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Earth and Ocean Tides: Theory and Analysis

Conveners: T. Baker, H.T. Hsu

PRESIDING

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Paper No	Time	Type	Title	Authors
ETS-03-01	08:30-09:00	I/O	What have we really learned about the Earth from tidal gravity, tilt and strain observations?	W. Zürn
ETS-03-02	09:00-09:15	C/O	An estimation of the errors in the gravity ocean tide loading computations	M. S. Bos, T.F. Baker
ETS-03-03	09:15-09:30	C/O	Design of a local ocean tide model in the nearby of El Hierro (Canary Islands)	J. Arnoso, M. Benavent, B. Ducarme, F.G. Montesinos
ETS-03-04	09:30-09:45	C/O	Tidal Gravity and Oceanic Loading Obtained with LCR-ET20 Instrument at Station Hong-Kong, China	H.Z. Hsu, W. Chen, XD Chen, S. Gao, M. Liu, H.P. Sun
ETS-03-05	09:45-10:00	C/O	Testing the Oceanic and Earth Tidal Models using GGP and ICET Data Banks	A. Kopaev, B. Ducarme
	10:00-11:00		**COFFEE BREAK AND POSTER VIEWING**	
ETS-03-06	11:00-11:15	C/O	Tidal Gravity and Oceanic Loading Obtained with a Single and a Double Sphere SG at Stations Wuhan and Sutherland	H. P. Sun, J. Neumeyer, X.D. Chen, O. Dierks, J.C. Zhou, H.Z. Hsu
ETS-03-07	11:15-11:30	C/O	Validation of long period oceanic tides with superconducting gravimeters	J.-P. Boy, M. Llubes, R. Ray, J. Hinderer, N. Florsch
ETS-03-08	11:30-11:45	C/O	Accuracy Assessment of Ocean Tide Loading Computations for Precise Geodetic observations	K.H. Zahran, G. Jentzsch, G. Seeber
ETS-03-09	11:45-12:00	C/O	Analysis and prediction of ocean tides by the computer program VAV	B. Ducarme, A.P. Venedikov, R. Vieira, J. Arnoso
ETS-03-10	12:00-12:15	C/O	A modern, analytical approach to the harmonic development of the tide-generating potential	S. Casotto, F. Biscani
	12:15		**END OF SESSION**	
	12:15-13:30		**BBQ AT THE NATIONAL ARTS CENTRE**	
			POSTERS	
ETS-03-11		C/P	A comparison of ocean tide loading models with tidal gravity observations in the Canaries	J. Arnoso, R. Vieira, F.G. Montesinos, M. Benavent
ETS-03-12		C/P	Data processing of the Membach SG	M. Van Camp, O. Francis, M. Hendrickx
ETS-03-13		C/P	Surface deformation due to non-linear tides in the North Sea.	S. A. Khan, J. Wahr, O. B. Andersen
ETS-03-14		C/P	World Wide Synthetic Tide Parameters for Gravity, Vertical and Horizontal Displacements	K.H.Zahran, G.Jentzsch, G. Seeber
ETS-03-15		C/P	Analysis of SG tidal data by the programs ETERNA and VAV	B. Ducarme, L. Vandercoilden, A.P. Venedikov
ETS-03-16		C/P	Advances in Southern Ocean Tide Modeling	Y. Yi1, K. Matsumoto, A. Braun, C. K. Shum, Y. Wang

C: *Contributed*; **I:** *Invited*; **O:** *Oral*; **P:** *Poster*

ETS-03-01

What have we really learned about the Earth from tidal gravity, tilt and strain observations?

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In the past 4 to 5 decades extensive attempts have been undertaken to record Earth tide gravity, tilts and strains with ever increasing precision in order to answer important questions about the interior of the planet. For example:

--- What is the elastic and anelastic response of the Earth to tidal forcing, at the different tidal periods (i. e. Love numbers)?

--- What are the effects of lateral heterogeneities (in crust and mantle) on this response on local, regional and global scales?

