The first tidal analysis based on the CG-5 Autograv gravity measurements at Modra station

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Abstract: We present the tidal parameters estimated for the absolute gravity site in Modra (Slovakia). This is the first tidal analysis based on gravity measurements for this location. Relative gravity variations observed by Scintrex CG-5 Autograv gravimeter were used for the tidal analysis. We observed large and non-linear instrumental drift which cannot be effectively eliminated by polynomial approximation. Drift was eliminated by a filtering. New set of tidal parameters was estimated and analyzed with the focus on diurnal and semi-diurnal tidal waves. Time and frequency domain comparison between new parameters and those obtained from the superconducting gravimeter located in Vienna was performed. A maximum amplitude factor difference of 0.2% was found between main tidal waves corrected for ocean tides and non-hydrostatic body tide model. New estimated tidal parameters can serve for the correction of local relative gravity measurements.

Key words: tidal parameters, amplitude factor, gravimeter, relative gravity measurements, tidal analysis

1. Introduction

The aim of the gravity corrections is to prepare the gravity measurements for further processing. The largest variation of the gravity in static measurements comes from the gravitational effects of celestial bodies and their movements in space. These effects on gravity are known as tides. Efficient elimination of tides together with the elimination of atmospheric effects on gravity and polar motion effect is a prerequisite for the analysis and interpretation of gravity changes with respect to geophysical phenomena. The tide correction requires knowledge of tidal parameters, i.e. amplitude factor δ and phase difference α for the specific group of tidal waves. These can

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be obtained from geophysical models of the Earth (*Dehant et al., 1999*) or by analysis of observed gravity variation. The second mentioned approach is used in places where a continuous record of gravity variation is available. This is in case of high accuracy requirements observed by superconducting gravimeter. The high cost of superconducting gravimeter (SG) along with high operating costs are the main reasons for relatively small number of SG in Europe. The network of SG is supported by relative spring gravimeters (*Melchior, 1994*). The relatively low precision of spring gravimeter compared to SG is compensated by lower costs, wider range of applications and portability. The cost ratio of SG (GWR Instruments, Inc.) and spring gravimeters (CG-5 Autograv) is four to one. Simultaneous 15-day observation showed that the precision at 24 hour is 0.8 $nm.s^{-2}$ for SG and 3 $nm.s^{-2}$ for CG-5 Autograv (*Riccardi et al., 2011*). Amplitude factor and phase difference determination for semi-diurnal and diurnal waves are the main task in the tidal analysis. Theoretical values are used for long periodic tidal waves. Most of the tidal analyses are focused on the estimation of tidal parameters for waves in the frequency range from 0.5 to 4 cpd (cycles per day). Main tidal waves (amplitude larger than 100 $nm.s^{-2}$) correspond to the diurnal (1 cpd) and semi-diurnal (2 cpd) variations.

In this paper we present the tidal parameters for diurnal and semi-diurnal waves estimated from the gravity variation observed by Scintrex CG-5 Autograv gravimeter at the Modra station. This type of gravimeter is primarily used for field measurements and rarely for static measurements. CG-5 Autograv gravimeter works on the principle of a vertical spring. That is in contrast to the general level spring balance principle used in the most tidal analyses based on spring gravimeters (*Arnoso et al., 2001; Baker and Bos, 2003; Pálinkáš, 2006; Timofeev et al., 2006; Fernandéz et al., 2008*). The reason for this is that the vertical spring gravimeter introduces significantly larger drift into the measurements. The drift was in our case the gravity variation after tide, atmospheric and polar motion corrections. The drift itself is not a big issue if it can be approximated by a low degree polynomial. The drift of SG is mostly approximated by the first degree polynomial (*Van Camp and Francis, 2007*). The interpretation of long periodic gravity variation becomes more complicated when high degree polynomials are needed for the drift elimination. The combination of non-linear drift and relatively short time series are the main complications in tidal analysis. However, as we will show later, a suitable measurement preprocessing entering the tidal analysis helps to minimize this problem.

