Comparison of Ocean Tide Loading Models Using Strain Data Measured in the Sopronbánfalva Geodynamic Observatory, Hungary

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Abstract

Tidal strain observations carried out in the Sopronbánfalva Geodynamic Observatory (SGO) in Hungary are used to test thirteen different ocean tide loading models for diurnal and semi-diurnal tidal harmonic constituents O1, K1 and M2. Strain data with one minute sampling rate were corrected for temperature and barometric pressure and decimated to one hour sampling rate. Strain data, corrected in this way, were subjected to correction for ocean load. In the case of the diurnal tidal constituents O1 and K1 the measured amplitude factors of nearly 0.5 became close to the theoretical as a result of the correction, while in the case of the M2 semi-diurnal wave the measured amplitude factor of almost 1 hardly changed due to correction. It was only found a negligible difference between the individual global ocean tide loading models mainly due to using different Earth models and Green functions. The effect of the diurnal (O1 and K1) and the semi-diurnal (M2) ocean tide loading components is in the same order of magnitude at the SGO. The large residual vectors after the correction suggest that local effects need further investigation.

Keywords

Earth tide, Extensometer, Tidal parameters, Ocean tide loading, Strain

Introduction

Ocean tide surface loading causes both radial and tangential displacements of the Earth surface and changes of gravity. This latter comprises effects resulting from radial displacement in the Earth’s gravity field, the internal redistribution of mass, and the direct gravitational attraction of the tidal water mass [1-5].

Various authors have been dealing with testing and comparison of recent global ocean tide models on the basis of gravimetric [6-17], displacement (GPS) [18-25], extensometric [15,16,26,27] and tilt measurements [28-30].

In this paper, the efficiency of ocean loading corrections are compared using thirteen different ocean tide loading models for the diurnal and semi-diurnal tidal harmonic constituents O1, K1 and M2 on the basis of strain data observed in the SGO in 2017.

Measurement Site and Instrument

Extensometric measurements were carried out in the SGO which is located on the Hungarian-Austrian border in the Sopron Mountains. The coordinates of the observatory are: Latitude 47°40'55'' N; longitude 16°33'32'' E; the altitude is 280 m a.s.l. The yearly mean temperature in the gallery is 10.4...
°C and the yearly and daily temperature variations are less than 0.5 °C and 0.05 °C, respectively. The instrument is a 22 m long quartz-tube extensometer with capacitive transducer. The azimuth of the extensometer is 116°, and its scale factor is 2.093 ± 0.032 nm mV⁻¹. Observation site and construction of the extensometer and its calibration are described in detail by Mentes [31,32].

Data Processing

Strain, temperature and barometric pressure data recorded with a sampling rate of one minute were used for correction by the T-soft program [33]. Data series were despiked and ungapped. The long-term constituent of the strain and temperature data were approximated by fitting a polynomial of 9th order to the raw data series and were subtracted from strain and temperature data, respectively. Theoretical tide was subtracted from the remaining strain data and then strain data were corrected for the temperature and barometric pressure by simple linear regression method and after the correction the theoretical tide was added back. During the correction procedure time lags between strain and temperature and barometric pressure data were taking into consideration. Then the data were low-pass filtered and decimated to one hour sampling and processed by ETERNA 3.40 Earth tide data processing program package [34] using the Wahr-Dehant Earth model [35,36] and the HW95 tidal potential catalogue [37].

For the ocean tide load prediction the SPOTL routines [38] and the ocean load provider service [39] were used. The name of the SPOTL codes are: gr.mmmmmm.www.pnn,c[e|m]. The mmmmmm string denotes the Earth model. The SPOTL uses three different Earth models, which are denoted namely the Gutenberg-Bullen Model A average Earth (gbaver) and two extreme models of the Earth’s crust and mantle structure [40], one oceanic (gbocen) and one continental shield (gbcont). www denotes: Who computed the function: the source code is wef for W.E. Farrell [1], who computed and tabulated all Green functions. pnn denotes: 01 coarse grid; 02 fine grid (about 20 m for the innermost range) running to much closer to the center (about 100 m). The ce suffix denotes a reference frame with the center of mass of solid Earth and the cm a reference frame with the common center of mass of the load and the Earth.

For ocean load correction of strain data ten ocean tide models have been used with SPOTL, supplemented by the local model osu.mediterranean.2011: EOT11a [41], HAMTIDE11a [42], OSU.TPXO72atlas, OSU.TPXO72, TPX070 [43], DTU10

Figure 1: Outline of tidal ocean loading correction. Theoretical tidal vector \( \vec{R}(R,0) \), observed tidal vector \( \vec{A}_m(A_m,\alpha_m) \), observed residual vector \( \vec{B}(B,\beta) \), ocean loading vector \( \vec{L}(L,\lambda) \), corrected tidal vector \( \vec{A}_c(A_c,\alpha_c) \) and remaining residual vector \( \vec{X}(X,\xi) \). The vectors are defined by their amplitudes \( (R, A_m, B, L, A_c, X) \) and phases \( (\alpha_m, \beta, \lambda, \alpha_c, \xi) \).
Results and Discussion

Without external forces the common centre of mass of oceans and the solid Earth will remain fixed in space. Since the ocean tides cause water mass displacements, its centre of mass moves periodically and it is compensated by an opposite motion of the centre of mass of the solid Earth. Accordingly, in these three cases the ocean load was calculated relative to the fixed common mass center of the ocean and the solid Earth and the moving center of mass of the solid Earth. In both cases the calculations were carried out using elastic [1] and visco-elastic Earth model STW105 [53].

