Investigating the effect of tide parameterization and gravity field models on SLR solutions

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Abstract Satellite laser ranging (SLR) as a proven geodetic technique provides a wide and significant contribution to scientific studies of the Earth/Atmosphere/Ocean systems. In particular, modelling of the Earth and pole tides plays a very important role when analyzing SLR data. The accuracy of the determined satellite orbits is highly dependent on the models used for dynamic orbit determination. Gravity field models, which are represented by a series of spherical harmonic coefficients, have an impact on the satellite orbit and its precision. In addition, different empirical model parameterization used during SLR data analysis also has significant influence on the computed spherical harmonics, satellite orbits and their accuracies. In this contribution we investigate the impact of different SLR parameterizations on gravity field models used for precise satellite orbit determination. Data from satellites LAGEOS 1 and 2 were analysed using four different parameterization schemes namely: IERS1, IERS2 and IERS3 Earth tide models and pole tides. These are compatible Earth tide models of different complexity derived from IERS2010, a standard model of the International Earth Rotation and Reference Systems Service (IERS) and the standard IERS2010 pole tide model, and they aim to study their impacts on SLR solutions. The results indicate that the combination of IERS3, which is the most complex Earth tide model and the standard IERS2010 pole tide model, has a significant influence on the accuracy of gravity field models in precise orbit determination. In particular almost all the evaluated models give the smallest RMS values when IERS3 and pole tides are jointly selected in the analysis software during SLR data analysis, which indicates that the most complex models are also the most accurate. This work therefore validates the currently accepted IERS2010 Earth tide and pole tide models.

Keywords Satellite laser ranging · Gravitational field · Pole tides · Earth tides · LAGEOS

1 Introduction

Gravity field models derived from satellite laser ranging (SLR) tracking data are utilized in various fields of research. For instance, they can be used to study the inner structure of the Earth, for computation of the geoid, reference systems, satellite orbits etc. The quality of the computed satellite orbits depends on the preferred gravity field model and its inherent accuracies. On the other hand, the accuracy of gravity field models is dependent on proper modelling of parameters that describe the disturbing forces acting on a satellite as it orbits the Earth. Factors such as availability, type and quality of SLR data also play a significant role.

The gravitational attraction of the celestial bodies (Sun, Moon and planets) exerts a direct force on Earth orbiting satellites. Some of these forces act on the rotating Earth thereby inducing deformations of the solid Earth. The motion of the Earth (i.e. in orbit around the Sun and spinning around its instantaneous axis of rotation) and the coupled solar and lunar forces of attraction give rise to tidal deformations. Tidal deformations occur in the solid Earth, the ocean and in the atmosphere. Time varying deformations within the Earth system are consequences of solid Earth tides (Earth and pole tides).

Generally, solid Earth and pole tides manifest as time-varying components of the gravity field. As a consequence, the Earth's gravitational field exhibits periodic variations which tend to affect the motion of satellites. Time variations in the global gravity field are often extracted from geodetic satellite data. They are commonly used to study a variety of geodynamic and atmospheric processes. In most geodetic applications, both the Earth and pole tides ought to be properly modelled so that their influence can be accounted for in geodetic observables. At present, the solid Earth tide components embedded in spherical harmonic coefficients (geopotential models) are accounted for by using classical models which have been incorporated into various IERS conventions and technical notes, the latest being IERS2010.

The main objective of this paper is to investigate the contributions of Earth and pole tides on the observed minus computed (O−C) residuals across selected gravity field models by use of different configurations in the SLR Data Analysis Software (SDAS) package developed at HartRAO (Combrinck and Suberlak 2007). Contributions from the Earth and pole tides on the spherical harmonic coefficients (and also on O−C residuals) are computed using models based on IERS 2010 conventions as reported in Petit and Luzum (2010).

2 Effect of solid Earth tides on geopotential coefficients

2.1 Earth tides

The effects of solid Earth tides on the free space potential are often modelled as temporal variations in the standard geopotential coefficients C_{nm} and S_{nm}. These contributions are typically expressed in terms of frequency independent Love numbers up to degree and order 3 to start with; additional (smaller) contributions due to frequency dependent corrections can be applied for up to 34 constituents. Tidal deformation effects require the use of three k-parameters (these are the Love and Shida numbers), k_{nm} and $k_{nm}^{(\pm)}$ (with the exception of $n = 2$) to characterize the changes produced in the free space potential by tides of spherical harmonic of degree and order (nm) (Wahr and Sasao 1981). In the case where mantle anelasticity is taken into account, anelasticity may introduce small imaginary parts to the k_{nm} and $k_{nm}^{(\pm)}$ terms that reflect a phase lag in the deformation response of the Earth to the tidal forces. In addition, anelasticity may also affect the Earth's deformational response to effects arising from direct action of the tide generating potential (e.g. ocean tides and wobbles of the mantle and the core regions).

