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Intercomparison and evaluation of some contemporary global geopotential models

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Abstract. The performance of five global Earth gravitational models, published after 1995, was examined through tests with data (mostly) withheld from the development of these models. We considered the models: JGM-3 (Tapley et al., 1996), GRIM4-C4 (Schwintzer et al., 1997), TEG-3 (Tapley et al., 1997), EGM96 (Lemoine et al., 1998) and GPM98A (Wenzel, 1998). The test data that we used for model evaluations include satellite tracking measurements acquired over several spacecraft at various inclinations and altitudes, geoid undulations (or height anomalies) determined from GPS positioning and leveling observations, Dynamic Ocean Topography (DOT) information implied by an ocean circulation model, as well as hydrographic estimates of (relative) DOT. Over 9307 GPS/leveling geoid undulation values distributed over North America, Europe and Australia, EGM96 (to degree 360) outperforms all other models tested, yielding a standard deviation of the undulation differences of ±37.2 cm. Considering that the available GPS/leveling data are located over some of the best surveyed areas (gravimetrically), this value is consistent with the predicted (commission plus omission) geoid error of EGM96, whose global rms value equals ±45.3 cm. Over the ocean, the performance of EGM96 is superior to that of all other models tested, as judged by the results of comparisons with both the POCM_4B circulation model DOT output and with the hydrographic DOT estimates. GPM98A was found to be inaccurate over medium wavelengths, and is not considered suitable for orbit determination applications.

1. Introduction

Since 1995 several groups and individual investigators have developed and published global

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Table 1 - Five global models of the Earth's gravitational potential considered in this study.

Model	*Nmax*	Reference
JGM-3	70	Tapley et al., 1996
TEG-3	70	Tapley et al., 1997
GRIM4-C4	72	Schwintzer et al., 1997
EGM96	360	Lemoine et al., 1998
GPM98A	1800	Wenzel, 1998

models of the Earth's gravitational potential, in the form of spherical harmonic coefficient sets. Comprehensive comparisons that could be used to assess the accuracy of these models, and identify their respective strengths and weaknesses, are of interest to both model developers and model users. A study of this kind was reported by Pavlis et al. (1993). Since then, a plethora of new information (especially GPS/leveling geoid undulation data) has become available, which is of great value to these studies. Formulation refinements (e.g., Rapp, 1997) also contribute to more rigorous testing procedures that better reveal model performance. These advances prompted the present study. Table 1 lists the five models considered here. These combination solutions represent (at least nominally) 'general purpose' models, i.e., models that are not specifically 'tailored' either to a particular satellite's orbit, or to regional terrestrial data. Apart of maximum spherical harmonic degree Nmax, these models differ in satellite tracking data, terrestrial and altimeter data, data weighting, estimation technique, and estimated parameters involved in their development. For example, in GRIM4-C4 DOT parameters were not estimated simultaneously with the potential coefficients, unlike JGM-3, TEG-3 and EGM96. The low degree (70) surface gravity normal equations used in JGM-3 and TEG-3 were based on older data (from OSU), hence more recent gravity data releases (e.g., over the former Soviet Union), have not been exploited in the development of these models. EGM96 contains a significant amount of (high-low) SST data from both TDRSS and GPS satellites, and incorporates the most complete and up-to-date surface gravity information available at the time of its development. EGM96 however, unlike TEG-3 and GRIM4-C4, does not use altimeter cross-over data (but does use direct altimetry). GPM98A, above degree 20, is the result of the analysis of a global high-resolution merged set of gravity anomalies, and uses the EGM96 coefficients up to degree 20. All these differences among the various models have their consequences in the respective model's performance in specific applications (e.g., orbit determination, geoid undulation determination, DOT estimation).

Space limitations do not allow for a detailed description of the theory underlying the various comparisons. We concentrate therefore on results, giving only that information which is essential to describe the various tests, and appropriate references for further details.

2. Results

2.1. Orbit pit comparison

These tests are primarily sensitive to long and medium wavelength components of the

Table 2 - Summary of orbit tests. All tests used daily IERS pole series and ITRF96 station positions and velocities. No global parameters are estimated, and the data complement remains the same for all models tested. No dynamic editing (i.e. n–σ) is performed.

