EGM2008 and PGM2007A evaluation for South America

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Abstract. The Earth Gravitational Model (EGM) development team released the Preliminary Gravitational Model (PGM2007A) and the final EGM2008. These models are completed to degree and order 2160 and contain additional spherical harmonic coefficients extending to degree 2190 and order 2160. A total of 1,190 GPS points available on Bench Marks (GPS/BM) in South America and 85,018 mean free air gravity anomalies in a grid of 5' are used to evaluate the following gravity field models: EGM96, EIGEN-GL04S1, EIGEN-GL04C, GGM02S, GGM02C, PGM2007A and EGM2008. The results are presented in terms of statistics and histograms of the discrepancies between GPS geoid heights as well as gravity disturbances and the seven important Global Geopotential Models. The modern models represent a substantial improvement on the gravitational field representation in South America and EGM2008 shows the best result compared to previous models.

Keywords. Geopotential model, geoid modeling, GPS

1 Introduction

There are essentially three classes of Global Geopotential Models (GGMs) according to Rapp (1997), Balmino *et al.* (1997), Featherstone (2002) and Rummel *et al.* (2002):

1-Satellite-only GGMs: derived solely from the analysis of orbits of artificial Earth satellites.

2-Combined GGMs: derived from a combination of satellite, altimetry, land, shiptrack and airborne gravity observation data. The additional information allows an increase of the maximum spherical harmonic degree of the GGMs.

3-Tailored GGMs: an existing satellite-only or combined GGM adjusted with new data, not necessarily used before.

The limitations of satellite information are power-decay of the gravitational field with altitude; the inability to track complete satellite orbits using ground-based stations; imprecise modeling of atmospheric drag, non-gravitational and third-body perturbations; finally incomplete sampling of the global gravity field due to the limited number of satellite orbital inclinations available. Nowadays, with dedicated satellite gravity missions, many old limitations are redressed (Featherstone, 2002). The other limitations are spatial coverage and quality of the additional data used.

The new gravity missions as Challenging Minisatellite Payload (CHAMP) and Gravity Recovery and Climate Experiment (GRACE) are allowing the best knowledge of the long wavelength component of the Earth gravitational field. These missions are the beginning of what is often called the "geopotential international decade" and the scientific community expects a great advance with the Gravity Field and Steady-State Ocean Circulation (GOCE) mission.

This paper mainly focuses on two important combined GGMs: PGM2007A and EGM2008. Geoidal heights derived from GPS/BM and terrestrial gravity data are used to evaluate these models for South America and for Brazil. Other GGMs are validated too: EGM96 (Combined model complete to degree and order 360) (Lemoine *et al.*, 1998a; Lemoine *et al.*, 1998b); EIGEN-GL04S1 (satellite-only GRACE model complete to degree and order 150); EIGEN-GL04C (combined GRACE model complete to degree and order 360) (Förste *et al.*, 2006); GGM02S (satellite-only GRACE model complete to degree and order 160); GGM02C (combined GRACE model complete to degree and order 200).

The height anomaly and gravity disturbances are computed using the very high degree harmonic synthesis program Harmonic_synth_v2 developed by Holmes and Pavlis (2008). It is important to mention that in both PGM2007A and EGM2008 the second-degree zonal harmonic coefficient $\{\overline{C}_{20}\}$ is expressed in the "Zero Tide" system, as far as the permanent tide is concerned (Holmes and Pavlis, 2008).

2 GPS data on benchmark

GPS observations carried out on benchmarks of the spirit levelling network in South America, which have been delivered under the SIRGAS (Geocentric Reference System for Americas) project (SIRGAS, 2002), are used for testing the gravimetric determination of the geoid as well as the selected GGMs. At the moment there are GPS/BM data available from the following countries: Brazil, Argentina, Ecuador, Venezuela and Chile (Blitzkow, 1999). A total of 1,190 GPS points are available in South America with 696 points in Brazil (Figure 1).

Table 1 shows the results in terms of mean value, RMS, extreme values of the differences among height anomalies of several GGMs for different degree and order (60, 120, 360 and 2160) and GPS/BM geoidal heights for South America. Table 2 shows the same statistic analysis for Brazil.

In Figures 2 to 6 one can see the histograms of the discrepancies between GGM and GPS/BMs for specific maximum degrees and orders (60, 120, 360). PGM2007A and EGM2008 are more consistent with GPS/BM than the other GGMs, even for low degrees and orders. For degree and order 2160 both models of this order are the best with the final model slightly better than the preliminary. Figure 1 shows the GPS/BM distribution with a colour schedule for differences between EGM2008 height anomalies and GPS/BM geoidal heights. This information is still sparse and not distributed homogeneously, so that this result is geographically limited, but most of the greater differences are in the Andes.

