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OCEAN TIDAL LOADING FROM THE GRAVITY MEASUREMENTS AT JÓZEFOSŁAW OBSERVATORY

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ABSTRACT. Ocean tidal loading is important source of disturbances in precise gravity measurements. Nowadays gravimeters reached unprecedented relative accuracy and loading signal can be observed also at large distances from the oceans.

In this paper theoretical calculations are compared with analysis made on the basis of observations collected in Józefosław Observatory during last three years with use of LCR-ET spring gravimeter. Long series of consisted data allowed for investigation in small subtle gravity signals. Subtracting body tides from tidal analysis results yields discrepancies of a few nm/s^2 for main tidal constituents which are in good agreement with computed ocean loading using most recent ocean models.

Keywords: ocean tidal loading, gravity measurements, LCR gravimeter

1. INTRODUCTION

The Astro-Geodetic Observatory of the Warsaw University of Technology in Józefosław (20 km south from the downtown of Warsaw) conducts various geodetic and geophysics researches (Rogowski et al., 2010). Comprehensive long series research of gravity field make it unique place in Poland. Since 2001 gravity laboratory is equipped with *LaCoste&Romberg Earth Tide no. 26* spring gravimeter with electrostatic feedback intended for continuous stationary measurements (Bogusz, 2002). This instrument serves mainly for determination of the local tidal parameters and investigation of the atmospheric influence on gravity. Since the end of 2005 the scale factor is systematically controlled through periodically taken (once a month) parallel measurements with the FG5 no. 230 ballistic gravimeter since end of 2005 (Rajner and Olszak, 2010). To avoid vibration and mitigate background noise influence, the gravimeter is placed on the concrete pillar, separated from building construction in thermal-stable chamber, six meters below ground level.

The recorded gravity signal varies in the range of few hundreds of μGal[1] mainly due the solid Earth tides which express the response of viscoelastic Earth to astronomical forces

[1] $1\,\mu Gal = 10\,nm/s^2$

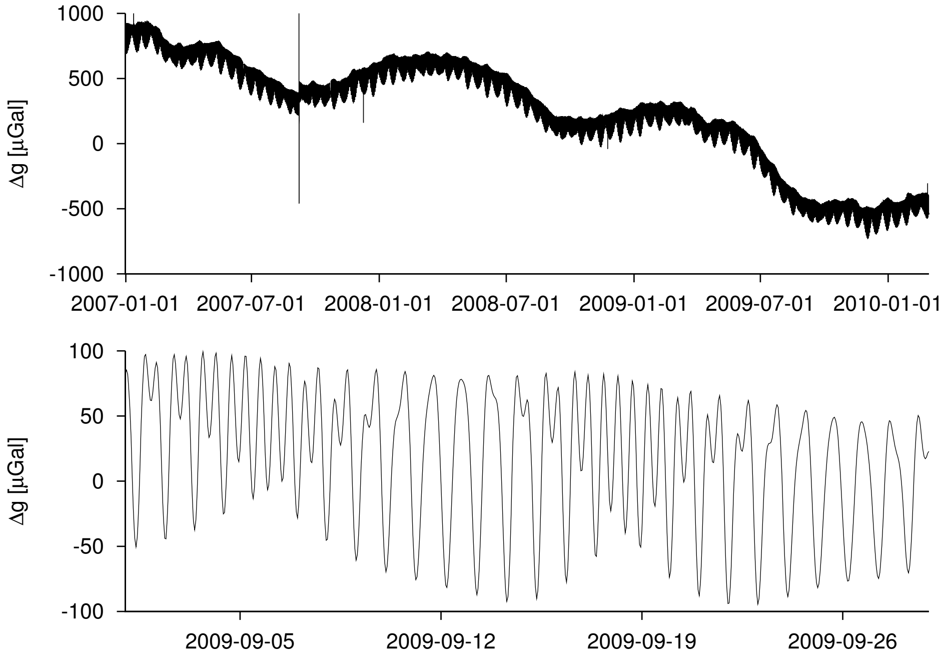

Fig. 1. Raw gravity measurements. Upper graph shows all data used in this study. Lower graph gives some details in an arbitrary chosen time window.