Presented tidal parameters were estimated for the Modra station. This station (λ = 17.2750°, ϕ = 48.3733°, h = 532.9 m) is located in south-western Slovakia in the Small Carpathians Mountains (Fig. 1). This area falls under the Modra massif, built mostly by granodiorite. The surface has been superimposed by a quaternary loamy-stony to boulder diluvium with variable thickness (*Paňáková et al., 1987*). Absolute gravity point (SK-402) as well as the points of EUREF Permanent Network (MOPI and MOP2) are located in the studied area. The closest superconducting gravimeter to the studied area is located at Conrad Observatory (Austria) involved in the Global Geodynamics Project (GGP) (*Crossley et al., 1999*). Gravimeter that is currently operating at this station was located in Vienna until October 2007 (*Meurers, 2004*). Therefore Vienna tidal parameters were used as a reference due to the distance of only 70 km from the Modra Observatory. We assume that the differences of the tidal parameters between the Modra and Vienna are negligible concerning the obtained accuracy of estimated parameters and a short distance between both stations. Absolute gravity measurements carried out in the territory of the Slovak Republic are corrected for tides using tidal parameters obtained at the Pecný station (Czech Republic). For this reason, the tidal parameters for SG Pecný were included in the comparison.

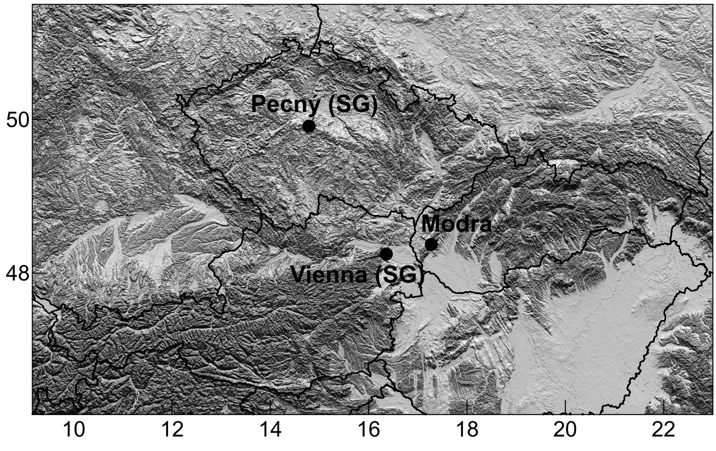

Fig. 1. Location of the Modra station.

2. Data acquisition

The CG-5 gravimeter allows continuous recording of gravity changes together with the tilt angles and ambient temperature. The gravimeter was placed at the pillar of the absolute gravity point in the building complex of the Astronomical and geophysical observatory in Modra. Gravity variation was sampled every 65 seconds. This means that the resulting gravity was an average of 60 second long measurement. The reading time of every sample was shifted to the midpoint of all readings and corrected for the internal clock drift. Measured values were reduced by internal firmware for linear drift, instrumental tilt, temperature variation close to the sensor as well as the tide correction. The value of the applied tide correction provided in the output file should be added to a given gravity variation in order to obtain the uncorrected gravity variation suitable for the tidal analysis. This, however, introduces a systematic error into the measurements as pointed out in (*Meurers, 2012*). The problem is that the tide correction in the output file is rounded towards zero, instead of rounding to the nearest number (resolution of 10 nm.s^{-2}). Restoration of such correction would result in underestimation of tidal parameters. To overcome this rounding problem, tide correction was restored using *Longman's (1959)* formula, referred to as the tide correction used in CG-5 (*Scintrex, 2009*). The gravimeter itself is not primarily designed for static measurements. This is reflected in the provided software package. Neither does it allow a remote access to the measured data nor control of the measurement. It was not rare that the measurement was unexpectedly stopped even with correct instrument setting. This failure can be attributed to the gravimeter firmware. Some of the observations were stopped due to the power cut at the observatory. Gravimeter was also used for field measurements. These factors affected the final length of available time series. Original measurements covered 418 days. In order to prepare the time series for tidal analysis only series longer than ten days were used. The final block of time series entering tidal analysis covered 380 days. The longest available continuous time series was 52 days long. Time coverage is shown in Fig. 2.

