Evaluation of EGM2008 by comparison with other recent global gravity field models

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Abstract

The new gravity field model EGM2008 has been evaluated by comparisons with other, satellite-only as well as combined global gravity field models. Our evaluation comprises orbit adjustment tests, comparisons of the spectral behaviour, GPS/leveling tests and ocean geoid comparisons.
For the GPS/leveling tests and the ocean geoid comparisons the new EGM2008 model outperforms all other tested models. Orbit adjustment tests for CHAMP, GRACE and other satellites show a very good inner consistency for EGM2008 and its corresponding satellite-only model ITG-GRACE03S. In these tests EGM2008 shows no major performance differences to the other tested models.

Keywords

Earth gravity field model, Global gravity field recovery, GRACE, CHAMP, LAGEOS, EGM2008, ITG-GRACE03S, EIGEN-5, GPS/leveling, Ocean geoid

Introduction

The recently released new global gravity field model EGM2008 (Pavlis et al. 2008) with a resolution of maximum degree and order of 2159 (including additional coefficients extending to degree 2190 and order 2159) represents a milestone in the development of global gravity field models. It is of general interest to evaluate this new high resolution model by comparison with other recent global gravity field models. In this paper we present results of the comparison of the new EGM2008 with other satellite-only as well as combined models. Our evaluation of EGM2008 comprised orbit computations, comparisons of the spectral behaviour, GPS/levelling tests and comparisons of the ocean geoid.

The global gravity field models included in our evaluation of EGM2008 were the following satellite-only and combined models:

- **EGM96** (Lemoine et al. 1998)
  This is a combined gravity field model of maximum degree/order 360. This pre-CHAMP model has been composed from various SLR and other satellite data and terrestrial gravity data from gravimetry and altimetry. Since the launch of CHAMP and GRACE, EGM96 is no longer state of the art. But since this model represented a standard during the last decade, we included it in some of our evaluation tests.

- **GGM02C** (Tapley et al. 2005),
  This model is a combination of the coefficients of the GRACE-only model GGM02S (Tapley et al. 2005) with EGM96 and has a maximum degree/order of 200. It was computed by the Center for Space Research (CSR) at the University of Texas at Austin.

- **GGM03S** (Tapley et al. 2007)
  This recently released GRACE satellite-only model has a maximum degree/order 180. It can be considered as an upgrade of GGM02S including the latest GRACE CSR processing standards release 4 (Bettadpur 2007)

- **ITG-GRACE03** (Mayer-Gürr et al. 2007)
  This is a GRACE satellite-only model of a maximum degree/order of 180, published by the Institute for Theoretical Geodesy (ITG) of the University of Bonn. The coefficients of this model including their variance/covariance matrix have been used as satellite-part in the combination of terrestrial and satellite data for EGM2008.

- **JEM01-RL03B** (by courtesy of Mike Watkins and Dah-Ning Yuan, 2008)
  This GRACE satellite-only model is of a maximum degree/order of 120. The originator of this model is NASA/JPL in Pasadena. JEM01-RL03B has been computed in accordance to the JPL Level-2 Processing Standards (Watkins and Yuan 2007). The coefficients of this model including their variance/covariance matrix have been used as satellite-part of PGM2007A, a preliminary version of EGM2008.

- **EIGEN-GL04C** (Förste et al. 2008a)
  This combined gravity field model has been released in 2006. It is an outcome of the joint gravity field processing between GRGS Toulouse and GFZ Potsdam. The satellite-part of EIGEN-GL04C is based on GRACE and LAGEOS data and the maximum degree/order of this model is 360.

- **EIGEN-5C** and **-5S** (Förste et al. 2008b)
  The combined gravity field model EIGEN-5C is an upgrade of EIGEN-GL04C and has a maximum degree/order of 360. The model is again a combination of GRACE and LAGEOS mission data of a maximum degree/order 150 (= **EIGEN-5S**) plus 0.5 x 0.5 degrees gravimetry and altimetry surface data. The combination of the satellite and surface data has been done by the combination of normal equations, which are obtained from observation

equations for the spherical harmonic coefficients. The included satellite data have been processed by GFZ Potsdam (GRACE for February 2003 - January 2007) and GRGS Toulouse (GRACE for August 2002 - January 2007 and LAGEOS for January 2002 – December 2006). The satellite data processing has been done in accordance to the GRACE GFZ Level-2 Processing Standards for Release 4 (Flechtner 2007). This comprises for instance arc lengths of 1 day for GRACE and 10 days for LAGEOS including the usage of EIGEN-GL04C as a-priori gravity field.

