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RESEARCH NOTE

Comparison of Earth-tide parameters over a large latitude difference

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SUMMARY

Gravity Earth-tide observations at the station of Thessaloniki with a LaCoste–Romberg gravity meter equipped with electrostatic feedback were analysed in order to obtain accurate amplitude and phase-difference tidal parameters. The observations cover a total number of 162.5 days. The frequency transfer-function of our measuring system was defined using the step-response procedure. The Tamura tidal development was used as normal tidal potential. A standard deviation of the weight unit equal to 7.007 nm s^{-2} resulted from the adjustment procedure before the correction due to barometric pressure changes. Taking into account the barometric pressure changes trough a linear regression model this standard deviation dropped to 6.821 nm s^{-2}, showing that these changes only slightly affect the observations. The computed amplitude factors and phase differences for O1 and M2 were compared with corresponding parameters from stations distributed over a large latitude difference, in order to study the latitude dependence of the gravimetric body tide factors. The comparison showed that in South Europe the tidal parameters fit, with some local discrepancies, to other stations in Central Europe after correction for ocean load.

Key words: Latitude dependence, tidal parameters.

1 INTRODUCTION

The interest about the behaviour of the lithosphere in our region was recently increased due to the strong earthquakes ($M > 6.5\,\mathrm{R}$) that have occurred since August 1999 in Istanbul and Athens. The response of the lithosphere to tidal loading is useful information for geophysicists to study the behaviour of the crust. Accurate amplitude and phase-difference parameters for the main tidal constituents are necessary for such kind of studies.

It is well-known that the amplitude factor parameters are latitude-dependent. However, the latitude effect may be disturbed by local anomalies, related with local characteristics of the crust, which are worthwhile for geophysical interpretation. Besides Melchior's (1983) study of the worldwide distribution of the amplitude factors of the main tidal waves, regional comparisons are reported (see, e.g. Ducarme *et al.* 1985). Since 1985, several improvements in the observing systems (electrostatic feedback, superconducting gravimeters) allowed the computation of more accurate tidal parameters.

In October 31, 1990 the LCR-G 265F was installed in the tidal station of the Department of Geodesy and Surveying, Aristotle University of Thessaloniki (see the 'Directory of instruments' by Melchior 1994) for Earth tide measurements. The tidal parameters resulted from the analysis of these measurements gave the opportunity for a new comparison.

The LCR-G 265 was fitted with a Schnüll-Röder-Wenzel (SRW) electrostatic feedback (Schnüll *et al.* 1984) with extended range of -140–$+160\,\mu\mathrm{m\,s^{-2}}$. After the installation of the SRW feedback the readout voltage of the LCR 265 in feedback mode was calibrated on the 'vertical calibration line' of Hannover University (Kanngieser *et al.* 1983). Calibration yielded

$$g = 1.063552R - 113.5568 \times 10^{-6}R^2,$$

where g in $10^{-5}\,\mathrm{m\,s^{-2}}$ and R the readout voltage in mV.

There are many advantages of the feedback system in comparison with the CPI (Röder *et al.* 1988). Among others, the independence of the feedback's sensitivity and of the frequency transfer function from tilt are very favourable in using the gravimeter for observation of the Earth tides. In the following sections the instrumental phase-lag determination, the preprocessing and the analysis of the observations and the comparison of the adjusted parameters with corresponding parameters from other stations distributed over a large area with respect to the latitude, are described.

2 RESPONSE IN FEEDBACK MODE

The electrostatic feedback system is equipped with an active low pass filter in order to reduce the noise voltage due to microseismic disturbances and thus to increase the reading precision. Due to this filter, the frequency-transfer function of the measuring system must be determined. This is necessary for phase-lag correction of Earth-tide observations. The frequency transfer function can be observed

Table 1. Transfer function of the complete measuring system (in feedback mode).

