Evaluation of GOCE/GRACE derived Global Geopotential Models over Argentina with collocated GPS/Levelling observations

C. Tocho[1], G.S. Vergos[2], M.C. Pacino[3]

[1] Facultad de Ciencias Astronómicas y Geofísicas, Universidad Nacional de La Plata, ctocho@fcaglp.unlp.edu.ar

[2] Department of Geodesy and Surveying, School of Rural and Surveying Engineering, Aristotle University of Thessaloniki, vergos@topo.auth.gr

[3] Facultad de Ciencias Exactas, Ingeniería y Agrimensura, Universidad Nacional de Rosario, Argentina

Abstract

This paper presents the results of the evaluation of recent GOCE/GRACE Global Geopotential Models (GGMs) over Argentina. Since the Gravity and steady state Ocean Circulation Explorer (GOCE) dedicated satellite gravity field mission was launched in March 2009, several global geopotential models have been computed and released. GOCE's mission was designed to provide models of the Earth's gravity field on a global scale with high-accuracy in the medium wavelength spectral band (maximum degree/order 200-250). Comparisons of geoid heights derived from different GGMs with GPS/Levelling derived geoid heights over Argentina have been carried out in both absolute and relative sense, to assess and validate the accuracy of GGM models over the entire country. The analysis has been carried out with actual GOCE-only, GOCE/GRACE and combined global gravity field models. In all cases, EGM2008 has been used as the baseline model, since it provides the overall best results. From the results, it was concluded that the latest Release 3 GOCE-only, TIM and SPW, GGMs provide improved accuracies by 1-4 cm compared to the Release 1 models. As far as the combined GOCE/GRACE models, GOCO and DIR, are concerned, the overall best results come from the Release 1 of the DIR model, probably due to the a-priori information from EIGEN5C used in its development. The Release 3 version of the GOCO GGMs improves the Release 1 model by 4 cm, while the same level of improvement is found between the Release 3 and Release 2 of the DIR GGMs.

Keywords

GOCE/GRACE GGMs, GPS/Levelling data, absolute and relative differences, Argentina

1. Introduction

The main focus of this paper is the evaluation of the GOCE-only and GRACE-GOCE combined satellite-only models against GPS/Levelling observations in Argentina. GPS/Levelling-derived geoid heights are used as independent (external) control for the assessment of the GGM geoid heights on a network of 542 GPS/Levelling benchmarks (BMs) over Argentina.

The dedicated gravity field satellite missions CHAMP, GRACE, and GOCE have contributed significantly to improve the representation of the Earth's gravity field and its temporal variations. The European Space Agency launched the GOCE (Gravity-field and steady-state Ocean Circulation Explorer) mission in March 17, 2009. The objective of the mission is to map gravity field features with ±1-2 cm accuracy for geoid undulations and ±1 mGal for gravity at spatial scales down to 120-140 km (degree/order 250). The measurement principle of the GOCE satellite is based on a combination of satellite gravity gradiometry (SGG) and Satellite-to-Satellite Tracking in high-low mode (SST-hl) (Drinkwater et al., 2007).

2. Methodology for validation

2.1 Evaluation of Global Geopotential Models

The evaluation of GGMs can be performed by an external comparison to geoid heights calculated from GPS and spirit levelling over collocated BMs. Hereafter, we call these geoid heights as the geometric geoid heights for brevity keeping in mind that it is not a strict term. GPS-derived ellipsoidal heights and orthometric heights referenced to a local datum constitute an important type of dataset in order to determine discrete precise geoid undulations by the geometrical approach. Geometric geoid undulation on land can be determined both in an absolute and relative sense (height differences between two benchmarks points *i* and *j*) according to the following equations:

$$N^{GPS/Levelling} = h_i - H_i \quad (1)$$

$$N_j^{GPS/Levelling} - N_i^{GPS/Levelling} = \Delta N_{ij}^{GPS/Levelling} = \Delta h_{ij} - \Delta H_{ij} \quad (2)$$

where h is the ellipsoidal height from GPS and H is the orthometric height. However, the use of Eq. (1) has some limitations due to systematic and random errors in the derived heights *h* and *H*. There are systematic and gross errors in levelling, especially at higher altitudes. Levelling points are often difficult to access and they are sometimes covered by vegetation or destroyed. Other limitations include the assumptions and theoretical approximations made in the normal/orthometric correction; the effect of not taking into account the differences between the ellipsoidal normal and the plumb line (deflection of the vertical), which can cause an error in the geometric geoid determination. The latter is of the order of 0.08-0.1 mm for the GPS/Leveling BMs over the Andes, where the deflection of the vertical takes values greater than 29 arcsec and the BMs ellipsoidal heights are of the order of 3500-4000 m. Therefore, it should be kept in mind that even for the BMs at high altitudes, this error is insignificant, while on the other hand, since actual measurements of the deflection of the vertical and the GPS/Leveling BMs are not available, a rigorous error propagation cannot be carried out. The geometric geoid heights cannot be derived at sea, given that the Mean Dynamic Ocean Topography (MDOT) should be known, so interpolation is difficult near the coast. The main errors in ellipsoidal height determination come from satellite or orbits, signal propagation and receiver errors; spirit leveling height determination is mainly affected, especially with today's digital levels, by the length of the leveling baselines, total height difference to be determined, collimation and rod errors, atmospheric refraction and Earth's curvature (Tocho, 2006). Despite systematic errors, geometric geoid heights can be derived with a high relative and absolute accuracy over reasonable distances. GPS/Levelling data have a poor spatial distribution.