The used surface data are identical to those included in EIGEN-GL04C except of new gravity anomaly data sets for Europe (H. Denker, IfE Hannover, 2007, personal communication), the Arctic Gravity Project gravity anomaly data (Forsberg and Kenyon 2004) as updated in 2006 and newer Australian gravity anomalies (W. Featherstone, Curtin University of Technology, personal communication, 2008)

Spectral behaviour

Figure 1 shows a comparison of the spectral behaviour of EGM2008 versus some other recent global gravity field models. This plot displays the degree variance differences of the long-to-medium wavelengths range up to degree and order 240 for EGM2008 in comparison to EIGEN-5C, EIGEN-5S, GGM03S and ITG-GRACE03S.

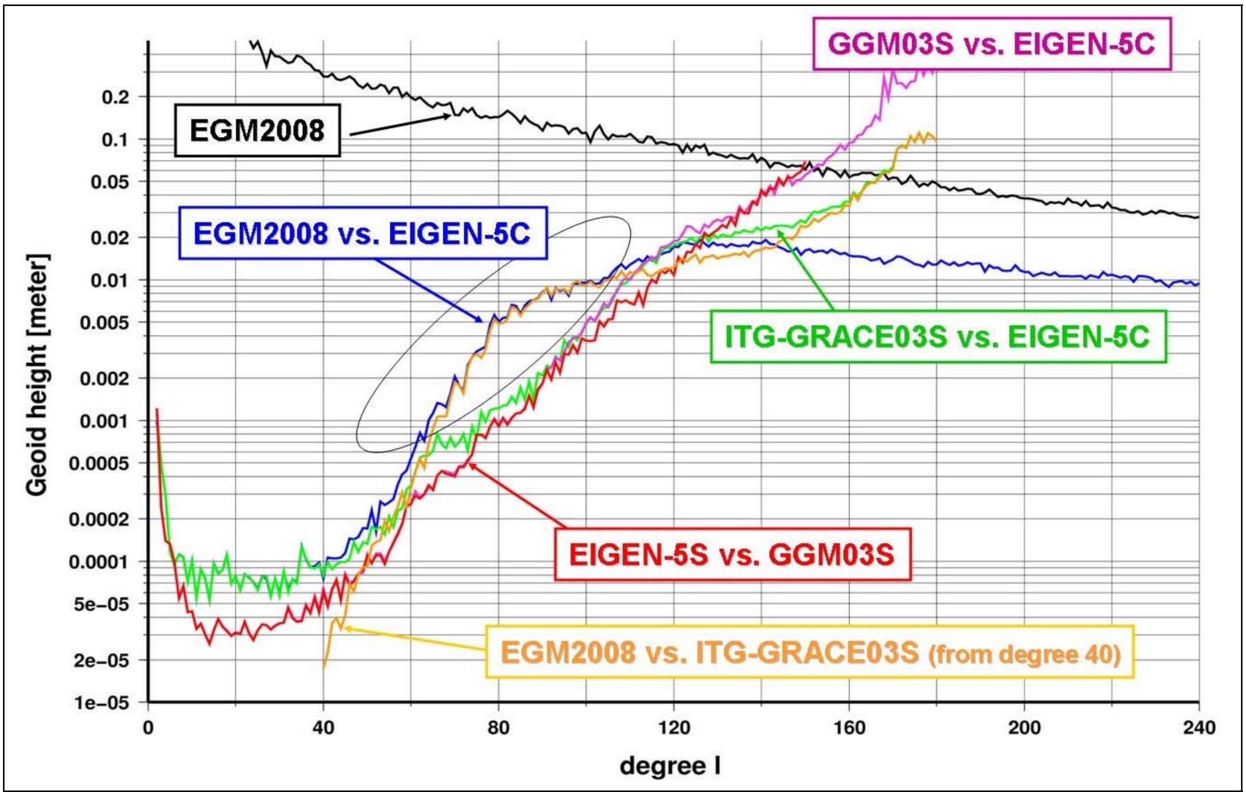

Figure 1: Degree variances in terms of geoid heights for EGM2008 in comparison to other global gravity field models

When looking into the degree variance behaviour of EGM2008 (figure 1, blue and yellow lines), we see noticeable differences to the other displayed gravity field models (green, red and purple lines): Whereas the EIGEN-models, GGM03S and ITG-GRACE03S have a very similar spectral behaviour up to degree/order 120, the EGM2008 degree variances show a remarkable different behaviour between degree 70 and 100 (this is marked by the blue circle in figure 1). This "bump" should be caused by the combination of the terrestrial data with GRACE data, since ITG-GRACE03S doesn't show this behaviour (see the yellow line). It is remarkable that even the ITG-GRACE03S model, on which the EGM2008 is based, shows a behaviour which is very similar to the other models. Compared with the combined model EIGEN-5C, we suspect that the "bump" in the degree variance spectrum of

EGM2008 between degrees 70 and 100 is caused by a stronger weighing of the terrestrial data (which exhibits more signal power in this frequency band) versus the satellite data.

