Environmental effects in tilt data of Nokogiriyama Observatory
(extended abstract)

Gerhard Jentzsch[1], Steffen Graupner[1], Adelheid Weise[1], Hiroshi Ishii[2] and Shigeru Nakao[3]

1. Tilt measurements at the Geodynamic Observatory Nokogiriyama, Japan

Nokogiriyama Observatory of Tokyo University, Earthquake Research Institute (ERI), established in summer 1993, is situated on the eastern side of the entrance to the Tokyo Bay, located at the foot of a hill at about 600 m distance east from the coastline. It comprises underground galleries and a building for data acquisition (Chen & Ishii, 1994). In connection with several neighbouring observatories the purpose is the monitoring of seismicity and crustal deformation in the earthquake area around Tokyo Bay, as well as the testing of new sensors (Ishii, 1995; Nakao et al., 2000). Thus, the instrumentation includes quartztube extensometers, water tube tiltmeters (ERI), a LaCoste-Romberg gravimeter, borehole strainmeters, various seismometers, meteorological instruments and a tide gauge station. In addition to the already existing water tube tiltmeters, the borehole tiltmeter No. 106 of the Askania type (Graf, 1964; Jacoby, 1966) was installed in a 10 m deep borehole inside the gallery close to the ERI tiltmeters, in April 1997. It operated with only a small drift until June 1999. First results of this comparison show a good correspondence between the signals of the two instruments. During the Earth-Tide Symposium in Mizusawa in 2000 we presented some results of the comparison of these tiltmeters (Ishii et al., 2001; Graupner, 2001).
In this extended abstract we provide additional information about environmental effects and ocean loading observed with the two tiltmeters. A more comprehensive paper including all results from Nokogiriyama as well as a comparison to other tilt measurements is in preparation.

2. Tidal results and drift

The tidal amplitude factors γ shown in Fig. 2 (from Ishii et al., 2001) are of an unusual order of magnitude: Instead of the theoretical value of around 0.7 we observe values of up to 10 due to ocean loading. Furthermore, there are significant differences between diurnal and semidiurnal tidal constituents. In E-W direction both instruments provide similar γ – factors, while in N-S direction the observed γ – factors for the water tube tiltmeter is generally about 30 % above the values for the Askania tiltmeter with slight deviations in the diurnal and semidiurnal bands. The phases fit well in both directions (not shown). The spectra (Fig. 1; Ishii et al., 2001) show tidal amplitudes well above the noise levels. The N-S noise levels are in the same order of magnitude as in previous observations at other sites (Weise et al., 1999), but due to the near coast, in connection with environmental influences, the noise levels in E-W direction are higher by a factor of 3 (note: The data of the ASKANIA tiltmeter, azimuth of 41° from the North, are transformed to N-S and to E-W, whereas the watertubes are constructed in these directions). In Tab. 1 the observed main tidal amplitu-des, the noise levels in the tidal bands as well as the signal/noise-ratios are given. The high tidal amplitudes are caused by strong ocean tidal loading. Since the noise levels in E-W are also bigger than in N-S, the signal-to-noise ratios are similar in both directions (up to 560).

The long-term drifts of the curves point to more local deformations than to instrumental effects. In our published paper (Ishii et al., 2001) the time series show a very good correlation in N-S for all periods and the same in E-W for medium periods at a week to months, but there is a general different aperiodic drift (Fig. 1 in Ishii et al., 2001). The reason is not quite clear, but it may be related to the difference inside the gallery of more than 50 m, whereas the east-west component is quite adjacent.