The gravity is beside tidal variation strongly influenced by the atmosphere. For this reason pressure variation registration is necessary. Meteorological station 30 m far from our point was used for this purpose. It

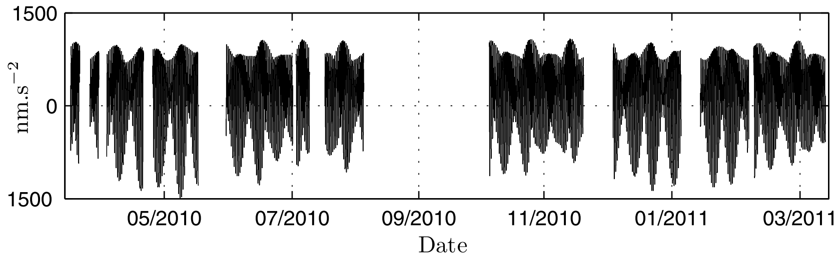

Fig. 2. The time coverage of the gravity measurements at Modra station.

provides pressure variation sampled every 20 minutes. Correct tidal parameter estimations require accurately calibrated gravimeter. Superconducting gravimeter is usually calibrated by a comparison with a co-located absolute gravimeter (AG). This procedure can also be used for spring gravimeters. However, spring gravimeters are due to the inaccessibility of SG or AG mostly calibrated at calibration baseline. In our case the gravimeter calibration factor was controlled at the baseline Hochkar (26.10.2010) and baseline Modra-Vinosady (6.11.2010). Calibration factor provided by the manufacturer was confirmed in both cases. Error in the calibration factor would be reflected in the estimated amplitude factors.

For comparison purposes tidal parameters for GGP station Vienna as well as Pecný were estimated. Gravity variation and pressure variation observed by SG sampled every hour were used in this case. These data are available through the on-line portal of the Information System and Data Center (ISDC)[1]. Current calibration factor provided by their operators together with frequency response of the decimation filter were used for the estimation of the tidal parameters (*Hábel, 2012*).

3. Data processing and tidal analysis

The program ANALYZE (*Wenzel, 1997*) contained in the software package ETERNA 3.40 (*Wenzel, 1996*) was used for the tidal analysis. Amplitude factors and phase differences were estimated for tidal waves in the frequency range from 0.50137 up to 7 cpd. Constant air pressure admittance factor

[1] `http://isdc.gfz-potsdam.de/`

was estimated together with tidal parameters. Elimination of the drift was the main challenge in the tidal analysis. Even the polynomial of the sixth degree was not suitable for the drift approximation in case of longer time series. Therefore it was necessary to eliminate the drift by filtering. This is closely connected to the second problem which arises from the length of the time series. Typical drawback of the filtering is the cut-off of the signal at both ends of the input signal. This leads to the time series shortening. Elimination of this problem is connected to the filter design. The task was to design a filter with the fewest number of coefficients that meets the requirements in the frequency domain. A finite impulse response (FIR) low-pass and zero-phase filter with 153 coefficients was designed. Filter provided in the ETERNA package has 167 coefficients. This results in the filter length difference of 14 hours. Both filter frequency responses together with frequencies of main tidal waves are shown in the Fig. 3. Drift-free signal was

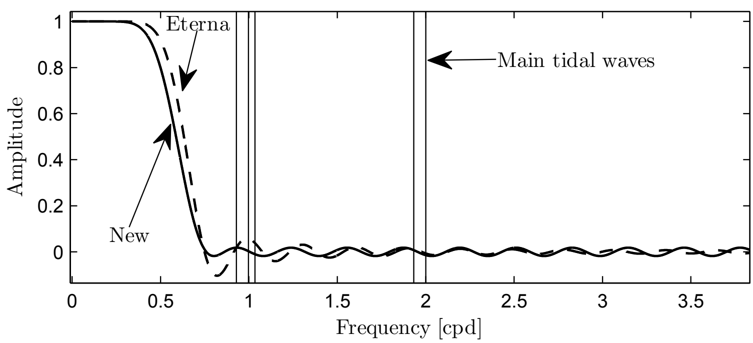

Fig. 3. Frequency response for ETERNA filter and new designed filter for drift elimination.