The ocean loading correction (see Figure 1) was carried out according to Neumeyer, et al. [54]. The L amplitude and λ phase of the ocean tide load vectors were determined from the above-mentioned different ocean tide loading models and were subtracted from the observed strain tidal vectors \( \overrightarrow{A}_m(A_m,\alpha_m) \) in case of the O1, K1 and M2 tidal waves to obtain the corrected tidal strain vectors \( \overrightarrow{A}_c(A_c,\alpha_c) \). The remaining residual \( X \) depends on the accuracy of the instrument calibration, the local effects, such as the cavity effect, the inaccurate corrected temperature, air pressure and on the accuracy of the ocean tide model.

Results and Discussion

Results of the tidal evaluation of the measured strain data in case of the tidal constituents O1, K1 and M2 without ocean tide loading corrections are shown in Table 1. In the SGO the obtained amplitude factors for the diurnal waves (O1, K1) are about 0.5, half of the theoretical value, while for the semi-diurnal wave M2 it is about 1. Table 2, Table 3, Table 4 and Table 5 show the amplitudes (L) and phases (λ) of the ocean tide load, the amplitudes (A) and phases (α) of strain corrected for the ocean tide load, the amplitudes (X) and phases (ξ) of the residues and the corrected amplitude factors (η) in case of different Earth and global ocean tide loading models.

Table 2 shows the O1 tidal constituents corrected for ocean tide loading with SPOTL in case of different Earth models and 10 global ocean tide models. The uncorrected amplitude factor is 0.5323 (see Table 1), while the corrected amplitude factors (average: 1.025 ± 0.001) are somewhat higher than one in the case of solid Earth model with the center of mass (ce suffix denotes the reference frame with the center of mass of solid Earth) and somewhat lower (average: 0.928 ± 0.003) in the case of the Earth model with the common center of mass of the load and the Earth (cm suffix denotes the reference frame with the center of mass of the load and the Earth). Similar results were obtained for K1 (see Table 3) for which the uncorrected amplitude factor was 0.5283. The corrected average amplitude factors are 1.026 ± 0.001 (ce) and 0.966 ± 0.002 (cm). The measured amplitude factor for M2 is 1.0036 (see Table 1), while the corrected average values (see Table 4) are 1.059 ± 0.004 (ce) and 1.039 ± 0.007 (cm). In both cases the corrected values are higher than the measured value, but similarly to O1 and K1 the corrected values are higher in case of reference frame with the center of Earth (ce) than in the case of common center of load mass and the center of Earth.

Table 5 shows the results of correction of the O1, K1, M2 waves for ocean tide loading derived from three ocean loading models (FS2012, FS214b and GOT00.2) with different Earth models calculated by the ocean load provider service. In case of the elastic and visco-elastic Earth models almost identical corrected amplitude factors (η) were obtained for O1, K1 and M2 waves but these were some-

Table 1: Tidal results calculated from strain data corrected for temperature and barometric pressure.

| Wave | Theoretical amplitude R [nstr] | Measured amplitude A_m [nstr] | Measured phase lag α_m [degree] | Amplitude factor η | Measured residual B [nstr] | Phase of the residual β [degree] |
|------|--------------------------|-----------------------------|-----------------------------|-----------------|---------------------------|-----------------------------|
| O1   | 6.5932                   | 3.5098                      | -6.3118                     | 0.5323          | 3.1286                    | 187.0846                    |
| K1   | 9.2690                   | 4.8964                      | -3.4378                     | 0.5283          | 4.3912                    | 183.8339                    |
| M2   | 5.0573                   | 5.0754                      | -14.4836                    | 1.0036          | 1.2768                    | 263.6103                    |

Citation: Mentes G (2021) Comparison of Ocean Tide Loading Models Using Strain Data Measured in the Sopronbánfalva Geodynamic Observatory, Hungary. Int J Earth Sci Geophys 7:044
Table 2: Results of correction of the O1 wave for ocean tide loading derived from 10 ocean loading models with different Earth models calculated by SPOTL routines. The observed values, not corrected for ocean tide loading, are in Table 1.

