An assessment of satellite-only Earth gravitational models based on comparisons with gravity anomalies and combined gravitational models

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Abstract: Ground gravity anomalies and combined Earth Gravitational Models (EGMs) were used for an assessment of after-CHAMP satellite-only derived models. Several features of the models are compared and discussed in this investigation. For instance, the spectral signal and error characteristics, their gravity contribution at different harmonic degrees in comparison with observed gravity anomalies, the differences between them at different areas of the Earth up to different harmonic degrees depending on their spectral error characteristics and their contribution in detecting systematic errors in gravity due to different reasons. The analysis showed that at least to degree 120 the agreement between the EGMs is noteworthy. This agreement is extended to the statistics of the reduced gravity anomalies, in spite of the differences in their spectral error characteristics. At higher degrees the differences are larger, with the combined models to show better results.

Keywords: Earth gravitational model, Spectral characteristics, Long- and medium-wavelength discrepancies

1. Introduction

The precision of pre-CHAMP satellite-only EGMs was limited due to several reasons such as (Featherstone, 2005): limited resolution of the Earth's gravitational field with altitude, inability to track complete satellite orbits from ground-based stations, imprecise modeling of atmospheric drag, non-gravitational and third-body gravitational perturbations and incomplete sampling due to a limited number of orbital inclinations.

On the other hand, combined EGMs are also limited in precision due to the above-mentioned reasons and problems related with the terrestrial data used. These problems could be due to several causes, such as (Arabelos and Tscherning, 2010): height system errors, including ellipsoidal heights which have been used as orthometric heights, reference system errors, drift of the gravimeters, noise from topography/density – typically free-air anomalies have been confused with Bouguer anomalies or the other way around, effects of sea-surface topography included in the gravity anomalies derived from altimetry, correlated errors in combined EGMs originating from one or more of the aforementioned causes.

It is expected that recent EGMs, based on dedicated satellite gravimetry will overcome the limitations mentioned above related to older satellite-only EGMs (see e.g. Tscherning et al., 2001; Rummel et al., 2002; Featherstone, 2002).

The limitations on combined EGMs could not be removed unless correction of errors of the terrestrial gravity data. However, it is expected dedicated satellite field missions to contribute in solving this problem, at least at the lower to medium frequencies of the gravity spectrum.

In a recent paper (Tscherning and Arabelos, 2011), the ability of the GOCE gradient data, covering a period of two years, to recover the free-air gravity field in places of the Earth with known gravity data was investigated. The predicted free-air gravity anomalies using Least Squares Collocation (LSC) and *Tzz* or/and *Txx* gradients are compared to the ground free-air gravity data. Simultaneously, the ground gravity data were reduced to GOCE EGMs SWP (Migliaccio et al., 2010), TIM (Pail et al., 2010; Schuh et al., 2010) and DIR (Bruinsma et al., 2010; Metzler and Pail, 2005) release 1 as well as to TIM and DIR release 2. The comparison in terms of the standard deviation of the differences (predicted – ground truth) and reduced gravity anomalies showed that in most cases better results were yielded by the EGMs.

In this paper, ground free-air gravity anomalies and combined EGMs such as EGM2008 (Pavlis et al., 2008), GRACE, LAGEOS and gravity anomaly data based EIGEN-GL05C (Förste et al., 2008), are used in an attempt to assess satellite-only models. Apart from SPW, TIM and DIR, the CHAMP-only derived EIGEN-CHAMP03s (Reigber et al., 2004), the GRACE-only derived ITG-Grace2010 (Kurtenbach et al., 2009; Mayer-Gürr et al., 2010), the GRACE and GOCE derived GOCO01S (Pail et al., 2010) and GOCO02S (Goiginger et al., 2011) are involved in the investigation.

In the framework of this study, another issue was to find possible long- and medium-wavelength discrepancies between the satellite-only EGMs and the ground gravity data in an attempt to assess the ability of these models in identifying the problems of the ground gravity data mentioned above.

The computations of section 2 include the comparison of the spectral characteristics of the EGMs under investigation, the statistics of ground gravity anomalies at different extended areas of the Earth before and after their reduction to the models, and the inter-comparison of the models contribution at the positions of the ground gravity anomalies. Finally, the long- and medium-wavelength discrepancies between the gravity field at different areas of the Earth and the GOCE derived TIM2 are investigated.

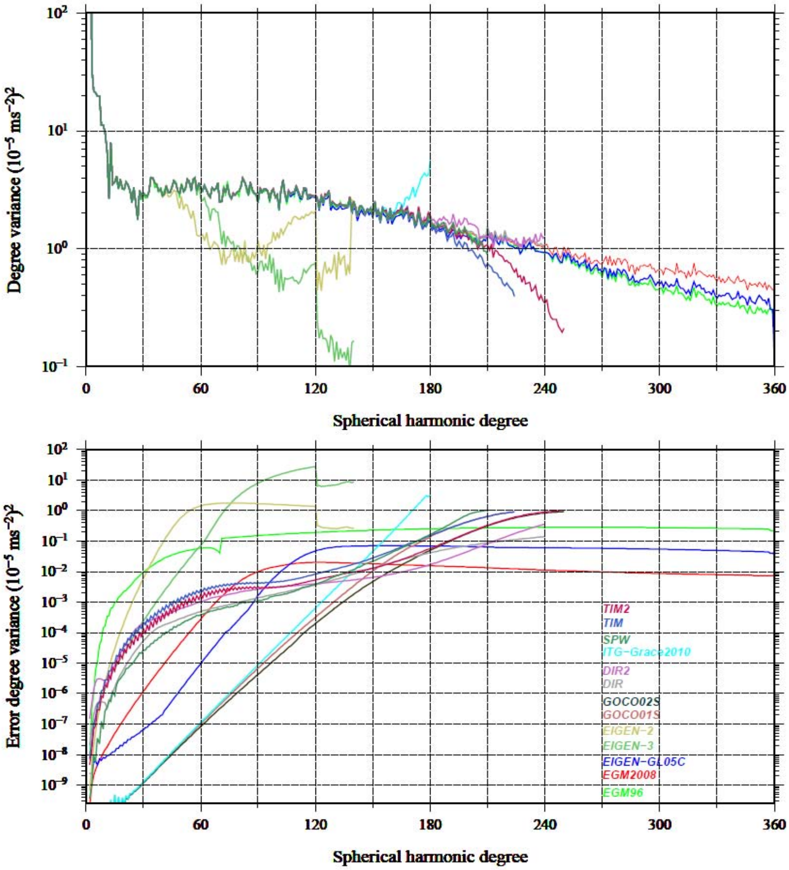

Figure 1. Degree variances (upper) and error degree variances (lower) of various combined and satellite-only derived Earth gravitational models.

2. Computations

2.1 Spectral characteristics of the EGMs

In Figure 1 the spectra of the signal (upper part) and the error (lower part) for the above-mentioned models along with the older combined EGM96 (Lemoine et al., 1998) and CHAMP-only derived EIGEN-2 (Reigber et al., 2003), are shown. With the exception of EIGEN-2 and EIGEN-3, the degree variances of all models agree well up to about harmonic degree 160. EIGEN-2 and EIGEN-3 contain full power up to about degree 40 and 60, respectively. Their error-degree variances exceed that of EGM96 at degree 32 and 58, respectively.

Taking into account the spectra characteristics of the EGMs showed in Figure 1, we can classify the models (excluding EGM96, EIGEN-2 and EIGEN-3) in three groups: (a) the combined models EIGEN-GL05C and EGM2008, (b) the Grace-only and Grace and GOCE generated models ITG-Grace2010, GOCON01S and GOCON02S and (c) the GOCE-only generated models SPW, TIM, TIM2, DIR and DIR2. The error degree variances of group (b) exceed the error degree variances of group (a) only after degrees ranging from 150-185. On the other hand, the error degree variances of group (c) present the following behavior with respect to that of group (a). From degree 2 to degrees ranging from 62-80 for EGM2008 and from 88-95 for EIGEN-GL05C are larger, then become smaller up to degrees ranging from 140-145 for EGM2008 and from 160-170 for EIGEN-GL05C and again become larger from these degrees up to their maximum degree of expansion. This behavior supports the hypothesis that the GOCE data can contribute in improving the medium harmonics of the EGMs (between the degrees 90 and about 180). However, the numerical experiments carried out with ground gravity data showed very similar results in terms of the statistics of the reduced gravity anomalies by the models under investigation up to harmonic degree 120. This finding is related with the hypotheses used in estimating the accuracy of the harmonic coefficients.

2.2 EGMs and terrestrial gravity data

The contribution up to harmonic degree 120 of the most representative EGMs to the gravity field in different areas of the Earth is shown in Table 1. The harmonic degree 120 was selected in an attempt to examine the hypothesis that different satellite dedicated missions could improve our knowledge at medium frequencies of the gravity spectrum. In spite of the different error spectra characteristics, the very good agreement of the statistics of the reduced gravity anomalies at each area, by the 9 models (GOCO01S was not included in this experiment) is noteworthy. The differences in terms of the mean value and standard deviation of the reduced free-air gravity anomalies do not exceed several tenths of mGal (1 mGal = 10^{-5} m s^{-2}). The combined models EIGEN-GL05C and EGM2008 show slightly better results than the satellite-only derived models in most test areas (with the exception of SPW in Oklahoma and DIR2 in Taiwan).

The contribution of the satellite-only derived models up to their maximum harmonic degree of expansion is shown in Table 2. In this experiment, the combined EIGEN-GL05C and EGM2008 were used up to degree 250. Although a direct comparison is fair only between GOCO02S, TIM2, EIGEN-GL05C and EGM2008, useful information could be gained from the discussion of all statistics of Table 2. First of all, the differences (observed-model) in terms of mean value and standard deviation between the combined models are generally small (several tenths of mGal), with the exception of Taiwan (several mGals). Comparing to the satellite generated models, these results are better in all test areas by several mGals. Among the satellite-only derived models, best results in terms of the standard de-

Table 1. Statistics of observed and reduced free-air gravity anomalies in different places of the Earth, using satellite-only and combined EGMs up to degree 120. The best results in terms of the standard deviation are colored in blue. Unit is mGal.