--- How large are possibly the nonlinearities in these responses?

--- Is the response locally or regionally time-variable due to earthquake preparation and/or hydrogeological processes?

--- Can we derive information about the Earth's cores from the tides?

and so forth. In this paper an attempt will be made to assess realistically and provocatively the answers obtained from these observations relating to the interior of the Earth. These results have to be compared (unfavorably) to some extent with the achievements obtained simultaneously from global seismology.

ETS-03-02

An estimation of the errors in the gravity ocean tide loading computations

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The accuracy of the ocean tide loading values have always been restricted by the errors in the ocean tide models. However, due to more and better satellite altimetry data and new assimilation techniques, the accuracy of the ocean tide models have improved significantly. It is therefore appropriate to examine all the errors made in the loading computations to see if the uncertainty in the ocean tide models is still the limiting factor.

Knowledge of the error budget would be of great help for the study of the Earth's body tide where one tries to quantify the inelasticity of the solid Earth. The difference between the gravimetric factors for an elastic and inelastic Earth is around 0.10%. Thus, to achieve this objective the accuracy of the observations needs to be better than this value. Since the observed signal also contains the ocean tide loading, the removal of this loading needs to be accurate enough to keep the distortion of the remaining data below this threshold. Next, to validate ocean tide models themselves using tidal gravity observations knowledge of the numerical error of the loading computation is necessary.

ETS-03-03

Design of a local ocean tide model in the nearby of El Hierro (Canary Islands)

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The largest source of uncertainty in the ocean loading computation is due to errors in the ocean tide models. In coastal areas and small islands the relatively coarse grid of global ocean tide models (even the most recent with 0.25°*0.25° resolution) would create discretization errors of the loading effects in the near-field. We design a new local/regional ocean tide model in the nearby of El Hierro (Canary Islands). In this model, the original grid representation is taken from a global ocean tide model. The grid cells were subdivided recursively until the required resolution was reached. The land/sea distribution was derived from two different sources. One for the local area, which is taken from the Digital Terrain Model of El Hierro Island. The other one is a High-resolution Shoreline Database to fit the regional ocean tide model to the coast of the remaining Canary Islands region. The recent advancements for data assimilation techniques with the TOPEX/Poseidon altimetry data has been used to constrain this new model.

ETS-03-04

Tidal Gravity and Oceanic Loading Obtained with LCR-ET20 Instrument at Station Hong-Kong, China

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Based on the cooperative scheme between Institute of Geodesy and Geophysics (IGG), Chinese Academy of Sciences, and the Hong-Kong Polytechnic University, the tidal gravity observations obtained with a LCR-ET (No.20) instrument at station Hong-Kong/China in the period from August, 2002 to December 2003 are studied systematically. The original observations are carefully preprocessed, the peaks and steps are carefully corrected, a long drift is modeled using polynomials. The new tidal gravity parameters are calculated based on the Eterna package, the residual amplitudes and background noise in temporal and frequency domains are compared. The tidal gravity parameters are used to check the suitability of the various ocean tidal models.

ETS-03-05

Testing the Oceanic and Earth Tidal Models using GGP and ICET Data Banks

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We have used the most recent oceanic tidal models e.g. FES'99/02, GOT'00, CSR'4, NAO'99 and TPXO'5/6 for tidal gravity loading computations using LOAD'97 software. Resulting loading vectors were compared against each other in different regions located at different distances from the sea coast. Results indicate good coincidence for majority of models at the distances larger than 100-200 km, excluding some regions where mostly CSR'4 and TPXO'5 have problems. Outlying models were rejected

for this regions and mean loading vectors have been calculated for more than 200 tidal gravity stations from GGP and ICET data banks, representing state of the art of tidal loading correction. Corresponding errors in delta-factors and phase lags are generally smaller than 0.1 % resp. 0.05 deg, that means that more attention should be applied to the calibration values and phase lag determination accuracies. Corrected values agree with DDW model values very well (within 0.2 %) for majority of GGP stations, whereas some of very good (Chinese network) ICET tidal gravity stations clearly demonstrate statistically significant (up to 0.5 %) anomalies that seem to be not connected either with calibration troubles or loading problems. Various possible reasons including instrumental and geophysical ones will be presented and discussed.