created by subtracting the filtered signal from the input signal. Both filters require one hour sampling of the input signal. Available time series were sampled every 65 seconds. Resampling of the original signal was realized with the help of the second low-pass zero-phase filter. This filter served for the elimination of the high-frequency noise. Also in this case should be the number of filter coefficient as low as possible. The GGP recommends the filter g1m1h.nlf[2]. This filter allows the noise elimination and decimation of the 60 second signal to one hour signal. The filter consists of 4303 coefficients,

[2] `http://www.eas.slu.e du/GGP/processinggeneral/g1m1h.dat`

i.e. total length of 3 days. It can be implemented in the ETERNA package. It should be noted that this filter is designed for long-term measurements acquired by SG. Our measurements consisted of several relatively short time series. Application of this filter results in a significant loss of data in our case. Furthermore it requires a resampling of the original signal (CG-5) to one minute samples. For this reason new FIR low-pass zero-phase filter with 2601 coefficients and cut-off frequency of 9.6 cpd was designed. The length difference between the combined ETERNA/GGP filters and newly designed filters was 39 hours. Application of these filters means the total difference of 16.25 days.

Two strategies were applied for the estimation of tidal parameters. The first strategy denoted as R1 was based on ETERNA/GGP filters and gravity variation together with atmospheric pressure sampled every minute. Linear interpolation was used for the resampling. The second strategy denoted as R2 used new filters and original signal of gravity variation sampled every 65 seconds together with resampled atmospheric pressure. Tidal parameters estimated in the second strategy were corrected for the effect of the amplitude changes due to the filtering. Effect of the filters implemented in the ETERNA package is corrected automatically. Working flow diagram is presented in Fig. 4.

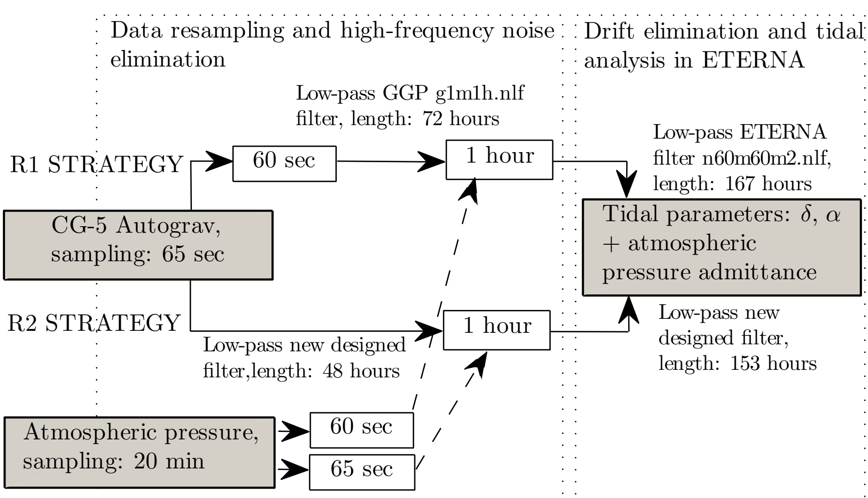

Fig. 4. Working flow diagram.

