Limitations of High Precision Tidal Prediction

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ABSTRACT : The most demanding applications are tidal gravity predictions. We examine if the nms^{-2} precision can be reached. It correspond roughly to a 4.10^{-4} of the tidal range (TR) at mid latitude. High precision tidal prediction requires either tidal factors derived from tidal observations or modelled tidal factors based on the response of the Earth to tidal forces and on the ocean tides contribution. Both methods rely on a precise knowledge of the astronomical tides. The accuracy of the astronomical tides is very large and different tidal prediction programs agree within 10^{-5}TR. A reduced tidal development (1200 terms in Tamura) still insures a precision of 2.10^{-4}TR. For tidal predictions based on observations the calibration is the main limiting factor and 0.1% remains a target still difficult to reach. The records length limits the separation of the different tidal groups. If the tidal factors of different tidal waves within the same group are not the same, systematic errors are introduced. For example neglecting the resonance around ψ_1 in the K_1 group, can introduce an error at the level of 3.10^{-4}TR. For tidal predictions based on modelled tidal factors the choice of the model for the response of the Earth to tidal forces is critical as differences between recent models are slightly larger than 0.1%. The best models seem to fit the observations within 5.10^{-4}. The evaluation of the indirect effect of the ocean tides is critical and general conclusions are only valid at distances larger than 100km from the coast, where improved grid is not compulsory for tidal loading computations. In the best cases we can reach a precision of 5.10^{-4}TR. Our conclusion is that the accuracy of 0.1% is generally difficult to reach and that 5.10^{-4} is nowadays the limit of accuracy using long series of observations of regularly calibrated instruments.

Keywords: tidal predictions, body tides, astronomical tides, ocean tides loading

1. Introduction:

Among the different applications of tidal prediction tidal gravity is the most demanding one. Absolute gravity measurements reach nowadays a precision of 10^{-9}g or 10nms^{-2} (1µgal). A good metrological practice requires an accuracy 10 times better for all the corrections to be applied, including tidal gravity corrections. Tidal predictions should reach an accuracy of 1nms^{-2} , which corresponds roughly to a 4.10^{-4} of a 2,500nms^{-2} (250µgal) tidal range (TR). Moreover long period (LP) tides have to be included. However as high precision absolute measurements require observations during one day or more, a large part of the tidal effect is averaged out, but not the LP tides. For gravity prospecting the measurements are always differential and the precision required is one order of magnitude lower. As a matter of fact tidal predictions with an accuracy of 0.1% will generally be sufficient. However in the following considerations we shall check if the level of the nms^{-2} (4.10^{-4}TR) can be reached. The considerations developed for gravity tides can be easily extrapolated for the other tidal components. Another point is that we should consider here the maximum discrepancy and not the standard deviation of the tidal prediction The reason is that in gravity prospecting we consider isolated values. As pointed above absolute measurements are the exception as they average the short period tides.

Astronomical tides are very accurately computed from tidal potential developments (see section 2), but for an elastic Earth it is necessary to take into account the deformation of the Earth and the additional change of potential induced by this deformation. The result is known as “body tides”. For gravity, the amplitude change is expressed by the ratio δ_E between the tides on the elastic Earth and the amplitude of the astronomical tides A_{th}. As the tidal forces are applied also to the fluid parts of the Earth i.e. the ocean and the atmosphere, the reaction of these fluids produces additional gravity, tilt and strain changes superimposed exactly on the frequencies of the body tides. After correction of the atmospheric effects, the different constituents of the tidal effects at a given tidal frequency can be represented by rotating vectors (Fig. 1).

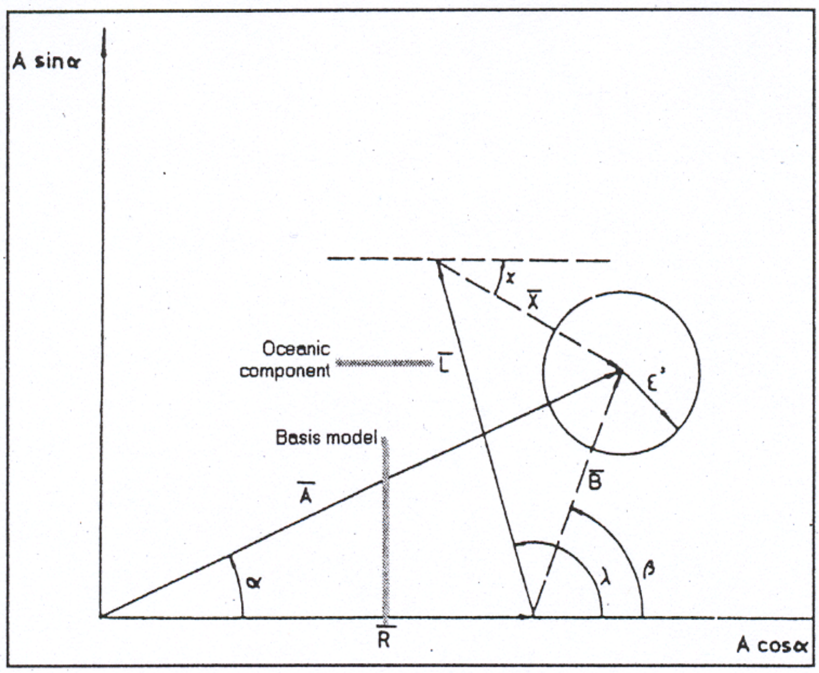

Figure 1: Phasor plot at a given tidal frequency showing the relationship between the observed tidal amplitude vector **A**(A,α), the Earth model **R**(R,0), the computed ocean tides load vector **L**(L,λ), the tidal residue **B**(B,β)=**A-R** and the corrected residue **X**(X,χ)=**B-L**, after Melchior (1994). See the text for further explanation.

Let us consider:
• the observed amplitude vector

A = (δA_{th},α), where δ is the observed tidal amplitude factor and α is the observed phase difference;
• the body tides tidal amplitude vector

R=($\delta_E A_{th}$,0), where δ_E is the expected tidal amplitude factor according to a given Earth model;
• the ocean load vector

L(L,λ) indirect effect computed from a given ocean tide model

For tidal prediction we can follow two approaches:
• a direct approach based on the tidal factors (δ,α), derived from tidal records.