Satellite	Arcs	Arc Parameterization
LAGEOS *a* = 12 273 km *e* = .0048 *i* = 109.9º	Three monthly arcs: 880331, 880430, 880530 10145 SLR observations	state vectors C_R along-track constant EA/15 days measurement bias per station per arc along-track 1-CPR EA/15 days †
Ajisai *a* = 7870 km *e* = .0011 *i* = 50.0º	Eight 5-day arcs: 890404, 890409, 890414, 890419, 890424, 890429, 890504, 890509 4801 SLR observations	state vectors C_R C_D /day measurement bias per station per arc
LAGEOS–2 *a* = 12 163 km *e* = .0132 *i* = 52.0º	Five 10-day arcs: 951117, 960115, 960423, 960612, 960801 4974 SLR observations	state vectors along-track constant EA/5 days measurement bias per station per arc long-track 1-CPR EA/5 days †
Stella *a* = 7173 km *e* = .0013 *i* = 98.6º	Five 10-day arcs: 951117, 960115, 960423, 960612, 960801 2953 SLR observations	state vectors C_D/day along-track constant EA/5 days measurement bias per station per arc along-track 1-CPR EA/5 days †
GFZ–1 *a* = 6728 km *e* = .0013 *i* = 51.7º	One 24-day arc: 960804 Uses new low-altitude drag model 3372 SLR observations	state vector drag scale factor every 8 revolutions 1 measurement bias per arc along-track 1-CPR EA/arc †
Starlette *a* = 7331 km *e* = .0211 *i* = 49.8º	Eight 10-day arcs: 960702, 960712, 960811, 960830, 960919, 961009, 961029, 961118 10161 SLR observations	state vectors C_R C_D /day along-track 1-CPR EA/5 days †
TRMM *a* = 6728 km *e* = .0002 *i* = 35.0º	Three arcs: 971219 (10 days), 980101 (7 days), 980118 (6 days) Uses new low-altitude drag model 24396 TDRSS Range observations 24731 TDRSS Range-Rate observations	state vectors drag scale factor every 4 revolutions cross-track C_L per arc range and range-rate biases per pass
TOPEX/POSEIDON *a* = 7716 km *e* = .0004 *i* = 66.0º	Four 10-day cycles: 10 (921221), 19 (930320), 21 (930409), and 46 (931213) 14144 SLR observations 187553 DORIS observations	Second generation precise orbit determination parameterization (see Marshall et al.,1995 for details)

1-CPR = 1-cycle-per-revolution EA= empirical acceleration † Not used in tests that do not estimate 1-CPR accelerations

Table 3 - Tracking data residuals from tests estimating 1-CPR accelerations. EGM96 tides used in all cases, and all gravitational models were truncated to degree 70. RMS of fit in (cm) for satellite laser ranging data.

	GPM98	GRIM4-C4	TEG-3	JGM-3	EGM96
LAGEOS	3.5	3.7	3.7	3.7	3.5
LAGEOS-2	3.1	3.1	3.0	3.1	3.1
Stella	106.9	18.2	11.2	12.4	7.0
GFZ-1	561.5	331.1	274.4	138.0	97.6
Starlette	237.8	12.2	7.1	7.5	7.2

gravitational field. The absolute magnitude of the rms of fit to the tracking data depends highly on the orbit parameterization (see also, Ries, 1997). Consistent parameterization was used for all models tested here, as shown in Table 2. Some of the satellites used in these tests are well represented in the current models (e.g., LAGEOS, Starlette), therefore even if the test is based on withheld data, that does not guarantee independence. The tests should be viewed as a 'necessary but not sufficient' condition for the long/medium wavelength accuracy of a model. Tracking data over orbits completely foreign to a model's satellite data complement are ideally suited for testing purposes. This is the case for the TRMM orbit test, which benefits from comparatively good Tracking and Data Relay Satellite System (TDRSS) tracking coverage over the western Pacific and central Atlantic Oceans.

