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Tidal gravity observations in Eastern Siberia and along the Atlantic coast of France

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Abstract

Tidal gravity observations had been performed during more than 2 years (April 2001–September 2003) in Eastern Siberia with the LCR402. Simultaneously the gravimeter LCR1006 was recording in Chizé Observatory, not far from La Rochelle, in France. In France the station Chizé is the third of a network extending from “Aquitaine” (Ménesplet) to Brittany (Mordelles).

All stations are located far enough from the sea to avoid very local effects in ocean tide loading. The main goal of the project was to compare the observed tidal parameters with the modelled ones, using different ocean models, i.e.: SCW80, CSR3, FES95, ORI96, CSR4, FES02, GOT00 and NAO99.

A general conclusion is that the predictions using all the ocean tide models are in agreement within 0.2% for the area of Khabarovsk (Eastern Siberia). We may thus consider that a mean of all the oceanic models will have a precision better than 0.1%. It would thus be very difficult to improve the models using tidal gravity observations in this area.

However, for the Atlantic coast of France the tidal parameters derived from different ocean tide models can disagree at the level of 3%. The observed results are close to the predictions derived from CSR3, CSR4 and FES02 models.

Keywords: Tidal gravity observations; Ocean tides models; Tidal loading

1. Introduction

Tidal gravity observation is an efficient tool for the comparison of different ocean tide models by determining how the computed ocean tide loading effects fit to the observations. It is then possible to recommend one or several models for tidal gravity corrections.

Several authors made already such comparisons (Melchior and Francis, 1996; Baker and Bos, 2001, 2003). These studies were based on global or at least continental networks of tidal gravity observations. Here we want to study places where the ocean tides are large or complex. This is why we selected two regions: the Atlantic coast of France

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(Francis and Melchior, 1996) and the Russian territory along the Pacific Ocean. The observations were performed using LaCoste and Romberg (LCR) gravity meters.

In France the station Chizé ($\phi = 46.147°$N, $\lambda = 0.426°$E, $H = 70$ m), observed with LCR1006, is the third of a network extending from Aquitaine (Ménesplet; $\phi = 45.019°$N, $\lambda = 0.105°$E, $H = 60$ m) to Brittany (Mordelles; $\phi = 48.067°$N, $\lambda = 1.833°$W, $H = 32$ m). The stations are situated at a distance larger than 50 km from the coast in order to avoid local effects, which are not well represented by global models. The results of the two first stations, observed with LCR906, were presented at the 14th Symposium on Earth Tides (Ducarme et al., 2001).

Khabarovsk/Zabaikalskoe ($\phi = 47.630°$N, $\lambda = 134.747°$E, $H = 65$ m) is the first station of a planned network in the far east of Russia. It is located far from the Pacific coast in order to become a reference station for further studies. The observations have been performed with LCR402.

The gravimeters are equipped with a MVR feedback system (van Ruymbeke et al., 1995) providing a frequency-modulated signal. The frequency is counted during 1 min by a microprocessor controlled MICRODAS system (van Ruymbeke et al., 1995). The data are stored on computer. Temperature and pressure were recorded in the room using an EDAS system (van Ruymbeke et al., 1999). The preprocessing is made using the interactive Tsoft software (Van Camp and Vauterin, 2005). The data are decimated to 1-h ordinates for a classical tidal analysis using the ETERNA3.4 software (ANALYZE, Wenzel, 1994) or the VAV03 program (Venedikov et al., 2003).

For the main tidal waves we determine the amplitude A and the phase difference α, i.e. the vector $\mathbf{A}(A, \alpha)$, with respect to the astronomical tide of amplitude A_{th}. The amplitude factor δ is defined as the ratio A/A_{th} (Melchior, 1983).

We build the modelled tidal factors based on the body tide amplitude $\mathbf{R}(R = A_{th}\delta_{DDW}, 0)$ computed from the DDW99 non-hydrostatic inelastic model (Dehant et al., 1999) and the ocean load vector $\mathbf{L}(L, \lambda)$ computed from eight different ocean tides models. The modelled vector $\mathbf{A}_m(A_m, \alpha_m)$ is given as

$$\mathbf{A}_m = \mathbf{R} + \mathbf{L}$$

The modelled amplitude factor δ_m is simply given by the ratio $\mathbf{A}_m/A_{th}$.