• an indirect approach based on predicted tidal factors (δ_m, α_m), derived from the modelled tidal vector

$$\mathbf{A_m}(\delta_m A_{th}, \alpha_m) = \mathbf{R}(\delta_E A_{th}, 0) + \mathbf{L}(L, \lambda) \quad (1)$$

The two approaches should be equivalent if:
-the instrument is well calibrated;
-the Earth response and the tidal loading are well modelled.
We shall first consider the different factors influencing the precision of the tidal prediction.
The accuracy of the determination of observed tidal factors depends on:
- the calibration of the instrument (section 3.1)
- the astronomical tides (section 2)
- the length of the tidal record (section 3.2)

For the predicted tidal factors we should take into account:
- the response of the Earth to tidal forces (section 4.1)
- the ocean tides contribution (section 4.2)
- the astronomical tides (section 2)

For tilt and strain it should be necessary to model also the topography and cavity effects besides ocean tides contributions.
As the astronomical tides computation is a common factor we shall first consider this topic.

2. Astronomical tides computations

The first factor determining the precision of the tidal predictions is the number of terms or tidal waves considered in the tidal development. A recent study of the most recent tidal developments by Kudryavtsev (2004) confirmed the increase of precision with the number of terms: RATGP95 (Roosbeek, 1996, 6,499 terms, 5ngal), HW95 (Hartmann and Wenzel, 1995, 12,935terms, 1.23ngal), KSM03 (Kudryavtsev, 2004, 28,806terms, 0.39ngal). HW95, used as a standard by the ETERNA software (Wenzel, 1996), insures thus a precision of 5.10^{-6}TR. A previous tidal development TAM1200 (Tamura,1987, 1,200 terms) is already correct at the level of 2.10^{-4}TR (Ducarme, 2006). It is still widely used in BYTAP-G (Tamura et al., 1991), VAV (Venedikov and Vieira, 2004), T-soft (Van Camp and Vauterin, 2005) and ICET software.

The first step of the tidal prediction is the precise evaluation of the direct influence of the Moon, the Sun and the planets, generally called the “astronomical tides”. It is based on the developments of the tidal potential (Melchior, 1978). To derive a tidal prediction we have to consider a scale factor often referred as “Doodson” constant, a geometrical part depending on the position at the surface of the Earth (geodetic coefficients), which is different for each tidal component, and the harmonic part, which is a sum of sinusoidal terms. The development of the tidal potential provides for each term a normalised amplitude and an argument which is a linear combination of the astronomical arguments of the celestial bodies. Only 6 arguments, chosen by Doodson, are required for the Luni-solar tides. Concerning the planetary influences, Tamura was the first to introduce tidal terms coming from Jupiter and Venus, arriving to a total of 8 arguments. Roosbeek and Hartmann-Wenzel introduced additional arguments for Mars, Mercury and Saturn to arrive to a total of 11 astronomic elements.
Comparisons between the ICET and ETERNA software can be found in Ducarme, 2006. The tidal prediction computed using the TAM1200 potential is equivalent in PREDICT (ETERNA) and MT80TW (ICET) to better than 10^{-5}TR.

3. Precision of the observed tidal factors

The main uncertainty on the observed tidal factors comes from the calibration of the instruments. If the record length is less than one year the liquid core resonance will produce spurious effects inside the K_1 group. It should be noted also that the LP tides are generally not well determined as they require very long tidal records. It is always possible to use modeled tidal factors to replace missing observed values. A discussion of the modeling of the LP tides will be given in section 4.2.

