Combining terrestrial, marine and satellite gravity for geoid modelling in Venezuela

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1. Introduction

Since 1993 different geoid models have been calculated for Venezuela. Here, the recently published SRTM topography and GEBCO bathymetry, and the new geopotential solutions obtained with the CHAMP gravity mission, are used to calculate a new national geoid (*VGM03: Venezuelan Geoid Model 2003*) with improved resolution and quality. The new geoid has 1-kilometer resolution and combines all terrestrial and marine gravity data available in the region. The calculation is based on Least Squares Collocation (LSC) and Fast Fourier Transform (FFT) methods. The poster focuses on the gain achieved with the new data sets.

2. Data available

- 560.000 point free-air gravity anomalies from PDVSA, IGAC, BGI and GEODAS/NGDC databases.
- 2.9 million 30"x30" topographic-isostatic mean gravity anomalies to "fill-in" terrestrial areas without data.
- 3.5 million 30"x30" mean gravity anomalies derived by multi-mission altimetry (with data from 8 missions up to december 2002), specifically calculated for this work.
- A hybrid geopotential global model: TEG-4 (up to 70/70) and EGM96 (above 70, up to 360) was used as reference.
- 3"x3" terrain elevations from SRTM-NASA and 1'x1' depths of the GEBCO 2003 bathymetry for a new digital terrain model with about 210 million heights.
- The POCM-4B model to correct for mean dynamic topography.
- GPS/levelling measurements from LGFS, IGVSB, IGAC and DGFI for quality assessment on land.
- Mean sea surface profiles of TOPEX/Poseidon (9 years), ERS-2 (6 years), GFO (3 years) and JASON-1 (1 year) for quality assesment on sea.

3. Geoid estimation method

The remove-restore technique and the Residual Terrain Model (RTM) method have been applied to derive the quasigeoid. LSC was used to combine and grid the heterogeneous residual gravity anomalies Δg_{RES}. These were transformed to residual height anomalies ζ_{RES} through evaluation of the Stokes integral in spherical approximation by the exact one-dimensional Fast Fourier Transform (1D-FFT) method with 100% zero padding. The RTM contributions (Δg_{RTM}, ζ_{RTM}) were calculated by means of the numeric integration of residual terrain heights relative to a mean topography of 30'x30' resolution. Geoid-quasigeoid differences (N-ζ) were calculated using the digital terrain model and Bouguer anomalies obtained from the Δg_{RES}. Subsequently, the ζ were transformed to geoid undulations N. Ellipsoidal corrections (δN_{ELLIP}) to the spherical approach of the Stokes solution complete the gravimetric geoid. $N_{GPS/levelling}$-N_{GRAV} differences in 320 stations of 7 local nets were used to control the gravimetric geoid on land and to produce the final hybrid geoid.

4. Results

4.1. Improving the geopotential reference model

Data of the CHAMP gravity mission are already incorporated in the geopotentials models TEG-4 and EIGEN-2. They were used to correct long wavelength (> 500 km) errors in the EGM96 model. TEG-4 and EGM96 (both up to 70/70) show differences of ± 2 m (Fig. 1a). Two hybrid models were formed, TEG4(70)+EGM96(71-360) and EIGEN2(40) + EGM96(40-360).

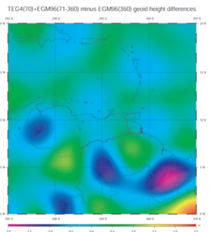
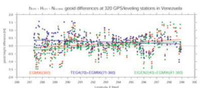


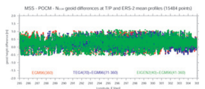
Fig. 1a

The comparison of the TEG4/EGM96 with 320 GPS/levelling points in Venezuela shows a 10% smaller rms as with EIGEN2/EGM96. On land, the use of the hybrid model reduces a clear E-W inclination of EGM96 relative to the Venezuelan height system (Fig. 1b). At sea, comparisons with T/P and ERS-2 profiles (15484 points) don't reveal significant improvement (Fig 1c).



