Evaluation of GOCE Gravity Models with SLR Orbit Tests

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Abstract

This report for the IAG Joint Working Group 2.3 is an assessment of various GOCE gravity field models. The GOCE models were evaluated by assessing the model performance for satellite orbit dynamics based on Satellite Laser Ranging (SLR) observations. Tests show all recent GOCE and GRACE-based gravity field models perform similarly in terms of the RMS fit of the SLR observations (for all models the RMS does not differ by more than 1 cm). GOCE_TIM models perform best for many of the satellites in this particular test. The estimate of C20 is likely to be a dominant source of long-wavelength gravity model error when SLR or GPS measurements are not used.

Orbit tests

Satellite orbit fits are a traditional measure of gravity model accuracy, testing primarily the long-wavelength components. This is a particularly demanding test for the GOCE and GRACE-based gravity models because Earth gravity models had previously depended on the tracking to various geodetic satellites to determine the low spherical harmonics degree part of the field, which led to these fields being noticeably tuned to their particular orbit inclinations. Satellite Laser Ranging (SLR) data from a global network of well-determined tracking stations can provide an unambiguous and precise measurement of the satellite orbit accuracy, especially for those compact spherical (cannonball) satellites such as Starlette, Stella, Ajisai, LAGEOS-1 and -2. These satellites, along with the BE-C satellite, Larets and LARES, are an important resource for measuring the long-term variations of the Earth's gravity field and geocenter variations [Cheng and Tapley, 2004, Cheng et al., 2013a and b], and testing the model performance of the newly developed GOCE gravity fields for satellite orbit dynamics. Those satellites were also widely used in geodesy and geodynamics study, such as observing the seasonal geocenter motion and providing a time series of the spherical harmonic degree 2 terms used for the ILRS (International Laser Ranging Service) contribution to the ITRF2013 reference frame. These tests also benefit for evaluating the orbit accuracy for those satellites due to the 'errors' in Earth's gravity field models.

Validation of GOCE models by orbit tests using SLR data has been reported by others, for example, by Gruber et al. [2011] (using only Lageos 1 and 2) and Baur et al. [2014] (using only Lageos 1 and Starlette) using different time periods and likely different models and parameterization. The results are not consistent. For example, a large RMS for Starlette orbit fits was reported by Baur et al. [2014].

Three-day orbit fits to the SLR tracking of 8 satellites during the year 2013 were used to evaluate the performance of several gravity fields in this test. The fields tested include EGM2008 [Pavlis et al., 2012], GGM05S [Tapley et al., 2013], EIGEN6C2 [Förste et al., 2012], EIGEN6C4 [Förste et al., 2014], GOCE03S [Mayer-Guerr et al., 2012], GO_CONS_GCF_2_DIR_R3 [Bruinsma et al., 2010], GO_CONS_GCF_2_DIR_R4 [Bruinsma et al., 2013], GO_CONS_GCF_2_DIR_R5 [Bruinsma et al., 2014], GO_CONS_GCF_2_TIM_R3 and GO_CONS_GCF_2_TIM_R4 [Pail et al., 2011], and GO_CONS_GCF_2_TIM_R5 [Brockmann et al., 2014] (the latter models hereafter denoted by GOCE_DIR and GOCE_TIM). GGM05S is the only solution that contains only GRACE information, while the GOCE_TIM models used exclusively GOCE data (GPS and gradiometer). The remaining fields contain some combination of GRACE, GOCE, CHAMP, SLR and terrestrial gravity information. The lower degree portion of EGM2008, GOCE03S, and the GOCE_DIR and EIGEN6C models included GRACE data. The gravity information from SLR tracking of LAGEOS was used in development of the series of the EIGEN6C and GOCE_DIR models and GOCE03S included SLR tracking to LAGEOS 1 and 2.

Table 1 lists the orbit characterization [semi-major axis (a), eccentricity (e) and inclination (*i*)] at 1 January 2013, the number of arcs, the average number of observations per arc, and the average number of tracking stations for the satellites used in this analysis. The measurement and force models were consistent with that used for RL05 GRACE gravity solution [Bettadpur, 2007] based on the IERS2010 Conventions except for the gravity model. The SLRF2005/LPOD2005 coordinates were used for the SLR tracking stations [Ries, 2008]. In addition to the same GOT4.7 ocean tide and ocean pole tide models, the same Atmosphere-Ocean De-aliasing (AOD) time series used in the RL05 GRACE processing were used in the SLR orbit fits.