We can directly compare the vectors $\mathbf{A}$ and $\mathbf{A}_m$ to evaluate the adequacy of the corresponding ocean tides model.

As early as 1979, Schwiderski constructed ocean tide models (SCW80, Schwiderski, 1980) by the method of hydrodynamic interpolation introducing tide gauge data on coast lines and islands. He provided for the first time with the relatively complete and basic ocean tidal model for loading correction in geodesy and geophysics. Since 1994, a series of new ocean tidal models have been developed based on the Topex/Poseidon (T/P) satellite altimeter data. In the first generation of models we consider here CSR3 (Eanes and Bettadpur, 1995), FES95 (Le Provost et al., 1994) and ORI96 (Matsumoto et al., 1995). These models were extensively tested in Shum et al. (1997). Most of the more recent ones used hereafter represent updates of the previous ones: CSR4, NAO99, GOT00 and FES02.

The tidal loading vector $\mathbf{L}$ was evaluated by performing a convolution integral between the ocean tide models and the load Green's function computed by Farrell (1972). For the first generation of models the effect of the imperfect mass conservation is corrected on the basis of the code developed by Moens (Melchior et al., 1980). Following Zahran (2000) suggestion we computed also mean tidal loadings for different combinations of models.

2. Calibration of the gravimeters

At Zabaikalskoe, the calibrations of LCR402 records were performed manually using the micrometer and the usual ramp procedure by steps of 10 dial divisions (van Ruymbeke, 1998). A similar method had been used with LCR906 (Ducarme et al., 2001) at the stations in France.

At Chizé, the LCR1006 is equipped of a step motor driving the micrometric screw and was programmed to perform automatic calibrations. This calibration technique has been described in van Ruymbeke et al. (2001). A major failure of the computer occurred, at the beginning of October 2002. The automatic calibration system was put out of use and recording interrupted until December 2002. In 2003 the calibrations were performed manually, using the usual ramp procedure, because the automatic calibration system was put out of use by a computer failure.

Smoothed calibration tables were built to follow the sensitivity changes between the calibrations (Ducarme, 1970). As usual (Ducarme et al., 2001; Wahabi et al., 2001), long-term sensitivity fluctuations are found at level of 1% in stable environmental conditions and up to a few percent in perturbed stations such as Zabaikalskoe or even Chizé.

In Brussels the results of the tidal gravity observation are normalised on $\delta_{O_1} = 1.1530$ (ICET Data Bank DB92, Melchior, 1994).

For LCR1006, a 136-day record in Brussels gave for O_1 (van Ruymbeke et al., 2001)

$$\delta = 1.1560 \pm .0016, \qquad \alpha = -0.113^\circ \pm 0.078^\circ$$

A normalisation factor of 0.99740 had to be applied and in Chizé the analysis was thus performed using the modified calibration factor $K = 1.02817\,\mathrm{nm\,s^{-2}}/0.01$ dial in place of the maker's value $1.03085\,\mathrm{nm\,s^{-2}}/0.01$ dial.

At Zabaikalskoe, the analysis was performed using the maker's calibration factor $K = 1.06188\,\mathrm{nm\,s^{-2}}/0.01$ dial, as a 35-day record of LCR402 at Brussels, just before the installation at Zabaikalskoe, gave for O_1:

$$\delta = 1.1540 \pm 0.0040, \qquad \alpha = 0.061^\circ \pm 0.195^\circ$$

No normalisation factor was thus required.

The calibration factor of LCR906 was checked in Ménesplet against the SCINTREX CG3M S265. A 72-day tidal record of this instrument gave for M_2:

$$\delta = 1.1879 \pm 0.0015, \qquad \alpha = 6.10^\circ \pm 0.07^\circ$$

in agreement with LCR906.

$$\delta = 1.1896 \pm 0.0004, \qquad \alpha = 6.02^\circ \pm 0.02^\circ$$

It was thus not necessary to apply a normalisation factor on LCR906.

