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On the comparison of tidal gravity parameters with tidal models in central Europe

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ABSTRACT

Two accurately calibrated superconducting gravimeters (SGs) provide high quality tidal gravity records in three central European stations: C025 in Vienna and at Conrad observatory (A) and OSG050 in Pecný (CZ). To correct the tidal gravity factors from ocean loading effects we compared the load vectors from different ocean tides models (OTMs) computed with different software: OLFG/OLMP by the Free Ocean Tides Loading Provider (FLP), ICET and NLOADF. Even with the recent OTMs the mass conservation is critical but the methods used to correct the mass imbalance agree within 0.1 nm/s^2. Although the different software agrees, FLP probably provides more accurate computations as this software has been optimised. For our final computation we used the mean load vector computed by FLP for 8 OTMs (CSR4, NAO99, GOT00, TPX07, FES04, DTU10, EOT11a and HAMTIDE). The corrected tidal factors of the 3 stations agree better than 0.04% in amplitude and 0.02° in phase. Considering the weighted mean of the three stations we get for O1 $\delta_c = 1.1535 \pm 0.0001$, for K1 $\delta_c = 1.1352 \pm 0.0003$ and for M2 $\delta_c = 1.1621 \pm 0.0003$. These values confirm previous ones obtained with 16 European stations. The theoretical body tides model DDW99/NH provides the best agreement for M2 (1.1620) and MATH01/NH for O1 (1.1540) and K1 (1.1350). The largest discrepancy is for O1 (0.05%). The corrected phase α_c does not differ significantly from zero except for K1 and S2. The calibrations of the two SG's are consistent within 0.025% and agree with Strasbourg results within 0.05%.

1. Introduction

The tidal gravity observations obtained since 1997 with Superconducting Gravimeters (SGs, Hinderer et al., 2007) participating at the Global Geodynamics Project (GGP, Crossley et al., 1999) are of unprecedented quality. The data have been used very early to study the ocean tides loading effects and the quasi-elastic reaction of the Earth to tidal forces (Baker and Bos, 2001, 2003; Ducarme and Sun, 2001; Boy et al., 2003; Bos and Baker, 2005; Ducarme et al., 2007). More recently tidal gravity observations of 16 stations including 9 SGs within the West European Network (WEN) have been analyzed (Ducarme et al., 2009). This part of the world is interesting for such studies as the ocean tides loading is weak, especially for the diurnal waves O1 and K1 (Baker and Bos, 2003). The error on the mean corrected tidal factors for the principal tidal waves O1, K1 and M2 was lower than 0.05% in amplitude and 0.01° in phase. For O1 and M2 the best agreement was found with the DDW99/NH (Dehant et al., 1999) model. For K1 the MAT01/NH (Mathews, 2001) is closer because the Free Core Nutation (FCN) period is more precisely introduced in this model. No relevant difference between the results of the SG's and of the spring gravimeters was found in Ducarme et al. (2009). However the dispersion of the individual stations was still rather large: some stations were offset by 0.2% and the standard deviation on the global set reached 0.1%. Moreover a mean residual phase advance on O1 and M2 could be interpreted as a 5 s excess correction of the instrumental time lags. One can suspect two main sources of errors associated to these results:

- The calibration of several SGs was only provisional (Baker and Bos, 2003);
- A 5 s error on the instrumental time lag correction being unlikely one can suspect systematic effects on the tidal loading corrections. There are indeed contradictions between results obtained with different ocean tides models.

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To improve the precision it is thus necessary to reduce calibration errors below 0.05% and to reach a precision of the tidal loading evaluation better than 0.15 nm/s^2 for waves reaching 300 nm/s^2 amplitude as it is the case for O1 and M2 at mid-latitudes. The central European stations meet our requirements for the following reasons:

- Three stations equipped with modern SGs, recently recalibrated (Meurers, 2012, Palinkas and Kostelecký, 2010) by comparison with absolute FG5 gravimeters (Francis, 1997), are present in this area: Pecný, CZ (PE: 49.9137 N, 14.7856E, 534.58 m a.s.l.), Vienna, A (VI: 48.2489°N, 16.3565°E, 192.74 m a.s.l.) and Conrad observatory, A (CO: 47.9283°N, 15.8598°E, 1044.12 m a.s.l.). The claimed uncertainties of calibrations are below 0.05%.
- Central European stations are less influenced by ocean tides loading (OTL) than the West European stations. M2 loading is decreased by 50% reaching 10 nm/s^2 only. As no oceanic water masses are present within a radius of several hundred kilometres, the OTL computations are simplified (Section 3) and we should get more reliably corrected tidal factors.

