Research Article

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Ocean tide, Baltic Sea and atmospheric loading model tilt comparisons with interferometric geodynamic tilt observation - case study at Lohja2 geodynamic station, southern Finland

Abstract: Ocean loading models, Baltic Sea loading and atmospheric loading tilt models are compared with the long interferometric water level tilt meter recordings at the Lohja2 geodynamics laboratory in southern Finland. The tilt meter shows a high response to different loading phenomena, and it can be used to study earth dynamics, earth structure modeling, and 2D surface mass loading model validation. Special attention is paid on the Baltic Sea and atmospheric loading tilt oscillations. The four ocean loading models used show deviating values compared to the measured earth tide tilt parameters. The CSR4.0 ocean loading model fits best to analyzed tidal tilt observations at the site. After reductions of earth tides, ocean, the Baltic Sea and atmospheric loading tilt, the largest residual tilt signals are located in frequency bands below 0.5 cycle/day.

Keywords: Atmospheric loading, Baltic Sea loading, earth tides , interferometric tilt meter, ocean tide loading

1 Introduction

High precision tilt measurements offer a tool for determination of the loading effects caused by oceans, regional and local sea and lake mass variations, atmospheric mass variation and local hydrology (Jentzsch, 1997). Oceans are globally the main surface mass loading sources, but they are more than 1000 km from the observation site Lohja2. In some tidal potential wave groups (e.g. M2 in the semid-

iurnal tidal band) the ocean loading tilt signal may still exceed up to few tens of a percent of the earth tide tilt signal at Lohja2 (Kääriäinen and Ruotsalainen, 1989). Lohja2 geodynamical station located about 30 km north of the coast of the Baltic Sea. The small tidal loading tilt signal of the Baltic Sea has not been separated well enough from the total non-tidal loading signal yet. It can be done, if tidal and non-tidal wave characteristics of the Baltic Sea are well determined.

Earth tides are a well-known phenomenon and for reerences see e.g. Melchior (1983), Chojnicki (1989) and Agnew (2007). Main disturbances in the determination of earth tide amplitudes and phases are caused by ocean and atmospheric loading. Ocean tide loading models can be combined with the Earth tide models and tilt observations as shown e.g. in Jentzsch (1997), Kääriäinen and Ruotsalainen (1989) and Melchior (1983). Ocean tide loading models can this way be verified with the earth tide observations. According to Zschau (1978), the phase values of the earth tides observations are delayed by 0.01 - 0.001 degrees from the tidal potential model. We can set the zero phase accordingly for the theoretical earth tide model phase values.

The Baltic Sea mass variation contains a rich spectrum of different oscillation phenomena. The wind-driven free oscillation patterns on the surface of the Baltic Sea are complicated by the shape of the gulfs and islands according to Witting (1911), Lisitzin (1959) and Wübber and Krauss (1979). This makes the Baltic Sea level tidal height modelling challenging, because some of the independent free oscillation wave phenomena (seiches) have frequencies in the tidal frequency bands, but have completely different phases. Accordingly, the Baltic Sea crustal loading has an influence on high precision geodetic measurements inland far from the coast line. Standard geodetic tidal loading models, which may include the Baltic Sea, cannot take into account free oscillation loading correctly in the same frequency band because of the randomly existing phase.

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Our Baltic Sea mass variation modelling is based on the tide gauge data and surfaces created. The tide gauge data is obtained from the Finnish Meteorological Institute (Finnish data) and the Baltic Oceanographic Observation System (BOOS, http://boos.org, data from other countries around the Baltic Sea). The tide gauge data is given in the national annual mean sea level height systems. Sea level data contains different height system epoch based deviations (few centimeters) , but their influence on load models is small and cannot be observed. Glacial Isostatic Adjustment (GIA) of the Fennoscandian crust and Relative Sea Level (RSL) rise further complicates the exact determination of the loading phenomenon in Fennoscandia, but they need longer observation periods (few decades) to be detected in loading research.

