INTERACTIONS BETWEEN EARTH AND OCEAN TIDES*

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Abstract. By interactions between earth and ocean tides, one understands the disturbing effects on the earth tides generated by the ocean tides, also called indirect effects or loading effects. Precise computations of the loading effects are needed in various research fields. The modelling of these effects and particularly what must be done in order to improve the accuracy of their evaluation is treated. Then, a status on what is presently going on with the oceanic tidal modelling will be given. Finally, the results of a few experiments of gravity loading data inversion will be presented and discussed.

Introduction.

The regular movements of the oceanic waters associated with the tides cause load tides. These are generated by the deformation of the earth's crust under the pressure of the oceanic tidal load but also by the redistribution of the water masses. One can define three groups of loading effects : the displacements (vertical and horizontal), the accelerations (horizontal and vertical) and the strain tensor elements. Because of the magnitude of the loading effects (several centimeters for the radial displacement) and the considerable increase of the accuracy of the various observational systems used in geophysical research, the loading effects appear like disturbing effects that must be taken out before performing further studies. This is the case for the three following examples :

- Schuh and Moehlmann (1989) showed that correcting the VLBI (Very Long Baseline Interferometry) observables for the ocean loading effect decrease significantly the a posteriori delay and delay rate errors of the least square fits of those VLBI experiments with stations near ocean coasts and on islands. In extreme cases, stations coordinates and baseline length may change by few centimetres after applying the ocean loading correction.
- The precise computation of the geodetic satellite orbit requires a model of the earth's gravity potential and particularly of the potential due to the body tides, the oceanic tides and the loading tides. These loading tides must be taken into account to reach an orbit error lesser than 15 cm on the radial component of the satellite position as anticipated for the furure altimetric satellite Topex-Poseidon (Stewart et al., 1986).
- It is well- known that the line spectrum of a gravity tide record contains two main components :(1) the earth's body tide signal due to direct astronomical forces and (2) a smaller signal arising from the loading of the ocean tides. The difference between these two

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modelled components and the observations provides us with residues which contain useful informations upon ocean tide model errors and body tide anomalies. Moreover, one must add problematical instrumental errors due to variation of the instrumental sensitivity or to systematic experimental errors like calibration (Baker et al., 1989 & 1991). The classical gravitymeters (Lacoste-Romberg) have a precision of the order of the accuracy of the computation of the loading effects which is estimated at about 10% of the amplitude of the gravity loading tide, i.e 0.1 to 1.5 microgals. This accuracy is certainly lesser than the precision of the superconducting gravitymeters whose precision is better than 10 nanogals (3σ) in the frequency domain - i.e probably a factor 10 greater than the current limit of accuracy for modelling the direct astronomical tide. When a sufficiently accurate gravity loading correction will be available, the study and interpretation of the tidal residues will be more precisely and more deeply conducted : in particular, about the possible correlation between earth tides residues and heat flow (Yanshin et al., 1986; Robinson, 1991; Rydelek et al., 1991; Melchior and Ducarme, 1991a).

These examples reflect the disturbing effects of the ocean tides on the earth tides. Reciprocally, the earth tides and ocean tide loading cause radial displacements of the sea floor and potential perturbations which cannot be neglected in hydrodynamic ocean tide models (Hendershott, 1972).

In 1972, Farrell published a remarkable and authoritative work on the computation of the loading effects which is the basis for all the new developments which bring either little amendment or simply up-dated earth's model. Baker (1985) made a comprehensive review of the different methods of tidal loading computations.

The Farrell's procedure consists in evaluating a convolution integral over the loaded region (the oceans) with a kernel (so-called Green's functions) which is the response of the media (the earth) to a mass-point load. It is a computionally heavy procedure as the convolution integral is performed over all the ocean surface. Indeed, a loading effect $\vec{L}$ at the geographical location (φ,λ) is given by :

$$\vec{L}(\varphi,\lambda) = \rho w \int\!\!\int_{\text{oceans}} G(\varphi,\lambda;\varphi',\lambda')\, \vec{h}(\varphi',\lambda')\, dS'$$

where ρ_W is the mean density of the sea water, G the appropriate Green's function (say for the displacement, acceleration or strain observable $\vec{L}$), $\vec{h}$ ocean tide vector and dS' the surface area.

Accuracy Assessment.

The accuracy of the evaluation of the loading effects depends on these three ingredients : the Green's functions (i.e. the earth model used to compute them), the oceanic tidal model and the discretization of the integral. The latter element being largely dependent on the spatial resolution of the cotidal maps, it will be considered as a part of the errors of the ocean tide model.