	Observed	GOCO02S 120	ITG 120	SPW 120	TIM 120	DIR 120	TIM2 120	DIR2 120	EIGEN-GL05C 120	EGM2008 120
Australia: $-43.7^o \le \varphi \le -9.0^o$, $112.9^o \le \lambda \le 153.6^o$, 1,117,054 point values										
Mean value	4.901	-0.499	-0.506	-0.475	-0.473	-0.478	-0.480	-0.495	-0.586	-0.504
Stand. Dev.	24.504	18.547	18.550	18.539	18.569	18.552	18.551	18.549	18.529	18.583
Max. value	248.602	207.970	207.985	208.059	207.889	207.835	207.785	207.880	208.608	208.260
Min. value	-211.327	-198.918	-198.916	-198.922	-198.916	-199.297	-199.002	-198.900	-199.546	-198.845
Arctic zone: $64.0^o \le \varphi \le 90.0^o$, $0^o \le \lambda \le 360.0^o$, 56,878 point values										
Mean value	0.662	-1.201	-1.193	-1.200	-1.195	-1.201	-1.195	-1.200	-1.197	-1.189
Stand. Dev.	29.814	22.339	22.339	22.345	22.479	22.342	22.437	22.341	22.333	22.329
Max. value	245.740	195.465	195.609	195.343	195.382	195.521	195.382	195.426	197.529	195.662
Min. value	-181.110	-203.868	-203.740	-203.850	-204.388	-204.043	-204.679	-203.954	-203.498	-204.624
Arctic zone: $64.0^o \le \varphi \le 90.0^o$, $0^o \le \lambda \le 360.0^o$, 673,920 $5' \times 10'$ mean values										
Mean value	3.500	-0.157	-0.149	-0.174	0.898	-0.173	0.283	-0.160	-0.179	-0.150
Stand. Dev.	27.680	20.698	20.698	20.716	22.097	20.697	21.347	20.706	20.680	20.673
Max. value	233.550	201.252	201.396	201.128	200.987	201.309	200.708	201.174	203.232	201.391
Min. value	-185.180	-205.187	-205.147	-205.286	-204.845	-205.220	-204.883	-205.350	-205.051	-204.884
Canadian plains: $56.0^o \le \varphi \le 680^o$, $-126.0^o \le \lambda \le -106.0^o$, 14,177 point values										
Mean value	-10.768	0.823	0.818	0.829	0.819	0.858	0.822	0.881	0.813	0.787
Stand. Dev.	22.419	18.608	18.604	18.610	18.644	18.645	18.613	18.628	18.669	18.593
Max. value	133.000	118.340	118.468	118.368	118.541	118.483	118.205	117.971	118.546	118.079
Min. value	-81.100	-89.703	-89.603	-89.583	-89.478	-89.390	-89.813	-89.775	-88.659	-89.520

Table 1 continued

	Observed	GOCO02S 120	ITG 120	SPW 120	TIM 120	DIR 120	TIM2 120	DIR2 120	EIGEN-GL05C 120	EGM2008 120
Oklahoma: 33.0º ≤ φ ≤ 36.0º, −101.0º ≤ λ ≤ −96.0º, 9,608 4 km × 4 km grid values										
Mean value	-2.352	2.885	2.872	2.904	2.839	2.885	2.840	2.839	2.926	2.943
Stand. Dev.	24.606	19.412	19.404	19.391	19.394	19.402	19.405	19.410	19.415	19.447
Max. value	79.000	83.274	83.176	83.115	82.884	83.107	83.221	83.128	83.918	84.065
Min. value	-62.000	-40.630	-40.550	-40.388	-40.616	-41.034	-40.602	-40.528	-40.474	-40.840
Scandinavia: 54.0º ≤ φ ≤ 64.0º, 12.0º ≤ λ ≤ 30.0º, 66,904 point values										
Mean value	-9.179	-0.562	-0.555	-0.556	-0.570	-0.567	-0.583	-0.557	-0.591	-0.566
Stand. Dev.	18.578	13.667	13.694	13.642	13.654	13.639	13.648	13.629	13.572	13.657
Max. value	71.740	68.767	68.740	69.086	68.947	68.793	68.783	68.857	70.012	68.395
Min. value	-84.021	-52.873	-52.874	-52.375	-52.564	-52.680	-52.840	-52.634	-51.703	-53.198
Taiwan: 21.5º ≤ φ ≤ 25.5º, 119.5º ≤ λ ≤ 122.5º, 4,800 3′ × 3′ grid values										
Mean value	15.248	-5.381	-5.388	-5.204	-5.361	-5.354	-5.428	-5.402	-5.257	-4.919
Stand. Dev.	70.128	62.108	62.100	62.158	62.100	62.090	62.096	62.113	62.200	62.279
Max. Value	339.389	291.296	291.259	291.723	291.354	291.374	291.183	291.308	291.945	292.737
Min. Value	-224.920	-214.639	-214.700	-214.527	-214.815	-215.295	-214.718	-214.639	-212.872	-214.842
Antarctica: −90º ≤ φ ≤ −50º, −180º ≤ λ ≤ 180º, 57,140 point values										
Mean value	6.142	4.952	4.961	4.959	5.136	4.942	5.171	4.945	4.904	4.961
Stand. Dev.	36.716	31.050	31.056	31.054	31.108	31.050	31.131	31.051	30.984	31.071
Max. value	259.500	268.309	268.340	268.476	268.431	268.770	267.962	268.445	271.075	267.782
Min. value	-377.800	-357.618	-357.602	-358.541	-359.610	-357.529	-359.232	-357.600	-361.508	-357.320
Mediterranean: 31.1º ≤ φ ≤ 45.6º, -5.7º ≤ λ ≤ 35.5º, 25,447 5′ × 5′ mean values										
Mean value	-10.207	-4.523	-4.524	-4.515	-4.509	-4.515	-4.508	-4.503	-4.528	-4.520
Stand. Dev.	44.981	28.073	28.075	28.071	28.079	28.077	28.083	28.081	28.007	28.108
Max. value	142.430	139.789	139.819	139.765	139.689	139.478	139.679	139.872	139.581	139.873
Min. value	-227.050	-165.543	-165.673	-165.314	-165.638	-165.567	-165.599	-165.636	-162.286	-166.013

Table 2. Statistics of observed and reduced free-air gravity anomalies in different places of the Earth, using satellite-only and combined EGMs. The best results in terms of the standard deviation of the combined models are colored in blue and of the satellite-only derived models in red. Unit is mGal.

	Observed	GOCO02S 250	ITG 180	SPW 210	TIM 224	DIR 240	TIM2 250	DIR2 240	EIGEN-GL05C 250	EGM2008 250
Australia: $-43.7^o \le \varphi \le -9.0^o$, $112.9^o \le \lambda \le 153.6^o$, 1,117,054 point values										
Mean value	4.901	-0.843	-0.552	-0.596	-0.648	-0.385	-0.822	-0.890	-0.339	-0.266
Stand. Dev.	24.504	15.159	19.044	15.795	15.409	14.419	15.184	15.788	14.149	14.288
Max. value	248.602	213.944	207.138	218.644	205.970	224.539	214.201	219.317	224.788	220.846
Min. value	-211.327	-205.797	-203.448	-191.736	-199.474	-204.009	-206.266	-204.811	-202.521	-200.341
Arctic zone: $64.0^o \le \varphi \le 90.0^o$, $0^o \le \lambda \le 360.0^o$, 56,878 point values										
Mean value	0.662	-1.117	-1.123	-1.090	-1.119	-1.105	-1.121	-1.118	-1.110	-1.109
Stand. Dev.	29.814	18.985	20.543	19.364	19.323	18.106	19.092	20.963	17.686	17.707
Max. value	245.740	188.637	207.148	187.506	181.184	183.107	188.556	190.524	181.666	180.386
Min. value	-181.110	-191.581	-212.203	-204.758	-195.354	-192.300	-191.658	-194.236	-183.585	-193.569
Arctic zone: $64.0^o \le \varphi \le 90.0^o$, $0^o \le \lambda \le 360.0^o$, 673,920 $5' \times 10'$ mean values										
Mean value	3.500	-0.069	-0.279	-0.247	0.856	-0.198	0.282	-0.617	-0.292	-0.207
Stand. Dev.	27.680	17.967	18.920	17.988	19.721	16.399	18.666	26.349	15.925	15.841
Max. value	233.550	169.020	187.946	165.755	158.706	163.390	168.989	170.753	162.235	161.085
Min. value	-185.180	-206.093	-233.212	-223.960	-216.182	-203.034	-206.357	-199.582	-203.349	-202.319
Canadian plains: $56.0^o \le \varphi \le 680^o$, $-126.0^o \le \lambda \le -106.0^o$, 14,177 point values										
Mean value	-10.768	-0.364	-0.098	0.757	0.755	0.191	-0.333	-0.366	0.462	0.427
Stand. Dev.	22.419	15.694	17.146	16.589	16.713	15.399	15.782	16.014	15.107	15.088
Max. value	133.000	87.322	110.620	97.578	93.393	85.270	87.353	89.427	88.739	88.109
Min. value	-81.100	-117.133	-97.181	-106.531	-108.115	-114.929	-117.542	-119.084	-114.888	-118.323