The tidal contributions due to Earth tides are modelled based on the Wahr model (Wahr and Sasao 1981) and incorporated into IERS 2010 conventions (Petit and Luzum 2010). The IERS 2010 Earth tide model adopts frequency independent nominal Love numbers (nm, for $n = 2$ and $n = 3$ for all m) which are used to evaluate the part of the tidal potential coefficients and compute the corresponding changes $\Delta \bar{C}_{nm}$ and $\Delta \bar{S}_{nm}$ (these are temporal corrections to geopotential coefficients $\bar{C}_{nm}$ and $\bar{S}_{nm}$) in the time domain using the lunar and solar ephemeris (Wahr and Sasao 1981; Petit and Luzum 2010). The induced contributions (i.e. ΔC_{nm} and ΔS_{nm}) due to the nm part of the tidal generating potential in the normalized geopotential coefficients having the same (nm) in the time domain are expressed in terms of the k_{nm} Love number using Eq. (1) as reported in Petit and Luzum (2010),

$$\Delta \bar{C}_{nm} - i \Delta \bar{S}_{nm} = \frac{k_{nm}}{2n+1} \sum_{j=2}^{3} \frac{GM_j}{GM_\oplus} \left(\frac{R_e}{r_j} \right)^{n+1} \bar{P}_{nm} \left(\sin \phi_j \right) e^{-im\lambda_j}. \tag{1}$$

Here k_{nm} is the nominal Love number for degree n and order m, R_e is the equatorial radius of the Earth, $GM_\oplus$ and GM_j are gravitational parameters for the Earth and the Moon ($j = 2$) or Sun ($j = 3$) respectively, r_j is the distance from geocentre to Moon or Sun and ϕ_j and λ_j are the body-fixed geocentric latitude of the Moon or Sun and east longitude (from Greenwich) of the Sun or the Moon respectively. In addition, the $\bar{P}_{nm}$ parameter in Eq. (1) is the normalized associated Legendre function. The contribution to the geopotential coefficients in the degree 4, C_{4m} and S_{4m} due to degree 2 tides are also computed in a similar method in terms of $k_{2m}^{(+)}$ as given in Eq. (2),

$$\Delta \bar{C}_{4m} - i \Delta \bar{S}_{4m} = \frac{k_{2m}^{(+)}}{5} \sum\nolimits_{j=2}^{3} \frac{GM_j}{GM_\oplus} \left(\frac{R_e}{r_j} \right)^{3} \bar{P}_{2m} \left(\sin \phi_j \right) e^{-im\lambda_j}, \quad (m = 0, 1, 2). \tag{2}$$

The nominal values of Love numbers are often used for an inelastic Earth and these are obtained by substituting the complex numbers in Eq. (1), as per Eq. (3)

$$\begin{aligned}
\Delta \bar{C}_{nm} - i \Delta \bar{S}_{nm} &= \frac{(R_e k_{nm} + i I_m k_{nm})}{2n+1} \sum_{j=2}^{3} \frac{GM_j}{GM_\oplus} \left(\frac{R_e}{r_j} \right)^{n+1} \bar{P}_{nm} \left(\sin \phi_j \right) e^{-im\lambda_j} \\
&= \frac{(R_e k_{nm} + i I_m k_{nm})}{2n+1} \sum_{j=2}^{3} \frac{GM_j}{GM_\oplus} \left(\frac{R_e}{r_j} \right)^{n+1} \bar{P}_{nm} \left(\sin \phi_j \right) \\
&\quad (\cos m\lambda - i \sin m\lambda) \\
&= \frac{(R_e k_{nm} + i I_m k_{nm})}{2n+1} \sum_{j=2}^{3} \frac{GM_j}{GM_\oplus} \left(\frac{R_e}{r_j} \right)^{n+1} \bar{P}_{nm} \left(\sin \phi_j \right) \\
&\quad ((\cos m\lambda \mathrm{R}_e k_{nm} + \sin m\lambda I_m k_{nm}) + i \left(\cos m\lambda I_m k_{nm} - \sin m\lambda \mathrm{R}_e k_{nm} \right)) \\
&= \frac{1}{2n+1} \sum_{j=2}^{3} \frac{GM_j}{GM_\oplus} \left(\frac{R_e}{r_j} \right)^{n+1} \bar{P}_{nm} \left(\sin \phi_j \right) \\
&\quad (\mathrm{R}_e k_{nm} + i I_m k_{nm}) \left(\cos m\lambda - i \sin m\lambda \right)
\end{aligned} \tag{3}$$

Table 1 Nominal frequency independent values used to compute solid Earth tide external potential Love numbers (Source: IERS2010 conventions)

Elastic Earth				Inelastic Earth		
n	m	k_{nm}	$k_{nm}^{(+)}$	$R_e k_{nm}$	$I_m k_{nm}$	k_{nm}^{+}
2	0	0.29525	−0.00087	0.30190	−0.00000	−0.00089
2	1	0.29470	−0.00079	0.29830	−0.00144	−0.00080
2	2	0.29801	0.00057	0.30102	−0.00130	−0.00057
3	0	0.093				
3	1	0.093				
3	2	0.093				
3	3	0.094				

where $\mathrm{R}_e k_{nm}$ and $I_m k_{nm}$ are the real and imaginary part of the complex Love numbers respectively. The parameter values utilized in the computation of solid Earth tide external potential Love numbers are given in Table 1.

