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LAGEOS Sensitivity to Ocean Tides

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Abstract

Satellite Laser Ranging (SLR) to LAGEOS has a remarkable contribution to high-precise geodesy and geodynamics through deriving and validating various global geophysical models. This paper validates ocean tide models based on the analysis of satellite altimetry data, coastal tide gauges, and hydrodynamic data, *i.e.*, CSR3.0, TOPEX4.0, CSR4.0A, FES2004, GOT00.2, and the CSRC Schwiderski model. LAGEOS orbits and SLR observation residuals from solutions based on different ocean tide models are compared and examined. It is found that LAGEOS orbits are sensitive to tidal waves larger than 5 mm. The analysis of the aliasing periods of LAGEOS orbits and tidal waves reveals that, in particular, the tidal constituent S_2 is not well established in the recent ocean tide models. Some of the models introduce spurious peaks to empirical orbit parameters, which can be associated with S_2, S_a, and K_2 tidal constituents, and, as a consequence, can be propagated to fundamental parameters derived from LAGEOS observations.

Key words: satellite geodesy, ocean tides, SLR, LAGEOS, orbit determination.

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1. INTRODUCTION

Satellite Laser Ranging (SLR) greatly contributes to deriving various geodetic and geophysical parameters (Smith and Turcotte 1993), *e.g.*, to deriving Earth orientation parameters (Schutz *et al.* 1989, Sośnica *et al.* 2014), static and time-variable Earth's gravity field (Cheng *et al*. 1997, Bianco *et al*. 1998, Maier *et al*. 2012), station coordinates and velocities (*e.g*., Schillak and Wnuk 2003, Lejba and Schillak 2011), crustal deformations (Schillak *et al*. 2006), and elastic Earth parameters (Rutkowska and Jagoda 2010, 2012). The orbits of LAGEOS satellites equipped with laser retro-reflectors can be very well determined through the SLR observations with the accuracy at a level of a few millimeters, as well as through the minimized area-to-mass ratios of LAGEOS, and, as a consequence, a minimized impact of non-gravitational orbit perturbations. This implies that LAGEOS orbits are subject to orbit perturbations of gravitational origin to the greatest extent, and thus, are very well-suited for the validation of geodynamical models, *e.g*., Earth gravity field and ocean tide models.

The tidal forces are caused almost uniquely by the gravitational attraction of the Moon and the Sun. These forces are responsible for the solid Earth, atmosphere, and ocean tides as a consequence of the mass redistribution and gravity changes in the system Earth. Up to now, ocean tide models (OTM) were typically validated by computing monthly tidal elevation differences between models (Wünsch *et al*. 2005), by comparing with global tide gauge datasets (Ponchaut *et al*. 2001, Zahran *et al*. 2006), by comparing with sea level Topex/Poseidon (T/P) time series analysis (Shum *et al*. 1997) or by comparing of the simulations of tidal elevation differences at footpoints of GRACE (Wünsch *et al*. 2005). In this paper, OTM are evaluated using LAGEOS and the impact of the OTM on the orbit determination of the LAGEOS satellites is investigated. An intrinsic comparison is carried out using seven different OTM based on analysis of satellite altimetry data, *e.g*., TOPEX/Poseidon: CSR3.0 (Eanes and Bettadpur 1996), TOPEX4.0 (Egbert *et al*. 1994, Egbert and Erofeeva 2002), a model based on analysis of gravity field changes observed by different satellite missions: CSR4.0A (Eanes 2004), and hydrodynamic models with assimilation from observed tidal data, *i.e*., altimeter: FES2004 (Lyard *et al*. 2006), GOT00.2 (Ray 1999), EOT08A (Savcenko and Bosch 2008), and coastal tide gauges: CSRC Schwiderski (Schwiderski 1980).

2. LAGEOS ORBIT MODELING

The orbits of LAGEOS satellites are estimated using a development version of the Bernese GNSS Software version 5.2 (Dach *et al*. 2007) with the SLR extensions. The definition of the satellite orbits consists of the list of models applied along with estimated deterministic (Keplerian elements) and empirical orbital parameters. Estimating empirical parameters, which absorb insufficiently known perturbing forces, is necessary, because of modelling deficiencies in some forces acting upon a satellite. These parameters are related to modelling deficiencies of the solar radiation pressure (direct and re-radiated by the Earth's surface), thermal thrust, mismodellings and variations in gravity field and ocean tide models.

In the 7-day LAGEOS solutions, a multistep collocation method of 2-minute intervals and a polynomial degree of 12 was adopted for the numerical integration. The full unconstrained set of six osculating orbital parameters is estimated together with the empirical force model, which comprises:

In along-track: $S_0 + S_S \sin(u) + S_C \cos(u)$,

In out-of-plane: $W_S \sin(u) + W_C \cos(u)$,

where S_0 stands for a constant acceleration in the along-track direction, S_S and S_C are once-per-revolution sine and cosine along-track accelerations, respectively, W_S and W_C are once-per-revolution sine and cosine accelerations in the out-of-plane direction, and u is an argument of latitude of the satellite within the orbital plane. Additionally estimated parameters are: stations coordinates (all stations), range biases for selected stations – one set of parameters per every week, and Earth orientations parameters (*i.e.*, pole coordinates and length-of-day) – one set of parameters per day.