ETS-03-06

Tidal Gravity and Oceanic Loading Obtained with a Single and a Double Sphere SG at Stations Wuhan and Sutherland

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Based on the cooperative scheme between Institute of Geodesy and Geophysics (IGG), Chinese Academy of Sciences, GeoForschungsZentrum (GFZ) Potsdam in Germany, the tidal gravity observations obtained with a single SG at station Wuhan/China and a double sphere SG at station Sutherland/South African for same period from March 31, 2000 to June 1, 2003 are studied systematically. The peaks, steps and short term interruptions in the original observations are carefully checked and corrected, the tidal gravity parameters are calculated based on the Eterna package, the residual amplitudes in temporal and frequency domains for both stations are compared. The ocean loading vectors are calculated with a discrete numerical integral technique, the suitability of the ocean tidal models is evaluated and the corresponding results when using various models are compared. It is found that the determined accuracy of the tidal parameters and background signals at both stations are at sa! Me level. The average reduction of the loading correction based on the 11 global oceanic models is given as 85% (O1) and 73% (M2) (Wuhan) and 70% (O1) and 99% (M2) (Sutherland). Comparing to the theoretical models, the average discrepancies of the amplitude factors are reduced from 2.13% to 0.23% (O1), from 1.16% to 0.33% (M2) (Wuhan), and from 0.72% to -0.15% (O1), from 3.21% to - 0.05% (S2) and from 2.95% to -0.09% (K2) (Sutherland).

ETS-03-07

Validation of long period oceanic tides with superconducting gravimeters

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Thanks to the long term stability of superconducting gravimeters (SG), we are able to study the signature of long period ocean tidal loading, with periods close to 14 days (Mf), 30 days (Mm) and half a year (Ssa).

We extracted from the Global Geodynamics Project (GGP) network a subset of about 20 SG records and compared the observed ocean tidal loading to the estimated loading with most recent tidal models. The

fortnightly and monthly tidal components have been now successfully extracted from the long time series (1992-now) of satellite altimetry (Topex/Poseidon and Jason).

Due to its inclination, Topex/Poseidon is only recovering ocean tides for latitude below 66 degrees; high latitude areas are also characterised by a lack of tide-gauge or bottom pressure data. Gravity measurements appear then to be one of the few tools to validate ocean tidal models at high latitudes. A special attention is therefore paid for the high latitude SGs (New Alesund in the Artic, Sutherland in South Africa and Syowa in Antarctica).

ETS-03-08

Accuracy Assessment of Ocean Tide Loading Computations for Precise Geodetic observations

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Three TOPEX/POSEIDON derived models (CSR3.0, FES95.2 and TPXO.2) besides of the classical SCHW80 model were selected for an accuracy assessment study. The covariance functions of the differences between the tide gauge observations and the interpolated tidal constituents from the selected ocean tide models were used as a base for the combination of some of these models. Evaluating the selected models using ground-based tidal measurements is carried out by comparing the elastic parameters calculated with these models to the corresponding parameters measured at 59 tidal gravity stations. Furthermore comparisons are made to the elastic parameters from two different types of tiltmeters. The site deformation of a number of selected GPS permanent stations due to ocean tide loading will be discussed. Site deformation differences are compared, applying the selected ocean tide models. In addition, accuracy assessment of GPS coordinate determination applying ocean-tide loading corrections estimated from the selected ocean tide models will be considered. Efficiency of the selected models of the change of tidal constituents in shallow water areas and shelf regions due to the local resonance effects is also investigated.