3 Official geoid model for Brazil

The official geoid model in Brazil is MAPGEO2004 (IBGE, 2004; Lobianco *et al.*, 2005). It is computed using EGM96 up to degree and order 180 as the reference field (Figure 7). The reduced Helmert mean gravity anomalies are estimated in blocks of 10' x 10'. For the ocean the KMS-99 satellite altimetry model is used (Andersen and Knudsen, 1998). A DTM is also derived with a resolution of 1' x 1'. It was obtained from digitization of topographic maps, combined with the GLOBE model (Hasting and Dunbar, 1999) where topographic maps were unavailable. The processing of the modified Stokes integral proposed by Featherstone et al. (1998) is carried out using FFT. This modification applies a Meissl (1971) modification to the Vaníček and Kleusberg (1987) kernel.

Table 3 shows statistics of the differences between geoidal heights of MAPGEO2004 and GPS/BM in Brazil (696 points). Looking to the results of PGM2007A, EGM2008 (n=m=360 or 2160) and EIGEN-GL04C (n=m=360) (Table 2), the conclusion is that these models are slightly better than the official geoid model. This probably depends on that the new GGMs have been computed using slightly more gravity information than MAPGEO2004.

Table 1. Statistics of the differences between height anomalies computed by the GGMs and GPS/BM geoidal heights for South America.

n=m	Statistics	EGM2008	PGM2007A	EGM96	EIGEN-GL04C	EIGEN-GL04S1	GGM02C	GGM02S
		(m)	(m)	(m)	(m)	(m)	(m)	(m)
60	**Mean**	-0.15	-0.14	-0.17	-0.20	-0.20	-0.18	-0.18
	RMS dif.	1.75	1.75	1.84	1.77	1.77	1.77	1.77
	Max.	6.2	6.2	5.8	6.3	6.3	6.3	6.3
	Min.	-8.8	-8.8	-8.8	-9.1	-9.1	-9.1	-9.1
120	**Mean**	0.12	0.13	0.10	0.06	0.07	0.09	0.09
	RMS dif.	1.09	1.10	1.16	1.10	1.10	1.08	1.10
	Max.	3.8	3.9	4.3	3.9	3.8	3.8	4.0
	Min.	-4.1	-4.1	-4.4	-4.2	-4.1	-4.2	-4.1
360	**Mean**	0.28	0.30	0.24	0.22			
	RMS dif.	0.72	0.73	0.80	0.70			
	Max.	2.8	2.9	3.7	3.1			
	Min.	-3.3	-3.2	-3.3	-2.9			
2160	**Mean**	0.22	0.24					
	RMS dif.	0.68	0.69					
	Max.	3.4	3.4					
	Min.	-3.3	-3.2					