The data of SG C025 at Vienna (4278 days) and Conrad observatory (1877 days) were pre-processed at the Department of Meteorology and Geophysics, University of Vienna, Austria and decimated to 1 h before analysis according to ETERNA software with PERTSEV59 filter (Wenzel, 1996). The data of OSG050 at Pecný (1920 days) were pre-processed at the Research Institute of Geodesy, Topography and Cartography, Geodetic Observatory Pecný, Czech Republic, decimated to 10 min and analysed by ETERNA software with filter N10M10M2. The RMS errors on the unit weight are 0.463 nm/s^2 at Vienna, 0.601 nm/s^2 at Conrad and 0.617 nm/s^2 at Pecný. The applied decimation filters have negligible amplitude attenuation within the D and SD frequency band. The tidal analysis results do not depend on the choice of the applied high pass filters used in ETERNA as the filter characteristics are considered accordingly. Local pressure correction was used as a standard and global pressure correction was tested later on.

2. Computation of corrected tidal factors

All the tidal gravity observations have been reprocessed using the ETERNA tidal analysis software (Wenzel, 1996, 1997) to determine, for a given tidal wave, the observed amplitude A and phase difference α with respect to the astronomical tide, i.e. the vector $\mathbf{A} = (A, \alpha)$ in polar coordinates. The amplitude factor δ is defined as the ratio A/A_{th} (Melchior, 1983) with respect to the astronomical tide of amplitude A_{th}. Several models of the Earth response to the tidal forces have been developed in the last ten years (Dehant et al., 1999; Mathews, 2001). The tidal gravity observation vector $\mathbf{A}(\delta A_{th}, \alpha)$ can be compared with the body tides models $\mathbf{R}(\delta_{th} A_{th}, 0)$, if we subtract the tidal loading effects $\mathbf{L}(L, \lambda)$ to get the so called "corrected" tidal parameters: amplitude factor δ_c and phase difference α_c.

$$\mathbf{Ac}(\delta_c A_{th}, \alpha_c) = \mathbf{A}(\delta A_{th}, \alpha) - \mathbf{L}(L, \lambda) \approx \mathbf{R}(\delta_{th} A_{th}, 0) \quad (1)$$

The tidal loading vector $\mathbf{L}$ (Jentzsch, 1997), which takes into account the direct attraction of the water masses, the flexion of the ground and the associated change of potential, is generally evaluated by performing a convolution integral between the ocean tide models and the load Green's function computed by Farrell (Farrell, 1972).

The error on the corrected tidal gravimetric factors depends on the error of the tidal gravity observations on one side and of the ocean tides loading computation on the other.

With SGs the formal errors of the main tidal waves (O1, K1 and M2), deduced from the least squares adjustment, are lower than five parts per billion for the amplitude factors and 0.002° for the phase differences and are thus completely negligible compared to the other error sources. The error on $\mathbf{A}$ is directly linked to the calibration of the instrument in amplitude for A and in phase for α. However δ_c depends also on the astronomical tidal amplitude A_{th} used in the analysis program. For the main tidal waves there is a slight time dependence of A_{th} (0.01% in 25 years for the diurnal waves). It is a reason why older tidal developments including CTE505 (Cartwright and Edden, 1973) should no more be used. Since Tamura (1987) this dependence is taken into account. A comparison between results obtained using Tamura (1987) and Hartmann and Wenzel, 1995 tidal developments does not show differences at the level of 0.01% on δ_c and 0.01° on α_c.

The computed load vector $\mathbf{L}$ is directly involved in Eq. (1). We tried to improve its determination compared to Ducarme et al., 2009:

- In the 2009 study only the ICET program (Melchior et al., 1980), with or without conservation of the water masses, was applied to compute $\mathbf{L}$. We used two additional loading providers: the Institute of Geodesy and Geophysics, CAS, based on the SPOTL version of program NLOADF (NLF, Agnew, 1997) and the Free Ocean Tide Loading Provider site (FLP, Bos and Scherneck, http://holt.oso.chalmers.se/loading) based on the software OLFG/OLMP (Scherneck, 1991; Bos and Baker, 2005; Penna et al., 2008).
- We decided also to avoid the use of different versions of the same Ocean Tides Model (OTM) e.g. FES95, FES99, FES02 and FES04, or CSR3 and CSR4. We decided to discard the oldest models. We finish with a set of 5 models: CSR4, NAO99, GOT00, TPX07 and FES04. We also selected 3 additional recent OTM, available from FLP only: DTU10, EOT11a and HAMTIDE, which have been used for Vienna and Conrad (Meurers, 2012). A description of these models can be found in Kim and Shibuya (2013).

3. Comparison between different ocean tide loading computations

Bos and Baker (2005) presented an extended study of the error sources affecting the ocean tide loading (OTL) computations. They developed a specific software called CARGA for that purpose. The authors showed that, by choosing an appropriate interpolation of the Green's function, a refined integration mesh and a high-resolution coastline, a "numerical accuracy" of better than 1% can be obtained for European stations. It corresponds to a precision between 0.1 and 0.15 nm/s^2 for M2. Most of the tidal loading errors are proportional to the tidal amplitudes. It is obvious for the values adopted for the density of the water (between 1025 and 1035 kg/m^3), but the maximum effect of the latter on the computed OTL is only 1%. Errors on the coast lines definition will also produce larger errors in regions of large tidal amplitude.