| Earth model | Ocean tide model | Amplitude of the ocean tide load | Phase of the ocean tide load | Corrected strain amplitude | Phase of the corrected strain | Amplitude of the remaining residual | Phase of the remaining residual | Corrected amplitude factor |
|-------------|------------------|---------------------------------|-------------------------------|---------------------------|--------------------------------|-----------------------------------|--------------------------------|---------------------------|
| gbocen.ce   | eot11a           | 0.182                           | 37.869                        | 6.777                     | 4.168                          | 3.286                             | 8.621                          | 1.028                     |
|             | hamtide11a       | 0.159                           | 38.559                        | 6.756                     | 4.072                          | 3.265                             | 8.451                          | 1.025                     |
|             | osu.tpxo72atlas  | 0.160                           | 42.219                        | 6.751                     | 4.149                          | 3.261                             | 8.616                          | 1.024                     |
|             | tpxo70           | 0.170                           | 40.758                        | 6.761                     | 4.170                          | 3.271                             | 8.645                          | 1.026                     |
|             | fes952           | 0.173                           | 39.506                        | 6.767                     | 4.163                          | 3.276                             | 8.623                          | 1.026                     |
|             | fes2004          | 0.160                           | 39.651                        | 6.756                     | 4.102                          | 3.265                             | 8.513                          | 1.025                     |
|             | osu.tpxo72       | 0.164                           | 41.468                        | 6.756                     | 4.154                          | 3.265                             | 8.620                          | 1.025                     |
|             | dtu10tr          | 0.164                           | 39.949                        | 6.758                     | 4.125                          | 3.267                             | 8.557                          | 1.025                     |
|             | csr4tr           | 0.166                           | 39.345                        | 6.761                     | 4.123                          | 3.270                             | 8.549                          | 1.025                     |
|             | schw1             | 0.150                           | 38.033                        | 6.750                     | 4.022                          | 3.258                             | 8.356                          | 1.024                     |
| gbav        | eot11a           | 0.168                           | 41.242                        | 6.759                     | 4.169                          | 3.268                             | 8.647                          | 1.025                     |
|             | hamtide11a       | 0.160                           | 38.749                        | 6.757                     | 4.082                          | 3.266                             | 8.470                          | 1.025                     |
|             | osu.tpxo72atlas  | 0.161                           | 42.407                        | 6.752                     | 4.159                          | 3.261                             | 8.635                          | 1.024                     |
|             | tpxo70           | 0.171                           | 40.899                        | 6.762                     | 4.180                          | 3.272                             | 8.664                          | 1.026                     |
|             | fes952           | 0.175                           | 39.612                        | 6.768                     | 4.172                          | 3.277                             | 8.641                          | 1.026                     |
|             | fes2004          | 0.162                           | 39.830                        | 6.757                     | 4.112                          | 3.266                             | 8.532                          | 1.025                     |
|             | osu.tpxo72       | 0.165                           | 41.635                        | 6.756                     | 4.164                          | 3.266                             | 8.640                          | 1.025                     |
|             | dtu10tr          | 0.165                           | 40.109                        | 6.759                     | 4.135                          | 3.268                             | 8.575                          | 1.025                     |
|             | csr4tr           | 0.167                           | 39.491                        | 6.762                     | 4.133                          | 3.271                             | 8.568                          | 1.026                     |
|             | schw1             | 0.152                           | 38.319                        | 6.751                     | 4.034                          | 3.259                             | 8.379                          | 1.024                     |
| gbcont.ce   | eot11a           | 0.166                           | 42.862                        | 6.755                     | 4.191                          | 3.264                             | 8.698                          | 1.024                     |
|             | hamtide11a       | 0.158                           | 40.370                        | 6.753                     | 4.104                          | 3.262                             | 8.521                          | 1.024                     |
|             | osu.tpxo72atlas  | 0.160                           | 44.211                        | 6.748                     | 4.185                          | 3.257                             | 8.694                          | 1.023                     |
|             | tpxo70           | 0.169                           | 42.506                        | 6.758                     | 4.204                          | 3.268                             | 8.719                          | 1.025                     |
|             | fes952           | 0.173                           | 41.107                        | 6.764                     | 4.195                          | 3.273                             | 8.694                          | 1.026                     |
|             | fes2004          | 0.160                           | 41.516                        | 6.753                     | 4.137                          | 3.262                             | 8.588                          | 1.024                     |
|             | osu.tpxo72       | 0.163                           | 43.419                        | 6.752                     | 4.189                          | 3.261                             | 8.698                          | 1.024                     |
|             | dtu10tr          | 0.163                           | 41.752                        | 6.755                     | 4.158                          | 3.264                             | 8.629                          | 1.025                     |
|             | csr4tr           | 0.166                           | 41.165                        | 6.758                     | 4.160                          | 3.267                             | 8.629                          | 1.025                     |
|             | schw1             | 0.149                           | 39.987                        | 6.746                     | 4.054                          | 3.255                             | 8.426                          | 1.023                     |
| Average     |                  | 0.164                           | 40.618                        | 6.757                     | 4.139                          | 3.266                             | 8.587                          | 1.025                     |
| STD         |                  | 0.007                           | 1.582                         | 0.006                      | 0.047                          | 0.006                             | 0.094                          | 0.001                     |
what higher when motion correction was applied in case of the diurnal waves (O1 and K1), while for the semidiurnal wave M2 the opposite values were obtained.

Comparing the residues in Table 2, Table 3, Table 4 and Table 5, it can be seen that the amplitudes (X) of the residual vectors changed only slightly compared to the measured ones (B), while the phase angles decreased significantly. Large residues remaining after the correction suggest that local effects (e.g. cavity) affect the measurement site, which requires further study. The amplitudes (L) of the ocean load vectors are in the same order of magnitude for the diurnal (O1, K1) and semidiurnal (M2) waves at the site of the SGO.

### Conclusions

Strain measurement was used to test thirteen global ocean tide loading models. Tidal parameters corrected for ocean tide loading were calculated. All models provided virtually the same result. In the case of the diurnal tidal constituents O1 and K1 the measured amplitude factors of nearly 0.5 became close to 1 as a result of the correction, while in the