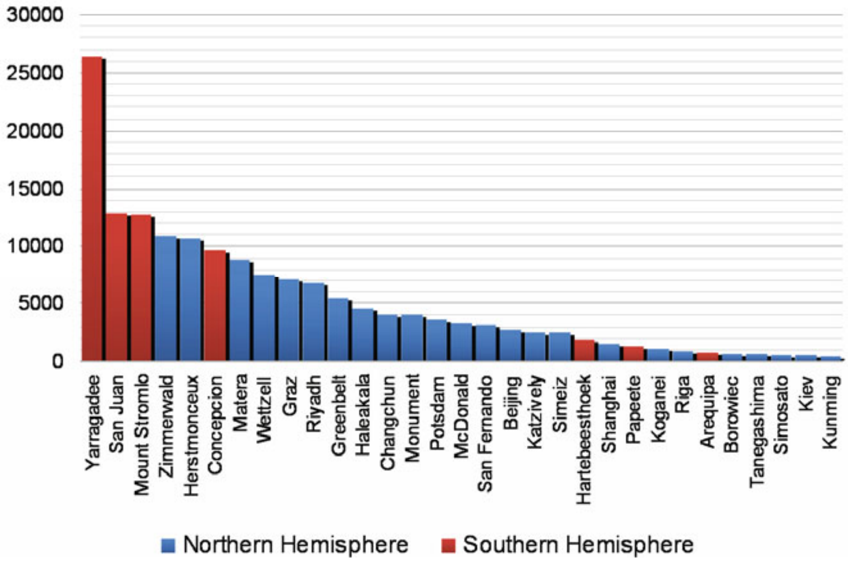


Fig. 1. Number of SLR normal points gathered by ILRS stations to LAGEOS-1 and LAGEOS-2 in 2008.

The reference frame SLRF2008 and Earth orientation IERS-08-C04 series (Bizouard and Gambis 2014) were used as *a priori* information. In general, the 7-day LAGEOS solutions and all models used are in very good agreement with the solutions derived by the International Laser Ranging Service (ILRS; Pearlman *et al*. 2002) Analysis Centers with some modifications, *e.g*., using of atmospheric tidal loading model for crust displacements

Table 1

Ocean tide models validated using LAGEOS orbits (after Sośnica 2014)

Type of model	Description
Length of arc	7 days
Data editing	2.5 sigma editing, maximum overall sigma: 25 mm
Satellite center of mass	Station- and satellite-specific
Troposphere delay	Mendes–Pavlis delay model + mapping function (Mendes and Pavlis 2004)
Cut-off angle	3 degrees
Gravity field model	EGM2008 up to degree and order 30 (Pavlis *et al*. 2012)
Relativity	Light time propagation correction and Schwarzschild orbit perturbation according to IERS Conventions 2010 (Petit and Luzum 2010)
Third-body	Earth's Moon, Sun, Venus, Mars, Jupiter, ephemeris: JPL DE405 (Folkner *et al*. 1994)
Subdaily pole model	IERS2000 (Kolaczek *et al*. 2000)
Tidal forces	Solid Earth tide model, Earth pole tide model, and ocean pole tide model applied – IERS Conventions 2010, Atmospheric tidal loading (Ray and Ponte 2003)
Nutation model	IAU2000
Solar radiation pressure	Direct radiation: applied with fixed solar radiation coefficient $C_R = 1.13$
Numerical integration	Interval: 2 minutes, polynomial degree: 12, collocation method (Beutler 2005)
Earth orientation parameters (*a priori*)	*A priori* C04 series from IERS, consistent with ITRF2008 (Bizouard and Gambis 2014)
Reference frame (*a priori*)	SLRF2008/ITRF2008 (Altamimi *et al*. 2011)
Range biases	Estimated for: Simeiz, Zimmerwald (IR)

and the gravity field model EGM2008 (Pavlis *et al*. 2012) up to degree and order 30. *A priori* terrestrial reference frame SLR2008 is the ILRS version of ITRF2008 (Altamimi *et al*. 2011) with some additional stations that were not included in ITRF2008 solution (namely, for some older and some newer SLR sites or SLR sites affected by earthquakes). A list of the most important models used in the LAGEOS solutions can be found in Table 1.

Data of the year 2008 are adopted for the comparison of seven ocean tide models. Figure 1 illustrates the number of SLR normal points to both LAGEOS satellites gathered by the ILRS stations. In total 139 000 SLR normal points are available in this year. The number per week varies between 1932 and 3804. For two selected ocean tide models, namely for FES2004 and CSR4.0A, 10-year LAGEOS solutions (2002-2012) are additionally generated in order to investigate the influence of particular tidal constituents.

3. OCEAN TIDE MODELS (OTM)

Ocean tide models are typically expressed by the coefficients of amplitudes and waves of particular discrete frequencies (Petit and Luzum 2010):

$$\xi(\phi,\lambda,t)=\sum_f Z_f(\phi,\lambda)\cos\left(\theta_f(t)-\psi_f(\phi,\lambda)\right) , \qquad (1)$$

where Z_f is the amplitude of wave f, λ is the longitude, and Φ is the latitude of the point, ψ_f is the phase longitude (referred to the Greenwich meridian) and θ is the Doodson argument. The hydrodynamical effects of ocean tides can be expanded as periodic variations of the normalized Stockes' coefficients of degree n and order m. After the expansion into spherical harmonic functions the equation yields (Petit and Luzum 2010):

$$\xi(\phi,\lambda,t)=\sum_f\sum_{n=1}^{N}\sum_{m=0}^{n}P_{nm}(\sin\phi)\sum_{+}^{-}C^{\pm}_{f,n,m}\left(\theta_f+\chi_f\pm m\lambda\right)+S^{\pm}_{f,n,m}\left(\theta_f+\chi_f\pm m\lambda\right) , \qquad (2)$$

where $C^{\pm}_{f,n,m}$, $S^{\pm}_{f,n,m}$ are prograde and retrograde normalized spherical harmonic coefficients of the main wave f of degree n and order m, χ_f is the phase bias according to the Shureman conventions and P_{nm} represents the normalized associated Legendre function. The practical implementation of ocean tide models consists of the list of astronomical amplitudes for semi-diurnal waves M_2, S_2, N_2, K_2, the diurnal waves K_1, O_1, P_1, Q_1, the long-period waves M_f, M_m, S_a, S_{sa}, and also for other waves, *e.g*., quarter-diurnal waves. For an extensive study concerning the impact of the particular tidal waves on the LAGEOS-1 and LAGEOS-2 orbits please refer to Iorio (2001), whereas the analysis of the spectrum of tidal perturbations on the orbital elements of LAGEOS-1 is described by Dow (1990).