4. Results and discussion

Results in the form of amplitude factors and phase differences are presented in Table 1. Table contains only important tidal waves with amplitude larger than 100 nm.s^{-2} (see Appendix I for the full list of estimated parameters for R2 strategy). Tidal parameters for Vienna estimated from SG hour data are shown in the same table. This comparison is possible due to the short distance between both stations. The correct comparison of tidal parameters requires correction for ocean loading. This correction was based on ocean tides model provided by M.S. Bos and H.-G. Scherneck website[3]. The final ocean loading correction is the average of three ocean tide models, namely

Table 1. Comparison of the observed (estimated) and corrected tidal parameters together with their precision (σ)

Strategy:		Modra R1		Modra R2		Vienna	
Wave		δ/σ_δ	α/σ_α [°]	δ/σ_δ	α/σ_α [°]	δ/σ_δ	α/σ_α [°]
O1	*obs.*	1.1485 0.0007	0.12 0.03	1.1484 0.0007	0.12 0.03	1.14976 0.00003	0.113 0.001
	corr.	1.1520	0.00	1.1520	0.00	1.15337	-0.013
P1	*obs.*	1.1510 0.0033	0.06 0.16	1.1485 0.0029	0.06 0.14	1.14867 0.00007	0.146 0.003
	corr.	1.1507	-0.07	1.1483	-0.07	1.14831	0.004
K1	*obs.*	1.1355 0.0011	0.17 0.06	1.1350 0.0010	0.17 0.05	1.13571 0.00002	0.195 0.001
	corr.	1.1349	0.03	1.1345	0.03	1.13502	0.041
M2	*obs.*	1.1827 0.0005	1.02 0.02	1.1826 0.0004	1.02 0.02	1.18338 0.00002	1.072 0.001
	corr.	1.1612	0.02	1.1612	0.02	1.16169	0.005
S2	*obs.*	1.1814 0.0012	0.07 0.06	1.1813 0.0011	0.05 0.05	1.18060 0.00004	0.102 0.002
	corr.	1.1609	-0.23	1.1608	-0.24	1.15953	-0.229

EOT11a, GOT4.8 and HAMTIDE. Differences between strategies (R1 and R2) are negligible compared to the precision. Tidal parameters for the R2 strategy are estimated with better precision as a result of the larger number of measurements entering the tidal analysis. This is supported by the lower

[3] http://froste.oso.chalmers.se/loading

average noise level at tidal frequencies in the case of R2. This noise level is 20 times higher than the results from SG. Corrected amplitude factor for P1 wave Modra R1 shows the largest difference compared to the Vienna tidal parameters, but this difference is negligible compared to the precision of estimated parameters. The overall comparison shows satisfactory results, despite the fact that the used SG time series were significantly longer and had fewer interruptions than the CG-5 time series.

Comparison of tidal parameters corrected for ocean tides with the non-hydrostatic body tide model WDD (*Dehant et al., 1999*) is presented in the Table 2. In this case the difference between theoretical amplitude factors due to the different position of the stations is negligible. This table shows a good agreement between estimated tidal parameters and theoretical values.

Table 2. Comparison of the mean corrected amplitude factors with the WDD/NHi body tide model

Strategy:		Modra R1	Modra R2	Vienna
Wave	$\delta_{WDD/NHi}$	$\delta_{WDD/NHi} - \delta_{corr}$ [‰]		
O1	1.1543	1.95	2.03	0.79
P1	1.1491	-1.41	0.72	0.69
K1	1.1346	-0.30	0.09	-0.40
M2	1.1620	0.62	0.68	0.24
S2	1.1620	0.93	1.01	2.10
Mean		*0.36*	*0.90*	*0.68*

Figure 5 shows the calibration factor calculated as the ratio of amplitude factors. There is no clear evidence of the calibration factor error or dependence of the factor on tidal wave period or amplitude. There is also no significant error in the S2 wave, which is expected in case of spring gravimeters as the result of the lack of air pressure compensation (*Arnoso et al., 2001*). This confirms good pressure protection declared by the CG-5 manufacturer (*Scintrex, 2009*).