Table 2 continued

	Observed	GOCO02S 250	ITG 180	SPW 210	TIM 224	DIR 240	TIM2 250	DIR2 240	EIGEN-GL05C 250	EGM2008 250
Oklahoma: $33.0^{\circ} \leq \varphi \leq 36.0^{\circ}$, $-101.0^{\circ} \leq \lambda \leq -96.0^{\circ}$, 9,608 4 km × 4 km grid values										
Mean value	-2.352	1.179	0.506	1.073	1.407	1.214	1.149	0.751	1.188	1.069
Stand. Dev.	24.606	16.131	19.950	17.960	17.801	16.068	16.055	16.510	15.732	15.766
Max. value	79.000	64.903	75.147	73.052	73.062	67.895	65.030	66.895	67.950	68.810
Min. value	-62.000	-46.267	-51.307	-52.096	-47.879	-42.457	-46.199	-49.548	-46.455	-46.896
Scandinavia: $54.0^{\circ} \leq \varphi \leq 64.0^{\circ}$, $12.0^{\circ} \leq \lambda \leq 30.0^{\circ}$, 66,904 point values										
Mean value	-9.179	-0.940	-0.742	-0.936	-1.035	-0.987	-0.951	-1.062	-0.888	-0.865
Stand. Dev.	18.578	11.582	12.739	11.514	11.954	10.398	11.669	12.511	9.984	10.004
Max. value	71.740	70.159	75.818	75.703	73.162	81.634	70.826	77.175	77.786	75.915
Min. value	-84.021	-48.211	-54.825	-47.786	-48.721	-52.242	-48.576	-52.785	-50.145	-48.504
Taiwan: $21.5^{\circ} \leq \varphi \leq 25.5^{\circ}$, $119.5^{\circ} \leq \lambda \leq 122.5^{\circ}$, 4,800 3′ × 3′ grid values										
Mean value	15.248	-0.257	-1.420	-0.936	-0.901	0.397	-0.264	0.102	-1.146	1.155
Stand. Dev.	70.128	49.679	54.623	51.884	51.802	48.001	49.573	49.098	50.059	46.569
Max. Value	339.389	226.306	245.985	229.941	231.582	216.376	225.470	230.145	244.333	204.519
Min. Value	-224.920	-186.739	-193.162	-195.386	-196.781	-181.549	-186.382	-182.438	-165.538	-168.796
Antarctica: $-90^{\circ} \leq \varphi \leq -50^{\circ}$, $-180^{\circ} \leq \lambda \leq 180^{\circ}$, 57,140 point values										
Mean value	6.142	4.280	4.708	3.989	4.160	4.076	4.466	3.953	4.116	4.282
Stand. Dev.	36.716	27.100	29.438	28.235	27.900	26.601	27.248	27.904	25.526	26.432
Max. value	259.500	269.844	287.563	271.007	275.554	276.797	269.674	275.087	281.022	272.524
Min. value	-377.800	-367.515	-351.188	-363.549	-369.620	-356.959	-364.330	-354.852	-360.538	-352.649
Mediterranean: $31.1^{\circ} \leq \varphi \leq 45.6^{\circ}$, $-5.7^{\circ} \leq \lambda \leq 35.5^{\circ}$, 25,447 5′ × 5′ mean values										
Mean value	-10.207	-1.341	-2.750	-2.163	-1.897	-0.978	-1.293	-1.155	-0.863	-0.733
Stand. Dev.	44.981	21.419	24.086	23.120	22.359	21.199	21.420	21.793	20.665	20.911
Max. value	142.430	136.987	139.788	126.698	130.814	133.671	137.354	140.448	134.581	131.702
Min. value	-227.050	-134.015	-131.575	-122.873	-125.036	-140.371	-134.653	-135.447	-139.000	-141.022

viation of the differences (observed-model) are shown in the case of DIR (maximum harmonic degree 240), while DIR2 presents problems, especially in the Arctic zone. TIM2 shows slightly better results with respect to TIM which could be attributed to the increased degree of expansion from 224 to 250. Generally speaking, the results in terms of the mean value and the standard deviation of the differences (observed-model) of the satellite-only derived models GOCO02S, SPW, TIM, DIR, TIM2 and DIR2 are similar, but with the aforementioned exceptions. Finally, the lower degree of expansion for the statistics related to ITG-Grace2010 has to be taken into account.

2.3 Inter-comparison of EGMs

The statistics of the reduced gravity anomalies to EGMs showed in section 2.2 might be seen as a result of the very good agreement of their degree variances up to about harmonic degree 160. However, these statistics do not explain the differences in their error spectral characteristics. In this section, inter-comparison of the EGMs contribution to gravity anomalies was carried out at extended areas of the Earth such as Australia, the Arctic zone and Antarctica, in order to identify special features of the models at different harmonic degrees. The contribution of the EGMs was computed at places where ground gravity measurements took place, at different harmonic degrees.

Table 3 shows the statistics of the differences between the contributions of satellite generated models and combined models to degree 32, at positions of gravity measurements over Australia. Although the error spectral characteristics of the models under consideration differ substantially, even at low harmonic degrees, the statistics of the contribution differences up to this degree show very good agreement. Larger discrepancies in terms of the standard deviation occurred between EIGEN5C – EIGEN03s, EIGEN5C – DIR2 and EGM2008 – EIGEN03s (0.05mGal), while the minimum or maximum differences do not exceed 0.14 mGal in absolute values.

However, at higher harmonic degrees the situation is changed. The statistics of the differences between different models contribution at positions of gravity measurements over Australia up to harmonic degree 120, where the error degree variances of the satellite only generated EGMs are smaller than those of EIGEN-GL05C and EGM2008, is shown in Table 4a. The smallest discrepancy in terms of standard deviation (0.09 mGal) appeared between ITG-2010s and GOCO02S. This impressive agreement confirms the good agreement of their error spectral characteristics up to degree 120. The largest discrepancy (0.64 mGal) appeared between EIGEN-GL05C and SPW. The discrepancies in terms of the minimum/maximum differences are larger between EGM2008 and the satellite-only derived models, ranging between -3.7 and 3.8 mGal.

Table 3. Statistics of the differences between combined and satellite-only derived EGMs to degree 32, at positions of gravity measurements over Australia. Unit is mGal.

	AUSTRALIA (1,117,054 point free-air gravity anomalies)							
	EIGEN-5C				EGM2008			
	Mean value	Standard deviation	Minimum difference	Maximum difference	Mean value	Standard deviation	Minimum difference	Maximum difference
EIGEN-03s	-0.003	0.051	-0.136	0.122	-0.002	0.051	-0.133	0.126
GOCO02S	0.000	0.001	-0.002	0.001	0.002	0.002	-0.002	0.007
ITG-2010s	-0.001	0.001	-0.005	0.003	0.000	0.001	-0.002	0.003
SPW	0.001	0.016	-0.040	0.041	0.003	0.016	-0.036	0.046
TIM	0.009	0.032	-0.080	0.082	0.011	0.032	-0.077	0.082
DIR	0.000	0.003	-0.007	0.009	0.002	0.004	-0.006	0.014
TIM2	0.011	0.031	-0.076	0.074	0.013	0.032	-0.076	0.077
DIR2	0.002	0.051	-0.122	0.137	0.001	0.004	-0.008	0.010

Table 4a. Statistics of the differences (column – row) between EGM2008 and satellite-only derived EGMs to degree 120, at positions of gravity measurements over Australia. Unit is mGal.

		AUSTRALIA (1,117,054 point free-air gravity anomalies)					
Max. degree 120		ITG-2010s	SPW	TIM2	DIR2	EIGEN-GL05C	EGM2008
Mean	GOCO02S	0.008	-0.024	-0.018	-0.004	-0.087	0.005
Stand. Dev.		0.088	0.258	0.151	0.118	0.549	0.297
Min. value		-0.269	-0.857	-0.540	-0.413	-3.696	-1.504
Max. value		0.274	0.802	0.509	0.537	3.386	2.406
Mean	ITG-2010s	-	-0.031	-0.026	-0.012	-0.005	-0.003
Stand. Dev.			0.262	0.203	0.171	0.583	0.314
Min. value			-0.917	-0.684	-0.681	-3.713	-1.408
Max. value			0.778	0.655	0.744	3.431	2.396
Mean	SPW		-	0.005	0.020	-0.111	-0.029
Stand. Dev.				0.280	0.267	0.644	0.389
Min. value				-0.941	-0.942	-3.443	-1.640
Max. value				0.937	0.893	3.779	2.428
Mean	TIM2			-	0.014	-0.106	0.023
Stand. Dev.					0.139	0.567	0.316
Min. value					-0.400	-3.432	-1.666
Max. value					0.416	3.481	2.285
Mean	DIR2				-	-0.091	0.009
Stand. Dev.						0.560	0.310
Min. value						-3.594	-1.581
Max. value						3.314	2.370
Mean	EIGEN-GL05C					-	-0.082
Stand. Dev.							0.604
Min. value							-2.894
Max. value							3.678

Table 4b. Statistics of the differences (column – row), between EGM2008 and satellite-only derived EGMs to degree 180, at positions of gravity measurements over Australia. Unit is mGal.

		AUSTRALIA (1,117,054 point free-air gravity anomalies)					
Max. degree 180		ITG-2010s	SPW	TIM2	DIR2	EIGEN-GL05C	EGM2008
Mean	GOCO02S	-0.307	-0.026	-0.032	0.005	-0.193	0.054
Stand. Dev.		7.247	1.649	0.439	1.001	1.513	1.068
Min. value		-24.451	-6.804	-1.564	-4.245	-7.463	-4.229
Max. value		27.920	6.113	1.897	3.575	8.633	5.930
Mean	ITG-2010s		0.281	0.274	0.312	-0.500	0.361
Stand. Dev.			7.372	7.456	7.629	7.578	7.522
Min. value		-	-26.128	-28.333	-28.346	-26.311	-27.626
Max. value			26.118	26.030	25.319	27.277	24.988
Mean	SPW			-0.006	0.031	-0.219	0.080
Stand. Dev.				1.675	1.626	2.123	1.774
Min. value			-	-6.020	-6.449	-9.073	-7.630
Max. value				7.158	5.245	8.790	7.250
Mean	TIM2				0.037	-0.225	0.086
Stand. Dev.					0.945	1.550	1.118
Min. value				-	-4.058	-8.016	-4.511
Max. value					3.732	8.194	6.046
Mean	DIR2					-0.188	0.048
Stand. Dev.						1.654	1.317
Min. value					-	-7.530	-5.059
Max. value						7.421	5.327
Mean	EIGEN-GL05C						-0.139
Stand. Dev.							1.122
Min. value						-	-6.736
Max. value							7.984

In Table 4b, the corresponding statistics are shown up to harmonic degree 180, where the error degree variances of the satellite only EGMs exceed the corresponding of EIGEN-GL05C and EGM2008. It is noteworthy that the standard deviation of the differences between ITG-2010s and all other EGMs included in this Table exceeds 7.6 mGal, and the corresponding minimum and maximum differences ranges between -28 and 28 mGal. As regards the remaining models, the differences in terms of standard deviation range between 0.4 and 2.1 mGal and the minimum/maximum differences between -8 and 8.2 mGal.

Figures 2-8 show characteristic patterns of the differences of gravity anomaly contribution of the EGMs included in Tables 4a and 4b, over Australia. The differences up to harmonic degree 120, between the GRACE and GOCE generated GOCO02S and the GRACE-only generated ITG-2010s are shown in Figure 2 (left), while the differences between ITG-2010s and the combined EGM2008 are shown in Figure 2 (right).

