Further improvements in the determination of the marine geoid in Argentina by employing recent GGMs and Sea Surface Topography models

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Abstract. During the last six years, extensive efforts have been put for the determination of the marine geoid in the Atlantic coastal area of Argentina. Up until recently, the main focus has been directed in the development of combined solutions through heterogeneous data, such as gravity anomalies, altimetric sea surface heights and bathymetric information employing both space and frequency domain methods. With the advent of the gravity-field dedicated satellite missions of CHAMP and GRACE and the development of more accurate satellite-only and combined global gravity models (GGMs), improved solutions have been acquired. Nevertheless, one point that still needed attention was the incorporation of proper, in terms of accuracy, sea surface topography models for the reduction of altimetric sea surface heights to the geoid. With that in mind, and the fact that 2008 is a benchmark year for GGMs due to the presentation of the new NGA GGM (EGM08), additional efforts have been carried out for the determination of new improved solutions for the marine geoid in Argentina.

This work focuses on the determination of combined solutions through the combination of all available gravity and satellite altimetry data for the area under study, while digital bathymetric data are used to compute topographic effects and reduce the data in the usual remove-compute-restore scheme. Finally, the new improved Combined Mean Dynamic Topography (CMDT) model by Rio for the area under study is used to reduce the altimetric data to the geoid. All these are carried out using the latest GGMs employing CHAMP and GRACE data, i.e., EIGEN-GL04C, EIGEN-CG01C, EIGEN-CG03C and GGM02C, together with the new EGM08. Combination methods such as Input Output System Theory (IOST) is investigated, while purely altimetric, gravimetric and combined marine geoid models are determined as well. The quality of the estimated new marine geoid solutions is assessed through comparisons with previous solutions, stacked Topex/Poseidon (T/P) sea surface heights, Jason-1 and Envisat data.

Keywords. EGM08, Global Gravity Models (GGMs), mean dynamic topography, Atlantic Ocean, Argentina.

1 Introduction

The main objective of this paper is to investigate the possibility of improving the accuracy of the marine geoid models available offshore Argentina employing the new Global Gravitational Model EGM2008 (Pavlis et al., 2008) and the Rio Combined Mean Dynamic Topography Model (Rio and Hernandez, 2004).

EGM2008 has been recently release to public by the U.S. Geospatial-Intelligence Agency (NGA) EGM Development Team. It is developed up to degree and order 2159, and contains additional spherical harmonics coefficients extending to degree 2190 and order 2159.

Sea Surface Heights (SSHs) refer to the Mean Sea Surface (MSS), therefore in order to estimate geoid heights from altimetry data we need to reduce the SSHs to the geoid using a Mean Dynamic

Topography Model (MDT). This is an important step in altimetric geoid and/or gravity field determination and can be viewed as an equivalent to the free-air reduction of surface and marine gravity anomalies to the geoid. Neglecting that reduction will result in the determination of the MSS and not the geoid. Since the MDT varies between -2.2 m and 70 cm with a standard deviation of ±62 cm in a global scale (Koblinsky et al., 1999) it becomes apparent that such considerations are mandatory and not optional (Vergos et al. 2005a, b). Assuming that the geoid is stationary, we can compute altimetric geoid heights as:

$$GEOID=SSHs-MDT \quad (1)$$

In the frame of this work, pure gravimetric and altimetric geoid models as well as a combined solution using the Multiple Input Multiple Output System Theory (MIMOST) (Sideris, 1996; Andritsanos et al., 2000, 2001) have been determined. The area under study is located in the Atlantic Coastal region of Argentina, bounded between 34°S to 55°S in latitude and 56°W (304°E) to 70°W (290° E) in longitude.

Both the purely gravimetric and altimetric solutions were computed using the following reference Global Gravity Models: EGM96 (Lemoine et al., 1998), the models based on CHAMP and GRACE satellite mission data: EIGEN-CG01C (Reigber et al., 2006), EIGEN-CG03C (Förste et al., 2005), EIGEN-GL04C (Förste et al., 2008), GGM02C (Tapley et al., 2005) and EGM2008 up to maximum degree 2190 (Pavlis et al., 2008).