4. SENSITIVITY OF LAGEOS ORBITS TO OCEAN TIDES

The truncation of OTM up to a particular degree/order (d/o) or to a minimum size of a tidal wave is important on one hand to minimize computational time, and on the other hand, to investigate the sensitivity of LAGEOS orbits to small tidal waves. In order to study the impact of the maximum d/o of OTM on LAGEOS orbits, six solutions were generated using the CSR4.0A model up to maximum d/o 2, 4, 8, 12, 20, and 30. The RMS of the observation residuals and the comparison between estimated and predicted orbits are shown in Table 2.

Table 2

The sensitivity of LAGEOS orbits to maximum degree/order of OTM and the size of tidal wave using CSR4.0A (mean values for 2008)

OTM up to d/o	Maximum size of tidal wave [mm]	RMS of residuals [mm]	Comparison of estimated and predicted orbits		
			RMS of radial prediction [mm]	RMS of along-track prediction [mm]	RMS of out-of-plane prediction [mm]
2	∞	568.94	–	–	–
4	∞	10.29	23.5	405.9	205.4
8	∞	7.42	29.9	399.1	200.6
12	∞	7.42	29.8	399.0	200.6
20	∞	7.41	29.8	398.9	200.6
30	∞	7.41	29.8	398.7	200.4
30	2000	9.63	30.3	404.7	203.8
30	500	7.91	29.9	397.0	199.9
30	50	7.45	29.9	398.3	200.4
30	5	7.42	29.8	398.9	200.4
30	0.5	7.41	29.8	398.7	200.4

Using maximum d/o 2 or 4 is definitely insufficient, because it gives a significant loss of accuracy of the solution (RMS: 569 and 10 mm, respectively). LAGEOS satellites are very sensitive up to d/o 8 of OTM. Using OTM up to d/o 30 may slightly improve RMS of observation residuals (difference of 0.01 mm), and the orbit prediction, especially in the along-track direction (by 0.8 mm). Degree 8 is an absolute minimum needed for reasonable LAGEOS solutions, but it is recommended that OTM should be used up to d/o 30 for LAGEOS orbit determination in order to avoid orbit degradation due to model truncation.

The sensitivity of LAGEOS solutions to amplitudes of ocean tides is analyzed by choosing only the tides exceeding the particular threshold. Table 2 shows six different test cases with the maximum considered size of the tides set to: 2000, 500, 50, 5, and 0.5 mm, and the approach, where regardless of the size, all waves are considered (∞). Big values of RMS residuals for maximum wave size of 2000 and 500 mm (9.63 and 7.91 mm, respectively) indicate that taking into consideration smaller waves is obligatory when processing LAGEOS data. Small differences are visible between the solutions based on OTM maximum size of 50 and 5 mm. Waves smaller than 0.5 mm have no impact on LAGEOS solutions. Therefore, taking into account at least all waves larger or equal 5 mm is highly recommended.

The high sensitivity of LAGEOS orbits is striking, in particular because the uncertainties of amplitudes (formal errors) of tidal waves in OTM may exceed 50 mm, *i.e.*, about one order of magnitude more than the sensitivity of LAGEOS orbits. This confirms that using the LAGEOS satellites is suitable for validating the low-degree part of OTM.

5. VALIDATION OF OCEAN TIDAL MODELS

Different OTM are validated by comparing the quality of LAGEOS-1 and LAGEOS-2 orbits (see Table 3). Three hydrodynamic models based on tide gauge observations (CSRC Schwiderski) or tide gauges and satellite altimetry (FES2004, GOT00.2) are compared with the hydrological models based on satellite altimetry data (CSR3.0, CSR4.0A, TOPEX4.0) and with one empirical model based on many satellite missions (EOT08A). Most of the OTM are based on the analysis of satellite altimetry data stemming from TOPEX/Poseidon (T/P) mission. Above and below latitude of 66°N and 66°S (given by the T/P or Jason-1/2 satellite inclination), and for shallow sea areas, the tidal waves are of inferior quality. Moreover, some of the models contain missing water areas in the model description (*e.g.*, the Baltic Sea, Black Sea, and Red Sea).

Table 3

Ocean tide models validated using LAGEOS orbits

Model	Type	Mainly based on	Reference
CSR3.0	hydrological	Topex/Poiseidon (T/P)	Eanes and Bettadpur (1996)
CSR4.0A	hydrological	T/P, GRACE	Eanes (2004)
TOPEX4.0	hydrological	T/P	Egbert *et al*. (1994)
EOT08A	empirical	T/P, ERS-1/-2, GFO, Jason-1, Envisat	Savcenko and Bosch (2008)
FES2004	hydrodynamic	tide gauges, T/P, ERS	Lyard *et al*. (2006)
GOT00.2	hydrodynamic	tide gauges, T/P, ERS	Ray (1999)
CSRC Schwiderski	hydrodynamic	tide gauges	Schwiderski (1980)

FES2004 is the model that is recommended by the IERS Conventions 2010 (Petit and Luzum 2010). Compared to the CSR3.0, which was recommended by IERS Conventions 2003 (McCarthy and Petit 2004), FES2004 has the benefit that the treatment of the secondary waves is specified.