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

$$N^{GGM} = \zeta + N_0 + \frac{\Delta g_B}{\bar{\gamma}} H \quad (3)$$

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:

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

degree of the GGM expansion used, $\overline{P}_{nm}$ denotes the fully normalized associated Legendre functions and $\Delta\overline{C}_{nm}$ and $\Delta\overline{S}_{nm}$ are the differences of the fully normalized potential coefficients of the gravitational potential minus the coefficients of the normal gravity potential. The third 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 DTM2006 model to represent Earth's topography. N_o represents the contribution of the zero-degree harmonic to the GGM geoid undulations with respect to a specific reference ellipsoid. It has been computed according to the formula (Heiskanen and Moritz 1967, Eq. 2.182):

$$N_0 = \frac{GM - GM_0}{R\gamma} - \frac{W_0 - U_0}{\gamma} \quad (5)$$

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 numerical values for the defining geocentric gravitational constant and the derived physical constant of the potential at the GRS80 ellipsoid (Moritz, 2000) are: GM_o=398600.500010^{9} m^{3} s^{-2} and U_o=62636860.850 m^{2} s^{-2}). The Earth's geocentric gravitational constant GM and the gravity potential at the geoid W_{o} have been set to $GM=398600.4418\ 10^{9}$ m^{3}s^{-2} and W_o=62636856.00 m^{2}s^{-2}, as given by the IERS Conventions (2010). Mean Earth's radius R has been taken equal to 6371008.7714 m and the normal gravity γ at the surface of the ellipsoid has been computed by the closed formula of Somigliana (Heiskanen and Moritz, 1967). The mean value of N_o in the area under study is -0.437 meters.

All computations of the zero-degree term N_0 used in this study have been performed 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):

$$C_{2,0}^{Tide-free} = C_{2,0}^{Zero-free} + 3.1108 \times 10^{-8} \frac{0.3}{\sqrt{5}} \quad (6)$$

2.2 Validation by using GPS/Levelling-derived geoid undulations in absolute and relative sense

Geoid undulation (N^{GGM}) can be computed from a set of normalized coefficients in spherical harmonic approximation using Eq. (3). The quality of the GGM can then be evaluated by comparing these geoid undulations with those from GPS/Levelling ($N^{GPS/Levelling}$). Theoretically,

$$N^{GGM} - N^{GPS/Levelling} = 0 \quad (7)$$

but in practice, there are lots of factors that affect Eq. (7). These factors are described by Kotsakis and Sideris (1999), Tocho (2006) and Tziavos et al. (2012). Datum inconsistencies and systematic effects are the most important ones that cause discrepancies in Eq. (7).

Most of the geoid studies that use GPS/Levelling-derived geoid as an external evaluation are based one the following deterministic model to model their deviations:

$$l_i = h_i - H_i - N_i^{GGM} = a_i^T x + v_i \quad (8)$$

where x is a vector of unknown parameters, a_i is the design matrix of known coefficients, and v_i is the residual random noise term (Tziavos et al., 2012). The model of Eq. (8) is applied to all reliable GPS network points and the least squares adjusted values for the residuals give a realistic picture of the absolute level difference between the GGM geoid and the GPS/Levelling data, so that they are taken as the final external indication of the geoid accuracy (Tocho, 2006; Vergos and Sideris, 2002).

The most common parametric models used are the simplified four-parameter and five-parameter similarity transformation models (MODEL A and MODEL B, respectively) given by Heiskanen and Moritz (1967, see the discussion in Section 5.9 and Eq. 5.55):

$$a_i^T x = x_0 + x_1 \cos\varphi_i \cos\lambda_i + x_2 \cos\varphi_i \sin\lambda_i + x_3 \sin\varphi_i \qquad (9)$$

$$a_i^T x = x_0 + x_1 \cos\varphi_i \cos\lambda_i + x_2 \cos\varphi_i \sin\lambda_i + x_3 \sin\varphi_i + x_4 \sin^2\varphi_i \quad (10)$$

where φ_i and λ_i are the latitude and longitude of the GPS/Levelling points, x_0 is the bias between the vertical datum implied by the GPS/Levelling data and the datum of the GGM, x_1, x_2, and x_3 are the translation parameters implied by the GPS/Levelling data and the geopotential model.