Global Geopotential Model	MIN. [m]	MAX. [m]	MEAN [m]	RMS [m]
EGM96(360)	-1.34 (-1.24)	1.35 (1.23)	0.12 (0.00)	± 0.53 (± 0.44)
EIGEN2(40)+EGM96(41-360)	-1.47 (-1.25)	1.52 (1.23)	-0.01 (0.00)	± 0.56 (± 0.44)
TEG4(70)+EGM96(71-360)	-1.02 (-1.11)	1.57 (1.20)	0.26 (0.00)	± 0.44 (± 0.40)

Fig. 1b



Global Geopotential Model	MIN. [m]	MAX. [m]	MEAN [m]	RMS [m]
EGM96(360)	-0.47 (-0.73)	1.04 (0.73)	0.29 (0.00)	± 0.25 (± 0.24)
EIGEN2(40)+EGM96(41-360)	-0.54 (-0.75)	1.11 (0.74)	0.29 (0.00)	± 0.28 (± 0.25)
TEG4(70)+EGM96(71-360)	-0.54 (-0.75)	1.00 (0.75)	0.23 (0.00)	± 0.25 (± 0.24)

Fig. 1c

4.2. New Digital Terrain Model

The new DTM (VDTM03) with 90 m resolution on land was obtained from SRTM (*Shutte Radar Topography Mission*) data (Fig. 2a). Subsequently, it was compared with GTOPO30 used in the previous geoid solutions (Fig. 2b). There are significant differences at the South of Venezuela. The *Macizo Guayanes* formation is clearly exaggerated by GTOPO30.

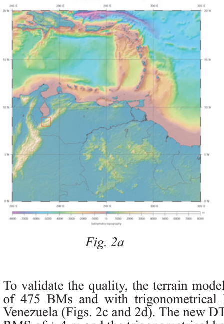


Fig. 2a

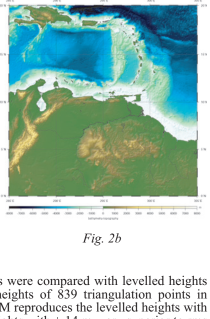
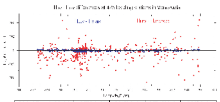


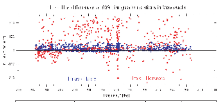
Fig. 2b

To validate the quality, the terrain models were compared with levelled heights of 475 BMs and with trigonometrical heights of 839 triangulation points in Venezuela (Figs. 2c and 2d). The new DTM reproduces the levelled heights with RMS of ± 4 m and the trigonometrical heights with ± 14 m, very superior to rms values of ± 67 m and ± 122 m for GTOPO30, respectively.



Digital Terrain Model	MIN. [m]	MAX. [m]	MEAN [m]	RMS [m]
GTOPO30	-367 (-355)	392 (414)	-22 (0)	± 68 (± 67)
SRTM3	-13 (-10)	10 (10)	-2 (0)	± 4 (± 4)

Fig. 2c



Digital Terrain Model	MIN. [m]	MAX. [m]	MEAN [m]	RMS [m]
GTOPO30	-276 (-416)	717 (568)	73 (0)	± 131 (± 122)
SRTM3	-24 (-40)	60 (40)	-24 (0)	± 17 (± 14)

Fig. 2d

The Figs. 2e and 2f show an 1°x1° area in the Venezuelan Andes (this area is highlighted in the Fig. 2a). The SRTM model shows much more details.

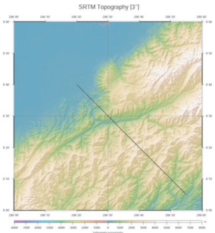


Fig. 2e

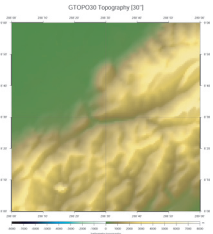


Fig. 2f

In the profile shown in the Figs. 2e and 2g, GTOPO30 appears as a low-pass filter of the SRTM topography.