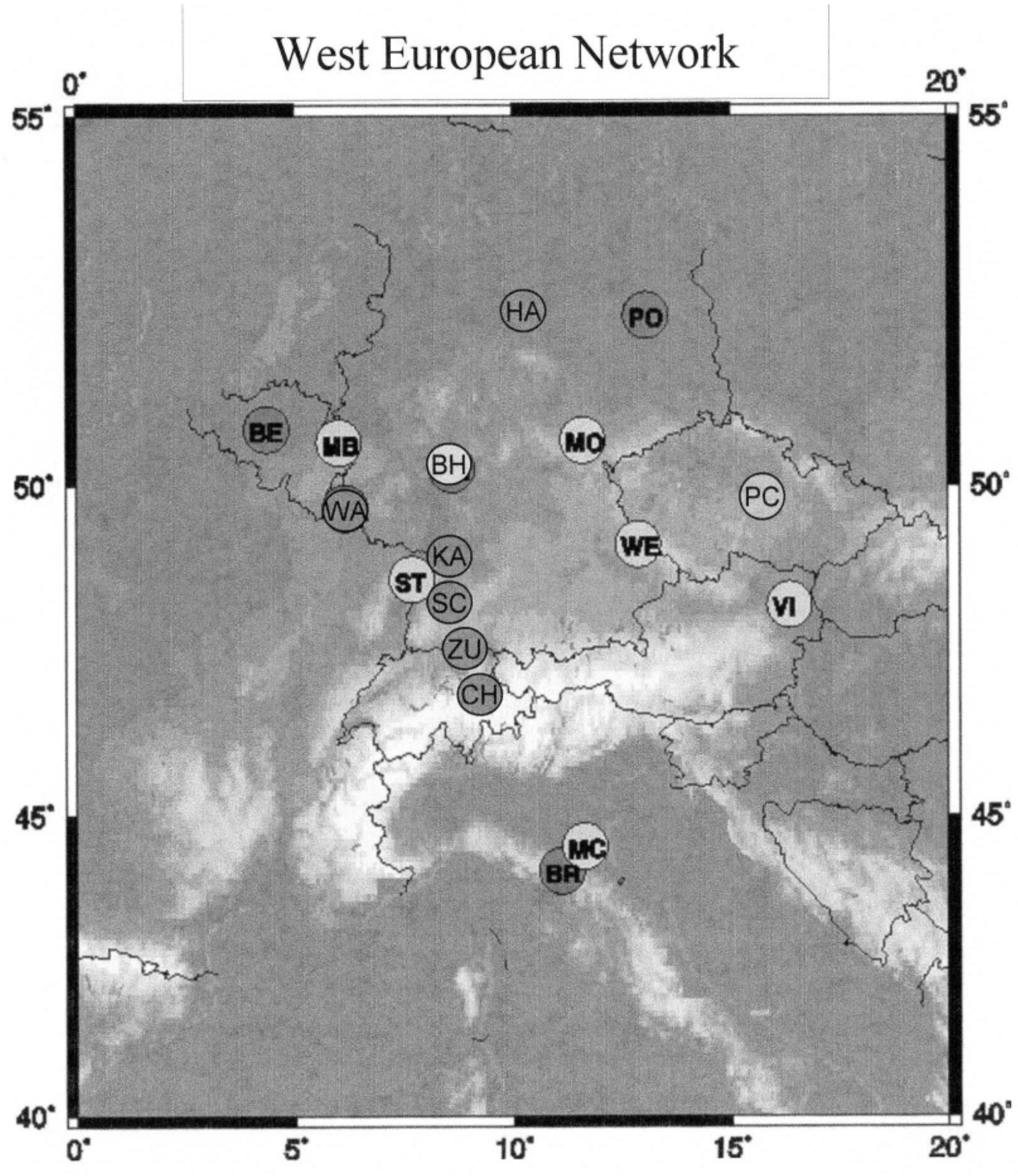

Figure 2. Selected stations in the West European network (Ducarme et al., 2008)

New GGP: MB (Membach), ST (Strasbourg), BH (Bad Homburg), MC (Medicina), MO (Moxa), WE (Wettzell), VI (Vienna).
Older stations: BE (Brussels), WA (Walferdange), KA (Karlsruhe), SC (Schiltach), ZU(Zürich), CH (Chur), HA (Hanover), PO (Potsdam), PC (Pecny).
BR (Brasimone) not used

3.1 Calibration of the gravimeters

It is necessary to model the instrument transfer function in amplitude and phase, at least at the tidal frequencies. Very precise techniques have been developed for the determination of the transfer function (Richter and Wenzel, 1991 ;Van Camp et al., 2000). Time lag corrections are precise at the level of the second i.e. 0.01° on M_2 or 2.10^{-4} TR at the equator. An extensive study including 16 tidal gravity station in Western Europe (Fig. 2) arrived to the conclusion that the level of 0.1% is already difficult to reach for the amplitude calibration (Ducarme et al., 2008b). This network is subdivided in two parts: 7 stations of the Global Geodynamics Project (GGP) (Crossley et al., 1999) equipped with modern "compact tidal" (CT) and "double sphere" (CD) superconducting gravimeters (SG) and 9 other ones, where older model T SG's or spring gravimeters were used.
The GGP SG's have been calibrated using parallel tidal recording with absolute FG5 gravimeters, as described in Francis (1997). Most of the instruments used in the additional stations have been calibrated against the Hanover vertical calibration line (Kangieser and Torge, 1981; Kangieser et al., 1983), either directly or indirectly.
The precision of a single calibration can be derived from the difference between the tidal factors obtained with collocated instruments. SG's simultaneously calibrated using the same absolute FG5 gravimeter show that the agreement is of the order of 0.05% (Ducarme et al., 2008b). Regularly repeated calibrations in Strasbourg lowered the RMS error to 0.03% (Rosat et al., 2008).
Referring to Figure 1, we can define the so called "corrected" tidal parameters: amplitude factor δ_c and phase difference α_c, by the relation.

$$\mathbf{A_c}(\delta_c A_{th}, \alpha_c) = \mathbf{A} - \mathbf{L} \qquad (2)$$

As the ocean tides loading is well constrained in this part of Europe, the variations observed in the corrected amplitude factors can be considered as reflecting the calibration errors. The standard deviation of the seven GGP stations calibrated with FG5 instruments is 0.08%. The dispersion of the nine additional stations is only slightly larger (Ducarme et al., 2008b).

A promising approach for the calibration of gravimeters is the use of inertial accelerations. For that purpose the instrument is placed on a platform and submitted to vertical accelerations at different frequencies. Such a platform was developed for spring gravimeters (van Ruymbeke,1989; van Ruymbeke et al., 2008). A precision of 0.1% has been achieved. For SG's the three usual supports are replaced by step motors which are gently lifting up and down the instrument in a sinusoidal way (Richter et al.,1995; Wilmes et al., 2008). All elements of the system are designed to insure a precision of 10^{-4}. However the precision is still limited to 0.05%.

As a conclusion we can state that the best precision achieved nowadays is:

•Superconducting gravimeters
- parallel registration with absolute gravimeters
  3.10^{-4} to 10^{-3}
- inertial accelerations
  scheduled 10^{-4} effective 0.510^{-3}

•Spring gravimeters
- vertical baseline 10^{-3}
- inertial accelerations 10^{-3}

It should be noted that the normalisation of spring gravimeters at a fundamental station, as it was realised for example during the Trans World Tidal Gravity Profiles (Melchior, 1994), did not generally insure a precision better than 3.10^{-3} (Ducarme et al., 2008a).

3.2 Effect of the record length

As the ocean tides loading is strongly frequency dependant, we cannot extrapolate the tidal factors obtained for one wave to a neighboring one. It is thus important to resolve a maximum of tidal groups to avoid systematic errors. Records shorter than 6 months should be avoided as the main waves P_1 and K_2 cannot be separated from their neighbors K_1 and S_2.
Moreover, due to the liquid core resonance, the Nearly Diurnal Free Wobble (NDFW) modifies the body tides amplitude factors inside the diurnal band (Melchior,1978; Dehant et al., 1999). The resonance effect is concentrated inside the K_1 group. A minimum time span of one year is required to resolve the complex tidal structure of this group, which includes the two annual (ψ_1 and S_1) and semi-annual (φ_1 and P_1) modulations of K_1. P_1 amplitude factor is reduced of 0.45%, and K_1 of 1.7%, while ψ_1 is amplified of 10% and φ_1 of 1.4%. If the record length is shorter than 6 months, the error will reach 7.10^{-4}TR at a latitude of 50°, due to the differential resonance between K_1 and P_1. Tidal records shorter than 1 year will not allow the separation of the annual modulations inside the K_1 group and produce residues at the level of 3.10^{-4}TR. However this effect can be strongly reduced by the introduction of a resonance model inside the group. It has been implemented in MT80TW.

4. Precision of predicted tidal factors

Besides the astronomical tides evaluation, the precision of the predicted tidal factors depends on the precision of the **R** and **L** vectors i.e. the precision of the body tides model and of the tidal loading computation.

