The ICAGM07 Geoid Model for the North-East Atlantic (Iberia – Canary - Azores)

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ABSTRACT

The Iberia-Canary-Azores gravity and geoid model (ICAGM) is a project within the Iberian countries aimed at the determination of a high precision geoid model. This geoid intends to be a geographic extension of EGG97 to the west limit of European plate tectonics (Azores archipelago) and to the south of Canary islands. The main purpose of this geoid surface is to establish the connection between the existing vertical reference systems in Iberia and Azores and Canary islands and also to be the reference surface for real time kinematics positioning within this geographic area. A gravity database with all available gravity data sources were included for the gravity field determination, including 113382 terrestrial free-air gravity anomalies, 533918 shipborne anomalies and 653395 altimeter derived gravity anomalies from KMS02 model. Shipborne marine gravity data was carefully edited, validated and adjusted. The adjusted marine data was combined with satellite altimeter derived gravity by least squares optimal interpolation, improving the spectral and spatial resolution of the derived gravity field. Land gravity data from Azores, Canary and Madeira islands and Iberian peninsula were merged with the marine data and a gravity grid with a resolution of about 0.025 degrees was determined by least squares collocation. On land, a new digital terrain model with a resolution of 100m was constructed from the compilation of altimetric data from cartographic charts and from SRTM mission and on sea the 500m Gebco grid was used. The recent released GGM02C geopotential model extended to degree and order 360, using EGM96 coefficients above order 200, was used. The geoid model was computed from these data using the Helmert's second condensation method and the Stokes´ integral was evaluated with spherical FFT. The geoid model was compared with GPS-leveling data on Iberia (Portugal and Spain), and on 7 different vertical *data* used on Azores, Madeira and Canary archipelagos. The comparisons indicates an overall precision of 10 cm for Portugal and 12 cm for Spain. Vertical datum offsets are ranging from 100 cm in Canary to 36cm in S. Miguel island on Azores, with an offset of 16 cm between Portugal and Spain mainland. The later offset is close to the 18 cm obtained from the EUVN, revealing a very good precision of this geoid model for the vertical *data* unification.

INTRODUCTION

This investigation is part of ICA project, a joint project between University of Lisbon and University Complutense of Madrid funded by GRICES/FCT and CSIC and has the main objective of derive a high precision gravity and geoid model on the North-East Atlantic – Iberia-Canary-Azores that will be useful for : **a)** vertical datum unification between Portugal, Spain and Azores, Madeira and Canary islands, **b)** conversion between orthometric and ellipsoidal vertical systems. **b)** estimation of ocean circulation.

DATA

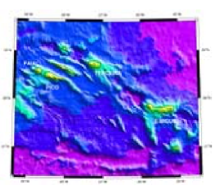
LAND DATA: Land data were acquired by several institutions most of them from IGN (Instituto Geografico Nacional, Spain), IGP (Instituto Geografico Portugues, Portugal) and Instituto Astronomia y Geodesia of the University Complutense. There are gravity measurements on all land areas. On Azores islands there are 2074 measurements, on Madeira island 55, on Portugal mainland 9104, on Spain 31579 and on Canary and Africa, 19532 measurements. The most recent observations were made on Faial in July 2006. All data were transferred to IGSN71 system and the anomalies converted to GRS80.

MARINE DATA: Marine gravity data were supplied by the NGDC (National Geophysical Data Centre, USA, GEODAS data, Version 4.1.18) and it covers an area with the following limits (20°<φ<50°,40°W<λ<10°E). The complete data set, obtained from a simple merge of data files, was cleaned from repeated missions recorded in different data banks resulting in a data set with 856141 data points and 824 tracks. All data were transferred to IGSN71 system and the anomalies converted to GRS80. The validation, adjustment and external quality assessment of the marine gravity data was achieved by the cross over error (COE) computation and adjustment.

SATELLITE DERIVED GRAVITY ANOMALIES (KMS02 MODEL): There are several public domain altimetric derived gravity anomalies data sets with a global coverage. KMS02 (Andersen et al., 1999) shows the best agreement with ship-borne gravity data and because of this we have adopted this model as our background model. The model, KMS02, with a resolution of 0.033°, covers all marine study area overrunning land areas as Azores and Canary islands. Because of altimetric gravity data degradation on coastal regions, a mask with the coastal line with an offshore buffer of 20 km were constructed and used to clean all satellite data inside that area.