GREEN'S FUNCTIONS

The Green's functions which are the different components of the response of the earth to a point mass load are related to the properties of the earth through the load Love numbers. These numbers are obtained by solving the equation of motion, the stress-strain relation and the Poisson's equation for a spherical radially stratified gravitating earth model with a unit mass pressing on the earth's free surface. These equations taking into account the rheological properties of the earth, the load Love numbers thus depend upon the seismological models used to evaluate them. At small distance, the loading Green's functions are sensitive to regional structures of the crust and mantle at the depth corresponding to the distance between the load and the observation point. For distance greater than 500 km, the loading effects look as if the earth has a laterally homogeneous structure as described by a global reference earth model. Then a more realistic description of the earth response to a load should be expected from a local refinement of the earth model near the observation point.

The Green's functions can be classified into two different groups : those which have been computed under the assumption that the earth responds elastically under the tidal frequencies and those which take into account the viscoelasticy behavior of the earth's mantle. The main discrepancies between elastic and viscoelastic Green's functions appear for small angular distance (≤1°) between the load and the observation point and are due to the low viscosity of the asthenosphere.

Gravity loading computations with elastic and viscoelastic Green's functions using profile of the Gutenberg-Bullen model or of the PREM at coastal and continental stations generally disagree by only 1-2% in magnitude and less than 1° in phase (Francis and Dehant, 1988; Francis and Mazzega, 1990). These results agree with those previously obtained by Baker (1980) and Pagiatakis (1990) among others. Baker compared Green's functions computed for various radially stratified elastic earth models and found differences of 0.01 to 0.05 µgals on the loading effects in Britain for a signal of a few µgals. On the other hand, Pagiatakis computed Green's functions for a self-gravitating, compressible, layered, anisotropic, viscoelastic and rotating earth with an inner core and a fluid outer core. The rotation of the earth and anisotropy in the upper mantle affect load Love numbers by a few per cent and there is a weak latitude dependence of load Love numbers for $n \leq 4$. At diurnal frequencies viscoelastic load Love numbers are 1-2 per cent larger than their corresponding elastic values. In general, the differences between the Gravity loading estimations with the Pagiatakis' and the Farrell's Green's functions are lower than 2% (Pagiatakis, 1988). More recently, Scherneck (1990) computed complex Green's functions for a shield structure with thick crust and a cold upper mantle. Moreover, viscoelastic rheology in the mantle is incorporated by using absorption band model for transient creep. This was done in the framework of the interpretation of various tidal observations conducted in central Scandinavia. The difference with respect to Farrell's Green's functions are small in the case of the most components.

On the other hand, Mao (1990) makes use of a viscoelastic selfgravitating half-space model in order to include particular local rheological structure. Nevertheless, no estimations of the impacts on the computed loading effects are given but since the difference with the Farrell's Green's functions are small, no great overthrow should be expected.

All the works on Green's functions for elastic and viscoelastic earth model agree on one point : the variations on the loading computations in terms of the choice between the different Green's functions are of the order of few per cent i.e of the order of 0.01 μgals for the gravity and 0.1mm for the displacement. These are at the same level of precision than the best nowadays instrumental performances.

THE OCEAN TIDES MODELS

Global ocean tides models

The Schwiderski (1980a-b) ocean tidal model with a resolution of 1°x1° for the 11 principal constituents is still probably at the present day the most accurate global model, as it provides worldwide the closest results to gravity measurements (Melchior, 1981; Melchior & De Becker, 1983; Melchior & Ducarme, 1991b). Nevertheless, the supremacy of the Schwiderski should be dethroned by ocean tides models derived by altimetry in the near future. For instance, the Cartwright and Ray (1991) ocean tides model computed form geosat data is being tested and perhaps will replace the Schwiderski model in the Geophysical Data Record (GDR) prepared for the Topex-Poseidon mission. Woodworth (1985) tested the Schwiderski model with independent tide gauge data not used in the model and he found a combined tide accuracy of about 15 cm and that the model is less reliable where it is not constrained by data : at high latitude, in Bays or Gulfs or in shallow waters.