The quality of the estimated new marine geoid solutions is assessed through comparisons with older geoid solutions computed by the authors (Tocho et al., 2005a, b), stacked Topex/Poseidon (T/P) Sea Surface Heights, JASON1 data and ENVISAT altimetric observations.

2 Computation strategy and Results

As Global Gravity Models (GGMs) play an important role in the remove-compute-restore technique the first test was to validate the new EGM2008 model in the area under study. Table 1 shows the statistics of the differences between EGM2008 and the other Global Gravity models; the difference between EGM2008 and EGM96 is depicted in Figure 1. The differences are mainly over the Argentinean mainland. From a comparison with the differences between EGM96 and GGM02C, these differences seem to come mostly from GRACE data. From Table 1 it is also worth mentioning that the differences between the latest NGA combination GGM and the latest GFZ models (namely EIGEN-CG03C and EIGEN-GL04C) are at the ±20 cm and ±19 cm level while the range reaches the 5.26 m and 4.9 m respectively.

Table 1: Statistics of the differences between geoid heights computed from the new EGM2008 and the other GGMs. Values in parenthesis refer to oceanic regions. Unit: (m)

	min	*max*	*mean*	*σ*
$N^{EGM2008}-N^{EGM96}$	-4.13	2.60	0.013	0.58
	(-1.83)	(1.38)	(-0.06)	(0.31)
$N^{EGM2008}-N^{EIGEN-CG01C}$	-1.75	3.30	-0.008	0.25
	(-1.30)	(1.15)	(0.005)	(0.20)
$N^{EGM2008}-N^{EIGEN-CG03C}$	-1.63	3.63	-0.012	0.25
	(-1.15)	(1.03)	(-0.013)	(0.20)
$N^{EGM2008}-N^{EIGEN-GL04C}$	-1.73	3.17	0.002	0.24
	(-1.39)	(1.25)	(0.002)	(0.19)
$N^{EGM2008}-N^{GGM02C}$	-2.06	2.99	0.001	0.34
	(-1.66)	(2.01)	(0.007)	(0.32)
$N^{EGM96}-N^{GGM02C}$	-2.39	2.99	-0.012	0.62
	(-1.54)	(1.86)	(0.076)	(0.38)

In the frame of the present work, nineteen geoid models have been computed in the area under study. These include six purely gravimetric solutions, 12 purely altimetric solutions and 1 combined solution. All the solutions were estimated using the remove-restore technique. The processing sequence for the estimations is extensively outlined in (Tocho et al., 2005a, b).

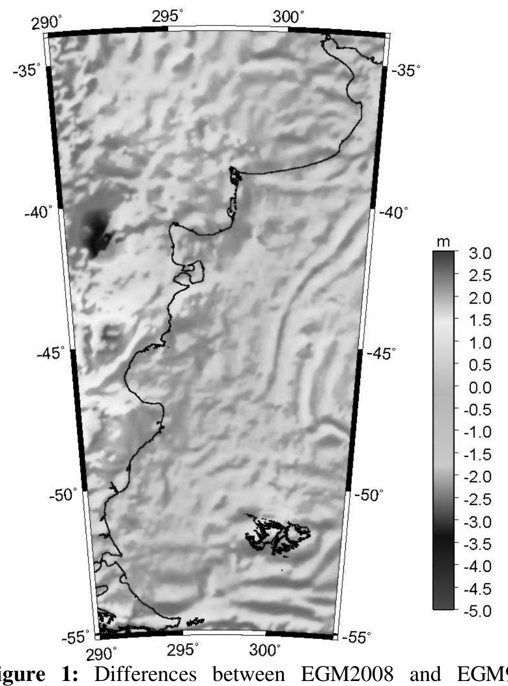

Figure 1: Differences between EGM2008 and EGM96 geoid heights

The purely altimetric solutions have been computed using 70510 ERS1-GM SSHs corresponding to all cycles from November 28th, 1994 to March 21st, 1995. These raw SSHs have been corrected from all instrumental errors and geophysical effects that affect altimetric measurements, obtaining in this way Corrected Sea Surface Heights (CSSHs) (AVISO 1998). These heights refer to the mean sea surface, so they have to be reduced to the geoid by removing the contribution of the MDT. The EGM96 Dynamic Ocean Topography (EGM96.DOT) (Lemoine et al., 1998), complete to degree and order 20 and the Rio Combined Mean Dynamic Topography (Rio and Hernandez 2004) were used to take into account the MDT. Both models are presented in Figures 2 and 3 respectively, where it is evident that the EGM96 MDT model presents a very simplistic and smooth version of the sea surface topography and of the circulation of the area compared to the Rio model. Of course this is normal, given that the EGM96.DOT model has been computed 15 years ago and incorporates fewer data than the Rio model. In any case, the availability of the Rio MDT model allows for a more rigorous treatment of the sea surface topography contribution in geoid modeling.

