Evaluation of the EGM2008 Gravity Model

Minkang Cheng, John C. Ries and Don P. Chambers
Center for Space Research, University of Texas at Austin, USA
3925 West Braker Lane, STE 200, Austin, TX 78759, USA
e-mail: cheng@csr.utexas.edu

The EGM2008 gravity model was evaluated using three techniques that assess the model performance on the modeling of satellite dynamics and the geoid accuracy over the ocean and land at different wavelengths. The tests include orbit tests with SLR and GRACE data, GPS leveling tests, and ocean circulation and marine geoid tests.

1. Orbit tests

Satellite orbit fit is one traditional measure of the gravity model accuracy in primarily the long-wavelength. This is a particularly demanding test for the GRACE-based gravity models because Earth gravity models had previously depended on the tracking to various geodetic satellites to determine the low 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 compact spherical (cannonball) satellites such as Starlette, Stella, Ajisai, LAGEOS-1 and -2. These satellites, along with the BE-C satellite, are an important resource for measuring the long-term variations of the Earth's gravity field [Cheng and Tapley, 2004].

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	557	13
Lageos 2	12165376	0.00141	52.65	116	550	13
Ajisai	7868998	0.00138	50.01	119	1233	15
Starlette	7332571	0.02007	49.84	119	709	14
Stella	7181361	0.00147	98.28	119	355	13
BEC	7492969	0.02577	41.16	119	964	9

A series of 3-day orbit fits to the SLR tracking of six satellites during the year 2003 was used to evaluate the performance of several gravity fields, including the EGM-96 [Lemoine et al., 1998], PGM2007A, EGM2008, GGM02C [Tapley et al., 2005], GGM03S [Tapley et al., 2007], EIGEN-GL04C (GFZ04C), EIGEN-GL05C (GFZ05C) [Förste et al., 2007], and ITG03S [Mayer-Guerr, 2007]. Table 1 lists the orbit characterization [semi-major axis (a), eccentricity (e) and inclination (i)] at 1 January 2003, the number of arcs, the 3-day average number of observations and the average number of tracking station for the satellites used in this analysis. The measurement and force models were consistent with that used for RL 04 GRACE gravity solution [Bettadpur, 2007] based on the IERS2003 standard except for the gravity model, and the ITRF2005 station coordinate with corresponding EOP series were used. In addition to the same FES2004 ocean tide and ocean pole tide models, the same Atmosphere-Ocean De-aliasing (AOD) time series used in the RL04 GRACE processing were used in the SLR orbit fits.

The sensitivity of a satellite to the gravitational perturbation is altitude dependent. The maximum degree and order of the gravity field used are 20x20 for LAGEOS-1 and -2, and 70x70 for BEC, Starlette, Stella and Ajisai. The orbit fits were performed both with and without the adjustment, every 3-days, of once-per-revolution (1-cpr) empirical accelerations for the radial and cross-track components. When the empirical accelerations are not adjusted, more of the long-wavelength gravity model error signals are preserved in the SLR residuals. The drag coefficient, *Cd* for Starlette, Stella, Ajisai and BEC, and the empirical along-track acceleration, *Ct*, for LAGEOS-1 and -2, were adjusted every 12 hours.

The RMS of the SLR residuals should reflect the relative performance of the various gravity field models at the longer wavelengths. Figures 1 and 2 compare the SLR residual RMS from 3-day orbit fits from using EGM96 (red circles), PGM2007A (blue circles) and GGM02C (open circles) for LAGEOS-2 and Starlette. The pattern is similar for LAGEOS-1, Ajisai, Stella and BEC. 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 different gravity fields, including EGM96, PGM2007A, EGM2008, GGM02C, GGM03S, GFZ04C, GFZ05C and ITG03S.