Some other, possible choices for the height combination problem, are to model the differences with a simple bias (μ) and two scale (δs_H and δs_N) factors. These models correspond to a height-dependent corrector surface in terms of the generalized equation (Kotsakis and Katsampalos, 2010):

$$h_i - (1+\delta s_H)H_i - (1+\delta s_N)N_i = \mu + v_i \quad (11)$$

that can be further discomposed in the following parametric models (MODELS C, D and E, respectively):

$$a_i^T x = \mu + \delta s_H H_i + \delta s_N N_i \quad (12)$$

$$a_i^T x = \mu + \delta s_H H_i \quad (13)$$

$$a_i^T x = \mu + \delta s_N N_i \quad (14)$$

To evaluate the relative accuracy of the GGM geoid models against the GPS/Levelling-derived geoid heights, relative geoid heights differences have been formed for all the baselines and plotted as a function of the baseline length in parts per million (ppm). The relative differences in ppm were formed after all outliers have been removed.

$$\Delta N_{ij} = (N_j^{GGM} - N_i^{GGM}) - (N_j^{GPS/Levelling} - N_i^{GPS/Levelling}) \quad (15)$$

$$\Delta N_{ij}\left[ppm\right] = \frac{\Delta N_{ij}\,[mm]}{S_{ij}\,[km]} \quad (16)$$

where the spherical distance in degrees is evaluated, and then converted to *km* by assuming that 1^o is ~110 km, as:

$$S_{ij} = a\cos\left(\sin\varphi_i \sin\varphi_j + \cos\varphi_i \cos\varphi_j \cos\left(\lambda_i - \lambda_j\right)\right) \quad (17)$$

3. Data used for GGM validation

3.1 GPS/Levelling data

GPS/Levelling height information on 567 points across Argentina has been collected through the National Geographic Institute of Argentina (IGN). From this database, we selected all GNSS stations on benchmarks. The geodetic coordinates (ϕ, λ, h) are referred 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. GPS/Levelling networks like the POSgAR07 and some province geodetic networks have been used for the external evaluation of the GGMs geoid accuracy.

The levelling heights *H* correspond to the National Altimetric Network, which was measured by the Military Geographic Instituto (IGM), today National Geographic Institute (IGN), using spirit and/or trigonometric levelling techniques. Their values refer to the equipotential surface of Earth's gravity field that coincides with mean sea level at the Vertical Datum fundamental tide-gauge reference station located in the city of Mar del Plata, with unknown W_o value.Most countries do 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):

$$H^{TF} = H^{MT} - 0.68(0.099 - 0.296\, sin^2 \varphi) \quad (18)$$

It is not possible to define the orthometric height accuracy, since the network was not uniformly adjusted and no gravity corrections have been applied. Therefore its formal accuracy is largely unknown, even though we can assume that lowland stations have been determined with higher accuracy compared to stations at higher elevations. As far as the geodetic coordinates are concerned, their mean errors are at σ_x=±0.005 m, σ_y=±0.005 m and σz=±0.005 m. These GPS/Levelling points are located in area with varying topography, and their distribution is shown in Figure 1.

FIGURE 1

3.2 Global Geopotential Models

Since 2010, ESA and the GOCE-related research teams have released three generations of GOCE GGMs. Models from the first, second and third release (R1, R2 and R3) are based on two, eight, and twelve months of data, respectively. Each generation includes three solutions using different approaches for gravity field recovery, the direct approach (DIR, the time-wise approach (TIM) and the space-wise approach (SPW).

Geoid undulations have been computed at the 542 GPS/Levelling benchmarks using the 15 GGMs shown in Table 1.

Table 1: GGMs used for evaluation.

Models	n_{max}	***Data***	***References***
EGM2008	2190	S(GRACE), G, A	Pavlis et al., 2012
EIGEN-51C	359	S(GRACE, CHAMP), G, A	Bruinsma et al., 2010
EIGEN-6C	1420	S(GOCE, GRACE, LAGEOS), G, A	Förste et al, 2011
GOCO01S	224	S(GOCE, GRACE)	Pail et al., 2010
GOCO02S	250	S(GOCE, GRACE, CHAMP, SLR)	Goiginger et al., 2011
GOCO03S	250	S(GOCE, GRACE, CHAMP, SLR)	Mayer-Gürr et al., 2012
ITG-GRACE2010S	180	S(GRACE)	Mayer-Gürr et al., 2010
DIR-R1	240	S(GOCE + background model EIGEN-51C)	Bruinsma et al., 2010
DIR-R2	240	S(GOCE+ background model ITG-GRACE2010S)	Bruinsma et al., 2010
DIR-R3	240	S(GOCE, GRACE, LAGEOS)	Bruinsma et al, 2010
TIM-R1	224	S(GOCE)	Pail et al., 2011
TIM-R2	250	S(GOCE)	Pail et al., 2011
TIM-R3	250	S(GOCE)	Pail et al., 2010a
SPW-R1	210	S(GOCE)	Migliaccio et al, 2010
SPW-R2	240	S(GOCE)	Migliaccio et al, 2011