The atmospheric loading tilt is already well-know from studies for over 100 years. Until the global atmospheric models became available, loading models were based on the mass distribution deduced from the atmospheric pressure field. Nowadays, global and regional meteorological services provide world-wide, continent-wide as well as national atmosphere models based on both ground and satellite observations. There are also operational atmospheric loading services, see e.g., http://loading.u-strasbg.fr. Recent atmospheric and non-tidal ocean loading time series for gravity and tilt is available e.g. by Boy et al. (2009). They modelled ocean response to air pressure variation according to the inverted barometer principle and taking into account general ocean circulation. They also provide continental hydrology loading models.

Gebauer et al. (2010) have studied the influence of topography around a station on atmospheric loading signal for four Central European stations of different topography. Based on the results in Gebauer et al. (2010) there is no need for special handling of atmospheric loading data due to the flat topography around the Lohja 2 station.

2 Geodynamic tilt measurements in southern Finland

Crustal tilt measurements by the Finnish Geodetic Institute started in 1967 at the Lohja1 geodynamic station in Ojamo mine, Lohja southern Finland and later in Lohja2 station Tytyri mine using Verbandert-Melchior horizontal pendulums (Kääriäinen and Ruotsalainen, 1979). Long interferometric Michelson and Gale (1919) type water level tilt meter has been developed further since 1965 at the Finnish Geodetic Institute (Kukkamäki,1965). The first version of a 177 meter long east-west water level tilt meter (EWWT) was designed and installed at the Lohja2 geodynamic station in 1974. The operating principle, tilt recordings and the first earth tide analysis results were published by Kääriäinen (1979). A 62 meter long north-south water level tilt meter has been recording in the same mine since 1983 (Kääriäinen and Ruotsalainen 1989). Earth tide tilts were reanalyzed and ocean loading tilt model comparisons were also carried out by Kääriäinen and Ruotsalainen (1989). The very seldom observed resonance frequency of the Nearly Diurnal Free Wobble (NDFW) was observed the first time in the east-west water level tilt meter by the diminishing amplitude factors of diurnal wave groups $\psi 1$ and $\varphi 1$. Also, a preliminary comparison to non-tidal tilt residuals to horizontal air pressure gradients were carried out with both instrument data. Both instruments operated up to 1996.

Parallel recording with water level tilt meters in Lohja2 station and an Askania borehole tilt meter at the Metsähovi Geodetic Station, Kirkkonummi, was carried out in 1986 - 1991. Lohja2 located about 20 km west from the Metsähovi station. Observed tidal amplitudes fit well together (mean deviations in amplitude 0.2 nanorad), but tidal phase values were more homogenous varying between 0 - -5.6 degrees in water tube tilt meters in Lohja. In the bore hole tilt meter in Metsähovi, they were more heterogeneuous varying between -3.9 – 7.2 degrees. Ground water pumping from the borehole well near the bore hole tilt meter (instrumental depth 62 m below the bedrock surface) at Metsähovi caused extra signal in tilt observations at Metsähovi. Atmospheric and local hydrological loading tilts at the Metsähovi station were preliminarily studied by Weise (1992). Weise et al. (1999) determined the initial Baltic Sea loading estimation based on earth tide recordings at the Lohja and Metsähovi stations.

3 Modernized third generation interferometric fluid level tilt meter of the Finnish Geodetic Institute

The designing and building of automated and interferometric water level tilt meter started in 2000 at the Finnish Geodetic Institute by Ruotsalainen (2001). Due to the automated fringe detection and improved resolution, it has been possible to detect different kinds of geodynamic signals. They are microseism, free oscillation of the earth body after big earthquakes, earth tides, and crustal sur-

face mass loading of oceans, the Baltic Sea, atmosphere, regional and local hydrology. Figure 1. shows the northern end of the present setup of the construction of the north-south oriented tilt meter (NSWT) at the Lohja2 station.
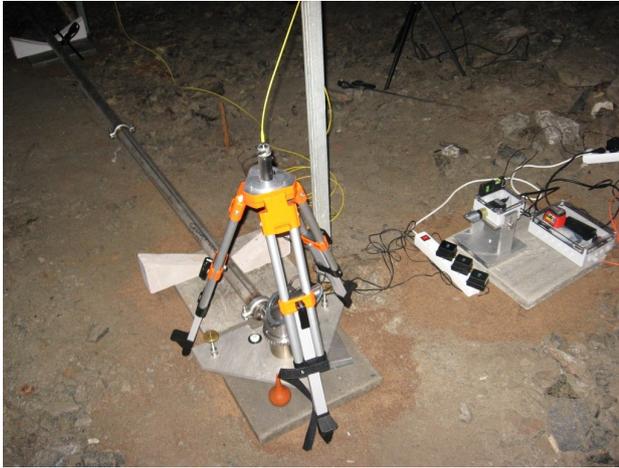

