Geoid model of the Philippines from airborne and surface gravity

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Summary

A new preliminary geoid model for the area of the Philippines has been computed from gravity data measured during the 2014 DTU-Space and NAMRIA/NGA airborne gravity survey, supplemented with marine satellite altimetry gravity data, NAMRIA 1st and 2nd order land gravity data, and data from the newest satellite gravity data from the GOCE mission (Release 5). Digital terrain models used in the computation process was based on 15” SRTM data.

The geoid model is a surface (N) which describes the theoretical height of the ocean and the zero-level surface on land. The geoid is required to obtain orthometric height H (“height above sea level”) from GPS by

$$H = h^{GPS} - N \quad (1)$$

where h^{GPS} is the GPS ellipsoidal height, and H the levelled (orthometric) height.

The computed Philippines geoid *ph_geoid2014* is computed in a global vertical reference system, shifted with a constant of +80 cm to approximate the average geoid offset relative to GPS and levelling in the Manila areas. A preliminary fitted geoid to ITRF GPS and levelling *(ph_geoid_fit)* was also done; some apparent outliers in data need to be corrected, before a suitable fit is possible, and a GPS geoid consistent with the existing vertical datum in the Philippines is obtained. Likely many outliers are due to geodynamic effects, associated with volcanic activities and earthquakes.

The airborne gravity survey

The airborne gravity survey was carried out in the spring 2014, using a Cessna Caravan aircraft from Air Juan in Manila. Gravity was measured with a LCR gravimeter system (S-38), as well as a Chekan-AM gravimeter. The primary instrument (LCR) gave a standard deviation of 2.6 mGal from 287 survey cross-overs, a good result considering the mountains and large variations in the gravity field. Fig 1 shows the airborne gravity free-air anomalies, and the flight elevations.

A separate report will come shortly on the aerogravity operations and processing. The airborne survey was sponsored by the US National Geospatial-Intelligence Agency (NGA), as part of projects to improve the global gravity field model EGM2008, under the umbrella of the NGA-Danish Geodata Agency BECA agreement.

