Investigation of topographic reductions for marine geoid determination in the presence of an ultra-high resolution reference geopotential model

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Abstract. During the last decade, the realization of the satellite gravity missions of CHAMP and GRACE, the acquisition of new gravity data and the development of novel processing methodologies has led to the determination of more accurate and higher in resolution global geopotential models. The spatial scale of ~110 km that EGM96 could represent has improved today with EGM2008 to the level of ~16 km (full wavelength). This advance in the representation of higher frequencies by the geopotential models may signal the need to reassess the methodologies and techniques traditionally used for local and regional geoid determination. The traditional procedure followed is that of the remove-compute-restore method. The input functionals related to the Earth's gravity field are first reduced to a reference geopotential model, then the topographic effects are taken into account through one of the available reduction methods, computations follow using the reduced observations, and finally the contribution of the global geopotential model and the topographic indirect effects are added back to the computed reduced geoid values. One crucial point to this operation is that the attraction of the masses considered with a topographic reduction scheme is supposed to represent the medium and high frequencies in the gravity field, which still remain in the data, in principle even after they have been reduced to a geopotential model. Given that the best available digital depth models have a resolution of 30 arcsec, which translates to roughly 1 km spatial wavelength, it becomes apparent that the contribution of such a model to the reduction of gravity and geoid data, when a high resolution geopotential model is used as reference, is questionable or should be at least investigated. This final point is the main goal of this paper, i.e., to investigate the contribution of the available digital depth models to the reduction of gravity anomalies and geoid heights when a geopotential model with the resolution of EGM2008 is used. To this extent, marine gravity anomalies and satellite altimetry sea surface heights are used off-shore the Atlantic coast of Argentina. EGM2008 is used as a reference surface to reduce the available gravimetric and altimetric observations, and the latest bathymetry model from the Scripps Institute of Oceanography group (SIOv11.1) is employed in order to compute topographic reductions based on the Residual Terrain Model (RTM) scheme. The results acquired are validated in terms of the reduction they provide to the available input data, both the mean and the standard deviation of the residuals, as well as in terms of the spectral content of the residual signal spectrum. Conclusions and recommendations on the use of topographic reductions and the treatment of topographic effects for geoid modelling in the presence of a high-resolution geopotential model are also drawn so as to ensure the consistency between data used and results acquired.

Keywords. EGM2008, Global Gravity Model (GGM), mean dynamic topography, bathymetry models, Atlantic Ocean, Argentina.

1 Introduction

The most popular scheme used during the last years for geoid modeling is based on the well-known remove-compute-restore (RCR) method (Forsberg 1993, Sideris 1994). This method is based on removing the long wavelengths by a Global Gravity Model (GGM) while the short-wavelengths are supposed to be modeled by available Digital Topography and Bathymetry Models (DTMs and

DBMs respectively). To that extent, the available DTMs and DBMs should contain enough high-resolution information and be accurate enough in order to represent frequencies shorter than those of the GGM, for a rigorous use of the RCR method.

With the advent of the CHAMP, GRACE and GOCE missions and the realization of the EGM2008 GGM (Pavlis et al. 2008), the available GGM have much more power up to very-high degrees and increasing accuracy. EGM2008 has been recently released to public by the U.S. Geospatial-Intelligence Agency (NGA) EGM Development Team. It presents a spherical harmonics expansion of the geopotential to degree and order 2159, while additional spherical harmonics coefficients to degree 2190 and order 2159 are also available. The full degree and order of EGM2008 (2159) translates to a spatial resolution of ~5 arcmin, but in the present study it has been used only up to degree 1834 since above that the signal-to-noise ratio is smaller than 1 (see Figure 1).

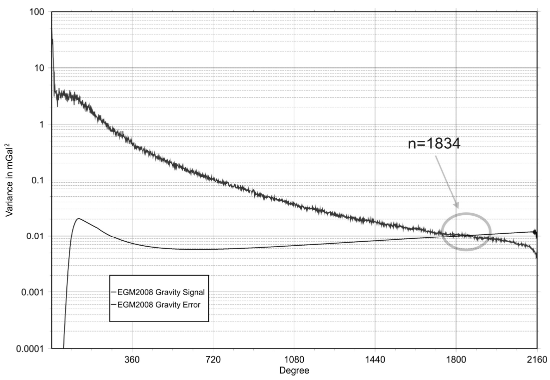

Figure 1: By degree EGM2008 signal and error power.