from the Moon, Sun and other external bodies. Other disturbances, reaching several μGal, are stemming from tectonic movements, geophysical fluids loading (atmosphere, hydrosphere), pole tide, ocean non-tidal and tidal loading and other effects (e.g Kroner and Jentzsch, 1999; van Dam et al., 2001; Boy and Hinderer, 2006). These phenomena have broad range of frequencies from minutes to years. Ocean tides has significant indirect influence on land gravity measurements, especially for the near-shore sites. This effect could reach up to 10% (Farrell, 1972; Melchior, 1978). Thus gravity measurements are often applied for constraining ocean tide models (Baker and Bos, 2003). Even for continental sites this effect is non-negliable emphasizing importance of an appropriate correction in the high precision gravity measurements.

This paper deals with determination of indirect ocean effect from continuous gravity measurements and comparing it with predicted one using different ocean tides models - case study of spring gravimeter recording in Józefosław. It is well known that the most precise continuous gravity measurements are presently obtained using the superconducting gravimeters (Hinderer and Crossley, 2004). Nevertheless, the spring gravimeters can challenge with them under the favourable conditions and with the carefulness in maintenance (Zürn et al., 1991).

2. GRAVITY RESULTS

The data discussed here are 1 minute samples collected during 2007-2009 period. Different origin perturbation in the considered data could be clearly seen (Fig. 1). During the preprocessing raw observations were de-gapped and de-spiked using *remove-restore* technique in `Tsoft` software (Van Camp and Vauterin, 2005). Before analysis the data was high-pass filtered (cut-off frequency 0.7 cycle per day) and decimated to hourly resolution. Spring-type gravimeters are known to suffer from large non-linear drift. Moreover, seasonal variation of drift is observed due to humidity changes, particularly in metal-type LCR

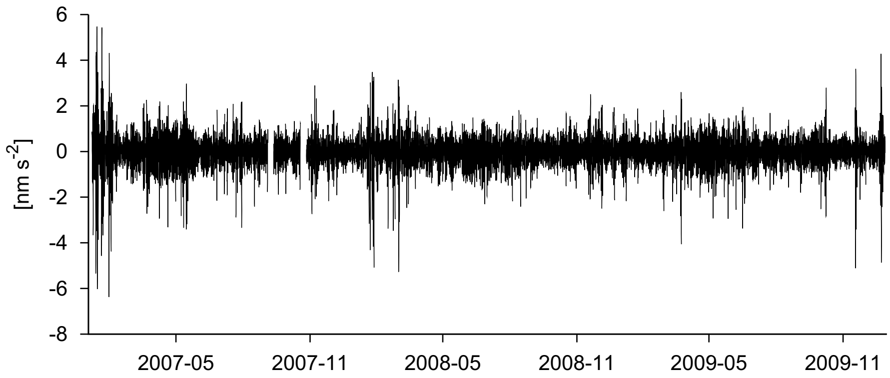

Fig. 2. Residual values of measurements

gravimeters (el Wahabi et al., 2000) what is the present case (Fig. 1). Therefore analysis was restricted to diurnal and semi-diurnal tidal bands. Long period tidal constituents were not determined. Fortunately, the long period components are of much less importance than the short period ones.

Tidal gravity parameters in diurnal and semi-diurnal frequency bands were computed using the international standard processing technique. Harmonic analysis was performed using the least-squares method with the `ETERNA` package (Wenzel, 1996) and utilizing a refined method developed by Chojnicki (1973). The HW95 tidal potential catalogue was applied (Hartmann and Wenzel, 1995). According to the common practice in gravity analysis, atmospheric pressure admittance was determined as a single regression factor using gravity residuals and barometer records. Consequently, empirical factor $-3.45\ nm\,s^{-2}\,hPa^{-1}$ was used.