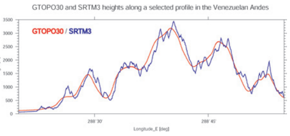


Fig. 2g

Residual Gravity Anomaly	MIN. [mGal]	MAX. [mGal]	MEAN [mGal]	RMS [mGal]
Δg_{RES} GTOPO30	-205.4	215.7	-0.6	± 21.5
Δg_{RES} SRTM3	-204.9	211.8	-0.4	± 20.0

Table 1

Terrain reductions calculated with the SRTM DTM result in residual gravity anomalies 7% smaller (smoother) compared to those calculated with GTOPO30 (see Table 1).

4.3. MSS and GAS models

A Mean Sea Surface (MSS) model has been generated from the multi-mission altimeter data (see e.g. the GFO data, Fig. 3a). The MSS model (VMSS03) is shown in Fig. 3c. The multi-mission heights were fixed to the T/P mission by crossover adjustment and then referred to the ITRF00/GRS-80. Geosat GM data was included with resolution of 10 Hz. At the coast the altimeter data was extrapolated by LSC using a local geoid model (VGM02) (Fig. 3b). After repeat-track-averaging, the geodetic phase data from Geosat and ERS-1 were combined with mean profiles of the ERM missions. Data gridding to 30"x30" resolution were carried out with LSC. Residual orbital and oceanic variability errors were reduced using Wiener filtering. VMSS03 was then compared with mean profiles of the JASON-1 mission and other previous MSS (Fig. 3c). The RMS of the differences between VMSS03 and JASON-1 profiles is ± 4 cm.
After correction for the POCM-4B dynamic topography, VMSS03 was transformed to gravity values through the inverse Stokes integral evaluated with FFT (Fig. 3d). The Gravity Anomaly Surface (GAS) obtained (VGAS03) was compared with GEODAS marine shipborne gravity and other GAS. The RMS of the differences between VGAS03 and GEODAS database is ± 6.8 mGal.

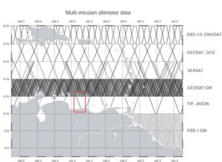


Fig. 3a

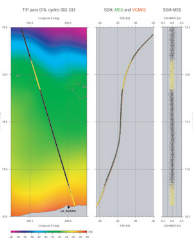
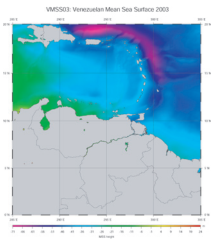
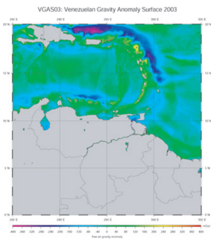


Fig. 3b



Mean Sea Surface	MIN. [m]	MAX. [m]	MEAN [m]	RMS [m]
S&Sv9.2	-0.57 (-0.50)	0.52 (0.56)	0.00 (0.00)	± 0.12 (± 0.11)
GSFC00	-0.10 (-0.14)	0.22 (0.16)	0.05 (0.00)	± 0.04 (± 0.04)
KMS01	-1.07 (-1.06)	0.90 (0.72)	0.04 (0.00)	± 0.17 (± 0.15)
CLS01	-0.16 (-0.21)	0.17 (0.15)	0.02 (0.00)	± 0.04 (± 0.04)
VMSS03	-0.04 (-0.11)	0.22 (0.11)	0.09 (0.00)	± 0.04 (± 0.04)