Results for orbit tests including the estimation one-cycle-per-revolution (1-CPR) empirical accelerations are shown in Table 3. Estimation of these parameters reduces the sensitivity to odd zonal and resonant perturbations. Results that do not include the estimation of the 1-CPR terms are shown in Table 4. The test results for the high altitude satellites (LAGEOS and LAGEOS-2), which are most sensitive to the longest wavelengths, show little difference between the models when the 1-CPR terms are estimated. These differences become significant for the 30-day LAGEOS arcs when the 1-CPR terms are not estimated, but not so for the shorter 10-day LAGEOS-2 arcs, possibly indicating an improvement in the longer period perturbations using EGM96. For Starlette, EGM96 and TEG-3 are substantially better than GRIM4-C4 and GPM98A. At low altitudes (Stella, GFZ-1, and TRMM), EGM96 produces significantly better results than the other models. As expected, GPM98A performs as EGM96 on the high orbiters,

Table 4 - Tracking data residuals from tests *not* estimating 1-CPR accelerations. EGM96 tides used in all cases, and all gravitational models were truncated to degree 70. RMS of fit in (cm) for range (r), and (mm/s) for range-rate (r-r).

	GPM98A	GRIM4-C4	TEG-3	JGM-3	EGM96
LAGEOS	4.4	4.5	4.9	4.8	4.4
LAGEOS-2	3.9	4.0	3.9	3.9	3.9
Stella	133.6	26.1	16.0	18.1	9.4
GFZ-1	778.5	569.4	340.2	162.3	106.9
Starlette	242.0	15.5	10.1	11.3	10.0
Ajisai	18.6	6.1	5.4	5.4	5.1
TRMM (r)	201.4	243.6	360.7	303.2	177.7
TRMM (r-r)	4.5	4.7	7.3	6.2	3.9

Table 5 - TOPEX/POSEIDON orbit comparisons. All gravitational models were truncated to degree 70.

Model	RMS Fit to Tracking Data SLR (cm)	DORIS (mm/s)	RMS Difference With JPL Reduced-Dynamics Orbit Radial (cm)	Along-track (cm)	Cross-track (cm)	Total Position (cm)
GPM98A	12.1	0.66	11.7	39.0	16.9	44.1
GRIM4-C4	3.9	0.56	3.0	8.9	6.2	11.4
TEG-3	3.6	0.56	2.5	6.9	4.6	8.7
JGM-3	3.6	0.56	2.3	6.7	4.5	8.5
EGM96	3.7	0.56	2.5	7.1	4.8	9.0

but is unacceptably poor for Starlette and the low-altitude SLR targets.

The high-low satellite-to-satellite tracking of TRMM provides higher sensitivity to the medium wavelength contribution of gravity, particularly over the low latitude ocean regions where most of the tracking data are located. Improved modeling of the oceanic gravity field over the tropics should result in improved performance on this test. The relative performance of the models in the TRMM tests is as expected considering the relative contribution of altimeter data in each model, with EGM96 providing the best performance, and TEG-3 the worst.

The TOPEX/POSEIDON (T/P) altimetric satellite is especially valuable for testing the orbit determination performance of a gravitational model due to the multiple and precise tracking data types available for this spacecraft (SLR, DORIS, GPS). High-precision trajectories estimated at JPL from GPS tracking and the reduced-dynamics approach, permit an independent assessment of the accuracy of trajectories estimated from SLR and DORIS data, in the dynamic mode. Table 5 shows the average values of the results obtained over the four cycles tested (see Table 2), for some statistics of interest.

JGM-3 performs best in the T/P orbit comparisons. However, one should recall that the JPL reduced-dynamics orbits use the JGM-3 implied orbit information as a (weak) dynamic constraint, therefore comparisons with the JPL orbits somewhat favor that model. JGM-3, TEG-3 and EGM96 perform quite similarly, with EGM96 being only marginally inferior. GRIM4-C4 performs less satisfactorily (considering also that this model incorporated TOPEX altimetric cross-over data). The performance of GPM98A is quite poor.