GEOPOTENTIAL MODEL: Based on GRACE data a new generation of Earth geopotential gravity field models were derived: EIGEN-CG03C (N=360, CHAMP+GRACE+surface data))(Förste et al., 2005) , EIGEN-GL04C (N=360, GRACE+ LAGEOS+surface data)(Förste et al., 2006) and GGM02C (Tapley et al., 2005). GGM02C model results from the combination of GGM02S geopotential model (determined only from GRACE data) with terrestrial gravity information (surface gravity and mean sea surface) a higher resolution global gravity model was developed, GGM02C, complete to degree and order 200. The higher degrees were constraint to the harmonic coefficients of EGM96 and the (2,0) harmonic was constraint to its long-term mean value from EGM96 (Lemoine et al.,1998). In this work, GGM02C original model complete to order and degree 200 was extended to degree and order 360 by using the EGM96 coefficients.

DIGITAL TERRAIN MODEL: A digital terrain model covering Iberia-Canary-Azores area was constructed. The model is the result of the compilation and reprocessing of medium scale maps on land (1:25,000) and ship track data with single beam and multi beam acquisition (around Azores archipelago). In order to accommodate different needs and different scale maps two different resolutions were adopted for the DTM. On land and surrounding areas, Iberia, Azores and Madeira, it was chosen a grid resolution of 0.001° x 0.001° (about 100 m). The far area has a resolution of 0.005° with the limits 40W:8E and 20N:50N (see figure) These resolutions are multiple of each other and are both integer multiples of one degree.

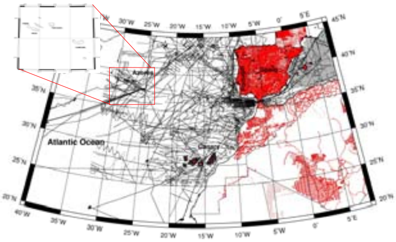


Digital Terrain Model

On the left: DTM of Azores region with a resolution of 100 m.

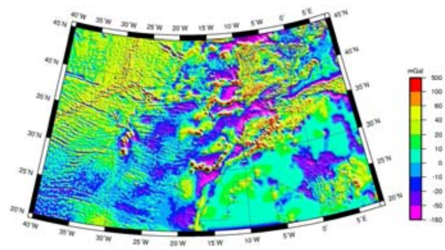
On the right: DTM of the entire ICA area with a resolution of 500 m.

Marine and land gravity



Gravity data distribution

Gravity anomaly model (Faye anomalies)



Free-air gravity anomalies

Gravity data merging process was done in three steps: first, land data was analyzed for temporal variations and for bias between surveys, second, land data were merged with satellite derived gravity anomalies and a background grid was derived and at last the shipborne data were merged with the background model by least squares optimal interpolation.

The process of gridding is subject to aliasing in the presence of high-frequency signal. With gravity data, part of this high frequency signal is due to the topography and can be removed from the original signal by removing the residual terrain model (RTM) effect on the Bouguer plate.

In the RTM method, the terrain effect and the geopotential field were removed producing smooth gravity anomalies and the residual gravity anomalies are given by:

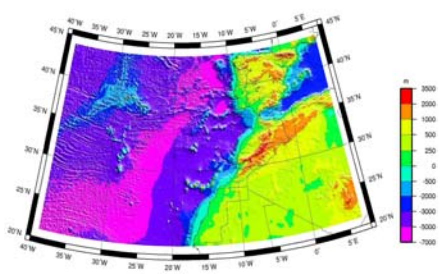
$$\Delta g_{RTM} = \Delta g_{FA} - \Delta g_{GM} - 2\pi G\rho\,(H_P - H_{ref}) + tc$$

The tc term is the gravimetric terrain correction, computed from the irregularities of the topography, after removing of a Bouguer plate and the Δg_{GM} are resulting gravity anomalies from the geopotential model.

The gridding was made by least squares collocation. Data was detrended prior to gridding removing the mean value and a Gauss Markov covariance function model was used with a correlation length of 20 km. The computation point was the centre of a cell with a resolution of 0.025 degrees extending from 20N to 45N in latitude and 40W to 8E in longitude and contains 1000 rows and 1920 columns.

The last step was the merging of shipborne data with the background gravity model. The discrepancies between the background model and the shipborne measurements were computed and exhibit a mean value of -0.37 mGal and a standard deviation of 7.1 mGal. Since marine gravity data were correctly adjusted into a coherent reference system by a minimum constraint (given by the most recent cruise) the bias is removed by adding 0.37 mGal to all marine data. At last, the shipborne data were merged with the background model by least squares optimal interpolation, for further details see Catalão (2006).

Finally the term $2\pi G\rho(H_P-H_{ref})$ was repositioned, resulting in a grid of reduced Faye anomalies corresponding to the Helmert condensation method $\Delta g_{Helmert} = \Delta g - \Delta g_{GM} + tc$. The grid data has a mean of 0.25 mGal and a standard deviation of 15.96 mGal, with a minimum of -288.79 mGal and a maximum of 384.31 mGal, see figure above where the free-air anomalies are depicted.