Fig. 3c



Gravity Anomaly Surface	MIN. [mgal]	MAX. [mgal]	MEAN [mgal]	RMS [mgal]
S&Sv9.1	-25.3 (-27.6)	27.5 (26.2)	0.9 (0.0)	± 7.0 (± 6.9)
GSFC00	-82.7 (-83.8)	68.7 (71.3)	0.7 (0.0)	± 7.1 (± 7.0)
KMS01	-71.8 (-72.7)	67.7 (63.6)	-0.1 (0.0)	± 8.4 (± 8.2)
VGAS03	-27.0 (-19.8)	28.3 (19.8)	0.9 (0.0)	± 6.8 (± 6.6)

Fig. 3d

4.4. Correction of marine gravity data using the altimetric gravity anomalies

Marine gravity suffer from calibration errors in ports and instrumental drifts. This changes the absolute level of profiles observed at different epochs and produces track-line patterns in the derived gravity anomalies (Fig.4a). To correct these errors, the 126 ship trajectories from the GEODAS database were fixed to the uniform altimetric gravity data VGAS03 by crossover adjustment using a bias and tilt model (Fig. 4b). An example is shown in the Fig. 4c using the profile 67010179 indicated in the Fig. 4a. Table 2 shows statistics of marine gravity measurements before and after correction.

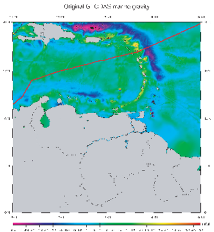


Fig. 4a

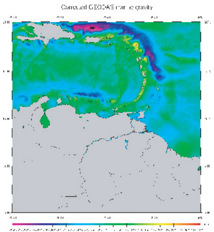


Fig. 4b

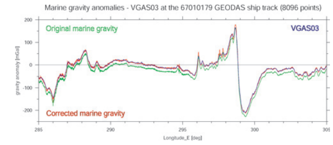


Fig. 4c

GEODAS marine gravity	MAX. [mGal]	MIN. [mGal]	MEAN [mGal]	RMS [mGal]
Original – TEG4/EGM96	145.9	-164.8	-7.1	± 38.7
Corrected – TEG4/EGM96	110.9	-120.7	-3.1	± 31.3

Table 2

4.5. Remove-Restore technique and gravimetric geoid

Remove step: the gravity anomalies Δg, first standardized and validated, were reduced by the contributions of the geopotential model $\Delta g_{TEG4/EGM96}$ and of the topography/bathymetry Δg_{RTM}. Then they were gridded by LSC (Fig. 5a). *Stokes evaluation*: residual height anomalies ζ_{RES} were obtained by the spherical 1D-FFT method (Fig. 5b). To minimize border effects, data inside an additional zone of 5° width around the effective computation area were also treated. *Restore step*: the contributions $\zeta_{TEG4/EGM96}$ and ζ_{RTM} were added to the ζ_{RES} to obtain the quasigeoid. Incorporating the N-ζ differences gave the gravimetric geoid (Fig. 5c).

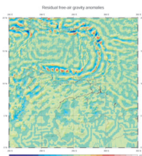


Fig. 5a

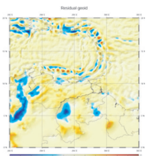


Fig. 5b

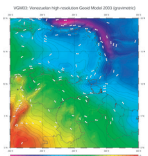


Fig. 5c

4.6. Corrector surface and final geoid

The gravimetric geoid was compared to 320 GPS/levelling derived geoid heights. Discrepancies up to +1.45 m with a long wavelength structures (λ~120 km) are observed (Fig. 6a). These errors are attributed to the national levelling network and the gravimetric solution. After modeling the discrepancies with LSC, they were added as a corrector surface to the gravimetric geoid. The hybrid geoid VGM03 is the result (Fig. 6b). Statistics of VGM03 components are shown in Table 3.