One must point out that additional constituents can be derived from the available modelized constituents. Assuming the smoothness of the response of the ocean to astronomical tidal forcing and defining the admittance as the ratio of the observed tide to the equilibrium tide, it is possible to obtain the admittance of unmodelized constituents by interpolation in the frequency domain. By this mean, Le Provost et al. (1991a) computed global oceanic maps for $2N_2$, μ_2, ν_2, L_2 and T_2 tides. The RMS errors of the ocean tidal prediction by adding these 5 new constituents have been reduced from 6 cm to 3 or 4 cm at some test points.

Some attempts to evaluate the impact of the errors of the M_2 ocean tide model on the loading effects calculation have been undertaken by Hsu and Mao (1984) and by Scherneck (1989). Hsu and Mao assumed a 5 cm error on the average tidal height of the Schwiderski's model and deduced errors on the gravity correction due to influence of the tidal height lesser than 0.12 μgals. On the other hand, Scherneck estimated the propagation of errors in the ocean tide models through the computation of loading effects with the assumption that the tide model errors are to be spatially correlated. Preliminary results for the Bad Homburg site suggests a σ(loading tide error) of 0.1 μgals for σ(oceanic tide error) of 5 cm (at 95% of confidence interval). All these estimations should be taken as indicative because they are limited by our poor knowledge of the errors of the ocean tide models (only qualitative informations are available). It is as difficult to model the errors of an ocean tide model as to improve the model itself.

The mass conservation problem.

Except models with zero flow boundary conditions, it is well-known that most of global ocean tidal models do not conserve mass for various reasons : nonlinear effects, numerical methods, permeability of the coastlines and map discretization. This is even the case for the Schwiderski's model as displayed in figure 1 where the nonconserved quantity for each constituents are compared with the mean amplitudes. The problem is more crucial for the long period tides.

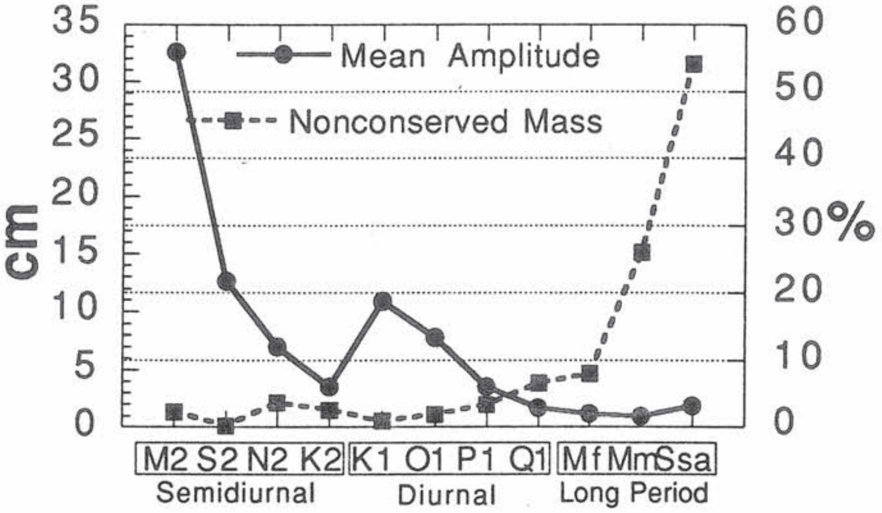

Figure 1 : Mean tidal amplitudes of the 11 constituents of the Schwiderski's ocean tide model (left scale) and ratio of the amplitude of the nonconserved tidal mass to the mean amplitude (right scale).

It was already shown by Farrell (1973) that when adding mass conservation to a model that lacks it, there is a better fit between computed and observed gravity loading tide. This is the only justification for imposing an arbitrary mass conservation. In central Europe, Baker et al. (1991) showed the very significant improvement between the model calculations and observations in the case of M_2 when mass is conserved. It clearly demonstrates the importance of mass conservation in ocean tide models.

Two alternative methods have been tried by Melchior et al. (1980) : (a) a uniform correction which consists in the introduction of a sheet of water of constant thickness with a constant phase; (b) a correction proportionnal to the amplitude which is thus larger in the coastal area. Both procedures give the same results at the 0.1 μgal level. They have been compared with the results of Goad (1980) who developed a procedure based on integrated Green's functions which insures the mass conservation.

For the M_2 tide, the nonconserved tidal height has a magnitude equal to 2% of the mean amplitude. When correcting for the deficiency of tidal mass, the gravity tidal loading vector changes of about 10% (15% in central Europe, Baker et al. 1991) which is a non-negligeable quantity. This physically justified correction is obtained by a purely mathematical artifice. This former point is the main grievance against this kind of correction.

Local ocean tides models.