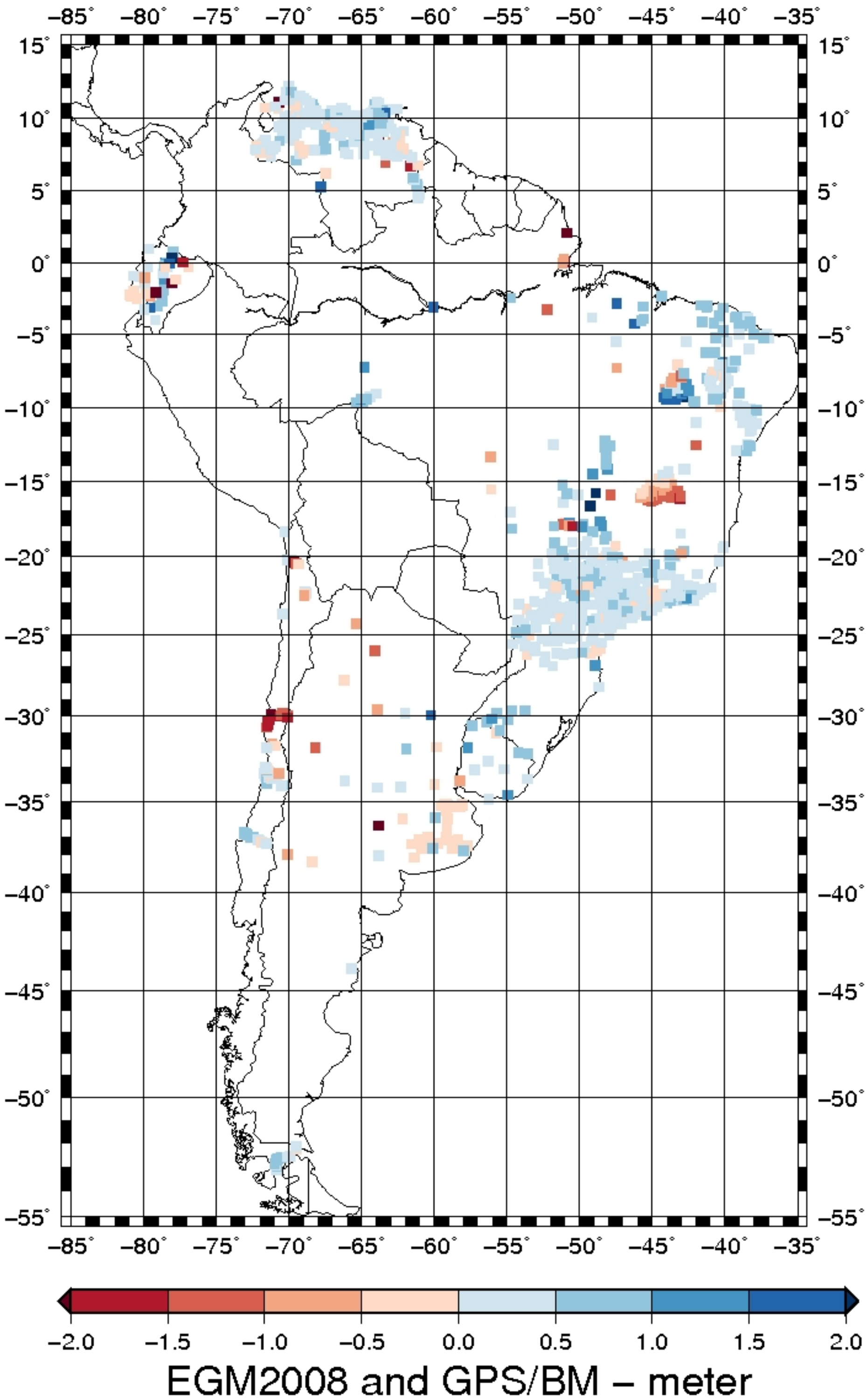

Fig. 1 Distribution of the GPS/BMs and illustration of the differences between EGM2008 height anomalies and GPS/BM geoidal heights.

Table 2. Statistics of the differences between height anomalies of the GGMs and GPS/BM geoidal heights for Brazil

n=m	Dataset	EGM2008 (m)	PGM2007A (m)	EGM96 (m)	EIGEN-GL04C (m)	EIGEN-GL04S1 (m)	GGM02C (m)	GGM02S (m)
60	**Mean**	0.26	0.26	0.34	0.25	0.25	0.27	0.27
	RMS dif.	1.06	1.05	1.15	1.05	1.05	1.05	1.05
	Max.	3.85	3.71	3.95	3.76	3.76	3.78	3.79
	Min.	-4.30	-4.22	-3.71	-4.29	-4.29	-4.26	-4.26
120	**Mean**	0.34	0.34	0.43	0.34	0.34	0.35	0.40
	RMS dif.	0.79	0.81	0.88	0.79	0.80	0.77	0.80
	Max.	2.95	3.00	3.27	2.82	2.97	2.81	3.01
	Min.	-3.38	-3.36	-3.25	-3.42	-3.41	-3.32	-3.32
360	**Mean**	0.31	0.32	0.40	0.32			
	RMS dif.	0.58	0.60	0.75	0.62			
	Max.	2.81	2.90	3.73	3.12			
	Min.	-3.05	-3.03	-3.03	-2.85			
2160	**Mean**	0.29	0.29					
	RMS dif.	0.56	0.58					
	Max.	2.78	2.87					
	Min.	-3.05	-3.03					

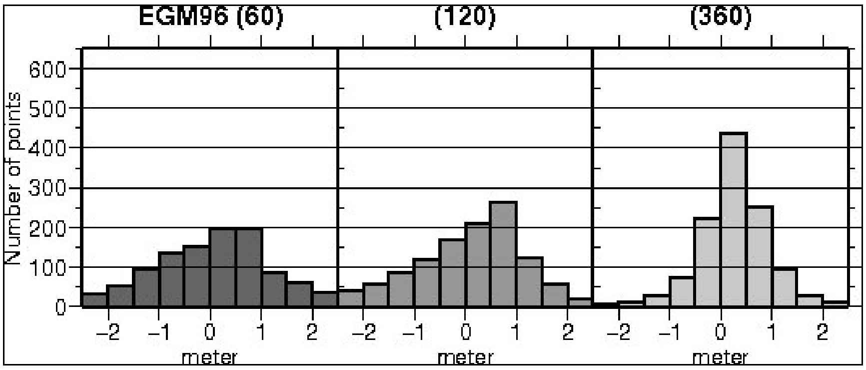

Fig. 2 Histograms of discrepancies between EGM96 height anomalies and GPS/BM geoidal heights.

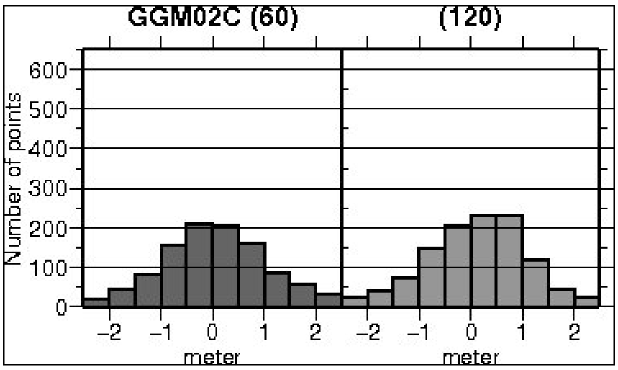

Fig. 3 Histograms of discrepancies between GGM02C height anomalies and GPS/BM geoidal heights.

