeters. The latter is restricted only to spheroidal modes, however toroidal ones also can appear in spectral analysis as a consequence of coupling with spheroidal ones, especially through Coriolis force. This oscillation can be observed for long time. In very quiet sites it is even possible to observe this modes during silent days when there was no source of excitation in solid Earth (Suda et al., 1998). This continuous vibration is believed to be of atmospheric or oceanic origin. Unfortunately we are unable to observe this so-called “hum” as this amplitudes are at nanogal level, much lower that our noise content.

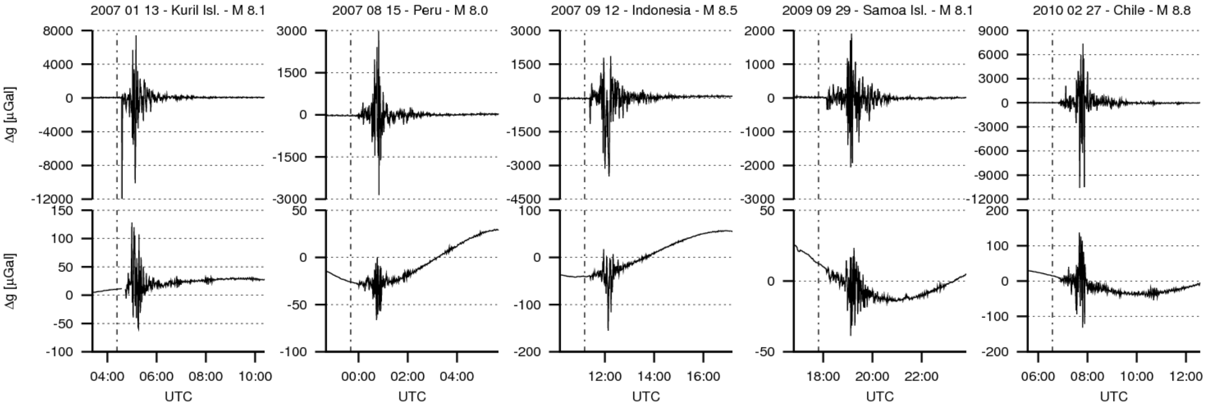

Fig. 3. Raw (top) and filtered (bottom) records of LCR ET26 gravimeter from great earthquakes. Vertical bars indicate start of the event. Note different scale on vertical axis.

The quick look at the spectrogram of residuals (see supplementary figures and enhanced on line text) shows that earthquakes are easily recognizable in the records.

Figure 4 shows an example of normal mode registration. The amplitude spectra are computed on the basis of almost 40 hours window a few hours after Chilean earthquake in 2010. All fundamental spheroidal modes are well resolved. We can see even fine structure of ${}_0S_7$ mode which is due coupling with nearby modes. We can easily connect every significant peak with theoretical prediction. The vertical bars in figures depict frequencies for spheroidal modes which were taken from Masters and Widmer (1995) for the PREM model (Dziewoński and Anderson, 1981). Due to high noise level we are not able to investigate in deviations in terms of lateral heterogeneity in mantle or splitting and coupling due to earth flattening and rotation (Zürn et al., 2000; Rosat et al., 2007). This example shows even the gravest modes like „breathing" and „football" mode (${}_0S_0$ and ${}_0S_2$ respectively).