2.2 Pole tides

The pole tides cause spatial variations in the gravitational potential due to Earth rotation. These tides are caused by smaller perturbations in the direction of the Earth's spin axis arising from the tidal effects from the Moon relative to a point fixed in the Earth. The spin produces a centrifugal force, which depends on the angular distance between the spin axis and a reference point. As the spin axis moves, this distance and the centrifugal force changes. The pole tide deformation effects on the station coordinates (up to ∼cm) arises from the first order perturbation associated with the centrifugal potential caused by the Earth's rotation. Rotational deformations due to polar motion can be modelled by assuming that the perturbation in the centrifugal potential is related to the Earth's rotation. Thus considering (x, y, z) as the terrestrial system of reference, a first order perturbation of the centrifugal potential (ΔV) can be expressed in Eq. (4), as reported in Petit and Luzum (2010),

$$V = -\frac{1}{2}\left[r^2\left|\vec{\Omega}\right|^2 - \left(\vec{r}.\vec{\Omega}\right)^2\right], \tag{4}$$

where $\vec{\Omega} = \Omega\left(m_1\hat{x} + m_2\hat{y} + (1 + m_3)\,\hat{z}\right)$, Ω is the mean angular velocity of rotation of the Earth, m_1 and m_2 are small dimensionless parameters describing the time dependent offset of the instantaneous rotation pole from the mean, m_3 is the fractional variation in the rotational rate, r is the geocentric distance to the station. Neglecting the m_3 term, due to its small influence, the first order perturbation in the potential (ΔV) can be written in terms of m_1 and m_2 as in Eq. (5),

$$\Delta V\,(r, \theta, \lambda) = -\left(\frac{\Omega^2 r^2}{2}\right)\sin 2\theta\,(m_1\cos\lambda + m_2\sin\lambda)\,. \tag{5}$$

The coordinates (in the International Terrestrial Reference Frame) of the position of the Earth's mean rotation pole due to secular variations are given in terms of the polar motion variables $\left(x_p, y_p\right)$ and are obtained by running averages $\bar{x}_p$ and $-\bar{y}_p$, thus

$$m_1 = x_p - \bar{x}_p, \quad m_2 = -\left(y_p - \bar{y}_p\right). \tag{6}$$

Table 2 Coefficients of the IERS (2010) mean pole model

Degree i	Until 2010.0		After 2010.0	
	$\bar{x}_p^i/\text{mas yr}^{-i}$	$\bar{y}_p^i/\text{mas yr}^{-i}$	$\bar{x}_p^i/\text{mas yr}^{-i}$	$\bar{y}_p^i/\text{mas yr}^{-i}$
0	55.974	346.346	23.513	358.891
1	1.8243	1.7896	7.6141	−0.6287
2	0.18413	−0.10729	0.0	0.0

In order to achieve the most accurate results for the polar motion variables estimates of the mean pole are commonly utilised. Nowadays the conventional mean pole of the IERS conventions (2003) is replaced with the IERS conventional mean pole incorporated in the IERS conventions (2010). The latest version of the IERS conventional mean pole is composed of a cubic model validated over the period from 1976.0 to 2010.0 and a linear model for extrapolation after 2010.0. Generally, the IERS (2010) mean pole model can be described as per Eq. (7)

$$\bar{x}_p\,(t) = \sum_{i=0}^{3} (t - t_0)^i \times \bar{x}_p^i \qquad \bar{y}_p\,(t) = \sum_{i=0}^{3} (t - t_0)^i \times \bar{y}_p^i, \tag{7}$$

where t_0 is 2000 and the coefficients of $\bar{x}_p^i$ and $\bar{y}_p^i$ are given in Table 2.

In order to show the effects of pole tides to the accuracy of gravity field models Eq. (5) can be expressed as Eq. (8)

$$\Delta V\,(r, \theta, \lambda) = -\frac{\Omega^2 r^2}{2} \sin 2\theta\, R_e \left[(m_1 - i m_2)\, e^{i\lambda} \right]. \tag{8}$$

The deformation caused by the pole tide produces time-dependent perturbations in the exter-nal potential is given by Eq. (9)

$$\Delta V = -\frac{\Omega^2 r^2}{2} \sin 2\theta\, R_e \left[k_2\,(m_1 - i m_2)\, e^{i\lambda} \right]. \tag{9}$$

These perturbations are related to changes in the geopotential coefficients C_{21} and S_{21}, which describe the position of the Earth’s figure axis. Using the value $0.3077+0.0036i$ for the Love number k_2 the time-dependent perturbations in the C_{21} and S_{21} geopotential coefficients can be estimated as follows

$$\begin{aligned} \Delta\bar{C}_{21} &= -1.333 \times 10^{-9}\,(m_1 - 0.0115 m_2)\,, \\ \Delta\bar{S}_{21} &= -1.333 \times 10^{-9}\,(m_1 - 0.0115 m_2)\,, \end{aligned} \tag{10}$$

where m_1 and m_2 given in arcseconds.