3. Station Chizé

The station Chizé is located 70 km from the Atlantic coast of France in the “Deux Sévres” Department, Region “Poitou-Charente”. The gravimeter LCR1006 is installed in an old army bunker on a pillar going 4 m deep. The room was not thermostatised and temperature was thus not stable. As usual (Ducarme et al., 2001) a large annual wave is present in the drift of the instrument.

As seen from Table 1, two different analysis methods ETERNA and VAV03 agree within the rms errors. However the rms error on the unit weight, which was $4.8\,\mathrm{nm\,s^{-2}}$ in Brussels, reaches $14.5\,\mathrm{nm\,s^{-2}}$ in Chizé. The records are somewhat noisier during the winter months and the automatic rejection procedure of VAV03 is not really improving the results. We can suspect short period temperature variations in the room as the main source of perturbation.

4. Comparison of the results along the Atlantic coast of France

The ocean tides regime is predominantly semi-diurnal in the Atlantic Ocean. The ocean loading is thus quite low in the diurnal band but large in the semi-diurnal one.

In Table 2 we present the tidal factors modelled using the DDW99 non-hydrostatic inelastic model and eight different ocean tides models. For M_2 the largest discrepancies between models are observed in Mordelles (3% for the

Table 1
Summary of tidal analysis results at Chizé

LCR1006	O_1 310.45[a]		M_2 360.60[a]		M_2/O_1
	δ	α	δ	α	
ETERNA	1.1378 ±0.0032	−0.53 ±0.16	1.1949 ±0.0018	6.22 ±0.09	1.050 ±0.004
VAV03	1.1357 ±0.0034	−0.50 ±0.18	1.1950 ±0.0015	6.24 ±0.07	1.052 ±0.004
Elim 7.5%	1.1360 ±0.0027	−0.67 ±0.14	1.1949 ±0.0014	6.16 ±0.07	1.052 ±0.003

δ, Amplitude factors; α; phase difference.
[a] Th. ampl. ($\mathrm{nm\,s^{-2}}$).

Table 2
Modelled tidal factors along the Atlantic coast of France based on the DDW99 non-hydrostatic inelastic model

	Ménesplet			Chizé			Mordelles		
	O_1[a] δ_m (α_m)	M_2[a] δ_m (α_m)	M_2/O_1[a]	O_1[a] δ_m (α_m)	M_2[a] δ_m (α_m)	M_2/O_1[a]	O_1[a] δ_m (α_m)	M_2[a] δ_m (α_m)	M_2/O_1[a]
SCW80	1.1461 (−0.21)	1.1875 (5.89)	1.036	1.1463 (−0.16)	1.1921 (5.51)	1.040	1.1434 (−0.20)	1.2224 (7.48)	1.069
CSR3	1.1440 (−0.29)	1.1882 (6.60)	1.039	1.1440 (−0.25)	1.1944 (6.14)	1.044	1.1397 (−0.30)	1.2482 (8.28)	1.095
FES95	1.1481 (−0.14)	1.1840 (5.70)	1.031	1.1481 (−0.10)	1.1901 (5.34)	1.037	1.1445 (−0.14)	1.2353 (7.18)	1.079
ORI96	1.1457 (−0.08)	1.1841 (5.70)	1.043	1.1458 (−0.04)	1.1895 (5.34)	1.038	1.1423 (−0.05)	1.2293 (7.25)	1.076
CSR4	1.1456 (−0.18)	1.1893 (6.66)	1.038	1.1458 (−0.14)	1.1952 (6.18)	1.043	1.1419 (−0.17)	1.2478 (8.20)	1.093
NAO99	1.1459 (−0.09)	1.1880 (5.87)	1.037	1.1460 (−0.05)	1.1946 (5.43)	1.042	1.1418 (−0.07)	1.2596 (6.93)	1.103
GOT00	1.1465 (−0.14)	1.1869 (5.72)	1.035	1.1466 (−0.11)	1.1928 (5.37)	1.040	1.1431 (−0.16)	1.2384 (7.21)	1.083
FES02	1.1454 (−0.13)	1.1889 (5.78)	1.038	1.1455 (−0.10)	1.1956 (5.45)	1.044	1.1420 (−0.14)	1.2493 (7.37)	1.094

δ_m, Amplitude factors; α_m, phase difference.
[a] Wave.

modelled amplitude factors and more than 1° for the modelled phase differences). In such conditions, our tidal gravity observations can provide useful constrains in the semi-diurnal band in order to select the best oceanic model in this area.