The estimated tidal parameters (amplitude factors and phases) for main tidal constituents are shown in Table 1.[2] High quality of gravity records and auxiliary data were confirmed while checking residuals (Fig. 2) after fitting measurements to theoretical prediction. The standard deviation reached as much as $0.98\ nm\,s^{-2}$.

Contrary to the tilt or strain tidal observations in case of gravity, global models deduced for a stratified Earth are reliable and local geological structures has minor significance (Harrison, 1985). Keeping this in mind one could use the equation (Melchior, 1978),

$$\mathbf{B}(B,\beta) = \mathbf{A}(A_{theo}\cdot\delta,\varphi) - \mathbf{R}(A_{theo}\cdot\delta_{WD},0), \tag{1}$$

to subtract the body tide ($\mathbf{R}$) from the observation ($\mathbf{A}$). The reminder ($\mathbf{B}$) yields other geophysical phenomena which occur at the same tidal frequencies, such as the ocean tidal loading. In consequences we assume that ($\mathbf{B}$) yields observed ocean tidal loading. In eq. (1) the uppercase letters mean amplitude while the greek letters denote phases. Theoretical value of the astronomical tide (tidal forces for the rigid Earth, A_{th}) were computed on the basis of the tide generating potential catalogue, observed gravimetric factors (δ) and phases (φ) were estimated by the least-squares method. Theoretical amplitude factors were taken from the most commonly used *Wahr-Dehant* model (δ_{WD}, Wahr, 1981; Dehant, 1987). The phases of theoretical tide were set to zero as the viscosity of Earth do not introduce significant phase lag (Zschau, 1978). Table 1 contains all relevant results.

[2]In this paper negative values mean phase lag. Phases are referred to local meridian. This convention adopted by solid tides community is not necessary oceanographers meaning of phases

Tab. 1. Observed (**A**) tidal parameters (pressure correction applied), model (**R**) tidal parameters along with observed ocean loading (**B**) for main tidal constituent. Phases were omitted for the amplitudes lower than 1 $nm\,s^{-2}$.

			R	**A**					**B**	
$f\,[cpd]$	Tidal group code	$A_{theo}\,[\frac{nm}{s^2}]$	δ_{WD}	δ	m_δ	$m_\delta\,[\frac{nm}{s^2}]$	$\varphi\,[^\circ]$	$m_\varphi\,[^\circ]$	$B\,[\frac{nm}{s^2}]$	$\beta\,[^\circ]$
0.5014-0.9114	Q_1	57.7	1.1529	1.1480	0.0005	0.03	-0.069	0.024	0.3	
0.9114-0.9480	O_1	301.3	1.1527	1.1505	0.0001	0.03	0.087	0.005	0.8	
0.9480-0.9819	M_1	23.7	1.1521	1.1518	0.0014	0.03	0.062	0.071	0.0	
0.9819-0.9986	P_1	140.2	1.1472	1.1486	0.0002	0.03	0.129	0.012	0.4	
0.9986-1.0014	S_1	3.3	1.1438	1.1949	0.0152	0.05	-6.199	0.734	0.5	
1.0014-1.0041	K_1	423.6	1.1317	1.1361	0.0001	0.03	0.103	0.004	2.1	25
1.0041-1.0068	ψ_1	3.3	1.2374	1.2892	0.0100	0.03	1.805	0.447	0.2	
1.0068-1.0236	φ_1	6.0	1.1676	1.1663	0.0061	0.04	-0.015	0.298	0.0	
1.0236-1.0575	J_1	23.7	1.1547	1.1572	0.0011	0.03	0.038	0.056	0.1	
1.0575-1.4702	OO_1	13.0	1.1540	1.1530	0.0018	0.02	-0.005	0.087	0.0	
1.4702-1.8803	$2N_2$	8.7	1.1571	1.1683	0.0024	0.02	1.216	0.119	0.2	
1.8803-1.9141	N_2	54.3	1.1571	1.1774	0.0005	0.03	0.957	0.025	1.5	44
1.9141-1.9504	M_2	283.8	1.1571	1.1827	0.0001	0.03	0.642	0.005	8.2	27
1.9504-1.9843	L_2	8.0	1.1571	1.1964	0.0055	0.04	0.063	0.265	0.3	
1.9843-2.0027	S_2	132.0	1.1571	1.1749	0.0002	0.03	-0.197	0.011	2.4	-13
2.0027-2.4519	K_2	35.9	1.1571	1.1788	0.0007	0.02	0.077	0.033	0.8	
2.4519-7.0000	M_3M_6	3.4	1.0690	1.0826	0.0042	0.01	0.104	0.220	0.0	