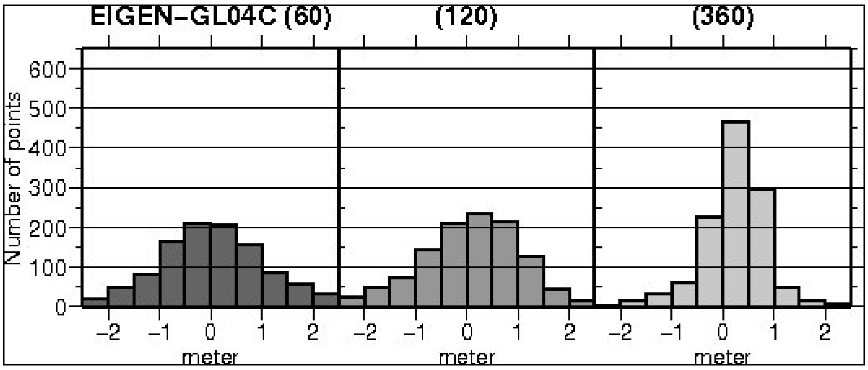

Fig. 4 Histograms of discrepancies between EIGEN-GL04C height anomalies and GPS/BM geoidal heights.

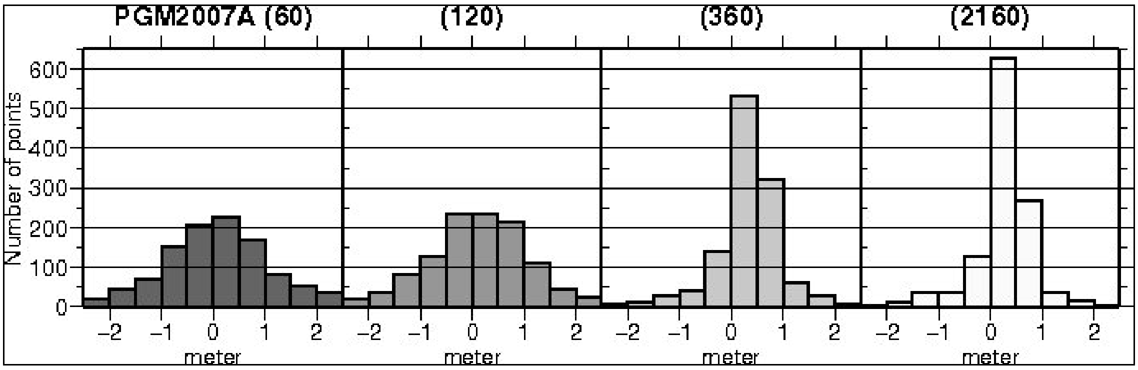

Fig. 5 Histograms of discrepancies between PGM2007A height anomalies and GPS/BM geoidal heights.

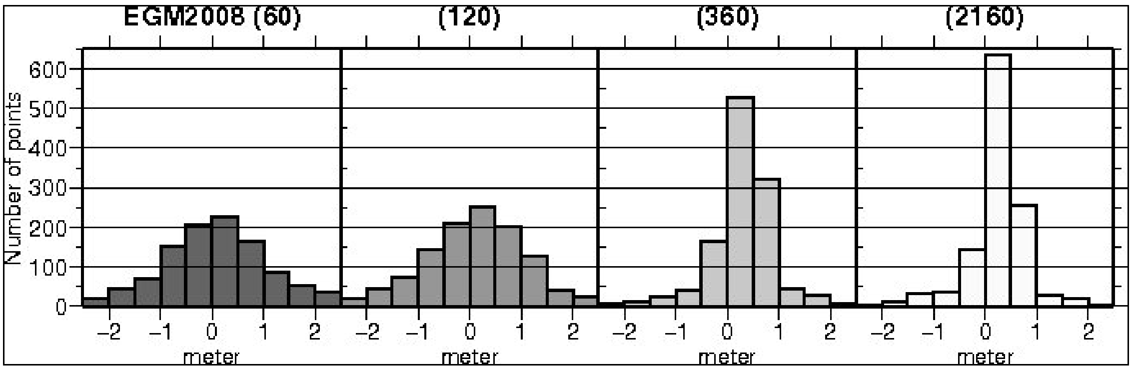

Fig. 6 Histograms of discrepancies between EGM2008 height anomalies and GPS/BM geoidal heights.