(Data: S = Satellite Tracking Data, G = Gravity Data,
A = Altimetry Data
GRACE (**G**ravity **R**ecovery **A**nd **C**limate **E**xperiment)
CHAMP (**CHA**llenging **M**ini-satellite **P**ayload)
GOCE (**G**ravity field and steady state **O**cean **C**irculation **E**xplorer)
LAGEOS (**La**ser G**EO**dynamics **S**atellite)
SLR (**S**atellite **L**aser **R**anking)

Table 1 gives an overview of their resolution, which depends on the maximum spherical harmonic degree, and the data used to derive them. The models used are the new combined global gravity field model including GOCE data from the collaboration of GFZ-Potsdam and GRGS-Toulouse EIGEN-6C, the GRACE only derived model ITG-GRACE2010S the Gravity Observation Combination (GOCO) GGMs GOCO01S, GOCO02S and GOCO03S, the pre-GOCE models EIGEN-51C and EGM2008 both of them combined ones using satellite, gravity and altimetry data.

DIR-R1, DIR-R2 and DIR-R3 are the three different releases of the direct approach GOCE GGMs. The three of them are based on two, eight, and twelve months of GOCE gravity gradients, attitude information, and gradiometer observations, respectively. They differ in the a-priori information used. DIR-R1 used EIGEN-5C (Förste et al., 2008) as a-priori gravity field information model up to degree/order 360 and also used reduced dynamic orbits. DIR-R2 used ITG-GRACE2010S up to degree/order 150 as a-priori information and kinematics orbits. DIR-R3 used the DIR-R2 up to degree/order 240 and kinematics orbits.

TIM-R1, TIM-R2 and TIM-R3 are the three different releases of the time-wise approach. No a-priori gravity field information has been applied. They differ in the number of months of GOCE data used which includes: gravity gradients, kinematics orbits, and attitude and gradiometer observations. SPW-R1 is the first release of the space-wise model. The first GOCE quick-look model and EGM2008 model are incorporated as a-priori models. The input data in this model includes: satellite tracking data derived from the on-board GPS, gravity gradients observed by the on-board electrostatic gradiometer, kinematics orbits with their error estimates are used for SST gravity field recovery while reduced dynamic orbits are used for geo-locating gravity gradients and attitude. The SPW_R2 was also investigated. GOCO (Combination of GOCE data with complementary gravity field information) is a project initiative with the objective to compute high-accuracy and high-resolution static global gravity field models based on data of the satellite gravity missions CHAMP, GRACE, and GOCE, satellite altimetry, and SLR data. The satellite-only model GOCO01S based on GOCE and GRACE was the first computed. The second solution, GOCO02S, was computed with eight months of GOCE, seven years of GRACE, eight years of CHAMP and five years of five SLR satellites. The latest release is the GOCO03S was also used for comparison. ITG-GRACE2010S is an unconstrained static field from of GRACE data only. ITG-GRACE2010S is a mean field of the entire Earth including atmosphere and ocean masses. EIGEN-51C is a combined global gravity field model to degree/order 359. It consists of six years of CHAMP and GRACE data and the DNSC08 global gravity anomaly data set. Finally, EGM2008 is a spherical harmonic model of the Earth’s gravitational potential complete to degree/order 2159 with some additional coefficients up to degree 2190 and order 2159. EGM2008 is a model that combines the ITG-GRACE03S gravitational model with free-air gravity anomalies defined on a 5 arc-minute equiangular grid. This grid was formed by merging terrestrial, altimetry-derived, and airborne gravity data.

4 GGM validation on collocated GPS/Leveling BMs

4.1 Absolute differences between GGMs and GPS/Levelling data

Software *harmonic_synth_v02*, provided by the National Geospatial-Intelligence Agency (NGA), is used to compute the geoid values from the 15 GGMs. Table 2 shows the results in terms of mean value and standard deviation (std) of the absolute differences between GPS/Levelling geoidal heights and geoid heights of several GGMs evaluated in this paper for different degree and order of expansion (60, 80, 140, 180, 210, 220, 224, 240, 250, 360, 1420, 2160 and 2190). The statistics in Table 2 are before the fit of any parametric model mentioned in section 2.2. Before applying such models, the GPS/Levelling points having large gross error in either the GPS or the levelling data were removed. The statistics shown in Table 2 have been computed after the removal of points with gross errors, applying a 3 std test using EGM2008 to degree/order 2160. The final GPS/Levelling dataset in Argentina, after removing 25 suspicious stations, consists of 542 stations.