1) Institut für Geowissenschaften, Friedrich Schiller Universität Jena, Burgweg 11, 07749 Jena, Germany
2) Tono Research Institute of Earthquake Science, 1-63 Yamanouchi, Akiyo-cho, Mizunami City, Gifu 509-6132, Japan
3) Earthquake Research Institute, Uni Tokyo, No. 1-1, Yayoi 1-chome, Bunkyo-ku, Tokyo 113, Japan

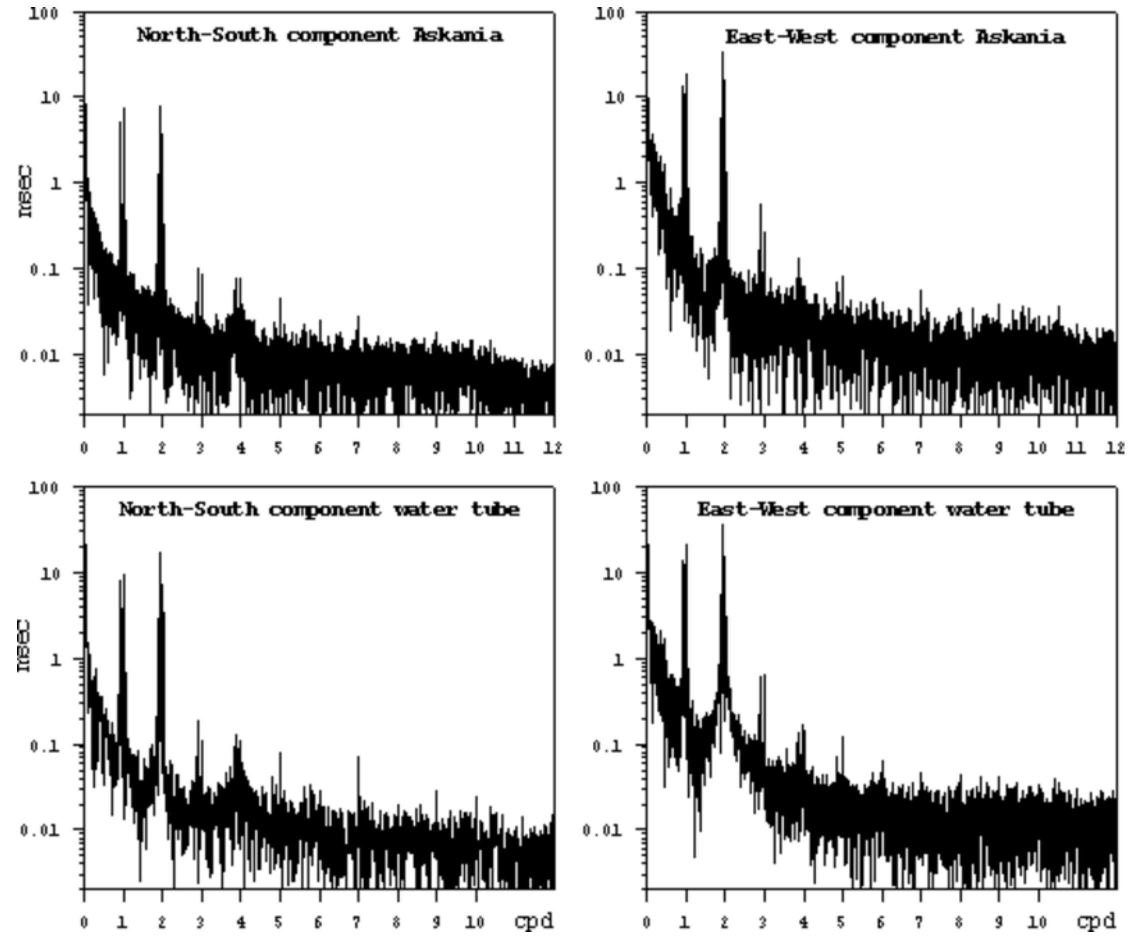


Figure 1. Amplitude spectra of hourly data for both tiltmeters and N-S and E-W components.