For coastal and island stations, the discretization of the Schwiderski model is not sufficient so that people have recommended to incorporate refined local models into a global model. It is to be mentioned that paradoxically most of the VLBI stations are located near the coast where the ocean loading effects are strongest and worst modelled .

The local ocean tide models can supply the global ones by two ways : either by replacing locally the global model or by completing the global model. Replacing locally a global ocean tide model by a regional model with a better spatial resolution and known to be more accurate do not give necessarily a better agreement between observed earth tide residues and computed loading effect (Jahr, 1989). This is due to the inconsitency that may appear at the connection between the two models. Moreover, what must be done to globally conserve the tidal mass when mixing two models remain a critical question. On the other hand, to add regional models of marginal seas which are not covered by the global one seems to be in every case very efficient. For example, in order to estimate the gravity loading tide due to the Mediterranean sea not modelled by Schwiderski (1980a-b), we used the tidal solution computed at the GRGS (Toulouse) with the finite element model of Le Provost and Vincent (1991b). The results for the M_2 tide are given in table 1 and they are significant with respect to the precision of the superconducting gravitymeters which are installed at these stations.

Stations	Amplitude in microgals	Local Phase in degrees
Strasbourg	0.050	-57.8
Bruxelles	0.030	-49.2
Bad Homburg	0.036	-58.4

Table 1 : M_2 load gravity tide due to the Mediterranean sea.

In summary, as Scherneck (1990) wrote : "Ocean loading computations comparing the different Green's functions concluded that errors in regional and global ocean tide models are about one order of magnitude more important than loading Green's functions from reasonably different earth's models".

Present status of ocean modelling

This section will concern only global oceanic tidal models because local modelling is a too wide research field. Nevertheless, I wish to emphasize Scherneck's work (1991) on regional ocean tides modelling in relation with the loading computations. The modelling of global oceans tides may be theoretical, semi-empirical or empirical. The theoretical approach consists in solving the hydrodynamical equations of tides, say extended Laplace's Tidal Equation, including our knowledge of the potential of the tide-generating force and the geometry of the responding basins (ie., Hendershott, 1977; Zahel, 1980). In the semi-empirical approach, theoretical calculations are constrained by direct measurements (Parke & Hendershott, 1980; Schwiderski,1980a-b), whereas empirical models are constructed solely on the basis of direct measurements. At the present time, the best models proceed from semi-empirical method. Nevertheless, such models suffer from a lack of tidal observations in the deep ocean. Thanks to satellite altimeter, this kind of information is now available.

Nowadays, there are essentially two directions to model ocean tides : a purely hydrodynamical modeling and an empirical approach. In addition, methods based on assimilation techniques are conducted in order to combine the hydrodynamical model and the empirical model in an optimal way to give rise to a new generation of ocean tides models taking into account every kind of information about the modelled phenomenon.

HYDRODYNAMICAL MODEL

There is at present day only one purely hydrodynamical global model of ocean tides under development with the aim of a centimetric accuracy on the main constituents (Le Provost & Vincent, 1991b). This in-time spectral model solves the classical depth integrated shallow water equations written in spherical coordinate frame related to the earth. A quadratic law description of the botom friction is adopted. The model is formulated in a variational form numerically solved by a finite element technique allowing mesh refinement in shallow areas in order to better describe the physical processes occuring there. The finite element formulation rigorously guarantees the mass conservation and the loading potential is included. The model has been very recently applied to the computation of tides in the Atlantic, Indian and Pacific oceans. The first solutions are under calibration and validation.

EMPIRICAL MODELS

Several kinds of instruments directly or indirectly observe the ocean tides. Those which give the best direct measurements are the altimeter onboard satellite and tide gauge measurements, while gravity tides observations are the most famous indirect sensor of oceanic movements.

altimetry

SEASAT provided the first extraction of ocean tides from altimeter data. Essentially, three complementary methods were developed (see Woodworth & Cartwright 1986). The first method (Cartwright & Alcock, 1981) provides "point measurements" of the tides at the crossovers of the Seasat repeat ground track. The other two methods involve spatial expansions of M_2 in terms of eitheir surface spherical harmonics (Mazzega, 1985) or Platzman normal modes of the world ocean. Ponctual estimations of the ocean tides and feasability studies have been carried out by Mazzega and Jourdin (1991) based on Inverse Theory making use of spatial covariances. These first attempts proved satellite altimetry as a potential source of tidal knowledge but the results were limited by the noise of the dataset and its shortness (one month).