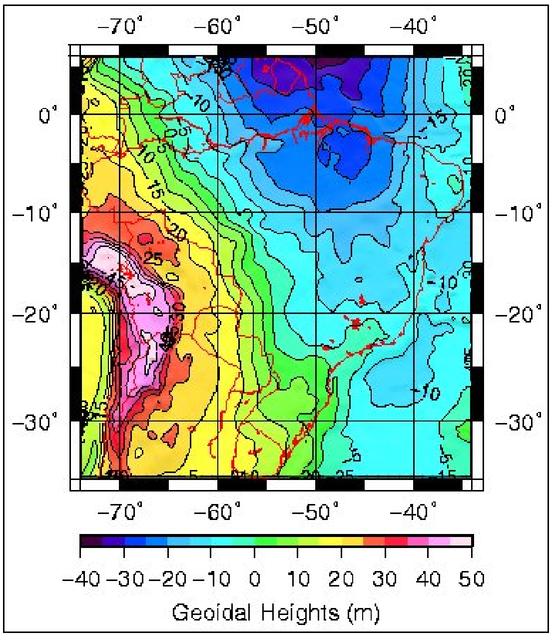

Fig. 7 MAPGEO2004, the official geoid model in Brazil.

Table 3. Statistics of the differences between geoidal heights of MAPGEO2004 and GPS/BM for Brazil (696 points)

	MAPGEO2004 (m)
Mean	-0.57
RMS dif.	0.68
Max.	2.48
Min.	-3.97

4 Terrestrial gravity data

South American Gravity Project (Green and Fairhead, 1991) was the first great effort in collecting and validating gravity data over the continent. This initiative is important to indicate the terrestrial and marine gravity distribution and to identify the major gaps. In 1991, the Anglo-Brazilian Gravity Project (ABGP) started some new efforts to fill in the gaps in Brazil. This project was a cooperation program between LTG/EPUSP (Laboratory of Topography and Geodesy - Polytechnic School, University of São Paulo), Brazilian Institute of Geography and Statistics (IBGE) and Geophysical Exploration Technology (GETECH), supported by U.S. National Geospatial-Intelligence Agency (NGA). After seven years of activities this project was responsible for an outstanding improvement on the gravity point distribution, mainly in the Amazon region, including rivers and airstrips along small villages.

The activities of ABGP were extended to other countries in the continent in 2000 as South America Gravity Studies (SAGS). Presently a total of 849,363 terrestrial gravity points are available in South America.

The gravity anomalies derived from terrestrial gravity data are compared with gravity disturbances derived from GGMs. Mean gravity anomalies in a grid of 5’ x 5’ (from 25° N to 60° S to 100° W to 25° W) are obtained from the complete Bouguer anomaly using point gravity data, except for Colombia where only mean free air gravity anomalies are available (Rodríguez, 2003). For these computations the SHGEO software is used, developed at the University of New Brunswick, available to EPUSP and IBGE through the Project PIGN (*Projeto de Infraestrutura Geodésica Nacional*). The total grid number is 85,018. The digital terrain model used for different purposes is SAM_3sv2 (Matos and Blitzkow, 2008).

Table 4 shows the results in terms of mean value, RMS and extreme values of the differences between gravity anomalies derived from terrestrial gravity data and gravity disturbances derived from GGMs; the same degrees and orders as before are used. Figures 8 to 12 show the histograms of the discrepancies. One can see that PGM2007A and EGM2008 with n=m=360 are better adjusted to the terrestrial gravity data than the other GGMs.

Figures 13 to 16 show the discrepancies between terrestrial gravity anomalies and gravity disturbances derived from EGM96, EIGEN-GL04C, EGM2008 (n=m=360) and EGM2008 (n=m=2160), respectively. There is a visible improvement between EGM96 and EIGEN-GL04C, although not considerable. To the same degree and order (360) the improvement of EGM2008 is visible in the north and middle of Argentina as well as southeast and south of Brazil. Finally, looking to the full degree and order of EGM2008 (n=m=2160) the improvement is remarkable in the whole South America, mainly around mountainous regions. Nevertheless, the main discrepancies are correlated with high and rough topography, especially over the Andes.

Table 4. Statistics for the discrepancies between terrestrial gravity anomalies and gravity disturbances derived by GGMs (85,018 points).

n=m	Dataset	EGM2008	PGM2007A	EGM96	EIGEN-GL04C	EIGEN-GL04S1	GGM02C	GGM02S
		(mGal)	(mGal)	(mGal)	(mGal)	(mGal)	(mGal)	(mGal)
60	**Mean**	0.84	0.83	-0.97	-0.78	-0.78	-0.79	-0.79
	RMS dif.	47.54	47.52	48.21	48.16	48.16	48.17	48.17
	Max.	692.48	692.29	696.83	695.62	695.62	695.61	695.59
	Min.	-209.25	-209.51	-215.53	-222.34	-222.34	-222.36	-222.33
120	**Mean**	-0.94	-1.05	-3.04	-2.60	-2.61	-2.62	-2.60
	RMS dif.	42.85	42.84	43.77	43.45	43.42	43.45	43.53
	Max.	581.12	580.22	599.64	585.50	582.38	585.60	582.05
	Min.	-232.66	-232.95	-244.81	-235.10	-233.65	-235.95	-234.54
360	**Mean**	-2.28	-2.42	-4.73	-4.52			
	RMS dif.	28.94	28.97	31.97	31.89			
	Max.	401.83	389.19	377.61	386.99			
	Min.	-338.21	-321.75	-292.86	-303.91			
2160	**Mean**	-0.19	-0.33					
	RMS dif.	20.43	20.41					
	Max.	372.12	356.75					
	Min.	-492.40	-437.62					