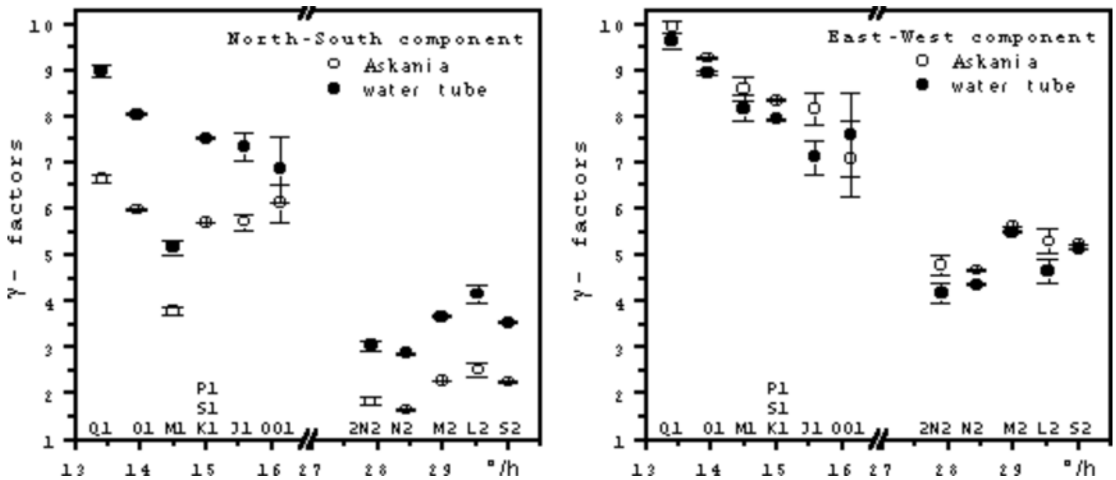


Figure 2. Amplitude factors of both tiltmeters for the major tidal constituents: The error bars indicate the least square deviations as given from the program ETERNA (Wenzel, 1994; 1997).

2. Environmental effects

Air pressure and rain induced tilt signals are prominent and also highly reproduceable features in both data sets. A particular strong rain event is plotted in detail (Fig. 3) and illustrates the simultaneous and equally strong reaction of both tiltmeters. Such rain events describe an unclosed loop in the projection plane, while pressure events are characterized by a prevailing forward/backward deflection in E-W direction (comp. Weise et al., 1999).

Because of their characteristic tilt patterns, it is possible to seperate the effects of air pressure and rain (Fig. 4). If rain and pressure changes occur at the same time, the

Table 1. Observed amplitudes of the main tidal waves, the noise level and s/n ratios.

tidal band		ASKANIA-borehole tiltmeter N-S	ASKANIA-borehole tiltmeter E-W	ERI-type watertube tiltmeters N-S	ERI-type watertube tiltmeters E-W
diurnal	K_1 [msec]	17.9	43.6	23.5	41.6
	noise [msec]	0.045	0.174	0.070	0.161
	S/N ratio	398	250	335	258
semi-diurnal	M_2 [msec]	17.2	71.8	27.5	70.7
	noise [msec]	0.043	0.128	0.054	0.161
	S/N ratio	400	561	509	439
ter-diurnal	M_3 [msec]	0.21	0.97	0.34	0.95
	noise [msec]	0.019	0.058	0.035	0.072
	S/N ratio	11	17	8	13
standard deviation m_0 [msec]		0.94	2.96	1.17	2.42

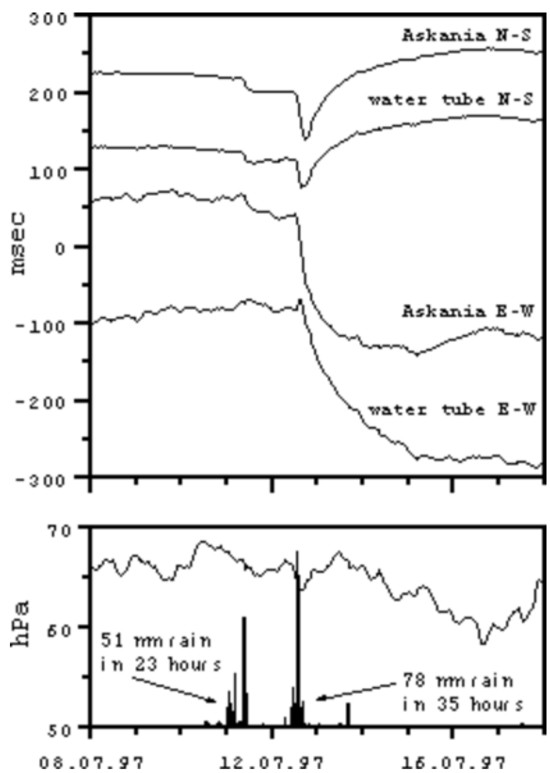


Figure 3. Rain event, air pressure of July 12, 1997, tilt signals, tides removed.