The results can also diverge by the choice of the Earth models used to evaluate the response of the Earth to tidal loading by means of the Green's functions (Jentzsch, 1997). As a rule of the thumb one can state that an anomaly at a given depth under the load will affect OTL at twice the corresponding distance from the load. As the Earth's models differ mainly in the upper layers, the discrepancies will essentially affect the results for coastal stations. Moreover, as the OTL signal in gravity is still observed at great distance, the influence of the water masses close to the station is generally only a fraction of the global elastic effect. It is not true for tilt, and OTL has been proposed as a tool for the study of lithosphere structures (Zschau, 1976), the penetrating depth being half the distance to the load. For our Central European stations we can safely use any of the commonly used Green's functions. The Green's functions based on a Gutenberg-Bullen Earth model are used by the three software codes in this study.

There is an important source of error, which does not depend on the tidal amplitudes: the conservation of the tidal water masses during one tidal cycle. For a given tidal constituent an OTM provides an evaluation of the amplitude and phase of the tidal vector on a regular grid. To check the mass conservation it is necessary to compute the sum of all these tidal vectors multiplied by the surface area of the mesh cell. It is never exactly equal to zero and this mass defect should be corrected. The origin of the problem can be found in numerical integration errors during the computation procedure but also in tidal flow through the borders of the model area, which are not perfectly following the coast or, in the earlier models, were ignoring some adjacent sea or bay. The magnitude of the mass imbalance has strongly decreased with the increasing accuracy of the OTMs, which followed the introduction of satellite altimetry. For M2 the effect is ten times smaller with FES04 using a $0.125^\circ \times 0.125^\circ$ grid than with the old Schwiderski (1980) model with a coarse $1^\circ \times 1^\circ$ grid. To force the conservation of mass principle on the OTM, a layer of tidal water of constant thickness and a certain phase lag can be subtracted from the OTM (Agnew, 1983). According to Bos and Baker (2005), the computed equivalent water layer thickness (up to 1 mm for O1 as well as for M2) is associated with load vectors between 0.1 and 0.4 nm/s^2 at Strasbourg. Melchior et al. (1980) conserve the water mass by subtracting at each mesh cell an amount of mass (water thickness multiplied by the cell size) that is proportional to the amplitude of the tidal constituent at that location. The total mass subtracted from the model is equal to the mass imbalance. The consistency of the two methods will be discussed hereafter.

Bos and Baker (2005) performed also a comparison of different OTL software, including OLFG/OLMP and SPOTL, but the ICET program was not considered. A direct comparison in this study is thus useful.

Fig. 1 displays a general comparison of all the load vector computations for the waves O1, K1 and M2 at station Pecný. The scale is the same for each graph. The phase is local and the lags are negative following the Earth Tides convention. The error bars on the mean of 5 OTMs (CSR4, NAO99, GOT00, TPX07 and FES04) correspond to the 95% confidence interval. There is a close agreement between the mean OTL computed with ICET and NLF, without conservation of the water masses. The same holds for the evaluations by ICETmc and FLP, which introduce a mass conservation algorithm. However there are systematic differences of the order of 0.2 nm/s^2 between the two approaches. For a 300 nm/s^2 wave such as O1 or M2 it corresponds to discrepancies in the corrected tidal factors of the order of 0.06% in amplitude and 0.03° in phase. Such an error is too large compared to the level of precision reached by SGs. It is thus necessary to select the most accurate mass conservation technique. The results obtained with ICETmc (correction proportional to tidal amplitude) and FLP (constant layer) agree within 0.1 nm/s^2, fulfilling our precision requirement of 0.15 nm/s^2. It is noteworthy that the dispersion of the different OTMs is largely reduced when the mass conservation is used (ICETmc and FLP). It confirms that the treatment including the mass conservation effect is improving the results.

As expected the dispersion is smaller for O1 than for M2, due to the large difference in tidal loading amplitude, correlated with

