Assessment of different-generation GOCE-only and GOCE/GRACE Earth Global Gravity Models over Argentina using terrestrial gravity anomalies and GPS/Levelling data

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Abstract

The Gravity field and steady-state Ocean Circulation Explorer (GOCE) dedicated satellite gravity field mission was launched by the European Space Agency (ESA) on March 17, 2009. Since then, several Global Geopotential Models (GGMs) have been released based on data collected by GOCE.

This paper evaluates different GOCE-only and GOCE/GRACE GGMs using 567 available GPS/Levelling points and terrestrial free-air gravity anomalies in Argentina. EGM2008 and EIGEN-51C models are also included in the evaluation procedure, even though they are not based on GOCE data. The idea of using these models is to identify any improvements of the new GOCE-only or GOCE/GRACE GGMs in Argentina. The truncation of the Stokes coefficients at a certain spherical harmonic degree n_1 produces an omission error. In order to reduce this omission error, synthetic GGMs are evaluated by adding signal from EGM2008 and topographic effects through a Residual Terrain Model (RTM) to the satellite GGMs models. The evaluation is performed with an incremental step of one in harmonic degree, so that the most detailed possible evaluation of the GOCE-only and GOCE/GRACE GGMs will be performed. The results show that EGM2008 is better than all GGMs, used for evaluation in this study, in terms of the standard deviation of the geoid heights are concerned. This superiority is marginal and statistically insignificant, being at the 3-2 mm level. GOCE/GRACE GGMs are significantly better than EGM2008 in terms of the range of the differences with the GPS/Levelling data, since they reduce the 1.964 m of the EGM2008 range by as much as 0.21 m for DIR_R5.

Contrary to the results for the validation with the GPS/Levelling data, all the GOCE and GOCE/GRACE GGMs are better at the 0.1 mGal level for the gravity anomaly differences.

Keywords: Global Earth gravity field models, geoid heights, gravity anomalies, GOCE.

1. Introduction

Since the launch of the GOCE (Gravity field and steady-state Ocean Circulation Explorer) satellite mission in 2009, ESA (European Space Agency) has started delivering a great variety of Global Geopotential Models (GGMs) based on different volumes of GOCE data. The latter refers to effective volumes of approximately two months, six to eight months, twelve months, twenty-seven months, and the complete mission lifetime, including the lower orbit data up to the re-entry of the satellite in November 2013, corresponding to the first release (R1), second release (R2), third release (R3), fourth release (R4) and fifth generation solutions (R5), respectively. Three different strategies have been applied for the determination of the Earth's gravity field, based on GOCE data. They are denoted as direct (DIR) solution, time-wise (TIM) solution and space-wise (SPW) solution. In addition to ESA's solutions, several combined models based on the combination of GOCE data with complementary gravity-field related information from other satellite missions like GRACE (Gravity Recovery and Climate Experiment), and terrestrial data have been developed. We will refer to these models, as GOCE/GRACE GGMs. GRACE and GOCE are complementary in terms of spectral sensitivity. EIGEN (European Improved Gravity model of the Earth by New techniques) solutions, GOCO (Gravity Observation Combination) solution and GOGRA (a combined gravity field model using GOCE and GRACE) are some examples of the GOCE/GRACE GGMs used in this study. The present paper assesses the accuracy of GOCE-only and GOCE/GRACE GGMs through comparisons with independent data like terrestrial gravity anomalies and geoid undulations derived by GPS and spirit levelling. Within that scheme, the focus is put on Argentina, where the evaluation of all available GOCE, GOCE/GRACE and combined GGMs is carried out with GPS/Levelling and gravity anomaly data.

2. Methodology for GGM evaluation

The evaluation of the GOCE, GOCE/GRACE and combined GGMs was carried out in terms of geoid undulations and gravity anomalies differences against local datasets. Geoid heights and gravity anomalies from several GGMs (N^{GGM} and Δg^{GGM}, respectively) have been compared against (a) "geometric" geoid heights represented by collocated GPS/Levelling observations on BMs ($N^{GPS/Levelling}$) and (b) point land free-air gravity anomalies (Δg) over Argentina. The residual geoid heights and residual gravity anomalies have been evaluated as:

$$\Delta N = N^{GPS/Levelling} - N^{GGM}\Big|_{2}^{n_1} - N^{EGM2008}\Big|_{n_1+1}^{2160} - N^{RTM} - N_0 , \quad (1)$$

$$\Delta g_{res} = \Delta g_f - \Delta g^{GGM}\Big|_{2}^{n_1} - \Delta g^{EGM2008}\Big|_{n_1+1}^{2160} - \Delta g^{RTM} , \quad (2)$$

where, ΔN denotes the geoid heights differences at the GPS/Levelling BMs between the GPS-derived geoid heights ($N^{GPS/Levelling}$) and those derived by the GGM under investigation, generally denoted as (N^{GGM}).

The computation of GGM geoid undulations (N^{GGM}) has been carried out as (Heiskanen and Moritz 1967, Eqs. 8.100-8.102):

$$N^{GGM} = \varsigma + \frac{\Delta g_B}{\bar{\gamma}} H , \quad (3)$$

where, H is the orthometric height, Δg_B is the Bouguer gravity anomaly and ζ represents the height anomaly. The height anomaly has been computed from spherical harmonic series expansions based on the spherical harmonic coefficients of each model and the Geodetic Reference System 1980 (GRS80) normal gravity field parameters by the following expression:

$$\zeta(r,\theta,\lambda) = \frac{GM}{\gamma r} \sum_{n=2}^{n_1} \sum_{m=0}^{n} \left(\frac{a}{r}\right)^n \left(\overline{\Delta C}_{nm} cos m\lambda + \overline{\Delta S}_{nm} sen m\lambda\right) \overline{P}_{nm}(cos\theta) , \quad (4)$$

where, n_1 is some maximum degree of expansion of the GGM, $\overline{P}_{nm}$ denotes the fully normalized associated Legendre functions and $\overline{\Delta C}_{nm}$ and $\Delta\overline{S}_{nm}$ are the differences of the fully normalized potential coefficients of the gravitational potential minus the corresponding coefficients of the normal gravity potential. The second term in Eq. (3) is to convert the height anomaly to a geoid height. The Bouguer correction is determined within the *harm_synth* software (Pavlis et al., 2012) using the spherical harmonics expansion of the DTM 2006.0 model (Pavlis et al., 2012) to represent Earth's topography.

For the GGMs in Eq. (1) the evaluation is carried to some maximum degree of expansion n_1 *(* $N^{GGM}\Big|_{2}^{n_1}$ *)*, while EGM2008 (Pavlis et al., 2012) is used as a fill-in information for the rest of the geoid signal from degree n_1+1 to degree 2160 ($N^{EGM2008}\Big|_{n_1+1}^{2160}$). The truncation of the GGM model coefficients at spherical harmonic degree 2160 produces an omission error (Torge 2001, p 273). Residual Terrain Modelling (RTM) is one approach that is suitable to compute and reduce this omission error (Hirt et al., 2010). Residual Terrain Model (RTM) effects on geoid heights (N^{RTM}) represent the topographic signal above degree 2160.

In Eq. (1) the zero-degree geoid term (N_o) is evaluated as in Heiskanen and Moritz (1967, Eq. 2.182).

$$N_0 = \frac{GM - GM_0}{R\gamma} - \frac{W_0 - U_0}{\gamma}\,, \tag{5}$$

where the parameters GM_o and U_o correspond to the geocentric gravitational constant of the reference ellipsoid and the normal gravity potential, respectively. The GRS80 ellipsoid is used as the reference ellipsoid for all numerical computations (Moritz, 2000), while the Earth's geocentric gravitational constant GM and the gravity potential at the geoid W_o is set to GM=398600.4415 10^9 m^3s^{-2} and W_o=62636856.0 m^2s^{-2}, as given by Petit and Luzum (2010). The mean Earth radius R is taken equal to 6378136.3 m and the normal gravity γ at the surface of the ellipsoid is computed by the closed formula of Somigliana (Moritz, 2000). The same spectral enhancement approach is used for the analysis of the free-air gravity anomaly data Eq. (2).