With GEOSAT, a lot of work has been initiated in many directions (see the review of Cartwritght, 1991). Wagner (1990a-b) proposed solutions based on mean values of the altimeter data. The most complete solutions for the principal diurnal and semi-diurnal constituents have been recently published by Cartwright and Ray (1991) who made use of the admittance concept in their analysis of two years of Geosat altimetry. Their solutions are being under validation procedures by different means : comparison with the Schwiderski's model and in-situ data as well as techniques involving altimeter data. The final goal is to determine the best oceanic tidal model for the future altimeter missions like Topex-Poseidon. Up to now, only qualitative models were obtained due to the complexity of the errors budget of the altimetry measurements. Although altimetry provides the necessary data coverage, the success is today limited by a major difficulty : the orbit error (error in the computed radial height of the satellite of the order of a meter).

Present and future altimetry missions, like ERS1 (ESA) and TOPEX-POSEIDON (NASA/CNES), open cheerful prospects for tidalists since the accuracy of the orbitography of TOPEX should be of the order of a decimeter in absolute terms. At this stage, it is interesting to note that the satellite orbit is disturbed by the potential of the direct tides as well as by the potential of the oceanic and loading tides that we want to improve. Hopefully, the corrections of such effects are well determined since the satellite orbiting at about 1000 km of altitude, it is only sensitive at the low coefficient of the harmonic expansion of the tide.

tide gauge

Tide gauge data have been widely used to constrain semi-empirical models as well as to check ocean tide models. Since the work of Villain in 1952, empirical modelling of the ocean tides has been partly abandonned due to the emergence of the computer allowing numerical integration of the LTE. In the framework of the development of an empirical model from altimeter data, Francis and Mazzega (1991) computed an empirical model solely on the basis of deep sea and coastal tide gauge measurements. The optimal interpolation of these data based on "inverse theory" uses a priori spatial covariance functions of the tidal heights as deduced from the Schwiderski's model. One advantage of such a technique is the production of a formal error map associated with the solution. This estimated error is a key ingredient in the assimilation procedure with hydrodynamical model. The solution for the M_2 tide is relatively good when compared to in-situ data and the Schwiderski's model even in the open oceans where only few data are available. This lack of data will be fulfilled by using altimeter data. Indeed, the inverse method allows mixing of different kinds of data all together in an optimal way and it is now enlarged to include altimeter data.

Assimilation of empirical models into hydrodynamical models

The third approach which should be rather thought as the "final step" for modelling ocean tides consists in mixing the hydrodynamical and empirical models in an optimal way by means of a statistical technique, say assimilation. New generation of very accurate ocean tide models should be obtain taking the best of the two former approaches. Papers on this subject have been presented by Jourdin, Granwunder and Zahel at the IUGG in Vienna (1991). Zahel (1991) recently published a paper on this field in full growth.

Inversion of Gravity Loading Data

Because observed gravity earth tides involve loading effects which are the major perturbations on the earth tides, it is therefore possible, in principle, to invert tidal loading observations for both the distribution of the ocean tides and the elastic properties of the earth. In practice, the elastic properties of the earth conditioning the Green's functions are assumed to be perfectly known, only informations on ocean tides are deduced. I will recall first the pioneering work of Kuo and Jachens (1977) on "Indirect mapping of ocean tides by solving inverse problem for tidal gravity observations" which was confined to regional oceanographic areas and secondly recent results by Francis and Mazzega (1990a) on global mapping of ocean tide from gravity loading (GLD) data of the ICET (International Center of Earth Tides) data bank.

Kuo and Jachens (1977) tried to map ocean tides by inverting Gravity tides data together with tide gauges measurements. A linear programming inversion method has been used to produce M_2 and O_1 tidal maps for the northeastern Pacific and a M_2 map for the north atlantic. These are in significantly better agreement with some ocean-bottom tide gauge measurements which were not included in the inversion than the a priori models of Tiron et al. (1967).

Francis and Mazzega (1990a, Jourdin et al. 1991) have inverted 233 selected gravity data from the ICET data bank to produce a global M_2 map of the oceanic tide. The solution was obtained by an inverse method using covariance functions deduced from the Schwiderski's model and from the global chart of gravity loading effects of Francis and Mazzega (1990b). The solution exhibits the well-known features of the M_2 tide, the main amphidromic points being relatively well positioned with the right phase rotation but the success in the amplitude recovery is rather moderate. The results are more qualitative than quantitative. The origin of this modest results can be accredited to : (1) the poorly geographical distribution of the stations due to the continental shapes (especially in the southern hemisphere), (2) GLD observations contain informations not only on oceanic tides, (3) instrument calibration and systematic errors : the assumption of a white noise of 0.5 μgals is a too simple error model and (4) the inversion cannot propagate information at long distance due to the characteristic of the kernel of the convolution integral.