Figure 1: Northern end of the NSWT tilt meter. (Photo: Hannu Ruotsalainen).

The NSWT tilt meter consists of a 50.4 m long stainless steel tube (diam. 50.3 mm) half filled with water, two end pots, and two Fizeau type level sensing interferometers. The water surface and a spherical glass surface below it are illuminated by a laser beam (wavelength 543 nm, beam diameter 15 mm) and interference fringes are observed with Basler A602f CMOS cameras. Images are transferred to remote computers (200-260m from the interferometers) via IEEE1394 fiber optic extension bus. Interferograms are interpreted into water level height changes in real time by computer program with a 15 Hz sampling rate.

The wavelength of the HeNe laser is L_v = 543 nm (in a vacuum) and in the air L_{air} =L_n/n_{air} =542.8 ±0.1 nm., where n_{air} = 1.00028±0.00001 is the refraction coefficient of air. One level sensing unit is one interference phase P= $L_{air}/(2 \times n_w)$ =542.8±0.1nm/(2×1.333±0.010)=204.6±1.0 nm, where the refraction coefficient of water is n_w = 1.333±0.010. The level sensing 1.0±0.1 nm resolution from a recorded interferogram is a straightforward process by using C++ program for interference phase determination. Tilt resolution for 50.40±0.01 m long tube tiltmeter is then T_r = 2.0±0.2nm/50.40±0.01m =0.04±0.004 nanoradian. We get independently from the NSWT data after high frequency filtering by the earth tide analysis the least squares error estimate 30 − 70 picoradians for amplitudes of observations of four separated wave groups. See table 1.

4 Crustal tilt recording sample from Lohja2 geodynamic station
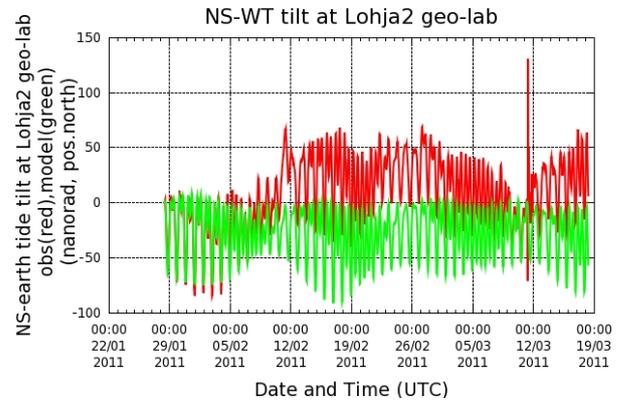

Figure 2: Geodynamical tilt recording of the interferometric water level tilt meter (red) and earth tide model tilt (green).

Interference tilt recording (Fig. 2) is first preprocessed by correcting artificial (man-made) and natural (earthquakes) jumps. Data filtering is carried out by convolution using Vienna filter parameter files from the Global Geodynamic Project (http://www.eas.slu.edu/GGP/ggphome.html). Earth tide analysis is carried out by programs developed by Wenzel (1996). The tidal potential development by Tamura (1987) and Wahr-Dehant-Zschau earth model (Wenzel, 1996) was used.

