Efficiency of tidal corrections on absolute gravity measurements at the Membach station

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Abstract. We review the correction of the tidal signal applied on absolute gravity measurements. Harmonic and non-harmonic tidal potentials are reviewed, as well as different tidal parameter sets (gravimetric factors and phase leads). It focuses on the FG5 absolute gravimeter and on the new "g" software provided by Micro-g solutions. In particular, we give a precise description of the widely used "Berger" correction, which has never been clearly referenced. We show that the accuracy of this correction is better than the µGal level but can be still improved by the use of another correction included in the "g" software.

1. Introduction

The Sun and the Moon exert tidal accelerations with maximal peak to peak amplitudes of 250 µGal. This is the most important signal affecting gravity measurements, if we except transient seismic perturbations. The calculation of tidal phenomena requires a representation of the tidal potential. Nowadays very accurate tidal potentials based on the relative position of the Moon, the Sun and the planets (Wenzel, 1996a) allow us to compute the gravimetric tides for a rigid Earth at the nanoGal level.

As the Earth is not a homogeneous and perfectly rigid body, it reacts to the astronomical forcing in a complex way. The response of the Earth to this excitation can be separated in deformations (the body tides), changes in the Earth's orientation in space (forced nutation and precession) and changes in the Earth's rotation rate (Wahr, 1981). Some of the most important tidal parameters are the frequency dependent tidal gravimetric factor δ and the phase lead κ. In the frequency domain, δ is the transfer function between the tidal force exerted along the perpendicular to the ellipsoid and the tidal gravity changes along the vertical as measured by a gravimeter (see Dehant and Defraigne, 1999). It depends on the direct attraction of the celestial bodies, on the Earth's deformation and on the consecutive mass redistribution inside the Earth. The lead κ represents the phase difference between the observed wave and the astronomical wave. A perfectly elastic Earth provides $\delta \cong 1.16$ and $\kappa = 0$. The tidal parameter sets δ and κ can be deduced from observations or numerical models for each frequency of the tidal force.

The problem is complicated by the ocean tides, which cause additional variations of g at the same frequencies but with different phases than the Earth tide. This ocean tide attraction and loading effect reaches several µGal in amplitude for the M_2 semi-diurnal wave in Western Europe. Accurate models are now available to correct this effect, see e.g. Melchior and Francis (1996).

In this paper, we study the influence of the different tidal models used to correct absolute gravity measurements. The most accurate and commercially available absolute gravimeter (AG) is the FG5 from Micro-g Solutions (Niebauer et al., 1995). A test mass is repeatedly dropped and its position is measured as a function of time. A total of 700 time-position points are recorded over the 20-cm-length of each drop. In routine operation, the drops are repeated every 10 seconds, 100 times per hour. The average of 100 drops is a "set". Usually one set per hour is performed and the average value of all sets provides the final "gravity value" of one experiment.

This study must not be considered as a comparison at a theoretical level between different tidal models; for this purpose see e.g. Wenzel (1996a). It does not intend to validate theoretical models, but rather aims at illustrating and testing the different options provided by the new "g" software from Micro-g Solutions, released in January 2000, and their implications on the data processing. First, we provide some basic explanations on Earth tides and describe the different tidal corrections applied on absolute gravity measurements. We present here several tests of the tidal corrections available on the g-software, which could become a standard for absolute data acquisition and processing. We investigated the influence of these corrections on the gravity values, as well as on the standard deviation. For this purpose we performed tests during a one-year series of gravity values, in order to detect any systematic effect that could bias long term variations of the gravity. We considered 22 absolute gravity values at the Membach station (Eastern Belgium) between 2000-08-31 and 2001-09-10 (table 1). Each gravity value consisted in the average of about 48 sets, but with variations from 12 to 180 sets, depending on the measurement campaign.

Table 1: Details of the 22 gravity values used in Figure 2. For all data but the 13th one, there is one set per hour.