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
EGM96	1.49	1.34	5.60	4.95	9.14	11.07
PGM2007A	1.49	1.29	4.95	3.85	3.02	9.04
EGM2008	1.51	1.38	5.31	4.63	2.91	9.28
GGM02C	1.47	1.28	4.83	3.47	3.22	9.03
GGM03S	1.41	1.30	5.28	3.25	1.76	9.22
GFZ04C	1.44	1.26	4.62	3.06	2.56	8.93
GFZ05C	1.43	1.25	4.67	3.14	2.60	8.95
ITG03S	1.51	1.39	5.20	4.58	2.90	9.27

The results shown in Table 2 and Figures 1 and 2 suggest that in comparison with EGM96, the PGM2007A has slightly improved the lower degree (< 20) portion based on the tests for LAGEOS-2, but significantly improved the higher degree portion based on the tests from Starlette, Stella, Ajisai and BEC. The performance of the EGM2008 model is very similar to the ITG03S model, which was used as satellite-only basis for EGM2008. One also can see a slight degradation compared to other GRACE models.

Table 3 compares the results with the adjustment of the once-per-revolution empirical accelerations in the orbit fit. The adjustment of the 1-cpr acceleration parameters can remove the effect of errors in the zonal and resonance coefficients, as well as accommodate part of the errors in the nongravitational force models. Comparison of the relative residual RMS for the cases (where the once-per-revolution acceleration parameters were estimated) attempts to isolate the improvements in the gravity coefficients other than the zonal and resonance coefficients.

Based on the orbit fits of these six geodetic satellites using SLR data, the performance of PGM2007A and EGM2008, in general, is at the same level as the other GRACE-based gravity models GGM02C, EIGEN-GL04C (GFZ04C), EIGEN-GL05C (GFZ05C), and ITG-GRACE03S(ITG03S) for degree/order less than 70. However, in comparison with PGM2007A, EGM2008 slightly degraded the orbit fit for all of satellites in the case of without adjusting the 1-cpr acceleration parameters (Table 2). The results were more mixed in the case of adjusting the 1-cpr acceleration parameters (Table 3).

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

Model	Lageso-1	Lageos-2	Ajisai	Starlette	Stella	BEC
EGM96	1.04	0.97	5.24	3.58	6.54	9.04
PGM2007A	0.95	0.86	4.40	1.63	1.91	7.54
EGM2008	0.95	0.86	4.44	1.69	1.59	7.56
GGM02C	0.95	0.86	4.42	1.65	2.14	7.57
GGM03S	0.95	0.88	4.43	1.48	1.52	7.53
GFZ04C	0.95	0.86	4.41	1.64	2.56	7.49
GFZ05C	0.95	0.86	4.42	1.69	1.59	7.48
ITG03S	0.95	0.86	4.32	1.54	1.55	7.52

The last orbit test was to compare the residuals from the GRACE K-Band intersatellite range-rate residuals using EGM2008 with the model currently used for the Release-04 (RL04) processing at CSR. For the month of February 2008, the results were essentially identical, with a fit of 0.407 μ/sec for EGM2008 and 0.409 μ/sec for the RL04 processing.

2. GPS Leveling test

GPS leveling test is a comparison of the geoid undulation derived from GPS leveling data and the geoid undulation (N) calculated from a gravity model and/or terrestrial gravity data. This test is sensitive to the geoid components with wavelengths ranging from the shortest baseline to the longest baseline in the test network, reflecting the quality and treatment of satellite and/or surface gravity data used in the geoid determination. The RMS abort the mean of the ΔN at an area can be used to access the accuracy of the geoid over the land predicted from a gravity model (up to degree and order 360 in this test). The method, namely a 'degree-banded' approach (Huang and Véronneau, 2005) is used to perform high-pass filtering to the surface gravity data to allow the satellite model define the long-wavelength geoid components, and the surface gravity data determine the short wavelength geoid components, thus provides the most sensitive way to evaluate a satellite model without being seriously affected by the omission error of the satellite model, and isolation of the power of gravity signals to a certain degree range. Figure 3 compares the GGM02C, EIGEN-GL04C (GFZ04C), PGM2007A and EGM2008 geoids to 1149 GPS leveling data over Canada and the 6168 data for the US, respectively. The mean of the ΔN is calculated globally over Canada, but state-by-state for the US since there is a state-dependent systematic bias contained in the GPS leveling data over the US. The performance of the models below approximately degree 90 cannot be assessed since the cumulative GRACE model error is smaller than 2 cm that is within the noise range of GPS-leveling and surface gravity data. In the degree range from 90 to approximately 110, the results can be expected to mainly reflect the quality of the GRACE solution used. Above degree 110, the results can be expected to reflect the quality of the surface information incorporated. It is clear that EGM2008 model has significantly improved the geoid in these areas and approached to the noise level of GPS leveling data for both Canada and the US .