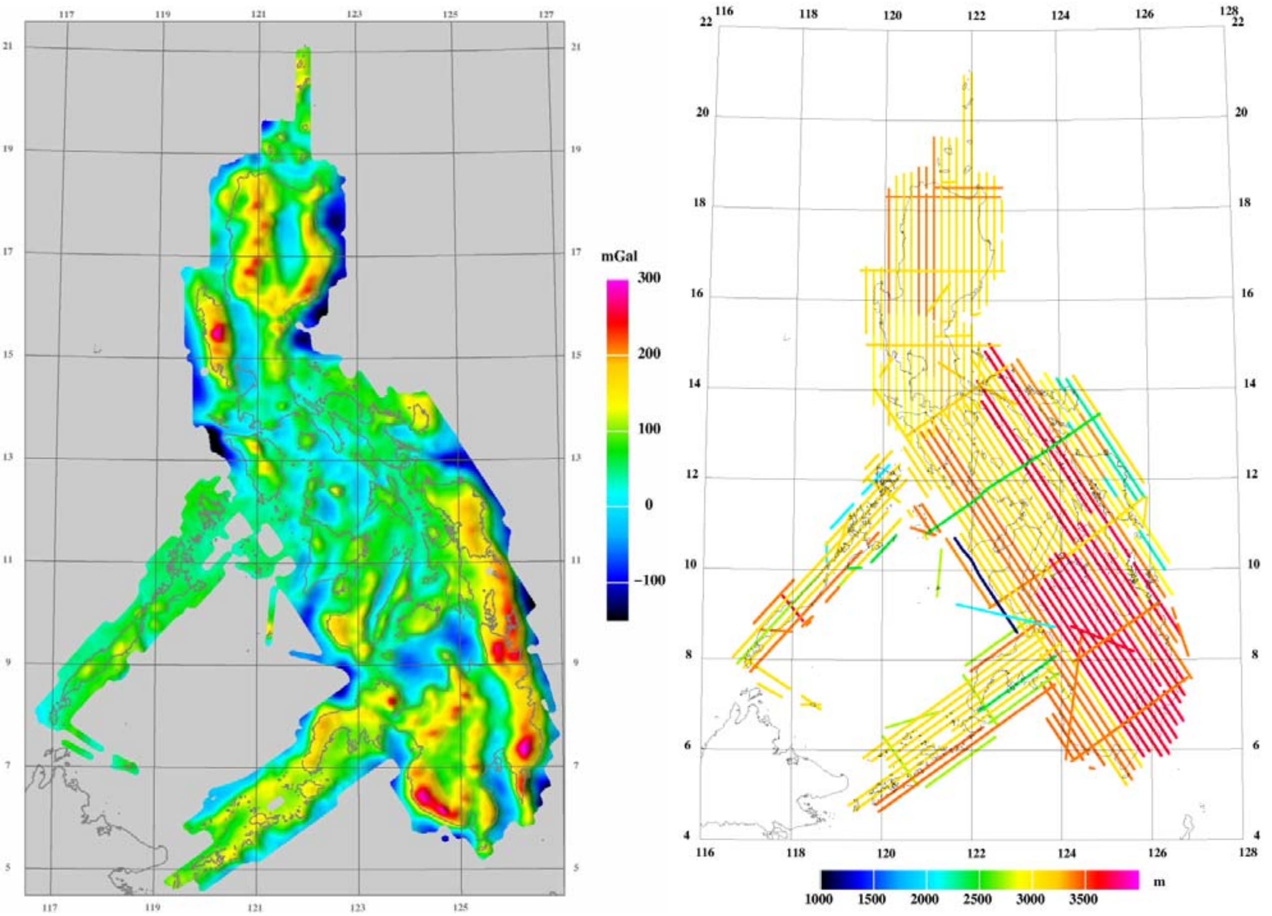

Fig. 1. Airborne survey free-air anomalies (left) and flight track elevations (right)

Gravimetric geoid computation - principles

The Philipines geoid is computed by the *GRAVSOFT* system, a set of Fortran routines developed through many years of research and project work at DTU-Space and Niels Bohr Institute, University of Copenhagen [1]. It forms the base of major recent geoid computation projects, such as the joint Nordic "NKG" geoid models, undertaken as joint geoid model computations of the Nordic and Baltic countries [2] under the auspices of the Nordic Commission for Geodesy (NKG), as well as the OSGM02 geoid model of the UK and Ireland [3], and several national geoid models done from airborne surveys in recent years (Malaysia, Mongolia, Indonesia and others).

The Philippines geoid has been computed by a "remove-restore" technique, where a spherical harmonic earth geopotential model (EGM/GOCE combination) is used as a base, and the geoid is computed from the global contribution N_{EGM}, a local gravity derived component N_2, and a terrain part N_3.

$$N_{grav} = N_{EGM} + N_2 + N_3 \tag{4}$$

The spherical harmonic expression as a function of latitude, longitude and height is of the form

$$N(\phi,\lambda,r) = \frac{GM}{R\gamma}\sum_{n=2}^{N}\left(\frac{R}{r}\right)^{n}\sum_{m=0}^{n}\left(C_{nm}\cos m\lambda + S_{nm}\sin m\lambda\right)P_{nm}(\sin\phi) \tag{5}$$

where GM, R and γ are earth parameters. For the EGM08/GOCE models used here, this involves more than 4 mio coefficients C_{nm} and S_{nm} derived from a very large set of global satellite data and regional (average) gravity data from all available sources, both open-file and classified, for details see http://earth-info.nga.mil/GandG/wgs84/gravitymod/egm2008/index.html.

The EGM08 model is incorporating GRACE satellite data, which determines the error spectrum of the EGM08 up to spherical harmonic degree 80 or so. New satellite data from the GOCE mission have recently been made available by the European Space Agency, for details see www.esa.int/goce. We have for the Philippines geoid used the latest GOCE spherical harmonic model ("Direct" Release 5 model), complete to degree and order 280. The EGM08 field has been updated with the GOCE data in the following way:

- *EGM08 used unchanged in spherical harmonic orders 2-80, and from 200 up*
- *GOCE R5 direct model used in band 90-180*
- *A linear blending of the two models done in bands 80-90 and 180-200*

The mixed spherical harmonic model (termed EGM08GOCE) has here been used to spherical harmonic degree N = 720, corresponding to a resolution of 15' or approximately 28 km. This choice of resolution is based on experience from recent DTU geoid projects in France (Auvergne), Malaysia, and Nepal, and appears to be a good "trade off" between the full resolution of EGM08 (degree 2160) and the local gravity data.