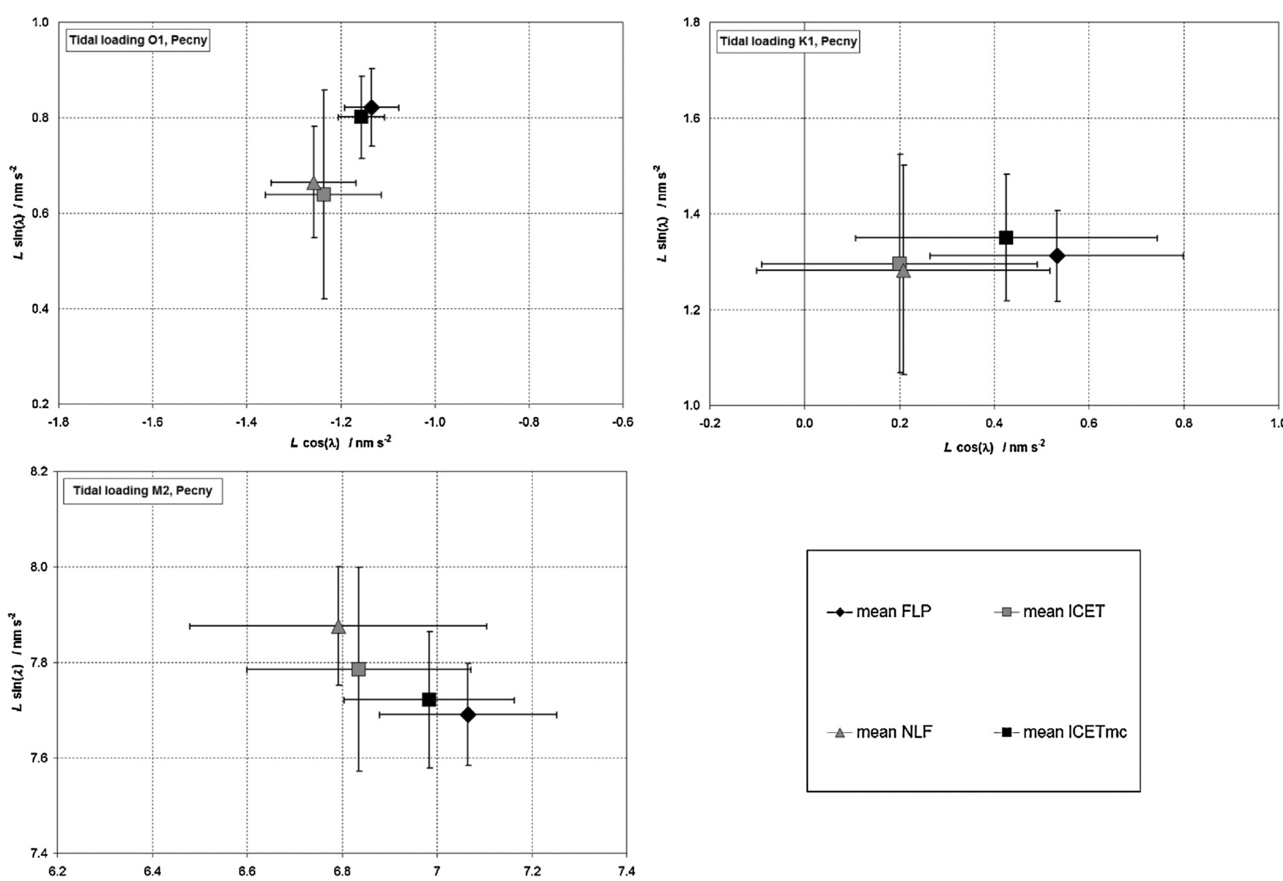

Fig. 1. Comparison of different OTL vectors at station Pecný: ICET, NLF (without mass correction) FLP, ICETmc (with mass correction). The mean values correspond to the mean of 5 OTMs: CSR4, FES04, GOT00, NAO99 and TPX07. Error bars correspond to a 95% confidence interval.

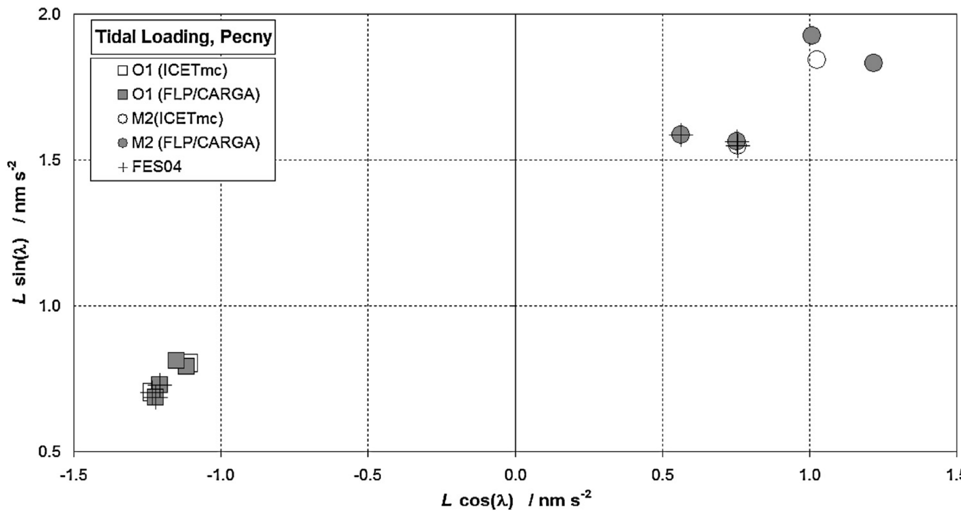

Fig. 2. Comparison of FLP/CARGA and ICETmc tidal load vectors for O1 and M2 at station Pecný. Two OTMs are used: FES04 and TPX07. To adjust the scale a constant vector (8,8) is subtracted from M2 tidal load vector.

the ocean tide amplitude in the Atlantic Ocean. A surprising point is the large scattering of results for the in phase component of K1, which is not reduced when the mass correction is applied. Kim and Shibuya (2013, Fig. 3b) observed a similar scattering at the station Strasbourg.