Contrary to the best available DTMs today (SRTM-class), which have a spatial resolution of 3 arcsec, the corresponding DBMs have a spatial resolution of 30 arcsec (best case scenario). This arises some questions as to whether their spatial resolution is enough in order to contemplate that of the EGM2008 model. Another possible limiting factor in the use of the currently available DBMs, for marine gravity and geoid modeling, is their accuracy. Errors in the DBMs will introduce errors in the estimated terrain effects thus deteriorating the quality of computed terrain reductions. These considerations where the source that set the main goal of the present study that is to evaluate the performance of the currently best available DBM towards marine geoid modeling employing the RCR method in the presence of an ultra-high degree GGM.

2 Computation strategy and results

In order to evaluate the performance of the currently best available DBM towards marine geoid modeling employing the RCR method, ERS1GM Sea Surface Heights (SSHs) and satellite altimetry derived marine free-air gravity anomalies from the Danish National Space Agency DNSC08 (Andersen and Knudsen 2008) high resolution (1 arcmin) model are used as input data. The satellite altimetry data were 70510 Corrected Sea Surface Height (CORSSHs) measurements from the Geodetic Mission (GM) of the European Remote-sensing Satellite 1 (ERS1), which are generated by the CLS Space Oceanography Division and provided by Archiving, Validation and Interpretation of Satellite Oceanographic data (AVISO 1998). The study is carried out off-shore the Atlantic coast of Argentina**,** limited by 34°S to 55°S in latitude and 70°W (290° E) to 56°W (304°E) in longitude.

Within the RCR frame, EGM2008 complete to degree and order 1834 is used as a reference geopotential model and the effect of bathymetry is taken into account through a Residual Terrain Model (RTM) reduction using the Scripps Institute of Oceanography SIOv11.1 (Smith and Sandwell 1997) bathymetry model (see Figure 2). The RIO Dynamic Ocean Topography (DOT) model (Rio and Hernandez 2004) is used to reduce the altimetric SSHs to the geoid.

For the RTM reduction, a reference elevation model is constructed from the fine one with 6 arcmin resolution (corresponding to degree 1834) by taking simple moving averages. In all computations the detailed DBM has been used, both for the near-zone and far-zone effects, since with the compute power available today there is little need to use coarser resolution terrain grids for the distant effects. The resulting residual geoid heights and gravity anomalies are evaluated both in terms of their statistics, compared to the EGM2008 reduced fields, as well as in terms of their spectra.

Table 1 presents the statistics of the available ERS1 SSHs, the DOT as computed on the ERS1 sub-satellite points, the EGM2008 contribution on the same points and reduced field N^{red}, which is the difference between the ERS1 SSHs minus the DOT, minus EGM2008. Note that in Table 1 N^{alt} denotes the DOT corrected ERS1 SSHs. The statistics of the DNSC08 and EGM2008 gravity anomalies as well as their differences can be seen in Table 2.

Following Forsberg (1984) the RTM reduction for gravity anomalies is computed as:

$$\delta g_{RTM} = 2\pi\Delta\rho(h - h_{ref}) \qquad (1)$$

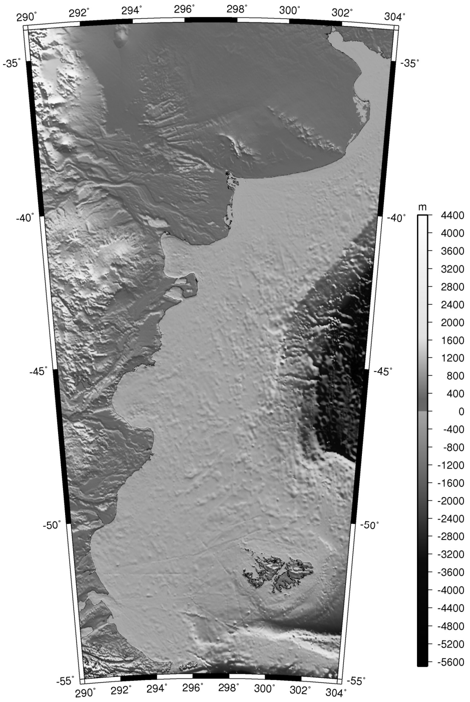

Figure 2: The area under study and its bathymetry according to the SIOv11.1 model.