3 Data

3.1 Gravity field models evaluated

In this study, five gravity field models downloaded from the International Centre for Global Earth Models (ICGEM) at http://icgem.gfz-potsdam.de/ICGEM/ were evaluated. These models namely: GRIM5C1, EIGEN-CG03C, AIUB-CHAMP01S, EGM2008 and AIUB-GRACE01S are described briefly.

3.1.1 GRIM5C1

The GRIM5C1 gravity field model reported by Gruber et al. (2000) was derived in a German-French joint collaboration between GFZ Potsdam and Le Groupe de Recherche de Géodésie Spatiale (GRGS) Toulouse. The model was computed up to degree and order 120. It incor-porated terrestrial and airborne mean gravity anomalies, altimetric gravity anomalies from NIMA and mean gravity anomalies derived from the GRIM5S1 model.

3.1.2 EIGEN-CG30C

The GRACE based gravity field model, EIGEN-CG03C, was generated by the GFZ-GRGS cooperation. This model is an upgrade of the combined gravity field model, EIGEN-CG01C reported by Foerste et al. (2005). It was computed by use of CHAMP, GRACE, and surface data (gravimetry and altimetry) up to degree and order 360 in terms of spherical harmonic coefficients.

3.1.3 AIUB-CHAMP01S

The satellite-only gravity field model, AIUB-CHAMP01S was derived from kinematic orbit positions of the CHAMP mission, computed from GPS satellite-to-satellite tracking data spanning March 2002 to March 2003 (Prange et al. 2009). Its spherical harmonic coefficients were solved for up to degree and order 90.

3.1.4 EGM2008

The EGM2008 model reported by Pavlis et al. (2012) is a high-resolution (∼10 km) combined global gravity field model released by the US National Geospatial Intelligence Agency (NGA). This model was computed up to degree and order 2160 with additional spherical harmonic coefficients up to degree 2190 and order 2160. It incorporated data from GRACE mission (Mayer-Guerr 2007), topographic data (Pavlis et al. 2007), altimetry data and gravity observations on land areas (Pavlis et al. 2007, 2012).

3.1.5 AIUB-GRACE01S

AIUB-GRACE01S is a GRACE-only static gravity field model complete to degree and order 120 in terms of spherical harmonics. The model was generated from GPS satellite-to-satellite tracking data and K-band range rate measurements out of the period from January 2003 to December 2003 using the celestial mechanics approach (Jaeggi et al. 2010).

3.2 Data characterization

In this study, SLR data sets from LAGEOS 1 and 2 spanning from January 2009 to April 2010 and archived from the ILRS (Pearlman et al. 2002) were analysed. These satellites orbit at an altitude of about ∼6,000 km above the Earth's surface making them almost insensitive to neutral atmospheric drag and easily tracked by most SLR tracking stations.

Table 3 Constants and reference frames utilised during data processing

Reference frame epoch	SLRF2005 (Luceri and Bianco 2007)
Inertial reference frame	J2000 (Johnston and de Vegt 1999)
Pole-tide correction (station position)	IERS2010 (Petit and Luzum 2010)
Correction for general relativistic effects	IERS2010 (Petit and Luzum 2010)
Earth–tide correction (station position)	Petrov (2005)
Earth tide acceleration of satellite	Rizos and Stolz (1985); or IERS2010
Ocean loading correction (station position)	Adjusted based on Scherneck (1991) model ILRS
Initial state vector	CPF
Solar radiation pressure	Solved for, reflected and direct, cannon ball model
Once per revolution parameters	Treated as consider parameters
Precession and Nutation of the Earth's polar motion	As per IERS96 conventions
IERS values for EOPs	Bulletin B, file eopc04.62-now
Atmospheric and pole tides	As per IERS conventions 2003
Ocean pole tides	Not considered
Atmospheric loading	Disabled
GRACE de-aliasing products	Not considered
Atmospheric drag	Coefficient of drag estimated, unmodelled component also estimated
Atmospheric/ocean/hydrological non-tidal displacement	Not implemented
Earth orientation	a-priori Earth orientation parameters and UTC-UT1 values as per IERS extrapolated to observation epoch
O−C outlier rejection	Selectable: set to 0.8 sigma
Mean pole	IERS2010
Maximum expansion of a background gravity field model	20 × 20
Range bias	Enabled
Time bias	Enabled
Data rejection	10 degrees elevation
Satellite COM offset	251 mm, ILRS standard value (Otsubo and Appleby 2003)
Orbital arc	1 day