We can consider two groups of models, the older models until 1996 (SCW80, CSR3, FES95 and ORI96) on one hand and the new generation of models (CSR4, NAO99, GOT00 and FES02) on the other. Mean modelled tidal amplitude factors and phase differences are presented in Table 3 for the older models (mean *a*), for the models of second generation (mean *b*) and for all the models (global).

At Chizé, it is striking that the M_2/O_1 ratio given in Table 2 are much lower than the value deduced from the observations, although this ratio is independent from the calibration. This discrepancy is obviously due to a too low amplitude factor of O_1, see Table 1. We can thus only draw conclusions for the semi-diurnal ocean loading effects.

Among the different ocean tide models the best fit with the observed results was obtained using CSR3, CSR4 or FES02 with less than 0.05% in amplitude and 0.1° in phase. Even the modelled M_2/O_1 ratio stays within the rms error of the observed value. The largest discrepancy is given by ORI96 and FES95. The global mean model in Table 3 gives a mean value close to the observed amplitude factor but with a discrepancy of 0.5° in phase.

In the semi-diurnal band there is a systematic increase of the modelled amplitude factors and phase differences between Ménesplet and Mordelles (Table 2). This fact is confirmed by the observations (Table 3). In each of these stations the best agreement between modelling and observations is obtained with CSR3, CSR4 or FES02. It is especially striking in Mordelles for the ratio M_2/O_1. The results of “mean *b*” fits better the observations than “mean *a*”. To get a better fit of LCR906 results it should be necessary to reduce the calibration factor of 0.2% in Ménesplet but to increase it by the same quantity in Mordelles. A systematic calibration error is thus unlikely. The observed phase differences agree very well with the modelled ones in Ménesplet and Mordelles.

5. Station Khabarovsk/Zabaikalskoe

The LCR402 was installed in a geophysical observatory located at Zabaikalskoe, not far from Khabarovsk city, some 300 km away from the Pacific Ocean. The gravimeter LCR402 was installed in a small building and the room was thermostatised by means of an electrical heating system. However, in winter time there are frequent power interruptions and in summer the external temperature can rise above the reference temperature of the thermostat. The result is a rather erratic behaviour of the drift and many interruptions when the instrument was going out of scale. Altogether 450 days were used for tidal analysis.

As seen from Table 4 there is a systematic difference of 1% between amplitude factors computed for summer and winter months for the diurnal wave O_1. However, this effect remains within the associated rms error. The discrepancy is slightly larger with VAV03. The main concern is the temperature. During the summer months the external temperature was higher than the thermostat setting and diurnal temperature variations close to 0.5 °C were recorded in the room. This asymmetry between the cold and hot season was confirmed by the fact that the coefficient of efficiency of the temperature computed inside the tidal bands reaches 48 ± 4 nm/(s^{-2} K^{-1}) from May to September and only 23 ± 2 nm/(s^{-2} K^{-1})

Table 3
Comparison of observed and modelled tidal factors along the Atlantic coast of France

	Ménesplet LCR906			Chizé LCR1006			Mordelles LCR906		
	O_1[a] δ (α)	M_2[a] δ (α)	M_2/O_1[a]	O_1[a] δ (α)	M_2[a] δ (α)	M_2/O_1[a]	O_1[a] δ (α)	M_2[a] δ (α)	M_2/O_1[a]
Observed factors	1.1490 ± 0.0018	1.1896 ± 0.0004	1.035 ± 0.002	1.1378 ± 0.0032	1.1949 ± 0.0018	1.050 ± 0.004	1.1389 ± 0.0006	1.2459 ± 0.0005	1.094 ± 0.001
Observed phases	(-0.24 ± 0.09)	(6.02 ± 0.02)		(-0.53 ± 0.16)	(6.22 ± 0.09)		(-0.11 ± 0.03)	(7.60 ± 0.02)	
Models									
Mean *a*	1.1460 (−0.18)	1.1859 (5.97)	1.035	1.1460 (−0.14)	1.1915 (5.58)	1.040	1.1425 (−0.17)	1.2338 (7.55)	1.080
Mean *b*	1.1458 (−0.13)	1.1882 (6.01)	1.037	1.1460 (−0.10)	1.1945 (5.61)	1.042	1.1422 (−0.13)	1.2487 (7.43)	1.093
Global	1.1459 (−0.16)	1.1871 (5.99)	1.036	1.1460 (−0.12)	1.1930 (5.60)	1.041	1.1423 (−0.15)	1.2412 (7.49)	1.087