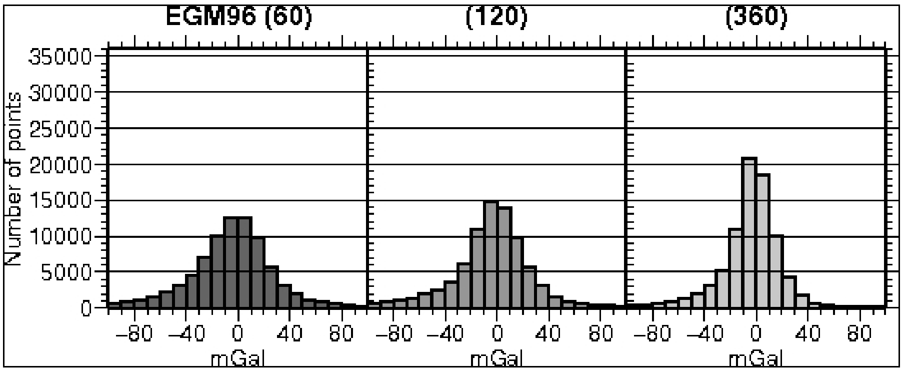

Fig. 8 Histograms of the discrepancies between terrestrial gravity anomalies and gravity disturbances derived from EGM96.

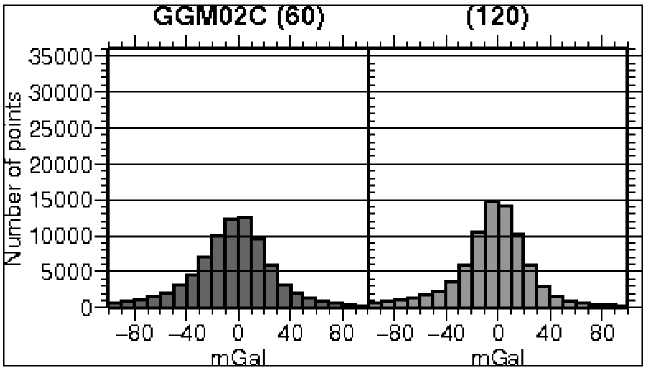

Fig. 9 Histograms of the discrepancies between terrestrial gravity anomalies and gravity disturbances derived from GGM02C.

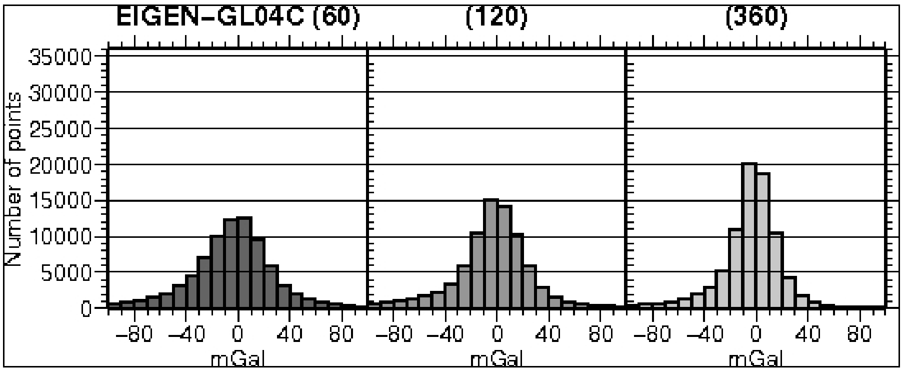

Fig. 10 Histograms of the discrepancies between terrestrial gravity anomalies and gravity disturbances derived from EIGEN-GL04C.