Table 1: Statistics of the available ERS1 SSHs, DOT, EGM2008 contribution and reduced fields. Unit: [m]

	max	min	mean	rms	std
$ERS1^{SSHs}$	19.010	0.589	11.259	11.673	±3.079
DOT	1.807	0.955	1.482	1.494	±0.192
$N^{EGM2008}$	18.995	1.014	11.071	11.442	±2.890
N^{alt}	17.732	-0.52	9.777	10.208	±2.933
N^{red}	0.912	-3.21	-1.294	1.316	±0.239

Table 2: Statistics of the available DNSC08 gravity anomalies, EGM2008 contribution and reduced fields Unit: [mGal]

	max	min	mean	rms	std
Δg^{DNSC08}	135.07	-134.66	3.57	25.82	±25.57
$\Delta g^{EGM2008}$	135.96	-137.63	3.57	25.97	±25.72
Δg^{red}	21.36	-29.81	0.00	3.67	±3.67

where H is the bathymetric depth given by a global bathymetry model, h_{ref} is the depth of a smooth mean reference surface (the 6 arcmin model in this case as previously described) and $\Delta\rho$ is the density contrast between Earth's crust and seawater.

For all terrain effects computations the GRAVSOFT (Tscherning et al. 1992) suite has been used to create the reference bathymetric grid and estimate the RTM reduction on geoid heights and gravity anomalies. The primary use of the RTM reduction is to obtain residual SSHs, so that after that step prediction and interpolation can be performed with a smoother field. The statistics of the RTM effects computed using different density contrasts are presented in Table 3 together with the residual Sea Surface Heights that represent the medium wavelengths of the geoid heights and can be considered as residual geoid heights (N^{res}).

Table 3: Statistics of the RTM-effects and residual ERS1 geoid heights for various density contrasts. Unit: [m]

	max	min	mean	rms	std
			Δρ=2.67 g/cm³		
N^{RTM}	1.233	-1.490	0.080	0.191	±0.174
N^{res}	0.955	-3.164	-1.374	1.409	±0.309
			Δρ=2.47 g/cm³		
N^{RTM}	1.083	-1.308	0.071	0.168	±0.152
N^{res}	0.948	-3.172	-1.365	1.396	±0.296
			Δρ=2.3 g/cm³		
N^{RTM}	0.955	-1.153	0.062	0.148	±0.134
N^{res}	0.943	-3.179	-1.357	1.386	±0.286
			Δρ=2.2 g/cm³		
N^{RTM}	0.880	-1.063	0.058	0.136	±0.124
N^{res}	0.939	-3.183	-1.352	1.380	±0.280
			Δρ=2.1 g/cm³		
N^{RTM}	0.805	-0.972	0.053	0.125	±0.113
N^{res}	0.936	-3.187	-1.347	1.375	±0.275
			Δρ=1.6 g/cm³		
N^{RTM}	0.429	-0.518	0.029	0.067	±0.060
N^{res}	0.920	-3.206	-1.323	1.347	±0.252
			Δρ=1.4 g/cm³		
N^{RTM}	0.278	-0.336	0.019	0.044	±0.039
N^{res}	0.913	-3.214	-1.313	1.336	±0.246
			Δρ=1.3 g/cm³		
N^{RTM}	0.265	-0.324	0.015	0.033	±0.029
N^{res}	0.908	-3.218	-1.302	1.324	±0.242