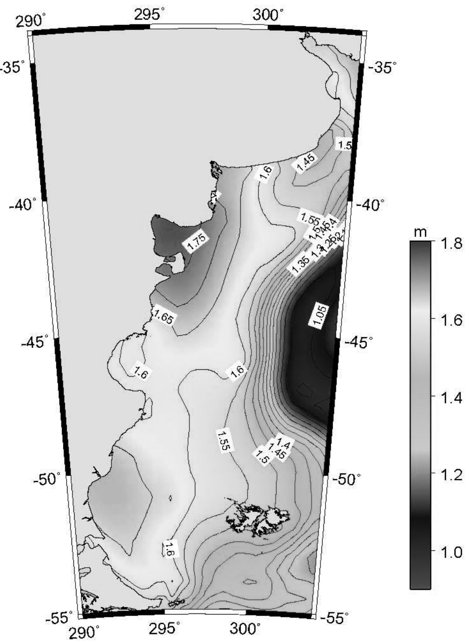

Figure 2: Rio CMDT

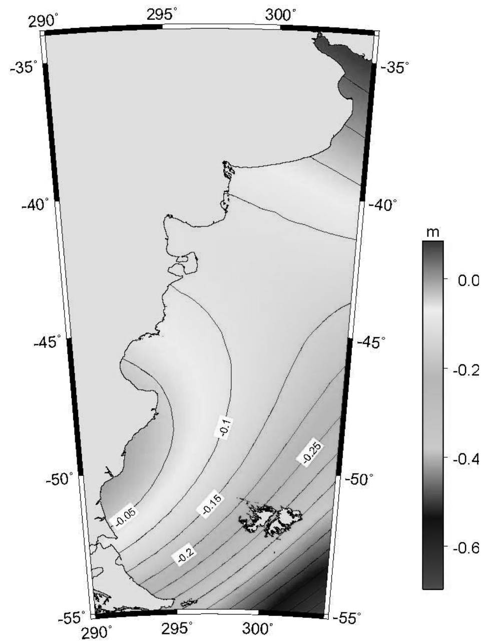

Figure 3: EGM96.DOT

Then, following the remove-restore method, the contribution of the six global geopotential models and the contribution of the bathymetry, using the Sandwell and Smith model (1997) were removed from the corrected SSHs, obtaining residual geoid heights. From these residual geoid heights a 3 rms test was performed in order to detect blunders and then they were interpolated on a $3' \times 3'$ grid. A low-pass filter was applied to the residual grid to reduce the high sea surface variability in the area under study. Finally, the contribution of the bathymetry and the geopotential models were restored yielding the final geoid solutions. The statistics of the final models, reduced with the Rio CMDT and the EGM96.DOT are presented in Table 2 and Table 3 respectively.

The gravimetric geoid solution were based on terrestrial and satellite altimetry-derived gravity ano

Table 2: Statistics of the final altimetric geoid solutions computed with the Rio CMDT. Unit: (m)

	min	*max*	*mean*	*σ*
N^{ERS1}(EGM2008)	0.691	19.260	11.221	±2.933
N^{ERS1}(EGM96)	0.423	19.276	11.235	±2.939
N^{ERS1}(EIGENCG-01C)	0.583	18.889	11.143	±2.935
N^{ERS1}(EIGENCG-03C)	0.495	18.922	11.208	±2.933
N^{ERS1}(EIGENGL-04C)	0.669	18.853	11.166	±2.932
N^{ERS1}(GGM02C)	0.706	18.993	11.202	±2.933