Fig. 2 presents an additional comparison of the ICETmc results for O1 and M2 with computations by FLP and the CARGA program (M. Bos, personal communication) for the highest resolution models TPX07 and FES04. ICETmc results are consistent with FLP/CARGA within 0.2 nm/s^2. As expected the discrepancy between the software codes is slightly larger for M2 than for O1. The most striking fact is the large disagreement between the two OTMs. As a matter of fact FES04 is systematically offset from all the other models. FES04 is thus not suitable for the European area.

We can conclude that:

- As expected (Bos and Baker, 2005) the mass conservation is still critical with the recent OTMs but the two approaches to correct its deficiency agree within 0.1 nm/s^2;
- The ICET software is providing results very close either to the software NLF or FLP and CARGA, depending on the introduction of a mass conservation algorithm. It confirms the validity of previous results obtained with ICET software (Ducarme and Sun, 2001; Ducarme et al., 2007, 2009);
- The FES04 model is not suitable for Western Europe.

4. Comparison between the corrected tidal factors and consistency of calibrations

As the OLFG/OLMP program has been optimised and as results are available for 8 tidal models instead of 5 only for the other providers, it was decided to use FLP only to determine the corrected tidal factors at the 3 stations for O1, K1 and M2 (Table 1 and Fig. 3). The standard deviation σ is associated with the dispersion of the eight OTMs considered (CSR4, NAO99, GOT00, TPX07, FES04, DTU10, EOT11a and HAMTIDE). Its value is thus very similar for each station (Table 1). The stations Vienna and Conrad, where the same SG C025 was installed, provide very close results (Meurers, 2012; Meurers et al., 2013). The largest discrepancy reaches 0.01% on M2. However as the same instrument C025 was used in both stations it is only a proof of the stability of its calibration after reinstallation. At Conrad Observatory calibrations performed in parallel using a Scintrex Autograv CG5 gravimeter were in agreement within 0.04%.

Pecný is slightly offset with respect to the two other stations. Results obtained at Pecný with Askania gravimeter ASK228

Table 1
Corrected tidal factors, mean of 8 OTM, FLP computation σ_i standard deviation.

Station	O1		K1		M2		M2/O1
	δ_c	α_c (°)	δ_c	α_c (°)	δ_c	α_c (°)	
Pecný	1.15373	-0.012	1.13551	0.042	1.16206	0.037	1.00722
	±0.00007	±0.004	±0.00019	±0.004	±0.00017	±0.006	±0.00018
σ_i	0.00019	0.011	0.00053	0.010	0.00048	0.018	
Vienna	1.15337	−0.011	1.13507	0.044	1.16207	0.017	1.00755
	±0.00006	±0.003	±0.00016	±0.004	±0.00015	±0.008	±0.00016
σ_i	0.00018	0.010	0.00045	0.010	0.00042	0.024	
Conrad	1.15340	−0.017	1.13511	0.028	1.16217	0.018	1.00760
	±0.00006	±0.003	±0.00016	±0.004	±0.00015	±0.005	±0.00016
σ_i	0.00018	0.010	0.00044	0.011	0.00041	0.014	
DDW99/H	1.15282		1.13244		1.16049		1.0066
DDW99/NH	1.15429		1.13451		1.16199		1.0067
MAT01/NH	1.15402		1.13495		1.16159		1.0066