The RTM effects on both geoid heights and gravity anomalies are estimated from an SRTM (Shuttle Radar Topography Mission) based on 3 arc-second resolution Digital Terrain Model (Tocho et al., 2012; Tziavos et al., 2010). As far as the tide system is concerned, all computations were carried out in the Tide Free (TF) system, so when a given GGM refers to the Zero Tide (ZT) system, the $\overline{C}_{20}$ coefficient is converted to TF using the following formula (Rapp et al., 1991):

$$C_{2,0}^{Tide-free} = C_{2,0}^{Zero-free} + 3.1108\times10^{-8}\frac{0.3}{\sqrt{5}}\,. \tag{6}$$

Geometric geoid undulation on land can be determined in an absolute sense according to the following equation:

$$N^{GPS\,/\,Levelling} = h - H\,, \tag{7}$$

where, h is the ellipsoidal height from GPS and H is the orthometric height. Eq. (7) is evaluated, in this study, including levelled heights instead of orthometric heights. As most countries, Argentina does not make any luni-solar correction for precise levelling, so that their orthometric heights refer to the Mean Tide system (MT). Therefore, orthometric heights needed to be converted from the MT to the TF with the expression (Ekman, 1989):

$$H^{TF} = H^{MT} - 0.68(0.099 - 0.296\,sin^2\varphi)\,. \tag{8}$$

Both the geoid height and gravity anomaly differences are evaluated with an incremental step of one harmonic degree, so that the most detailed possible evaluation of the GGMs will be achieved. Finally, it should be pointed out that the computed RTM effects represent a maximum harmonic degree of 216,000, i.e., the omission error is at the mm-level. A more detailed discussion of the followed methodology and conventions is given in Tocho et al.. (2014), Tziavos et al., (in press) and Vergos et al., (2014).

3. Global Geopotential Models, Gravity, and GPS/Levelling data over Argentina

3.1 Global Geopotential Models

Twenty one GGMs, up to their maximum degree and order (d/o), have been used in this study (Table 1). These models were released for public use via the International Centre for Global Earth Models (ICGEM) http://icgem.gfzpotsdam.de/ICGEM/ICGEM.html. EGM2008 complete to degree and order 2160 is used as the reference GGM against all GOCE-only and GOCE/GRACE based ones which are evaluated. It is used to fill-in medium and high frequency content for the rest of the geoid signal above the maximum degree and order (d/o) of expansion of the GOCE/GRACE models.

Some information on these GGMs and the amount of data they include, can be summarized as follows:

- EIGEN (European Improved Gravity model of the Earth by New techniques models):
  - EIGEN-51C is a combined gravity field model, complete to degree and order 360 from GRACE, LAGEOS and surface gravity data, released on September 29, 2008. This model is pre GOCE era.
  - EIGEN-6C was the first combined gravity field model complete to degree and order 1420 computed including GOCE Gravity Gradiometry (SGG) data, LAGEOS and GRACE data, augmented with the DTU10 surface gravity data (Andersen, 2010). It is the result of the collaboration of GFZ-Potsdam and GRGS-Toulouse and it was released on June 27, 2011.
  - EIGEN-6C2 is the first upgrade of EIGEN-6C which has been published in 2012.
  - EIGEN-6C3stat is a static pre-version of the future upgrade EIGEN-6C4 to d/o 1949.
- The satellite-only DIR models (DIR_R1, DIR_R2, DIR_R3, DIR_R4, and DIR_R5): The first, second, third, fourth and fifth generation of GOCE gravity field solution by the Direct (DIR) methodology, respectively. The fifth generation solutions span the complete GOCE mission lifetime, including the lower orbit data up to the re-entry of the satellite in November 2013. The time span covered is thus November 2009 up to November 2013.

Table 1: Pre GOCE-era GGMs: EGM2008 and EIGEN-51C, GOCE-only and GOCE/GRACE GGMs used for evaluation.

Models	Max d/o	Data	ICGEM name	References
EIGEN-51C	360	S(GRACE, LAGEOS),G,A	EIGEN-51C	Bruinsma et al., 2010
EIGEN-6C	1420	S(GOCE, GRACE, LAGEOS),G,A	EIGEN-6C	Förste et al., 2011
EIGEN-6C2	1949	S(GOCE, GRACE, LAGEOS),G,A	EIGEN-6C2	Förste et al., 2012
EIGEN-6C3stat	1949	S(GOCE, GRACE, LAGEOS),G,A	EIGEN-6C3stat	Förste et al., 2012
DIR_R1	240	S(GOCE)	GO_CONS_GCF_2_DIR_R1	Bruinsma et al., 2010
DIR_R2	240	S(GOCE)	GO_CONS_GCF_2_DIR_R2	Bruinsma et al., 2010
DIR_R3	240	S(GOCE, GRACE, LAGEOS)	GO_CONS_GCF_2_DIR_R3	Bruinsma et al., 2010
DIR_R4	260	S(GOCE, GRACE, LAGEOS)	GO_CONS_GCF_2_DIR_R4	Bruinsma et al., 2013
DIR_R5	300	S(GOCE, GRACE, LAGEOS)	GO_CONS_GCF_2_DIR_R5	Bruinsma et al., 2013
TIM_R1	224	S(GOCE)	GO_CONS_GCF_2_TIM_R1	Pail et al., 2010
TIM_R2	250	S(GOCE)	GO_CONS_GCF_2_TIM_R2	Pail et al., 2011
TIM_R3	250	S(GOCE)	GO_CONS_GCF_2_TIM_R3	Pail et al., 2011
TIM_R4	250	S(GOCE)	GO_CONS_GCF_2_TIM_R4	Pail et al., 2011
TIM_R5	280	S(GOCE)	GO_CONS_GCF_2_TIM_R5	Pail et al., 2011
GOCO01S	224	S(GOCE gradiometry, GRACE)	GOCO01S	Pail et al., 2010
GOCO02S	250	S(GOCE gradiometry and GOCE GPS-SST, GRACE, CHAMP, SLR)	GOCO02S	Goinginger et al., 2011
GOCO03S	250	S(GOCE gradiometry and GOCE GPS-SST, GRACE, CHAMP, SLR)	GOCO03S	Mayer-Gürr et al., 2012
ITG-GOCE02	240	S (GOCE)	ITG-GOCE02	Schall et al. 2014
GOGRA02S	230	S(GOCE, GRACE)	GOGRA02S	Yi et al., 2013
JYY-GOCE02S	230	S (GOCE)	JYY-GOCE02S	Yi et al., 2013
EGM2008	2160	S(GRACE),G,A	EGM2008	Pavlis et al., 2012

(Data: S = Satellite Tracking Data, G = Gravity Data, A = Altimetry Data
GRACE (Gravity Recovery And Climate Experiment)
CHAMP (CHAllenging Mini-satellite Payload)
GOCE (Gravity field and steady state Ocean Circulation Explorer)
LAGEOS (Laser GEOdynamics Satellite)
SLR (Satellite Laser Ranking)
GPS (Global Position System)
SST (Sea Surface Topography)

- The GOCE-only solutions TIM models (TIM_R1, TIM_R2, TIM_R3, TIM_R4 and TIM_R5): The first, second, third, fourth and fifth generation of GOCE gravity field solution by the Time-wise (TIM) approach.
- The satellite-only GOCO (Gravity Observation Combination) models (GOCO01S, GOCO02S, and GOCO03S). They are global gravity field models based on GOCE

gradiometry and GOCE GPS data with complementary gravity field from other satellite data like GRACE, SLR, and CHAMP.