No	Wave	Frequency (Degree/h)	Amplitude factor	Phase lag (Degree)
1	Q1	13.3987	1.0000	0.073
2	O1	13.9430	1.0000	0.076
3	M1	14.4967	1.0000	0.079
4	K1	15.0411	1.0000	0.082
5	J1	15.5854	1.0000	0.082
6	OO1	16.1391	1.0000	0.082
7	2N2	27.9682	1.0000	0.083
8	N2	28.4397	1.0000	0.083
9	M2	28.9841	1.0000	0.085
10	L2	29.5285	1.0000	0.088
11	S2	30.0000	1.0000	0.153
12	M3	43.4762	1.0000	0.178

using a signal generator and a recorder or can be computed by using the step response function (Wenzel 1994a). The step response of the complete measuring system was observed by digital recording of the output voltage (e.g. one reading per 3 s) during a momentary change of the dial. This was used to determine the frequency transfer function of the complete measuring system in feedback mode. The transfer function for the main tidal bands computed according to formulae given by Wenzel (1976, page 145–146) using the programme ETSTEP is given in Table 1. The LCR-G265F SRW feedback system's time lag derived from the step-response experiment showed a constant time lag over a frequency range from 10^{-6} cps to 10^{-3} cps.

3 GRAVIMETRIC EARTH-TIDE OBSERVATIONS

The data recording system consisted of a HP 3421A data acquisition and control unit, a HP-71B programmable calculator supplied with the HP-IL interface and a HP-9114B floppy disc drive. The system was programmed to perform a reading every 5 min with 5 1/2 digit resolution. The preprocessing of the data was carried out using the FORTRAN programme PRETERNA (Wenzel 1994b). After destepping, despiking and gap interpolation, from the 5 min samples hourly samples were computed. Due to several reasons (earthquakes, data acquisition failures etc.) from October 31, 1990 to June 9, 1991 only 162.5 days of observations were obtained. Accordingly, the observations were split into five segments. In Table 2 the period covered by each segment is shown together with the number of records of the 5 min sampling. The phases were corrected taking into account the transfer function of Table 1.

The analysis of the complete data set covering 162.5 days was performed using the FORTRAN programme ETERNA (Wenzel 1996). In this analysis the Perzev's 1959 filter with 51 coefficients and the Tamura tidal potential containing 1200 partial tides (Tamura 1987) were used. The effect of the barometric pressure changes on the gravimeter measurements (-2.45 ± 0.17 N m s^{-2}/hP) was taken into account through a linear regression model. The results of this analysis are shown in Table 3.

Table 2. Time spans used for final Earth tide analysis.

Segment	Start	End	No of records
I	1990.10.31 12:00	1990.11.26 11:00	7,890
II	1990.12.01 00:00	1990.12.11 23:00	3,513
III	1990.12.14 06:00	1991.02.20 05:00	19,920
IV	1991.04.10 00:00	1991.05.30 23:00	15,048
V	1991.06.03 00:00	1991.06.10 17:00	2,631

In the analysis using ETERNA the standard deviation of the weight unit was 6.821 N m s^{-2}. Ignoring the last correction the standard deviation was slightly higher (7.007 nm s^{-2}) showing that the barometric pressure changes only slightly affect the observations of the LCR-265F. This standard deviation is better than ever obtained by conventional registration mode (CPI output, analogue registration) for such a short period of registration (see also Torge & Wenzel 1977).

Another analysis of the same data set was carried out by the International Center for Earth Tides (ICET) (Melchior, personal communication 1994) yielding slightly different results. In this analysis the Venedicov's filter with 48 coefficients and the Cartwright-Tayler-Edden potential development were used. The standard deviation of this analysis given separately for the diurnal, semi-diurnal and ter-diurnal waves was 28.9, 12.3 and 8.4 nm s^{-2} respectively. The results of this analysis are shown in Table 4. However, the headings of these tables are different, depending on the individual output of each program used, but the comparison concerns the amplitude factor and the phase difference, as well as their error estimates.

In Tables 3 and 4 there are slightly different results in the estimated amplitude and phase difference parameters with the exception in the estimation of the amplitude factor for M2. In the author's opinion the different results could be attributed to the different filters, tidal models and methods of analysis used in each case. In the comparison of the next section, the symbol (SK1) was used for the tidal parameters of Table 3 (resulting from the analysis using ETERNA) and the symbol (SK2) for the corresponding of Table 4 (computed by ICET).

4 COMPARISON OF TIDAL PARAMETERS

The tidal station of Thessaloniki is situated at latitude 40.63°. This gave us the opportunity for a comparison of tidal parameters from stations distributed over a large latitude difference. From this comparison, information about the latitude dependence of the gravimetric body-tide factors could be obtained. However, the oceanic loading effect must be taken into account before the comparison (e.g. Tsun *et al.* 1983).