2.2. GPS/leveling undulation comparison

This type of comparison has been used over several years for model evaluation (e.g., Rapp and Pavlis, 1990). The proliferation of ever more accurate GPS observations that are made on precisely leveled points, has enabled a steady increase of the data available for model testing. Several colleagues have contributed GPS/leveling data which we used in this study, as shown in Table 6. While the current set of test data is significantly larger than the one available e.g., during the development of EGM96 (Lemoine et al., 1998), no test data were available to us over Africa, Asia, or S. America. The USA contribution to our data set constitutes ~56 % of the total available stations.

Table 6 - Available GPS/leveling data.

Set	Location	Stations	Source
1	Australia	909	J. Steed (AUSLIG)
2	Baltic States and Scandinavia	346	R. Forsberg
	Sweden		B.-G. Reit (National Land Survey)
	Latvia		J. Kaminskis (State Land Survey)
	Lithuania		E. Parseliunas (Vilnius Tech. Univ.)
	Denmark		B. Madsen
3	Canada	1131	A. Mainville (GSD, NRC)
4	Czech Republic	175	J. Simek (Geod. Obs. Pecny)
5	N-S European Traverse	60	Torge et al. (1989)
6	France	973	H. Duquenne
7	Lower Saxony, Germany	70	Grote (1996)
8	Hungary	299	A. Kenyeres (FOMI)
9	USA	5168	D. Milbert (NGS)
	Total:	9311	

Geoid undulations were determined from the available GPS/leveling data over Australia, Canada and USA, and height anomalies over the rest of the areas. In these three areas, we followed the procedure of Rapp (1997) for the conversion of model-derived height anomalies to geoid undulations, comparable with the GPS/leveling data. Table 7 gives the mean and standard deviation difference (σ) over each area. An overall measure of each model's performance over the ensemble of all available stations is given in Table 8. EGM96 outperforms all other models, followed by TEG-3; GPM98A and GRIM4-C4 perform poorly in this test. Considering that the available data are located over some of the best surveyed areas (gravimetrically), the performance of EGM96 is consistent with its predicted total (commission plus omission) geoid error, whose global rms value is ±45.3 cm (Lemoine et al., 1998, p. 10-37). However, certain regional differences between

Table 7 - GPS/leveling minus model geoid undulation statistics. All models complete to *Nmax* = 360. Units are cm.

	JGM-3†		TEG-3†		GRIM4-C4†		EGM96		GPM98A	
Set	Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ
1	2.1	52.1	4.4	48.3	14.3	57.2	-1.2	46.4	-4.9	71.7
2	-48.3	34.8	-58.6	30.0	-64.1	46.3	-57.1	26.0	-71.8	40.0
3	-107.5	64.6	-111.5	63.3	-114.3	57.9	-102.9	37.3	-106.8	105.1
4	-80.5	39.9	-75.1	47.1	-122.0	44.1	-65.0	21.9	-38.2	23.2
5	20.5	38.5	15.9	27.3	15.2	54.4	8.4	31.9	20.3	56.6
6	-125.4	34.5	-121.7	39.2	-81.6	95.3	-116.9	35.4	-121.6	36.6
7	-77.0	15.0	-53.3	15.3	-77.4	16.1	-60.6	13.5	-93.1	17.3
8	-15.6	39.5	-13.7	42.8	-54.3	34.4	-73.6	13.7	-30.9	15.3
9	-93.7	40.1	-94.3	37.2	-94.4	48.1	-97.5	39.0	-89.3	53.7

† EGM96 used for $n > 70$

EGM96-derived and GPS/leveling-derived geoid undulations do exist (Lemoine et al., 1998, Fig. 10.1.2-1). Over the USA some of these differences are correlated with mountainous terrain, while others have long wavelength signatures which may indicate shortcomings of the weighting (and/or the content) of the satellite-only information used in the combination solution (see also Smith and Milbert, 1997). Further studies are needed to address these issues.