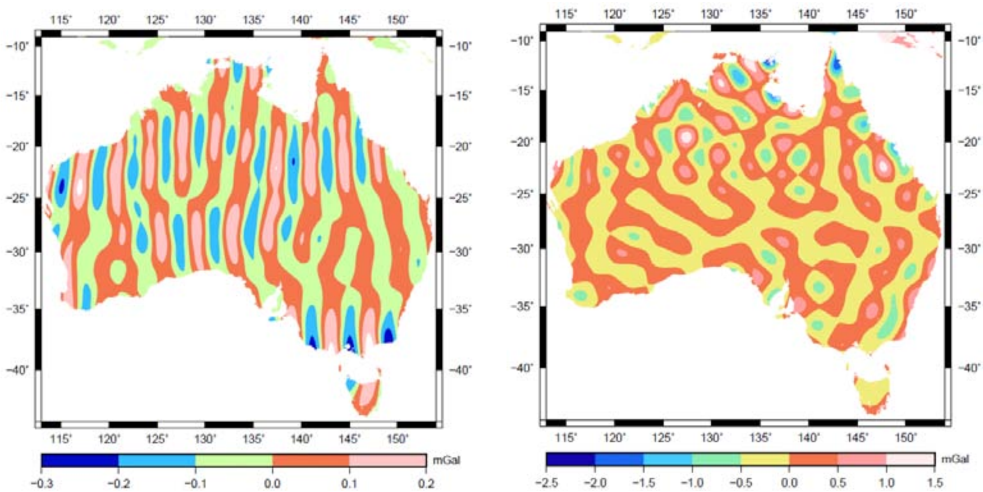

Figure 2. Differences GOCO02S – ITG-2010s (left) and ITG-2010s – EGM2008 (right) over Australia up to harmonic degree 120. Unit is mGal.

In Figure 2 (left), the sectorial spherical harmonics are clearly dominated, obviously due to GRACE data used in both models. The agreement between GOCO02S and ITG-2010s, up to degree 120, is impressive as it is also shown in Table 4a. In Figure 2 (right), the pattern above -25 degree shows a predominance of tesseral harmonics, while below -25 degree the situation is not clear.

Figure 3 shows the differences between GOCO02S and EGM2008 up to harmonic degree 120 (left) and up to 180 (right), respectively. In this case, up to degree 120 the tesseral harmonics are clearly dominated, while up to 180 both tesseral and sectorial are mixed.

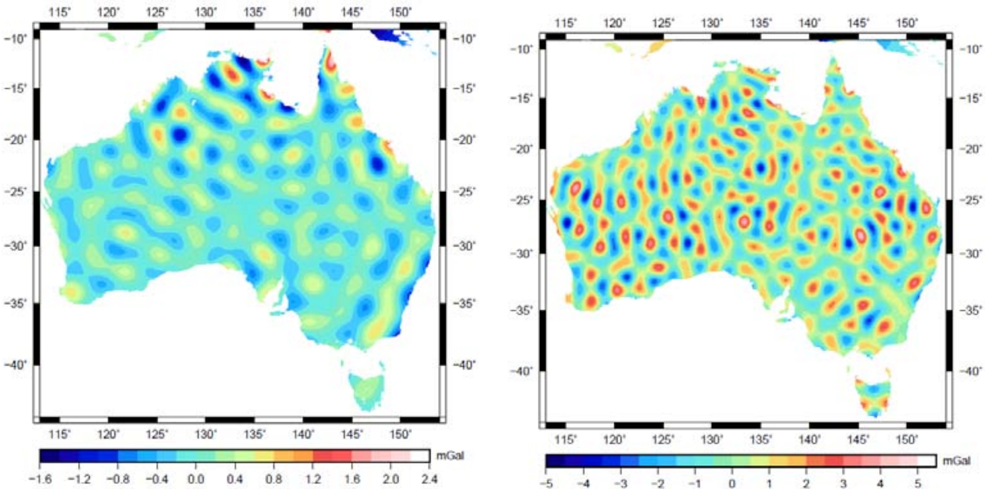

Figure 3. Differences GOCO02S – EGM2008 over Australia: up to harmonic degree 120 (left), up to 180 (right). Unit is mGal.

In Figure 4, the differences between ITG2010S and two GOCE-only generated DIR2 (left) and TIM2 (right), up to harmonic degree 120, are shown. In the left figure tesseral and sectorial harmonics are visible, while in the right the sectorial are dominated.

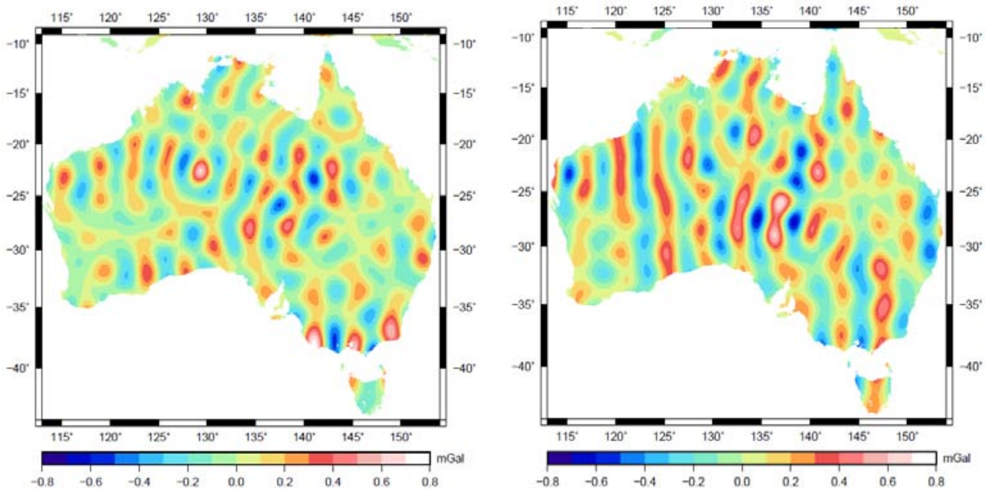

Figure 4. Differences ITG2010s – DIR2 (left) and ITG2010s – TIM2 (right) up to harmonic degree 120. Unit is mGal.

In Figure 5, the differences between the GRACE and GOCE generated GOCO02S and the GOCE-only generated DIR2 are shown up to harmonic degree 120 (left) and up to harmonic degree 180 (right). It looks similar pattern as in Figure 4, with a denser distribution in the right, due to increased degree of expansion.

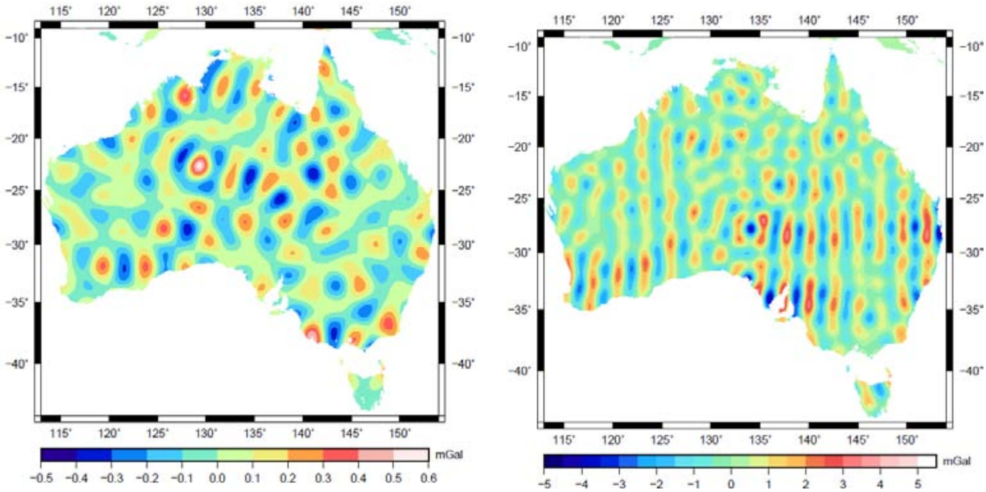

Figure 5. Differences GOCO02S – DIR2 over Australia: up to harmonic degree 120 (left), up to 180 (right). Unit is mGal.

In Figure 6, a very good agreement between GOCO02S and TIM2 is shown, not only up to degree 120 (left) but also up to degree 180 (right). In both cases tesseral and sectorial harmonics are visible.

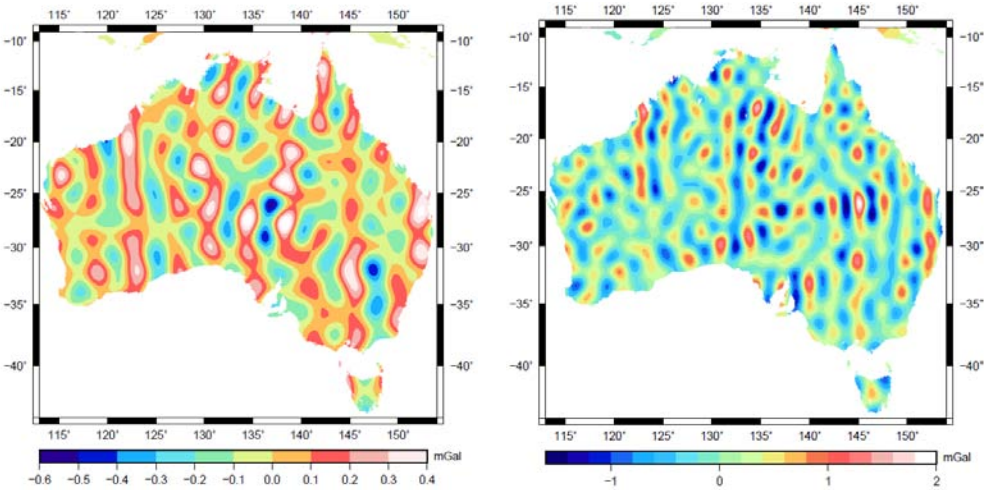

Figure 6. Differences GOCO02S – TIM2 over Australia: up to harmonic degree 120 (left), up to 180 (right). Unit is mGal.

In Figure 7 (left), the pattern of the differences between DIR2 and EGM2008, up to degree 120, shows domination of tesseral harmonics, while up to degree 180 tesseral and sectorial are mixed. The differences up to degree 120 range between -2 and 2 mGal and up to degree 180 between -5 and 5 mGal.