resulting figure is a superposition of both individual responses (comp. Braitenberg, 1999, for a review on the hydrologic induced strain-tilt signal and Dal Moro and Zadro, 1998).
Again, the general shape of the tilt changes is similar for the two instruments. For air pressure induced tilts a quantization attempt has been undertaken and yields regression coefficients of about 3.7 and 2.2 msec/hPa for the Askania
and the water tube tiltmeter, respectively. These values are valid only for the predominant E-W direction. Tilt changes caused by rain are not that clearly correlated to the amount of rainfall. However, there seems to be a treshold at about 20 mm of rain within 24 hours for any rain induced tilt signal to be identifiable.

There is no ground water sensor in the vicinity of the tiltmeters, because the water level is far below. Therefore, we cannot give an interpretation of the tilt source. But one can conclude that changes of pore pressure due to rain leaking into the highly porous rock may be one reason. In addition, there might also be a stress component due to different temperatures of the water and the rock.

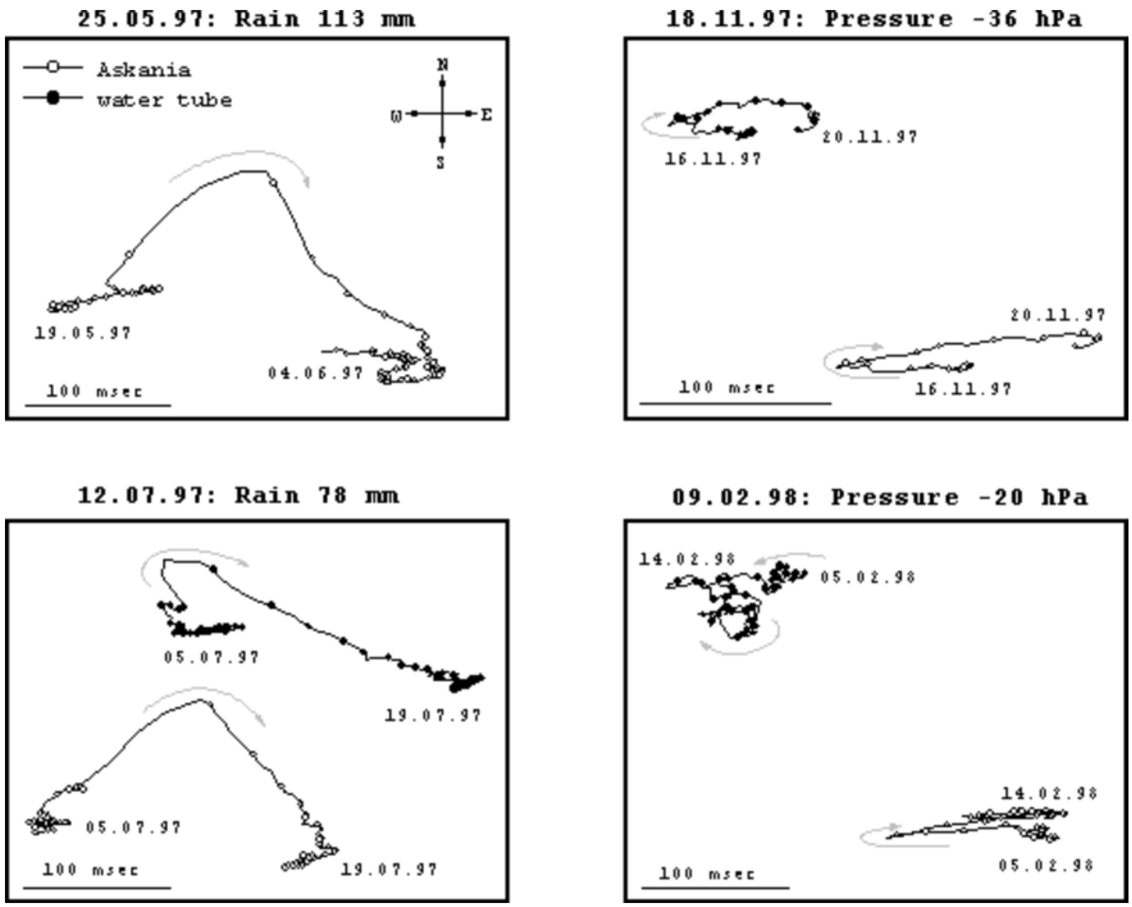


Figure 4. Classification of air pressure and hydrologically induced typical tilt patterns; general trend shown by arrows.

3. Loading tides

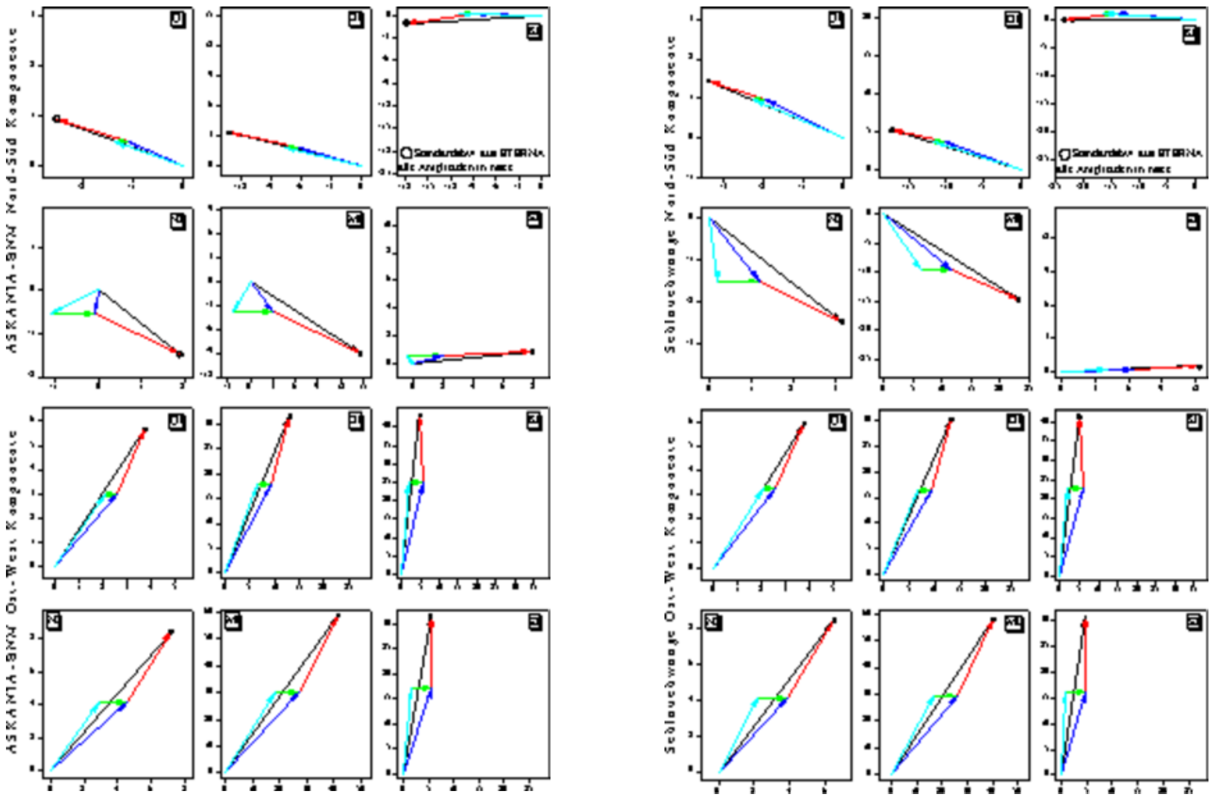
The observatory is situated on Boso peninsula forming the eastern margin of Tokyo Bay, about 600 m East of the shore line. Therefore, the tidal parameters are strongly disturbed by the loading tides of the adjacent Bay of Tokyo and the Pacific Ocean. Amplitude factors are amplified up to values of 10 and phases are shifted between 150° and 360° (N-S) and 40° and 120° (E-W), respectively.