4.1 The body tides models

Different body tides models are used by the different tidal prediction software.
•PREDICT is using latitude dependent tidal parameters for an elliptical, rotating, inelastic and oceanless Earth computed from the Wahr-Dehant-Zschau model (Dehant, 1987).
•MT80TW computes tidal predictions with δ_E values extracted from
- either (Dehant et al., 1999) :
  the DDW99 elastic (H)
  the DDW99 non-hydrostatic/inelastic (NH) models
- or the MAT01/NH inelastic (Mathews, 2001) model.

These models differ at the level of 10^{-3} (Table 1).
To discriminate the different theoretical models we compare the values of δ_E with the experimentally determined corrected amplitude factor δ_c computed by the relation (2).
A study based on the global GGP network (1997-2003) (Ducarme et al., 2007) provided a mean value $\delta_C(O_1) = 1.1546 \pm .0006$
It agrees within 0.1% with:
- the value $\delta_E = 1.1543$ computed from the DDW99/NH model
- and the value $\delta_E = 1.1540$ given by MAT01

A more recent study of the West European network (Ducarme et al., 2008b, Fig. 2) gave:

•For O1 the value δ_C =1.15340±0.00023 falling between the DDW99/H (1.1528) and the MAT01/NH (1.1540) inelastic models.
•For M2 the value δ_C =1.16211±0.00020 fitting very well the DDW99/NH (1.1620) and MAT01/NH (1.1616) inelastic models.
• For K1 the mean result δ_C =1.13525±0.00032 fitting the MAT01/NH (1.1349) inelastic model to better than 0.05%.
The conclusion is that MAT01/NH inelastic model seems to be the best choice, with an error close to 5.10^{-4}.

Table 1: Theoretical amplitude factors at 45° latitude

	O1 δ_{th}	K1 δ_{th}	M2 δ_{th}	O1/K1	M2/O1
DDW/H	1.1528	1.1324	1.1605	1.0180	1.0067
MAT01/NH	1.1540	1.1349	1.1616	1.0168	1.0066
DDW/NH	1.1543	1.1345	1.1620	1.0174	1.0066

4.2 The tidal loading computation

In continental stations the loading effect is generally at the level of a few microgal for the main waves, but one can observe huge effects in coastal areas. Moreover the variation of the tidal factors for a given value of the load vector depends of the amplitude of the astronomical tides at this latitude. As the diurnal gravity tides vanish at the equator, the corresponding tidal factors are not reliable at low latitude. It is the same at very high latitudes for both diurnal and semi-diurnal tides. It is thus difficult to issue general statements concerning the precision of modeled tidal factors and our examples are taken from middle latitude stations.
The ocean tides models provide at least the 8 main diurnal (Q_1, O_1, P_1, K_1) and semi-diurnal (N_2, M_2, S_2, K_2) and the fortnightly tide M_f. These waves cover most of the tidal spectrum. However in the diurnal band the frequencies higher than 1.024cycle/day (periods lower than 23h45m), corresponding to the small constituents J_1 and OO_1, are not always available. As the contribution of these groups represents only 6.5% of the diurnal tides, we can use the body tides values as a first approximation.
The LP tides deserve a careful treatment. Two recent studies (Ducarme et al, 2004; Boy et al, 2006) showed that, for the fortnightly lunar wave M_f, the tidal loading computations based on recent ocean tides models were in agreement with tidal gravity observations of superconducting gravimeters performed in the frame of GGP. The observations cannot determine precisely enough the monthly lunar wave M_m so that it is not yet possible to confirm its modelling. However Boy et al. showed that the ratio of the tidal loading vectors **L** for M_m and M_f is roughly equal to their amplitude ratio in the gravity tides and that the phases are similar. We can thus include M_m and M_f in one and a same group. In Siberia (Ducarme et al., 2008a) the 3 recent models (NAO99, TPX06, FES04) agree closely for M_f with a standard deviation better than 0.1% in amplitude and 0.05° in phase.
For the annual and semi-annual solar waves Sa and Ssa the tidal loading is not the main perturbation. The contributions from meteorological and hydrogeological sources are preponderant. Tidal gravity analyses on GGP data sets determined observed tidal factors larger than 2 for Sa (see for example Ducarme et al, 2006), while global models are required for effective pressure corrections (Neumeyer et al., 2004) and continental water storage fluctuations induce strong seasonal effects (Peter et al, 1995; Neumeyer et al, 2006). As these very long period tidal waves deserve a special treatment we suggest to use the body tides model values for tidal predictions.

The constant tidal effect called M_0S_0 should be treated with a special care in order to follow the resolutions of the International Association of Geodesy (IAG). For Gravity one should follow the "zero tide" correction principle i.e. one should remove only the astronomical part of the M_0S_0 tide and not the constant deformation. Clearly speaking the amplitude factor of M_0S_0 should be put equal to 1.
If tidal gravity observations have been performed in the area, it is often possible to select a best fitting ocean tides model, but generally the use of the mean of several models is largely improving the precision (Zahran, 2000; Zahran et al., 2005). In Figure 3 we consider 9 different ocean tides models (ORI96, CSR3, CSR4, FES95, FES02, FES04, NAO99, GOT00 and TPX06) and a sub-group of 6 more recent models (CSR4, FES02, FES04, GOT00, NAO99, ORI96, TPX06).