The tidal parameters of the main constitutes O1 and M2 for the stations Hannover (HA), Bruxelles (BR), Bad Homburg (BH), Karlsruhe (KA), Strasbourg (ST), Schiltach (BF), Zürich (ZU), Chur (CH) and Valle (VA) were extracted from the Black Forest Observatory (BF) data bank (Wenzel, personal communication, 1998; Timmen & Wenzel 1994). The tidal parameters for Sofia (SO) and Istanbul (IS) were supplied by Melchior (personal communication, 1996). The parameters for Metsähovi (ME) were taken from the analysis of the superconducting gravimeter GWR20 registrations (Virtanen & Kääriäinen 1995). The distribution of the Earth-tide stations is shown in Fig. 1. It should be mentioned that the stations of Thessaloniki and Istanbul are very close to the sea but the total oceanic contribution at M2 frequency is very low (about 2 per cent of the observed Earth tide) because the tides in the Aegean Sea are of small amplitude.

The oceanic loading contribution was taken into account using the Schwiderski model (Schwiderski 1980). The Schwiderski model does not include the Mediterranean Sea where the tidal amplitudes are weak (Arabelos & Spatalas 1992) as well the Black Sea, but could

Table 3. Adjusted tidal parameters for Thessaloniki (using the FORTRAN programme ETERNA).

No	From	To	Wave	Amplitude ($nm\ s^{-2}$)	Signal/ noise	Amplitude factor	Std. dev.	Phase diff. (Degree)	Std. dev. (Degree)
1	282	424	Q1	67.697	72.9	1.15195	0.01581	0.1201	0.7863
2	425	482	O1	352.816	379.7	1.14947	0.00303	−0.1413	0.1509
3	483	530	M1	27.091	29.2	1.12226	0.03849	−4.0582	1.9650
4	531	585	K1	487.840	525.1	1.13012	0.00215	0.1408	0.1091
5	586	626	J1	28.061	30.2	1.16251	0.03849	−0.2555	1.8970
6	627	731	OO1	15.266	16.4	1.15574	0.07034	−3.6388	3.4871
7	732	830	2N2	15.264	36.1	1.15389	0.03192	1.4972	1.5852
8	831	880	N2	97.505	230.9	1.17713	0.00510	0.8142	0.2481
9	881	936	M2	510.350	1208.5	1.17962	0.00098	0.3451	0.0474
10	937	975	L2	15.310	36.3	1.25200	0.03453	0.6349	1.5804
11	976	1108	S2	238.393	564.5	1.18435	0.00210	0.3460	0.1015
12	1109	1190	M3	6.834	21.1	1.05796	0.05009	0.2901	2.7128
13	1191	1200	M4	0.169	0.9	1.88563	2.00521	−119.8517	60.9293

Table 4. Adjusted tidal parameters for Thessaloniki according to the analysis carried out in ICET.

Wave argument	N	Wave	Estimated amplitude ($nm\ s^{-2}$)	RMS ($nm\ s^{-2}$)	Amplitude factor	RMS	Phase difference (Degree)	RMS
133.–136.	20	Q1	67.1	0.7	1.1425	0.0122	−0.111	0.610
143.–145.	16	O1	352.7	0.7	1.1488	0.0024	−0.139	0.121
152.–155.	15	NO1	2.8	1.5	1.1714	0.0618	−2.352	3.020
161.–163.	10	P1	162.9	0.8	1.1404	0.0056	0.686	0.281
164.–168.	23	S1K1	488.2	0.8	1.1309	0.0018	0.017	0.089
175.–177.	14	J1	28.3	0.7	1.1743	0.0271	−0.678	1.321
184.–186.	11	OO1	15.2	0.7	1.1495	0.0522	−3.940	2.597
233.–23A.	20	2N2	15.5	0.2	1.1679	0.0160	1.639	0.780
243.–248.	24	N2	97.5	0.3	1.1774	0.0035	0.900	0.169
252.–258.	26	M2	508.6	0.3	1.1755	0.0008	0.330	0.037
265.–265.	9	L2	15.2	0.4	1.2469	0.0351	−0.064	1.611
267.–273.	9	S2	238.1	0.3	1.1828	0.0017	0.629	0.080
274.–277.	12	K2	64.8	0.3	1.1830	0.0054	0.330	0.260
327.–375.	17	M3	6.7	0.2	1.0453	0.0344	0.539	1.870