Comparing the results acquired from the RTM reduction of the ERS1 SSHs (see Tables 1 and 3), it becomes evident that, whatever the density contrast used, there is no gain both in terms of the mean and the std of the field. In most cases, apart from the one that a density contrast of 1.3 gr/cm^3 has been used, the residual N^{res} field has larger mean and std. These signal that the available bathymetry model has insufficient resolution to depict more detailed bathymetric features than those included in EGM2008. Moreover, given that the SIOv11.1 DBM has been estimated by inverting satellite altimetry data, it can be concluded that such DBMs need to be augmented by soundings in order to determine collocated solutions with higher resolution and accuracy (Smith and Sandwell 1997). Of course, echo soundings are scarce, especially over such large regions, therefore the improvement in the DBMs by combined solutions would probably be only local.

The behaviour of EGM2008 is quite peculiar (see Table 1), since the reduced filed has a very large mean value (-1.3 m). This, is not reduced by the RTM reduction, which indicates that some signal(s) remain in the field which should be modelled. Similar mean value results have been achieved for EGM96 (Tocho et al. 2005a, 2005b) and may be due to the truncation of EGM2008 to degree 1834. On the other hand this behaviour might be due to the incorporation of the DOT model for the reduction of the ERS1 SSHs to the geoid. Notice that the DOT has a mean value of 1.5 m which is almost equal (with opposite sign) to that of the N^{res} field. In fact if the ERS1 SSHs are not reduced for the DOT, the EGM2008 reduced SSHs have a mean value of 0.19 m only, though the std increases to ±0.33 m. This may signal that part of the DOT of the area is included in EGM2008 spectrum, maybe due to the altimetry data used in its development. It should be noted though that when altimetric data are used for marine geoid modelling, their reduction for the DOT is mandatory whether else the surface determined is not the geoid but the mean sea surface. In similar studies performed in other areas of the world like the Mediterranean and off-shore Newfoundland such behaviour has not been observed either for EGM96 and EGM2008 (Vergos et al. 2005a, 2005b, 2007). The same holds for this particular area under study when other GGMs have been used (Tocho et al. 2007). This behaviour of EGM2008 remains to be investigated in future work.

Table 4 shows the statistics of both the RTM effect on gravity computed with Eq. 1, using various density contrasts, and the residual gravity anomalies computed using Eq. 2:

$$\Delta g_{res} = \Delta g_{FA} - 2\pi G\rho(h - h_{ref}) - \Delta g_{GM} \quad (2)$$

where Δg_{FA} are the free-air satellite gravity anomalies from DNSC08 model reduced by the residual terrain model reduction and the geopotential model. It should be noted that all density contrasts as in the case of ERS1 geoid heights (Table 3) have been tested as well, but only the ones with the best statistics after the reduction are reported.

For the reduction of the DNSC Δg similar results are obtained. Only with a density contrast of 1.3 gr/cm^3 a reduction in the standard deviation (std) was achieved by 0.02 mGal only (last line in Tables 2 and 4), which is clearly insignificant. EGM2008 performs very well in the contribution to Δg, since the reduced field has a zero mean and a std at the ±3.7 mGal level. The RTM reduction did not manage to provide significant improvement, which signals that EGM2008 contains all the power that the bathymetry has to offer. Therefore, higher-resolution DBMs should be employed, whether else the reduction of marine data for the bathymetry, within gravity field modeling and gravimetric geoid studies, may not have any meaning.

Table 4: Statistics of the RTM-effects and residual gravity anomalies for various density contrasts. Unit:[mgal]

	max	min	mean	rms	std
		Δρ=1.6 gr/cm^3			
Δg^{RTM}	16.62	-53.07	0.13	1.81	±1.80
Δgres	50.43	-21.15	-0.12	3.92	±3.91
		Δρ=1.5 gr/cm^3			
Δg^{RTM}	13.77	-48.97	0.10	1.53	±1.53
Δgres	46.34	-18.97	-0.09	3.81	±3.81
		Δρ=1.4 gr/cm^3			
Δg^{RTM}	10.84	-44.86	0.07	1.27	±1.27
Δgres	42.26	-16.65	-0.06	3.72	±3.72
		Δρ=1.3 gr/cm^3			
Δg^{RTM}	7.91	-40.76	0.05	1.01	±1.01
Δgres	39.22	-14.97	-0.04	3.65	±3.65