5 Ocean tide loading tilt models

We use D.C. Agnew's ocean loading program SPOTL (Agnew, 1997) and the ocean load provider of the Onsala Space Observatory (http://holt.oso.chalmers.se) for the Baltic Sea loading tilt and ocean loading tilt determinations, respectively. Four ocean tide models TPXO7.0 (Egbert and Erofeeva, 2002), CSR4.0 (Eanes, 1994), Schwiderski model (Schwiderski, 1980), FES2004 (Lyard et al. 2006) were used. Green functions based Gutenberg-Bullen earth model is used according to Farrell (1972) with SPOTL program. There are small differences between predicted diurnal loading tilt values, which can be recognized in Table 1 and Fig. 3. Differences between loading model amplitudes are smaller than nanoradian levels. We combine in complex plane four observed earth tide tilt wave groups vectors with ocean load model (correction) tilt vectors, and compare them to theoretical earth tide amplitudes with zero

phase. Some combined models do not fit well with the tidal model tilt vectors. This may indicate that the ocean loading models are not sufficiently precise in the sub-nanoradian accuracy level for analyzed tidal tilt parameters.

There is still some uncertainty in observation results because of the missing small Baltic Sea tidal loading tilt (model/observation) and possible cavity effect influence on tilt at the site (Jentzsch, 1997).
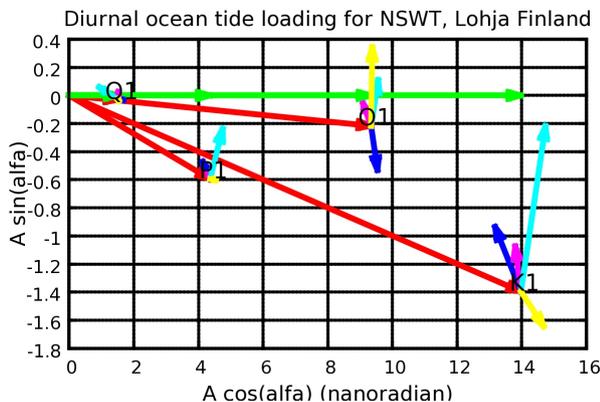

Figure 3: Green vectors along horizontal axis indicate theoretical model tilt (vector lengths are nanoradians from origin) with zero phase angle in complex plane. Red vector length indicates observed tilt amplitude and observed phase angle (alfa) indicated between horizontal axis and observation vector respectively (phase angle positive counterclockwice and negative clockwice). Ocean loading correction with amplitude and phase (sign changed from model table when the case is correction) is done according to vector addition, but now locating correction vector in the head of observation vector. It is easy to see how the ocean loading model can explain the deviation of observation compared to theoretical tidal model value. Terminology A cos (alfa) follow ing convention by Melchior (1983, page 332).

Ocean loading models are indicated by colors: Schwiderski model (blue), TPXO7.0 (purple), CSR4.0 (cyan) and FES2004 (yellow) for tidal potential wave groups Q1, P1, O1, K1.

The observed vectors in the wave groups Q1 and O1 fit quite well to the ocean loading model values. The most deviating are the vectors in P1 and K1 wave groups by phase and amplitude. According to Melchior (1983), and Goodkind (1983) the wave group O1 is not very disturbed by the Nearly Diurnal Free Wobble (NDFW), and it is therefore used for instrumental time lag estimation. Thereafter higher frequencies than O1 are disturbed up to the NDFW frequency. Phase deviation of the P1 and K1 wave group are most influenced, because they are located near the resonance frequency.

6 Loading by the Baltic Sea and atmospheric loading

The loading due to Baltic Sea mass variations is computed using a sea surface grid interpolated from hourly tide gauge data. The data are obtained from the Finnish Meteorological Institute (Finnish tide gauges) and from the Baltic Operational Oceanographic System (BOOS, http://boos.org other tide gauges). The grid surfaces are created using minimum-curvature-surface splines over the whole basin. The obtained hourly Baltic Sea mass variations are then computed into loading variables by the SPOTL program (Agnew, 1997, 2012). The variables are the load potential, gravity, tilt (2-D), strain (3-D) and displacement (3-D). The loading time series can then be used for correction of various geodetic measurements, e.g., by precise Global Navigation Satellite System (GNSS), Very Large Baseline Interferometry (VLBI), tilt meters, and superconducting and absolute gravity meters.
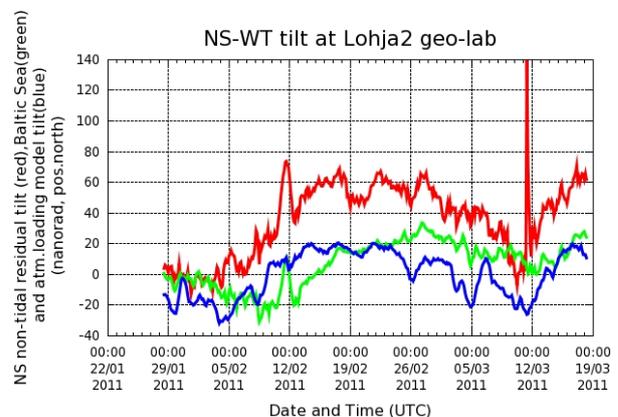