Synthetic gravity loading data have been calculated at the ICET stations by using the Schwiderski's model and then inverted. The difference between the ocean tide solutions obtained by the inversion of the synthetic and ICET data is shown in figure 2. It represents the projection of the instrumental errors, a part of the errors of the Schwiderski's model and all the non ocean tide signal contained in the ICET data in terms of tidal height.

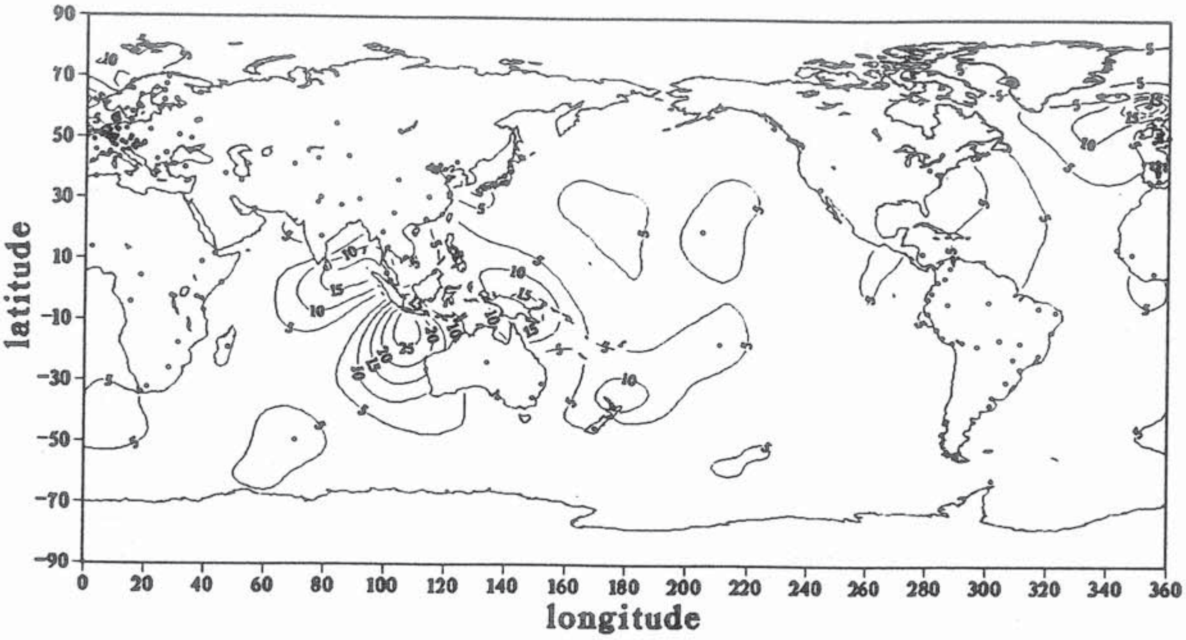

Figure 2 : difference between the ocean tide solutions obtained by inversion of synthetic data (computed by using the Schwiderski's model) and ICET data. Amplitude for the M_2 tide in cm. The ICET stations are located by a dot.

At the light of this experiment, it is clear that there is a non-negligeable amount of information in the ICET data bank but the problem consists in separating the different contributions. A key element is certainly the precision of the observations, as it cannot be improved, at least a better comprehension of the errors behaviour should be of a great help to model the ocean tides as well as to validate ocean tide models. The gravity loading data may play a major role in the validation process of ocean tide models because they are the only data being independent of the ocean tide models that offer a global test through the convolution integral all over the oceans. Once more, the validity of such a test is limited by the precision of the gravity loading data and by our knowledge of their contents.

Conclusion

The accuracy of the ocean tide loading correction essentially depends upon our ability to model the oceanic tide. Improved global ocean tide models with respect to the Schwiderski's model should be soon available thanks to present and future altimetry missions. Gravity tide observations should be useful to validate the new ocean tide models as far as their accuracy allows it. In addition, sufficiently accurate loading correction will allow to extract the part of the tidal residues due to instrumental errors and to the earth tide anomalies restarting more quantitative studies.

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