- ITG-GOCE02 gravity field model which was computed from 7.5 months of GOCE gradiometer and orbit data from November 2009 up to June 2010.
- GOGRA02S a GOCE/GRACE combined gravity field model estimated by Yi et al., (2013).
- JYY-GOCE02S is a GOCE-only GGM developed by Yi et al., (2013) through the analysis of GOCE gravitational gradient components.

3.2 Gravity data

The gravity database used in this study has been compiled using different data sources that have been were acquired using different procedures. Most of the data have been supplied by Instituto Geográfico Nacional (IGN) of Argentina. In the whole, 180,660 point gravity values are available as displayed in Figure 1. Most of the gravity values in the network originally referred to the old Potsdam datum, but today they have been converted to IGSN71 through the application of a shift of −14.93 mGal to the measured values. This conversion formula has been tested on more than 800 points that have been measurements in both systems which results in a mean difference of 0.2 mGal. Apart from the methodology and instrumentation, the overall accuracy for the gravity measurements is better than 0.5 mGal. Free-Air gravity anomalies were calculated in the classical sense as "gravity on the geoid minus normal gravity on the ellipsoid".

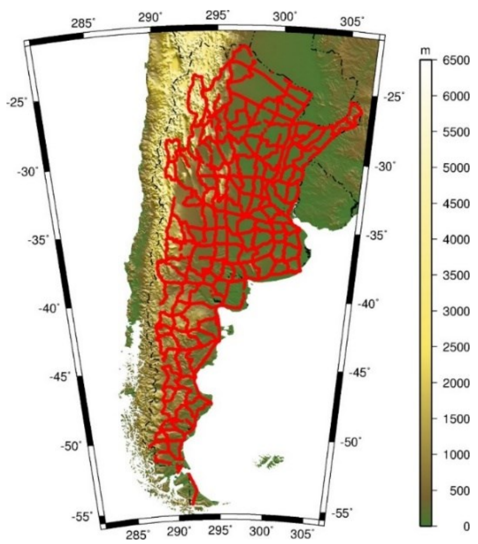


Figure 1. The gravity data base in Argentina

3.3 GPS/Levelling data

Many institutions in Argentina have established geodetic networks, mainly for cadastral purposes. Some of these points are coincident with levelling benchmarks, so they offer collocated GPS and Levelling information that can be used for the validation of GGMs. To this extent, GPS/Levelling height information on 567 points across Argentina has been supplied by the National Geographic Institute of Argentina. The geodetic coordinates (ϕ, λ, h) are framed to the POSgAR 07 (POSiciones Geodesicas ARgentinas) datum. POSgAR 07 is Argentina's official geodetic system and it was established through GPS measurements to realize the WGS84 (G1150) reference system in the country. The geocentric Cartesian coordinates of all stations were determined in ITRF2005 (epoch: 2006.632) and the ellipsoidal heights are given in the Tide Free system. The heights of the benchmarks are simple levelling heights without gravity related corrections. Thus, they are neither orthometric nor normal heights. Figure 2 depicts the distribution of the GPS/Levelling network that has been used in the following comparisons. As one can see in Figure 2, data are unevenly distributed, with the Buenos Aires plain being densely surveyed, while the Andes region is poorly covered.

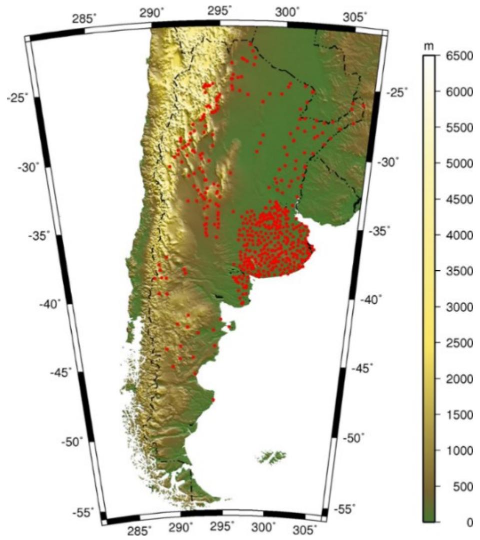


Figure 2. The GPS/Levelling database over the continental part of Argentina

4. Validation procedure

The external evaluation of GOCE-only and GOCE/GRACE GGMs is carried out with GPS/Levelling data on BMs and free-air gravity anomalies. The synthesis of the GOCE GGMs signal as outlined in Eq. (1) and (2) is evaluated per degree of the spherical harmonics expansion, through a combined use of geocol17 (Tscherning et al., 1992) and *harm_synth_v02* (Pavlis et al., 2012). The former is used to compute the contribution of the GOCE-only and

GOCE/GRACE GGMs to a maximum degree n_1 and the latter for the contribution of EGM2008 from degree n_1+1 to 2160. Finally, the RTM effects are computed with a modified version of the *tc* software, being a module of the GRAVSOFT package (Tscherning et al., 1992). Tables 2 and 3 present the statistics of the available GPS/Levelling and gravity anomaly data, respectively, along with the RTM contribution to both geoid heights and gravity.

Table 2: Statistics of the ellipsoidal, orthometric, GPS/Levelling geoid heights and RTM effects on the BMs. Units: [m].

	max	min	mean	rms	std
h	3386.681	17.373	291.446	546.259	±462.016
H	3347.687	2.293	272.559	532.636	±457.617
$N^{GPS/Levelling}$	40.732	5.116	18.887	19.640	±5.386
N^{RTM}	0.649	-0.647	-0.031	0.113	±0.109

Table 3: Statistics of the available free-air gravity anomalies and RTM effects. Units: [mGal].

	max	min	mean	rms	std
Δg_f	498.16	-136.57	4.815	99.512	±99.39
Δg^{RTM}	77.37	-124.38	-7.55	17.493	±15.78

4.1 GGM spectral evaluation and external validation with GPS/Levelling data

Table 4 presents the statistics in terms of range, mean value, and standard deviation (std) of the absolute differences between the GPS/Levelling derived geoid heights available in the area under study and the synthesised GGM geoid heights enhanced with EGM2008 and RTM contributions. Note that in Table 4, we report the best GGM d/o, i.e., the n_1 (see Eq. 1) that provides the overall best results w.r.t. the GPS/Levelling data in terms of the standard deviation (std) of their differences. In the same Table, the results for EGM2008 (n_1 =2160) are used as reference for the other GGMs.

Table 4 shows that, EGM2008 with n_1=2160 has the overall best agreement with the GPS/Levelling-derived geoid for Argentina, with a standard deviation of ±0.216 m and a mean value of 0.288 m. EGM2008 is superior to all GGMs used for evaluation, even from the latest fourth and fifth-generation GOCE Earth gravity field models, as far as the standard deviations of the differences are concerned. This superiority is marginal and statistically insignificant, being at the 3-2 mm level for DIR_R5 and TIM_R5, respectively, but it indicates that EGM2008 cannot be outperformed by the GOCE-only or GOCE/GRACE GGMs over Argentina. This can be attributed to the fact that most of the Argentinian gravity database has been used during the development of EGM2008; hence, the latter represents very well the gravity field even over the remote Andes region. Moreover, the distribution of the available GPS/Levelling BMs is such that it follows the gravity survey traverses (see Figure 2) and are located mostly in lowland areas. Therefore, during the external evaluation they do not provide an independent GGM quality check, as would for instance happen if GPS/Levelling BMs over un-surveyed areas would be available.