f	frequency	cpd	cycle per day
A_{theo}	theoretical amplitude for rigid Earth	δ_{WD}	gravimetric factor in Wahr-Dehant model
δ	gravimetric factor	m_δ	gravimetric parameter determination error
φ	phase	m_φ	phase determination error

Residual part is given in the gravity units because the amplitude factor would have no meaning for this phenomena. Additionally phases for this vector are given only if amplitude is larger than 1 $nm\,s^{-2}$. This results clearly shows predominantly semi-diurnal characteristic of ocean loading for Józefosław. This is in agreement with the tides regime for North Atlantic and North Sea.

3. OCEAN LOADING

Gravity variation due to ocean tides are caused by (i) vertical displacement of the gravity station, (ii) gravitational potential changes owing to the redistribution of mass in the Earth and (iii) direct Newtonian attraction of the ocean tide mass (Farrell, 1972). The last effect is negliable for the continental sites.

Farrell (1972) computed Green's function for the Gutenberg-Bullen Earth model. Later Goad (1980) improved the numerical approach which is a commonly used method in the gravity loading computation. Pagiatakis (1990), Kaczorowski (1995, 1998) and other authors consequently improved the integrated Green's function by adding effects from Earth rotation, viscosity using modern Earth models. This refinements are not significant in the ocean loading determination for continental sites such as Józefosław case. Therefore we used those originally given by Farrell. Computation of the ocean loads done as convolution of an appropriate Green's function with model of the ocean tide distribution (Farrell, 1972),

$$\mathbf{L}(\mathbf{r}) = \rho \cdot \iint_{ocean} G(|\mathbf{r} - \mathbf{r}'|) \cdot \mathbf{H}(\mathbf{r}')\,\mathrm{d}A \tag{2}$$

where ρ means density of sea water, $G(|\mathbf{r} - \mathbf{r}'|)$ is gravitational Green's function, and $\mathbf{H}(\mathbf{r}')$ height of ocean element area dA, at position vector **r'**. This integration is practically done by a summation over gridded numerical ocean models. For this purpose `SPOTL` package (Agnew, 1997) as well as on-line ocean tide loading provider were applied.[3]

Presently dozens of global ocean tide models exist. These are of different origin and developed by different research group. They are constructed on the basis of in-situ tide gauge data only, or of altimetric data from `TOPEX/POSEIDON` mission while others utilize the hydrodynamic Laplace's equation. Modern ocean models combine the numerical computation constrained with all available data sets. Detailed description of these models can be found in the literature (e.g. Schum et al., 1997; Baker and Bos, 2003).

In this study we used several modern and commonly used models. Only some of them are listed in Tab. 2 but as it will be shown below they give similar results for the Józefosław site. The models shown are CSR4.0 (Eanes and Bettadpur, 1995), FES99, FES2004 (Le Provost et al., 1995), GOT4.7 (Ray, 1999), TPXO.7.2 (Egbert et al., 1994). The older model of Schwiderski (1980, SCHW) have been used as a standard for many years hence have been also included in the present work. One should keep in mind that this model could give erroneous outcome. Nevertheless, for continental sites it still gives reasonable results.