Table 3: Statistics of the final altimetric geoid solutions computed with the EGM96.DOT. Unit: (m)

	min	*max*	*mean*	*σ*
N^{ERS1}(EGM2008)	0.580	19.379	11.184	±3.065
N^{ERS1}(EGM96)	0.346	19.387	11.206	±3.071
N^{ERS1}(EIGENCG-01C)	0.545	19.138	11.236	±3.054
N^{ERS1}(EIGENCG-03C)	0.458	19.209	11.300	±3.052
N^{ERS1}(EIGENGL-04C)	0.631	19.144	11.258	±3.057
N^{ERS1}(GGM02C)	0.669	19.169	11.294	±3.052

malies, while they were computed using the remove-compute-restore technique, employing the 1D-FFT spherical Stokes's convolution formula (Haagmans et al., 1993) for the prediction of residual geoid heights. Before the prediction of the residual geoid, the free-air gravity anomalies have to be reduced by a geopotential model during the remove step. Furthermore, the effect of the topography/bathymetry was taken into account through a topographic reduction. In this study, Helmert's second method of condensation was used to account for the terrain effects. The final gravimetric geoid is obtained in the restore step adding back the effect of the topography and the geopotential model. Six different gravimetric geoid models were obtained; each one was referenced to a different GGM, while the statistics of final models are summarized in Table 4.

Table 4: Statistics of final gravimetric geoid solutions (m)

	Min	*max*	*mean*	*σ*
N^{GRAV}(EGM2008)	1.032	19.526	11.833	±3.103
N^{GRAV}(EGM96)	1.034	20.017	11.809	±3.083
N^{GRAV}(EIGENCG-01C)	1.118	19.631	11.849	±3.103
N^{GRAV}(EIGENCG-03C)	1.150	19.599	11.848	±3.115
N^{GRAV}(EIGENGL-04C)	1.055	19.616	11.836	±3.112
N^{GRAV}(GGM02C)	1.054	20.411	11.875	±3.127

3 Geoid model validation

For the validation of the estimated geoid solutions, stacked T/P, JASON1 and ENVISAT SSHs were used. Table 5 shows the statistics of geoid height differences between EGM2008 and EGM96 with T/P, ENVISAT and JASON1 SSHs reduced with the CMDT model (m). In all the cases, the differences between the geoid solutions from these Global Gravity Models and the mentioned SSHs were computed and minimized using a four parameter similarity transformation model. From Table 5 it is evident that EGM08 brings significant improvement in the determination of the Earth's gravity field, since it outperforms EGM96, in all cases, by 11-14 cm. Moreover, and with respect to the different altimetric data used, it can be concluded that ENVISAT SSHs are superior to T/P ones by ±4 cm and by ±2 cm compared to JASON1. Furthermore, JASON-1 SSHs present a ±2 cm improvement in terms of the std of the differences, compared to T/P. The latter is in line with the conclusions drawn in Tocho et al., (2007) and Vergos et al., (2007) where a validation of T/P, ENVISAT and JASON-1 SSHs has been performed.

The T/P, JASON1 and ENVISAT SSHs were corrected with the EGM96.DOT and the Rio CMDT. The statistics of the differences between the T/P, JASON1 and ENVISAT SSHs and the pure altimetric geoid solutions can be seen in Table 6 and with the gravimetric solutions in Table 7.

Table 5: Geoid heights differences between EGM2008 & EGM96 and T/P, JASON1 and ENVISAT SSHs after bias and tilt fit. Unit[m]

	min	*max*	*mean*	*σ*
$N^{EGM2008}$-$N^{T/P}$	-1.140	0.700	0.000	±0.180
N^{EGM96}-$N^{T/P}$	-1.160	1.460	0.000	±0.293
$N^{EGM2008}$-$N^{ENVISAT}$	-0.650	0.510	0.000	±0.140
N^{EGM96}-$N^{ENVISAT}$	-1.230	1.620	0.000	±0.271
$N^{EGM2008}$-N^{JASON1}	-0.460	0.590	0.000	±0.160
N^{EGM96}-N^{JASON1}	-1.050	1.500	0.000	±0.296

Table 6: Statistics of geoid height differences between T/P, ENVISAT and JASON1 SSHs and the estimated altimetric geoid solutions using Rio CMDT & EGM96.DOT. Unit: (m)