They also have high mass-to-area ratios ($\sim$1,450 kg/cm^2), which further minimizes the impact of non-gravitational forces on the LAGEOS orbits. The LAGEOS data analysed in this study spanned from January 2009 to April 2010. About 13 ILRS tracking stations were considered for the data analysis. These include: Yarragadee, McDonald, Zimmerwald, Wettzell, Monument Peak, Hartebeesthoek, Herstmonceux, Greenbelt, Riyadh, Graz, Mount-Stromlo, Beijing and Arequipa. The global distribution of these tracking stations is however imbalanced hence achieving a well distributed SLR observations is still a challenge. The data were processed using constants and reference frames listed in Table 3.

Table 4 Summary of the compatible models derived from IERS2010 with their respective corrections to spherical harmonic coefficients of a geopotential model

Compatible models from IERS2010	Corrections to a typical geopotential model
IERS1	$C_{20}, C_{21}, C_{22}, S_{21}, S_{22}$
IERS2	IERS1 + $C_{30}, C_{31}, C_{32}, C_{33}, S_{31}, S_{32}, S_{33} + C_{40}, C_{41}, C_{42}, S_{41}, S_{42}$
IERS3	IERS1 + IERS2 + frequency independent components
Pole tides	C_{21}, S_{21}

3.3 Analysis method

Data analyses were performed using the HartRAO SLR analysis software, SDAS reported in Combrinck and Suberlak (2007). The analysis software was expanded by Combrinck through the inclusion of additional, menu-selectable algorithms to support testing a large number of global gravity models and solid tide modelling scenarios. The software system comprises a classical processing scheme as used in various global space-geodetic software programs which include dynamic orbit determination, generation of observation equations and parameter estimation by least-squares adjustment. Four sets of mathematical models were considered for evaluation and they were named IERS1, IERS2, IERS3 and IERS2010 stan-dard pole tide models. In the software IERS1, IERS2, IERS3 are compatible and selectable Earth tide models. The IERS1 model is the least complex Earth tide model and corrects degree 2 spherical harmonics of a given geopotential model. On the other hand, IERS2 in the analysis software is an extension of IERS1 with additional corrections to third and fourth degree spherical harmonics. Lastly, a complete model of Earth tides, the IERS3 is considered as the most complex model since it includes both IERS1 and IERS2 plus it takes into account the frequency independent components of the solid Earth tides. A summary of these models and their respective corrections to spherical harmonic coefficients is given in Table 4.

During SLR data analysis, the “on/disabled” configuration tests were conducted for each considered model thereby disabling one of the compatible models while the other two are enabled during processing. Four tests were conducted for each selected gravity field model based on LAGEOS 1 and 2 data. In the first test the IERS1 Earth tide model and pole tides (IERS2010 standard) were activated while disabling IERS2 and IERS3 in the software. The second test involved the activation of IERS2 and pole tides while IERS3 was disabled in the software to investigate their combined effects on the derived O−C residuals across the selected models. In third test the IERS3 and pole tides were implemented and lastly, in the fourth test the IERS3 was activated and pole tides were disabled during LAGEOS 1 and 2 data processing.

4 Results and discussion

Table 5 presents the results for the statistical orbital fits of LAGEOS 1 based on IERS1, IERS2, IERS3 and pole tide tests using the GRIM5C1, EIGEN-CG03C, AIUB-CHAMP01S, EGM2008 and AIUB-GRACE01S gravity field models. The listed statistical results considered in the tables are the mean standard deviation (SD) of the O−C residuals for each orbital test. Here the computed SD values are used as an indicator of the underlying gravity field model. Thus the SD values characterize the precision of fitting the observations if the set of

Table 5 Results of the mean SD extracted from LAGEOS 1 data for different tide parameterisation options

Model	Mean SD [cm] when IERS1 and pole tides are 'on'	Mean SD [cm] when IERS2 and pole tides are 'on'	Mean SD [cm] when IERS3 is 'on' and pole tides are disabled	Mean SD [cm] when IERS3 and pole tides are 'on'
GRIM5C1	1.621	1.593	1.592	1.588
EIGEN-CG03C	2.123	2.006	2.010	2.006
AIUB-CHAMP01S	1.635	1.613	1.615	1.614
EGM2008	1.622	1.609	1.600	1.581
AIUB-GRACE01S	1.600	1.605	1.589	1.554

adjusted parameters are indistinguishable. The different parameterization schemes performed using LAGEOS 1 and 2 data considering the five gravity field models are now compared and discussed.

4.1 LAGEOS 1

The following five GGM model comparisons based on the four parameterization schemes utilised LAGEOS 1 data.