Figure 4: The Baltic Sea loading model tilt (green) and atmospheric loading (blue) and NSWT non-tidal residual (red) at Lohja2 station.

The Baltic Sea loading tilt is compared with NSWT tilt meter observations, which are de-tided first using the earth tide model described above. Note that the ocean tide loading models may also contain a (small) Baltic Sea tidal signal. The tilt meter residual contains the presence of the non-tidal seiche oscillations of the Baltic Sea, a phenomenon, which has some periods also in the tidal frequency bands. This complicates the modelling of the Baltic Sea tidal loading. The non-tidal tilt residual of the NSWT, (Fig. 4 and Fig. 5) contains a large 120 nanoradian tilt oscillation following the great magnitude 9.0 Tohoku-Oki earthquake in 11.3.2011 (Japan).

Table 1: Amplitude and phase values of the observed N-S earth tide tilt, earth tide model tilt and ocean loading model tilt for Q1, P1, O1 and K1 tidal potential wave groups.

N-S tilt (amplitude/phase)	Wave group			
(nanorad/degree)	Q1	P1	O1	K1
Observed tilt	0.31 -1.2	0.91 -7.8	1.93 -1.3	2.89 -5.7
Obs. tilt error	+-0.03 +-1.6	+-0.06 +-1.1	+- 0.04 +-0.3	+-0.07 +-0.3
Model	0.31 0.0	0.83 0.0	1.76 0.0	2.56 0.0
Schwiderski	0.16 0.6	0.26 -152.1	0.37 58.0	0.92 -150.1
TPXO 7.0	0.23 -80.1	0.18 -143.2	0.40 -147.2	0.65 -118.6
CSR 4.0	0.59 -171.3	0.52 -42.8	0.39 -55.9	1.40 -57.2
FES2004	0.02 22.7	0.17 1.8	0.56 -86.0	0.74 19.4

The atmospheric loading tilt time series was provided by Boy et al. (2009) and it is compared also to de-tided tilt meter observations described above (Fig. 4). There exist few daily southward (negative) tilt oscillations in the atmospheric loading model tilt, but not in the tilt meter's non-tidal residual.

7 Combined atmospheric and the Baltic Sea loading tilt vs. non-tidal earth tide tilt comparison and residual spectrum
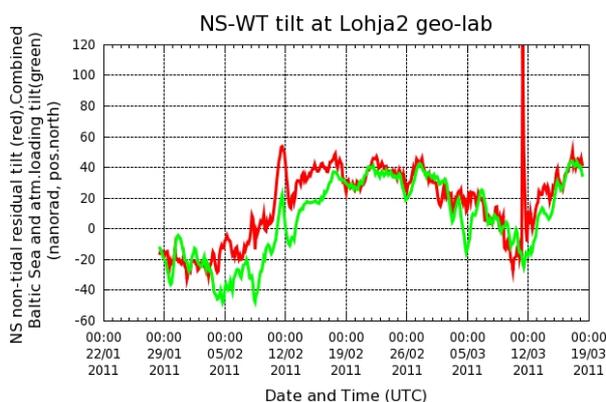

Figure 5: NSWT non-tidal residual tilt (red) is compared with the combined atmospheric loading NS-model tilt and the Baltic Sea loading tilt (green). At right side, there is a strong tilt residual caused by a magnitude 9.0 Tohoku-Oki earthquake in Japan 11.03.2011.