2.3. Ocean circulation model dot comparison

For these tests we used the POCM_4B model of Semtner and Chervin (see also, Stammer et al., 1996), and the general procedure used by Rapp et al. (1996). A "mean" Sea Surface Height (SSH) track of TOPEX over years 1993 and 1994, and the geoid undulations from a model, yield an estimate of the DOT, through a least-squares fit, in spherical harmonics. A corresponding estimate is obtained from POCM_4B. Both are then converted from spherical harmonic coefficients, to coefficients of an orthonormal (ON) expansion (Hwang, 1991), that is ocean domain specific. These coefficients allow for a spectral comparison of the two *independent* DOT estimates, strictly valid over the ocean domain. Fig. 1 shows the cumulative rms difference of the two types of DOT information as a function of degree, and lists the rms difference up to $N = 24$. GRIM4-C4 agrees the least with the POCM_4B information, while EGM96 agrees the most (GPM98A is not included here because it is identical to EGM96 up to degree 20).

2.4. Comparison with WOCE hydrographic data

We acquired estimates of the (relative) dynamic height, computed from hydrographic measurements collected over 39 sections of the World Ocean Circulation Experiment (WOCE). The geographic distribution of these sections is illustrated in Fig. 2. We form the difference Δ between the hydrographic estimate of the DOT ($\zeta_{Hydro.}$), and a model-implied value (ζ_{Model}). The latter is computed from the same TOPEX/gravity model spherical harmonic expansions used in the POCM_4B comparisons, taken up to degree 20 here. We computed the std. deviation (σ) of Δ, and the correlation between $\zeta_{Hydro.}$ and ζ_{Model}, for each section. Table 9 presents the overall results,

Table 8 - Overall statistics of GPS/leveling minus model geoid undulation. Total number of undulation differences that passed the ± 4 m edit criterion. Weighted (by number of points per area) mean standard deviation (σ) of undulation differences.

Model	**Num. of undulation differences**	**Mean σ (cm)**
JGM-3†	9305	43.7
TEG-3†	9307	42.1
GRIM4-C4†	9299	54.5
EGM96	9307	37.2
GPM98A	9307	58.4

† EGM96 used for $n > 70$

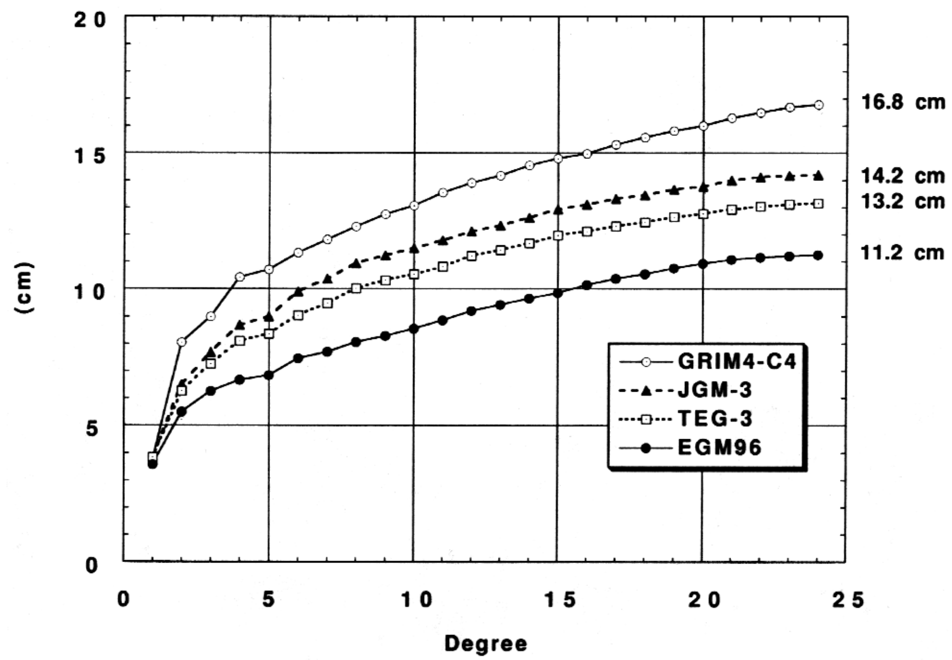

Fig. 1 - Cumulative RMS difference between the POCM_4B DOT and TOPEX/gravity model-implied DOT.

reflecting the performance of each model over the ensemble of hydrographic sections. These results are the weighted (by number of points per section) average σ, and the similarly weighted average correlation. It is reassuring that the classification of the models' performance in terms of average standard deviation, is the same here as in the POCM_4B comparisons. Since POCM_4B, the WOCE hydrography, and the model-implied DOT are mutually *independent*, a consistent reliable picture emerges from these comparisons: EGM96 provides the best overall oceanic geoid modeling capability, followed by TEG-3, JGM-3, and GRIM4-C4 whose performance is the worst.