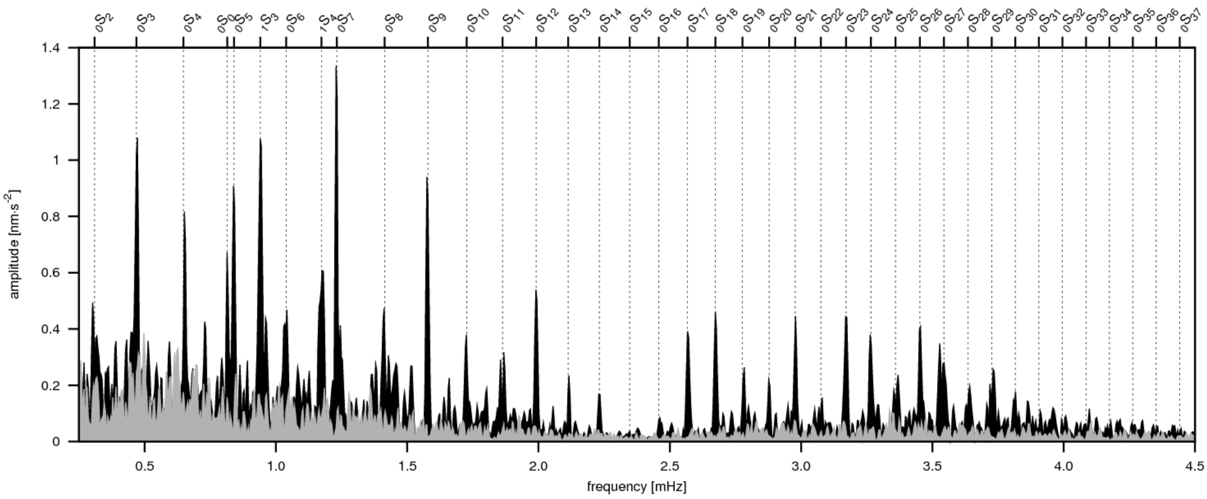

Fig. 4. Amplitude spectra from about 5h to 43h after Chilean (2010) earthquake (black). For comparison there is shown a spectra from window of similar length before earthquake which estimate noise level in measurements (gray).

3.1 Stacking spectra

Here we present also stacked spectra from several great earthquakes (shown in Fig. 3). The following formula was used,

$$A(f) = \left(\prod_{i=1...n} A(f)_i \right)^{1/n},$$

which yields simple geometrical mean. The amplitude of spectra (A) for specific frequency (f) is computed on the basis of n amplitudes from different earthquakes. This method confirms that spheroidal modes can be retrieved from our data. Here we also note increased noise below 2 mHz which is due to atmosphere and background noise as well. The stacked spectra are shown in Figure 5.

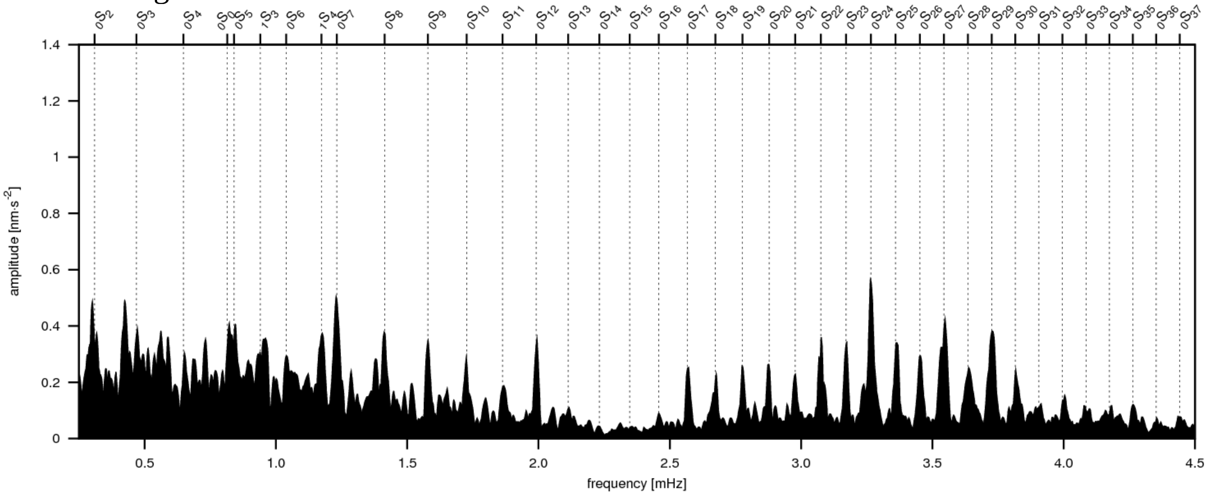

Fig. 5. Amplitude product spectra from selected great earthquakes

The increased noise in low frequencies is attributed to pressure induced gravity change. This effect is normally eliminated or reduced with single admittance atmospheric factor (Zürn and Widmer, 1995). Unfortunately this is not the case. We do not see any significant improvement in this band using atmospheric correction. We used admittance factor of -3.45 $nm \cdot s^{-2} \cdot hPa^{-1}$ which was obtained in previous tidal analysis (Rajner, 2010). Fig. 6 presents low frequency amplitude spectra with and without pressure correction. We do not found any significant change. Again we suspect the exceptionally high noise.