The 20 nanoradian downward shift exists from Feb. 3 to Feb. 18. The reason is unknown? On Jan. 29-30, Feb. 8, March 5, and March 10 the combined loading model has a large amplitude compared to the non-tidal tilt observation The real Baltic Sea surface can be curved in the middle of the sea in a different ways because of wind-driven and air pressure based surface stress compared with the adjusted minimum-curvature-surface spline surface based on tide gauge observations along the coast lines estimates.
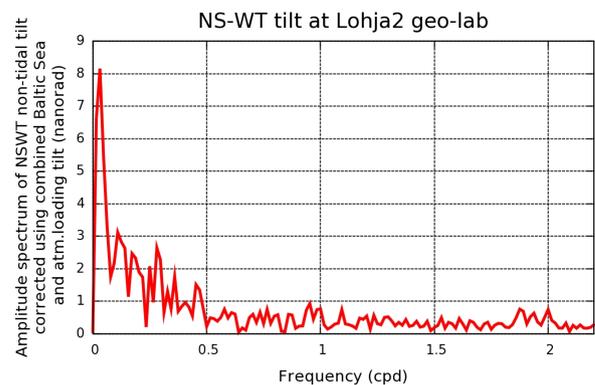

Figure 6: Amplitude spectrum of non-tidal residual tilt of the NSWT tiltmeter corrected by combined loading model tilts of the Baltic Sea and atmosphere.

Figure 6 shows spectral characteristics of non-tidal residual tilt of the NSWT tiltmeter after reduction by combined loading tilt of the Baltic Sea and atmosphere. On the left side of Fig. 6 the residual tilt signal has amplitudes from 1.5 upto 8 nanoradians in frequency bands below 0.5 cpd. Models do not have fit the non-tidal residual tilt of the NSWT in Lohja2 in that spectral band.

Combined the Baltic Sea and atmospheric loading tilt is less than a nanoradian in diurnal and semidiurnal bands and this confirms the well-known fact that in the Baltic Sea the tidal sea level amplitudes are only a few cm in the tidal frequency band. A completely other situation is the strong wind excitation when the Baltic Sea has several tens of cm amplitude eigenfrequency waves (seiches) (Witting, 1911, Lisitzin, 1958, Wübber and Krauss, 1979), which causes several tens of nanoradians loading tilt oscillation located also in the tidal frequency bands.

8 Conclusions

The earth tide tilt parameters together with the theoretical earth model tilt were compared to four different ocean loading models. CSR4.0 from those ocean loading models explain deviation between observed tilt and earth tide model tilt in four diurnal tidal wave groups. Ocean loading model amplitudes differ only at sub-nanoradian levels in each harmonic wave group at Lohja2 station.

It is shown by spectral analysis, that the non-tidal tilt residual of the NSWT tilt meter record at Lohja after reduction by model tilt of the Baltic Sea loading and atmospheric loading can explain signal content above a frequency of 0.5 cycle/day , but not explain signals below that frequency.

Amplitude of the non-tidal tilt signals in the NSWT tilt meter at Lohja2 station reach the size of the earth tide tilt at Lohja. Therefore, loading phenomena are important and to be studied for high precision geodesy and geodynamics near sea and ocean coast lines.

References

Agnew, D.C., 2007, Earth Tides, In Herring T.A., (Ed.), Treatise on Geophysics and Geodesy, New York, Elsevier.

Agnew D.C., 1997, NLOADF: a program for computing ocean-tide loading, J. Geophys. Res. 102: 5109-5110.

Agnew, D. C., 2012, SPOTL: Some Programs for Ocean-Tide Loading, SIO Techn. Rep., Scripps Inst. of Oceanogr., http://escholarship.org/uc/item/954322pg.

Baker T. F., 1980, Tidal gravity in Britain: tidal loading and the spatial distribution of the marine tide, Geophys. J., Royal Astron. Soc. 62: 249-267.

Boy, J.-P., Longuevergne L., Boudin F., Jacob T., Lyard F., Llubes M., Florsch N. and Esnoult M.-F., 2009, Modelling atmospheric and induced non-tidal oceanic loading contributions to surface gravity and tilt measurements, J. Geodyn., 48:182-188.