From the signal PSDs of the gravity data depicted in Figure 3, it is clear that EGM2008 has almost the same power as the original data. But, the two side-lobes in the EGM2008 PSD (circles) indicate that the geopotential model has some of its power in higher degrees and larger correlation length than the original Δg. These side-lobes are at wavelengths of harmonic degrees ~85-90 (~244 km), so they may indicate the influence of GRACE data in EGM2008. In any case they should be further investigated, since in similar tests in other areas (Mediterranean Sea) such effects are absent (Tziavos et al. 2010).

From the signal PSDs of the geoid heights shown in Figure 4, it is clear that EGM2008 has almost the same power as the original data. In the geoid height contribution of EGM2008 no side-lobes are observed, which is probably due to the fact that less power, compared to Δg, of the geoid height spectrum is contained in higher degrees. After the reduction to EGM2008, the remaining field does not present clear random characteristics (noise) since the mean value remains quite large. This is evident by the fact that the signal gain is reduced but not significantly, even after the RTM reduction. One factor that can explain that is the presence of part of the DOT signal in it, since the spectrum of the latter has power up to ~150 km in the area under study so its contribution will have impact on the residual field (bottom right in Figure 4).

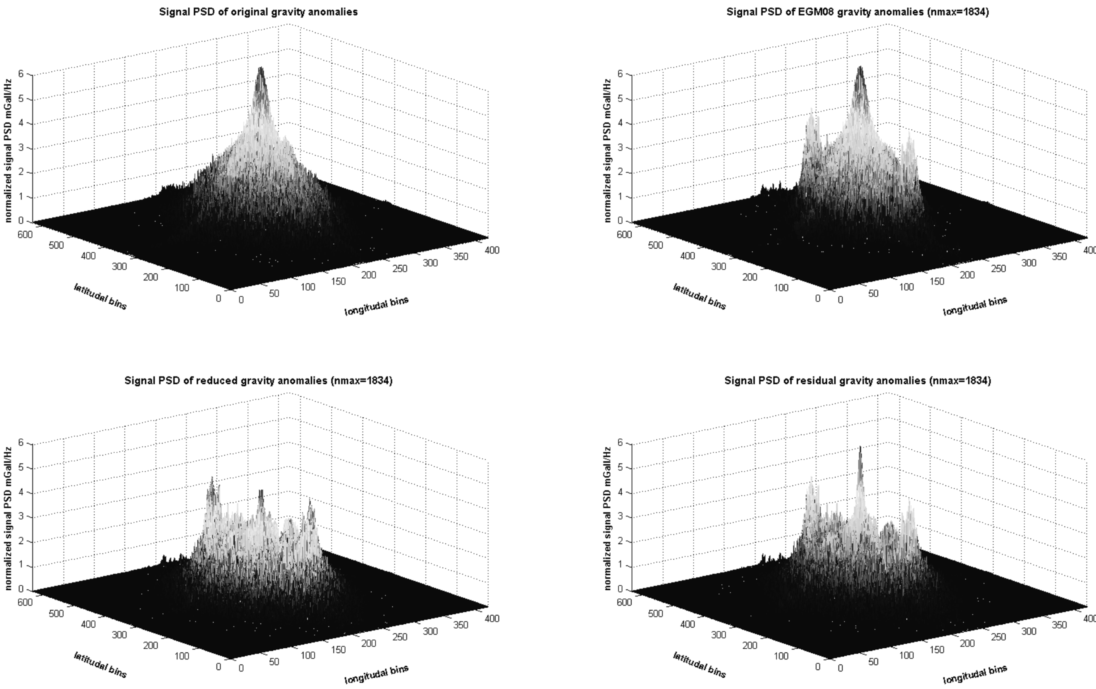

Figure 3: Signal PSDs of the original gravity data (top left), EGM2008 (nmax=1834) contribution (top right), reduced gravity (bottom left) and residual field after the RTM reduction (bottom right).