Beside the estimated tidal parameters the ANALYZE program provides also time series of residuals. These were tested with the aim to identify the origin of the amplitude factor discrepancies. Coherence between the CG-5 residuals and tidal signal does not exceed the value of 0.3 at main tidal frequencies. Similar coherence was observed in the residual-pressure and residual-temperature comparison. The CG-5 gravimeter was located

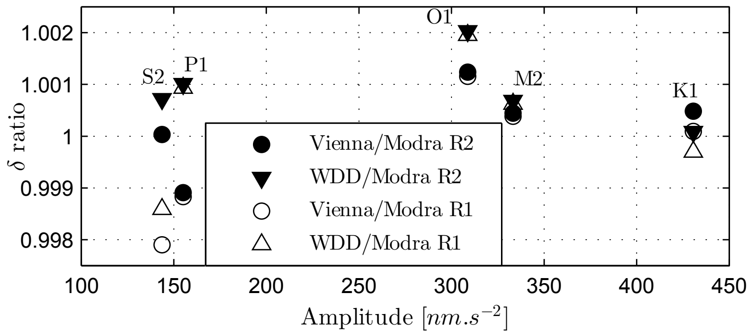

Fig. 5. Amplitude factor ratio for Vienna/Modra and WDD/Modra.

in the room with no temperature control. Measured ambient temperature varied within the range of 11 degrees. No correlation between the gravity variation and temperature was observed in the time domain even in case of rapid temperature changes. Spectral analysis of the room temperature variation showed dominant long-periodic frequencies. This means that the possible changes of gravity due to the temperature were eliminated by the filtering.

The calculated tidal effect on gravity was used for the time domain comparison. Tidal effect computation was based on the estimated tidal parameters and the *Tamura's (1987)* tidal potential development. The effect was computed for Modra station coordinates using tidal parameters for R2 strategy, Vienna and Pecný. The difference between R1 and R2 strategy is negligible. Theoretical tidal parameters for inelastic non-hydrostatic Earth model WDD were added for the comparison. These were generated in the TSoft software (*Van Camp and Vauterin, 2005*) and served for the calculation of solid Earth tides effect. Ocean tides effect computation was based on the EOT11a model (*Savcenko and Bosch, 2011*). Identical tidal parameters for long-periodic waves were used for this comparison. Difference between Vienna and selected approaches are presented in Table 3. The range of the difference between the tidal effect computed from Modra R2 strategy and Vienna tidal parameters slightly exceeds 10 nm.s^{-2}. This means that the new parameters estimated for Modra station can be used for correction of relative gravity measurements. Similar results were achieved with the combination of theoretical models WDD/EOT11e. Despite the distance of

Table. 3. Comparison of tidal effect difference

Vienna−	std [nm.s^{-2}]	max [nm.s^{-2}]	min [nm.s^{-2}]	range [nm.s^{-2}]
Modra R2	1.6	4.9	−5.5	10.4
WDD/NHi+EOT11e	1.7	4.5	−5.0	9.5
Pecný	1.1	2.7	−2.4	5.1

220 km between Vienna and Pecný the tidal effect difference is very small. The use of Pecný tidal parameters for the correction of absolute gravity measurements in the area of Slovakia does not introduce significant errors.

5. Conclusion

We have tested the possibility of using vertical spring Scintrex CG-5 Autograv gravimeter for long-term gravity observations. Time series of gravity variation at Modra station were used for this purpose. We observed strong and non-linear drift which is the main drawback of this gravimeter. Even high-degree polynomials are not suitable for the elimination of the drift in case of long-term observation. This makes it impossible to analyze long periodic variation like polar motion effect or global hydrological variation. However, CG-5 gravimeter can be used for the observation of gravity variation with periods of few days. Available CG-5 time series were used for the tidal analysis focused on the diurnal and semi-diurnal tidal waves. New set of tidal parameters for the Modra station was estimated. Two strategies were applied for this purpose and both show similar results. These parameters were compared to those estimated from SG observations at the closest GGP station in Vienna. This comparison included the ocean loading correction. A good agreement was found between estimated amplitude factors for Modra and Vienna station. This was confirmed by the comparison with theoretical body tide model. Even better results can be expected in case of longer time series used for tidal analysis. Time domain comparison showed that the new estimated tidal parameters for Modra station are suitable for correction of gravity measurements in the studied area. These results confirm that the Scintrex CG-5 Autograv gravimeter can be used for tidal observations, despite the fact that this gravimeter serves primarily for field measurements.