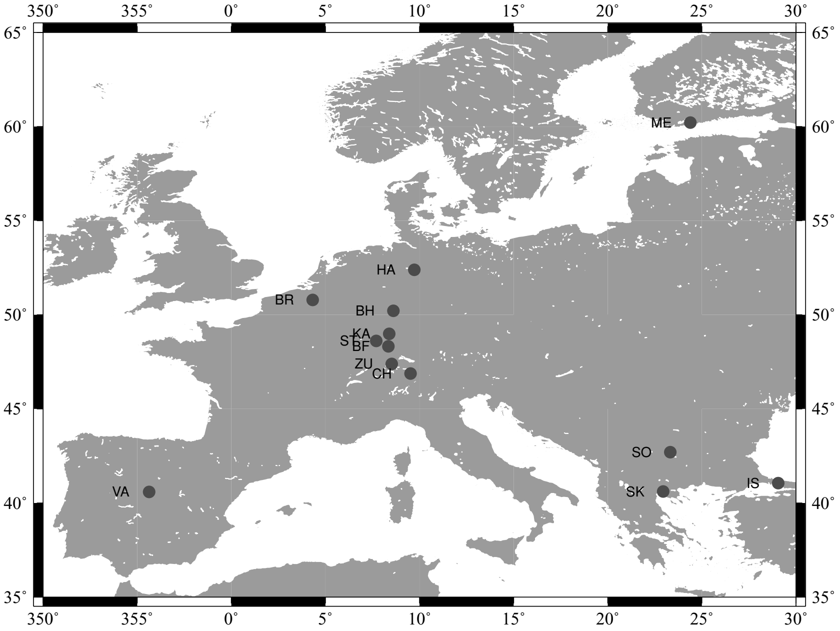

Figure 1. Distribution of the Earth-tide stations.

Table 5. Comparison of the ocean corrected diurnal O1 tidal parameters from stations distributed over a large latitude difference.

Station	Length (Days)	Latitude (Degree)	Amplitude factor ocean corrected	Amplitude factor Model	Phase (Degree) ocean corrected
Metsähovi (ME)†	46.0	60.22	1.1676 ± 0.0007	1.1517	−0.057 ± 0.036
Hannover (HA)	65.2	52.39	1.1534 ± 0.0010	1.1527	0.067 ± 0.062
Bruxelles (BR)	2901.0	50.80	1.1510 ± 0.0013	1.1529	0.110 ± 0.040
Bad Homburg (BH)	1004.0	50.23	1.1518 ± 0.0013	1.1530	−0.020 ± 0.050
Karlsruhe (KA)	92.5	49.01	1.1532 ± 0.0020	1.1531	0.050 ± 0.060
Schiltach (BF)	153.0	48.33	1.1515 ± 0.0026	1.1532	0.022 ± 0.030
Zürich (ZU)		47.40	1.1522 ± 0.0013	1.1534	−0.020 ± 0.040
Chur (CH)		46.90	1.1518 ± 0.0013	1.1534	−0.020 ± 0.060
Sofia (SO)		42.71	1.1493 ± 0.0014	1.1540	−0.159 ± 0.060
Istanbul (IS)		41.07	1.1564 ± 0.0035	1.1542	−0.281 ± 0.174
Thessaloniki (SK1)	162.5	40.63	1.1536 ± 0.0030	1.1543	−0.201 ± 0.151
Thessaloniki (SK2)	162.5	40.63	1.1529 ± 0.0024	1.1543	−0.199 ± 0.151
	Average		1.1537	1.1534	−0.059
	Standard deviation		0.0047		0.123

†Superconducting gravimeter.

Table 6. Comparison of the ocean corrected semi-diurnal M2 tidal parameters from stations distributed over a large latitude difference.

Station	Length (Days)	Latitude (Degree)	Amplitude factor ocean corrected	Amplitude factor Model	Phase (Degree) ocean corrected
Metsähovi (ME)†	46.0	60.22	1.1491 ± 0.0005	1.1563	−0.245 ± 0.025
Hannover (HA)	65.2	52.39	1.1581 ± 0.0010	1.1571	0.096 ± 0.022
Bruxelles (BR)	2901.0	50.80	1.1551 ± 0.0013	1.1572	0.010 ± 0.020
Bad Homburg (BH)	1004.0	50.23	1.1591 ± 0.0013	1.1573	−0.090 ± 0.030
Karlsruhe (KA)	92.5	49.01	1.1602 ± 0.0020	1.1574	−0.104 ± 0.030
Schiltach (BF)	153.0	48.33	1.1589 ± 0.0026	1.1575	−0.012 ± 0.030
Zürich (ZU)		47.40	1.1594 ± 0.0013	1.1576	−0.160 ± 0.020
Chur (CH)		46.90	1.1589 ± 0.0013	1.1577	−0.090 ± 0.020
Sofia (SO)		42.71	1.1541 ± 0.0005	1.1581	−0.207 ± 0.026
Istanbul (IS)		41.07	1.1587 ± 0.0011	1.1583	−0.039 ± 0.054
Thessaloniki (SK1)	162.5	40.63	1.1639 ± 0.0010	1.1583	−0.195 ± 0.047
Thessaloniki (SK2)	162.5	40.63	1.1598 ± 0.0008	1.1583	−0.211 ± 0.037
	Average		1.1579	1.1576	−0.104
	Standard deviation		0.0037		0.104