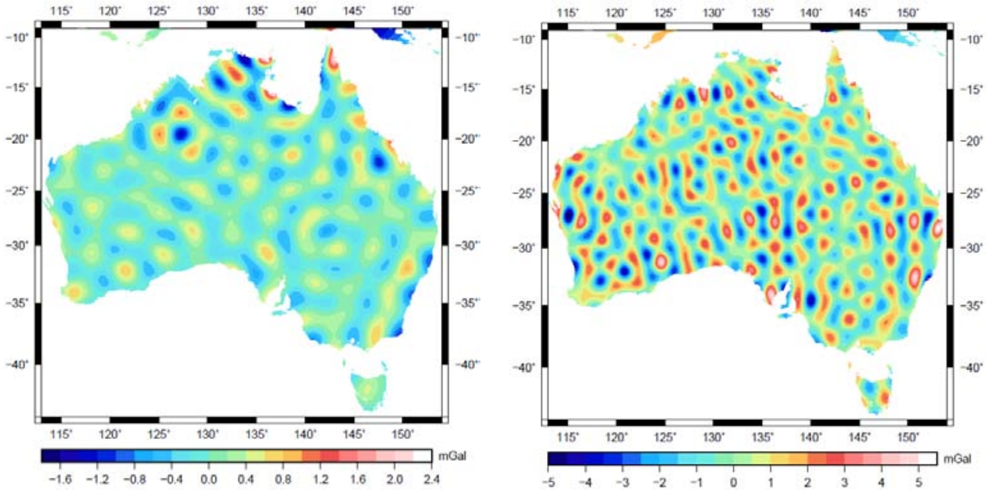

Figure 7. Differences DIR2 – EGM2008 over Australia: up to harmonic degree 120 (left), up to 180 (right). Unit is mGal.

Finally, Figure 8 shows very good agreement between TIM2 and DIR2 up to degree 120, with differences ranging between -0.5 and +0.5 mGal. Up to degree 180

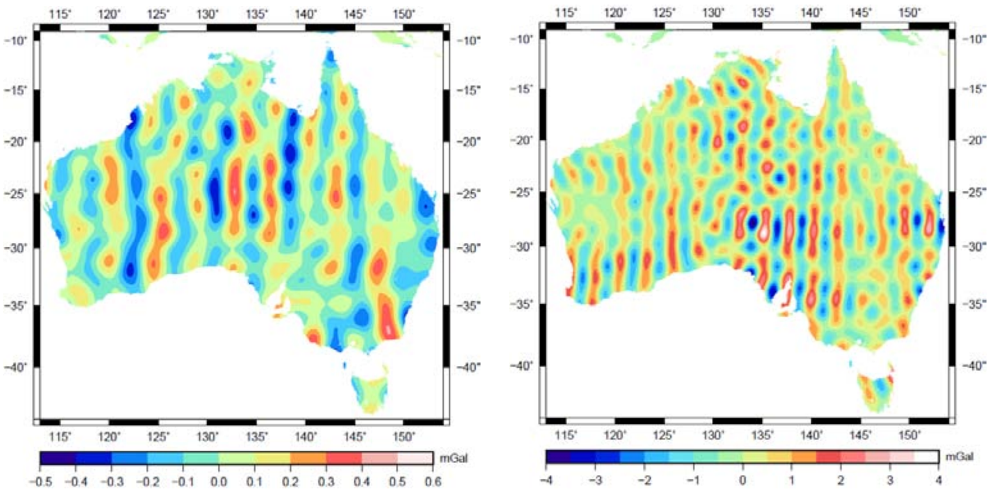

Figure 8. Differences TIM2 – DIR2 over Australia: up to harmonic degree 120 (left), up to 180 (right). Unit is mGal.

the range of the differences is increased from -4 to 4 mGal. It is interesting to note the systematic character of the sectorial appearance of the differences in both degrees of expansion.

Table 5a. Statistics of the differences (column – row) between EGM2008 and satellite-only derived EGMs to degree 120, at positions of gravity measurements over the Arctic zone. Unit is mGal.

Max. degree 120		ARCTIC ZONE (56,878 point free-air gravity anomalies)				
		ITG-2010s	SPW	TIM2	DIR2	EGM2008
Mean	GOCO02S	-0.008	0.001	-0.007	0.005	-0.012
Stand. Dev.		0.050	0.574	2.120	0.300	0.502
Min. value		-0.213	-6.526	-22.400	-2.896	-2.759
Max. value		0.195	8.334	37.695	2.670	2.417
Mean	ITG-2010s	-	0.007	0.001	0.007	0.004
Stand. Dev.			0.578	2.121	0.312	0.504
Min. value			-6.519	-22.391	-2.890	-2.776
Max. value			8.348	37.706	2.682	2.412
Mean	SPW		-	-0.006	0.000	0.011
Stand. Dev.				2.251	0.605	0.757
Min. value				-25.722	-8.253	-9.270
Max. value				36.394	5.486	7.545
Mean	TIM2			-	0.006	-0.005
Stand. Dev.					2.110	2.125
Min. value					-37.806	-36.626
Max. value					22.735	22.297
Mean	DIR2				-	-0.110
Stand. Dev.						0.586
Min. value						-3.288
Max. value						2.892

Table 5b. Statistics of the differences (column – row) between EGM2008 and satellite-only derived EGMs to degree 180, at positions of gravity measurements over the Arctic zone. Unit is mGal.

Max. degree 180		ARCTIC ZONE (56,878 point free-air gravity anomalies)				
		ITG-2010s	SPW	TIM2	DIR2	EGM2008
Mean	GOCO02S	-0.011	-0.002	-0.003	0.008	0.000
Stand. Dev.		4.761	1.551	2.818	4.737	1.543
Min. value		-18.390	-12.092	-36.315	-50.456	-7.764
Max. value		19.510	10.009	50.179	59.147	7.294
Mean	ITG-2010s	-	0.009	0.008	0.019	0.011
Stand. Dev.			4.962	5.564	6.724	4.872
Min. value			-20.359	-31.419	-49.954	-22.590
Max. value			19.276	43.174	58.586	20.879
Mean	SPW		-	-0.001	0.010	0.002
Stand. Dev.				3.010	4.812	2.002
Min. value				-36.216	-52.209	-8.898
Max. value				47.587	64.551	11.393
Mean	TIM2			-	0.011	0.003
Stand. Dev.					5.244	3.085
Min. value					-70.627	-46.905
Max. value					81.233	35.299
Mean	DIR2				-	-0.008
Stand. Dev.						4.923
Min. value						-60.986
Max. value						48.267

Table 6a. Statistics of the differences (column–row) between EGM2008 and satellite-only derived EGMs to degree 120, at positions of gravity measurements over Antarctica. Unit is mGal.

Max. degree 120		ANTARCTICA (57,140 point free-air gravity anomalies)				
		ITG-2010s	SPW	TIM2	DIR2	EGM2008
Mean	GOCO02S	-0.009	-0.006	-0.219	0.007	-0.008
Stand. Dev.		0.107	0.517	3.295	0.206	0.495
Min. value		-0.448	-12.626	-77.937	-1.115	-2.457
Max. value		0.425	5.884	28.925	1.631	1.896
Mean	ITG-2010s	-	0.002	-0.210	0.016	0.001
Stand. Dev.			0.532	3.299	0.244	0.509
Min. value			-12.613	-77.927	-1.117	-2.507
Max. value			5.890	28.935	1.644	1.938
Mean	SPW		-	-0.212	0.014	-0.002
Stand. Dev.				3.354	0.523	0.707
Min. value				-81.843	-6.401	-6.059
Max. value				32.775	13.118	12.875
Mean	TIM2			-	0.226	0.210
Stand. Dev.					3.289	3.334
Min. value					-27.462	-29.139
Max. value					77.519	77.858
Mean	DIR2				-	-0.015
Stand. Dev.						0.528
Min. value						-2.534
Max. value						2.040

Table 6b. Statistics of the differences (column – row) between EGM2008 and satellite-only derived EGMs to degree 180, at positions of gravity measurements over Antarctica. Unit is mGal.

Max. degree 180		ANTARCTICA (57,140 point free-air gravity anomalies)				
		ITG-2010s	SPW	TIM2	DIR2	EGM2008
Mean	GOCO02S	-0.031	0.003	-0.202	0.057	0.001
Stand. Dev.		7.431	2.466	3.292	2.204	2.697
Min. value		-29.565	-19.488	-78.031	-36.372	-21.634
Max. value		31.108	15.020	33.201	33.739	21.884
Mean	ITG-2010s	-	0.034	-0.172	0.088	0.032
Stand. Dev.			8.116	8.215	7.935	7.695
Min. value			-33.303	-75.906	-35.266	-31.185
Max. value			30.057	32.680	44.970	44.860
Mean	SPW		-	-0.205	0.054	-0.003
Stand. Dev.				4.124	2.959	3.536
Min. value				-88.762	-35.775	-21.842
Max. value				50.940	45.507	22.556
Mean	TIM2			-	0.260	0.203
Stand. Dev.					3.773	4.229
Min. value					-38.153	-35.303
Max. value					102.891	74.418
Mean	DIR2				-	-0.056
Stand. Dev.						3.409
Min. value						-34.212
Max. value						32.857

Figure 9 shows discrepancies between EGM02 and TIM2 at positions of gravity observations over the Arctic Ocean. Differences ranging between -5 and 5 mGal are shown in the main part of the area. The large discrepancies exceeding ±5 mGal appeared at latitudes above 83º N, where no GOCE data are available in TIM2. In both cases, the predominant pattern is that of tesseral harmonics.

Figure 10 shows discrepancies between EGM2008 and TIM2 at positions of gravity observations over Antarctica. Differences ranging between -5 and 5 mGal are shown in the main part of the area. The large differences exceeding ±5 mGal appeared at latitudes below 83º S, where no GOCE data are available in TIM2.