	Rio CMDT	***EGM96 DOT***
	σ	
$\Delta N^{T/P-ERS1}$ (EGM2008)	±0.188	±0.189
$\Delta N^{T/P-ERS1}$ (EGM96)	±0.189	±0.194
$\Delta N^{T/P-ERS1}$ (EIGENCG-01C)	±0.194	±0.191
$\Delta N^{T/P-ERS1}$ (EIGENCG-03C)	±0.191	±0.190
$\Delta N^{T/P-ERS1}$ (EIGENGL-04C)	±0.190	±0.189
$\Delta N^{T/P-ERS1}$ (GGM02C)	±0.189	±0.191
$\Delta N^{JASON1-ERS1}$ (EGM2008)	±0.164	±0.166
$\Delta N^{JASON1-ERS1}$ (EGM96)	±0.166	±0.169
$\Delta N^{JASON1-ERS1}$ (EIGENCG-01C)	±0.169	±0.166
$\Delta N^{JASON1-ERS1}$ (EIGENCG-03C)	±0.166	±0.164
$\Delta N^{JASON1-ERS1}$ (EIGENGL-04C)	±0.164	±0.171
$\Delta N^{JASON1-ERS1}$ (GGM02C)	±0.171	±0.166
$\Delta N^{ENVISAT-ERS1}$ (EGM2008)	*±0.143*	*±0.140*
$\Delta N^{ENVISAT-ERS1}$ (EGM96)	±0.140	±0.150
$\Delta N^{ENVISAT-ERS1}$ (EIGENCG-01C)	±0.150	±0.145
$\Delta N^{ENVISAT-ERS1}$ (EIGENCG-03C)	±0.145	±0.146
$\Delta N^{ENVISAT-ERS1}$ (EIGENGL-04C)	±0.146	±0.144
$\Delta N^{ENVISAT-ERS1}$ (GGM02C)	±0.144	±0.145

4 Combined solution

The combined geoid model was determined with the FFT-based Multiple Input–Multiple Output System Theory. MIMOST theory with double input and single output combined solution was based on the formulas given by Sideris (1996) and Andritsanos et al., (2001). The combined geoid solution was estimated in a smaller area between 40°S to 50°S in latitude and 56°W (304°E) to 66°W (294° E) in longitude. The inputs of MIMOST were

Table 7: Statistics of geoid height differences between T/P, ENVISAT and JASON1 SSHs and the estimated gravimetric geoid solutions. Unit: (m)

	Rio CMDT (σ)
$\Delta N^{T/P-GRAV}$ (EGM2008)	±0.263
$\Delta N^{T/P-GRAV}$ (EGM96)	±0.275
$\Delta N^{T/P-GRAV}$ (EIGENCG-01C)	±0.283
$\Delta N^{T/P-GRAV}$ (EIGENCG-03C)	±0.291
$\Delta N^{T/P-GRAV}$ (EIGENGL-04C)	±0.295
$\Delta N^{T/P-GRAV}$ (GGM02C)	±0.319
$\Delta N^{JASON1-GRAV}$ (EGM2008)	±0.242
$\Delta N^{JASON1-GRAV}$ (EGM96)	±0.261
$\Delta N^{JASON1-GRAV}$ (EIGENCG-01C)	±0.271
$\Delta N^{JASON1-GRAV}$ (EIGENCG-03C)	±0.281
$\Delta N^{JASON1-GRAV}$ (EIGENGL-04C)	±0.282
$\Delta N^{JASON1-GRAV}$ (GGM02C)	±0.306
$\Delta N^{ENVISAT-GRAV}$ (EGM2008)	±0.206
$\Delta N^{ENVISAT-GRAV}$ (EGM96)	±0.214
$\Delta N^{ENVISAT-GRAV}$ (EIGENCG-01C)	±0.223
$\Delta N^{ENVISAT-GRAV}$ (EIGENCG-03C)	±0.234
$\Delta N^{ENVISAT-GRAV}$ (EIGENGL-04C)	±0.235
$\Delta N^{ENVISAT-GRAV}$ (GGM02C)	±0.266

residual gravimetric geoid heights and residual altimetric geoid heights with the contribution of the EGM2008 model removed in order to avoid long wavelength errors and with the altimetric data reduced with EGM96.DOT.