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| gbecn.cm | eot11a | 0.624 | 148.167 | 6.127 | 6.665 | 2.672 | 15.434 | 0.929 |
|----------|-------|-------|---------|-------|-------|-------|--------|-------|
| hamtide11a | 0.621 | 149.556 | 6.119 | 6.537 | 2.663 | 15.168 | 0.928 |
| osu.tpxo72atlas | 0.635 | 147.751 | 6.121 | 6.761 | 2.668 | 15.670 | 0.928 |
| tpxo70 | 0.636 | 149.075 | 6.111 | 6.660 | 2.656 | 15.476 | 0.927 |
| fes952 | 0.652 | 153.129 | 6.072 | 6.597 | 2.613 | 15.002 | 0.921 |
| fes2004 | 0.622 | 148.183 | 6.128 | 6.650 | 2.673 | 15.396 | 0.929 |
| osu.tpxo72 | 0.634 | 147.915 | 6.120 | 6.744 | 2.667 | 15.635 | 0.928 |
| dtu10tr | 0.624 | 147.928 | 6.129 | 6.680 | 2.674 | 15.462 | 0.928 |
| schw1 | 0.595 | 148.262 | 6.148 | 6.652 | 2.690 | 14.970 | 0.928 |

| gbav.cm | eot11a | 0.624 | 148.030 | 6.127 | 6.675 | 2.673 | 15.455 | 0.929 |
|----------|-------|-------|---------|-------|-------|-------|--------|-------|
| hamtide11a | 0.621 | 149.428 | 6.120 | 6.547 | 2.664 | 15.189 | 0.928 |
| osu.tpxo72atlas | 0.635 | 147.633 | 6.122 | 6.771 | 2.669 | 15.691 | 0.928 |
| tpxo70 | 0.636 | 148.945 | 6.112 | 6.607 | 2.674 | 15.417 | 0.927 |
| fes952 | 0.651 | 152.994 | 6.073 | 6.407 | 2.615 | 15.022 | 0.921 |
| osu.tpxo72 | 0.634 | 147.788 | 6.121 | 6.755 | 2.668 | 15.337 | 0.930 |
| dtu10tr | 0.624 | 148.056 | 6.129 | 6.660 | 2.674 | 15.482 | 0.930 |
| schw1 | 0.595 | 148.232 | 6.130 | 6.618 | 2.674 | 15.337 | 0.930 |

| gbcont.cm | eot11a | 0.629 | 148.071 | 6.123 | 6.701 | 2.669 | 15.528 | 0.929 |
|----------|-------|-------|---------|-------|-------|-------|--------|-------|
| hamtide11a | 0.626 | 149.448 | 6.116 | 6.573 | 2.660 | 15.261 | 0.928 |
| osu.tpxo72atlas | 0.640 | 147.646 | 6.118 | 6.801 | 2.665 | 15.773 | 0.928 |
| tpxo70 | 0.641 | 148.954 | 6.108 | 6.689 | 2.654 | 15.574 | 0.926 |
| fes952 | 0.656 | 152.976 | 6.069 | 6.434 | 2.611 | 15.096 | 0.920 |
| fes2004 | 0.627 | 148.052 | 6.125 | 6.690 | 2.671 | 15.496 | 0.929 |
| osu.tpxo72 | 0.640 | 147.812 | 6.117 | 6.784 | 2.664 | 15.738 | 0.928 |
| dtu10tr | 0.629 | 147.834 | 6.125 | 6.717 | 2.671 | 15.556 | 0.929 |
| schw1 | 0.601 | 148.180 | 6.145 | 6.526 | 2.688 | 15.062 | 0.932 |

| Average | 0.628 | 148.750 | 6.120 | 6.636 | 2.665 | 15.392 | 0.928 |
| STD | 0.014 | 1.522 | 0.019 | 0.110 | 0.019 | 0.234 | 0.003 |
Table 3: Results of correction of the K1 wave for ocean tide loading derived from 10 ocean loading models with different Earth models calculated by SPOTL routines. The observed values, not corrected for ocean tide loading, are in Table 1.