From Table 2, EGM2008 with n_{max} 2160 shows the overall best agreement with the GPS/Levelling-derived geoid for Argentina with a standard deviation of ±24 cm and a mean value of 31 cm. Considering the standard deviation as the main indicator of the agreement; EGM2008 is the best global geopotential model that represents the long wavelength gravity field in Argentina.

Table 2: Mean and standard deviation of the GPS/Levelling derived geoid minus geoid heights computed with GGMs up to various truncation degrees for whole Argentina (before any fit to the residuals). Unit: [m].

n max	***60***	***80***	***140***	***160***	***180***	***210***	***220***	***224***	***240***	***250***	***360***	***1420***	***2160***	***2190***
#points:542	***mean***	***mean***	***mean***	***mean***	***mean***	***mean***	***mean***	***mean***	***mean***	***mean***	***mean***	***mean***	***mean***	***mean***
	std	***std***	***std***	***std***	***std***	***std***	***std***	***std***	***std***	***std***	***std***	***std***	***std***	***Std***
$N^{GPS}-N^{EGM2008}$	0.120	0.357	0.303	0.305	0.281	0.274	0.271	0.269	0.265	0.264	0.270	0.309	0.310	0.310
	±1.261	±0.981	±0.617	±0.574	±0.522	±0.451	±0.439	±0.439	±0.424	±0.409	±0.334	±0.245	±0.244	±0.244
$N^{GPS}-N^{EIGEN-51C}$	0.119	0.356	0.298	0.3	0.276		0.266				0.272			
	±1.261	±0.981	±0.616	±0.582	±0.528		±0.443				±0.394			
$N^{GPS}-N^{EIGEN-6C}$	0.117	0.354	0.299	0.302	0.280		0.267				0.269	0.306		
	±1.261	±0.980	±0.621	±0.575	±0.519		±0.439				±0.347	±0.252		
$N^{GPS}-N^{GOCO01S}$	0.117	0.354	0.300	0.305	0.293			0.283						
	±1.261	±0.980	±0.624	±0.580	±0.536			±0.486						
$N^{GPS}-N^{GOCO02S}$	0.117	0.354	0.300	0.302	0.282			0.265		0.261				
	±1.261	±0.980	±0.623	±0.575	±0.524			±0.453		±0.448				
$N^{GPS}-N^{GOCO03S}$	0.117	0.354	0.301	0.303	0.285			0.273		0.269				
	±1.261	±0.980	±0.623	±0.573	±0.523			±0.444		±0.440				
$N^{GPS}-N^{ITG-GRACE20}$	0.117	0.354	0.302	0.295	0.307									
	±1.261	±0.980	±0.626	±0.583	±0.577									
$N^{GPS}-N^{DIR-R1}$	0.127	0.364	0.307	0.310	0.289		0.278		0.273					
	±1.260	±0.981	±0.623	±0.579	±0.526		±0.439		±0.427					
$N^{GPS}-N^{DIR-R2}$	0.120	0.356	0.303	0.304	0.287		0.276		0.274					
	±1.261	±0.980	±0.623	±0.577	±0.527		±0.459		±0.489					
$N^{GPS}-N^{DIR-R3}$	0.119	0.355	0.301	0.299	0.281		0.271		0.268					
	±1.261	±0.980	±0.623	±0.569	±0.525		±0.441		±0.444					
$N^{GPS}-N^{TIM-R1}$	0.120	0.357	0.303	0.307	0.294			0.284						
	±1.263	±0.981	±0.622	±0.580	±0.537			±0.486						
$N^{GPS}-N^{TIM-R2}$	0.107	0.344	0.292	0.293	0.272		0.254			0.251				
	±1.263	±0.980	±0.624	±0.576	±0.524		±0.450			±0.449				
$N^{GPS}-N^{TIM-R3}$	0.114	0.350	0.297	0.299	0.279		0.267			0.263				
	±1.262	±0.981	±0.623	±0.573	±0.524		±0.443			±0.443				
$N^{GPS}-N^{SPW-R1}$	0.125	0.359	0.306	0.308	0.287	0.273								
	±1.259	±0.977	±0.622	±0.579	±0.540	±0.487								
$N^{GPS}-N^{SPW-R2}$	0.120	0.356	0.303	0.304	0.287	0.267			0.265					
	±1.261	±0.981	±0.624	±0.577	±0.529	±0.477			±0.474					