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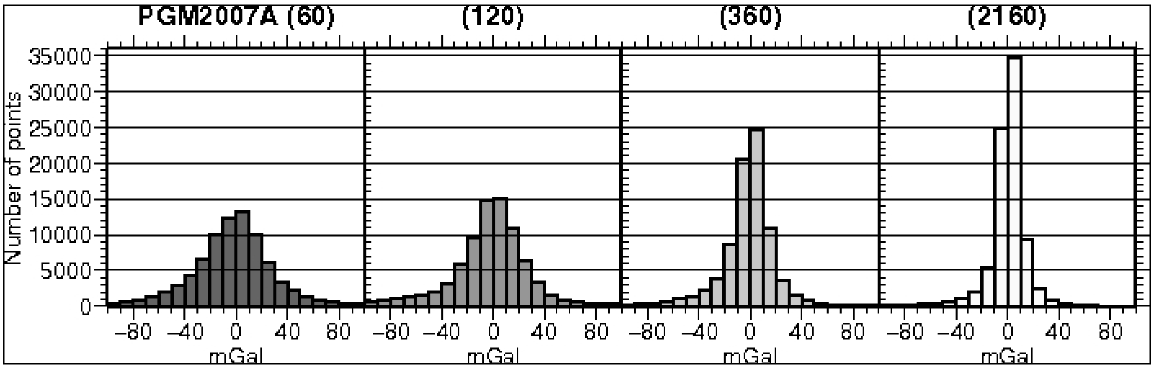

Fig. 11 Histograms of the discrepancies between terrestrial gravity anomalies and gravity disturbances derived from PGM2007A.

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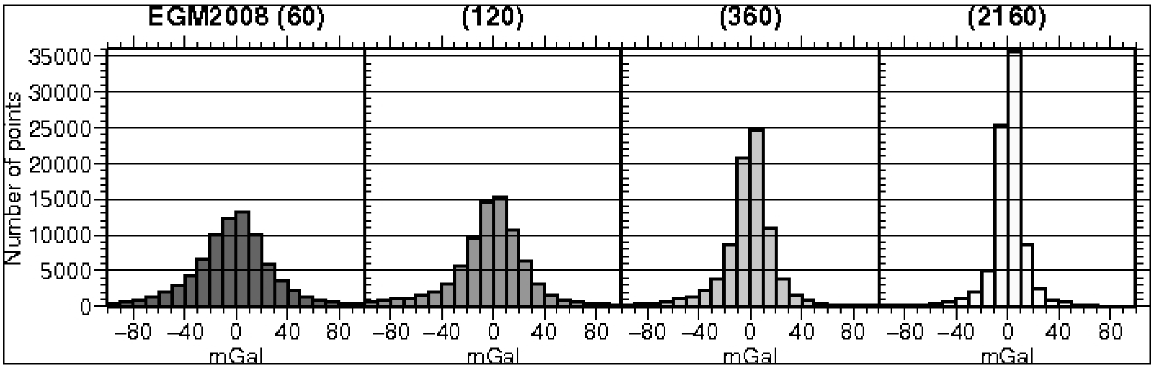

Fig. 12 Histograms of the discrepancies between terrestrial gravity anomalies and gravity disturbances derived from EGM2008.

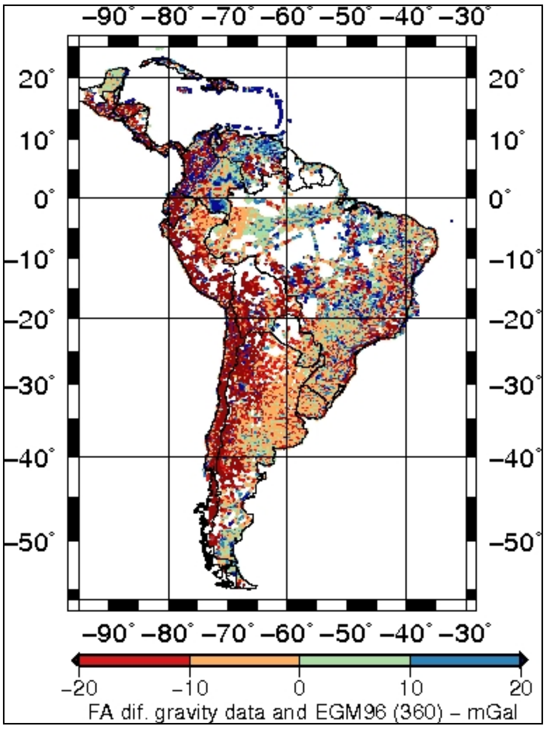

Fig. 13 Discrepancies between terrestrial gravity anomalies and gravity disturbances derived from EGM96.

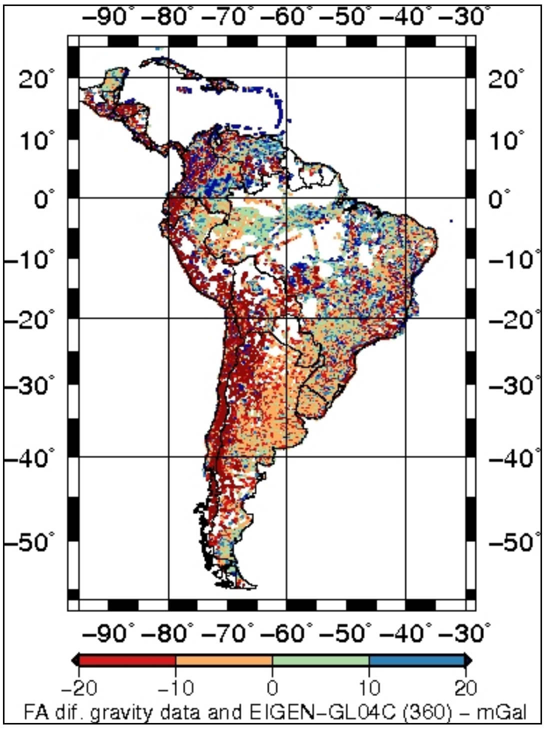

Fig. 14 Discrepancies between terrestrial gravity anomalies and gravity disturbances derived from EIGEN-GL04C.