The loading computations were carried out using the ocean tidal model of the National Astronomical Observatory NAO99b and NAOJb (global and for the Japanese area, resp., Matsumoto etal., 2000), and the software GOTIC2 (Matsumoto et al., 2001) based on GOTIC (Sato and Hanada, 1984). For the adjacent area the sea is gridded with a net of 2.25" N x 1.5" E, corresponding to a mesh of only about 50 m x 50 m. The evaluation of the results was performed according to Farrell (1972), Jentzsch (1997) and Jentzsch et al. (2000). Loading corrections for tilt measurements under similar conditions in the fjord region of southern Norway were applied by Jentzsch and Koß (1997).

The results of the loading computations are presented for the two main tidal waves both in the diurnal and the semi-diurnal tidal bands. The results in terms of vector diagrams reveal that the theoretical tides are the smallest signal for all waves and the loading tides are by far the biggest (Fig. 5). Therefore, it was to expect that the remaining residuals are still fairly big after subtraction of the tidal model and loading tides. But, since the tidal parameters obtained for both tiltmeters correlate quite well (esp. in the phase differences) also the residuals show a very good correlation.

The loading signals in E-W are bigger than in N-S by a factor of about 2 to 3. In N-S the observed loading is explained by the models by about 60% to 90%, whereas in E-W the results are between 40% and 50%. We do not assume that the existing discrepancy between computed and observed loading tides are due to a misfit of the models; we rather suggest another explanation: First, the short distance to the sea is a great disadvantage, because from experience it seems to be impossible to model the tides at this small scale, esp. for tilt. Second, we must take into account another possible effect: strain-tilt coupling due to the strong ocean loading and the rough topography (comp. the basic work of Harrison, 1976).

In Fig. 5 the long solid arrows denote the observations, the small light errors in the center denote the theoretical tides, the thin solid arrows ending at the head of the observations show the oceanic load. The remaining two arrows are the residual vectors after subtraction of the ocean loading (dark) and after subtraction of ocean and theoretical tides (light), respectively.



Askania borehole tiltmeters ERI-type watertube tiltmeters

Figure 5. Phasor plot of tidal and loading vectors for constituents O1, K1 (upper row) and M2, S2 (lower row) for directions N-S and E-W: See text for explanation; the small circles at the heads of the arrows denote errors from ETERNA-Analyis. (from Graupner, 2001)

4. Acknowledgements

The idea of this work was realised during a stipendium of the Japanese Society for Promotion of Sciences (JSPS) offered to co-author Jentzsch. During this visit the borehole was prepared with the help of ERI. Later, the co-worker of Jentzsch, M. Ramatschi, installed the tiltmeter in the observatory. The analyses of the data were mainly carried out by co-auther Graupner (2002) in the frame of his thesis work. Parts of the project were funded by the German Research Society (Deutsche Forschungsgemeinschaft) and by the European Union (research grant CT960205). All this is gratefully acknowledged.

5. References

Braitenberg, C., 1999. The hydrologic induced strain-tilt signal – a review. Bull. d'Inf. Marées Terrestres, 131, 10171-10181.

Chen, G. and H. Ishii, 1994. Inversion of Initial Stresses from Deformations of Tunnel Surface during Tunneling - Modeling by Using SRM Combined with BEM. Proc. 8th Int. Symp. on Recent Crustal Movements, Kobe, Dez. 6-11, 1993, 285 - 291.

Dal Moro, G. and M. Zadro, 1998. Subsurface deformations induced by rainfall and atmospheric pressure: tilt/strain measurements in the NE Italy seismic area. Earth and Planetary Science Letters, 164, 193 - 203.