Because the full-resolution gravity data used in the construction EGM08 is classified, there is no good information on the quality of the errors in EGM08 at the high wavelengths in SE Asia, and only 15' mean gravity data are assumed to be underlying EGM08. All spherical harmonic computations were done in a grid using the *geocol17* program in grid mode.

The terrain part of the computations were based on the RTM method, where topography is referred to a mean elevation level, and only residuals relative to this level is taken into account. The mean elevation surface were derived from the SRTM 15" detailed model through a moving average filter with a resolution of approximately 20' (37 km; slightly longer than the 15' data resolution implied by spherical harmonic degree 720, in order to have a more smooth residual gravity signal Δg_2). The difference in resolution between reference field and RTM is *not* a theoretical issue, as the remove-restore method takes any "double accounted" topography into account fully.

The method for the gravimetric geoid determination is *spherical FFT* with *optimized kernels.* This is a variant of the classical geoid integral ("Stokes integral"), in which there is a proper weighting of the long wavelengths from EGM08 and the shorter wavelengths from the local gravity data. Mathematically it involves evaluating convolution expressions of form

$$N_2 = S_{ref}(\Delta\varphi, \Delta\lambda) * [\Delta g_2(\varphi, \lambda)\sin\varphi] = F^{-1}[F(S_{ref})F(\Delta g \sin\varphi)] \tag{6}$$

Here S_{ref} is a modified "Stokes" kernel, $\Delta g_2 = \Delta g - \Delta g_{EGM}$ is the EGM08GOCE-reduced free-air gravity anomalies, and F is the 2-dimensional Fourier transform operator. For details see references [2]-[4] and further references therein.

The Philippines geoid is computed on a grid of 0.025° x 0.025° resolution (corresponding to roughly 2.7 x 2.5 km grid). The area of computation is 04°-22°N and 112-128°E, covering a major part of the South China Sea and the Spratly Islands as well.

The computations have been based on least squares collocation and Fast Fourier Transformation methods. The FFT transformations involve 1440 x 1280 grid points, corresponding to 100% zero padding.

The data are gridded and downward continued by least squares collocation using the planar logarithmic model. A number of GRAVSOFT programs are involved in this process (*gpcol1, spfour, gcomb, geoip),* and jobs for the processing have been set up in a directory structure, outlined in Appendix 1.

The final gravimetric geoid solution was computed by the following steps:

- *Subtraction of EGM08GOCE spatial reference field (in a 3-D "sandwich mode")*
- *RTM terrain reduction of surface gravimetry, after editing for outliers*
- *RTM terrain reduction of airborne gravimetry*
- *Reduction of DTU-10 satellite altimetry in ocean areas away from airborne data*
- *Downward continuation to the terrain level and gridding of all data by least-squares collocation using a 1° x 1° moving-block scheme with 0.6° overlap borders*
- *Spherical Fourier Transformation from gravity to geoid*
- *Restore of RTM and EGM08GOCE effects on the geoid*
- *Correction for the difference between quasigeoid and geoid (using a Bouguer anomaly grid)*
- *Shifting of the computed geoid by +80 cm to approximately fit to Manila tide gauge datum*

No real evaluation of different geoid results by precise GPS-levelling was possible, due to the limited accuracy of the available GPS levelling data. Based on experience in other regions the general accuracy of the geoid is assumed to be around 10 cm on average across all of the Phillipines, and better relatively in local errors with good surface gravity coverage (Manila area).