5.1 RMS of observation residuals and orbit predictions

Seven series of LAGEOS solutions are generated, each based on a different OTM. Table 4 shows the mean values of the RMS of the observations residuals of LAGEOS solutions. Although all solutions show RMS errors at a comparable level, an association of the solutions with four groups is possible. The first group with the smallest RMS of residuals contains those models which are based, to a great extent, on the T/P satellite mission. These are: CSR3.0, CSR4.0A, and TOPEX4.0 with the RMS values of 7.40, 7.41, and 7.44 mm, respectively. It seems that the models based on LEO altimetry satellite missions may give a benefit to higher satellite like LAGEOS. EOT08A model has an average RMS of observation residuals about 0.6 mm larger than the aforementioned models and 0.4 mm smaller than FES2004 and GOT00.2. EOT08A is based on six different satellite missions and a long time series of observations. The third group contains two hydrodynamic models with T/P observations, namely FES2004 and GOT00.2. The RMS of residuals for these models yield 8.41 mm, *i.e.*, it is about 1 mm (12%) worse than for exclusively T/P based models (CSR3.0 and TOPEX4.0). The oldest

Table 4

RMS of observation residuals and comparison between predicted and estimated 7-day LAGEOS orbits using the Helmert transformation (mean values for 2008)

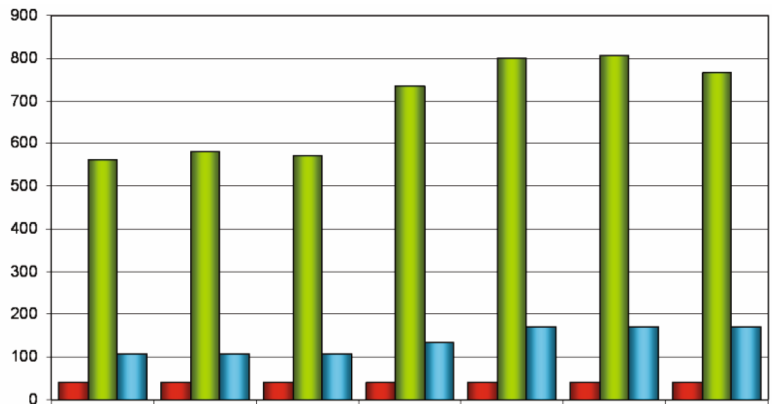
Ocean tide model	RMS of residuals [mm]	Comparison of estimated and predicted orbits including the Helmert transformation			
		RMS of radial prediction [mm]	RMS of along-track prediction [mm]	RMS of out-of-plane prediction [mm]	Scale [ppb]
CSR3.0	7.40	30.1	387.7	200.5	–0.10
CSR4.0A	7.41	29.8	398.7	200.4	–0.05
TOPEX4.0	7.44	30.1	392.9	202.8	–0.10
EOT08A	8.02	30.8	497.2	257.9	0.04
FES2004	8.41	31.1	536.6	299.6	0.17
GOT00.2	8.41	31.2	542.7	303.3	0.15
CSRC Schwiderski	8.72	31.1	553.2	280.9	0.00

model, namely the CSRC (Schwiderski 1980) hydrodynamic model, is characterized by the largest RMS of the residuals of 8.72 mm.

The differences between solutions using different OTM (max. 1.32 mm of RMS) are slightly larger than the differences between solutions using different Earth gravity field models (max. 1.16 mm of RMS, see Sośnica *et al.* 2012). This implies that the modelling of ocean tides is one of the key factors influencing the quality of LAGEOS orbits.

Table 4 contains the result of the orbit comparisons between estimated and predicted orbits when the Helmert transformation parameters are estimated. A classification of all models into three groups is possible on the basis of the along-track (*S*) and the out-of-plane (*W*) components from Table 4. The first group, with RMS in *S* about 400 mm and in *W* about 200 mm, contains CSR3.0, CSR4.0A, and TOPEX4.0, *i.e.*, this group corresponds to the first group when classifying the models according to RMS. Then, the second group with EOT08A that has RMS about 500 mm in *S* and 260 mm in *W*. Finally, FES2004, GOT00.2, and the CSRC Schwiderski which have the RMS of *S* and *W* predictions at the level of 540 and 300 mm, respectively. The radial (*R*) component does not indicate any significant differences between compared models.

A comparison between predicted and estimated orbits without estimating Helmert parameters is shown in Fig. 2. The direct comparison of orbits (without estimating rotations, translations, and a scale) shows even bigger RMS in the *S* component, implying some difficulties in establishing the rota-



	CSR30	CSR40A	TOPEX40	EOT08A	FES2004	GOT00.2	CSRC Schwiderski
Radial	40.6	40.1	40.5	41.0	41.2	41.4	41.6
Along-track	562.6	580.9	571.6	734.0	798.4	807.6	766.9
Out-of-plane	107.1	108.9	108.9	135.0	168.9	170.0	170.0

Fig. 2. Comparison between predicted and estimated orbits using different OTM, mean values for 2008; units: mm.

tion parameters in weekly SLR solutions. On the other hand, discrepancy of the *W* component is smaller than the discrepancy of the same component from Table 4.

The largest differences in OTM are between d/o 10 and 30. LAGEOS orbits are mostly sensitive to OTM up to d/o 8. Therefore, the older class hydrological OTM with a poorer spatial resolution as compared to the hydrodynamic models, may possibly lead to better LAGEOS orbits, provided that they contain good estimates of the low-degree spherical harmonic coefficients. The larger RMS of residuals in LAGEOS solutions using hydrodynamic models may be due to some deficiencies in the "datum definition" of these models. For lower orbiting satellites, *e.g.*, for GRACE, the best results can be achieved using EOT08A and FES2004 (Meyer *et al*. 2012), due to the satellite orbit sensitivity to all the tidal constituents, and not only to low degree coefficients of OTM.

5.2 Empirical orbit parameters

Empirical parameters absorb, to a certain extent, deficiencies in modelling the gravitational and non-gravitational forces acting on the LAGEOS satellites. Thus, the comparison of these parameters estimated using different OTM allows us to study the magnitude of errors still present in particular models.

5.2.1 Empirical orbit parameters in out-of-plane

Figure 3 top illustrates W_S values in 2008 for LAGEOS-1 and LAGEOS-2. The average value of W_S for LAGEOS-1 is about 5×10^{-10} ms^{-2}, whereas it is negative for LAGEOS-2 and yields about 7×10^{-10} ms^{-2}. The variations W_S series mainly correspond to variations of C_{20} in 2008 (see Sośnica *et al.* 2012).