According to the notation proposed by Melchior (1978),

$$\mathbf{R}(R,0) = \mathbf{A}(A_{theo} \cdot \delta, \varphi) - \mathbf{L}(L,\lambda) - \mathbf{X}(X,\chi), \tag{3}$$

or equivalently,

$$\mathbf{X}(X,\chi) = \mathbf{B}(B,\beta) - \mathbf{L}(L,\lambda), \tag{4}$$

[3] `http://froste.oso.chalmers.se/loading/`

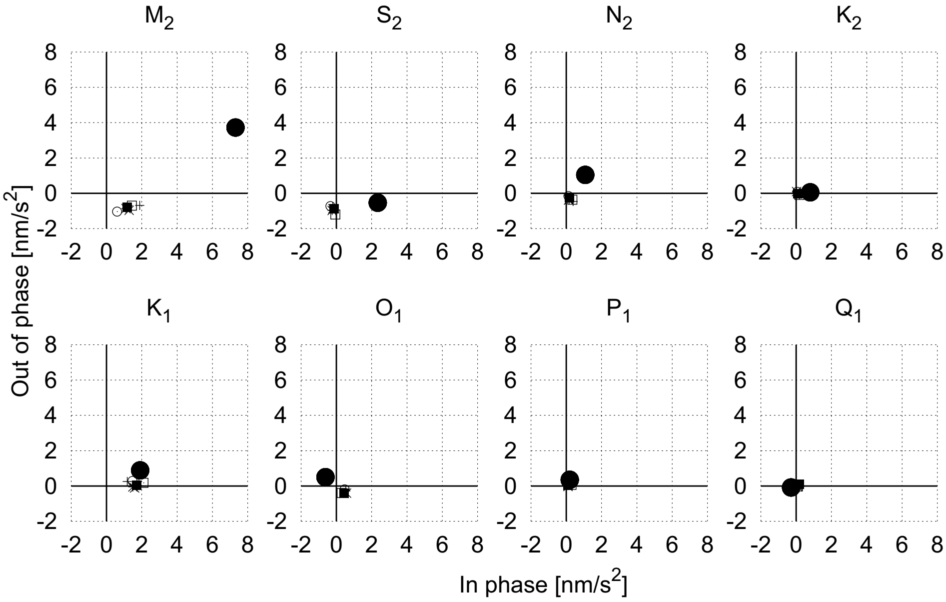

Fig. 3. Phasor plots for the main tidal constituents. Filled circle shows residual vector when the body tide was subtracted from the tidal analysis results (**B**). Other marks show residual vector with the ocean loading correction applied (**X**) for different ocean tide models (see Tab. 2). As the models give similar results, we do not differentiate them on the plot.

we computed residual values of observation (**X**) after subtracting body tide (**R**) and ocean loading effect (**L**). Table 2 presents numerical values of the estimated vector described above. One could observe improvement i.e. smaller values of the residual vector, when the loading correction was applied (**X**, Tab. 2) in comparison to the case when the observations were corrected for the body tides only (**B**, Tab. 1). The most convincing results are obtained for the M_2 constituent which is also the largest ocean loading component. The only exception was found for the K_1 term but the ocean loading correction do not worsen results significantly for this constituent and residual reach 2 $nm\,s^{-2}$ only. Moreover, as it was expected, different models are in very good agreement for the Józefosław site because the errors of ocean models are reduced at distances of several hundreds of kilometers from ocean. Such an agreement is not likely for the near-shore sites.

Fig. 3 shows phasor plots for the largest tidal constituent in Józefosław. Nevertheless, as the ocean loading effect is at the level of few $nm\,s^{-2}$, we conclude that the improvement is obvious. Some discrepancies may stem from the errors in calibration factor and instrumental phase lag determination, however further improvements are unlikely due to the gravimeter nominal accuracy.

4. CONCLUSION

The results presented in this paper indicate that even for site at a large distances from the ocean the indirect ocean influence on gravity measurements is significant. This effect is small (2 μGal peak to peak) nevertheless it has to be taken into account in the precise continuous or absolute gravity measurements.