Orbit adjustment tests

One measure of the long-to-medium wavelength accuracy of a gravity field model is the fit of observations to the adjusted satellite orbit. In this study we calculated satellite laser ranging (SLR) residuals for various satellites in two different manners:

- For CHAMP and GRACE after an orbit determination by using GPS-SST and accelerometer data (CHAMP and GRACE) and K-Band Range-Rate data (GRACE), where the SLR measurements were not included into the orbit adjustment.
- For a number of other satellites after on orbit determination by using SLR data (including PRARE and DORIS observations for ERS-2 and ENVISAT, respectively).

The used satellites, the number of the included SLR observations and the measurement time periods are given in table 1. Table 2 gives the parameterization of the adjusted orbits except of CHAMP and GRACE. For CHAMP and GRACE the orbit fits were performed with the adjustment of the following empirical parameters in addition to the orbital elements, GPS ambiguities and clocks:

- One scaling factor and one bias parameter per arc for each of the three acceleration components,
- Additionally for CHAMP: one thruster parameter per arc and thruster pair, one scaling factor per component and arc for the Lorentz force on the accelerometer proof mass,
- Additionally for GRACE K-band: Range bias 1/rev per arc, range acceleration and range-rate bias per revolution

Satellite	**Number of included SLR observations / Data period / Tested arcs: Number and lengths**
GFZ-1	2029 / October 1995 / 5 x 3 days
STELLA	1528 / October 1997 / 5 x 3 days
STARLETTE	1815 / October 1997 / 5 x 3 days
AJISAI	6760 / October 1997 / 5 x 3 days
LAGEOS-1	3140 / October 1997 / 3 x 6 days
LAGEOS-2	2591 / October 1997 / 3 x 6 days
ERS-2*	7944 / September – October 1997 / 6 x 6 days
ENVISAT**	10176 / July 2002 / 7 x 4...8 days
WESTPAC	1587 / July – August 1998 / 5 x 6 days
JASON	20003 / Nov ... Dec 2004 / 6 x 10 days
CHAMP	358 / October 2001 / 4 x 1.5 days
GRACE	592 / September 2002 / 4 x 1.5 days

Additionally included other observations for ERS-2 resp. ENVISAT:
* 24837 PRARE-Range and 24435 PRARE-Doppler observations
** 130404 DORIS observations

Table 1: SLR data and test arcs of the orbit computation tests

The orbit fit results for CHAMP and GRACE are given in table 3. We carried out our orbit computations for these two satellites with different maximum degrees of the spherical harmonic coefficients to investigate possible degree-related differences between the tested gravity field models. First of all, the obtained best orbit fit residuals of all tested models are of the same order of magnitude of about 5 cm. This finding indicates that EGM2008 has no major performance differences with the other tested models for the investigated degree range up to 150. But when looking in detail we see noticeable differences between the tested models:

- The residuals for EGM2008 and ITG-GRACE03S decrease continuously for CHAMP as well as for GRACE when increasing the maximum used degree from 70 up to 150. This finding indicates a good inner consistency of both gravity field models with respect to CHAMP and GRACE and is in contrast to all the other tested models, which show a different behaviour for GRACE. Here with the other models the best orbit adjustment results were already reached around degree 90, but the residuals rise again by a few millimetres higher maximum degrees are used.
- The best orbit fit results are obtained with GGM02C in the case of CHAMP and with the EIGEN models and GGM03S in the case of GRACE.

Satellite	**Cd* and Cr****	**Empirical accelerations**
GFZ-1	Cd: 1/6h	1/rev per arc for along- and cross-track
STELLA	Cd: 1/day	1/rev per arc for along- and cross-track
STARLETTE	Cd: 1/day	1/rev per arc for along- and cross-track
AJISAI	Cd: 1/day	1/rev per arc for along- and cross-track
LAGEOS-1	—	1/rev per arc for along- and cross-track + 1/day for along-track
LAGEOS-2	—	1/rev per arc for along- and cross-track + 1/day for along-track
ERS-2	Cd: 1/day	1/rev per arc for along- and cross-track
ENVISAT	Cd: 1/6h Cr: 1/arc	1/rev per arc for along- and cross-track
WESTPAC	Cd: 1/day	1/rev per arc for along- and cross-track
JASON	Cd: 1/6h Cr: 1/arc	1/rev per arc for along- and cross-track

*Cd = Scaling factor for the atmospheric drag
**Cr = Scaling factor for the solar radiation pressure

Table 2: Parameterization (in addition to the solved-for orbital elements) of the adjusted orbits, except of CHAMP and GRACE

It should be of interest to compare the results between combined models and their corresponding satellite-only models:

- In the case of CHAMP, EGM2008 gives noticeable larger residuals for all tested maximum degrees than ITG-GRACE03S. The differences between the residuals of both models are larger than one millimetre. For GRACE, EGM2008 shows a better performance than ITG-GRACE03S between degree 70 and 110, but ITG-GRACE03S gives again smaller residuals for degrees 120 and 150. From our point of view, these results for CHAMP and those of the degrees 120 and 150 for GRACE indicate a slight degradation of EGM2008 versus ITG-GRACE03S for the tested degree range which could be due to a not-optimum combination of the terrestrial data with the satellite components.
- In contrast to EGM2008/ITG-GRACE03S, the differences between the corresponding orbit fit residuals for the pair EIGEN-5S/C are significantly smaller (only a few tenths of millimetres except of degree 70 for CHAMP)

The orbit adjustment results for the other tested satellites are given in table 4. Again we used different maximum degrees for the gravitational spherical harmonic coefficients to investigate possible degree-related differences between the tested gravity field models. For most of the satellites we tested maximum degrees of 70 and 120 while for GFZ-1 the orbit adjustment tests has been carried out for a wider range comprising maximum degrees between 50 and up to 150.

Satellite	max. degree used	GGM02C	GGM03S	JEM1-RL03B	EIGEN-GL04C	EIGEN-5S	EIGEN-5C	ITG-GRACE03S	EGM2008
CHAMP	**70**	**17.62**	**16.71**	**19.66**	**17.94**	**17.68**	**17.86**	**15.97**	**16.74**
	80	**9.39**	**9.51**	**9.48**	**9.50**	**9.66**	**9.69**	**8.69**	**9.34**
	90	**6.12**	**6.10**	**6.15**	**6.12**	**6.14**	**6.14**	**5.96**	**6.02**
	100	**5.89**	**5.96**	**5.95**	**5.97**	**6.01**	**6.03**	**5.58**	**5.97**
	110	**5.48**	**5.53**	**5.51**	**5.61**	**5.60**	**5.59**	**5.39**	**5.57**
	120	**5.32**	**5.45**	**5.35**	**5.44**	**5.55**	**5.51**	**5.38**	**5.51**
	150	**5.19**	**5.44**	**--**	**5.41**	**5.56**	**5.49**	**5.30**	**5.46**
GRACE	**70**	**14.11**	**15.00**	**14.03**	**14.93**	**14.92**	**14.93**	**16.06**	**15.49**
	80	**7.39**	**6.54**	**7.35**	**6.51**	**6.43**	**6.44**	**8.24**	**7.27**
	90	**5.76**	**5.05**	**5.75**	**5.03**	**4.92**	**4.93**	**6.30**	**5.57**
	100	**5.40**	**5.20**	**5.41**	**5.20**	**5.09**	**5.09**	**6.12**	**5.54**
	110	**5.61**	**5.31**	**5.64**	**5.31**	**5.20**	**5.19**	**5.84**	**5.45**
	120	**5.50**	**5.28**	**5.55**	**5.25**	**5.17**	**5.15**	**5.39**	**5.46**
	150	**5.54**	**5.27**	**--**	**5.24**	**5.19**	**5.14**	**5.38**	**5.43**

Table 3: SLR residuals (cm) after an orbit determination based on GPS-SST and accelerometer data (CHAMP, GRACE) and K-Band Range-Rate data (GRACE). The SLR data were not included in the orbit adjustment.

For all satellites except of GFZ-1 there is practically no change of the orbit adjustment residuals for EGM2008 as well as for the other tested models when the maximum used degree is decreased from 70 to 120. The differences between the results for degrees 70 and 120 are less than about half a millimetre for all gravity field models, which does not indicate any significant degree dependence. This is not a big surprise, since all these satellites orbit at higher altitudes than CHAMP, GRACE and GFZ-1, resulting in a lesser sensitivity to the gravity field (i.e., the effect of model differences is attenuated).

For GFZ-1 the orbit adjustment results are different. This satellite has a low altitude of about 400 km and is sensitive for spherical harmonic coefficients beyond degree 70 (König et al 1999). Therefore we started with a maximum degree of already 50 and increased it up to 150. First of all, the orbit adjustment residuals for GFZ-1 rise for all tested models including EGM2008 when increasing the maximum used degree up to 150. But this is not a surprise, since all tested models are based on GRACE data which means that these models are “tailored” for GRACE-like, near polar satellite orbits. It is therefore not unusual to find a worse inner consistency for other orbit types like GFZ-1 with its inclination of 51.6°. On the other hand, it’s remarkable that the orbit adjustment residuals are nearly identical up to degree 90 for all tested gravity field models. Up to degree 90 the differences between all models are on the scale of a few tenths of millimetres only, which is insignificantly small. But when increasing the maximum degree up to 120 and 150 the differences between the tested models rise up to about 1 cm and EGM2008 gives the worst results. Like our orbit test results for CHAMP and partially for GRACE (see table 3) ITG-GRACE03S performs again better than EGM2008. The best orbit fit results for GFZ-1 at the maximum used degree of 150 were obtained for EIGEN-models and GGM03S.