3. Marine geoid tests

More accurate mean dynamic ocean topography (DOT) maps can be used to determine the sub-surface geostrophic currents with greater detail. These circulation maps are very useful for evaluating the improvement of the geoid computed from a gravity field, since small changes in the geoid can lead to significant changes in the circulation, especially in the tropics. The DOT in this test is determined from the mean sea surface (CSRMSS98) minus the marine geoid from a test gravity field. The zonal and meridional circulation from a topography map are computed using forward-backward difference between adjacent grids and accounting for the changes in the area of an equi-angle grid away from the equator. See Tapley et al. (2003) for further details about this procedure.

The large-scale zonal and meridional geostrophic currents from various DOT maps are compared to the World Ocean Atlas 2001(WOA01) data relative to 4000 m (courtesy of V. Zlotnicki). The comparison is to degree/order 120, and 400 km smoothing has been applied. Higher resolution is not supported since the WOA01 data has already had a similar level of smoothing applied. With the accuracy of the GRACE-based gravity solutions, this test may now be limited by errors in the long-term topography. We included the results for EGM96, GG02C, EIGN-GL04C, EIGN-GL05C, GGM03S, ITG-GRACE03S (GRACE-based component of EGM2008), PGM2007A and EGM2008 to evaluate the impact of the combination on the performance. Table 4 summaries the results. There is some degradation in the results from ITG-GRACE03S to EGM2008, but it seems to be relatively minor.

Table 4. Ocean circulation comparisons

Model	Standard Deviation (cm/s)		Correlation	
	Zonal	Meridional	Zonal	Meridional
EGM96	8.18	7.00	0.352	0.288
GGM02C	3.04	3.23	0.914	0.482
EIGEN-GL04C	3.01	3.01	0.916	0.543
EIGEN-GL05C	3.24	3.10	0.903	0.513
GGM03S	2.91	2.97	0.921	0.550
ITG-GRACE03S	2.91	2.94	0.921	0.558
PGM2007A	3.25	3.14	0.920	0.517
EGM2008	2.97	2.99	0.918	0.551

We demonstrate the improvement of EGM2008 over the ocean for smaller wavelengths by comparing it to mean sea surface profiles determined from TOPEX/Poseidon (T/P) data from September 20, 2002 to December 31, 2003, when T/P had been shifted to a new groundtrack between its old groundtrack. These data are used because the groundtrack is different from any of those from previous altimeter missions used to create the gravity models, and so represent new observations of the marine geoid. We create residuals along each satellite pass calculated from MSS - WOA01 DOT – geoid at different wavelength filtering (shorter and longer than 300 km [half-wavelength]). The WOA01 DOT is computed to a reference level of 4000 m, and the geoid is evaluated using coefficients to spherical harmonic degree/order 360. The mean was removed along each altimeter pass before computing the RMS. The results indicate that EGM2008 and PGM2007A perform well at both the longer and the shorter wavelengths. Since the GGM02C model was extended to 360x360 using EGM96, it is not surprising that the results are the same for the short wavelengths. PGM2007A and EGM2008 demonstrate smoother geoid residuals (see Fig. 4), which is likely the reason for the better statistics shown in Table 5.

Figure 4 illustrates the smooth geoid residuals for EGM2008. The residuals are the difference between a 'high-frequency DOT' defined as (GSFCMSS00-geoid) and the same DOT smoothed to 900 km. This removes most of the long-wavelength dynamic topography so that smaller scale artifacts can be seen. In previous models, significant 'striations' were apparent in such maps.

Table 5. Short-wavelength geoid comparisons (to degree and order 360)

Model	> 300 km	< 300 km
EGM96	9.3	12.7
GGM02C(+EGM96)	8.2	12.7
EIGEN-GL04C	8.7	13.1
EIGEN-GL04C	7.8	12.6
PGM2007A	7.5	11.7
EGM2008	7.6	11.8

Summary

The orbit fit tests show all recent GRACE-based models performing similarly. The GPS leveling test also indicates excellent performance with EGM2008, and the test now appears to be limited by the data errors rather than geoid errors. In the ocean circulation test, PGM2007A and EGM2008 can be used to recover accurate circulation features, as demonstrated by the high correlation with the World Ocean Atlas 2001. EGM2008 also performs best in the short-wavelength marine geoid test, providing smooth short-wavelength marine geoid residuals.