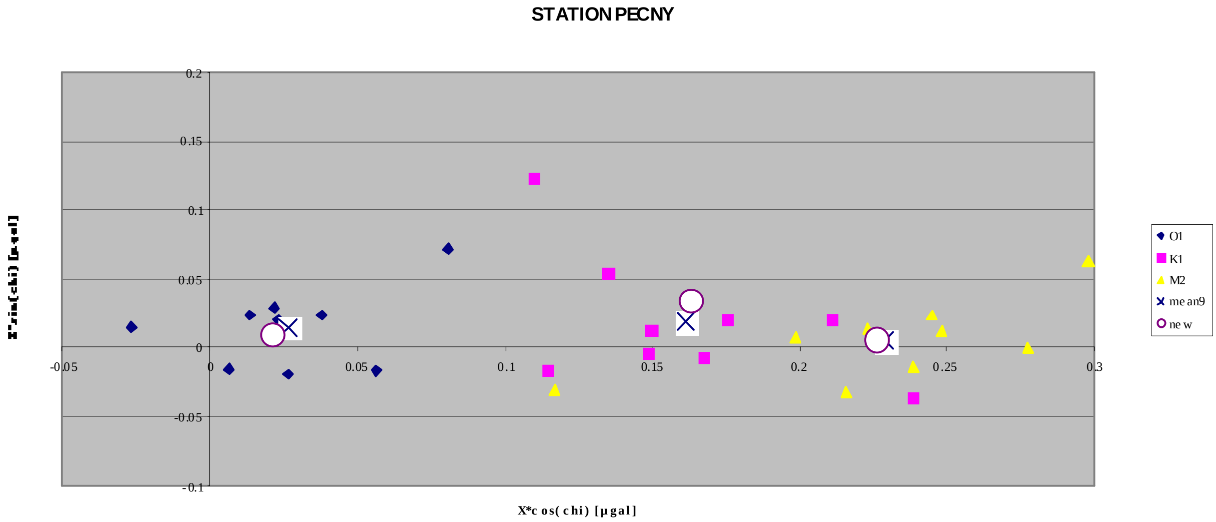

Figure 3: dispersion of the final residue **X** computed from 9 ocean tides models for a continental station (Pecny, CZ)
X: mean of 9 models, O: mean of 6 recent models

Let us consider the 16 European stations of Figure 2. The standard deviation of the 9 different ocean tides models is close to 0.3µgal for O_1 and M_2, i.e. 0.1% of the amplitude of these tidal waves. The use of the mean of 9 different models could reduce the accidental error contribution down to 3.10^{-4} of the tidal range.
Let us consider the trans-Siberian tidal gravity profile (TSP, Ducarme et al., 2008a). On the Siberian territory the tidal factors modelled using 9 different ocean tides models have a standard deviation close to 0.1% (0.05°) for the diurnal waves and 0.2% (0.1°) for M_2. Using the mean of 9 ocean tides models we can thus insure a precision of 0.03% (0.015°) in the diurnal band and 0.06% (0.03°) in the semi-diurnal one. The RMS error of 3 recent models of the LP tide M_f is lower than 0.025%. The global RMS error due to load computations can be kept below 5.10^{-4}TR.

The case of 4 gravity stations installed along the Atlantic coast of France (Timofeev et al., 2006), at 100km from the sea shore, is less favourable, due to the very large semi-diurnal ocean tides loading of the Gulf of Biscay. The standard deviation of the 9 different ocean tides models is close to 0.3µgal for O1, but it reaches 1µgal for M2! It follows that the use of the mean of 9 ocean tides models will still have a global uncertainty at the level of 0.2µgal, close to 10^{-3}TR. Among the different ocean tide models the best fit with the observed tidal factors

was obtained using CSR3, CSR4 or FES02 with less than 0.05% in amplitude and 0.1° in phase.
We can conclude that the use of the mean of several tidal models can reduce the uncertainty to 5.10^{-4}TR for inland stations in well constrained areas, but that at 100km from the coast the uncertainty can easily reach 10^{-3}TR.

5. Statements concerning the final precision

For each of the two approaches we can draw a table giving the best precision that can be reached as well as the normal one. The three main contributions are listed together with the expected global precision. For the astronomical tides usual means that the TAM1200 tidal potential is used.
Table 2 presents the case of the observed tidal factors. As expected the main error source is the calibration. A precision better than 5.10^{-4} was only achieved by the SG of Strasbourg. It is probably more realistic to consider a precision of 0.1% for the time being. At this level of precision a reduced tidal development is sufficient for the astronomical tides computation.
For spring gravimeters only the best instruments can insure a precision of 0.1%. A more conservative figure is 0.3%.
For the modeled tidal factors (Table 3) the two main error sources are the tidal loading evaluation and the uncertainties on the response of the Earth to the tidal forces. Even in the best case the error budget is close to 0.1%. For coastal stations the error on tidal loading evaluation is very difficult to estimate. Tidal gravity observations can help to determine the best models for the considered region.

Table 2: Precision on the observed tidal factors for superconducting gravimeters (SG) and spring gravimeters

Calibration		Astr. tides		Rec.length		Total	
best	usual	best	usual	>1y.	<1y.	best	usual
SG							
$\leq 510^{-4}$	10^{-3}	5.10^{-6}	2.10^{-4}	-	3.10^{-4}	$\leq 510^{-4}$	10^{-3}
spring							
10^{-3}	3.10^{-3}	5.10^{-6}	2.10^{-4}	-	3.10^{-4}	10^{-3}	3.10^{-3}

Table 3: Precision of the modelled tidal factors

Loading		Earth mod.		Astr. tides		Total	
inland	<100km	best	any	best	usual	best	usual
5.10^{-4}	$>10^{-3}$	5.10^{-4}	10^{-3}	5.10^{-6}	2.10^{-4}	7.10^{-4}	$>10^{-3}$

6. ICET contribution

Which approach is the most efficient?
•The determination of precise observed tidal parameters is time consuming and requires expensive instruments.
•Modelled tidal parameters are inexpensive to compute but unreliable for coastal stations.
The International Centre for Earth Tides (ICET) prepared two kinds of modelled tidal factors, available from its web site http://www.upf.pf/ICET/.

For 1,000 stations around the world very precise tidal parameters based on different means of ocean tides models are proposed. We computed modeled tidal factors using 9 different ocean tides models (ORI96, CSR3, CSR4, FES95, FES02, FES04, NAO99, GOT00 and TPX06). The tidal loading vector **L** was evaluated by performing a convolution integral between the ocean tide models and the load Green's function computed by Farrell (1972). The Green's functions are tabulated according to the angular distance between the station and the load. The water mass is condensed at the center of each cell and the Green's function is interpolated according to the angular distance. This computation is rather delicate for coastal stations if the models are computed on a coarse grid, as the stations can be located very close to the center of the cell. The numerical effect can be largely overestimated. To avoid this problem our tidal loading computation checks the position of the station with respect to the center of the grid. If the station is located inside the cell, this cell is eliminated from the integration and the result is considered as not reliable (Melchior et al., 1980). We can consider two groups of models, the older models up to 1996 (ORI96, CSR3, FES95) on one hand, and the new generation of models (CSR4, FES02, FES04, GOTOO, NA099 and TPX06) on the other. 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's (2000, 2005) suggestion, we computed mean tidal loadings for different combinations of models: all the 9 models or only the 6 recent ones.
As many of the ocean tide models do not provide the smaller tidal constituents J_1, OO_1, M_3, M_4, we provide only the theoretical amplitude factors of the corresponding groups. For the long period constituents we use always the mean of the 3 recent models NAO99, TPX06 and FES04 to compute the loading for the fortnightly tide M_f and we include the monthly tide M_m as well as the shorter period tides in one and the same group M_f. As explained in section 4.1, we use the body tides model values for the annual and semi-annual solar waves Sa and Ssa.
To evaluate the real precision of the prediction based on modelled tidal factors we compared it with a prediction based on observed tidal factors in one of the best calibrated stations: Moxa