We can also observe that except for DIR-R2, DIR-R3 models the best standard deviation has been obtained with the highest maximum spherical harmonic degrees of the model expansion. The best GRACE/GOCE model is DIR-R1 which gives a standard deviation of ±42.7 cm to its maximum cut-off degree of n=240. The latter is 15 cm better than the GRACE-only model GRACE2010S (to degree and order 180). This is due to the contribution of GOCE and LAGEOS data to DIR-R1, its higher degree of expansion and the a-priori information from EIGEN-5C used in its development. When compared for the same spectral band (degree and order 180) DIR-R1 is 5 cm better than GRACE2010S. It is interesting to notice that DIR-R1 provides the overall best results in Argentina, even compared to the Release 2 and Release 3 models which contain more GOCE observations. GPS/Levelling comparisons suggest a geoid agreement of 42 cm to 49 cm for the full GOCE-only model expansions (degree and order 240-250) and biases of about 30 cm. Among the GOCE-only models, the TIM-R3 GGM provides the best results with a std at the ±44.3 cm being ~2 cm better than SPW-R2, even for lower spectral bands. The combined GOCE/GRACE models GOCO show an increasing improvement towards Release 3, which is better by 4 cm compared to Release 1. We can also see that for the same spectral bands, the GOCE/GRACE models perform equally well with EGM2008. So for the band between 160-250 the standard deviations of the differences for the R3 models is the same, within a couple mm, as that of EGM2008. It should be kept in mind that GOCE models were not expected to perform better than EGM2008, since extensive local gravity data over Argentina have been used in its development.

The available corrector surfaces have been first tested for the differences between GPS/Levelling geoid heights and the EGM2008 geoid model, so the one that performs the best, will be used to compute adjusted residuals with respect to the other GGMs geoidal undulations (see Table 3). From this evaluation, it was concluded that MODEL B, provides the best residuals after the fit, even though its performance is marginally better than that of MODEL A (1 cm in terms of the range).

Table 3 Statistics of the differences between GPS/Levelling and geoid heights from EGM2008 before and after fit of the residuals. Unit: [m].

n=2190	*max*	*min*	*mean*	*std*
Before fit	1.143	-0.820	0.310	±0.244
MODEL A	0.656	-1.026	0.000	±0.164
MODEL B	**0.653**	**-1.022**	**0.000**	**±0.164**
MODEL C	0.728	-1.133	0.000	±0.189
MODEL D	0.853	-1.142	0.000	±0.217
MODEL E	0.694	-1.136	0.000	±0.191

4.2 Relative and absolute Baselines analysis

Figure 2 shows the standard deviation of the absolute geoid differences in the test network ($\Delta N_{ij}^{GPS/Levelling} - \Delta N_{ij}^{GGM}$) of 542 GPS/Levelling benchmarks, as a function of the baseline length (up to 500 km). For the evaluation of the relative accuracy of the GGMs with respect to the GPS/Levelling data, relative geoid differences have been formed for all the baselines and plotted as a function of the baseline length in ppm. The maximum spherical harmonic expansions of the GOCE-only models DIR-R3, TIM-R3, SPW-R2; the GRACE-GOCE combined satellite-only model GOCO03S, EIGEN-6C and EGM2008 have been used. The relative accuracy value at a certain distance is the average value of all the baselines distances, which have been computed with an increment of 10 km among all GPS/Levelling stations. Figure 3 shows the comparisons of the relative geoid undulation accuracy for the different GGMs after a five-order similarity transformation model was applied.

FIGURE 2

FIGURE 3

The results show that the GOCE models have a similar behavior to each other. EGM2008 and EIGEN-6C’s relative accuracy is considerably better than the satellite-only models due to the contribution of the surface gravity data. The resolution of EIGEN-6C is about half of that of EGM2008. We can also see that the combined model EIGEN-6C outperforms EGM2008 for baselines of 20 to 170 km.

In Argentina, the statistics are computed using all 542 benchmarks. As seen in Figure 3 for EGM2008 the relative geoid agreement is, 13 to 4 ppm for short baselines up to 20 km, 1 to 0.3 ppm over baselines of 100 to 500 km, meanwhile the GOCE-only models show a relative agreement of 8 to 16 ppm for short baselines of 20 km and 6 to 0.6 ppm over baselines of 100 to 500 km. The relative errors of the GOCE models show a slowly increasing trend with decreasing baseline until 40 km where a very sharp increase starts. On the contrary, the combined models show a slower deterioration of their relative accuracy for baselines smaller than 40 km. This disproportional increase indicates the fast deterioration of the GOCE models for baselines shorter than 40 km due to the limited satellite resolution. EIGEN-6C model outperforms EGM2008 and the SPW2 and GOCO03S models are better than the latest version of the DIR and TIM models. The average relative accuracies is achieved for baselines up to 80 km.

Conclusions

From the evaluation of the differences between GPS/Lev and GGM geoid heights, on a network of 542 stations over Argentina, it can be concluded that the GOCE/GRACE GGMs provide comparable, to EGM2008, agreement within the satellite spectral band (80-250). The latter is of course superior overall due its high maximum degree and order of expansion and the inclusion of local gravity data. In terms of the relative accuracies achieved, EIGEN-6C outperforms EGM2008, which can be due to the contribution of GOCE data used in its development. DIR-R1 provides the overall best results among the GOCE/GRACE GGMs, in terms of the absolute accuracy, due to the a-priori information from EIGEN-5C used in its development. In the relative case, GOCO03S and SPW-R2 outperform by 0.5-1 ppm TIM-R3 and DIR-R3 for baselines between 20 and 160 km.