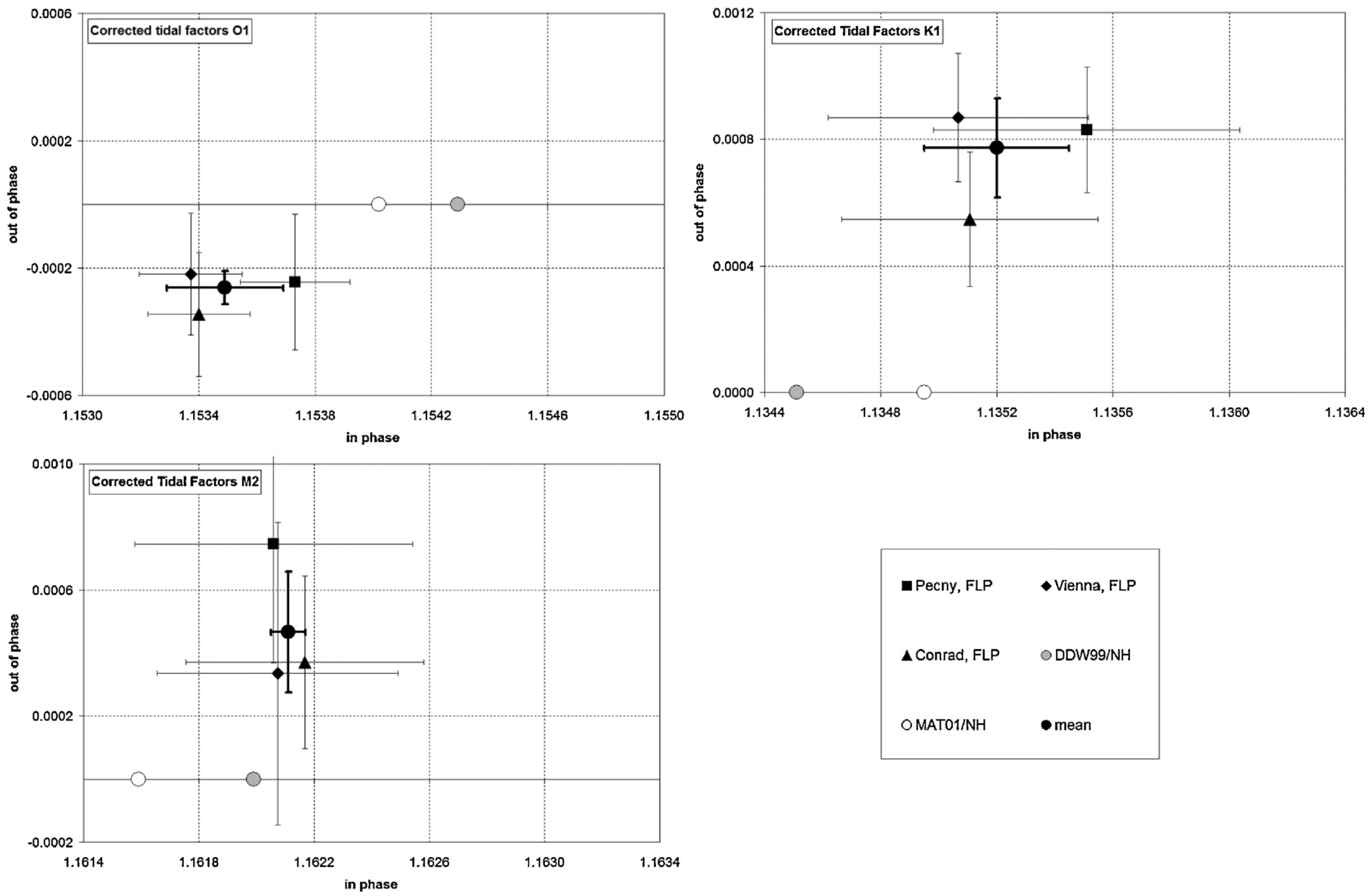

Fig. 3. Mean corrected tidal factors for O1, K1 and M2 using load vectors from the Free Ocean Tides Loading Provider (FLP). Error bars correspond to standard deviation. In phase: $\delta_c \cos\alpha_c$, Out of phase: $\delta_c \sin\alpha_c$

(Palinkas, 2006) were included in the WEN intercomparison (Ducarme et al., 2009). The amplitude factors of O1 and M2 obtained with ASK228 are 0.1% higher than the mean WEN values (Table 3) and the phases agree within 0.01°.

The comparison between C025 and OSG050 is now providing another external check. The discrepancy of Pecný corrected tidal factors obtained by OSG050 with respect to the mean of the two other stations (Table 2) is similar for O1 (0.03%) and K1 (0.04%). It is well below 0.01% for M2. The associated internal errors are of the order of 0.02% for all the waves in all the stations. Moreover the ratio M2/O1, which does not depend from the calibration, is slightly lower in Pecný but the difference is also lower than the associated RMS errors (Table 1). There is thus a slight local contribution besides the calibration error. The conclusion is thus that the agreement between the calibration of C025 and OSG050 is certainly better than 0.05%, probably closer to 0.025%.

Table 2
Comparison of the calibrations of OSG050 and C025 Discrepancy: [param(Pecný) – mean(param(Conrad), param(Vienna))]/param(Pecný).

Source	δ_c (O1) %	δ_c (K1) %	δ_c (M2) %	δ_c (M2)/δ_c (O1) %
Table 1	0.030	0.037	–0.006	–0.04

5. Comparison with body tides models

The values of the body tides models DDW99/NH and MAT01/NH are represented in Fig. 3. The values proposed by DDW99/H are out of scale.

For O1 the results are closer to MAT01/NH. The phases are slightly negative, see Table 1. However the phase differences do not differ significantly from zero. A negative phase on O1 could be produced by anelasticity in the mantle of the Earth.