Figure 3 does not illustrate any offsets for one or more OTM w.r.t. other models, but different variations can easily be noticed between days 105 and 222. In this period, FES2004 and GOT00.2 exhibit bigger amplitudes of variations in the consecutive weeks than the other models. In case of the LAGEOS-1 satellite, these variations could be associated with an eclipsing period. In 2008 there is one eclipsing period for LAGEOS-1 lasting from day 110 till day 203, which agrees with the periods of large variations in the FES2004 and GOT00.2 solutions.

The cosine once-per-revolution out-of-plane term (W_C, see Fig. 3 bottom) is very sensitive to OTM, as opposed to the different Earth gravity field models for which W_C does not exhibit any differences (*cf.* Sośnica *et al.* 2012). The differences of OTM are more apparent in case of W_C than W_S, because W_C is free from the impact of the variations of C_{20}. The CSR4.0A

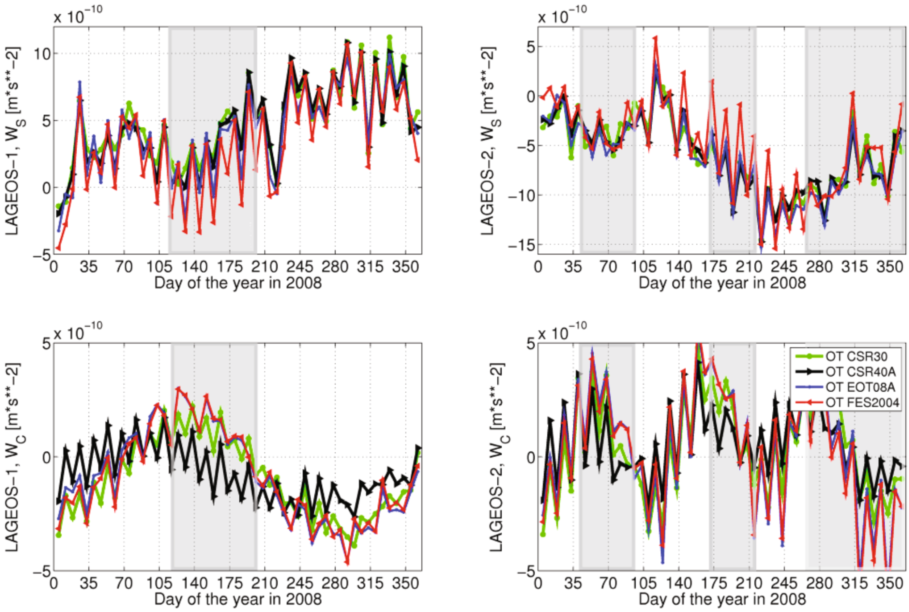


Fig. 3. Empirical orbit parameters in the out-of-plane direction for selected OTM. Eclipsing periods are shaded.

model shows the smallest amplitude and a different phase in the W_C series (see Fig. 3 bottom), whereas FES2004 and EOT08A indicate large variations in W_C for consecutive weeks.

The perturbing accelerations in the W direction influence the three orbital elements, defining the orientation of the satellite orbit in the inertial frame: right ascension of ascending node Ω, argument of perigee ω, and the inclination angle i. The relationships between the Euler angles and the accelerations in W read, according to Beutler (2005), as:

$$\frac{d\Omega}{dt} = \frac{r \sin u}{na^2 \sqrt{1-e^2} \sin i} W' \ , \tag{3}$$

$$\frac{d\omega}{dt} = \frac{1}{e}\sqrt{\frac{p}{GM}}\left[-\cos vR' + \left(1+\frac{r}{p}\right)\sin vS'\right] - \frac{r \sin u}{na^2 \sqrt{1-e^2} \tan i} W' \ , \tag{4}$$

$$\frac{di}{dt} = \frac{r \cos u}{na^2 \sqrt{1-e^2}} W' \ , \tag{5}$$

where W', R', and S' denote the accelerations in W, R, and S, respectively. The symbol a denotes a satellite semi-major axis, e is the orbital eccentricity, n is the mean motion, r is the length of satellite state vector, p is the semilatus rectum, v denotes the true anomaly, and GM is a product of gravitational constant and Earth's mass. It can be seen in the three equations (3-5) that the right ascension of the ascending node and the inclination angle are solely perturbed by forces in W, whereas the argument of perigee is also sensitive to perturbations in R and S.

Table 5 relates the impact of the major ocean tide constituents to the perturbations of orbital elements: Ω of LAGEOS-1, Ω of LAGEOS-2, and ω of LAGEOS-2. The ω of LAGEOS-1 is neglected here, because the orbit of LAGEOS-1 is near-circular, and thus, ω cannot be well established.

The spectral analysis of 10-year LAGEOS solutions using FES2004 and CSR4.0A reveals periods clearly referring to the tidal constituents perturbing orbital elements. Figure 4 exhibits the amplitudes of Fourier analysis of the W_C for LAGEOS-1 (top) and LAGEOS-2 (bottom). The solution using FES2004 shows peaks around 14.1, 24.8, 28.2, 28.6 days, and the largest peak for 280 days for LAGEOS-1. For LAGEOS-2 the peaks are for 15.1, 24.8, 26.3, 28.8, 33.5, 86, 111, 137, and 285 days. Most of the peaks refer to

Table 5

Aliasing periods and perturbations of LAGEOS orbits due to the ocean tides for degree 2, after Iorio (2001)

Tide	Ω of LAGEOS-1		Ω of LAGEOS-2		ω of LAGEOS-2	
	Period [days]	Amplitude [mas]	Period [days]	Amplitude [mas]	Period [days]	Amplitude [mas]
K_1	1043.67	156.55	**569.21**	35.69	**569.21**	177.76
O_1	1043.67	151.02	**569.21**	34.43	**569.21**	171.48
P_1	221.35	11.49	**138.26**	3.00	**138.26**	14.95
Q_1	**788.90**	24.67	690.88	9.03	690.88	44.98
K_2	**521.83**	6.24	**284.60**	6.24	**284.60**	5.95
M_2	**14.02**	75.59	**13.03**	75.65	**13.03**	72.12
	521.83		**284.60**		**284.60**	
S_2	**280.93**	9.45	**111.20**	6.87	**111.20**	6.55
N_2	449.30	12.93	312.00	16.49	312.00	15.72
T_2	**158.80**	0.28	85.27	0.27	85.27	0.26
M_m	**27.55**	0.54	27.55	1.00	27.55	0.69
S_a	**365.27**	20.55	**365.27**	37.71	**365.27**	26.17
M_f	**13.66**	0.62	13.66	1.13	13.66	0.78
S_{Sa}	**182.62**	5.98	**182.62**	10.98	**182.62**	7.62

Note: The periods related to the tidal constituents found in the spectral analysis of empirical orbit parameters are indicated in bold.