| Earth model | Ocean tide model | Amplitude of the ocean tide load | Phase of the ocean tide load | Corrected strain amplitude | Phase of the corrected strain | Amplitude of the remaining residual | Phase of the remaining residual | Corrected amplitude factor |
|-------------|------------------|---------------------------------|-----------------------------|---------------------------|-----------------------------|-----------------------------------|-----------------------------|--------------------------|
|             | L [nstr]         | λ [degree]                      | A_x [nstr]                  | α_x [degree]              | X [nstr]                    | ξ [degree]                        | n_c                         |                         |
| gbocen.ce   | eot11a           | 0.282                           | 35.946                      | 9.518                     | 2.724                       | 4.633                             | 5.604                       | 1.027                    |
|             | hamtide11a       | 0.278                           | 37.321                      | 9.510                     | 2.744                       | 4.626                             | 5.649                       | 1.026                    |
|             | osu.tpxo72atl    | 0.283                           | 38.759                      | 9.511                     | 2.797                       | 4.626                             | 5.757                       | 1.026                    |
|             | tpxo70           | 0.280                           | 38.125                      | 9.510                     | 2.770                       | 4.625                             | 5.703                       | 1.026                    |
|             | fes952           | 0.268                           | 38.863                      | 9.498                     | 2.745                       | 4.613                             | 5.659                       | 1.025                    |
|             | fes2004          | 0.289                           | 39.997                      | 9.525                     | 2.721                       | 4.640                             | 5.592                       | 1.028                    |
|             | osu.tpxo72       | 0.284                           | 37.139                      | 9.516                     | 2.761                       | 4.631                             | 5.680                       | 1.027                    |
|             | dtu10tr          | 0.282                           | 36.704                      | 9.515                     | 2.741                       | 4.630                             | 5.640                       | 1.027                    |
|             | csr4tr           | 0.247                           | 35.234                      | 9.489                     | 2.591                       | 4.603                             | 5.347                       | 1.024                    |
|             | schw1            | 0.272                           | 37.912                      | 9.504                     | 2.736                       | 4.619                             | 5.637                       | 1.025                    |
| gbav.ce     | eot11a           | 0.286                           | 35.999                      | 9.521                     | 2.738                       | 4.636                             | 5.631                       | 1.027                    |
|             | hamtide11a       | 0.278                           | 37.770                      | 9.509                     | 2.755                       | 4.625                             | 5.673                       | 1.026                    |
|             | osu.tpxo72atl    | 0.284                           | 39.223                      | 9.509                     | 2.809                       | 4.625                             | 5.782                       | 1.026                    |
|             | tpxo70           | 0.280                           | 38.550                      | 9.509                     | 2.781                       | 4.624                             | 5.726                       | 1.026                    |
|             | fes952           | 0.268                           | 39.304                      | 9.497                     | 2.754                       | 4.612                             | 5.679                       | 1.025                    |
|             | fes2004          | 0.289                           | 35.436                      | 9.524                     | 2.732                       | 4.639                             | 5.616                       | 1.028                    |
|             | osu.tpxo72       | 0.285                           | 37.578                      | 9.515                     | 2.772                       | 4.630                             | 5.704                       | 1.027                    |
|             | dtu10tr          | 0.282                           | 37.116                      | 9.514                     | 2.752                       | 4.629                             | 5.663                       | 1.026                    |
|             | csr4tr           | 0.247                           | 35.777                      | 9.489                     | 2.598                       | 4.603                             | 5.362                       | 1.024                    |
|             | schw1            | 0.272                           | 38.241                      | 9.503                     | 2.745                       | 4.618                             | 5.656                       | 1.025                    |
| gbcont.ce   | eot11a           | 0.294                           | 37.792                      | 9.522                     | 2.810                       | 4.638                             | 5.777                       | 1.027                    |
|             | hamtide11a       | 0.287                           | 39.538                      | 9.511                     | 2.827                       | 4.627                             | 5.818                       | 1.026                    |
|             | osu.tpxo72atl    | 0.292                           | 40.906                      | 9.511                     | 2.879                       | 4.627                             | 5.927                       | 1.026                    |
|             | tpxo70           | 0.289                           | 40.287                      | 9.510                     | 2.853                       | 4.626                             | 5.872                       | 1.026                    |
|             | fes952           | 0.276                           | 41.172                      | 9.498                     | 2.827                       | 4.613                             | 5.827                       | 1.025                    |
|             | fes2004          | 0.296                           | 37.265                      | 9.526                     | 2.805                       | 4.641                             | 5.764                       | 1.028                    |
|             | osu.tpxo72       | 0.293                           | 39.304                      | 9.517                     | 2.844                       | 4.633                             | 5.851                       | 1.027                    |
|             | dtu10tr          | 0.290                           | 38.983                      | 9.515                     | 2.825                       | 4.631                             | 5.812                       | 1.027                    |
|             | csr4tr           | 0.255                           | 37.607                      | 9.491                     | 2.672                       | 4.606                             | 5.514                       | 1.024                    |
|             | schw1            | 0.280                           | 40.052                      | 9.504                     | 2.816                       | 4.620                             | 5.800                       | 1.025                    |
| Average     |                 | 0.280                           | 37.957                      | 9.510                     | 2.764                       | 4.625                             | 5.691                       | 1.026                    |
| STD         |                 | 0.012                           | 1.631                       | 0.010                     | 0.064                       | 0.010                             | 0.129                       | 0.001                    |

Citation: Mentes G (2021) Comparison of Ocean Tide Loading Models Using Strain Data Measured in the Sopronbánfalva Geodynamic Observatory, Hungary. Int J Earth Sci Geophys 7:044
In the case of the M2 semi-diurnal wave, the measured amplitude factor of almost 1 hardly changed due to correction. It was only found a negligible difference between the individual tide loading models mainly due to the use of different Earth models, and Green functions. The effect of the diurnal (O1 and K1) and the semi-diurnal (M2) ocean tide loading components is in the same order of magnitude at the SGO. The large residual vectors after the correction suggest that local effects need further investigation.

**Acknowledgments**

This work was funded by the Hungarian National Research Fund (OTKA) under project K 109060. Special thanks to Tibor Molnár for his careful maintenance of the instruments.

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**Citation:** Mentes G (2021) Comparison of Ocean Tide Loading Models Using Strain Data Measured in the Sopronbánfalva Geodynamic Observatory, Hungary. Int J Earth Sci Geophys 7:044
Table 4: Results of correction of the M2 wave for ocean tide loading derived from 10 ocean loading models with different Earth models calculated by SPOTL routines. The observed values, not corrected for ocean tide loading, are in Table 1.