On the other hand, the other GGMs are significantly better than EGM2008 in terms of the range of the differences with the GPS/Levelling data, since they reduce the 1.964 m of the EGM2008 range by as much as 0.21 m (DIR_R5). This is a good indication that even though the GOCE GGMs do not manage to reduce the standard deviation of the differences compared to EGM2008; they indeed manage to provide more homogeneous geoid information hence reducing the range of the differences.

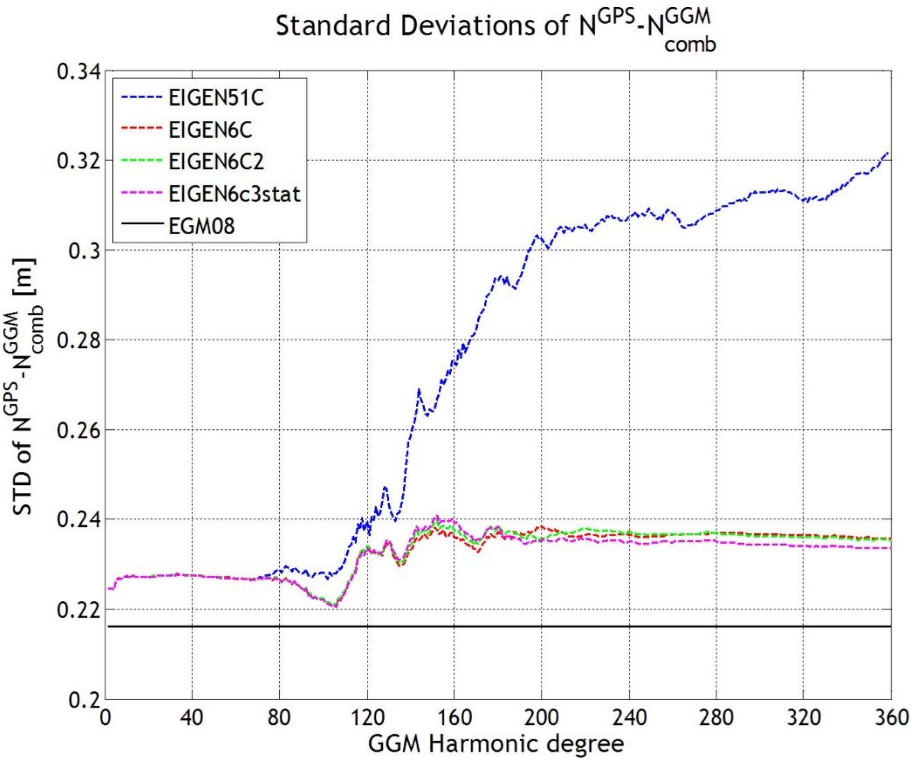
Table 4: Statistics of the differences between GPS/Levelling derived geoid heights and geoid heights from the GGMs (n_1 denotes the maximum d/o that the GGMs are used, whilst above that they are complemented with EGM2008 and RTM). Units: [m].

	n_1	range	mean	std
EGM2008	2160	1.964	0.288	±0.216
EIGEN-51C	64	1.955	0.289	±0.227
EIGEN-6C	104	1.854	0.286	±0.221
EIGEN-6C2	107	1.773	0.283	±0.221
EIGEN-6C3stat	107	1.794	0.283	±0.220
DIR_R1	106	1.878	0.297	±0.223
DIR_R2	102	1.819	0.289	±0.222
DIR_R3	105	1.814	0.287	±0.220
DIR_R4	106	1.791	0.286	±0.220
DIR_R5	107	1.754	0.284	±0.219
TIM_R1	103	1.774	0.288	±0.220
TIM_R2	104	1.780	0.275	±0.224
TIM_R3	103	1.777	0.279	±0.221
TIM_R4	107	1.765	0.286	±0.219
TIM_R5	107	1.764	0.286	±0.218
GOCO01S	107	1.770	0.283	±0.221
GOCO02S	107	1.767	0.283	±0.221
GOCO03S	107	1.771	0.283	±0.221
ITG-GOCE02S	103	1.773	0.283	±0.218
GOGRA02S	107	1.768	0.283	±0.221
JYY-GOCE02S	105	1.763	0.294	±0.220

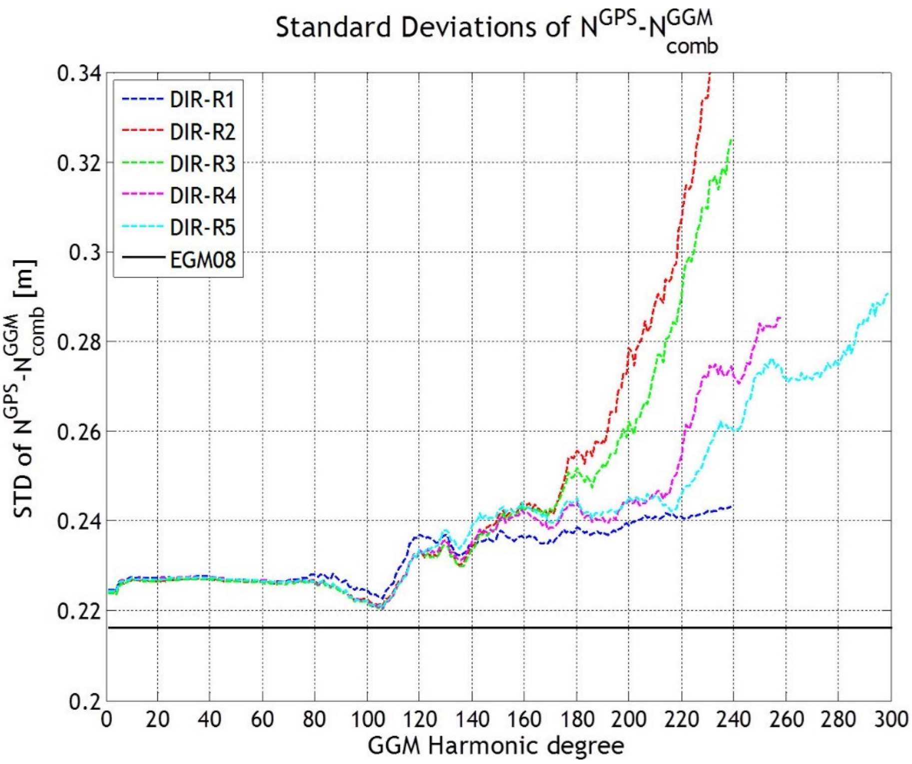
Moreover, the improved performance for the GOCE-only and GOCE/GRACE GGMs with the progression of their releases (R1 to R5) is clearly noticeable. For the DIR models, the standard deviation improves from 0.223 m for R1 to 0.219 cm for R5, while the range of the differences reduces by 0.124 m. The same holds for the TIM models, for which the standard deviation reduces by 0.002 m between the R1 and R5 versions. For the TIM GGMs, the dramatic improvement in the range of the differences, even for R1 is noticeable, since it is lower by 0.190 m compared to EGM2008. This can be attributed to the fact that the TIM GGMs are pure GOCE ones, while the DIR models incorporate GRACE data as well as some a-priori information (e.g., EIGEN-51C in DIR_R1, ITG-GRACE2010S in DIR_R2, etc.).