†Superconducting gravimeter.

contribute significantly to the measurements made in Thessaloniki and Istanbul. But according to Melchior (1997) this model gave better results for Sofia, Istanbul and Thessaloniki concerning M2 than CSR3.0 and FES95.2b, which include the Mediterranean Sea tides. However, due to the uncertainties in the oceanic loading computations, firm conclusions cannot be derived for the semi-diurnal waves.

The comparison of the tidal parameters mentioned above is summarized in Tables 5 and 6. The ocean-corrected amplitudes for O1 and M2 are shown in Figs 2 and 3 respectively while the corresponding ocean-corrected phases are shown in Figs 4 and 5. In all cases the Wahr–Dehant–Zschau model (Dehant 1987; Dehant & Zchau 1989; Wahr 1981) is shown.

The question raised in this comparison is about the 'error bars' in such results. The measurements in these stations were carried out with quite different equipment installed and maintained by different teams in different epochs. According to the analysis by ICET the internal errors, at least in the case of Thessaloniki, are of the order of 1 nm s^{-2}. The residual components $X \cos \chi$, $X \sin \chi$ as representative of the external errors are at the level of 1 nm s^{-2} that represents the 0.2 per cent of the M2 amplitude. The error bars in Figs 2–5 represent the confidence interval for significance level $a = 0.05$.

This is a preliminary analysis and the (relatively) large error bars of SK1, SK2 in Figs 2, 4 and 5 have nonetheless to be considered as a good result in view of the shortness of the data set. The fact that SK1 seems to be better than SK2 when they are different could be attributed to the tidal model used for the estimation of SK1. From Tables 5 and 6 and Figs 2 and 3 it is clear that in South Europe the tidal amplitude factors fit, with some local discrepancies, to other stations in Central Europe after correction for ocean load. The relatively large discrepancy of the Metsähovi amplitude parameters could be due to a calibration problem of the superconducting gravimeter. The same is valid for the phase differences as shown in Tables 5 and 6 and Figs 4 and 5.

If the local discrepancies are not due to errors, it should be very interesting to attempt an interpretation of them in terms of the

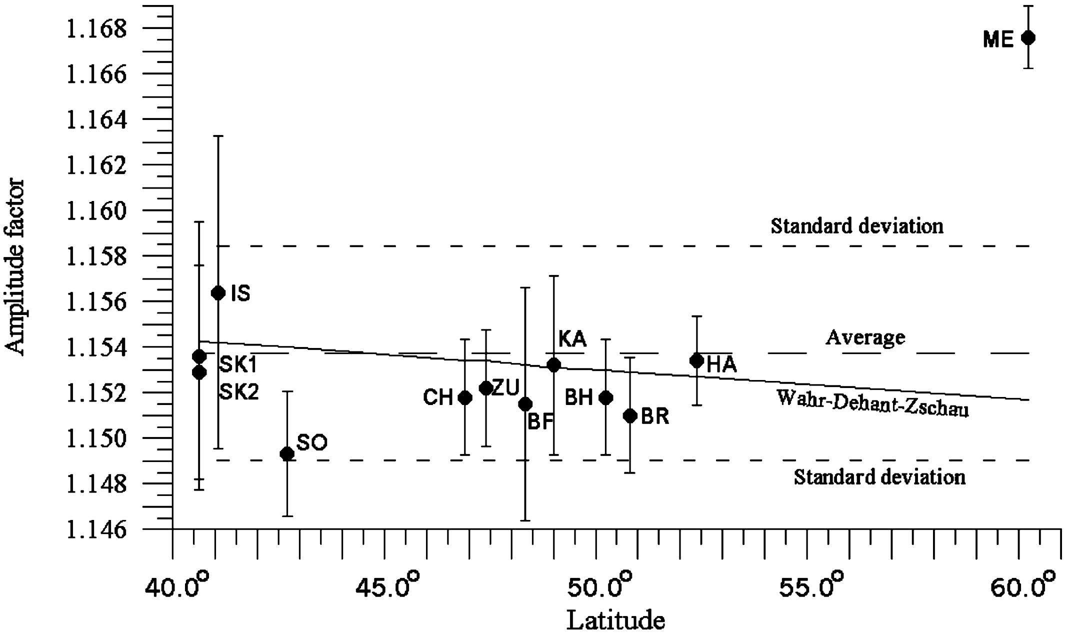

Figure 2. Ocean corrected amplitude factors O1.