Acknowledgements

Claudia Tocho received financial support from the University of La Plata and gratefully acknowledges the generous hospitality of Dr. George S. Vergos at the Department of Geodesy and

Surveying, Aristotle University of Thessaloniki, Thessaloniki, Greece. The authors are very grateful to the editors and reviewers for their comments and suggestions that improved the final manuscript.

References

Bruinsma SL, Marty JC, Balmino G, Biancale R, Förste C, Abrikosov O, Neumayer H (2010) GOCE gravity field recovery by means of the direct numerical method. In: Lacoste-Francis H (ed) Proceedings of the ESA living planet symposium, ESA Publication SP-686. ESA/ESTEC. ISBN: 978-92-9221-250-6; ISSN: 1609-042X.

Drinkwater MR, Haagmans R, Muzi D, Popescu A, Floberghagen, R, Kern M, Fehringer, M (2007) The GOCE Gravity Mission: ESA's First Core Earth Explorer. Proceedings of 3rd International GOCE User Workshop, 6-8 November, 2006, Frascati, Italy, ESA SP-627, ISBN 92-9092-938-3, pp. 1-8.

Ekman M (1989) Impacts of Geodynamic Phenomena on Systems for Height and Gravity. Bull Géodésique 63(3): 281–296.

Förste C, Bruinsma S, Shako R., Marty JC, Flechtner F, Abrikosov O, Dahle C, Lemoine JM, Neumayer KH, Biancale R, Barthelmes F, König R, Balmino G (2011). EIGEN-6 - A new combined global gravity field model including GOCE data from the collaboration of GFZ-Potsdam and GRGS-Toulouse; Geophysical Research Abstracts, Vol. 13, EGU2011-3242-2, EGU General Assembly.

Förste C, Flechtner F, Schmidt R, Stubenvoll R, Rothacher M, Kusche J, Neumayer KH, Biancale, Lemoine R, JM, Barthelmes F, Bruinsma S, König R, Meyer U ;EIGEN-GL05C - A new global combined high-resolution GRACE-based gravity field model of the GFZ-GRGS cooperation; Geophysical Research Abstracts, Vol. 10, EGU2008-A-03426, SRef-ID: 16077962/gra/EGU2008-A-03426, 2008.

Goiginger H, Höck E, Rieser D, Mayer-Gürr T, Maier A, Krauss S, Pail R, Fecher T, Gruber T, Brockmann JM, Krasbutter I, Schuh WD, Jäggi A, Prange L, Hausleitner W, Baur O, Kusche J (2011) The combined satellite-only global gravity field model GOCO02S; presented at the 2011 General Assembly of the European Geosciences Union, Vienna, Austria, April 4-8.

Heiskanen WA and Moritz H (1967) Physical Geodesy, W.H. Freeman and Company, San Francisco.

IERS Conventions (2010) Gérard Petit and Brian Luzum (eds.). (IERS Technical Note ; 36) Frankfurt am Main: Verlag des Bundesamts für Kartographie und Geodäsie, 2010. 179 pp., ISBN 3-89888-989-6.

Kotsakis C and Katsambalos K (2010) Quality analysis of global geopotential models at 1542 GPS/Levelling benchmarks over the Hellenic mainland. Surv Rev 42(318): 327-344.

Kotsakis C and Sideris MG (1999) On the adjustment of combined GPS/Levelling/geoid networks. J Geod 73(8): 412–421.

Mayer-Gürr T, Kurtenbach E, Eicker A, (2010) GRACE-only gravity field model ITG-Grace2010s, http://www.igg.uni-bonn.de/apmg/index.php?id=itg-grace2010.

Mayer-Gürr T., Rieser D., Höck E., Brockmann J..M., Schuh W.-D., Krasbutter I., Kusche J., Maier A., Krauss S., Hausleitner W., Baur O., Jäggi A., Meyer U., Prange L., Pail R., Fecher T., Gruber T. (2012) The new combined satellite only model GOCO03S**.** Abstract submitted to GGHS2012, Venice.

Migliaccio F, Reguzzoni M, Sanso F, Tscherning CC, Veicherts M (2010) GOCE data analysis: the space-wise approach and the first space-wise gravity field model presented at the ESA Living Planet Symposium 2010, Bergen, June 27 - July 2, Bergen, Norway.

Migliaccio F, Reguzzoni M, Sansò F, Tscherning CC, Veicherts M (2010) GOCE data analysis: the space-wise approach and the first space-wise gravity field model. In: Lacoste-Francis H (ed) Proceedings of the ESA living planet symposium. ESA Publication SP-686, ESA/ESTEC. ISBN:978-92-9221-250-6.

Moritz H (2000) Geodetic Reference System 1980. J Geod 4(1): 128-162.