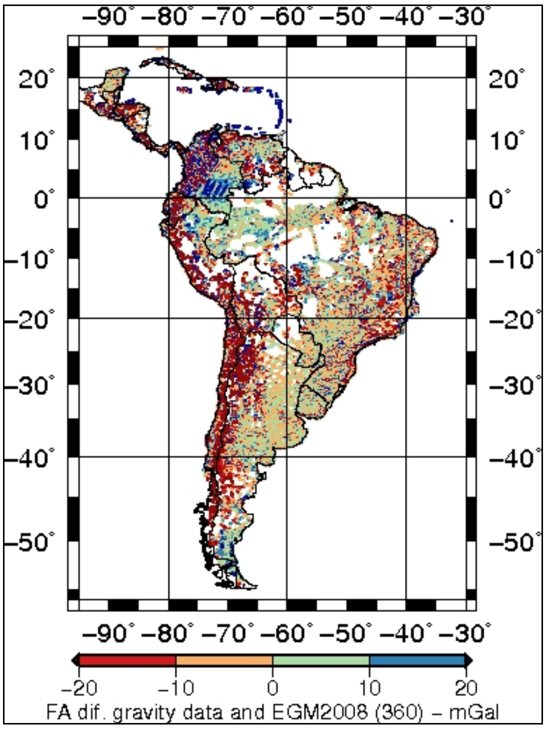

Fig. 15 Discrepancies between terrestrial gravity anomalies and gravity disturbances derived from EGM2008.

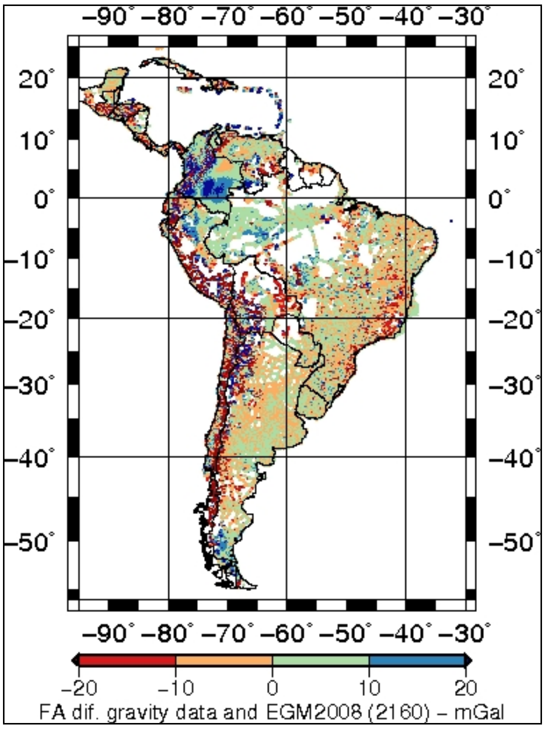

Fig. 16 Discrepancies between terrestrial gravity anomalies and gravity disturbances derived from EGM2008.

5 Conclusions

The validation of the geopotential models PGM2007A and EGM2008 are carried out over South America in terms of:
1 - GPS on Bench Marks;
2 – The geoid model MAPGEO2004;
3 – Terrestrial gravity anomalies.

The global gravity models EGM96, EIGEN-GL04S1, EIGEN-GL04C, GGM02S, GGM02C are also evaluated for different degrees and orders.

The statistics of the differences between the tested geopotential models and GPS/BM show that the best agreement is obtained with EGM2008 (n=m=2160) in South America. In Brazil, this geopotential model shows results slightly better than MAPGEO2004, the official geoid model for Brazil.

The gravity disturbances derived from EGM2008 show the best agreement when compared with terrestrial gravity anomalies. Most of the still existing inconsistencies of this GGM is in mountainous regions, mainly in the Andes.

The general conclusion is that the recent geopotential models, in particular EGM08, represent an important improvement on the knowledge of the gravitational potential in South America.

6 Acknowledgements

The authors acknowledge the contribution of the Civil and Military organizations in the following countries: Argentina, Brazil, Chile, Colombia, Ecuador, Paraguay, Uruguay and Venezuela. The activity has been partially undertaken with the financial support of Government of Canada provided through the Canadian International Development Agency (CIDA).

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