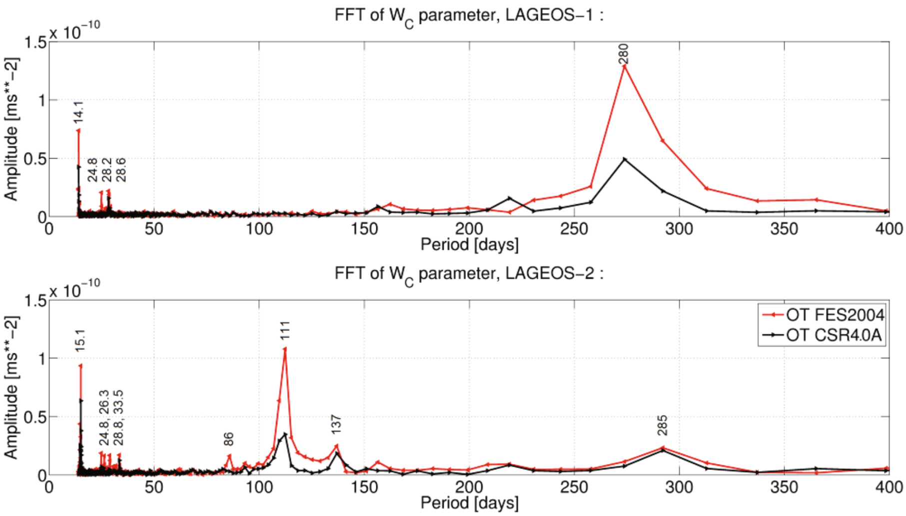


Fig. 4. Amplitude spectra (Fourier transform) of W_C empirical parameter from 10-year LAGEOS solutions using FES2004 and CSR4.0A.

the particular tidal constituents perturbing LAGEOS orbits. The periods of tidal constituents found in the spectral analysis of W_C or other empirical orbit parameters are indicated in bold in Table 5.

The largest peaks in Fig. 4, which are equal to 280 days and 111 days for LAGEOS-1 and LAGEOS-2, respectively, can be explained by the resonance between the diurnal and semi-diurnal tides and LAGEOS orbits. Due to the drift of ascending node $\dot{\Omega}_{L1}$, which is mainly due to C_{20}, the time interval between two consecutive passes (in the same direction) of the Sun through the orbital plane (the so-called draconitic year) can be expressed for LAGEOS-1 (with a prograde drift of $\dot{\Omega}_{L1}$ = 1050 days) as:

$$\frac{360°}{\frac{360°}{365.25}-\frac{360°}{\dot{\Omega}_{L1}}}\text{days} = \frac{365.25\cdot\dot{\Omega}_{L1}}{365.25-\dot{\Omega}_{L1}}\text{days} = 560 \text{ days} . \tag{6}$$

In analogy for LAGEOS-2 ($\dot{\Omega}_{L2}$ = 570 days, retrograde), the draconitic year is equal to 222 days. The diurnal tidal constituent S_1 imposes orbit perturbations having a period of the draconitic year, whereas the semi-diurnal constituent S_2 imposes orbit perturbations with a period of the half of the draconitic year (the semi-draconitic year). The perturbations due to S_2 have periods of 280 days and 111 days for LAGEOS-1 and LAGEOS-2, respectively. This explains the peaks found in Fig. 4 and the relations to the eclipsing seasons found in Fig. 3. Figure 4 suggests as well that deficiencies in the S_2 tide are the main quality limiting factor for the LAGEOS solutions. This can be, both, due to the deficiencies in the S_2 atmospheric tide, or due to the deficiencies in the S_2 ocean tide. The atmospheric tides are, however, much smaller as compared to ocean tides (Sośnica *et al*. 2013), and thus, cannot solely explain the large orbit perturbations. The differences between amplitudes of peaks in Fig. 4 suggest that, in particular, FES2004 contains the S_2 tide of inferior quality.

Most of the ocean tide models have largest residuals in the Polar Regions due to the absence of TOPEX/Poseidon and Jason data. The residuals, *e.g*., of EOT08A for tidal constituent S_2 in the Arctic Sea and near Antarctica exceed 5 cm (Savcenko and Bosch 2008), whereas from the study in Section 4 we know that the LAGEOS orbits are sensitive to the ocean tides larger than 5 mm.

For high-orbiting satellites the semi-draconitic year corresponds exactly to the eclipsing periods of the satellite orbits (with an exception of satellites in sun-synchronous orbits). This explains the relation between eclipsing periods and differences in empirical parameters found in Fig. 3. In fact, the differences are not directly due to the eclipsing seasons, but due to the alias with S_2 tide, which imposes the orbit perturbations of the same period as the eclipsing seasons.

Figure 4 top shows, in addition, a small peak around 285 days for the LAGEOS-2 orbit. The residuals of K_2 in the Polar Regions exceed 3 cm, whereas the residuals of M_2 are of the order of 5 cm, but only for the shelf areas, *e.g*., for EOT08A (Savcenko and Bosch 2008). Therefore, the peak of 285 days should be associated with deficiencies in K_2, rather than M_2, despite that both tides impose the perturbations on the LAGEOS satellites of the same period (see Table 5). The uncertainties for these tidal waves significantly exceed the sub-centimeter sensitivity of LAGEOS orbits to tidal waves found in Section 4. The perturbations imposed on LAGEOS-1 orbits due to the K_2 and M_2 tides have a period of 521.8 days; thus, an analysis of a longer time series is needed in order to detect these periods with a sufficient accuracy.