4.1.1 GRIM5C1

The GRIM5C1 gravity field model gives a slightly improved solution (1.592 cm) when the complex Earth tide model, IERS3 is jointly selected with pole tide on the analysis software. Based on the slightly increase of the mean SD of the O−C values the quality of the GRIM5C1 decrease when IERS3 model is selected and pole tides disabled followed by a combination of IERS2 model and pole tides. An O−C SD solution of 1.621 cm is obtained for a joint implementation of IERS1 and pole tides. Based on the recorded mean SD of the O−C residuals it can be concluded that the accuracy of the most accurate final orbit solution when using the GRIM5C1 model and LAGEOS 1 data can be achieved through inclusion of complete spherical harmonic components due to both Earth (IERS3) and pole tides added to those of the GRIM5C1 model.

4.1.2 EIGEN-CG03C

A joint implementation of IERS3 and pole tides and IERS2 and pole tides give an improved mean SD solution of 2.006 cm when the combined gravity field model, EIGEN-CG03C and LAGEOS 1 data are considered. It is apparent that contributions from Earth tides as modelled using both IERS2 and IERS3 models have less influence in the quality of the EIGEN-CG03C gravity field model. The SD solution slightly worsens with the implementation of IERS3 model and disabling of pole tides with a mean SD of 2.01 cm. A joint combination of IERS1 and pole tides further degrade the quality of the EIGEN-CG03C gravity field model resulting in a mean SD solution of 2.123 cm. There exist small differences in the solutions across all the tests. In addition, EIGEN-CG03C gives slightly higher mean SD results compared to the rest of the gravity field models. The deviation arises from errors in the adjustment procedure at GFZ during its computation (Foerste, private communication 2012).

4.1.3 AIUB-CHAMP01S

The CHAMP satellite-only model has a solution of 1.613 cm when IERS2 and pole tides are active in SDAS followed by the implementation of IERS3 and pole tides with 1.614 cm. The implementation of IERS3 with pole tides disabled slightly reduces the quality of the O−C SD solution. However, the differences in the solutions across the three orbital tests are extremely small; only of the order of 0.01 mm hence can be neglected. A mean SD of 1.635 cm is obtained when the IERS1 model and pole tides are jointly selected in the software.

4.1.4 EGM2008

The EGM2008 gravity field model exhibits the lowest O−C SD solution when IERS3 and pole tides are selected, followed by activation of IERS3 model with the pole tides disabled during data analysis. Activation of combination of the IERS2 model and pole tides worsens the O−C SD solution. A mean SD of 1.622 cm is obtained when the least complex Earth tide model, IERS1 and pole tides are jointly selected in the software. Although the differences in the SD solutions are very small across the four orbital tests, it can be concluded that the inclusion of full spherical harmonic coefficient components due to both Earth tides as modelled using IERS3 model and pole tides plays a significant role when using EGM2008 and LAGEOS 1 data.

4.1.5 AIUB-GRACE01S

The GRACE satellite-only model, AIUB-GRACE01S gives the best O−C SD solution when contributions from the Earth tides are modelled with IERS 3 in a joint combination with pole tides, followed by the selection of IERS3 with pole tides disabled in the SDAS analysis software. A joint implementation of IERS1 and pole tides reduces the O−C SD solution. The solution worsens further with active combination of IERS2 and pole tides. Based on the results obtained the quality of AIUB-GRACE01S can be achieved by including spherical harmonic coefficient components due Earth tides (IERS3) and pole tides when using LAGEOS 1 data.

4.2 LAGEOS 2

The following five GGM model comparisons are based on the four parameterization schemes utilised LAGEOS 2 data. Results are also summarised in Table 6.

4.2.1 GRIM5C1

The GRIM5C1 gravity field model has the lowest O−C SD solution of 1.387 m when LAGEOS 2 data are processed with IERS3 and pole tides activated followed by active combination of IERS2 and pole tides in SDAS with mean SD of 1.398 m. The solution worsens when both IERS1 pole tides are activated on the software during data processing giving a mean SD of 1.406 m. A mean SD solution of 1.407 m is obtained when the IERS3 is active and pole tides are disabled in the software. Based on these results it is apparent that the omission of pole tides reduces the quality of GRIM5C1 when using LAGEOS 2 data.

4.2.2 EIGEN-CG03C

The combined gravity field model, EIGEN-CG03C has the lowest O−C SD solution when LAGEOS 2 data are processed with IERS2 and pole tides activated followed by when the IERS3 is active and pole tides are disabled in the software. Standard deviation solution worsens when both IERS1 pole tides are activated on the software during data processing. An O−C SD solution of 1.753 cm is obtained when both IERS3 and pole tides are activated in the software. It is noticed that the inclusion of IERS3 spherical harmonic coefficients to those of the GGM and pole tides reduces the quality of the EIGEN-CG03C model though the differences are small such they can be neglected. These results contradict those obtained when LAGEOS 1 SLR data is utilized. However, the effects of adjustment errors are also noticed when LAGEOS 2 data are considered for processing.