Gravity value number	Date	Number of sets
1	2001-09-10	69
2	2001-07-29	62
3	2001-07-27	26
4	2001-06-28	48
5	2001-06-27	26
6	2001-06-06	23
7	2001-06-05	24
8	2001-03-19	75
9	2001-03-17	27
10	2001-01-12	180
11	2001-01-08	42
12	2000-12-13	148
13	2000-12-12	32 (=16 h)
14	2000-11-29	49
15	2000-11-28	19
16	2000-11-10	22
17	2000-10-12	51
18	2000-10-11	12
19	2000-09-27	21
20	2000-09-16	48
21	2000-09-14	40
22	2000-08-31	45

2. Tidal potentials and tidal parameter sets

The "g" software gives the possibility to choose between the "Berger" correction and the "ETGTAB" one (this latest nomenclature is derived from the ETERNA package of Wenzel (1996b)). The Berger correction imposes its tidal parameter set and uses a non-harmonic computation of the tidal potential. This is not the case with the ETGTAB option, which consists of a finite sum of sine and cosine, of which the arguments are the tidal frequencies (harmonic method, widely used nowadays).

Using the Berger and ETGTAB corrections, we tested two tidal potentials, as well as 5 different tidal parameter sets.

2.1 The tidal potentials

2.1.1 *Non-harmonic method: the Berger correction*

This correction has been used by most of the FG5 users. It is provided by a subroutine originally written in 1969 by Jonathan Berger at the Scripps Institution of Oceanography (Micro-g, 1995). This routine was later improved by J.C. Harrison, J. Levine, K. Young, D. Agnew, G. Sasagawa and J. Gschwind, in particular to take more recent ephemeris into account as well as the Honkasalo correction. The tidal potential is directly computed in the time domain : at each time point the positions of the Sun and the Moon are deduced, from these, the tides can be calculated directly at a given place. This non-harmonic "response" method roughly follows that given by Munk and Cartwright (1966).

2.1.2 *Harmonic method: the ETGTAB correction*

The Fourier transform of the expansion of the tidal potential in spherical harmonics yields a tidal potential catalogue. Several tidal potential catalogues are currently available differing in the number of waves and the accuracy. In particular, the Cartwright-Tayler-Edden (1971, 1973) catalogue contains 505 waves and is accurate to a maximum error of 0.24 μGal in time domain, while the Tamura (1987) potential catalogue contains 1200 waves and is accurate to a 0.06 μGal maximum error in time domain (Wenzel, 1996a). This widely fulfils the accuracy requirements to correct absolute gravity measurements. The ETGTAB tool in the "g" software implicitly uses the Tamura potential, which is contained in the "Etcpot.dat" file.

The tides generated by the Berger program were checked by D. Agnew (2001) against those got from Cartwright et al. (1971, 1973). The level of disagreement was less than 10^{-3}. We made another test between the Berger subroutine and the much more accurate Tamura (1987) potential on an arbitrary time interval (2000-11-01 to 2001-11-01). Using the constant delta factor of 1.1554 and a null lead for both potentials, the disagreement was less than 0.5 μGal or 3.7 x 10^{-3} (Figure 1a). Wenzel and Zürn (1990) found similar results by comparing the Cartwright et al. catalogue with the Tamura one. The errors of the Cartwright et al. catalogue are mainly due to the absence of the lunar tidal potential of degree 4 (Wenzel, 1996a), but this should not affect absolute measurements significantly.

3. The tidal parameters sets

With its maximal error of 0.5 μGal, the Berger potential has a fair good enough accuracy to remove Earth tides from absolute gravity measurements. However, the Berger correction implicitly uses a constant delta factor of 1.1554 for the second harmonics and a null phase lead. This is the major shortcoming of the non-harmonic model : it nearly does not handle frequency dependent effects, which are easily included in any harmonic method. For example, a resonance effect, caused by the liquid core, can not be taken into account (Nearly Diurnal Free Wobble NDFW, see e.g. Lambert, 1974). Nowadays Earth's models provide accurate frequency dependent tidal parameter sets, which incorporate the NDFW, but also the inertial effect, the Coriolis force, the Earth's flattening and anelasticity, etc (see e.g. Dehant et al. (1999), referred hereafter as DDW and Mathews (2001), referred as MHB2000).