The evolution of the GOCE-only and GOCE/GRACE GGMs can be seen as well from Figure 3, where the standard deviation of the differences per harmonic degree is depicted for the EIGEN GGMs (Figure 3a), the DIR GGMs (Figure 3b), and TIM GGMs (Figure 3c) and for other versions of GOCE-only and GOCE/GRACE GGMs (Figure 3d). Figure 3e shows the results of the newest GGMs evaluated in this study. All EIGEN GGMs have provided quite similar results, except for the combined gravity field model EIGEN-51C which has not contained GOCE data. All the DIR models have provided quite similar results up to ~80 d/o (Figure 3b), which reflects the consistency of the different releases in this spectral range. From 180 d/o onward the standard deviations have increased rapidly for all the DIR releases. For the TIM models, even though they are marginally worse than EGM2008, their evolution with the increasing number of GOCE data used in their development is evident. If we set an arbitrary std limit at the 0.24 m, this is met at d/o 151, 147, 152, 198, and 219 for R1, R2, R3, R4 and R5, respectively (see Figure 3c). Given that the difference between the R4 and R5 versions of DIR relies on the lower-orbit GOCE data acquired during the last stages of the mission, their value is prominent at the higher bands of the GGM spectrum. The DIR_R5 GGMs start to differentiate from the R4 ones at about d/o 190-195, while after d/o 215 they boost the geoid spectrum by about 10-20 harmonic degrees. The latter is viewed in terms of acquiring the same std as that of the R4 release in higher degrees of harmonic expansion.

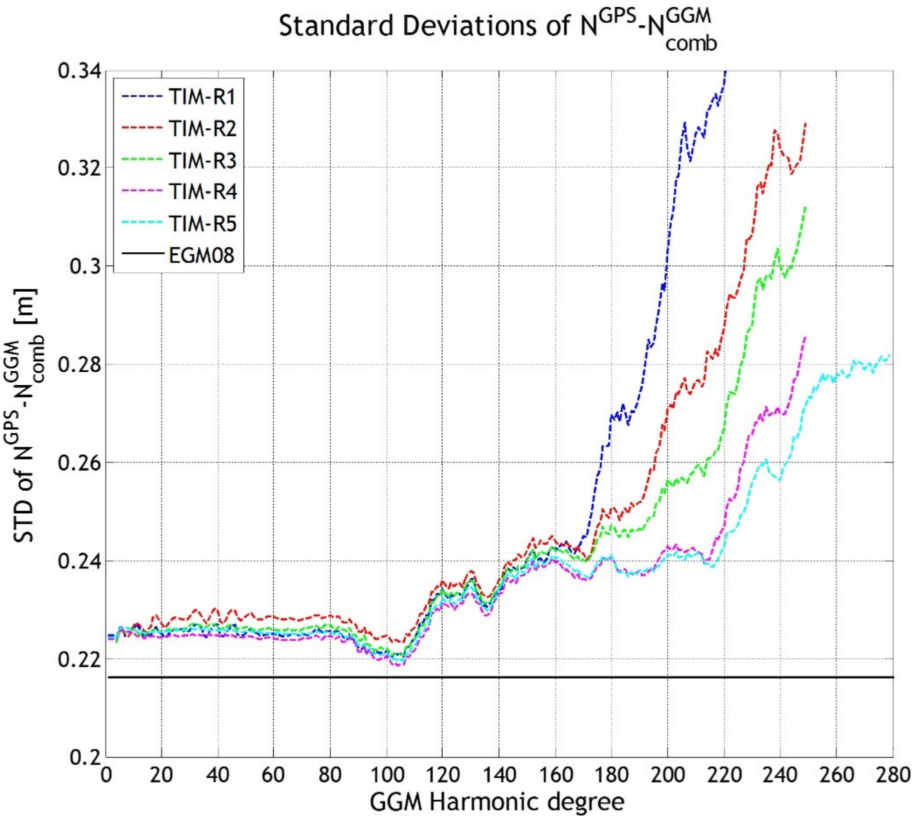
Before completing the evaluation with the GPS/Levelling data it is worth noting the performance of the latest entries in the GOCE/GRACE GGM family, i.e., GOGRA02S (see Figure 3d). Even though this model are based only on the second release of GOCE data, they provide up to some d/o comparable and slightly better results than the R5 GGMs. ITG-GOCE02S, being a pure GOCE-only model, is better than TIM_R5 and DIR_R5 up to d/o 105, while it follows TIM_R4 to d/o 172. This is indeed a very promising result for the followed short-arc approach during its development. GOGRA02S is slightly worse than ITG-GOCE02S and follows DIR_R5 up to d/o 215, but in any case, the results acquired are quite promising for the R4 and R5 versions of these new GGMs.


Standard Deviations of N^{GPS}-N^{GGM}_{comb}
EIGEN51C
EIGEN6C
EIGEN6C2
EIGEN6c3stat
EGM08
STD of N^{GPS}-N^{GGM}_{comb} [m]
GGM Harmonic degree

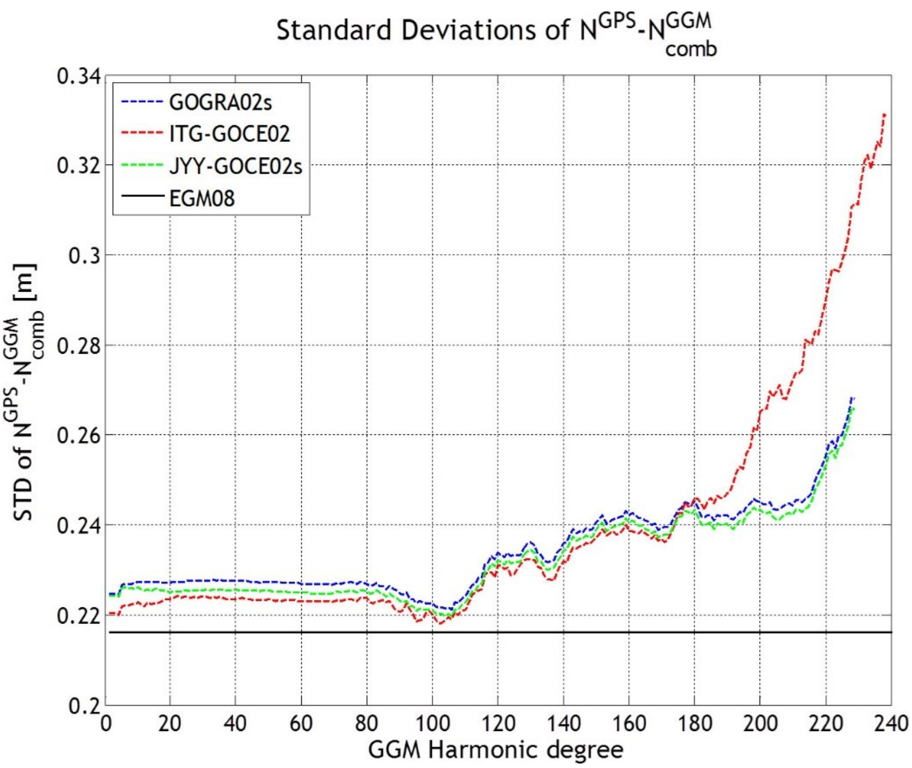
(a)


Standard Deviations of N^{GPS}-N^{GGM}_{comb}
DIR-R1
DIR-R2
DIR-R3
DIR-R4
DIR-R5
EGM08
STD of N^{GPS}-N^{GGM}_{comb} [m]
GGM Harmonic degree