(Fig. 2). The tidal coefficients are given in Table 4. Due to the large difference in the tidal parameters for the Ssa group, a strong semi-annual wave shows up with an amplitude of $2nms^{-2}$ in the difference between the two tidal predictions (Figure 4). For the shorter periods the differences does not exceed $\pm 3nms^{-2}$, i.e. $1.2\ 10^{-3}$TR. There is a scale difference of 4.10^{-4} producing a systematic effect of $\pm 0.5nms^{-2}$. It is a mixture of the errors due to the inaccuracy of the calibration and of the body tides model. The residual error is close to $\pm 2.5nms^{-2}$ i.e. 0.1% and corresponds principally to the inaccuracy of the ocean tides computation. The associated standard deviation is only $1nms^{-2}$ (4.10^{-4}TR). If we do not consider the LP tides, the error on the tidal correction of absolute gravity determinations obtained by observations averaged on several days will be of the same order of magnitude. It justifies the statement made in the introduction .

For less accurate tidal predictions we propose global tidal gravity parameters on a 0.5°x0.5° grid using the CSR3 or NAO99 ocean tide model for 9 waves (M_f, Q_1, O_1, P_1, K_1, N_2, M_2, S_2, K_2). Zhou J.C. et al. (2007) used the CSR3 ocean tides model together with a purely elastic Earth model. Ocean load vectors have been computed using the Agnew (1996, 1997) software. The NAO99 model was used at ICET with the Melchior et al. (1980) software. The computed load vectors were associated to a non hydrostatic/inelastic Earth model (Dehant et al., 1999) to compute modeled tidal parameters.

Interpolation software is proposed on the ICET WEB site to provide an output compatible with the most common tidal prediction software. The proposed software is an update of the WPAREX program developed by H. G. Wenzel for a bilinear interpolation inside the grid. If the input coordinates are not surrounded by 4 grid points error message is issued and the values at the closest point are selected..

If one of the grid points is too close from one cell of the ocean tides model a warning is issued, as the load vector computation is probably not accurate at this point.

Table 4: Observed (δ, α) and modelled (δ_m, α_m) tidal gravity factors for station Moxa.
N: number of waves in Tamura, 1987

Tidal Group	N	Frequency range (cycle per day)		δ	α (°)	δ_m	α_m (°)
						DDW99/NH 6 recent models	
M0S0	2	.000000	.000001	1.0000	0.000	1.0000	0.000
Ssa	32	.000002	.020884	1.2358	0.760	1.1570	0.000
Mf	247	.020884	.501369	1.1454	0.450	1.1411	0.410
Q1	143	.501370	.911390	1.1461	-0.186	1.1468	-0.132
O1	106	.911391	.981854	1.1488	0.124	1.1501	0.097
P1	17	.981855	.998631	1.1493	0.179	1.1503	0.161
K1	40	.998632	1.023622	1.1363	0.224	1.1358	0.156
J1	43	1.023623	1.044800	1.1566	0.166	1.1560	0.000
OO1	102	1.064841	1.470243	1.1535	0.118	1.1560	0.000
N2	149	1.470244	1.914128	1.1762	2.167	1.1784	2.062
M2	95	1.914129	1.984282	1.1850	1.581	1.1859	1.510
S2	17	1.984283	2.002736	1.1835	0.344	1.1866	0.607
K2	116	2.002737	2.451943	1.1859	0.581	1.1838	0.546
M3	81	2.451944	3.381378	1.0695	0.454	1.0700	0.000

Systematic comparisons between the precisely computed and the interpolated tidal gravity parameters for 24 GGP stations around the world showed that the differences on the mean amplitude factors are small i.e. less than 4.10^{-4} (Zhou J.C. et al., 2007). However the interpolated tidal parameters may become questionable at very high latitude or for the diurnal waves at the equator (section 4.2).

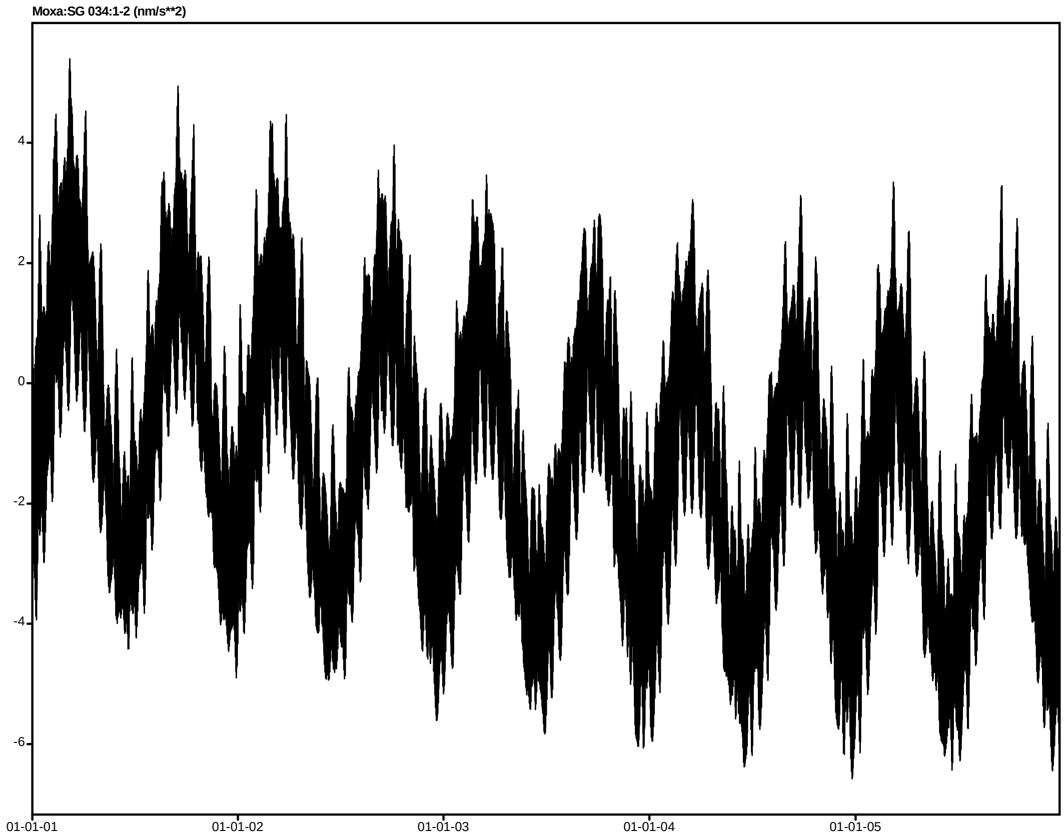

Figure 4. Difference between tidal prediction using the observed tidal parameters at Moxa and a modelling based on the DDW99/NH body tides model and the mean of 6 recent ocean tides models (Table 4). Units are nms^{-2}