δ,, Amplitude factors; α, phase difference (degree); mean *a*: SCW80, CSR3, FES95, ORI96; mean *b*: CSR4, FES02, GOT00, NAO99.
[a] Wave.

Table 4
Summary of tidal analysis results at Zabaikalskoe

	O_1 [a] 309.357 [b]		K_1 [a] 435.077 [b]		M_2 [a] 341.255 [b]		M_2/O_1 [a]
	δ	α	δ	α	δ	α	
ETERNA							
Winter	1.1862 ± 0.0074	0.785 ± 0.355			1.1726 ± 0.0062	0.668 ± 0.301	0.9885 ± 0.0096
Summer	1.1969 ± 0.0084	0.724 ± 0.402			1.1760 ± 0.0039	0.004 ± 0.186	0.9825 ± 0.0092
Global	1.1924 ± 0.0054	0.719 ± 0.262	1.16076 ± 0.00422	0.191 ± 0.208	1.1745 ± 0.0036	0.340 ± 0.175	0.9850 ± 0.0065
VAV03							
Winter	1.1840 ± 0.0084	0.750 ± 0.406			1.1734 ± 0.0049	0.680 ± 0.239	0.9911 ± 0.0094
Summer	1.2003 ± 0.0069	0.180 ± 0.330			1.1687 ± 0.0043	−0.028 ± 0.210	0.9736 ± 0.0081
Global	1.1915 ± 0.0058	0.568 ± 0.278	1.16753 ± 0.00458	0.529 ± 0.230	1.1721 ± 0.0033	0.358 ± 0.161	0.9837 ± 0.0066

δ: Amplitude factors, α: phase difference.
[a] Wave.
[b] Th. ampl. (nm s^{-2}).

Table 5
Modelled tidal factors at Zabaikalskoe based on the DDW99 non-hydrostatic inelastic model

	O_1[a]		K_1[a]		M_2[a]		M_2/O_1[a]
	δ_m	α_m	δ_m	α_m	δ	α_m	
SCW80	1.1868	0.770	1.1639	0.193	1.1736	0.585	0.9889
CSR3	1.1841	1.048	1.1639	0.288	1.1724	0.467	0.9901
FES95	1.1822	0.727	1.1633	0.232	1.1706	0.254	0.9902
ORI96	1.1839	0.921	1.1631	0.279	1.1755	0.489	0.9929
CSR4	1.1823	0.885	1.1624	0.333	1.1696	0.437	0.9887
FES02	1.1842	0.936	1.1607	0.428	1.1712	0.272	0.9890
GOT00	1.1822	0.858	1.1621	0.288	1.1722	0.469	0.9915
NAO99	1.1852	0.832	1.1638	0.301	1.1734	0.325	0.9900

δ_m: Amplitude factors, α_m: phase difference.
[a] Wave.

from October to March, while the pressure coefficient remains stable around $-10\,\mathrm{nm/(s^{-2}\,hPa^{-1})}$. Surprisingly the winter result seems more reliable.

The ocean tides regime is mixed diurnal and semi-diurnal in the Pacific Ocean close to Kamchatka, Kouriles and Sakhalin Islands. In Table 5 we present the tidal factors for Zabaikalskoe, modelled using the DDW99 non-hydrostatic inelastic model and eight different ocean tide models.

Here also we consider two groups of models (Table 6): the older models and the second generation ones. If we exclude SCW80, the maximum discrepancy is 0.3% for the modelled amplitude factors and 0.3° for the modelled phase differences of O_1. For M_2 wave these values are 0.4% and 0.25°, respectively. For M_2, ORI96 and CSR4 are slightly offset for what concerns the amplitude factor and the FES models predict a lower phase than the others.