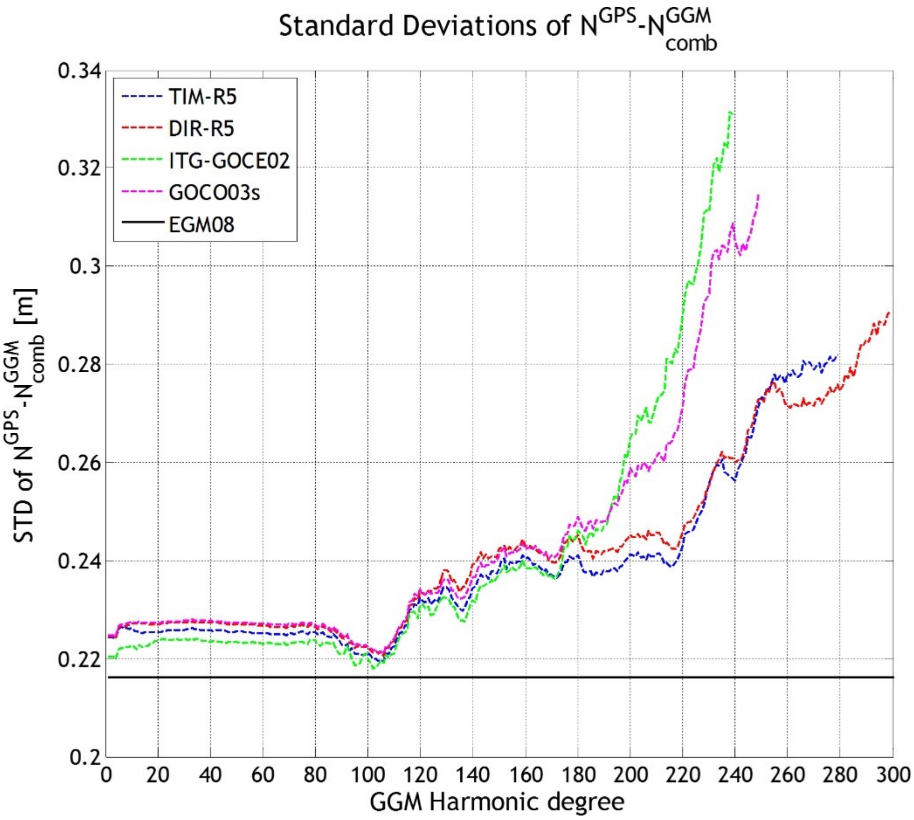
(b)


Standard Deviations of N^{GPS}-N^{GGM}_{comb}
TIM-R1
TIM-R2
TIM-R3
TIM-R4
TIM-R5
EGM08
STD of N^{GPS}-N^{GGM}_{comb} [m]
GGM Harmonic degree

(c)


Standard Deviations of N^{GPS}-N^{GGM}_{comb}
GOGRA02s
ITG-GOCE02
JYY-GOCE02s
EGM08
STD of N^{GPS}-N^{GGM}_{comb} [m]
GGM Harmonic degree

(d)



(e)

Figure 3. Standard deviations for the differences between the GOCE-only, GOCE/GRACE and combined GGMs with the GPS/Levelling geoid heights for various degrees of expansion. (a) various versions of the EIGEN models; (b) DIR_R1, DIR_R2, DIR_R3, DIR_R4 and DIR_R5; (c) TIM_R1, TIM_R2, TIM_R3 TIM_R4 and TIM_R5; (d) GOGA, JYY and ITG models; (e) comparison between the latest versions of the models studied.

4.2 GGM spectral evaluation and external validation with gravity data

Following the same validation procedure, Table 5 presents the statistics of the differences between the available local gravity data and the synthesised GGM and RTM contribution. Contrary to the results for the validation with the GPS/Levelling data, the GOCE and GOCE/GRACE GGMs manage to provide a slight improvement for the gravity anomaly differences. This improvement is marginal at the 0.1 mGal level and clearly statistically insignificant, given the accuracy of the gravity data themselves, but in any case, it is a good proof that the GOCE and GOCE/GRACE-based models perform equally well than EGM2008. Given that most, if not all, of the gravity data over Argentina have been incorporated in the EGM2008 development.

This is more clearly seen in terms of the range of the differences, which are ~3 mGal lower than those of EGM2008 for DIR_R4, TIM_R4, TIM_R5, ITG-GOCE02S and GOGRA02S. Figure 4a and Figure 4b shows the differences between EGM2008 and TIM_R4 with the local free-air gravity data, respectively.

Geographically, the larger differences with the local data are found over the highest peaks of the Andes with heights between 2500 m and 5000 m. It should be noted that this local gravity database has been compiled from an earlier version after a 3 rms blunder detection test. On the other hand some large free-air gravity anomaly values still exist over the highest Andes peaks (Figure 4a and 4b), therefore a more careful quality check is needed along with an investigation of the original gravity records (wherever possible).

Table 5: Statistics of the differences between the local and GGM-derived gravity anomalies. n_1 denotes the maximum d/o that the GOCE-only, GOCE/GRACE, EIGEN-51C GGMs are used, whilst above that they are complemented with EGM2008 and RTM. Units: [mGal].

	n_1	**range**	**Mean**	**Std**
EGM2008	2160	**652.00**	3.34	±23.99
EIGEN-51C	99	651.55	3.33	±23.91
EIGEN-6C	153	649.98	3.24	±23.89
EIGEN-6C2	152	649.42	3.22	±23.90
EIGEN-6C3stat	156	649.17	3.22	±23.86
DIR_R1	151	650.94	3.26	±23.93
DIR_R2	153	650.66	3.21	±23.89
DIR_R3	153	650.48	3.21	±23.90
DIR_R4	154	649.62	3.23	±23.87
DIR_R5	155	650.42	3.20	±23.89
TIM_R1	151	650.87	3.23	±23.91
TIM_R2	154	650.30	3.21	±23.89
TIM_R3	154	650.01	3.22	±23.89
TIM_R4	154	649.87	3.23	±23.87
TIM_R5	155	649.96	3.21	±23.88
GOCO01S	155	650.53	3.22	±23.88
GOCO02S	155	649.59	3.22	±23.88
GOCO03s	156	649.89	3.22	±23.87
ITG-GOCE02S	154	649.37	3.24	±23.89
GOGRA02S	155	649.85	3.22	±23.87
JYY-GOCE02S	155	650.10	3.22	±23.89

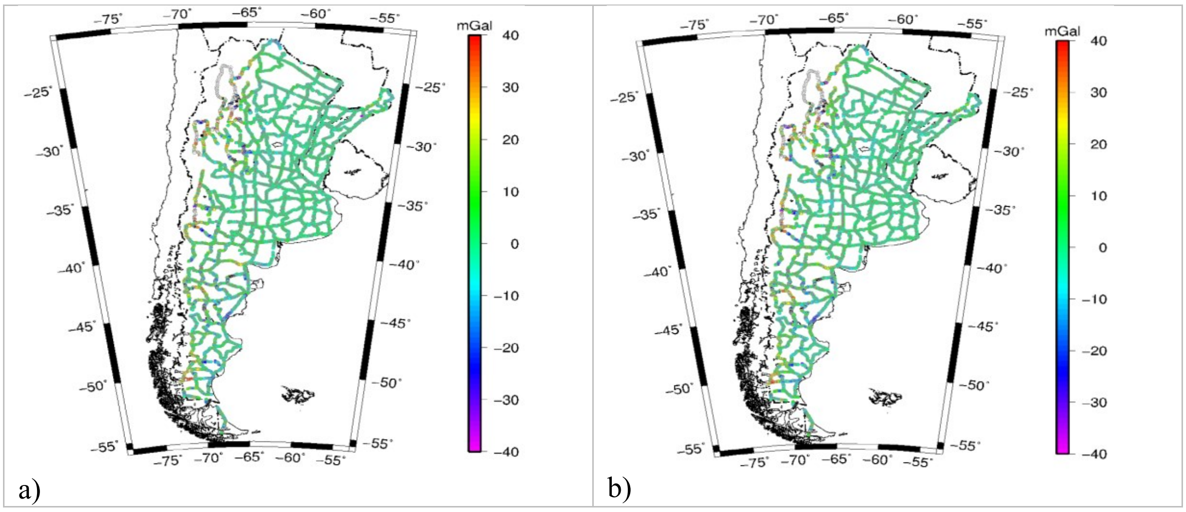
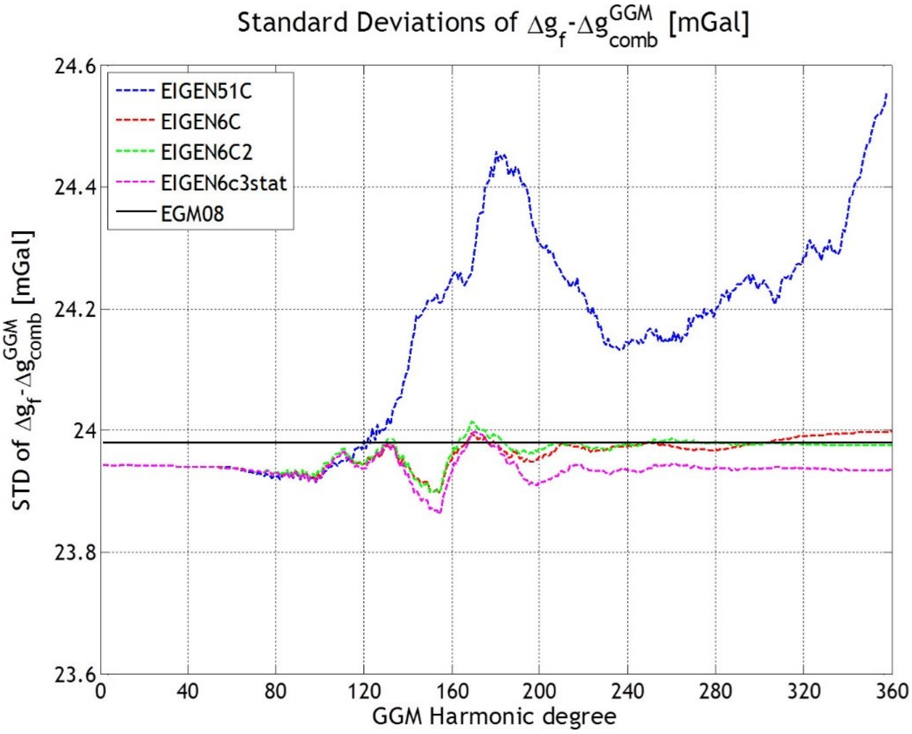