| Earth model | Ocean tide model | Amplitude of the ocean tide load | Phase of the ocean tide load | Corrected strain amplitude | Phase of the corrected strain | Amplitude of the remaining residual | Phase of the remaining residual | Corrected amplitude factor |
|-------------|------------------|----------------------------------|------------------------------|---------------------------|-------------------------------|----------------------------------|-------------------------------|-------------------------------|
| gbocen.ce   | eot11a           | 0.155                            | 112.319                      | 5.351                     | 15.308                        | 1.415                            | 86.548                        | 1.058                        |
|             | hamtide11a       | 0.164                            | 114.788                      | 5.343                     | 15.389                        | 1.419                            | 86.953                        | 1.057                        |
|             | osu.tpxo72atlas  | 0.149                            | 106.327                      | 5.368                     | 15.255                        | 1.415                            | 85.859                        | 1.061                        |
|             | tpxo70           | 0.166                            | 111.617                      | 5.352                     | 15.429                        | 1.426                            | 86.668                        | 1.058                        |
|             | fes952           | 0.159                            | 102.631                      | 5.378                     | 15.361                        | 1.428                            | 85.611                        | 1.063                        |
|             | fes2004          | 0.182                            | 114.356                      | 5.342                     | 15.589                        | 1.437                            | 87.252                        | 1.056                        |
|             | osu.tpxo72       | 0.149                            | 111.685                      | 5.354                     | 15.249                        | 1.410                            | 86.386                        | 1.059                        |
|             | dtu10tr          | 0.169                            | 110.058                      | 5.356                     | 15.464                        | 1.430                            | 86.548                        | 1.059                        |
|             | csr4tr           | 0.157                            | 112.819                      | 5.350                     | 15.329                        | 1.416                            | 86.635                        | 1.058                        |
|             | schw1             | 0.100                            | 93.336                       | 5.391                     | 14.713                        | 1.376                            | 84.231                        | 1.066                        |
| gbav.ce     | eot11a           | 0.169                            | 116.631                      | 5.337                     | 15.434                        | 1.421                            | 87.244                        | 1.055                        |
|             | hamtide11a       | 0.178                            | 118.733                      | 5.329                     | 15.512                        | 1.426                            | 87.643                        | 1.054                        |
|             | osu.tpxo72atlas  | 0.161                            | 111.146                      | 5.354                     | 15.377                        | 1.422                            | 86.535                        | 1.059                        |
|             | tpxo70           | 0.181                            | 115.899                      | 5.337                     | 15.566                        | 1.433                            | 87.399                        | 1.055                        |
|             | fes952           | 0.170                            | 107.098                      | 5.365                     | 15.479                        | 1.434                            | 86.239                        | 1.061                        |
|             | fes2004          | 0.198                            | 117.769                      | 5.328                     | 15.727                        | 1.444                            | 87.934                        | 1.053                        |
|             | osu.tpxo72       | 0.162                            | 116.492                      | 5.339                     | 15.366                        | 1.416                            | 87.099                        | 1.056                        |
|             | dtu10tr          | 0.182                            | 114.138                      | 5.342                     | 15.586                        | 1.436                            | 87.220                        | 1.056                        |
|             | csr4tr           | 0.170                            | 116.906                      | 5.336                     | 15.445                        | 1.422                            | 87.295                        | 1.055                        |
|             | schw1             | 0.111                            | 103.464                      | 5.374                     | 14.851                        | 1.382                            | 85.092                        | 1.063                        |
| gbcont.ce   | eot11a           | 0.138                            | 110.542                      | 5.358                     | 15.125                        | 1.401                            | 86.076                        | 1.059                        |