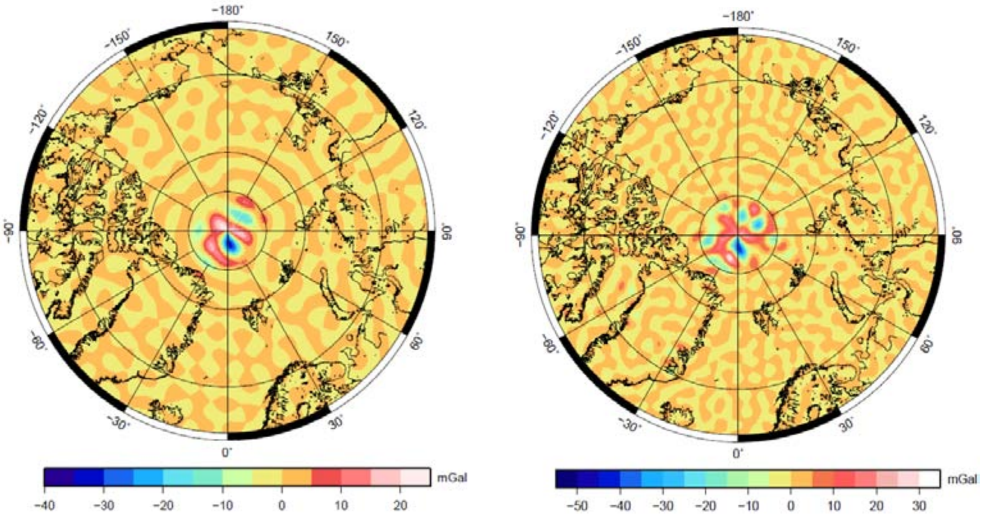

Figure 9. Discrepancies between EGM2008 and TIM2 over Arctic Ocean:
up to harmonic degree 120 (left), up to 180 (right).

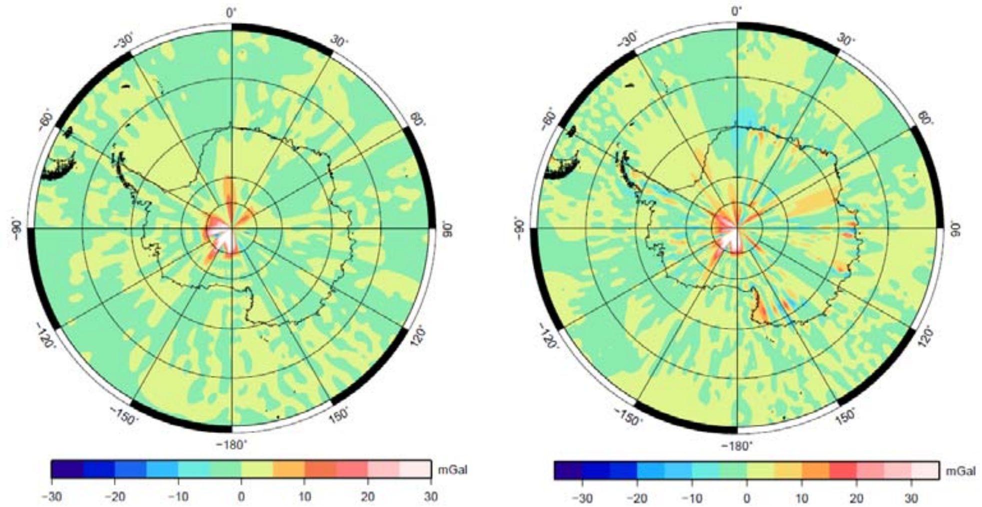

Figure 10. Discrepancies between EGM2008 and TIM2 over Antarctica:
up to harmonic degree 120 (left), up to 180 (right).

Figure 11 shows the gravity anomaly differences between DIR2 and EGM2008 over Taiwan for harmonic degrees 120 (left) and 180 (right). It is characteristic the sliding of the minimum difference from NW to SE and the increase of the range of the difference.

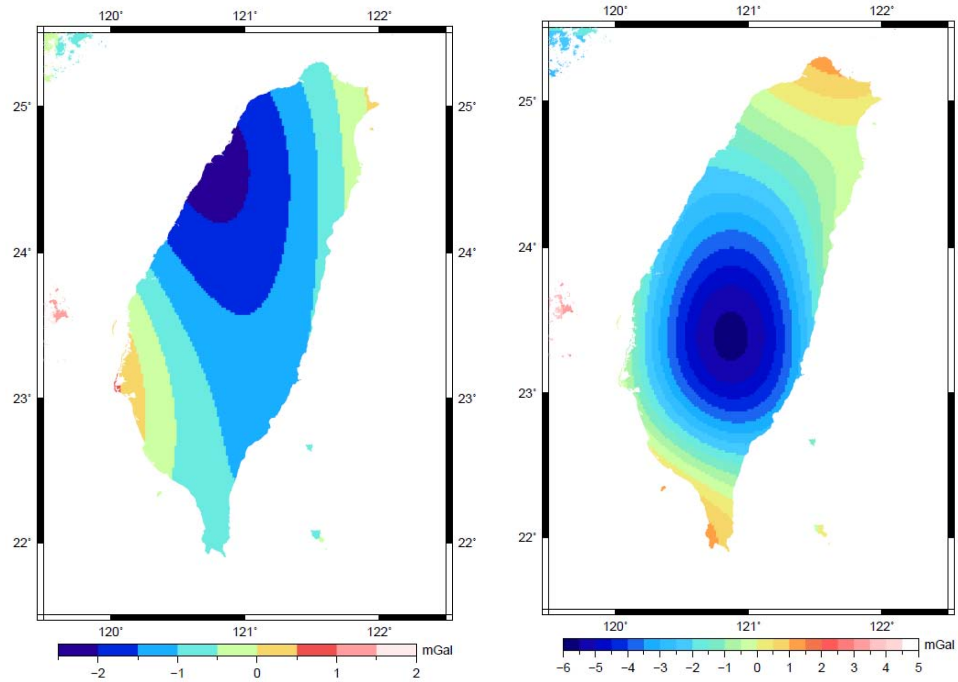

Figure 11. Differences between DIR2 and EGM2008 over Taiwan, up to harmonic degree 120 (left) and up to 180 harmonic degree (right).

2.4. Discrepancies between gravity field and satellite-only EGMs

Satellite generated models, such as EIGEN-2, have been used in detecting long-wavelength gravity anomaly errors (e.g. Featherstone 2005). EIGEN-2 which was derived from CHAMP-only had full power only up to about degree 40 as it is mentioned in section 2.2. The contemporary satellite-only generated EGMs have full power up to higher degrees, as it is shown in section 2, and therefore might be used to detect also medium-wavelength gravity anomaly errors. In this section, the same method used by Featherstone (2005) is used to detect long- and medium-wavelength gravity anomaly errors in different test areas of the Earth. For the sake of compatibility, the GOCE-only generated TIM2 was selected to be used in all the relevant experiments.

The degree-32 TIM2 gravity anomalies were evaluated for each terrestrial gravity anomaly over Australia, and then subtracted. The gravity observations were taken from the 2004 release of the Australian National Gravity Database. Since the terrestrial observations contain all frequencies, a 1,113 km low-pass cosine-arch-tapered filter was used to remove the differences beyond the harmonic degree 32.

The result of this procedure is shown in Figure 12 (left). It looks to be very similar to Figure 3 by Featherstone (2005). Figure 12 (right) shows medium-pass filtered differences between Australian land and degree-120 TIM2 gravity anomalies. In this case, a 297 km medium-pass cosine-arch-tapered filter was used to remove the differences beyond the harmonic degree 120.

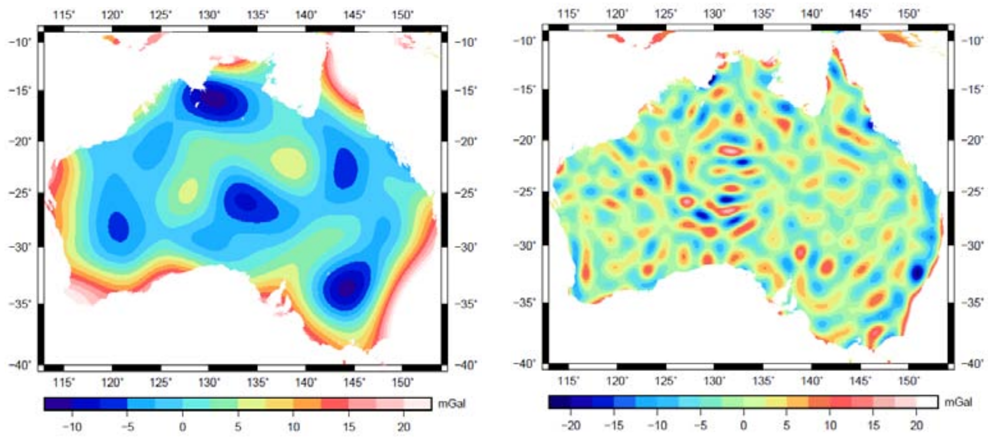

Figure 12. Low-pass filtered differences between Australian land and degree-32 TIM2 gravity anomalies (left). Medium-pass filtered differences between Australian land and degree-120 TIM2 gravity anomalies (right).

In Featherstone (2005), a high level correlation was reported between the filtered differences (terrestrial gravity anomalies – EIGEN-2 to degree 32) and the spatial coverage of the data. The correlation was attributed to long-wavelength errors in EIGEN-2, since the differences were large in relation to the expected few mGal errors in the Australian land gravity anomalies. A relevant discussion takes place in other test areas of this study.

Filtered differences between observed gravity anomalies and gravity anomalies derived from satellite-only EGMs can be computed by two different ways: (a) filtering the reduced gravity anomalies to the selected model or (b) filtering first the observed gravity anomalies and then subtracting the contribution of the model. It was expected that both ways would give the same result, but this is not the case. The reason is that the filtering procedure has effect also on the gravity anomaly field implied by the EGM. This is illustrated in Figure 13, where the degree-32 TIM2 gravity anomaly field (left) was changed after low-pass filtering using a 1,113 km low-pass cosine-arch-tapered filter (right). Another example of the same effect is shown in the case of Scandinavia. Therefore, in our opinion, this procedure gives a more or less general figure of the discrepancies between terrestrial and satellite-only derived gravity anomalies.