7. Conclusions

The final accuracy of tidal prediction based on previous tidal observations depends on the correct evaluation of the astronomical tides, the length of the tidal records and the accuracy of the calibration of the instrument.

Tidal predictions can also be performed on the grounds of "predicted tidal factors". The different elements contributing to the precision of such tidal predictions are:

- the astronomical tides;
- the response of the Earth to the tidal force;
- the ocean tides contribution.

The accuracy of the astronomical tides is very large and different tidal prediction programs agree within 10^{-5} of the tidal range (TR). A reduced tidal development (1200 terms in Tamura) still insures a precision of 2.10^{-4} TR.

For tidal prediction based on observation the records length limits the separation of the different tidal groups. If the tidal factors of different tidal waves within the same group are not

the same, systematic errors are introduced. The two main sources of difference between waves with close frequencies are the FCN in the diurnal band and differential ocean tides effects. Neglecting the resonance around ψ_1, can introduce an error at the level of 3.10^{-4}. Differential ocean tides effect depends on the magnitude of the local effects.
The calibration remains thus the main limiting factor and 0.1% remains a target still difficult to reach. The standard deviation on the corrected tidal factors of 16 selected stations in Europe reaches 0.1% in amplitude and 0.02° in phase.

For tidal predictions based on modelled tidal factors the choice of the model for the response of the Earth to tidal forces is critical as difference between recent models are slightly larger than 0.1%. Investigations based on 16 stations in western Europe showed that the MAT01 model fits the observations within 0.05% for O_1 as well as for M_2.
The tidal loading evaluation is critical and general conclusions are only valid at distances larger than 100km from the coast, where improved grid is not compulsory for tidal loading evaluation. We present case studies for Europe and Siberia. In the best cases we can reach a precision of 0.05%. In these areas the global error due to Earth model and tidal loading is thus below 0.1%. This level of precision is confirmed by tests performed on one of the best GGP station.
Up to now it is thus quite impossible to reach an accuracy of 4.10^{-4}TR for tidal prediction on a real Earth. It is even difficult to reach 10^{-3}TR, which is suitable for tidal correction of absolute gravity observations. At this level of precision a reduced tidal development is sufficient for the computation of astronomical tides. The modelling of tides with periods larger than 6 months is still unreliable.
As it is much less expensive to compute modelled tidal factors than to perform tidal gravity observations, the International Centre for Earth Tides (ICET) prepared two kinds of modelled tidal factors, available from its web site http://www.upf.pf/ICET/. For 1,000 stations around the world very precise tidal parameters based on different means of ocean tides models were computed. For less accurate tidal predictions we propose global tidal gravity parameters on a 0.5°x0.5° grid using the CSR3 or the NAO99 ocean tide model for 9 waves (M_f, Q_1, O_1, P_1, K_1, N_2, M_2, S_2, K_2). An interpolation software is also available.

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Bibliography

Agnew, D.C., 1996, SPOTL: some programs for ocean tide loading. SIO Reference series 96-8, scripts institution of oceanography, Woods Hole
Agnew, D.C., 1997: NLOADF: a program for computing ocean-tide loading. J. Geophys. Res., 102 (B3), 5109-5110.
Boy J.P., Llubes M., Ray R., Hinderer J., Florsch N., 2006: Validation of long-period oceanic tidal models with superconducting gravimeters. J. of Geodynamics, 41, 112-118.
Crossley, D., Hinderer, J., Casula, G., Francis, O., Hsu, H. T., Imanishi, Y., Jentzsch, G., Kääriaïnen, J., Merriam, J., Meurers, B., Neumeyer, J., Richter, B., Shibuya, K., Sato, T., Van Dam, T., 1999: Network of superconducting gravimeters benefits a number of disciplines. EOS, 80, 11, 121/125-126.
Dehant, V., 1987: Tidal parameters for an inelastic Earth. Physics of the Earth and Planetary Interiors, 49, 97-116, 1987.