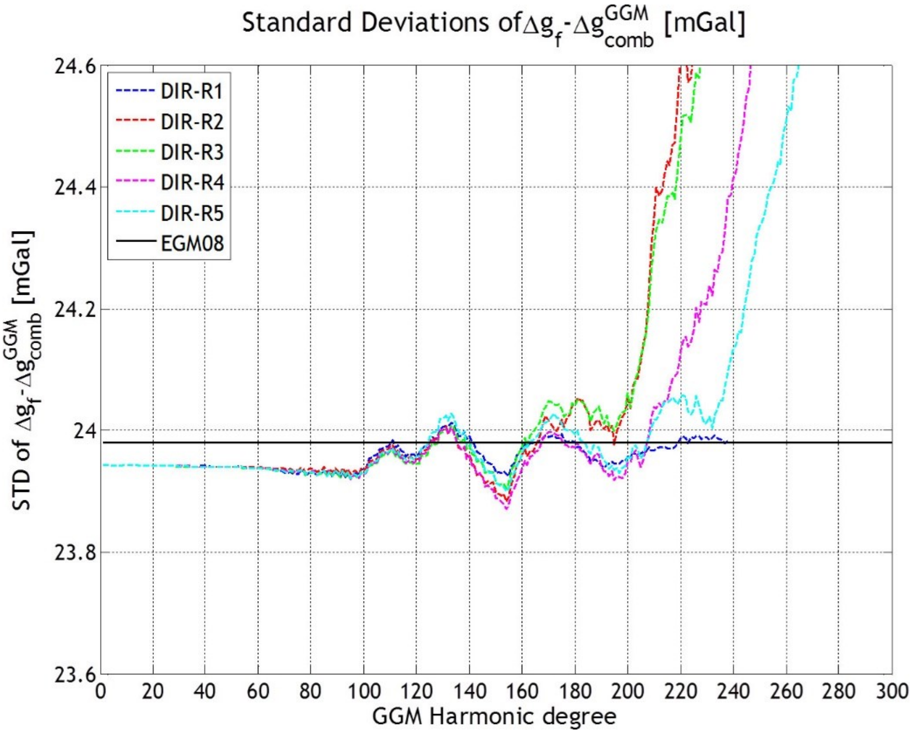
Figure 4. Differences between EGM2008 (left, d/o=2160, std=±24.0 mGal), and TIM_R4 (right, d/o=155, std=±23.7 mGal) with the local free-air gravity data.

Figure 5 depicts the standard deviation of the differences between gravity anomalies computed by the different GGMs and the terrestrial gravity anomalies per harmonic degree. Figure 5a shows the differences when the EIGENs models are used, Figure 5b and 5c for the different releases of DIR and TIM GGMs, respectively. Figure 5d for the latest versions of the various GGMs. All EIGEN GGMs have provided quite similar results up to ~ d/o 120 (Figure 5a), which reflects the consistency of the EIGEN solutions in this spectral range. Figure 5a also shows the big discrepancy for EIGEN-51C beyond d/o 120 due to this solution is not based on GOCE data. The EIGEN-6C combined GGM gives a similar fit to the EGM2008 beyond d/o 200, which can be expected because of the terrestrial gravity data included in that model. TIM_R1 is better than EGM2008 to d/o 158, which is boosted to d/o 166,167, 208 and 211 for TIM_R2, TIM_R3, TIM_R4 and TIM_R5, respectively (Figure 5c). ITGGOCE02S and GOGRAA02S do not show the same good performance as in the GPS/Levelling case unexpectedly. This behavior when evaluating a GGM against different external data can be attributed to the different spectral content between geoid heights and gravity anomalies. Gravity anomalies containing significant power to the medium to high frequencies, while geoid heights have most of their energy to the low to medium frequencies (Hirt et al., 2011; Schwarz 1985).



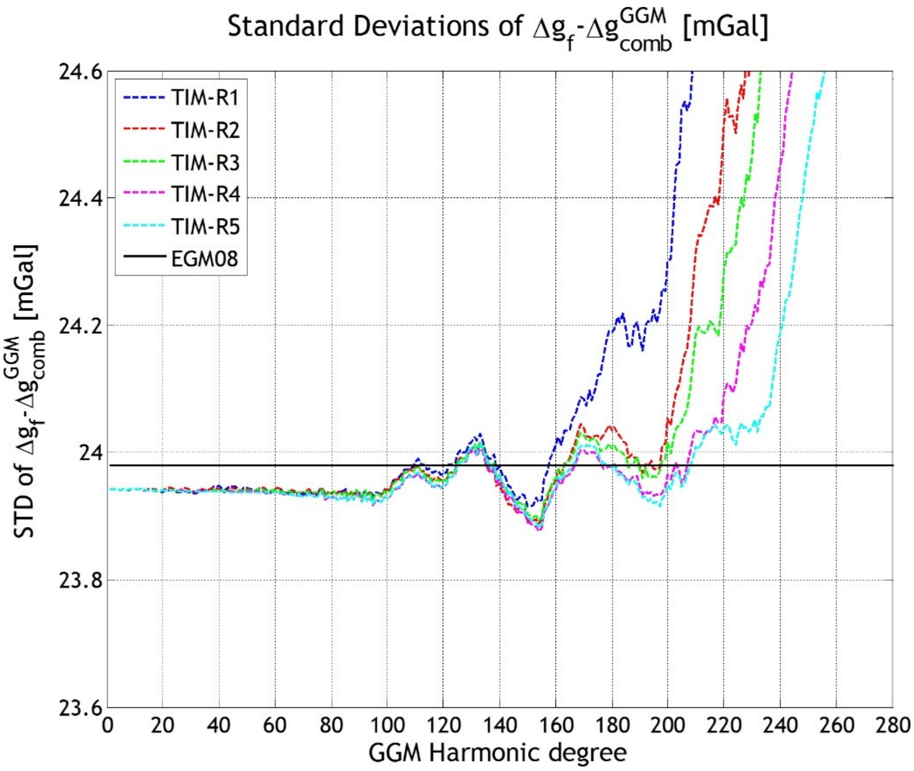
Standard Deviations of $\Delta g_f - \Delta g_{comb}^{GGM}$ [mGal]
EIGEN51C
EIGEN6C
EIGEN6C2
EIGEN6c3stat
EGM08
STD of $\Delta g_f - \Delta g_{comb}^{GGM}$ [mGal]
GGM Harmonic degree