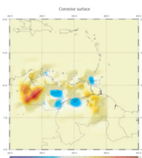


Fig. 6a

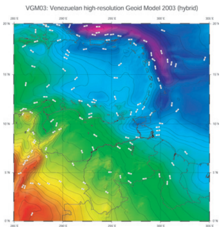


Fig. 6b

5. Validation

At sea VGM03 was compared with MSS profiles of the altimeter missions T/P, ERS-2, GFO and JASON-1 corrected by POCM-4B. On average, the differences show a magnitude of +26 cm (Fig. 7a). The VGM03 deviates from the synthetic mean geoid profiles with RMS ±9 cm. On land, the gravimetric version of VGM03 is compared with the GPS/levelling derived geoid undulations. The differences are now 22% smaller than with the gravimetric version of VGM02. For the new hybrid geoid the improvement with respect to VGM02 is almost 10%. VGM03 reproduces the national height system with RMS ±10 cm. However, deviations of up to +34 cm are even observed in some stations (Fig. 7b). The comparisons with the EGM96, CARIB97 and VGM02 models, summarized in the Table 4, confirm the improved performance of VGM03.

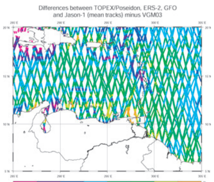


Fig. 7a

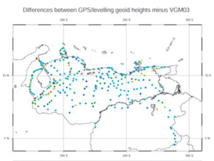


Fig. 7b

COMPONENT	MIN.	MAX.	MEAN	RMS
Δg	-383.91	396.82	-30.66	67.08
$\Delta g_{TEG4/EGM96}$	-358.08	391.42	-9.94	61.11
Δg_{RTM}	-184.71	337.18	-0.43	14.32
Δg_{RES}	-204.94	211.77	-0.08	19.42
ζ_{RES}	-3.23	2.59	-0.01	0.45
$\zeta_{TEG4/EGM96}$	-70.69	23.91	-24.52	20.04
ζ_{RTM}	-0.80	3.14	0.05	0.23
ζ	-70.53	22.80	-24.47	20.01
N-ζ	-0.83	0.50	-0.02	0.05
δN_{ELLIP}	-0.05	0.03	-0.02	0.02
N_{GRAV}	-70.58	22.84	-24.50	20.01
$N_{GPS/LEV}$-N_{GRAV}	-0.74	1.45	0.02	0.28
N_{VGM03}	-70.58	22.84	-24.48	20.03

Table 3. Statistics of VGM03 components (Δg in mGal, N y ζ in m).

DIFFERENCES	MIN.	MAX.	MEAN	STD.
N_{ALT}-N_{EGM96}	-0.97	1.16	0.23	0.30
N_{ALT}- $N_{CARIB97}$	-0.20	1.01	0.40	0.19
N_{ALT}-N_{VGM02}	-0.08	0.75	0.41	0.11
N_{ALT}-N_{VGM03}	-0.06	0.56	0.26	0.09
$N_{GPS/LEV}$-N_{EGM96}	-1.23	1.57	0.22	0.49
$N_{GPS/LEV}$-$N_{CARIB97}$	-0.99	1.35	0.13	0.43
$N_{GPS/LEV}$-N_{VGM02}	-0.30	0.34	0.01	0.11
$N_{GPS/LEV}$-N_{VGM03}	-0.31	0.30	0.00	0.10

Table 4. Results of validation. Comparations between VGM03 with EGM96, CARIB97 and VGM02 (differences in m).

6. Conclusions

New and more precise data have been used in the determination of VGM03, the most recent geoid model for Venezuela and the eastern Caribbean Sea. Essential improvements over the previous model are due to a geopotential reference model with CHAMP data included, an ultra-high resolution DTM obtained from SRTM, and MSS and GAS models derived with up-to-date altimeter data. Extensive quality assessments on land and at sea indicate that the new data has essentially increased the geoid precision. VGM03 has a consistent decimeter quality in the marine and terrestrial areas to the north of Venezuela, mainly those near to the coast or where the control by GPS was possible.
VGM03 is available at ftp://ftp.dgfi.badw.de/pub/acuna/VGM03/vgm03.zip

IUGG2003, Sapporo, Japan, 30.06 - 11.07.2003