In the previous section we reported a remarkably different spectral behaviour in the degree range from 70 to 100 for EGM2008 compared to all other tested models, i.e. the “bump” for EGM2008 in figure 1. If such a “bump” has an impact on the quality of EGM2008, this should be visible in the degree dependence of the orbit tests, in particular in comparison with ITG-GRACE03S, whose spectrum looks very similar to the other tested models. But the results for CHAMP and GRACE indicate no rising degradation of EGM2008 with respect to ITG-GRACE03S when increasing the maximum used

Satellite	Max. degree used	GGM02C	GGM03S	JEM1-RL03B	EIGEN-GL04C	EIGEN-5S	EIGEN-5C	ITG-GRACE03S	EGM2008
GFZ-1	150	14.49	14.14	—	13.81	13.62	14.23	14.34	15.00
	120	14.34	13.86	14.05	13.78	13.78	14.10	14.14	14.70
	110	13.16	12.68	12.76	12.62	12.71	12.86	12.99	13.55
	100	14.75	14.10	14.18	13.93	14.14	14.43	14.55	14.93
	90	8.09	8.04	8.05	8.08	8.05	8.05	8.04	8.11
	80	10.81	10.72	10.73	10.76	10.72	10.72	10.70	10.65
	70	12.07	12.03	12.05	12.01	12.01	12.01	12.01	12.02
	60	20.28	20.28	20.24	20.23	20.22	20.22	20.21	20.22
	50	31.79	31.77	31.76	31.76	31.74	31.74	31.73	31.75
STELLA	120	3.22	2.91	3.10	2.93	2.92	2.92	2.96	2.92
	70	3.25	2.91	3.13	2.92	2.91	2.91	2.94	2.89
STARLETTE	120	2.44	2.81	2.49	2.54	2.53	2.53	2.55	2.54
	70	2.43	2.78	2.49	2.54	2.54	2.54	2.56	2.53
AJISAI	120	3.17	3.37	3.18	3.16	3.15	3.15	3.17	3.18
	70	3.17	3.37	3.18	3.16	3.15	3.15	3.17	3.18
LAGEOS-1	120	1.02	1.03	1.02	1.01	1.01	1.01	1.01	1.02
	70	1.02	1.03	1.02	1.01	1.01	1.01	1.01	1.02
LAGEOS-2	120	1.01	1.02	1.01	1.02	1.02	1.02	1.02	1.01
	70	1.01	1.02	1.01	1.02	1.02	1.02	1.02	1.01
ERS-2	120	5.83	5.34	5.59	5.31	5.29	5.29	5.30	5.31
	70	5.85	5.36	5.61	5.32	5.30	5.30	5.32	5.32
ENVISAT	120	4.37	4.27	4.35	4.47	4.48	4.49	4.28	4.27
	70	4.38	4.28	4.37	4.50	4.52	4.52	4.29	4.29
WESTPAC	120	4.33	4.09	4.21	4.12	4.12	4.12	4.12	4.10
	70	4.37	4.10	4.20	4.11	4.11	4.11	4.12	4.09
JASON-1	120	1.84	1.83	1.84	1.83	1.82	1.82	1.81	1.89
	70	1.84	1.83	1.84	1.83	1.82	1.82	1.81	1.84

Table 4: SLR residuals (cm) after orbit determination for various satellites for different maximum used degrees of the spherical harmonic coefficients**.**

degree from 70 up to 100. In the case of GFZ-1 all tested models differ significantly only beyond degree 100 which is almost outside the questionable degree range. All this confirms that the degree dependencies of the orbit adjustment residuals for EGM2008 show no detectable correlation with the "bump" in the degree variance spectrum for all tested satellites.

GPS/leveling comparison

An independent comparison with external data can be made using geoid heights determined point-wise by GPS positioning and leveling ("GPS/leveling"). Table 5 shows the results for several gravity field models in comparison with EGM2008 using GPS/leveling points of the USA (Milbert, 1998), Canada (M. Véronneau, Natural Resources Canada, personal communication 2003), Germany (Ihde et al.

2002), Europe (Ihde, personal communication, 2008) and Australia (G. Johnston, Geoscience Australia and W. Featherstone, Curtin University of Technology, personal communication 2007). For this comparison, height anomalies were calculated from the spherical harmonic coefficient data sets and reduced to geoid heights (c.f. Rapp 1997). The topographic correction was done by using the DTM2006.0 model, which is available in spherical harmonic coefficients (Pavlis et al. 2007). For the comparison with the other gravity field models, the EGM2008 coefficients were used only till degree/order 360 (blue column). It is obvious that EGM2008 fits best in comparison with all other tested models. Only for Australia the EIGEN-5C model reaches the same level of the fit. To show the excellent performance of EGM2008 when the full resolution is applied, we additionally computed the GPS/leveling residuals for the maximum degree 2190 of this model (last column).