ETS-03-09

Analysis and prediction of ocean tides by the computer program VAV

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It is shown that the model of the tidal signal, used in the earth tide analysis since 1966, is equivalent to the model, proposed by Munk and Cartwright also in 1966. Due to this the VAV program can be used for the analysis of ocean tide data. The program has several specific options for the ocean tides. It can consider waves with arbitrary frequencies, till 11 cpd (cycles per day) for hourly data and still higher for data with time step smaller than 1 hour. This allows the investigation of the shallow water waves. The latter can be defined in a very convenient manner as linear combinations of tides or directly through the frequencies. It is possible to search the existence of unknown waves in given frequency band, including the appearance and disappearance in the time of such waves. Special attention is given to the determination and analysis of the mean sea level. The output includes the amplitudes and the phases of the main tides in every tidal group, as well as amplitudes and phases of all 1200 tides of the development of

Tamura, together with the additionally defined shallow water tides. VAV can make a long-term prediction of the tidal signal through data analysis or through the input of amplitudes and phases. A short-term prediction, including the drift, is also available. This operation may be important in the cases of strong wind and air-pressure changes. The short-term prediction can use large series of data, as well as very short series of the order of 48 hours. The paper presents examples of applications of the VAV program. The table shows a set of shallow water tides, obtained through the analysis of a series of 36 years (January, 1945 – December, 1980) ocean data, obtained in Oostend, Belgium.

Wave name	Frequency cpd	Ampli-tude cm	*MSD*	Phase degrees	MSD
2NM6	5.72424	0.890	±0.054	276.65	±3.51
2MN6	5.76053	2.931	0.054	303.26	1.06
M6	5.79682	5.449	0.054	327.22	0.57
MSN6	5.82826	1.423	0.054	4.66	2.19
MKN6	5.83373	0.589	0.054	354.54	5.30
2MS6	5.86455	5.624	0.054	15.12	0.56
2MK6	5.87002	1.582	0.054	13.81	1.97
2SM6	5.93227	1.286	0.054	72.37	2.42
MSK6	5.93775	0.807	0.054	72.81	3.86

ETS-03-10

A modern, analytical approach to the harmonic development of the tide- generating potential

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The current reference harmonic development of the tide-generating potential (TGP) lists many thousand terms obtained by a purely numerical approach using spectral analysis techniques on long time series calculated from numerical ephemerides of the Sun, the Moon and some of the planets. Some minor attempts have been made to develop the TGP analytically without reaching the extension of the numerical development. The availability of a very accurate analytical theory of the motion of the Moon, the identification of a new methodology for the analytical development and the availability of efficient algebraic manipulation systems has prompted us to attempt a new, fully analytical attack on/at this old problem, first successfully carried out by Doodson in 1921 by hand computation of the first 388 tidal constituents.

The new method of expansion invokes Wigner's rotation theorem of spherical harmonics to transform the Sun's and the Moon's motions from the ecliptical to the equatorial system in a form perfectly suitable to algebraic manipulation up to any desired spherical harmonic degree. The paper shows that the formulation proposed can easily handle the accurate modelling of the precessional and nutational motions of the Earth and the perturbations due to the figure of the Earth as well as the perturbations due to the planets, both direct and indirect. This approach is inherently free of the imperfections that sometimes bias the purely numerical methods.

This novel method has been implemented in a suite of Mathematica routines. The first results of the new development will be presented for the case of the lunisolar tidal expansion as a validation of the method. Partial results will also be given for the effects of Earth's precession and nutation on the TGP.

ETS-03-11

A comparison of ocean tide loading models with tidal gravity observations in the Canaries

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A comparison between global ocean tide models is carried out in the Canaries. Results from gravity tide observations, made with LaCoste & Romberg-G gravimeters with electronic feedback, have been used to test the models in two places located, respectively, in two distant islands of the Archipelago (Lanzarote and Tenerife Islands).
In both cases the stations are near to the coast. Whereas in Lanzarote Island the distance from the station to the coastline is of some 1.6 Km in Tenerife Island reaches some 20 Km, although in this last place the emplacement is located 2150 m above the sea level. A significant effect of the ocean tide is undergone in both places.
In order to calculate the gravity loading in those places, we have selected nine ocean tide models with grid size that ranges from 1°x1° till 0.5°x0.5° and 0.25°x0.25°, which is the case of the most recent models. In addition, for a more precise evaluation of the load, regional and local ocean tide models, which are adapted to the area of study, have been used to complement the global ones.
The results of the tidal gravity observations for the harmonics M2 and O1 have been applied to compare with ocean tidal loading provided by the nine global ocean models considered. Besides, we have tested the results obtained for different Earth models in order to evaluate its influence.