Table 1. Orbit characterization of satellites used in test

Satellite	a (m)	e	*i* (deg)	Arcs	Obs	Stations
LAGEOS 1	12266414	0.00396	109.86	119	668	19
LAGEOS 2	12165376	0.00141	52.65	116	573	17
Ajisai	7868998	0.00138	50.01	119	1301	18
Starlette	7332571	0.02007	49.84	119	736	16
Stella	7181361	0.00147	98.28	119	370	15
BEC	7492969	0.02577	41.16	119	773	13
Larets	7064115	0.00181	97.78	119	197	11
LARES	7820891	0.00151	69.55	119	716	16

The sensitivity of a satellite to the gravitational perturbation is altitude dependent. The maximum degree and order of the gravity field used here were 20x20 for LAGEOS-1 and -2, and 70x70 for BEC, Starlette, Stella, Ajisai, Larets and LARES. The choice of the size of gravity field is used in the standard SLR data processing with the mm accuracy for geodesy and geodynamic study being reported. The orbit fits were performed both with and without the adjustment, every 3-days, of a once-per-revolution (1-cpr) empirical acceleration for the transverse and cross-track components. When the empirical accelerations are not adjusted, most of the long-wavelength gravity model error signals are preserved in the SLR residuals. The drag coefficient, Cd, for Starlette, Stella, Ajisai, BEC, Larets and LARES and the empirical along-track acceleration, Ct, for LAGEOS-1 and -2, were adjusted every 0.5 to 1 day.

The RMS of the SLR residuals should reflect the relative performance of the various gravity field models at the longest wavelengths. Table 2 compares the results for the one-year average RMS for 3-day orbit fits without the adjustment of once-per-revolution empirical accelerations using the different gravity fields. Most of the models perform within 1 cm of each other, though there are some outliers. GOCO03S generally performs the worst, likely due to the value of C20, which is significantly different from the other models (replacement of the SLR derived C20 in GOCO03S improves the orbit fit to a level comparable with the other models). The results for the LARES satellite are of particular interest, as the remarkable density of this satellite (made of solid tungsten) reduces the effect of the surface forces to nearly negligible levels.

It should be noted that the value of C20 has a particularly large influence in these tests. This can be seen in the case denoted by GGM05S*, where the natural GRACE-derived estimate of C20 was used rather than the adopted replacement value from SLR based on Cheng et al. [2013]. In all cases, the performance with the SLR-derived value of C20 adopted for GGM05S is better, though the GOCE-TIM models perform somewhat better.

The GOCE_TIM models perform surprisingly well considering they rely only on GOCE information (GPS and gradiometer). They perform particularly well for Stella, Larets and LARES. It is well known that C20 has a significant long-term quadratic variation [Cheng et al., 2013], so that the epoch of the gravity field solution can influence the particular value of the C20 obtained. Since the testing period used here is 2013.0-2014.0, it may be that the C20 estimate obtained by the GOCE_TIM models, which depended on only GOCE data from 2009-2013, may be closer to the appropriate 2013 value of C20 than models that used GRACE data spanning a longer time period and representing an earlier mean epoch. To evaluate the sensitivity to the epoch of C20, the GGM05S solution was tested again but with the SLR-derived estimate for C20 from Cheng et al. [2013] evaluated at epoch 2013.5, the middle of the test period. The results shown in Table 2 and denoted by GGM05S** indicate that the fit did indeed improve for every satellite.

Table 2. Average laser ranging residual RMS (cm) from 3-day orbit fits without adjusting the once-per-revolution (1-cpr) empirical accelerations.

Model	Lageos-1	Lageos-2	Ajisai	Starlette	Stella	BEC	Larets	LARES
EGM2008	2.02	1.45	7.82	5.81	5.54	9.08	7.61	7.01
GGM05S*	2.07	1.54	8.42	7.44	5.80	9.29	7.70	7.31
GGM05S	1.90	1.18	6.75	4.00	4.62	8.86	7.10	5.05
GGM05S**	1.88	1.14	6.62	3.67	4.47	8.86	7.03	4.75
EIGEN6C2	1.89	1.19	6.90	4.30	5.80	8.91	7.93	5.30
EIGEN6C4	1.92	1.22	6.94	4.50	4.89	8.88	7.11	5.62
GOCO03S	2.16	1.69	9.03	8.11	6.94	9.44	8.34	8.63
GOCE_DIR3	1.90	1.11	6.58	3.85	4.48	9.00	6.92	4.39
GOCE_DIR4	1.90	1.19	6.56	4.24	5.41	9.09	7.41	4.98
GOCE_DIR5	1.92	1.22	6.92	4.50	4.89	8.87	7.11	5.62
GOCE_TIM3	1.90	1.11	6.58	3.85	4.48	9.00	6.92	4.39
GOCE_TIM4	1.79	1.18	6.89	4.42	3.23	10.37	6.15	3.76
GOCE_TIM5	1.83	1.11	6.50	3.50	2.92	8.97	6.27	4.20

Notes: GGM05S* is the same as GGM05S except for retaining the GRACE-derived estimate of C20; GGM05S** denotes replacing C20 with the SLR-derived value evaluated at the middle of the test period.