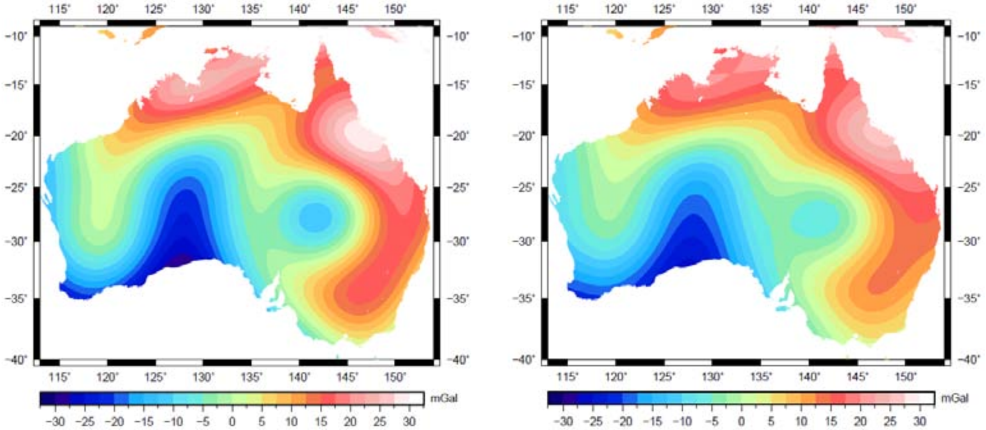

Figure 13. Long-wavelength gravity anomaly field over Australia, derived by TIM2 to degree 32 (left). The gravity field of the left figure low-pass cosine filtered (right). The 1,113 km low-pass cosine-arch-tapered filter used should have no effect on the unfiltered gravity field.

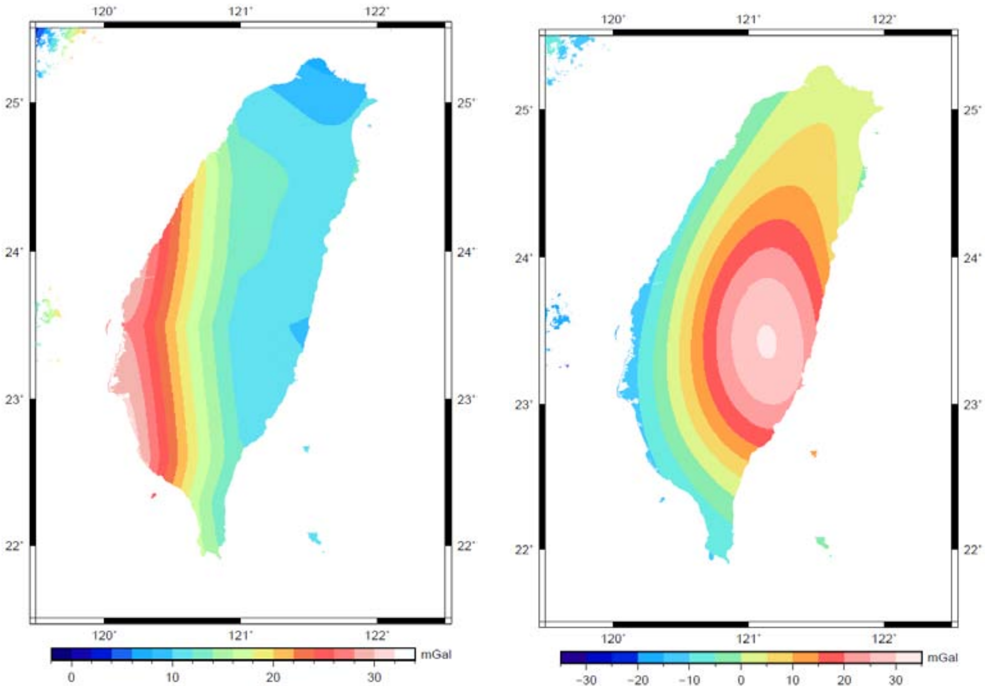

Figure 14. Low-pass filtered differences between gravity anomalies and degree-32 TIM2 gravity anomalies over Taiwan (left). Medium-pass filtered differences between gravity anomalies and degree-120 TIM2 gravity anomalies over Taiwan (right).

Figure 14 (left) shows the low-pass filtered differences between terrestrial and degree-32 TIM2 gravity anomaly field over Taiwan. A 1,145 km low-pass cosine-arch-tapered filter was used to remove the differences beyond the harmonic degree 32. Terrestrial gravity anomalies present a systematic E-W slope with respect to gravity anomalies derived from TIM2.

The right part of Figure 14 shows medium-pass filtered differences between terrestrial and TIM2 to degree 120 gravity anomalies over Taiwan. A 305 km low-pass cosine-arch-tapered filter was used to remove the differences beyond the harmonic degree 120. In this case, the medium wavelength discrepancies present the form of a mount with a peak of about 30 mGal. A discussion about correlations between the differences showed in Figure 14 and the special distribution or/and the accuracy of the data has no place, since the gravity data used in this area are 3′×3′ grid values and their accuracy is not known.

Figure 15 (left) shows the low-pass filtered differences between terrestrial and TIM2 to degree 32 gravity anomalies over Scandinavia. A 643 km low-pass cosine-arch-tapered filter was used to remove the differences beyond the harmonic degree 32. In the right part, the medium-pass filtered differences between terrestrial and TIM2 to degree 120 are shown. The length of the filter in this case was 172 km.

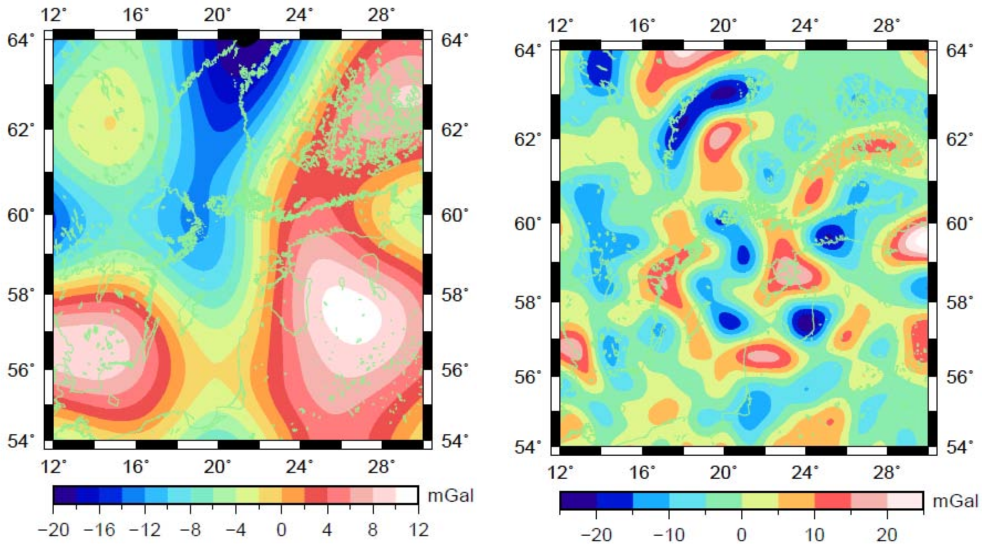

Figure 15. Low-pass filtered differences between terrestrial and TIM2 to degree 32 gravity anomalies over Scandinavia (left). Medium-pass filtered differences between terrestrial and TIM2 to degree 120 gravity anomalies over Scandinavia (right).

The left part of Figure 16 shows long-wavelength gravity anomaly field over Scandinavia, implied by TIM2 to degree 32 and the right part the same gravity field, low-pass filtered using a 643 km low-pass cosine-arch-tapered filter which should have no effect on the unfiltered gravity field. The comparison of the left and right part of this figure gives another characteristic example of changes of the gravity field to degree 32, resulted after filtering designed to remove frequencies above degree 32. In terms of the statistics, these changes are significant as it is shown in Table 7.

Table 7. Statistics of the differences between TIM2 to degree 32 gravity field over Scandinavia before and after filtering, using a 643 km low-pass cosine-arch-tapered filter. Unit is mGal.

	Mean value	Standard deviation	Minimum difference	Maximum difference
Before filtering	-9.890	6.299	-19.941	8.366
After filtering	-10.160	5.172	-18.563	3.568

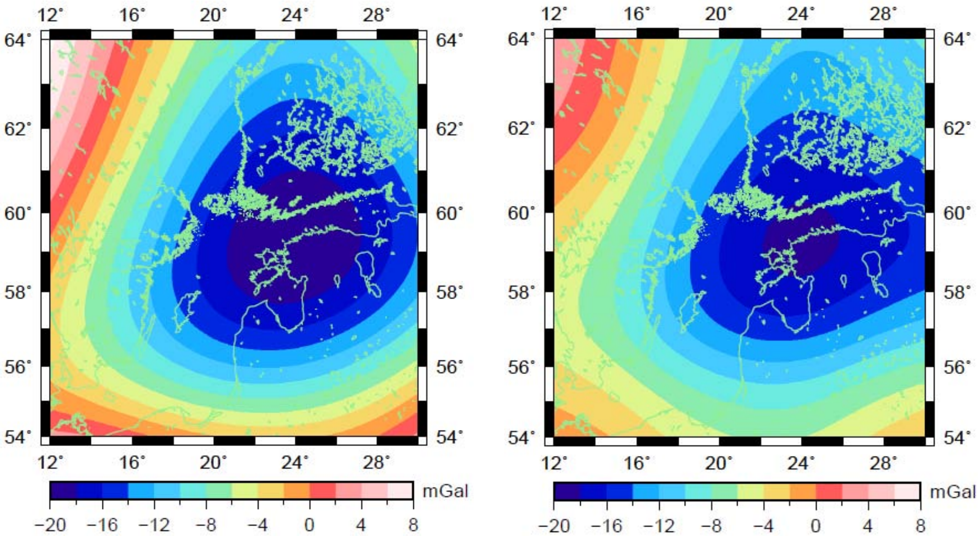

Figure 16. Long-wavelength gravity anomaly field over Scandinavia, implied by TIM2 to degree 32 (left). The gravity field of the left figure low-pass filtered (right). The 643 km low-pass cosine-arch-tapered filter used should have no effect on the unfiltered gravity field.