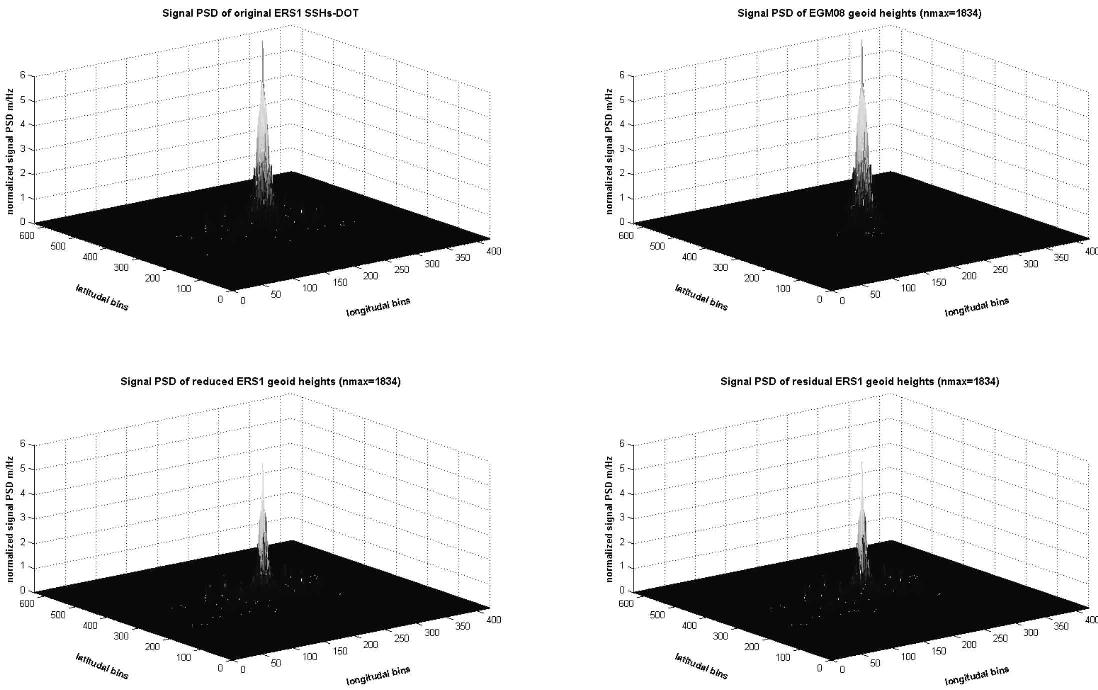

Figure 4: Signal PSDs of the original ERS1 SSHs (top left), EGM2008 (nmax=1834) contribution (top right), reduced geoid heights (bottom left) and residual field after the RTM reduction (bottom right).

Finally, it is worth mentioning that in related studies over continental regions where the DTM resolution is higher compared to that of the DBMs (3 vs. 30 arcsec), even when EGM2008 is used as a reference, a significant reduction of the mean and std of the residual field can be achieved (Tziavos et al. 2010).

3 Conclusions

From the results acquired, it can be concluded that the spatial resolution of the currently available DBMs is not enough in order to provide higher frequency content information compared to EGM2008 for marine gravity field and geoid modeling. Therefore, the methodology followed during the RCR scheme should be revised, at least when EGM2008, or other ultra-high degree geopotential models, are used as reference. Such high-resolution geopotential models representing the geoid can be used from now on for DOT and time-varying DOT modeling in combination with altimetry, GOCE- and GRACE-type of data. Unless the available global DBMs, which in most cases come from the inversion of altimetric observations, do not increase their spatial resolution, then they should be used in marine gravity field and geoid modeling with caution. If topographic reductions at sea are to be used for the latter, then higher-resolution DBMs should be developed from combination techniques (altimetry & soundings). Moreover, a new geodetic mission from altimetry, which will improve the across-track spacing of the currently available multi-mission altimetric record, may improve the currently available DBM resolution.

Acknowledgement

The terrain reductions presented in the paper have been computed with the GRAVSOFT package (Tscherning et al. 1992). We extensively used the Generic Mapping Tools (Wessel and Smith 1998) in displaying our results.

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