|             | hamtide11a       | 0.147                            | 113.334                      | 5.350                     | 15.214                        | 1.406                            | 86.492                        | 1.058                        |
|             | osu.tpxo72atlas  | 0.132                            | 102.679                      | 5.376                     | 15.076                        | 1.402                            | 85.294                        | 1.063                        |
|             | tpxo70           | 0.151                            | 109.519                      | 5.359                     | 15.268                        | 1.414                            | 86.197                        | 1.060                        |
|             | fes952           | 0.142                            | 99.686                       | 5.384                     | 15.173                        | 1.414                            | 85.122                        | 1.065                        |
|             | fes2004          | 0.165                            | 112.531                      | 5.350                     | 15.409                        | 1.423                            | 86.737                        | 1.058                        |
|             | osu.tpxo72       | 0.132                            | 109.279                      | 5.361                     | 15.066                        | 1.397                            | 85.868                        | 1.060                        |
|             | dtu10tr          | 0.151                            | 107.570                      | 5.364                     | 15.273                        | 1.416                            | 86.007                        | 1.061                        |
|             | csr4tr           | 0.140                            | 111.062                      | 5.356                     | 15.151                        | 1.402                            | 86.165                        | 1.059                        |
|             | schw1             | 0.089                            | 83.787                       | 5.403                     | 14.553                        | 1.366                            | 83.536                        | 1.068                        |
| Average     |                  | 0.154                            | 109.607                      | 5.356                     | 15.291                        | 1.415                            | 86.329                        | 1.059                        |
| STD         |                  | 0.024                            | 7.414                       | 0.018                      | 0.252                         | 0.018                            | 0.963                         | 0.004                        |
| gbecen.cm | eot11a | 1.052 | -88.895 | 5.246 | 2.365 | 0.273 | 52.501 | 1.037 |
|          | hamtide11a | 1.063 | -88.339 | 5.256 | 2.248 | 0.271 | 49.416 | 1.039 |
|          | osu.tpxo72atlas | 1.048 | -86.308 | 5.293 | 2.415 | 0.309 | 46.284 | 1.047 |
|          | tpxo70 | 1.034 | -87.026 | 5.280 | 2.562 | 0.309 | 49.807 | 1.044 |
|          | fes952 | 1.072 | -92.569 | 5.177 | 2.187 | 0.220 | 63.672 | 1.024 |
|          | fes2004 | 1.049 | -89.331 | 5.238 | 2.402 | 0.271 | 54.251 | 1.036 |
|          | osu.tpxo72 | 1.044 | -86.196 | 5.295 | 2.457 | 0.313 | 46.550 | 1.047 |
|          | dtu10tr | 1.082 | -88.332 | 5.256 | 2.038 | 0.258 | 46.507 | 1.039 |
|          | csr4tr | 1.063 | -88.323 | 5.256 | 2.250 | 0.272 | 49.400 | 1.039 |
|          | schw1 | 0.927 | -86.576 | 5.288 | 3.728 | 0.398 | 59.695 | 1.046 |
| gbav.cm | eot11a | 1.045 | -89.809 | 5.230 | 2.455 | 0.269 | 56.327 | 1.034 |
|          | hamtide11a | 1.055 | -89.241 | 5.240 | 2.334 | 0.267 | 53.177 | 1.036 |
|          | osu.tpxo72atlas | 1.040 | -87.177 | 5.277 | 2.502 | 0.303 | 49.466 | 1.044 |
|          | tpxo70 | 1.025 | -87.996 | 5.263 | 2.660 | 0.304 | 53.371 | 1.041 |
|          | fes952 | 1.066 | -93.404 | 5.162 | 2.275 | 0.221 | 68.050 | 1.021 |
|          | fes2004 | 1.041 | -90.249 | 5.222 | 2.504 | 0.268 | 58.227 | 1.033 |
|          | osu.tpxo72 | 1.036 | -87.122 | 5.278 | 2.536 | 0.306 | 49.735 | 1.044 |
|          | dtu10tr | 1.074 | -89.197 | 5.240 | 2.125 | 0.252 | 50.366 | 1.036 |
|          | csr4tr | 1.056 | -89.181 | 5.241 | 2.331 | 0.267 | 52.950 | 1.036 |
|          | schw1 | 0.918 | -87.797 | 5.268 | 3.830 | 0.396 | 62.792 | 1.042 |
| gbcont.cm | eot11a | 1.067 | -88.337 | 5.256 | 2.200 | 0.268 | 48.771 | 1.039 |
|          | hamtide11a | 1.077 | -87.798 | 5.266 | 2.091 | 0.268 | 45.742 | 1.041 |
|          | osu.tpxo72atlas | 1.063 | -85.664 | 5.306 | 2.258 | 0.308 | 42.756 | 1.049 |
|          | tpxo70 | 1.047 | -86.465 | 5.291 | 2.421 | 0.307 | 46.730 | 1.046 |
|          | fes952 | 1.087 | -91.195 | 5.187 | 2.014 | 0.212 | 59.191 | 1.026 |
|          | fes2004 | 1.063 | -88.686 | 5.250 | 2.244 | 0.267 | 50.369 | 1.038 |
|          | osu.tpxo72 | 1.059 | -85.614 | 5.307 | 2.294 | 0.311 | 43.125 | 1.049 |
|          | dtu10tr | 1.098 | -87.705 | 5.268 | 1.870 | 0.256 | 42.161 | 1.042 |
|          | csr4tr | 1.077 | -87.777 | 5.267 | 2.090 | 0.268 | 45.667 | 1.041 |
|          | schw1 | 0.939 | -85.675 | 5.302 | 3.593 | 0.396 | 56.918 | 1.048 |
| Average | 1.046 | -88.292 | 5.257 | 2.443 | 0.287 | 51.799 | 1.039 |
| STD     | 0.043 | 1.907  | 0.035  | 0.460 | 0.045 | 6.370  | 0.007 |
Table 5: Results of correction of the O1, K1, M2 waves for ocean tide loading derived from three ocean loading models with different Earth models calculated by the ocean load provider service. L amplitude of the ocean tide load, \( \lambda \) phase of the ocean tide load, \( A_c \) corrected strain amplitude, \( \alpha_c \) phase of the corrected strain, X amplitude of the remaining residual, \( \xi \) phase of the remaining residual, \( \eta_c \) corrected amplitude factor. The observed values, not corrected for ocean tide loading, are in Table 1.