4.2.3 AIUB-CHAMP01S

The CHAMP satellite-only model has the lowest O−C SD solution when LAGEOS 2 data are processed with IERS3 and pole tides activated followed by active combination of IERS2 and pole tides in SDAS. The solution worsens when both IERS1 pole tides are activated on the software during data processing. An O−C SD solution of 1.493 cm is obtained when the IERS3 is active and pole tides are disabled in the software. Differences in SD solutions across all the tests are extremely small; about 1 mm. However it is apparent that the omission of spherical harmonic coefficients due to the pole tides tends to reduce the quality of AIUB-CHAMP01S when using LAGEOS 2 data.

4.2.4 EGM2008

The EGM2008 gravity field model exhibits the lowest O−C SD solution when IERS3 and pole tides are selected, followed by activation of IERS3 model with the pole tides disabled during data analysis, with 1.431 and 1.504 cm solutions respectively. Activation of combination of the IERS2 model and pole tides worsens the O−C SD solution. A mean SD of 1.534 cm is obtained when the IERS1 model and pole tides are jointly selected in the software. The same combination gave poor solution with EGM2008 when using LAGEOS 1 data implying that there are no satellite dependence effects. Considering the results obtained with LAGEOS 1 data, this indicates the necessity of including the full spherical harmonic coefficient components due to Earth and pole tides when using EGM2008 and LAGEOS 1 and 2 data. In both cases (LAGEOS 1 and LAGEOS 2) results are slightly improved when including Earth and pole tides.

4.2.5 AIUB-GRACE01S

Similarly to EGM2008, the AIUB-GRACE01S gravity field model gives the best solution when contributions from the Earth tides are modelled with IERS 3 and pole tides implemented in the software, followed by the IERS3 model active and pole tides disabled during data analysis. A joint implementation of the IERS2 mode with pole tides reduces the O−C SD solution. The solution worsens further with the combination of the least complex Earth tide model, IERS1 and pole tides. Considering the similarities in the results from the two satellites it can be concluded that the full spherical harmonic coefficient components due to the Earth and pole tides need to be taken into account when using AIUB-GRACE01S and LAGEOS 2 data.

Table 6 Results of the mean SD extracted from LAGEOS 2 data for different tide parameterisation options

Model	Mean SD [cm] when IERS1 and pole tides are 'on'	Mean SD [cm] when IERS2 and pole tides are 'on'	Mean SD [cm] when IERS3 is 'on' and pole tides are disabled	Mean SD [cm] when IERS3 and pole tides are 'on'
GRIM5C1	1.406	1.398	1.407	1.387
EIGEN-CG03C	1.752	1.725	1.730	1.753
AIUB-CHAMP01S	1.493	1.381	1.395	1.378
EGM2008	1.534	1.505	1.504	1.431
AIUB-GRACE01S	1.510	1.484	1.480	1.469

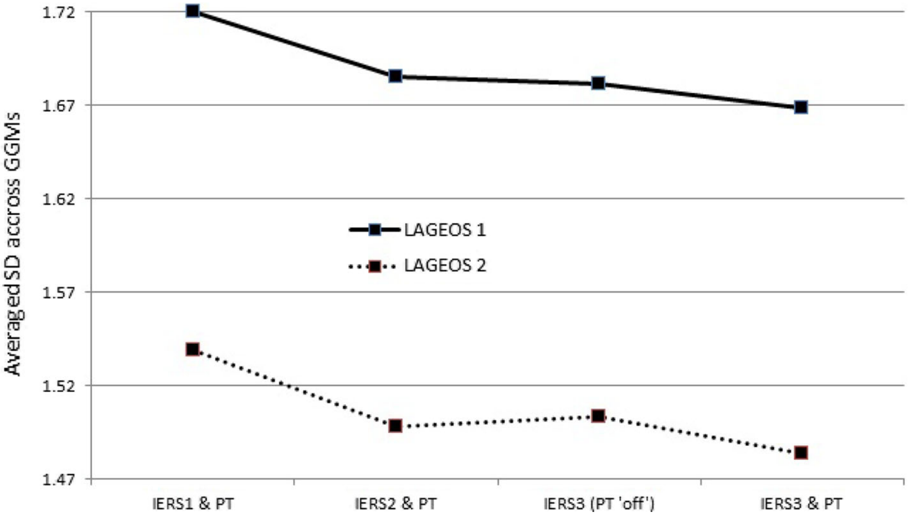

Fig. 1 Mean SD of the O−C residuals across the GRIM5C1, EIGEN-CG03C, AIUB-CHAMP01S, EGM2008 and AIUB-GRACE01S gravity field models based on LAGEOS 1 (dashed line) and LAGEOS 2 (solid line) data