(a)



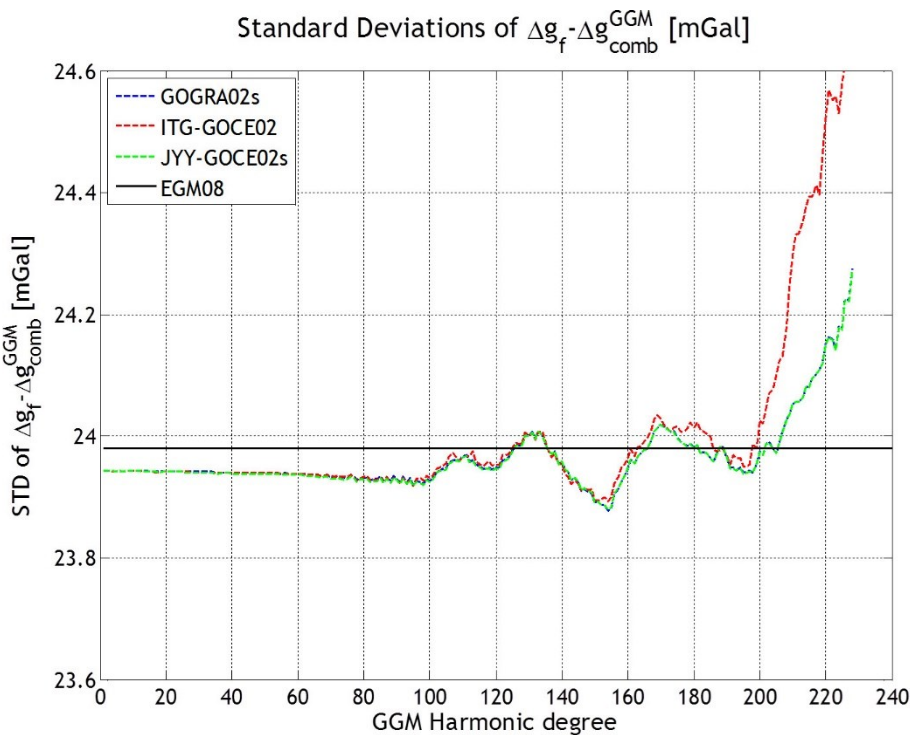
Standard Deviations of $\Delta g_f - \Delta g_{comb}^{GGM}$ [mGal]
DIR-R1
DIR-R2
DIR-R3
DIR-R4
DIR-R5
EGM08
STD of $\Delta g_f - \Delta g_{comb}^{GGM}$ [mGal]
GGM Harmonic degree

(b)



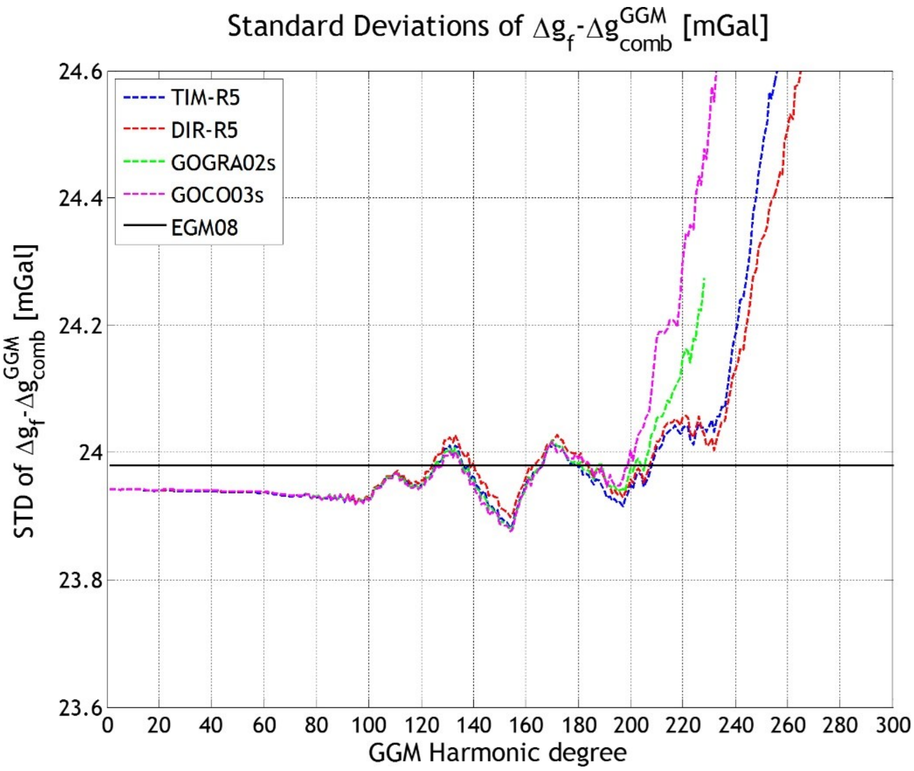
Standard Deviations of Δg_f-Δg_{comb}^{GGM} [mGal]
TIM-R1
TIM-R2
TIM-R3
TIM-R4
TIM-R5
EGM08
STD of Δg_f-Δg_{comb}^{GGM} [mGal]
GGM Harmonic degree

(c)



Standard Deviations of Δg_f-Δg_{comb}^{GGM} [mGal]
GOGRA02s
ITG-GOCE02
JYY-GOCE02s
EGM08
STD of Δg_f-Δg_{comb}^{GGM} [mGal]
GGM Harmonic degree

(d)



(e)

Figure 5. Standard deviations for the differences between the combined GOCE-only and GOCE/GRACE GGMs and local free-air gravity anomalies. (a) various versions of the EIGEN models; (b) DIR_R1, DIR_R2, DIR_R3, DIR_R4 and DIR_R5; (c) TIM_R1, TIM_R2, TIM _R3, TIM_R4 and TIM_R5; (d) GOGA, JYY and ITG models; (e) comparison between the latest versions of the models studied.

Conclusions

In this study, an evaluation of GOCE-only and GOCE/GRACE combined Global Geopotential Models have been carried out by comparing all of the models released by the European Space Agency High-level Processing Facility and some other GOCE and GRACE models with GPS/Levelling data and gravity observations in Argentina. The evaluation of the GGMs was also focused on their spectral comparison.

Considering the standard deviation as the main indicator of the agreement; EGM2008 is the best, by few mm, Global Geopotential Model that represents the long wavelength gravity field in Argentina as far as the geoid heights are concerned. Contrary, GOCE/GRACE GGMs are better at the sub-mGal level when gravity anomalies are considered.

A significant reduction of the range of the differences with the GPS/Levelling data was found, reaching 0.21 m for DIR_R5. For the validation with gravity anomalies a 3 mGal reduction of the range was reached for several of the latest GOCE GGMs, while TIM_R5 and DIR_R5 are better, compared to EGM2008, all the way up to d/o 210. Finally, it can be concluded that the lower-orbit GOCE data, during the mission end, are of significant value since they boost the spectrum by 20-40 harmonic degrees compared to the earlier releases of the GGMs.

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