Dataset	EGM96	GGM02C/ EGM96*	EIGEN-CG01C	EIGEN-GL04C	EIGEN-5C	EGM2008 Max. degree 360	EGM2008 Max. degree 2190
Europe (1234)	48	32	37	34	30	27	21
Germany (675)	29	17	22	18	15	14	4
Canada (1930)	36	26	27	25	25	23	13
USA (6169)	38	33	35	34	34	32	25
Australia (201)	30	25	26	24	24	24	22

Table 5: Root mean square (cm) about mean of GPS-Levelling minus model-derived geoid heights (number of points in brackets)
*GGM02C has been filled up to degree/order 360 with EGM96 coefficients

As a further example of the GPS/leveling results we show in figure 3 the plots of the fit of the individual GPS/leveling points for the European data set (Ihde, personal communication, 2008) to the EGM2008 geoid (computed till degree and order 360) in comparison to EIGEN-5C. At first view, the colour patterns of the two plots look similar. But a closer inspection reveals, that noticeable differences can be seen, for instance over Denmark, the Alps, South France or Sardinia. We assume that these differences are mainly caused by the different ground data sets used in EGM2008 and EIGEN-5C. These differences will be a subject for further investigations.

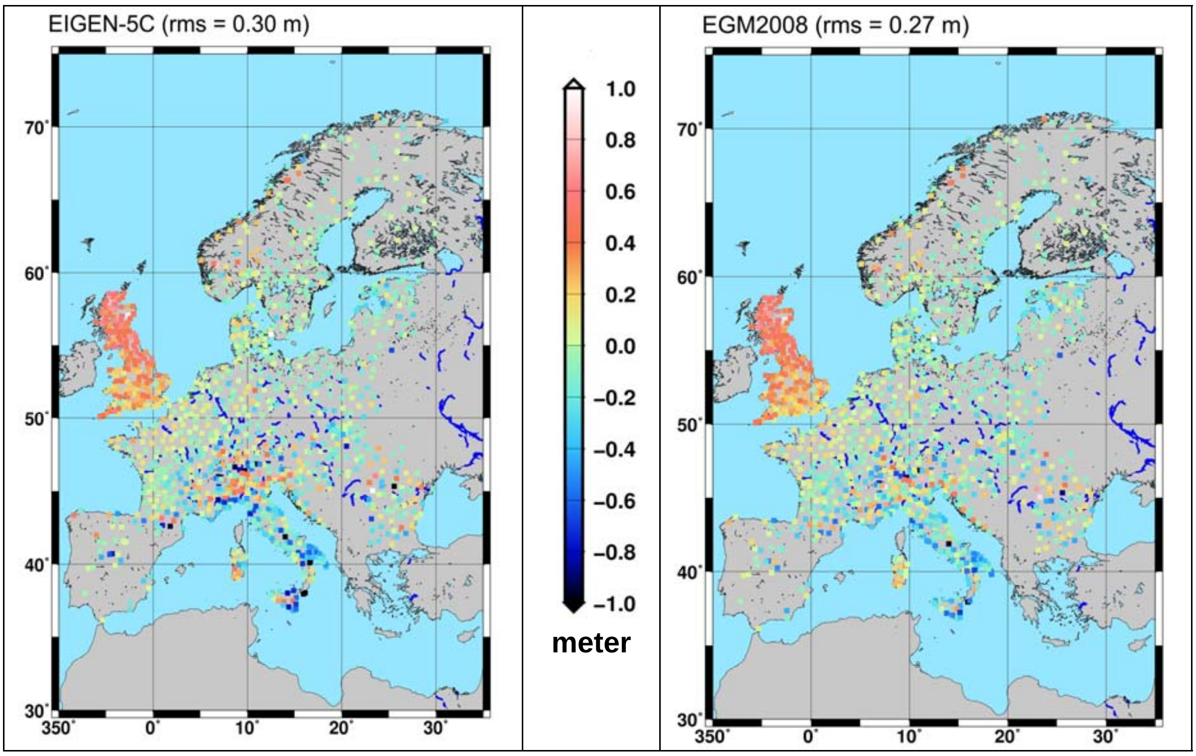

Figure 3: Geoid height differences (m) in Europe between GPS/levelling data and EIGEN-5C (left) resp. EGM2008 (right) up to degree/order 360

Geoid residuals over the oceans

We also computed geoid residuals over the oceans. These residuals are the differences between the geoid of the tested gravity field model and geoid undulations over the oceans derived from GFZ mean sea surface heights (MSSH, T. Schöne and S. Esselborn, 2005, GFZ, personal communication) minus ECCO sea surface topography (Stammer et al. 2002). This ocean geoid undulation data set is the same as used in the computation of EIGEN-GL04C and EIGEN-5C.