In general there are small differences in the calculated average SDs across the five selected gravity field models. This suggests that the choice of parameterization has a particular influ-ence on satellite orbit determination; the extent of the influence also has a dependency on the selected gravity field model. Differences in the solutions across all the performed orbital tests are extremely small; about 1 mm hence can be neglected. Figure 1 depicts the trend of the averaged mean SD of the O−C values across the five evaluated gravity field models for each tide parameterization test. Highest averaged mean SD solutions are obtained for IERS1 and pole tides parameterization test. This is expected since the IERS1 model applies to a minimum of spherical harmonic coefficients of a give geopotential model. In general a combination of the complex Earth tide model, IERS3 together with pole tides gives the best results in terms of O−C residuals. This implies that the addition of IERS2 and the frequency independent components has increased the complex model's ability to correct for effects resulting from Earth tides. In addition, based on the analysis, LAGEOS 2 produced better results suggesting that it should be the first choice to obtain satellite orbit parameters as it models the Earth tide effects more accurately.

5 Conclusions

The influence of tide parameterization on the accuracy of five gravity field models was analysed based on LAGEOS 1 and 2 SLR data. In particular, the Earth tides modelled by three compatible models of different complexity, IERS1, IERS2 and IERS3 in the SDAS package and IERS2010 standard pole tide model were used alternately to study their influences on the O−C residuals, acting as proxies for determining the accuracy of the gravity field models. The results indicate that different tide parameterizations have different impacts on the accuracy of gravity field models. However the recorded average SDs across the evaluated gravity field models is too small and can be neglected. Generally a combination of IERS3 together with pole tides gives the best results in terms of improved O−C residuals, confirming that the models that are currently recommended by the IERS convention 2010 improve the quality of the SLR solutions.

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References

Cartwright DE, Taylor RJ (1971) New computations of the tide-generating potential. Geophys J Roy Astr Soc 23:45–74

Combrinck L, Suberlak V (2007) Earth-tide as parameter of crustal motion to correction for SLR station displacement. SAJG 110:203–210

Foerste C, Flechtner F, Schmidt R, Meyer U, Stubenvoll R, Barthelmes F, Rothacher M, Biancale R, Bruinsma S, Lemoine J-M (2005) A new high resolution global gravity field model from the combination of GRACE satellite mission and altimetry/gravimetry surface gravity data. Geophys Res Abstr 7:04561

Gruber Th, Bode A, Reigber Ch, Schwintzer P, Balmino G, Biancale R, Lemoine J-M (2000) GRIM5-C1: combination solution of the global gravity field to degree and order 120. Geophys Res Lett 27(24):4005–4008

Jaeggi A, Beutler G, Mervart L (2010) RACE gravity field determination using the celestial mechanics approach: first results. In: Mertikas S (ed) Gravity, geoid and Earth observation. Springer, Berlin Heidelberg, pp 177–184

Johnston KJ, de Vegt C (1999) Reference frames in astronomy. Annu Rev Astron Astrophys 37:97–125

Luceri V, Bianco G (2007) The temporal ILRS reference frame: SLR2005. Lecture notes, fall 2007 ILRS workshop. Grasse Observatory, France

Mathews PM, Buffett BA, Shapiro II (1995) Love numbers for diurnal tides: relation to wobble admittances and resonance expansions. J Geophys Res 100(B9):9935–9948

Mayer-Guerr T (2007) ITG-Grace03s: The latest GRACE gravity field solution computed in Bonn. Joint Int. GSTM and DFG SPP Symposium, Potsdam, Germany. http://www.geod.uni-bonn.de/itg-grace03/mayer-guerr-gstm-potsdam-2007.pdf. Accessed 15–17 Oct 2007

Pavlis NK, Factor JK, Holmes SA (2007) Terrain-related gravimetric quantities computed for the next EGM. Proceed of the 1^{st} International Symposium of the International Gravity Field Service (IGFS), Istanbul, Turkey. Harita Dergisi 18:318–323

Pavlis NK, Holmes SA, Kenyon SC, Factor JK (2012) The development and evaluation of the Earth Gravitational Model 2008 (EGM2008). J Geophys Res 117:B04406. doi:10.29/2011JB008916

Pearlman MR, Degnan JJ, Bosworth JM (2002) The international laser ranging service. Adv Space Res 30(2):135–143. doi:10.1016/S0273-1177(02)00277-6

Petit G, Luzum B (2010) IERS technical note no. 36. IERS Conventions 2010. International Earth rotation and reference systems service, Frankfurt, Germany. ISSN:1019–4568, http://www.iers.org/TN36/

Prange L, Jaeggi A, Beutler G, Mervart L, Dach R (2009) Gravity field determination at the AIUB: the Celestial mechanics approach. In: Sideris MG (ed) Observing our changing Earth. Springer, Berlin, pp 353–362

Wahr JM, Sasao T (1981) A diurnal resonance in the ocean tide and the Earth's load response due to the resonant free "core nutation". Geophys J Roy Astr Soc 64(3):747–765