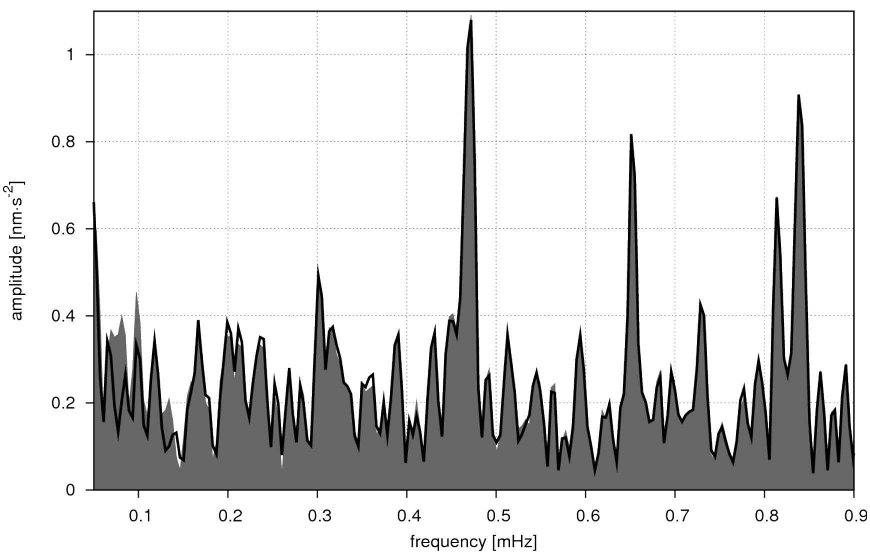

Fig. 6. Amplitude spectra from Chilean earthquake in low frequency normal mode band. The solid colors show results without pressure correction and the dark line shows results for records where atmospheric correction was applied. We used the factor -3.45 $nm \cdot s^{-2} \cdot hPa^{-1}$ from least square tidal analysis.

3.2 Quality factors

The quantitative evaluation of oscillations decaying is given here in terms of quality factor *Q*. We estimated spectra for single modes with moving window. Afterwards the exponential function was fitted and *Q* factor was estimated. Again this study is limited because modes are quickly lost in floor noise. Fig. 7 presents two examples of decaying amplitudes and fitted function for two modes. This examples are chosen arbitrarily. One should aware that for other modes we did not find such a good results.

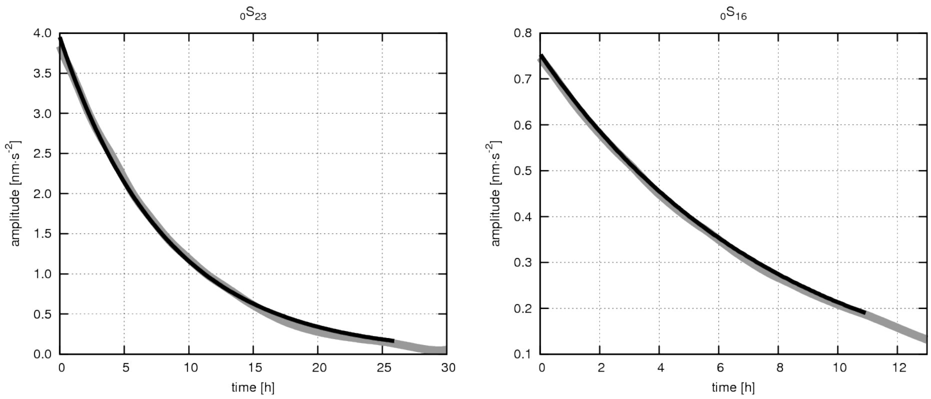

Fig. 7. Fitted exponential regression function for two modes. The estimated *Q* value for $_0S_{23}$ is 293 comparing to theoretical value of 259. For $_0S_{16}$ we found 284 when the expected from Earth model is 325 respectively. Applying standard pressure correction do not affect results significantly.

4 Conclusion

We confirmed that free modes are evident in *LCR ET* record. This small gravity changes which has amplitudes at $nm{\cdot}s^{-2}$ level are very well resolved. The eigenfrequencies are in good agreement with theoretical ones computed on the basis of Earth models. Nevertheless one should aware that these single results cannot be fully exploited in terms of knowledge of Earth's interior structure. We shows also that the noise level in Józefosław is very high and is the main limitation in precise gravity measurements in normal mode frequency band.

On-line material

For supplementary text with additional colored figures in high resolution, please see the website: www.geo.republika.pl/pub

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