The input noises for each dataset were generated using the standard deviation of the differences between ENVISAT SSHs and the gravimetric geoid (±13.5 cm) and between ENVISAT SSHs and the altimetric geoid (±14 cm). The statistics of the solutions in the small area can be seen in Table 8 and in Table 9 their validation with ENVISAT data. Figure 4 depicts the MIMOST combined solution for the area under study.

The results presented in Table 6 lead to some important outcomes. For all comparisons the superiority of EGM08 over all other models is evident. EGM08 provides smaller std of the differences, by 1 cm compared to EGM96 and by 4-6 cm compared to the CHAMP and GRACE combination models. Comparing the results presented in Table 7 with those from Table 6, the superiority of the altimetric models over the gravimetric ones is evident, since in all cases the std of the differences of the former is smaller by about 6-10 cm over the latter.

From the results presented in Table 9, it becomes evident that the combined model improves the gravimetric geoid model in purely marine areas and the altimetric one close to the coastline.

Table 8: Statistics of the geoid models in the inner area. (m)

	min	max	mean	σ
N^{ERS1}	0.579	15.281	10.078	3.306
N^{GRAV}	1.077	16.153	10.847	3.433
$N^{EGM2008}$	0.960	14.755	10.124	3.068
N^{COMB}	1.061	16.140	10.845	3.437

Table 9: Statistics of the differences between ENVISAT SSHs and the gravimetric, altimetric and combined solutions (EGM08 as reference). (After bias and trend removed). The ENVISAT SSHs reduced with EGM96.DOT. Unit:[m]

	min	max	mean	σ
N^{ERS1} -ENVISAT	-1.270	0.870	0.000	±0.142
N^{GRAV} -ENVISAT	-0.500	0.730	0.000	±0.134
$N^{EGM2008}$-ENVISAT	-0.710	0.530	0.000	±0.181
N^{COMB}- ENVISAT	-0.520	0.700	0.000	±0.136

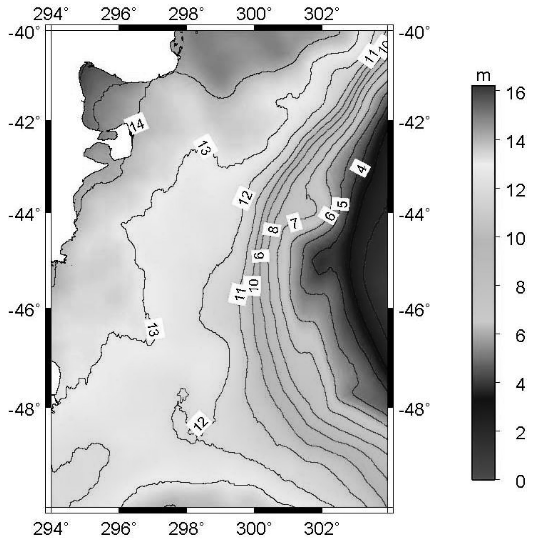

Figure 4: MIMOST solution

5 Conclusions-Future plans

The new NGA GGM EGM2008 was evaluated. When compared to EGM96 it provides a 11-13 cm improvement and an improvement of ~4-6 cm compared to CHAMP/GRACE GGMs. The Rio CMDT and EGM96.DOT were investigated for the reduction of altimetric sea surface heights to the geoid, and it became evident that it provides a much more realistic representation of the MDT in the area.

ENVISAT data provide higher accuracy compared to T/P and JASON1. The differences between ENVISAT SSHs and the gravimetric and altimetric geoid models, both referenced to EGM2008, dropped to ±14.5 and ±14 cm, respectively, in terms of the std (1σ). The combination improves the altimetric solution close to the coastline and the gravimetric one in the open ocean.

Other bathymetry models need to be evaluated, since an in-accurate model reduced the accuracy of the final solution and a detailed analysis of the combination of land and marine gravity data on the coastline should be carried out. The altimetric geoid models are ~2-8 cm better than the gravimetric.

The marine gravity data are probably not free-air reduced hence the large differences when using the Rio CMDT. The effect of the EGM96.DOT is removed with the bias and tilt fit. The new marine gravity Field DNSC08-GRA has to be evaluated to improve the accuracy of the gravimetric geoid.

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