Pail R, Goiginger H, Schuh WD, Hock E, Brockmann M, Fecher T, Gruber T, Mayer-Gurr, T, Kusche J, Jaggi A, and Rieser D, (2010) Combined satellite gravity field model GOCO01S derived from GOCE and GRACE. Geophysical Research Letters, Vol. 37, EID L20314, American Geophysical Union, ISSN 0094-8276, DOI: 10.1029/2010GL044906.

Pail R, Bruinsma S, Migliaccio F, Förste C, Goiginger H, Schuh WD, Höck E, Reguzzoni M, Brockmann JM Abrikosov O, Veicherts M Fecher T, Mayrhofer R, Krasbutter I, Sansò F, Tscherning CC (2011) First GOCE gravity field models derived by three different approaches. J Geod 85(11): 819-843, doi: 10.1007/s00190-011-0467-x.

Pavlis NK, Holmes SA, Kenyon SC, Factor JK (2012) The development and evaluation of the Earth Gravitational Model 2008 (EGM2008), J Geophys Res 117: B04406, doi: 10.1029/2011JB008916.

Rapp RH, Nerem RS, Shum CK, Klosko SM,. Williamson RG (1991) Consideration of Permanent Tidal Deformation in the Orbit Determination and Data Analysis for the Topex/Poseidon Mission. NASA TM 100775, Goddard Space Flight Center, Greenbelt, MD, 1991.

Tocho C, (2006) A gravimetric geoid modelling. Tesis Doctoral. Facultad de Ciencias Astronómicas y Geofísicas. Universidad Nacional de La Plata.

Tziavos IN, Vergos GS, Grigoriadis VN, Andritsanos VD (2012) Adjustment of collocated GPS, geoid and orthometric height observations in Greece. Geoid or orthometric height improvement? IAG Symp. 136, pp. 477-484.

Vergos GS, Sideris MG (2002) Evaluation of Geoid Models and Validation of Geoid and GPS/Leveling Undulations in Canada. IGeS Bulletin 12: 3 - 17.

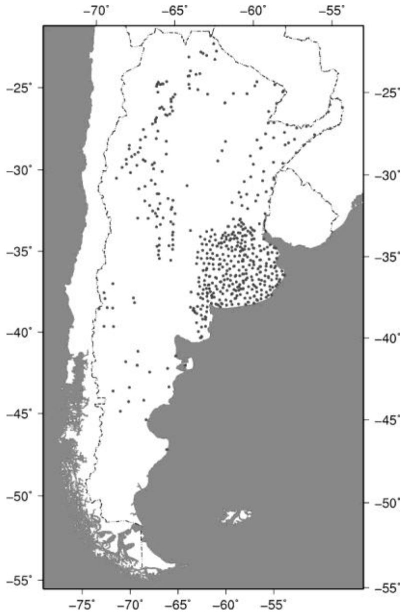

Fig. 1 Geographical distribution of the GPS/Levelling benchmarks in Argentina.

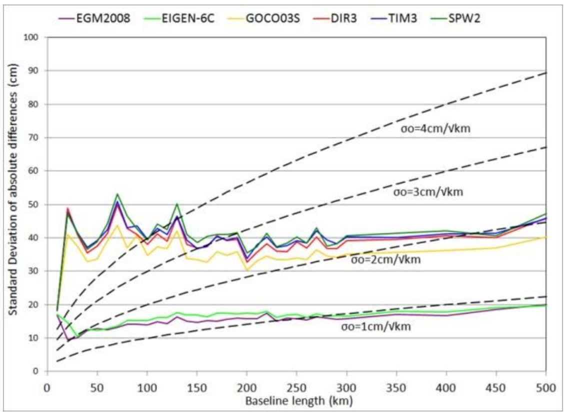

Fig. 2 Standard Deviation of the absolute differences in the test network $\Delta N_{ij}^{GPS/Levelling} - \Delta N_{ij}^{GGM}$ of 542 GPS/Levelling benchmarks, as a function of the baseline length up to 500 km.

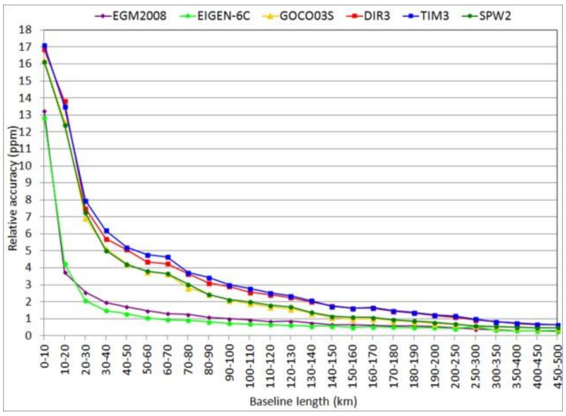

Fig. 3 Relative accuracy between GGMs models and GPS/Levelling derived geoid across Argentina (after a five- order similarity transformation model fit).