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Fig. 1 and 2 SRL Residual RMS from 3-day Orbit Fit

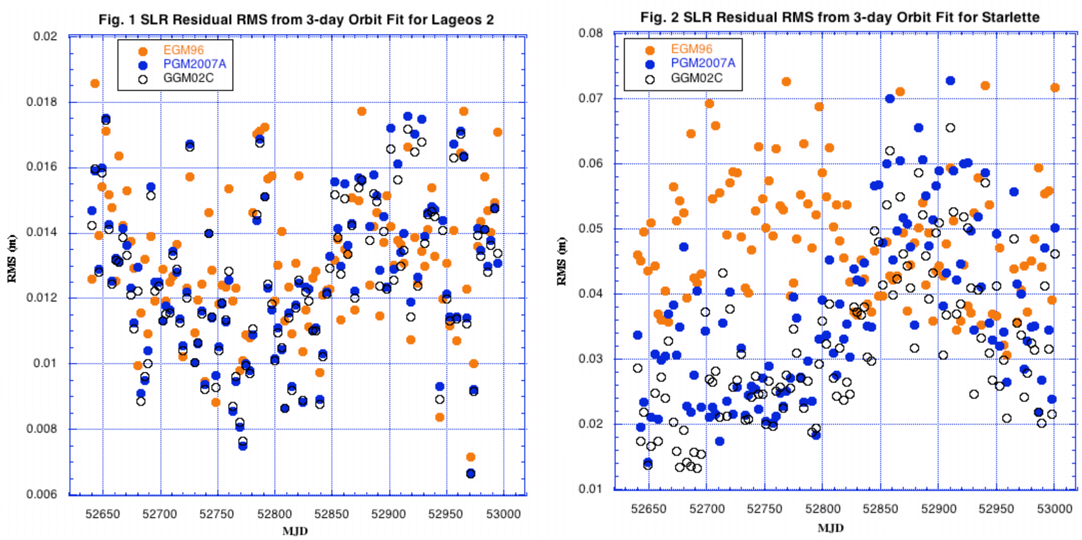

Fig. 3 Degree-banded GPS leveling test over Canada and US

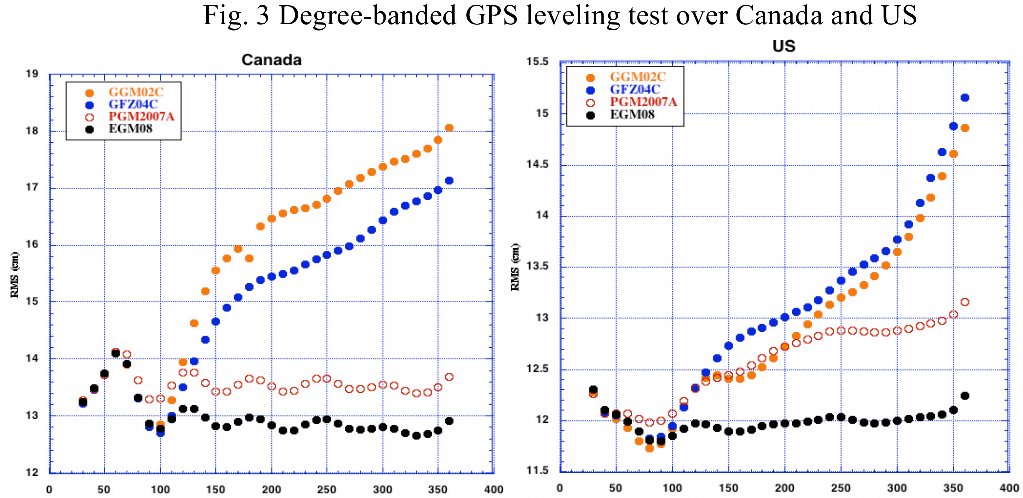

Fig. 4 Short wavelength geoid residuals from EGM2008 gravity model