3. Summary

Five global models of the Earth's gravitational potential were tested against (mostly) independent information. The models were: JGM-3, TEG-3, GRIM4-C4, EGM96, and GPM98A. The tests consisted of orbit fits, comparisons with GPS/leveling geoid undulations, DOT from

Table 9 - Comparison between DOT estimates from WOCE hydrographic data and model implied values (see text).

Model	σ (cm)	ρ (%)
JGM-3	12.2	78.5
TEG-3	11.9	77.9
GRIM4-C4	13.2	72.4
EGM96	11.0	81.4

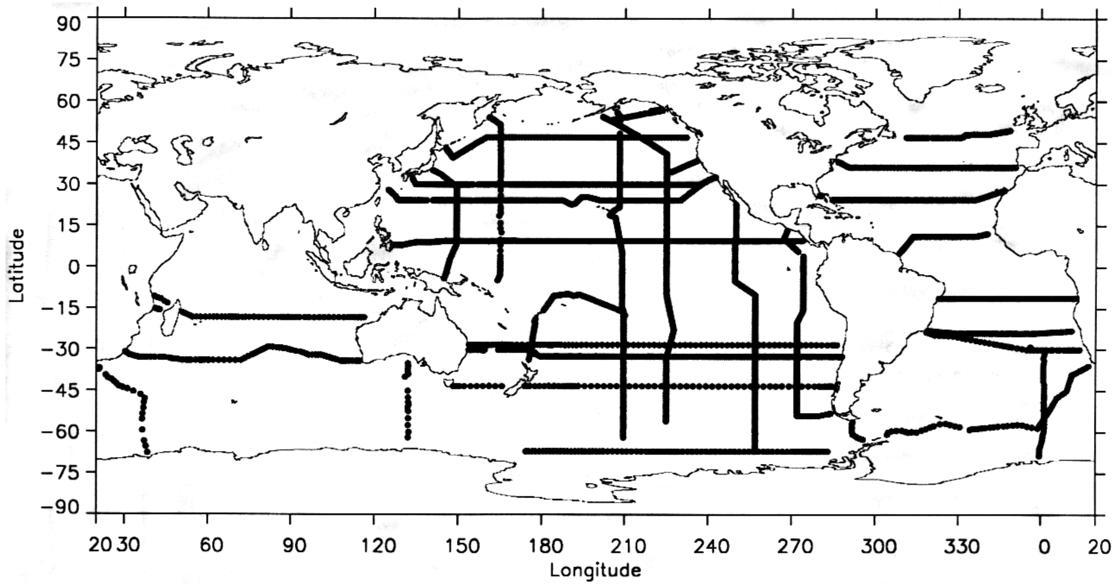

Fig. 2 - Location of WOCE hydrographic sections used in the tests.

POCM_4B, and DOT from WOCE hydrographic data. These comparisons indicated that EGM96 performs consistently better than the other models, particularly for geoid computations (over both ocean and land areas). The increased weight used for the surface gravity and altimeter data in EGM96, did not significantly degrade this model's performance in orbit computations (see also, Ries, 1997). It is possible, however, that models which incorporate altimeter cross-over data from spacecraft such as ERS-1, outperform EGM96 in the corresponding orbit modeling capability. Work is in progress to address these concerns. Finally, the degree 21 to 360 part of GPM98A was found to perform worse than EGM96 in GPS/leveling tests, in all the regions tested. GPM98A is not suitable for orbit computations, especially for satellites at medium and low altitudes. The newer solution GPM98C (Wenzel, this issue), extended the use of the EGM96 coefficients up to degree 180 (instead of 20), aiming to address our present findings.

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