ETS-03-12

Data processing of the Membach SG

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In August 1995, the Royal Observatory of Belgium installed the superconducting gravimeter (SG), GWR C021, at the geophysical station of Membach. This Geophysical Laboratory is located at the end of a 140 meter long tunnel cut into the side of a hill. A barometer is installed 2 m apart from the SG, and a meteorological station is recording at the entrance of the gallery. The data are downloaded to the Royal Observatory nearly every day and are carefully checked. We describe here the processing made on a daily and monthly bases, especially on gravity and pressure time series.

Basic daily processing of the SG data includes editing and correcting for steps (helium re-filling), spikes and other disturbances. A visual check is also performed on the SG auxiliary parameters: tilts, helium flow and heater signals.

The monthly processing consists in:
1) Controlling the amplitude calibration factor and air pressure admittance. Moreover, yearly comparisons with the absolute gravimeter FG5#202 have demonstrated that the calibration factor

remained stable at the level of precision of the calibration factor itself (i.e. 0.10 % for the gravity, 0.25 % for the pressure (the FG5 barometer is calibrated against standards regularly)). However, additional monthly control is done by detecting remaining tidal and air pressure signals in the corrected gravity residuals. These residuals are obtained by removing a synthetic tide; atmospheric effects (loading and mass attraction) using a linear admittance factor of -3.3 µGal/hPa, and polar motion effects.

2) Editing minute data: calibrated air pressure, synthetic "instrumental" and real tide, raw and corrected residuals and corrected gravity data

3) Editing hourly data: polar motion effect on gravity, calibrated air pressure, gravity residuals (not corrected and corrected for polar motion effect) and the gravity residuals (corrected for polar motion and the instrumental drift of 45 nm/s²/year). Decimation from 10 s data to minute and hourly ones are made by applying FIR LSQ filters, which do not cause any phase distortion.

4) The gravity and atmospheric pressure signals are recorded by two data acquisition systems St1 and St2, working independently. Therefore the monthly data processing also consists in comparing St1 with St2. This includes computing the differences of raw signals [St1-St2], controlling of possible changes in amplitude sensitivity and time-shifts between St1 and St2.

The processing are made using Tsoft.

ETS-03-13

Surface Deformation Due To Non-Linear Tides in the North Sea

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The indirect deformations of the Earth caused by variations in the surface load from non-linear tides are detectable by measuring e.g. surface displacements, tilt or gravity changes. To predict these shallow water loading deformations, an ocean tide model (describing the spatial and temporal distribution of the surface load) and a visco-elastic Earth model (describing how the Earth responds to the surface load) are needed. The ongoing satellite altimetry missions have improved considerably to model these effects. In this study, we use Topex/Poseidon (T/P) data to construct a model for the shallow water loading deformations at the third-diurnal and higher frequency tidal band. Furthermore, we compare our T/P results with vertical surface deformation observed using GPS at some selected locations in the coastal region of the North Sea.