Table 3. Average laser ranging residual RMS (cm) from 3-day orbit fits with adjusting the once-per-revolution (1-cpr) empirical accelerations

Model	Lageos-1	Lageos-2	Ajisai	Starlette	Stella	BEC	Larets	LARES
EGM2008	1.16	0.97	6.43	1.83	3.41	6.22	6.14	3.57
GGM05S	1.10	0.87	6.09	2.16	2.70	6.18	5.77	2.51
EIGEN6C2	1.11	0.89	6.12	1.95	3.28	6.18	5.95	3.07
EIGEN6C4	1.10	0.86	6.04	1.69	2.90	6.21	5.80	2.48
GOCO03S	1.15	0.94	6.32	1.95	3.48	6.27	6.26	3.39
GOCO_DIR3	1.09	0.84	5.99	1.68	2.68	6.24	7.11	2.09
GOCO_DIR4	1.11	0.89	5.39	1.79	2.90	6.43	5.53	2.74
GOCO_DIR5	1.10	0.86	6.02	1.68	2.90	6.18	5.80	2.48
GOCO_TIM3	1.08	0.84	5.99	1.68	2.68	6.24	5.63	2.09
GOCO_TIM4	1.10	0.93	6.41	2.37	2.56	6.30	5.48	2.48
GOCO_TIM5	1.08	0.86	6.13	1.79	2.14	6.26	5.47	2.02

Given the sensitivity of this test to the particular value of C20, one way to isolate its effect is to include the adjustment of the once-per-revolution empirical accelerations in the orbit fit. Adjustment of the 1-cpr parameters reduces the effect of errors in the zonal and resonance coefficients, as well as accommodates part of the errors in the nongravitational force models. The results for this case are shown in Table 3. The GOCE_TIM models still perform very well, but the performance for all models is generally within a few mm of each other. There are only a few instances where a model performs somewhat worse than the others.

The estimate of drag coefficients is used to account for the error in the modeling of drag force on the satellite, including the errors in the atmosphere density model and modeling of the interaction of the satellite surface with the incident molecular flow. Better gravity models can improve the orbit fits, but should have little effect on the estimates of the drag coefficients. Table 4 shows the average of the daily estimates of Cd/Ct from different gravity models (Ct being an empirical 'drag-like' acceleration to account for a variety of forces that affect the orbit in the along-track direction for the LAGEOS satellites). The average daily estimate is consistent within two digits for most of satellites. It might be interesting to investigate why GOCE-TIM4 and 5 appear to favor LAGEOS-1 at the expense of LAGEOS-2 in this test.

Table 4. Average daily Cd/Ct estimates from 3-day orbit fits without adjusting once-per-revolution (1-cpr) empirical accelerations. The Cd estimates are dimensionless drag parameters; the Ct estimates are empirical along-track accelerations for the LAGEOS satellites in units of nanometer/s^2.

Model	Lageos-1	Lageos-2	Ajisai	Starlette	Stella	BEC	Larets	LARES
EGM2008	-2.11	1.53	3.33	2.93	3.10	2.51	2.64	2.64
GGM05S*	-2.10	1.44	3.33	2.94	3.03	2.50	2.64	2.64
GGM05S	-2.12	1.76	3.33	2.94	3.04	2.51	2.64	2.64
GGM05S**	-2.13	1.77	3.33	2.94	3.04	2.51	2.64	2.64
EIGEN6C2	-2.08	1.60	3.33	2.96	3.07	2.51	2.64	2.64
EIGEN6C4	-2.05	1.66	3.33	2.95	3.06	2.51	2.64	2.64
GOCO03S	-1.97	1.22	3.33	2.95	3.10	2.51	2.63	2.64
GOCE_DIR3	-2.10	1.77	3.33	2.97	3.02	2.51	2.63	2.60
GOCE_DIR4	-2.11	1.63	3.33	2.94	3.01	2.48	2.60	2.60
GOCE_DIR5	-2.05	1.70	3.33	2.95	3.05	2.51	2.64	2.60
GOCE_TIM3	-2.10	1.77	3.33	2.97	3.02	2.51	2.63	2.60
GOCE_TIM4	-1.75	2.47	3.33	2.97	3.07	2.52	2.64	2.60
GOCE_TIM5	-1.98	2.03	3.33	2.96	3.00	2.51	2.64	2.60