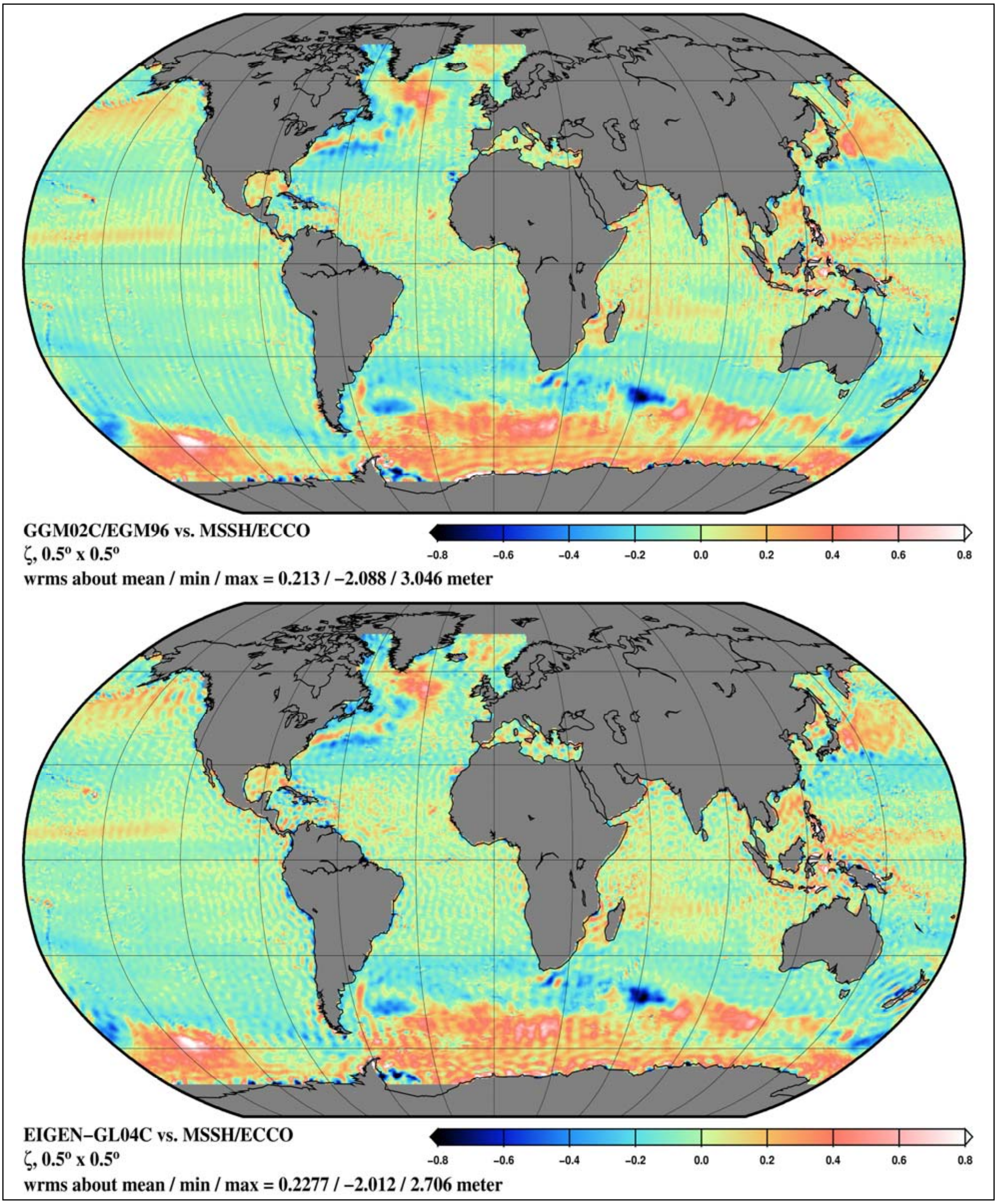

Figure 4: Ocean geoid residuals for GGM02C/EGM96 (top) in comparison to EIGEN-GL04C (bottom)