The large peaks from Fig. 4, of 14.1 and 15.1 days for LAGEOS-1 and LAGEOS-2, respectively, can be explained by the imposition of the annual tidal signal S_a and the groundtrack repeatability of satellites. The groundtrack repeatability of LAGEOS-1 is $gr_{L1} = 7\text{d}\ 23\text{h}\ 45\ \text{min}$ and of LAGEOS-2 it is $gr_{L2} = 8\text{d}\ 22\text{h}\ 58\text{min}$. The peaks close to 14 days can be explained by overlapping of the groundtrack repeatability, S_a, and generated 7-day arcs. The overlapping period for LAGEOS-1 reads as:

$$2\frac{2\pi}{\frac{2\pi}{gr_{L1}}+7\frac{2\pi}{365.25}}=14.0\ \text{days} \tag{7}$$

and for LAGEOS-2:

$$2\frac{2\pi}{\frac{2\pi}{gr_{L2}}+7\frac{2\pi}{365.25}}=15.1\ \text{days}\ . \tag{8}$$

Lemoine *et al*. (2004) found that the amplitudes of some constituents in FES2004 are underestimated as compared to those obtained from the LAGEOS multi-year solutions. The differences in the amplitudes of 18.6-year tide and 9.3-year tide even reach 6000% and the phases are shifted even by 140°. Lemoine *et al*. (2004) found also large differences in S_a and S_{Sa} constituents, but they could be explained in terms of the mass displacement in the system Earth. Ray *et al*. (2014) tried to explain the spurious peaks around 14 days in GNSS series by subdaily Earth orientation parameter tide model errors. They also found the differences in tides between 10 and 20%, which correspond to differences of 2 cm at GPS altitudes. All in all, some of the ocean tide constituents require a further improvement, because of the large differences of their amplitudes in different OTMs.

In conclusion, the analysis of the W_C empirical parameter has revealed deficiencies in ocean tide constituents and some substantial differences between OTMs. The largest perturbations correspond to the S_2 tide and the resonance between the S_a tide and the groundtrack repeatability of LAGEOS orbits. Smaller perturbations due to the K_2 tide (alternatively due to M_2) have also been detected.

5.2.2 Empirical orbit parameters in along-track

Now, the empirical forces in the along-track direction are discussed. The S_0 reveals almost no differences for most of OTM (thus not shown here). The differences in S_0 are at the 8×10^{-13} ms^{-2} level; therefore, it can be stated that S_0 is insignificantly affected by different OTM.

Tapley *et al*. (1993) claim that errors in the odd-degree diurnal and semi-diurnal ocean tide coefficients determine variability in both the real and imaginary parts of eccentricity excitation, while variability in the odd zonal harmonics causes variations with the same spectrum in the real part of the excitation of eccentricity vector. Therefore, bigger variations in S_C are expected, which is related to the real part of the excitation of the eccentricity vector. Figure 5 illustrates the series of S_S and S_C for LAGEOS-1. As expected, S_C demonstrates bigger differences between ocean tide models. Nev-

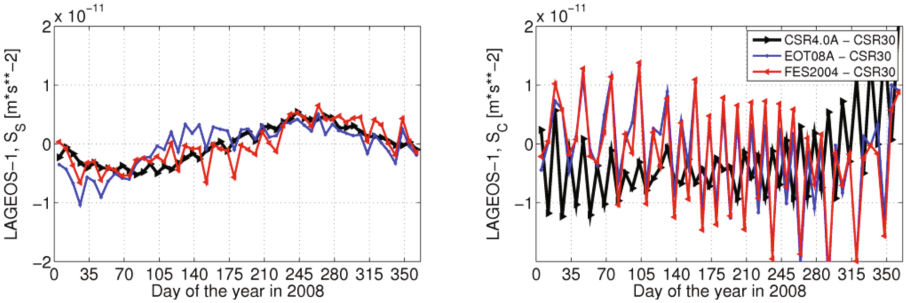


Fig. 5. Empirical LAGEOS-1 orbit once-per-revolution parameters in along-track for selected OTM. Differences w.r.t. CSR3.0.

ertheless, these differences are more than one order of magnitude smaller than for W_S and W_C, and smaller than those reported by Tapley *et al*. (1993).

For the S_S variations are smaller than for S_C for all models. However, the OTM affects the along-track empirical parameters only to a small extent. The major impact of OTM is reflected in the out-of-plane once-per-revolution parameters.

5.3 Orbit comparison

The orbits based on one OTM are compared with orbits based on all other models. The results of the direct comparison without estimating the Helmert parameters are presented in Table 6.

Table 6

Comparison between estimated orbits based on different ocean tide models: RMS of direct orbit differences (mean values for 2008; in mm)

Model \ Model	CSR40 A	TOPEX40	EOT08A	FES2004	GOT00.2	SCR Schwiderski
CSR3.0	4.5	2.0	10.6	14.6	14.5	13.6
CSR40 A	–	4.5	8.4	12.2	12.0	12.7
TOPEX40	–	–	10.3	14.1	14.1	13.6
EOT08A	–	–	–	7.3	7.5	13.1
FES2004	–	–	–	–	1.6	16.0
GOT00.2	–	–	–	–	–	15.8

The OTM based on analysis of satellite altimetry data (CSR3.0, CSR4.0A, and TOPEX4.0) agree very well. Especially, the RMS for the differences between TOPEX4.0 and CSR3.0 is very small, *i.e.*, 2.0 mm. There is also an excellent consistency (1.6 mm) between FES2004 and GOT00.2

(both dynamical models with assimilation from observed tidal altimeter data). Orbits based on EOT08A are quite similar to those based on CSR4.0A, FES2004, and GOT00.2 (RMS of 8.4, 7.3, and 7.5 mm, respectively). Good agreement between orbits based on dynamic OTM and satellite altimetry OTM is only achieved for EOT08A, which acts like "a link" between these two types of OTM.