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MDT Rio05 was produced by CLS Space Oceanography Division

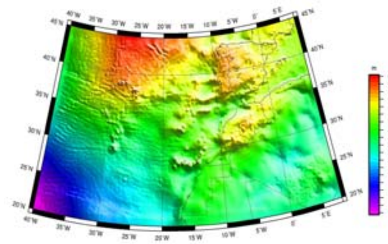
GEOID MODEL – ICAGM07

The concept of remove-restore used on the geoid computation implies that the low-frequencies and the high-frequencies gravity signal from the global geopotential model and topography, respectively, are removed before the application of Stokes integral and restored afterwards as geoid undulation and indirect effect. The final geoid undulation is given by:

$$N = N_{GM} + \frac{R}{4\pi\gamma}\iint S(\psi)\left(\Delta g - \Delta g_{GM} + t_c\right)d\sigma + N_{ind}$$

where N_{GM} is the geoid undulation derived from one of the geopotential models and N_{ind} is the indirect effect (Omang and Forsberg, 2000) as a result of using Helmert gravity anomalies on Stokes' formula.

The computation of the high resolution geoid model was based on the spherical FFT evaluation of Stokes integral. A Wong-Gore kernel modification has been used for spherical harmonic degrees less than 60 to limit the long-wavelength errors.



Geoid undulation

Results and conclusions

A synthetic geoid model was constructed as the difference of the mean sea surface height (MSSH), given by KMSS04 model, and the mean dynamic topography (MDT) given by MDT_Rio05 (produced by CLS Space Oceanography Division). This synthetic model was compared with 4 different geoid solutions computed with different geopotential models. Also GPS/levelling points over Portugal (n=134) and Spain (n=313) were used on this comparison. The results are presented on the next table. On sea, the four geopotential models have similar behaviour within a precision of 17 cm. This not so good score is due to some "gross" errors around Canary islands and the south-west coast of Portugal. On land, GGM02C model has a better performance than the others, with a gain of 5 cm relatively to EGM96 and 2 cm to the EIGEN models.

	MSSH-MDT		Portugal		Spain	
	mean	Std	mean	std	mean	std
EGM96	-1.25	0.170	-0.76	0.111	-0.88	0.167
GGM02C	-1.25	0.163	-0.86	0.103	-1.02	0.117
EIGEN-CG03C	-1.24	0.170	-0.86	0.132	-1.00	0.154
EIGEN-GL04C	-1.25	0.165	-0.90	0.116	-1.02	0.136

The geoid model, computed with GGM02C geopotential model, was compared with GPS-leveling data on Iberia (Portugal and Spain), and on 7 different vertical *data* used on Azores, Madeira and Canary archipelagos. Residuals of the geoid and the "geometric" geoid determined from the elipsoidal-orthometric pair of measurements (h-H) were computed for each vertical datum and presented in the table below.

	N vertices	mean	std	min	max
Portugal	134	-0.86	0.103	-1.087	-0.391
Spain	313	-1.02	0.117	-1.325	-0.398
S. Miguel (Azores)	77	-0.50	0.257	-0.860	0.112
Faial (Azores)	33	-0.60	0.064	-0.720	-0.501
Pico (Azores)	55	-0.64	0.196	-1.057	-0.297
Terceira (Azores)	61	-0.56	0.111	-0.837	-0.210
Lanzarote (Canary)	33	-0.05	0.081	-0.197	0.099
Madeira (Madeira)	37	-0.19	0.145	-0.440	0.091

From the comparison with GPS-leveling data we see that geoid accuracy is not homogeneous (over land areas) ranging from 6 cm on Faial to 25 cm on S. Miguel. However, on Azores, such results may be interpreted as the result of considerable horizontal and vertical surface deformation over time reaching on extreme volcanic events deformations of meters. Because of this, orthometric and ellipsoidal heights surveys over time, or separated decades, may contain local vertical deformations and may give only a first approximation to the gravimetric geoid accuracy. The same reasoning can be applied to Lanzarote.

It is clear from the statistical results in the table that there are offsets between the vertical *data*. The maximum offset is between Spain and Lanzarote with almost 1 m difference and an offset of 36 cm between Portugal and S. Miguel island. Also on Azores archipelago offsets of 14 cm are observed. On Iberia, an offset of 16 cm is determined between Portugal and Spain levelling networks. The later offset is close to the 18 cm obtained from the EUVN, revealing a very good precision of this geoid model for the vertical *data* unification. Further improvement on the geoid precision can be expected using a 4 parameter transformation removing possible datum inconsistencies and long wavelength errors.

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