For K1 MAT01/NH is close to the results of all the stations. A phase difference of 0.04° is observed in two stations (Pecný and Vienna) and 0.03° in Conrad. These values seem to deviate significantly from zero as the associated RMS errors are of the order of 0.01°. K1 frequency corresponds to an annual modulation of the meteorological wave S1. It is probably the origin of the observed residual phase on K1.

M2 is in agreement with DDW99/NH for all the stations. The phase differences are in good agreement in Vienna and Conrad. The phase at Pecný is systematically larger than in Vienna and Conrad.

The proportionality between the angular speeds of M2 and O1 and their phase lags suspected in Ducarme et al. (2009) has now completely disappeared in Table 1.

As the discrepancies between the stations are lower than 0.05%, it seems reasonable to compute the mean of the 3 stations (Table 3) and to compare it with the mean results of the 16 WEN stations (Ducarme et al., 2009). The agreement is excellent. The mean results of this study agree with the 16 WEN stations within 0.01%. In Table 3

Table 3
Final comparison of mean corrected tidal factors σ standard deviation on n stations, σ' standard deviation on n loading evaluations.

Station	n	O1		K1		M2		M2/O1
		δ_c	α_c (°)	δ_c	α_c (°)	δ_c	α_c (°)	
This study 3 stations		1.15350	−0.013	1.13523	0.039	1.16210	0.024	1.0075
σ	3	0.00020	0.003	0.00025	0.010	0.00006	0.013	
σ'	24	0.00024	0.010	0.00050	0.012	0.00042	0.020	
Ducarme et al. (2009) 16 stations WEN		1.15340	0.016	1.13525[a]		1.16211	0.031	1.0076
σ	16	0.00092	0.021	0.00090		0.00081	0.029	
Strasbourg		1.15308	−0.026	1.13477	0.031	1.16129	0.053	1.0071
σ'	8	0.00016	0.010	0.00051	0.012	0.00030	0.032	
DDW99/H		1.15282		1.13244		1.16049		1.0066
DDW99/NH		1.15429		1.13451		1.16199		1.0067
MAT01/NH		1.15402		1.13495		1.16159		1.0066

[a] 8 stations only (Table 5, Ducarme et al., 2009).

Table 4
weighted means $\bar{a}$ of the three stations e error on the mean, r sample standard deviation.

	O1		K1		M2	
	δ_c	α_c (°)	δ_c	α_c (°)	δ_c	α_c (°)
$\bar{a}$	1.15349	−0.013	1.13520	0.039	1.16211	0.023
e	0.00010	0.006	0.00027	0.006	0.00025	0.010
r	0.00020	0.003	0.00025	0.009	0.00006	0.011

the mean values are identical if we compute them directly for the 3 stations of Table 1 or directly from the 24 different tidal loading evaluations. It is not true for the associated standard deviations σ or σ', as σ reflects mainly the calibration errors while σ' is also affected by the dispersion of the tidal loading computations. It is worth to note that the results obtained in Ducarme et al. (2009) with 5 OTMs and the ICETmc option ($\delta_{O1}=1.1535$, $\alpha_{O1}=0.04°$ on one side and $\delta_{M2}=1.1622$, $\alpha_{M2}=0.02°$ on the other) are also in agreement with this new determination. Kim and Shibuya (2013), using the same 8 OTMs for the OTL evaluation but inelastic Green's functions, showed that station Strasbourg was fitting very closely the non hydrostatic Earth models. As the authors do not provide mean corrected tidal factors we performed a new global tidal analysis of C026 at Strasbourg (5387 days, 1997.03–2012.12) from the GGP data base (http://isdc.gfz-potsdam.de). The mean corrected tidal factors are given in Table 3. The phase differences agree within the associated standard deviations. Concerning the corrected amplitude factors the values at Strasbourg are lower with a discrepancy of 0.04% for O1, 0.04% for K1 and 0.07% for M2. The ratio M2/O1 (1.0071 ± 0.0002) is not far from the value at Pecný (1.0072 ± 0.0002). One should consider that there is probably a slight calibration disagreement close to 0.05%.

Finally one will find in Table 4 the weighted means $\bar{a}$, associated sample standard deviations r and errors of the weighted means e based on the following formula (Meurers et al., 2013)

$$\bar{a}=\frac{\sum_{i=1}^{n}W_i a_i}{\sum_{i=1}^{n}W_i},\quad W_i=\frac{1}{\sigma_i^2},\quad e=\sqrt{\frac{1}{\sum_{i=1}^{n}W_i}},$$

$$r=\sqrt{\frac{\sum_{i=1}^{n}(\bar{a}-a_i)^2}{n-1}} \tag{2}$$

where a_i is the mean value at one station and σ_i its standard deviation, $n=3$. As the internal errors are very similar in the three stations the weighted values do not differ significantly from the direct means of Table 3. The values of r are nearly equal to the values of σ in Table 3. It should be noted that for the phase of O1 and the amplitude factor of M2 the differences between stations are so small that r becomes much smaller than e.