The agreement between satellite altimetry OTMs (CSR3.0, CSR4.0A, and TOPEX4.0) and dynamical OTMs (FES2004 and GOT00.2) is rather poor (the RMS is at the level 12-15 mm). The RMS of differences is largest when comparing orbits based on the CSRC Schwiderski model with other models, *i.e.*, the RMS of 13 mm to OTMs based on satellite altimetry data, and to 16 mm for other dynamical OTMs.

Chapter 6 of IERS Conventions 2010 (Petit and Luzum 2010) indicates a 7 mm 3D-RMS difference of LAGEOS-1 orbits, when using FES2004 and CSR3.0. In this study it was found that the orbit difference is even 14.6 mm for 7-day LAGEOS-1 and -2 solutions. However, such a difference strongly depends on the applied orbit parameterization and the procedure used for orbit comparison, *e.g.*, a direct comparison, or a comparison with the estimation of the Helmert transformation parameters, *etc.*

5.4 Earth Orientation Parameters

Now, the impact of different OTM on the estimation of Earth Orientation Parameters (EOP, *i.e.*, pole coordinates and length-of-day) from the LAGEOS solutions is investigated. Ocean tides are one of the main contributors to the EOP variations (Beutler 2005), and, thus, EOP estimations can be used as indicators of the OTM quality. The mean differences with respect to IERS-

Table 7

Comparison between estimated Earth orientation parameters and the IERS-08-C04 series from the solutions based on different OTM (mean values for 2008)

Model	Mean bias			RMS of differences		
	X pole [μas]	Y pole [μas]	LoD [μs]	X pole [μas]	Y pole [μas]	LoD [μs]
CSR3.0	49	1	–4	186	179	48
CSR4.0A	61	0	–3	186	182	48
TOPEX4.0	60	1	–4	188	179	48
EOT08A	82	8	–6	206	197	51
FES2004	94	8	–4	220	208	52
GOT00.2	91	8	–4	219	207	52
CSRC Schwiderski	84	25	–6	236	223	55

08-C04 series, as well as weighted RMS of pole coordinates and length-of-day values are shown in Table 7. The X pole coordinate shows a bias when comparing to C04 series, amounting from 49 μas for CSR3.0 to 94 μas for FES2004. The mean bias for the X pole coordinate is smallest for CSR3.0, CSR4.0A, and TOPEX4.0 models and largest for FES2004 and GOT00.2. The Y pole coordinate, as well as the length-of-day, do not show any significant biases with respect to IERS-08-C04 series. The RMS of estimated pole coordinates ranges from 186 and 179 μas for CSR3.0 to 236 and 223 μas for the SCRS Schwiderski model, for the X and Y components, respectively. This implies that the estimated EOP values can be degraded by about 25% when using older-class or improper OTM.

6. DISCUSSION AND CONCLUSIONS

In all tests the most appropriate OTM for LAGEOS orbits are those based on altimetry observations from TOPEX/Poseidon (*i.e.*, CSR3.0, TOPEX4.0), or models based on T/P containing additional observations derived from GRACE and other gravity satellite missions (*i.e.*, CSR4.0A, EOT08A). Hydrological models supported by T/P (*i.e.*, FES2004 and GOT00.2) show big discrepancies, and the hydrological model based almost uniquely on coastal tide gauges (*i.e.*, CSRC Schwiderski) shows the largest deviations in most cases.

Even though the differences in OTM are at cm or sub-cm level, they can be detected by LAGEOS, because LAGEOS satellites are sensitive to tidal waves bigger or equal to 5 mm, whereas the errors of some tidal constituents exceed 50 mm in the current models. The minimum requested degree/order of ocean tide model expansion is 8 when processing SLR observations to LAGEOS. Using the OTM up to d/o 30 is, however, recommended, in order to avoid the degradation of the orbit determined through the model truncation. There is a good agreement between OTM based on the same type of observations and a significant disagreement between models based on different assumptions. Only orbits based on the EOT08A model indicate a quite high convergence of both the hydrological and hydrodynamic models (see Table 6).

The empirical orbit parameters indicate the smallest variations for CSR3.0, CSR4.0A, TOPEX4.0, and EOT08A in W_S parameter and for CSR4.0A in W_C parameter. The spectral analysis of W_C and W_S series reveals the deficiencies in the S_2 constituent, especially in the Polar Regions, due to the lack of altimetry data above 66°N and below 66°S, and some minor deficiencies in the annual S_a and S_{Sa} tides, as well.

When estimating gravity field parameters from LAGEOS, the W_C and W_S parameters are not estimated due to a direct correlation with C_{20} (Sośnica *et* *al*. 2012). In such a case, all spurious peaks from W_C and W_S may leak to LAGEOS-derived gravity field coefficients, in particular to C_{20}, which is one of the SLR core products.

The problems of orbit alias with the S_2 tide are well-known for GRACE gravity field solutions (*e.g.*, Chen *et al*. 2009, Meyer *et al*. 2012). Remarkably, the S_2 constituent limits the GRACE capability of recovering C_{20} variations. In this study it was found that not only GRACE solutions are affected by deficiencies in the S_2 tide in the latest OTM, but also SLR solutions and LAGEOS-derived parameters suffer from S_2 mismodellings.

The study reveals that the current OTM have a larger impact on the LAGEOS orbits than the *a priori* Earth gravity field models. The mean differences of RMS of residuals between solutions using different OTM (max. 1.32 mm of RMS) are larger than the mean differences between solutions using different Earth gravity field models with maximum values of RMS amounting to 1.16 mm (Sośnica *et al*. 2012).

The background models have a crucial impact not only on LAGEOS orbits, but also on all other SLR-derived parameters. In particular, polar motion or length-of-day are very sensitive to *a priori* ocean tide models. The difference in RMS of SLR-derived pole coordinates with respect to IERS-08-C04 series varies even up to 25% when using different ocean tide models.

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