The long- and medium-wavelength discrepancies between terrestrial and TIM2 gravity field over the Arctic region are shown in Figure 17. Up to harmonic degree 32 differences ranging between -70 and +50 mGal exist around the coasts and on the mainland of Greenland. However, most of the differences range between -10 and +10 mGal. Up to degree 120 differences up to -110 mGal exist around the

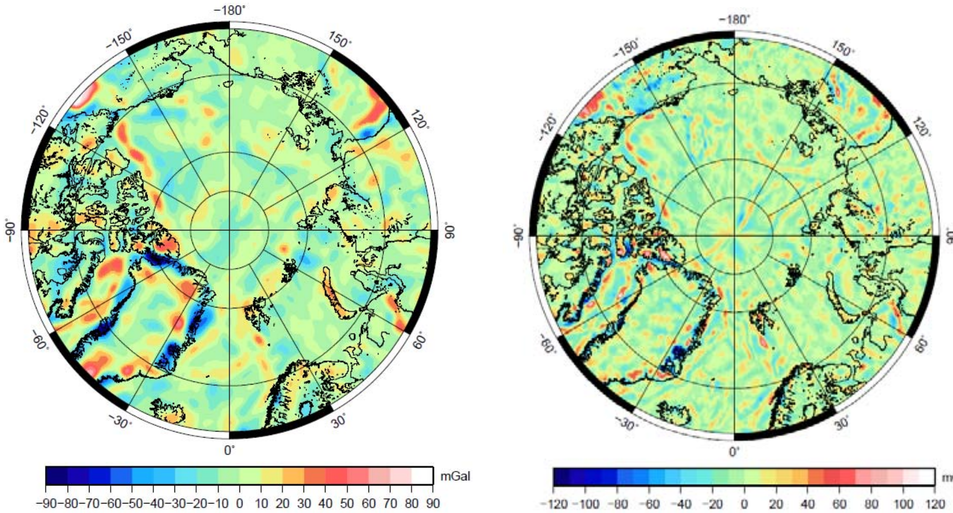

Figure 17. Long- and medium-pass filtered differences between terrestrial and TIM2 gravity field over the Arctic region. Left: up to degree 32. Right: up to degree 120.

coasts of Greenland, though the majority of the differences range between -30 and +20 mGal.

There is the question on the existence of possible correlation of these differences with the distribution or/and the accuracy of the data. Figure 19 shows the distribution of the gravity anomaly data in the Arctic region. Comparing Figures 17 (left) and 19, it is clear to see that there is not a significant correlation with the special coverage of the observations, but there is a correlation with the accuracy in Greenland, where the error of the gravity data exceeds 7 mGal. The comparison of Figure 17 (right) with Figure 19 does not show significant correlations.

Finally, the long- and medium-wavelength discrepancies between terrestrial and TIM2 gravity field over the Canadian plains are shown in Figure 18. Up to harmonic degree 32 differences ranging between -20 and +10 mGal are distributed on the entire area in a way similar to that of Scandinavia. Up to degree 120 differences up to -40 and +40 mGal are distributed on the N-W part of the area, while in the rest the differences are restricted between -20 and +20 mGal.

In Figure 20, the distribution and the accuracy of the gravity over the Canadian plains are presented. As it is shown in this figure, the spatial distribution of the gravity data is almost homogeneous, with the exception of the gaps in the three major lakes and along the S-W area, close to the Rocky Mountains. The accuracy of the majority of the gravity observations ranges between 1 and 4 mGal. The comparison of Figure 18 (left) with Figure 20 shows a correlation of the filtered differences with the accuracy of the observations, in an area where the accuracy is better than 2 mGal. With respect to Figure 18 (right), the correlation of the filtered

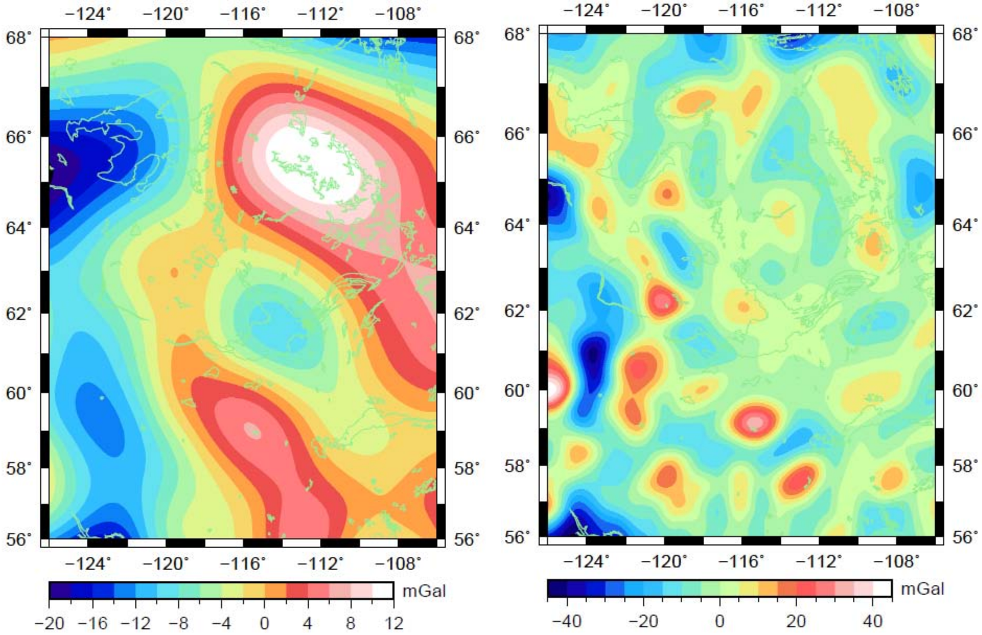

Figure 18. Long- and medium-pass filtered differences between terrestrial and TIM2 gravity field over the Canadian plains. Left: up to degree 32. Right: up to degree 120.

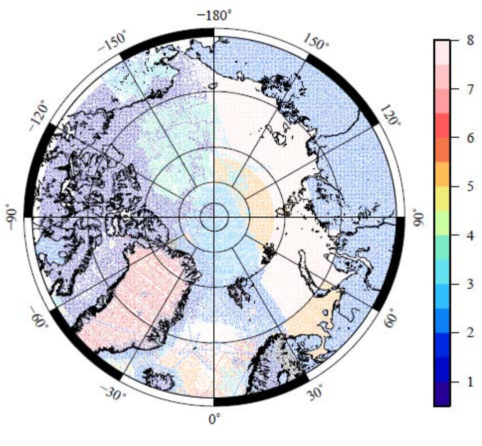

Figure 19. Distribution of point free-air gravity anomalies over the Arctic zone. The color scale indicates the accuracy of the free-air gravity anomalies derived from ten different surveys.

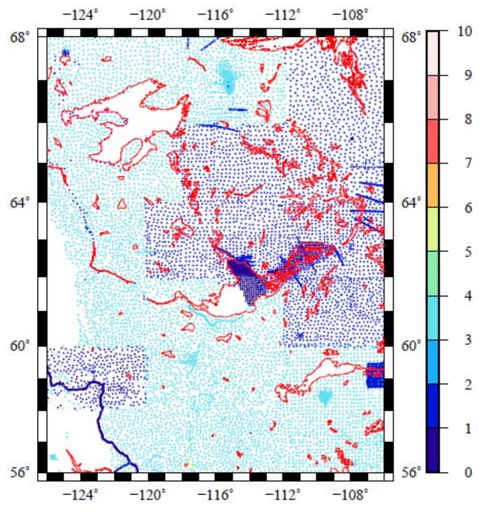

Figure 20. Distribution of point free-air gravity anomalies over the Canadian plains. The color scale indicates the accuracy of the free-air gravity data.

differences is rather related with the spatial distribution of the S-W part of the test area. However, the large discrepancies in relation with the accuracy of the terrestrial data are plausible and are due to long- and medium-wavelength errors in TIM2.

3. Conclusion

The degree variances of all models discussed in this investigation agree very well up to harmonic degree ~160, except from EIGEN-2 and EIGEN-3. However, the error spectra characteristics of the combined models are different.

With respect to the combined EGMs EIGEN-GL05C and EGM2008, the error degree variances of the EGMs derived from GOCE (SPW, DIR and TIM release 1 or 2) are larger from degree 2 to degrees ranging from 62-80 for EGM2008 and from 88-95 for EIGEN-GL05C. These become smaller up to degrees ranging from 140-145 for EGM2008 and from 160-170 for EIGEN-GL05C and larger from these degrees up to their maximum degree of expansion. This behavior supports the hypothesis that the GOCE data can contribute in improving the medium harmonics of the EGMs (between the degrees 90 and about 180).

The behavior of the error spectra characteristics of the GRACE-only derived ITG-GRACE2010 and the GOCE and Grace derived GOCO01S and GOCO02S relative to those of the combined EGMs EIGEN-GL05C and EGM2008 is also characteristic. Their error-degree variances exceed the error degree variances of the combined models only after degrees ranging from 150-185 degrees.

The numerical experiments carried out with ground gravity data showed very similar results in terms of the statistics of the reduced gravity anomalies by the models under investigation up to harmonic degree 120. This finding is related with the hypotheses used in estimating the accuracy of the harmonic coefficients. However, the statistics of the reduced gravity anomalies to higher degrees showed increased discrepancies up to several mGals. Up to harmonic degree 240, DIR yielded better statistical results of the reduced gravity anomalies than DIR2, especially in the Arctic zone. Finally, up to degree 250 the combined models EIGEN-GL05C and EGM2008 show better statistics of the reduced gravity anomalies than GOCO02S and TIM2.

The inter-comparison of the models in the extended test areas of Australia, the Arctic Zone and Antarctica showed interesting information about their behavior at harmonic degrees 120 or 180. This inter-comparison was carried out not only in terms of the statistics of the differences of their contribution at points of terrestrial observations, but also in terms of the shape of these differences. In Australia, the statistics showed that up to degree 120 the standard deviation of the differences remains below 0.5 mGal, while up to degree 180 ranges between 0.5 and 2 mGal, with the exception of differences involved ITG-2010. Similar situation but with increasing range of the standard deviation appeared for both harmonic degrees in the Arctic zone and in Antarctica. With reference to the shape of the differences, patterns with tesseral or sectorial harmonics appeared to dominate, depending on the method used for the development of the models, the particular properties of the data used and the degree of expansion.

The procedure detecting long- or medium-wavelength differences between terrestrial gravity anomalies and satellite-only derived EGMs shows considerable discrepancies in most of the test areas. Their correlation is not so strong with the spatial distribution or the accuracy of the data. With respect to wavelength, the differences at the medium-wavelengths are more serious. Regarding the areas considered, the differences in the Arctic zone are more significant. In general, the differences are large in relation to the estimated accuracy of the terrestrial data, so that it is plausible to attribute some of the differences to errors in the EGM. However, it is noteworthy that the filtering procedure does not remove only frequencies beyond the degree to which is designed.

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