Adjustment of the 1-cpr empirical acceleration parameters is an effective way to accommodate the errors in the zonal and resonance coefficients as well as part of the errors in the nongravitational force models. Since many of them are strongly perturbed by drag (Starlette, Stella, Larets) or solar radiation pressure effects (Ajisai), we can look to LARES, which is the best probe for studying the gravity model errors. This satellite is sensitive to gravity model error, since it is much lower in altitude than the LAGEOS satellites, but its density is so high (the ratio of the mass/surface ratio normalized to LAGEOS-1 is 2.6:1) that the residual surface forces are very small (comparable or better than LAGEOS). It was also not used in any of the gravity models tested here.

Table 5 shows the estimate of the 1-cpr parameters for the transverse (along-track) and cross-track accelerations. The Cos-t and Sin-t, and Cos-c and Sin-c represent the cosine (C) and sine (S) terms for transverse (t) and cross-track (c), respectively, in units of nanometers/sec^2 (nm/s^2). Table 5 shows that the mean S transverse and C cross-track are tiny and essentially the same for all fields. The mean C transverse terms are also tiny for models except for the models GOCE-DIR3/TIM3 and GOCE-TIM4. The S cross-track (Sin-c) terms are all significantly biased, suggesting that something else in the background model for LARES is causing an excessive nodal drift that the 1/revs are trying to accommodate. This bias is larger for EGM2008, GGM05S* and GOCO03S, reflecting the aforementioned effect of a biased value of C20, which requires larger Sin-c terms to offset.

A strong annual variation with an amplitude of 0.25 nm/s^2 is dominant in the C transverse (Cos-t), which could be due to hydrological excitation while the atmosphere and ocean mass variations were modeled through the Atmosphere-Ocean De-aliasing (AOD) model. It is also interesting that the S transverse (Sin-t) for all models are essentially identical. Spectral analysis reveals a strong signal with an amplitude of 0.34 nm/s^2 and a period of ~134 days in Sin-t, and a strong signal with an amplitude of 0.53 nm/s^2 and a period of 11.9 days appears in C cross-track (Cos-c) for all models. A signal with an amplitude of 0.58 nm/s^2 and a period of ~197 days is dominant in S cross-track (Sin-c) for all models. The 134-day signal is near the period of the node with respect to the Sun or, equivalently, the S1 tide perturbation period for LARES. The 11.9-day is near the perturbation period of the M2 tide band. The sources of these excitations in the LARES orbit are an interesting topic for further research. The significant reduction in the fits to LARES when adjusting the 1-cpr accelerations indicates that the time variable part of the gravity field is an important component limiting the fits indicated in Table 2.

Table 5. Average of the once-per-revolution (1-cpr) empirical accelerations estimate from 3-day orbit fits of LARES satellite (in units of nm/s^2).

Model	Cos-t	Sin-t	Cos-c	Sin-c
EGM2008	-0.062	-0.029	-0.019	-4.151
GGM05S*	-0.002	-0.028	-0.020	-4.859
GGM05S	-0.002	-0.028	-0.022	-2.788
GGM05S**	-0.002	-0.028	-0.021	-2.477
EIGEN6C2	-0.016	-0.029	-0.018	-2.708
EIGEN6C4	0.020	-0.028	-0.018	-3.373
GOCO03S	-0.019	-0.028	-0.015	-5.699
GOCE_DIR3	0.212	-0.026	-0.015	-2.139
GOCE_DIR4	-0.045	-0.029	-0.021	-2.142
GOCE_DIR5	0.020	-0.028	-0.018	-3.373
GOCE_TIM3	0.212	-0.026	-0.015	-2.139
GOCE_TIM4	-0.132	-0.028	-0.012	-1.058
GOCE_TIM5	-0.045	-0.028	-0.021	-2.152

Summary

The orbit fit tests show all recent GOCE and GRACE-based models perform similarly in cm level. The GOCE_TIM models did not include SLR or GRACE data, yet they perform here as well or better as models that did. After removing the effect of possible biases in C20, the results indicate that there is little to distinguish between the available mean gravity field models, suggesting that the temporal variations in C20 is likely to be a dominant source of long-wavelength gravity model error. It is well known that the value of C20 has a significant long-term trend, and the SLR data is essential in monitoring this trend for the most precise applications.

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