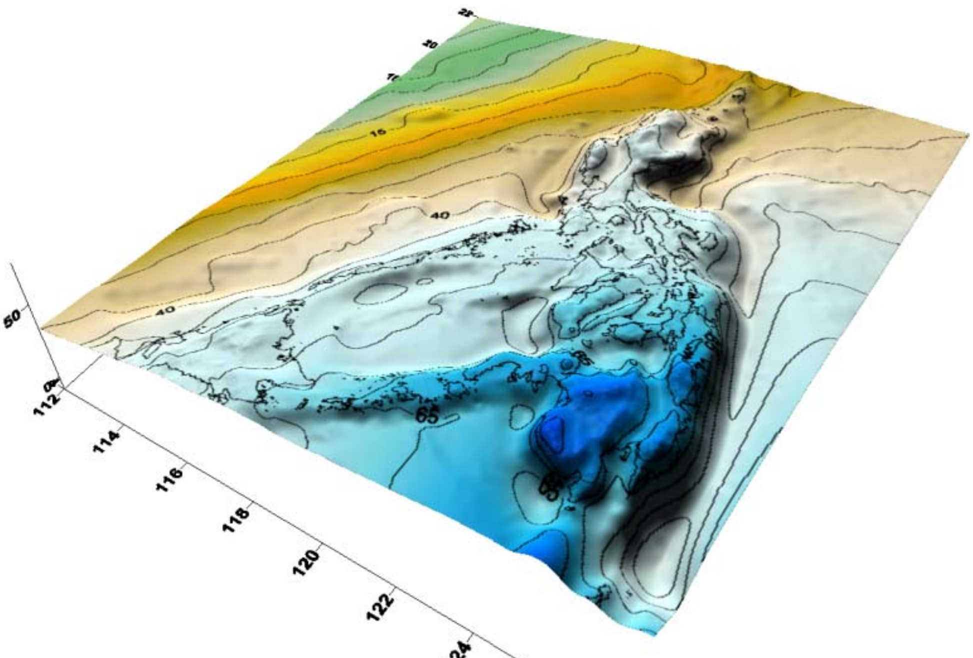

Fig. 2. The Philippines geoid 2014. Contour interval 5 m.

Data used and QC for the geoid computation

The Oct 2014 Philippines gravimetric geoid is based on the following data:

- Airborne gravity data
- Land gravity from NAMRIA, reformatted to GRAVSOFT and mildly edited
- DTU10 global gravity anomalies from multi-mission satellite altimetry. These data were selected only in the open ocean area, away from the airborne gravity
- SRTM 15” DEM data for the region
- EGM08 and GOCE RL5 satellite data

Some plots of the used and processed data are shown in the Figs. 3-5 below.