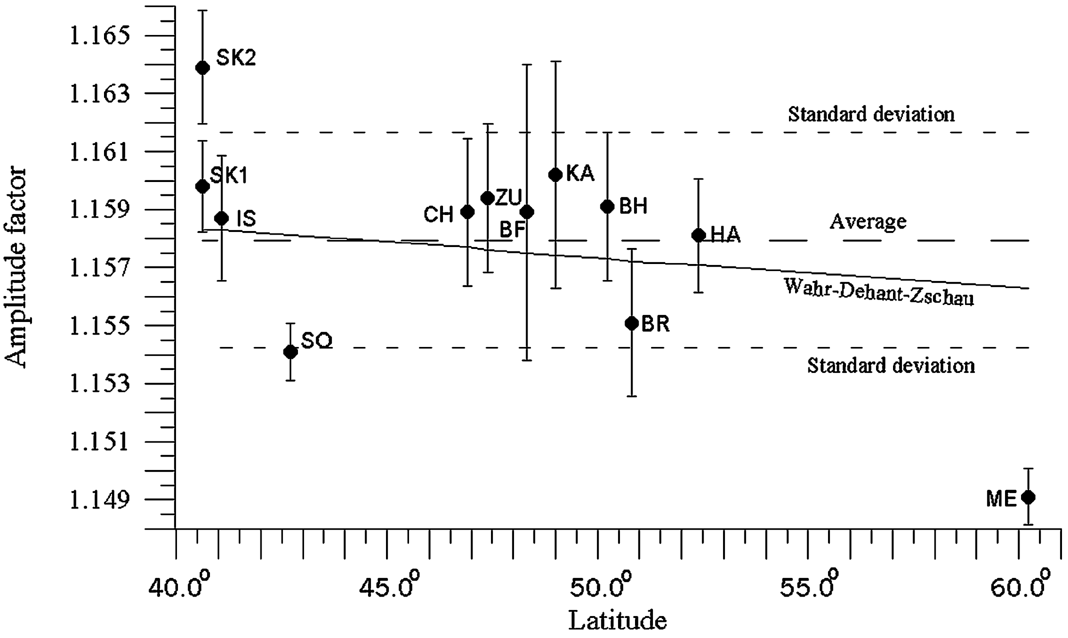

Figure 3. Ocean corrected amplitude factors M2.

(peculiar) behaviour of the upper crust in this area. The correctness of the parameters could be ascertained in the frame of a homogeneous network of Earth-tide stations.

5 CONCLUSION

The analysis of the gravity Earth tides observations in Thessaloniki, carried out with a LaCoste–Romberg gravity meter equipped with electrostatic feedback showed accuracy that is better than ever obtained by conventional registration mode, for such a short period of registration. The analysis of the same data set using ETERNA or the ICET software, gave somewhat different results. This is a characteristic example on how the results are affected from the analysis procedure (filtering, tidal model etc.). The internal errors of the order of 1 nm s^{-2} are in agreement with the residual components $X\cos\chi$, $X\sin\chi$.

The comparison of the tidal parameters over a large latitude difference (over 20°) showed that in South Europe the tidal amplitude factors, with some local discrepancies, fit to other Central European stations after correction for ocean load. A homogeneous network of Earth-tides stations in the region where discrepancies are shown would be very useful to ascertain that these discrepancies are not due to errors.