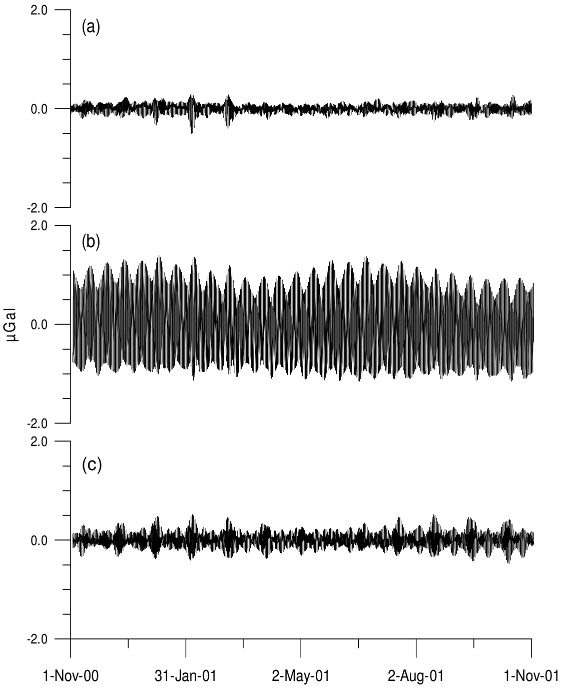

Fig. 1 Differences of synthetic gravity tides between different tidal potentials and/or tidal parameter sets, during an arbitrary time interval (from 2000-11-01 to 2001-11-01). (a) Difference between Berger and Tamura (same frequency independent tidal parameter set as Berger [$\delta = 1.1554$, $\kappa = 0$]). (b) Difference from Berger and Tamura (tidal parameter set from the DDW model). (c) Difference between Tamura (tidal parameter set from the data observed by the superconducting gravimeter GWR C021) and Tamura (set from the CG3M spring gravimeter).

By comparing synthetic tidal signals generated by the Berger (δ = 1.554) and the ETGTAB (Tamura + frequency dependent δ and κ from the DDW or MHB2000) models, we got differences in the time domain up to 1.4 µGal (Figure 1b). In the frequency domain, the discrepancy reached 0.9 µGal in the diurnal band, especially due to the NDFW effect not taken into account by Berger. In the semi-diurnal band it reached 0.16 µGal, mainly due to the inertial effect not considered by Berger.

In locations where a spring or superconducting gravimeter already measured the gravity for minimum 2 months, computing a tidal analysis provides tidal parameter sets. This is also feasible with an absolute gravimeter, as shown by Francis (1997), but this arduous task is instrument consuming. Using sets from observed data is the best solution, as the ocean loading effect and any other local effects are automatically taken into account.

4. Results from the "g" software

We calculated the differences between the Berger and the ETGTAB tide corrections afforded by "g" corresponding to the time intervals of the 22 Membach gravity values. The Berger tool imposes the frequency independent tidal parameter $\delta = 1.1554$ and $\kappa = 0$. Using ETGTAB, we tried 4 different tidal parameter sets:

1. The set automatically calculated by the OceanLoad software, supplied with "g". It contains 10 main wave groups selected in the DDW model.
2. A set provided by the MHB2000 model very similar to the DDW one. There are only small differences in the diurnal frequency band, due to the incorporation of a non-hydrostatic Earth's flattening. We selected 17 main waves.
3. A set containing 20 observed wave groups, provided by the analysis of a 4-year long recording made with the GWR-C021 superconducting gravimeter. This instrument continuously monitors the gravity at the Membach station (Francis et al. (2003)). This tidal parameter set is referred hereafter as C021.
4. A set containing 20 observed wave groups, provided by the analysis of a 53-day long recording made with the Scintrex CG-3M spring gravimeter at the Membach station. This tidal parameter set is referred hereafter as CG3M.

4.1 Ocean tide loading corrections

The Berger, DDW or MHB2000 models are based on an oceanless Earth. Therefore, the OceanLoad software computes not only the DDW Earth tide parameter set, but also a tidal parameter set dedicated to the ocean tide loading correction. The user can choose the Schwiderski, FES (Grenoble) or CSR (Texas) models. According to Melchior and Francis (1996) and Francis and Melchior (1996), these models do not differ from one another significantly. For example, we compared the Schwiderski model with the FES and the CSR ones. The models were run on 62 observed sets taken at Membach from 2001-07-27 to 2001-09-10. The differences in the calculated gravity values remained less than 0.1 µGal, as already noticed by Amalvict et al. (2001).

4.2 Berger vs. ETGTAB

To complete the Berger, DDW and MHB2000 models, we chose the Schwiderski model to correct the ocean loading effect. This was of course pointless for the C021 and CG3M observed tidal parameter sets. As it can be seen on Figure 2, no trend appeared in the differences between the gravity values obtained after using the Berger correction on the one hand and the ETGTAB on the other hand. Moreover, the differences remained widely inside the error bars, which turned out to be between 0.9 and 1.8 µGal in the worst case (Berger) and between 0.6 and 1.5 µGal in the best ones (C021 and CG3M). These error bars, not shown on Figure 2 for more legibility, represent one standard deviation in the observed gravity values.