ETS-03-14

World Wide Synthetic Tide Parameters for Gravity, Vertical and Horizontal Displacements

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The deformation of the ocean floor and adjacent land in response to the redistribution of water, which takes place during the ocean tide, is known as ocean-tide loading. Estimating the ocean tide loading requires a model of the ocean tides and knowledge of properties of the solid Earth. The body tide contributions can be added to the oceanic contribution to provide the Earth tide response. In the current

study, synthetic Earth tide parameters (amplitude factors and phase leads) have been developed on a world wide grid for gravity, vertical and horizontal displacements. However, beside the Earth tide parameters synthetic ocean tide parameters are also given separately

ETS-03-15

Analysis of SG tide data by the programs ETERNA and VAV

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The paper presents analysis results, obtained by the program ETERNA, version ANALYSE (Tamura development, Pertsev filter on 51 hours) and the last version of the program VAV. The programs have been applied on 14 stations with SG data, included in GGP.

Some elementary experiments show that both programs provide rather similar results. As shown here, the results become different when VAV is applied after a careful choice of the variant used, as well as by using its options for elimination of anomalies.

ETERNA uses a moving filtration with considerable losses of data in the case of many gaps. This imposes a preprocessing, trying to avoid the gaps, through reparations of anomalous data and interpolations of missing data. Unfortunately, these operations introduce a non-Gaussian and non-stationary noise, i.e. systematic errors.

For VAV the gaps may remain such as they are, because they do not increase considerably the losses of data. Something more, VAV allows an increase of the number of gaps through the elimination of strong anomalies, for the sake of an improvement of the precision. The elimination can be made automatically in several iterations and its effect is controlled by the estimates of the precision of the results.

Another way to improve the precision, found here, is to vary the time window TW (length of the filtered intervals) and the power K of the eliminated drift polynomials. It appeared that different TW are optimal for different tidal species. Generally, we have got that the “classical” TW = 48 hours is most suitable for the D species, TW = 24 fours – for the SD species and TW = 16 hours – for the high frequency species, i.e. TD, QD and so on.

The adjacent table is an example of the results obtained. As far as we can compare the estimates of the internal precision, provided by ETERNA and VAV, this example shows that VAV can provide more reliable results. Similar is the case in most of the series, analyzed in the paper.

SG data Cantley, Canada, 11.07.1989 – 31.12.2001							
Q1	O1	K1	N2	M2	S2	M3	M4
Results by **ETERNA/ANALYSE**, TW = 51h (filters with 51 coefficients)							
1.16519 ±.00054	**1.16605 ±.00010**	**1.14782 ±.00007**	**1.20922 ±.00022**	**1.20344 ±.00004**	**1.18394 ±.00010**	**1.07776 ±.00199**	**0.8240 ±.0836**
Results by **VAV/2004**, 2 iterations for elimination of anomalies							
TW = 48h, K = 2			TW = 25h, K = 2			TW = 16h, K = 2	
1.16554 ±.00029	**1.16599 ±.00006**	**1.14787 ±.00004**	**1.20900 ±.00009**	**1.20351 ±.00002**	**1.18401 ±.00004**	**1.07902 ±.00035**	**0.8448 ±.0220**

ETS-03-16

Advances in Southern Ocean Tide Modeling

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Tides in the polar region play a major role in sea ice and float glacial ice shelves dynamic as well as shifting of the grounding lines for ice mass balance studies. Recently, it has been demonstrated that tides significantly influenced the observations of sea ice thickness changes. Current ocean tide models are much less accurate in coastal seas and polar oceans than other ocean areas. In particular, ocean tides are largely unknown in part of the polar oceans which are covered by permanent or seasonal sea ice and which are beyond the geographical coverage of the TOPEX/POSEIDON (T/P) satellite. Here, we present analyses and preliminary ocean tide solutions using a combination of mostly high-latitude observing radar and laser satellite altimeters, including ERS-2, ENVISAT, and limited amount of ICESAT data. Ocean tide model in the Southern Ocean below 50°S are determined using these data in addition to also using T/P and JASON data. The satellite altimeter data at single- and dual satellite crossover points extensively used in the modeling to take advantage of an improved sampling in time that is known to be better than that of along-track altimeter data in coping with the tidal aliasing problems, which we will attempt to quantify. Finally, we tested both empirical model solutions using orthotides methodology and hydrodynamic model solutions assimilating single- and dual-satellite crossover data.