Dehant V., Defraigne P., Wahr J., 1999: Tides for a convective Earth. J. Geoph. Res., 104, B1, 1035-1058.
Ducarme B., Venedikov A.P., Arnoso J., Vieira R., 2004: Determination of the long period tidal waves in the GGP superconducting gravity data. Journal of Geodynamics, 38, 307-324
Ducarme, B., 2006: Comparison of some tidal prediction programs and accuracy assessment of tidal gravity predictions. Bull. Inf. Marées Terrestres, 141, 11175-11184
Ducarme, B., Neumeyer, J., Vandercoilden, L., Venedikov, A. P., 2006: The analysis of long period tides by ETERNA and VAV programs with or without 3D pressure correction. Bull. Inf. Marées Terrestres, 141, 11201-11210
Ducarme, B., Sun, H. P., Xu, J. Q., 2007 : Determination of the free core nutation period from tidal gravity observations of the GGP superconducting gravimeter network. Journal of Geodesy, 81, 179-187 *(DOI: 10.1007/s00190-006-0098-9)*
Ducarme, B., Timofeev, V. Y., Everaerts, M., Gornov, P. Y., Parovishnii, V. A., van Ruymbeke, M., 2008a: A Trans Siberian tidal gravity profile (TSP) for the validation of tidal gravity loading corrections. J. of Geodynamics,45, 73-82, *(DOI:10.1016/j.jog.2007.07.001)*
Ducarme, B., Rosat, S., Xu, J.Q., Vandercoilden, L., Sun, H.P., 2008b: European tidal gravity observations: Comparison with Earth Tides models and estimation of the Free Core Nutation (FCN) parameters. Accepted for publication in IAG Proc., Symp. GS003 "Earth Rotation and Geodynamics", XXIV IUGG General Assembly, Perugia, I.
Farrell, W.E., 1972: Deformation of the Earth by surface load. Rev. Geophys., 10, 761-779
Francis, O., 1997: Calibration of the C021 superconducting gravimeter in Membach (Belgium) using 47 days of absolute gravity measurements. International association of Geodesy Symp., Gravity, Geoid and Marine Geodesy, Segawa et al. (eds.), 117, 212-219
Hartmann, T. and Wenzel H.-G., 1995: Catalogue HW95 of the tide generating potential. Bull. Inf. Marées Terrestres, 123, 9278-9301.
Kangieser, E., Torge, W., 1981: Calibration of LaCoste-Romberg gravity meters, Model G and D. Bull. Inf. Bur. Grav. Int., 49,50-63.
Kangieser, E., Kummer K., Torge, W., Wenzel H.-G, 1983: Das Gravimeter-Eichsystem Hanover. Wissenschaftliche Arbeiten der Fachrichtung Vermessungswesen der Universität Hannover, 1203
Kudryavtsev, S.M., 2004: Improved harmonic development of the Earth tide generating potential. J. of Geodesy, 77, 229-838
Mathews, P.M., 2001: Love numbers and gravimetric factor for diurnal tides. Proc. 14th Int. Symp. on Earth Tides, Journal of the Geodetic Society of Japan, 47, 1, 231-236.
Melchior, P., 1978: The tides of the planet Earth. Pergamon Press, 609pp.
Melchior P., Moens M., Ducarme B., 1980: Computations of tidal gravity loading and attraction effects. Bull Obs. Marées Terrestres, Obs. Roy. Belg., 4, 5, 95-133.
Melchior, P., 1994: A new data bank for tidal gravity measurements (DB92). Physics Earth Planet. Interiors, 82, 125-155.
Neumeyer J., Hagedorn J., Leitloff J., Schmidt T., 2004: Gravity reduction with three-dimensional atmospheric pressure data for precise ground gravity measurements. Journal of Geodynamics, 38, 437-450.
Neumeyer, J., Schmidt, T., Stoeber, C., 2006: Improved determination of the atmospheric attraction with 3D air density data and its reduction on ground gravity measurements. IAG Symposia, Dynamic Planet 2005, Cairns, Australia, August 22-26 2005, 130, 541-548
Peter, G., Klopping, F.J., Berstis, K.J., 1995: Observing and modeling gravity changes caused by soil moisture and groundwater table variations with superconducting gravimeters in Richmond, Florida, U.S.A.. Cahiers du Centre Européen de Géodynamique et de Séismologie, 11, 147-158.

Richter, B. and Wenzel, H.-G., 1991: Precise instrumental phase lag determination by the step response method. Bull. Inf. Marées Terrestres, 111, 8032-8052.
Richter, B., Wilmes, H., Nowak, I., 1995: The Frankfurt calibration system for relative gravimeters. Metrologia, 32, 217-223.
Roosbeek, F., 1996: RATGP95: A harmonic development of the tide generating potential using an analytical method. Geoph. Journal Int., 126, 197-204.
Rosat, S., Boy, J., Ferhat, G., Hinderer, J., Amalvict, M., Gegout, P., Luck, B., 2008: Analysis of ten-year (1997-2007) record of time-varying gravity in Strasbourg using absolute and superconducting gravimeters: new results on the calibration and comparison with GPS. New Challenges in Earth's Dynamics, 1-5 Sept. 2008, Jena. To be published in Journal of Geodynamics.
Tamura Y., 1987: A harmonic development of the tide-generating potential. Bull. Inf; Marées Terrestres, 99, 6813-6855.
Tamura,Y., Sato, T., Ooe, M., Ishiguro, M., 1991: A Procedure for Tidal Analysis with a Bayesian Information Criterion, Geophysical Journal International, 104, 507-516.
Timofeev, V.Y., van Ruymbeke, M., Woppelmann, G., Everaerts, M., Zapreeva, E.A., Gornov, P.Y., Ducarme, B., 2006:Tidal gravity observations in Eastern Siberia and along the Atlantic coast of France. Proc. 15 Int. Symp. Earth Tides, J. Geodynamics, 41, 30-38.
Van Camp, M. Vauterin, P., Wenzel, H.G., Schott, P., Francis, O., 2000: Accurate transfer function determination for superconducting gravimeters, Geophys. Res. Let., **27**, 37-40.
Van Camp, M. and Vauterin P., 2005: Tsoft: graphical and interactive software for the analysis of time series and Earth tides. Computers & Geosciences, 31, 631-640.
van Ruymbeke, M., 1989: A calibration system for gravimeters using a sinusoidal acceleration resulting from a vertical periodic movement, Bull. Geod., 63, 223-235
van Ruymbeke, M., Naslin, M., Zhu, P., Noël, J., 2008: New developments in the calibration of gravitational instruments. Proc. New Challenges in Earth's Dynamics, 1-5 Sept. 2008, Jena. To be published in Journal of Geodynamics.
Venedikov, A.P., Vieira, R., 2004: Guidebook for the practical use of the computer program VAV – version 2003. Bull. Inf. Marées Terrestres, 139, 11037-11102.
Wenzel, H.-G., 1996: The nanogal software: Earth tide data processing package ETERNA 3.30. Bull. Inf. Marées Terrestres, 124, 9425-9439.
Wilmes, H., Nowak, I., Falk, R., Wziontek, H., 2008: Estimation of the transfer function and and calibration parameters of superconducting gravimeters. Proc. New Challenges in Earth's Dynamics, 1-5 Sept. 2008, Jena. To be published in Journal of Geodynamics.
Zahran, K.H., 2000: Accuracy assessment of Ocean Tide loading computations for precise geodetic observations. PhD thesis, Universität Hannover.
Zahran, K. H., Jentzsch, G., Seeber, G., 2005: World-wide synthetic tide parameters for gravity and vertical and horizontal displacements. J. Geod., 79, 293-299
Zhou J. C., Sun H. P., Ducarme B., 2007 : Validating the synthetic tidal gravity parameters with superconducting gravimeter observations. Bull. Inf. Marées Terrestres, 143, 11489-11497