We confirm the previous conclusions. MAT01/NH is closest for the diurnal waves with a discrepancy of 0.05% for O1 and 0.025% for K1. M2 fits perfectly DDW99/NH. The ratio M2/O1 is larger than the theoretical one by 0.1%. It is due to the fact that O1 is smaller than the models and M2 larger.

6. Global pressure correction

The data owners computed independently global pressure corrections for Conrad and Vienna on one side and Pecný on the other. The results are displayed in Table 5.

At Conrad and Vienna (Meurers et al., 2013) the correction is based on the ATMACS service by BKG (Klügel and Wziontek, 2009). It includes both the global and local part. Especially at CO, the 3D atmospheric models have a severe spatial resolution problem. Therefore an additional correction for local pressure

Table 5
Mean corrected tidal factors based on 5 ocean tides models (CSR4, NAO99, GOT00, TPX07, FES04) and computed by ICET, LP: corrected for local pressure only, ATMACS: global pressure from BKG (Section 7).

Station		K1		M2		S2		M2/O1
		δ_c	α_c (°)	δ_c	α_c (°)	δ_c	α_c (°)	
Pecný	LP	1.13628	0.042	1.16290	0.030	1.16124	−0.322	1.00762
	ATMACS	*1.13653*	*0.054*	*1.16293*	*0.029*	*1.16283*	*−0.307*	*1.00767*
Vienna	LP	1.13586	0.043	1.16275	0.015	1.16151	−0.328	1.00780
	ATMACS	*1.13601*	*0.056*	*1.16277*	*0.017*	*1.16261*	*−0.366*	*1.00780*
Conrad	LP	1.13588	0.025	1.16283	0.008	1.16106	−0.356	1.00786
	ATMACS	*1.13606*	*0.043*	*1.16287*	*0.010*	*1.16208*	*−0.346*	*1.00788*

effects is applied comparing the 3D model air pressure and observed pressure. The difference is corrected for by applying the single admittance concept. Hereby, the seasonal cycle visible in the differences and the higher frequency content is handled separately by applying admittance factors valid in the long period band (−2.2/−2.4 nm/s^2/hPa) and in the D and SD bands (−3.54/−3.36 nm/s^2/hPa). This, of course, is only a small correction, but copes with the problem that local pressure is not properly reflected in the ATMACS correction.

At Pecný the atmospheric correction has been computed by the combination of ATMACS data and local pressure data. The total atmospheric effect provided by ATMACS has been reduced for the effect correlated with modelled air pressure using a single admittance approach. After interpolation to the sampling rate of gravity data, the air pressure effect has been reintroduced based on the measured air pressure.

The use of a global pressure correction is affecting principally the amplitude factor of S2 that becomes nearly equal to M2 for what concerns its amplitude factor, while the phase difference is not affected.

7. Summary and conclusions

Ocean tides loading solutions in Central Europe have been computed using different software with or without imposing the conservation of the water mass during one tidal cycle. Even with the recent OTMs the mass conservation is critical. If it is not introduced there is a bias in the computation of the tidal loading vector up to 0.2 nm/s^2 but the methods used to correct the mass imbalance agree within 0.1 nm/s^2. ICET software provides results close to more recent programs such as FLP or CARGA, confirming previous results obtained with ICET software. The requested accuracy of 0.15 nm/s^2 on the mean OTL values is certainly reached.

Among the 8 different OTM's used in this study FES04 results are slightly offset. It is certainly dangerous to use a single OTM without comparison with other available models.

The agreement between the calibrations of OSG050 and C025 is certainly better than 0.05%. An agreement close to 0.05% was found with C026 results at Strasbourg.

Tidal gravity observations at three accurately calibrated SG stations have been compared with different body tides models. The results of the comparison can be summarized as follows:

- The corrected phase differences are close to zero for O1 and do not differ significantly from zero for M2 except perhaps at Pecný. For K1 a residual phase of 0.04° is observed at Pecný and Vienna but is slightly lower at Conrad.
- The mean of the three stations confirms the results obtained in Ducarme et al. (2009) but with a higher precision. The hydrostatic models are not convenient. MAT01/NH is the closest model for O1 (discrepancy 0.05%) and K1 (discrepancy 0.025%). DDW99/NH is the closest model for M2 (discrepancy 0.01%). The ratio M2/O1 is 0.1% larger than predicted by any model.

Given the regionally correlated uncertainties on the tidal loading corrections using a single OTM (up to 0.05%) on one side and the residual calibration error on a single instrument (≤0.05%) on the other it is still difficult to determine corrected tidal factors with an accuracy of 0.05% from the observations of a single instrument corrected using a single OTM. In this study the associated errors on the mean corrected tidal factors are close to 0.025% on δ_c and 0.01° on α_c.

The introduction of global pressure corrections is largely improving the amplitude factor of S2 that becomes very similar to M2, but is not correcting its anomalous phase difference.

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