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Appendix I: Estimated tidal parameters for Modra (R2 strategy)

Frequency		Wave		Tidal parameters			
from	to	name	theo.amp	δ	σ_δ	α	σ_α
[cpd]	[cpd]		$[nm.s^{-2}]$			[°]	[°]
0.501370	0.842147	SGQ1	2.2782	1.49692	0.07307	2.6928	3.4332
0.842148	0.860293	2Q1	7.8195	1.14660	0.02449	0.2716	1.2197
0.860294	0.878675	SGM1	9.4295	1.18651	0.02085	-2.2096	1.0078
0.878676	0.896968	Q1	59.0903	1.14599	0.00326	0.2107	0.1649
0.896969	0.911390	RO1	11.2160	1.14027	0.01818	0.1101	0.9265
0.911391	0.931206	O1	308.6218	1.14838	0.00065	0.1238	0.0329
0.931207	0.947991	TAU1	4.0228	1.06945	0.05220	0.2920	2.8415
0.947992	0.967660	NO1	24.2596	1.15721	0.00602	0.1472	0.3012
0.967661	0.981854	CHI1	4.6421	1.08731	0.04203	-1.7536	2.2441
0.981855	0.996055	PI1	8.3909	1.18358	0.03774	0.3553	1.8430
0.996056	0.998631	P1	143.5777	1.14851	0.00286	0.0590	0.1437
0.998632	1.001369	S1	3.3932	1.45791	0.17797	33.4269	7.0123
1.001370	1.004107	K1	433.8682	1.13503	0.00097	0.1693	0.0489
1.004108	1.006845	PSI1	3.3948	1.32142	0.11678	-0.3111	5.0703
1.006846	1.023622	PHI1	6.1775	1.13674	0.04940	-2.3265	2.4914
1.023623	1.035379	TET1	4.6408	1.13715	0.04283	-0.0008	2.1400
1.035380	1.057485	J1	24.2682	1.15825	0.00819	-0.2745	0.4002

1.057486	1.071833	SO1	4.0247	1.14491	0.04936	1.1859	2.4306
1.071834	1.090052	OO1	13.2731	1.16373	0.01240	0.0025	0.5990
1.090053	1.470243	NU1	2.5418	1.08805	0.05819	0.6471	3.0193
1.470244	1.845944	EPS2	2.4512	1.16700	0.05278	3.4332	2.6223
1.845945	1.863026	2N2	8.4053	1.14935	0.01778	2.7245	0.9018
1.863027	1.880264	MU2	10.1445	1.16024	0.01504	1.6234	0.7555
1.880265	1.897351	N2	63.5177	1.17784	0.00234	1.6829	0.1158
1.897352	1.914128	NU2	12.0656	1.17794	0.01219	1.5899	0.6020
1.914129	1.950419	M2	331.7436	1.18264	0.00044	1.0232	0.0216
1.950420	1.964767	LAM2	2.4463	1.18202	0.06245	3.0503	3.0142
1.964768	1.984282	L2	9.3777	1.17230	0.01510	0.9734	0.7348
1.984283	1.998996	T2	9.0191	1.20969	0.01855	0.1480	0.8667
1.998997	2.002736	S2	154.3307	1.18126	0.00108	0.0490	0.0516
2.002737	2.022488	K2	41.9307	1.18594	0.00366	0.5405	0.1743
2.022489	2.057484	ETA2	2.3455	1.17885	0.05753	5.8854	2.7438
2.057485	2.451943	2K2	0.6136	0.94025	0.14295	5.7692	8.7584
2.451944	2.881176	MN3	1.1877	1.07723	0.09881	0.8973	5.1642
2.881177	3.381378	M3	4.3338	1.06455	0.02832	0.6556	1.5291
3.381379	4.347615	M4	0.0526	3.02063	2.02606	-16.6049	38.3663