| Tidal wave | Ocean tide model | Earth model | Motion correction | \( L \) [nstr] | \( \lambda \) [degree] | \( A \) [nstr] | \( \alpha \) [degree] | X [nstr] | \( \xi \) [degree] | \( \eta \) |
|------------|-----------------|-------------|------------------|-------|----------------|--------|--------|--------|--------|------|
| O1         | FS2012          | Elastic     | No               | 0.175 | 78.829        | 3.187  | 6.993  | 6.685  | 3.328  | 1.014|
|            | FS214b          | Farrel      |                  | 0.165 | 81.586        | 3.176  | 6.993  | 6.674  | 3.322  | 1.012|
|            | GOT0.2          |             |                  | 0.091 | 46.008        | 3.200  | 6.993  | 6.697  | 3.335  | 1.016|
|            | FS2012          |             |                  | 0.165 | 81.586        | 3.176  | 6.993  | 6.674  | 3.322  | 1.012|
|            | FS214b          |             |                  | 0.165 | 81.586        | 3.176  | 6.993  | 6.674  | 3.322  | 1.012|
|            | GOT0.2          |             |                  | 0.089 | 40.081        | 3.203  | 6.993  | 6.701  | 3.337  | 1.016|
| Average    |                 |             |                  | 0.142 | 68.279        | 3.186  | 6.993  | 6.684  | 3.328  | 1.014|
| STD        |                 |             |                  | 0.037 | 17.952        | 0.011  | 0.000  | 0.011  | 0.006  | 0.002|
|            | FS2012          | Elastic     | Yes              | 0.728 | 63.731        | 3.580  | 6.993  | 7.077  | 3.531  | 1.073|
|            | FS214b          | Farrel      |                  | 0.805 | 63.158        | 3.639  | 6.993  | 7.135  | 3.560  | 1.082|
|            | GOT0.2          |             |                  | 0.645 | 59.295        | 3.560  | 6.993  | 7.057  | 3.522  | 1.070|
|            | FS2012          |             |                  | 0.727 | 63.903        | 3.578  | 6.993  | 7.074  | 3.530  | 1.073|
|            | FS214b          |             |                  | 0.805 | 63.158        | 3.639  | 6.993  | 7.135  | 3.560  | 1.082|
|            | GOT0.2          |             |                  | 1.917 | 82.483        | 4.059  | 6.993  | 7.555  | 3.751  | 1.146|
| Average    |                 |             |                  | 0.938 | 65.955        | 3.676  | 6.993  | 7.172  | 3.576  | 1.088|
| STD        |                 |             |                  | 0.441 | 7.554         | 0.174  | 0.000  | 0.174  | 0.080  | 0.026|
| K1         | FS2012          | Elastic     | No               | 0.172 | 16.539        | 4.559  | 3.743  | 9.450  | 1.805  | 1.020|
|            | FS214b          | Farrel      |                  | 0.179 | 13.154        | 4.568  | 3.743  | 9.460  | 1.806  | 1.021|
|            | GOT0.2          |             |                  | 0.292 | 71.656        | 4.509  | 3.743  | 9.401  | 1.794  | 1.014|
|            | FS2012          |             |                  | 0.172 | 16.539        | 4.559  | 3.743  | 9.450  | 1.805  | 1.020|
|            | FS214b          |             |                  | 0.165 | 81.586        | 3.176  | 6.993  | 6.674  | 3.322  | 1.012|
|            | GOT0.2          |             |                  | 0.089 | 40.081        | 3.203  | 6.993  | 6.701  | 3.337  | 1.016|
| Average    |                 |             |                  | 0.178 | 39.926        | 4.096  | 4.826  | 8.523  | 2.312  | 1.017|
| STD        |                 |             |                  | 0.059 | 27.547        | 0.641  | 1.532  | 1.298  | 0.720  | 0.003|
|            | FS2012          | Elastic     | Yes              | 0.505 | 34.408        | 4.833  | 3.743  | 9.724  | 1.859  | 1.049|
|            | FS214b          | Farrel      |                  | 0.805 | 63.158        | 3.639  | 6.993  | 7.135  | 3.560  | 1.082|
|            | GOT0.2          |             |                  | 0.645 | 59.295        | 3.560  | 6.993  | 7.057  | 3.522  | 1.070|
|            | FS2012          |             |                  | 0.505 | 34.408        | 4.833  | 3.743  | 9.724  | 1.859  | 1.049|
|            | FS214b          |             |                  | 0.805 | 63.158        | 3.639  | 6.993  | 7.135  | 3.560  | 1.082|
|            | GOT0.2          |             |                  | 1.917 | 82.483        | 4.059  | 6.993  | 7.555  | 3.751  | 1.146|
| Average    |                 |             |                  | 0.864 | 56.152        | 4.094  | 5.910  | 8.055  | 3.019  | 1.080|
| STD        |                 |             |                  | 0.487 | 17.063        | 0.547  | 1.532  | 1.191  | 0.823  | 0.033|
|      | FS2012  | Elastic  | Farrel | No   | -51.488 | 0.969  | 83.519 | 5.274 | 10.522 | 1.043 |
|------|---------|----------|--------|------|---------|--------|--------|-------|--------|-------|
|      | FS214b  |          |        |      | -52.518 | 0.955  | 83.519 | 5.270 | 10.376 | 1.042 |
|      | GOT00.2 |          |        |      | 44.475  | 1.757  | 83.519 | 5.556 | 18.323 | 1.099 |
|      | FS2012  | Visco-elastic |      |      | -51.488 | 0.969  | 83.519 | 5.274 | 10.522 | 1.043 |
|      | FS214b  |          |        |      | -52.518 | 0.955  | 83.519 | 5.270 | 10.376 | 1.042 |
|      | GOT00.2 |          |        |      | 48.649  | 1.790  | 83.519 | 5.570 | 18.630 | 1.101 |
| Average |        |          |        |      | -19.148 | 1.233  | 83.519 | 5.369 | 13.125 | 1.062 |
| STD   |        |          |        |      | 0.012   | 0.383  | 0.000  | 0.137 | 3.786  | 0.027 |
|      | FS2012  | Elastic  | Farrel | Yes  | -89.675 | 0.539  | 83.519 | 5.165 | 5.959  | 1.021 |
|      | FS214b  |          |        |      | -88.080 | 0.455  | 83.519 | 5.147 | 5.040  | 1.018 |
|      | GOT00.2 |          |        |      | -87.871 | 0.531  | 83.519 | 5.163 | 5.870  | 1.021 |
|      | FS2012  | Visco-elastic |      |      | -89.675 | 0.539  | 83.519 | 5.165 | 5.959  | 1.021 |
|      | FS214b  |          |        |      | -88.080 | 0.455  | 83.519 | 5.147 | 5.040  | 1.018 |
|      | GOT00.2 |          |        |      | 66.615  | 2.283  | 83.519 | 5.797 | 23.047 | 1.146 |
| Average |        |          |        |      | -62.794 | 0.800  | 83.519 | 5.264 | 8.486  | 1.041 |
| STD   |        |          |        |      | 0.098   | 0.664  | 0.000  | 0.238 | 6.524  | 0.047 |

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