Given the rms errors on the analysis results it is unlikely that our observations can really discriminate the best model for this area.

A drastic difference appears in Table 4 on the ratio M_2/O_1, which reaches in summer a low value of 0.983 (ETERNA) or even 0.974 (VAV03), while in winter we get 0.989 (ETERNA) or 0.990 (VAV03), very close to the modelled one. The discrepancy between the VAV03 and ETERNA3.4 analysis results is low except during the summer period. One should consider only the winter period results for O_1. However K_1, which is only separable using a complete year, is reasonable. The phase difference on M_2 is very low for summer data. It is another indication that we should consider the winter data set as more reliable. However, if we consider the associated rms errors the global analysis result fits very well most of the models.

Table 6
Comparison of observed and modelled tidal factors at Zabaikalskoe

	O_1[a]		K_1[a]		M_2[a]		M_2/O_1[a]
	δ	α	δ	α	δ	α	
Mean observed							
Global	1.1924 ± 0.0054	0.719 ± 0.262	1.1608 ± 0.0042	0.191 ± 0.208	1.1745 ± 0.0036	0.340 ± 0.175	0.9850 ± 0.0065
Winter	1.1862 ± 0.0074	0.785 ± 0.355			1.1726 ± 0.0062	0.668 ± 0.301	0.9885 ± 0.0096
	δ_m	α_m	δ_m	α_m	δ_m	α_m	
Mean models							
Mean *a*	1.1842	0.866	1.1636	0.248	1.1730	0.449	0.9905
Mean *b*	1.1835	0.878	1.1623	0.338	1.1716	0.376	0.9899
All models	1.1839	0.872	1.1629	0.293	1.1723	0.412	0.9902

δ: Amplitude factors, α: phase difference; mean observed: mean of ETERNA and VAV03; mean *a*: SCW80, CSR3, FES95, ORI96; mean *b*: CSR4, FES02, GOT00, NAO99.
[a] Wave.

Table 7
Results for the minor waves P_1 (144 nm s^{-2}) and S_2 (159 nm s^{-2}) at Zabaikalskoe

	Obs.	SCW80	CSR3	FES95	ORI96	CSR4	FES02	GOT00	NAO99	Mean
P_1										
δ	1.178	1.176	1.179	1.179	1.180	1.177	1.175	1.177	1.177	1.1775
ε_δ	±0.014									
α	0.37	0.17	0.34	0.22	0.25	0.35	0.49	0.32	0.26	0.30
ε_α	±0.66									
S_2										
δ	1.183	1.186	1.180	1.188	1.182	1.182	1.182	1.183	1.182	1.183
ε_δ	±0.008									
α	0.47	0.22	0.12	−0.08	−0.13	0.24	0.15	0.12	0.06	0.09
ε_α	±0.40									

δ: Amplitude factors, α phase difference; ε: rms error.

In the global analysis we were able to separate also two minor constituents P_1 and S_2 (Table 7). The results are in agreement with the modelling based on the different oceanic models. The dispersion around the global mean of all the oceanic models is here 0.2% on P_1 and S_2. For S_2, it is larger if we consider only the four older models.

6. Conclusions

Due to large diurnal perturbations of the tidal records, it was not possible to determine accurate tidal parameters in the diurnal band at Chizé station. However, we can derive interesting conclusions from the results of the three stations installed on the Atlantic coast of France. Generally speaking, CSR3, CSR4 and FES02 provide the best prediction in the three stations. We thus recommend the use of these models for the computation of ocean loading effects in this area.

For the area of Khabarovsk (Eastern Siberia), a general conclusion is that all the oceanic models are in agreement within 0.2% or 0.1° for O_1 or M_2. The dispersion is slightly reduced for the more recent models. We may thus consider that a tidal prediction based on the mean of all the oceanic models will have a precision better than 0.1%. It would thus be very difficult to improve the models using tidal gravity observations at this station. However, it is a good test of the reliability of the tidal gravity observations performed with LCR402 and it is planned to install another station closer to the Pacific ocean e.g. in Sakhalin Island, to have larger ocean loading effects and eventually discriminate the different models.

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