Farrell, W. E. (1972): Deformation of the earth by surface loads. Rev. Geoph. and Space Physics 10, No. 3, 761 - 797.

Graf, A., 1964. Erste Neigungsmessungen mit dem Vertikalpendel in einem 30 m Bohrloch. Comm. Obs. Roy. Bel., 236, Ser. Geophys. Nr. 69, 5ieme Symp. Int. sur la marées terrestres, Brüssel, 249 - 254.

Graupner, S., 2001. Hochpräzise Neigungsmessungen im geophysikalischen Observatorium Nokogiriyama/Tokyo. Diploma thesis, Institute of Geosciences, University of Jena, 191 p. (unpublished)

Harrison, J. C., 1976. Cavity and topographic effects in tilt and strain measurements. J. Geophys. Res., 81, 319 - 328.

Ishii, H., 1995. Developments of multi-component borehole instruments and application for earthquake prediction study. Abstract/Poster SA31G-17, XXI. General Assembly of the IUGG, Boulder.

Ishii, H., Jentzsch, G., Graupner, S., Nakao, S., Ramatschi, M. and Weise, A., 2001. Observatory Nokogiriyama / Japan: Comparison of different tiltmeters. Proc. 14th International Symposium on Earth Tides, Special Issue of the Journal of the Geodetic Soc. of Japan, 47/1, 155 – 160.

Jacoby, H. D., 1966. Das neue Bohrloch-Gezeitenpendel nach Graf. – Askania-Warte, 67, 12 - 17.

Jentzsch, G., 1997. Earth Tides and Ocean Tidal Loading. In: Wilhelm, H., Zürn, W. and H.-G. Wenzel (Eds.): Tidal Phenomena. Lecture Notes in Earth Sciences, 66, Springer, Berlin, 398 S.

Jentzsch, G. and S. Koß, 1997. Interpretation of long-period tilt records at Blasjö, Southern Norway, with respect to the variations in the lake level. Phys. Chem. Earth, V 22, Nr. 1, 25-31.

Jentzsch, G., Knudsen, P. and M. Ramatschi, 2000. Ocean tidal loading affecting precise geodetic observations on Greenland: Error account of surface deformations by tidal gravity measurements. Phys. Chem. Earth (A), Vol. 25, No. 4, 401 - 407.

Matsumoto, K., Takanezawa, T., and M. Ooe, 2000. Ocean tide models developed by assimilating TOPEX/Poseidon altimeter data into hydrodynamical model: A global model and a regional model around Japan. J. of Oceanography, 56, 567 - 581.

Matsumoto, K., Sato, T., Takanezawa, T., and M. Ooe, 2001. GOTIC2: A program for computation of oceanic tidal loading effect. Spec. Issue of the J. Geod. Soc. of Japan for the 14th Int. Symp. on Earth Tides, 243 - 248.

Nakao, S., Hirata, Y., Jentzsch, G., Ramatschi, M. and A. Araya (2000): Comparitive observation of pendulum type tiltmeters in Nokogiriyama observatory. (Abstract) 14th Int. Sym. on Earth Tides, Mizusawa.

Sato, T. and H. Hanada, 1984. A program for the computation of oceanic tidal loading effects “GOTIC”. Pub. Int. Lat. Obs. Mizusawa, 18, No. 1, 29-47.

Weise, A., G. Jentzsch, A. Kiviniemi and J. Kääriäinen (1999): Comparison of long-period tilt measurements: results from the two clinometric stations Metsähovi and Lohja, Finland. Journal of Geodynamics, 27, 237 - 257.

Wenzel, H.-G., 1994. Earth Tides Analysis Package ETERNA 3.0. Bull. d’Inf. Marées Terrestr., 118, 8719 - 8721.

Wenzel, H.-G., 1997. Analysis of Earth Tide Observations. In: Wilhelm, H., Zürn, W. and H.-G. Wenzel (Eds.): Tidal Phenomena. Lecture Notes in Earth Sciences, 66, Springer, Berlin, 398 S.