The ocean loading computed by the use of ocean tide models agree very well with the observed signal after subtraction of the body tides and correction for the atmospheric effect. The residual values are significantly reduced when using the ocean tide loading

Tab. 2. Ocean loading in Józefosław for different ocean tide models (**L**) and the residual values (**X**) for main tidal constituents. Phases were omitted when the amplitudes were lower than 1 $nm\,s^{-2}$.

	Semidiurnal															
				M_2				**S_2**				**N_2**				**K_2**
	$L\,[\frac{nm}{s^2}]$	$\lambda\,[°]$	$X\,[\frac{nm}{s^2}]$	$\chi\,[°]$	$L\,[\frac{nm}{s^2}]$	$\lambda\,[°]$	$X\,[\frac{nm}{s^2}]$	$\chi\,[°]$	$L\,[\frac{nm}{s^2}]$	$\lambda\,[°]$	$X\,[\frac{nm}{s^2}]$	$\chi\,[°]$	$L\,[\frac{nm}{s^2}]$	$\lambda\,[°]$	$X\,[\frac{nm}{s^2}]$	$\chi\,[°]$
GOT4.7	7.7	37	1.4	-38	2.6	9	1.0		1.7	57	0.4		0.8	-5	0.1	
FES99	7.6	38	1.6	-37	2.6	8	0.9		1.7	56	0.4		0.7	4	0.1	
FES2004	7.0	40	2.0	-20	2.6	5	0.8		1.7	65	0.6		0.6	12	0.2	
CSR4.0	7.3	37	1.6	-26	2.5	16	1.2	-93	1.6	62	0.5		0.7	11	0.2	
TPXO.7.2	7.6	37	1.4	-34	2.5	9	0.9		1.6	55	0.3		0.7	7	0.1	
SCHW	8.2	36	1.2	-60	2.7	5	0.8		1.6	52	0.2		0.7	-4	0.1	
	Diurnal															
				K_1				**O_1**				**P_1**				**Q_1**
	$L\,[\frac{nm}{s^2}]$	$\lambda\,[°]$	$X\,[\frac{nm}{s^2}]$	$\chi\,[°]$	$L\,[\frac{nm}{s^2}]$	$\lambda\,[°]$	$X\,[\frac{nm}{s^2}]$	$\chi\,[°]$	$L\,[\frac{nm}{s^2}]$	$\lambda\,[°]$	$X\,[\frac{nm}{s^2}]$	$\chi\,[°]$	$L\,[\frac{nm}{s^2}]$	$\lambda\,[°]$	$X\,[\frac{nm}{s^2}]$	$\chi\,[°]$
GOT4.7	1.0	68	1.5	-2	1.4	139	0.6		0.3	76	0.1		0.4	-174	0.1	
FES99	1.0	74	1.6	-4	1.5	143	0.7		0.4	81	0.1		0.4	-160	0.1	
FES2004	0.9	41	1.2	12	1.4	146	0.6		0.3	41	0.2		0.4	-180	0.2	
CSR4.0	0.7	104	2.1	5	1.3	136	0.5		0.3	101	0.3		0.3	-169	0.1	
TPXO.7.2	0.8	75	1.7	2	1.4	139	0.6		0.3	78	0.1		0.4	-161	0.2	
SCHW	0.7	58	1.5	11	1.4	148	0.5		0.2	74	0.2		0.4	-158	0.1	

correction. Due to the large distance to ocean all the ocean tide models used here give similar results. Therefore the choice of the individual one as well as the selection of the Green's function is not of crucial importance for the computation results.

Some discrepancies could stem from calibration factor accuracy (0.1% relative accuracy required) or instrumental phase lag determination (accuracy 0.06° required). Rajner and Olszak (2010) did not get satisfactory result due to the insufficient length of absolute gravity measurements. They estimated the error of the calibration factor slightly below the 1% level. Nevertheless results of the present study confirmed quality of gravity data collected in Józefosław and its usefulness in subtle gravity signal detection for geophysics and geodetic studies.

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