The largest discrepancy appeared on December 12, 2000 (gravity value #13), but remained lower than 0.40 µGal. At that time, the gravity value resulted from an average calculated on 16 hours only. This was not sufficient to smooth out the NDFW effect, not corrected by the Berger model. Such a phenomenon also occurred to a less extend for the gravity value #18, averaged on 12 hours, where the difference reached up to 0.34 µGal between CG3M and Berger.

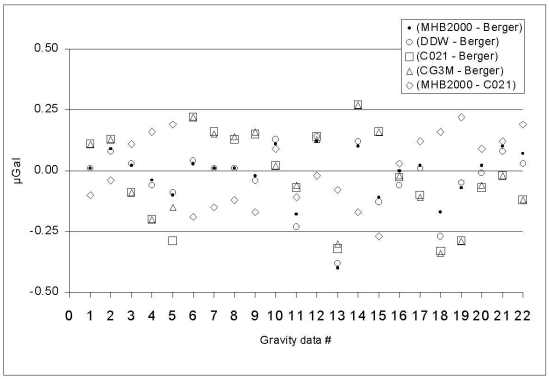

Fig. 2 Differences of the gravity values calculated applying the Berger correction and the ETGTAB correction (tidal parameter sets from the DDW and MHB2000 models, as well as from the observations of the CG3M spring gravimeter and the GWR C021 superconducting gravimeter). Details on the gravity values are in Table 1.

4.3 ETGTAB: DDW, MHB2000, C021 & CG3M

The differences between the gravity values calculated using the theoretical DDW and observed C021 parameter sets, or using MHB2000 and C021, remained lower than 0.29 µGal (Figure 2). The largest discrepancies occurred for sets #5, #15 & #19 and were mainly due to imperfections in the ocean loading model. Incidentally, the differences between the gravity values obtained after using the theoretical DDW and MHB2000 models were less than 0.10 µGal. Doing the same after applying the observed C021 and CG3M parameter sets, the differences were still less than 0.15 µGal.

4.4 The standard deviation

We compared the standard deviations of the gravity values after applying the different tide corrections. As seen in the Table 2, the best results were obtained for the C021 and CG-3M tidal parameter set. This was expected, especially for C021 as this instrument measures tidal amplitudes in the semi-diurnal and diurnal bands with a precision of about 1-2 nanoGal for an integration period of 2-3 years (Francis et al., 2003). It is also worth noting that the differences from the tidal signal calculated using the tidal parameter set from the C021 and the CG3M observed data remained lower than 0.5 µGal (Figure 1c).

The DDW and MHB2000 models coupled with Schwiderski provided standard deviations comparable to the C021 and CG3M ones. The small differences were mostly due to imperfections in the ocean loading model (for a review of the ocean loading models, see e.g. Baker and Bos, 2003) and to non-corrected environmental effects.

Table 2. Average of the standard deviations associated with each of the 22 gravity values.

Tidal correction	Average standard deviation [µGal]
Berger	1.19
ETGTAB+MHB2000	0.96
ETGTAB+DDW	1.02
ETGTAB+C021	0.92
ETGTAB+CG3M	0.94

5. Conclusions

We checked the accuracy of the tidal corrections calculated by the "g" software: on the one hand the Berger correction, which uses a non-harmonic tidal potential and a frequency independent tidal parameter set and on the other hand, the ETGTAB correction, which uses the harmonic Tamura potential and different frequency dependent tidal parameter sets.

The gravity values corrected using the Berger model differed by less than 0.4 µGal from the values obtained using Tamura potential and the DDW model. This discrepancy, similar to the FG5 precision, was mainly due to the neglection of the NDFW, not taken into account by the Berger's frequency-independent tidal parameter set. Taking sufficiently long AG recordings, say at least 20 h, we were able to smooth out the remaining tidal waves due to model imperfections. However, as the DDW set is automatically computed by the OceanLoad software, a by-product of "g", and because its accuracy is better than 0.25 µGal, we recommend this latest model for all routine FG5 data processing, especially when measuring for a few hours only.

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