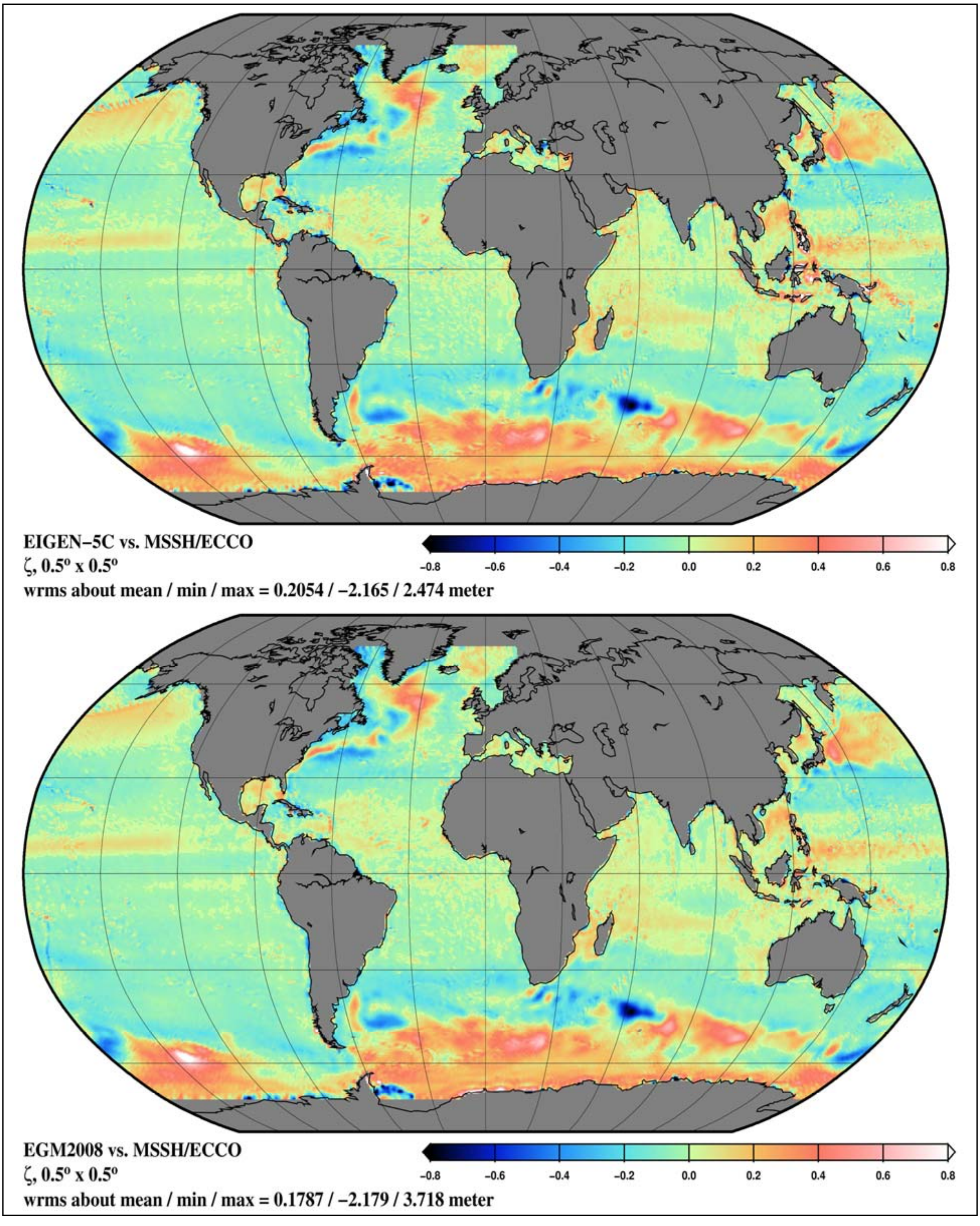

Figure 5: Ocean geoid residuals for EGM2008 (bottom) in comparison to EIGEN-5C (top)

Although the MSSH model is not error-free, our experience is that the calculation of such kind of residuals is an appropriate method to probe a gravity field model for artefacts like stripes and rings over the oceans. Figure 4 and 5 shows gridded maps of corresponding residuals with a resolution of 0.5° x 0.5° for GGM02C, EIGEN-GL04C, EIGEN-5C and EGM2008. Whereas GGM02C and EIGEN-GL04C show the well known unrealistic stripe and ring patterns (see figure 4), EIGEN-5C gives a significant improved picture with only some remaining weak striping patterns, for instance south of Alaska and east of the Philippines (see figure 5). Lastly EGM2008 is obviously free of stripes and other artefacts such as ringing. This improvement of EGM2008 compared to EIGEN-5C corresponds to a smaller corresponding wrms value of the geoid residuals (see the numbers just below the individual plots in figure 5: **0.1787** m vs. **0.2054** m).

Summary

In our investigation EGM2008 shows the best performance concerning the ocean geoid and comparisons with external GPS/levelling geoid information compared to other tested combined gravity field models. We also carried out orbit adjustment computations for EGM2008 in comparison to other combined and satellite-only gravity field models. In these tests EGM2008 shows no major performance differences to the other tested models. Furthermore, EGM2008 and its corresponding satellite-only model ITG-GRACE03S show a better inner consistency with respect to CHAMP and GRACE than the other gravity field models. We also did not find a correlation with the remarkable "bump" in the degree variance spectrum between degree 70 and 100.

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