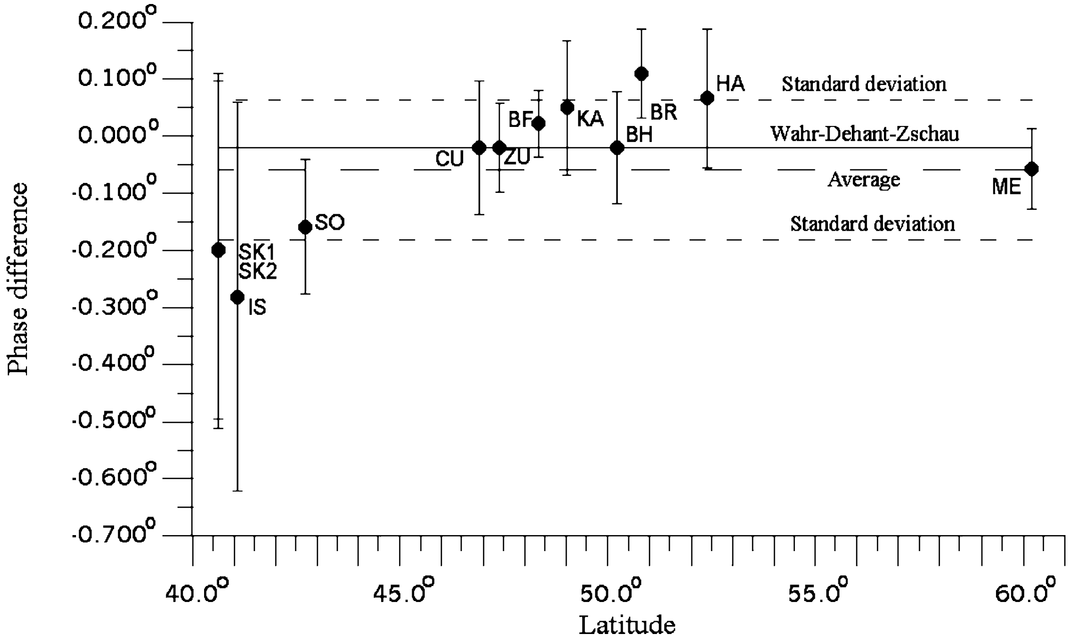

Figure 4. Ocean corrected phases O1.

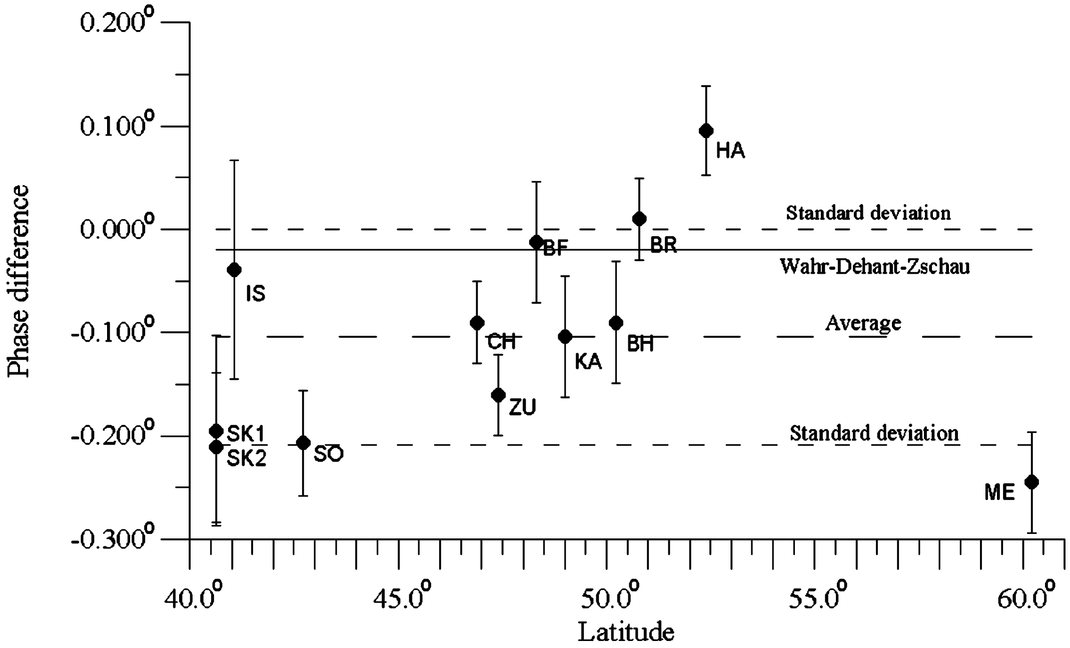

Figure 5. Ocean corrected phases M2.

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REFERENCES

Arabelos, D. & Spatalas, S.D., 1992. Tidal effects on satellite altrimeter data in a closed sea area, *Proceedings, First Continental Workshop on the Geoid in Europe,* Prague, May 11–14, 123–130. Research Institute of Geodesy, Topography and Cartography, Prague.