Chojnicki T., 1989, Earth Tides in Teisseyre R. (Ed.) Gravity and Low-frequency Geodynamics, PWN-Polish Scientific Publishers, Warszawa, Elsevier, Amsterdam, Oxford, New York, Tokyo.

Eanes, R. J., 1994, Diurnal and semidiurnal tides from TOPEX/POSEIDON altimetry. Eos. Trans. AGU, 75(16):108.

Egbert, G. D. and Erofeeva, L., 2002, Efficient inverse modeling of barotropic ocean tides. J. Atmos. and Oceanic Technol., 19:183-204.

Farrell W.E., 1972, Deformation of the Earth by Surface Loads, Rev. Geophys. Space Phys. 10:761-797.

Gebauer A., Steffen H., Kroner C. and Jahr T., 2010, Finite element modelling of atmosphere loading effects on strain, tilt and displacement at multi-sensor stations, Geophys. J. Int. 181:1593-1612.

Goodkind J. M., 1983, Q of the Nearly Diurnal Free Wobble, Proc. 9th Int. Symp. Earth Tides (ed. J. Kuo), Schweizerbart, Stuttgart, 569-575.

Jentzsch G., 1997, Earth Tides and Ocean Tidal Loading, in Wilhelm H., Zürn W., and Wenzel H.-G. (eds.) Tidal Phenomena, Lecture Notes in Earth Sciences 66, Springer.

Kukkamäki T. J., 1965, Recording secular land tilting with pipe level, Proc. 2nd Int. Conf. on Recent Crustal Movements, Acad. Sci. Fenn. A II, No. 90: 209.

Kääriäinen J., 1979, Observing the Earth Tides with a long water tube tilt meter, Ann. Acad. Sci. Fenn. A VI Physica No 424.

Kääriäinen J. , and Ruotsalainen, H., 1989, Tilt measurements in the underground laboratory Lohja2, Finland in 1977 – 1988, Publ. of the Finn. Geod. Inst., 110, Helsinki.

Lisitzin E., 1959, Uninodal seiches in the oscillation system Baltic proper, Gulf of Finland, Tellus, 4: 459-466.

Lyard, L., Lefevre, L., Letellier, T., and Francis, O., 2006, Modelling the global ocean tides: insights from FES2004, FES2004 Ocean Dyn., 56: 394-415.

Melchior P., 1983, The Tides of the Planet Earth, Pergamon Press, Oxford, New York, Toronto, Sydney, Paris, Frankfurt.

Michelson, A. A., and Gale, H. G, 1919, The rigidity of the Earth, Astrophys. J. 50: 330-345.

Ruotsalainen H. ,2001, Modernizing the Finnish Long Water-Tube Tilt meter, J. Geod. Soc. of Japan, Vol. 47, 1:28-33.

Schwiderski , E.W., 1980, On charting Global Ocean Tides, Rev. Geophys. Space Phys., 18,(1):243-268.

Tamura Y., 1987, A harmonic development of the tide generating potential, Bull. d' Inf. Marées Terr., 99:6813-6855.

Weise A., 1992,Neigungmessungen in der Geodynamik – Ergebnisse von der 3-Komponenten-station Metsähovi, PhD- thesis, Tech. Univ. of Clausthal, Germany, (in german).

Weise A., Jentzsch G., Kääriäinen J., and Kiviniemi A., 1999, Comparison of long period tilt measurement: Results from the two clinometric stations Metsähovi and Lohja, Finland, J. Geodyn. 27: 237-257.

Wenzel H.-G., 1996,The nanogal software: Earth tide data processing package Eterna 3.30, Bull. d'Inf. Marées Terr., 124:9425 – 9439.

Witting R., 1911, Tidvattnet i Östersjön och Finska viken, Fennia 29, No 2., (in swedish).

Wübber Ch., Krauss W., 1979, The two-dimensional seiches of the Baltic Sea, Oceanol. Acta , Vol. 2 - No 4.

Zschau J., 1978, Tidal friction in the Solid Earth: Loading Tides versus Body Tides, in P. Brosche, J. Sündermann (eds.) Tidal Friction and the Earth's Rotation, Springer Verlag, New York.