Dehant, V., 1987. Tidal parameters for an inelastic Earth, *Phys. Earth planet. Inter.,* **49,** 97–116.

Dehant, V. & Zschau, J., 1989. The effect of mantle inelasticity on tidal gravity: a comparison between the spherical and the elliptical earth model, *Geophys. J.,* **97,** 549–555.

Ducarme, B., Vieira, R. & Kääriäinen, J., 1985. A European tidal gravity profile over a 30° latitude difference (Kevo-Bruxelles-Madrid), *Proc. 10th Internat. Symp. Earth Tides,* 199–211. Consejo Superior De Investigationes Cientificas, Madrid.

Kanngieser, E., Kummer, K., Torge, W. & Wenzel, H.-G., 1983. Das Gravimeter Eichsystem Hannover, *Wiss. Arb. der Fachrichtung Vermessungswesen der Universität Hannover,* Nr., **120**.

Melchior, P., 1983. Effect of the ellipticity and inertial forces of the Earth on M2 and O1 tidal gravity measurements in the Trans-World profiles, *Proc. of the 9th Internat. Symp. Earth Tides,* ed. Kuo J.T., Schweizerbartsche Verlangsbuchhandlung, Stuttgart, 155–165.

Melchior, P., 1994. ICET as a World data centre for Earth tides, *Bull. Inf. Marées Terrestres,* **118,** 8777–8830.

Melchior, P., 1997. Earth tides in 1996, *The Earth and the Universe,* Volume dedicated to Prof. L.N. Mavridis on the occasion of his completing forthy-five years of academic activities, 469–481, Ziti Publishing, Thessaloniki.

Röder, R.H., Schnüll, M. & Wenzel, H.-G., 1988. SRW feedback for LaCoste–Romberg Gravimeters with extended range, *BGI, Bulletin d' Information,* **62,** 46–50.

Schnüll, M., Röder, R.H. & Wenzel, H.G., 1984. An improved electronic feedback for LaCoste-Robmerg gravity meters, *Bureau Gravimetrique International, Bulletin d' Information,* **55,** 27–36.

Schwiderski, E.W., 1980. On charting global ocean tides, *Rev. geophys. Space Phy.,* **18,** 243–268.

Tamura, Y., 1987. A Harmonic development of the Tide Generating Potential, *Bull. Inf. Marées Terrestres,* **99,** 6813–6855.

Timmen, L. & Wenzel, H.-G., 1994. Improved gravimetric Earth tide parameters for station Hannover, *Bull. Inf. Marées Terrestres,* **119,** 8834–8846.

Torge, W. & Wenzel, H.G., 1977. Comparison of Earth tide observations with nine different gravimeters at Hannover, *Proc. 8th Internat. Sympos. on Earth Tides,* Bonn19–24 September 1977, 632–640, Institut für Theoretische Geodäsie der Universität Bonn, Bonn.

Tsun, F., Hou-Tse, H., Zhen-Gang, C. & Huai-Bing, Y., 1983. Effect of the ocean tides on gravity observations, *Proc. 9th Internat. Sympos. Earth Tides,* 179–186, E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart.

Virtanen, H. & Kääriäinen, J., 1995. The installation of and first results from the superconducting gravimeter GWR20 at the Metsähovi station, Finland, *Rept Finnish Geod. Inst.,* **95:1**.

Wahr, J., 1981. Body tides on an elliptical rotating, elastic and oceanless earth, *Geophys. J. R. astr. Soc.,* **64,** 677–703.

Wenzel, H.-G., 1976. Zur Genauigkeit von gravimetrischen Erdgezeitenbeobachtungen, *Wiss. Arb. der Lehrstühle fur Geodäsie, Photogrammetrie und Kartographie an der technischen Universität Hannover,* Nr., **67,** Hannover.

Wenzel, H.-G., 1994a. Accurate instrumental phase lag determination for feedback gravimeters, *Bull. Inf. Marées Terrestres,* **118,** 8735–8752.

Wenzel, H.-G., 1994b. PRETERNA—a preprocessor for digitally recorded tidal data, *Bull. Inf. Marées Terrestres,* **118,** 8722–8734.

Wenzel, H.-G., 1996. The nanogal software: Earth tide data processing package ETERNA, *Bull. Inf. Marées Terestres,* **99,** 9425–9439.