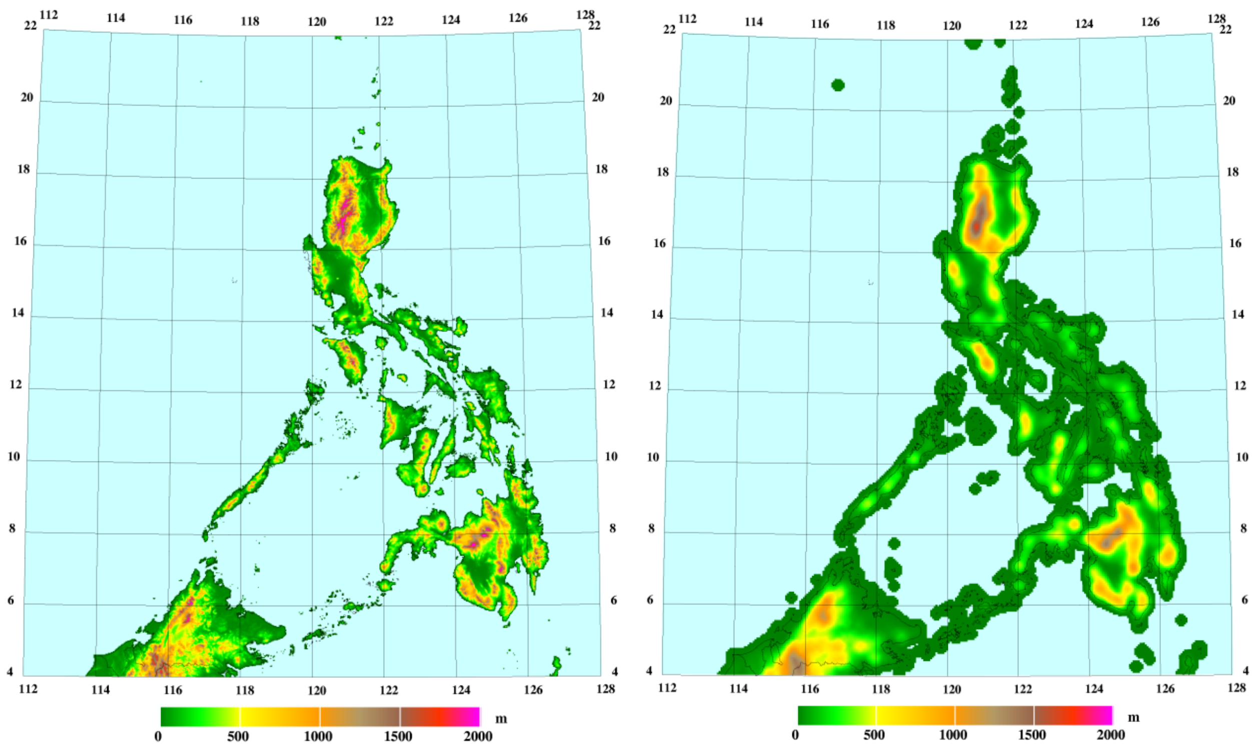

Fig 2. SRTM DEM data (left); low-pass filtered mean elevation surface (right), used as reference in RTM terrain reductions. Elevations in meters. Ocean depths are not used in the Philippines geoid computations.

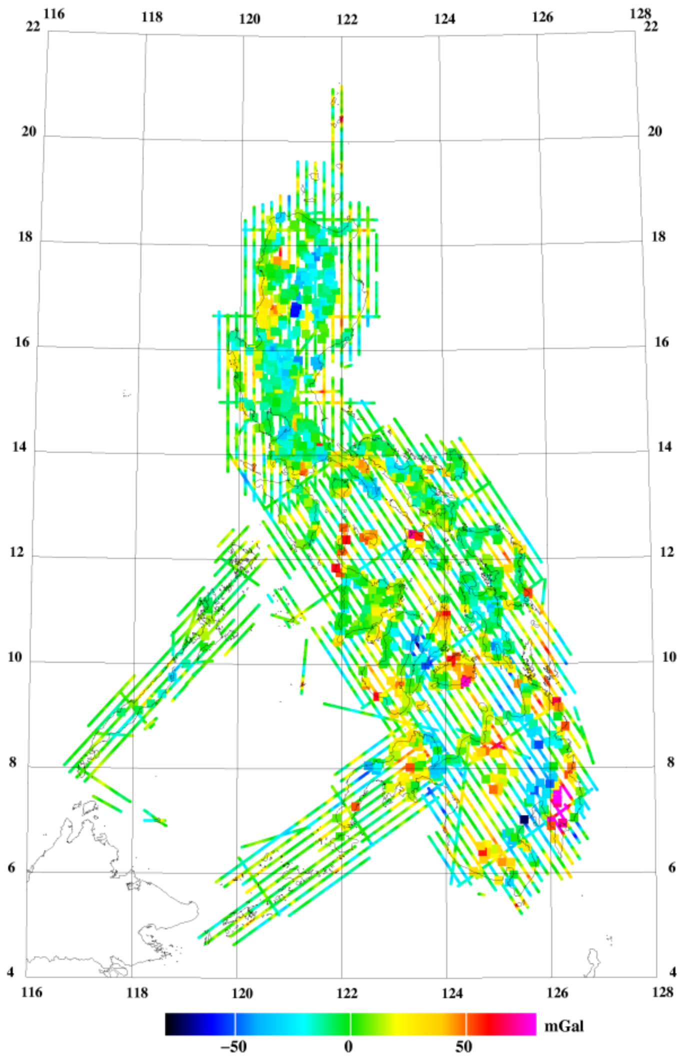

Fig 4. NAMRIA land gravity data(thicker dots) and the airborne gravity data after terrain- and EGM-reduction. Some outlier land gravity data with too large residuals were deleted in a process using"surfer".

The available data from the airborne and surface sources were quality controlled through plotting of the EGM08GOCE and terrain reduction residuals, showing a few (< 1%) obvious surface gravity outliers, which were deleted in the final geoid processing. The overall EGM/GOCE and RTM terrain "reduce" statistics for the data are shown in Table 1. Overall this statistics is good, with relatively small bias and standard deviation for all data sets.

Table 1. Statistics of remove steps in the Philippines gravimetric geoid computation (mGal)

Unit: mGal	Mean	Std.dev.
NAMRIA edited land gravity data (1261pts)	8.7	24.7
- above minus EGM08GOCE and RTM	0.9	21.4
Airborne gravity data (58515 pts)	1.5	20.7
- above minus EGM08GOCE and RTM	1.6	18.6
DTU10 altimetry gravity (28841 selected pts)	-9.6	12.3
- above minus EGM08GOCE and RTM	-0.3	10.8

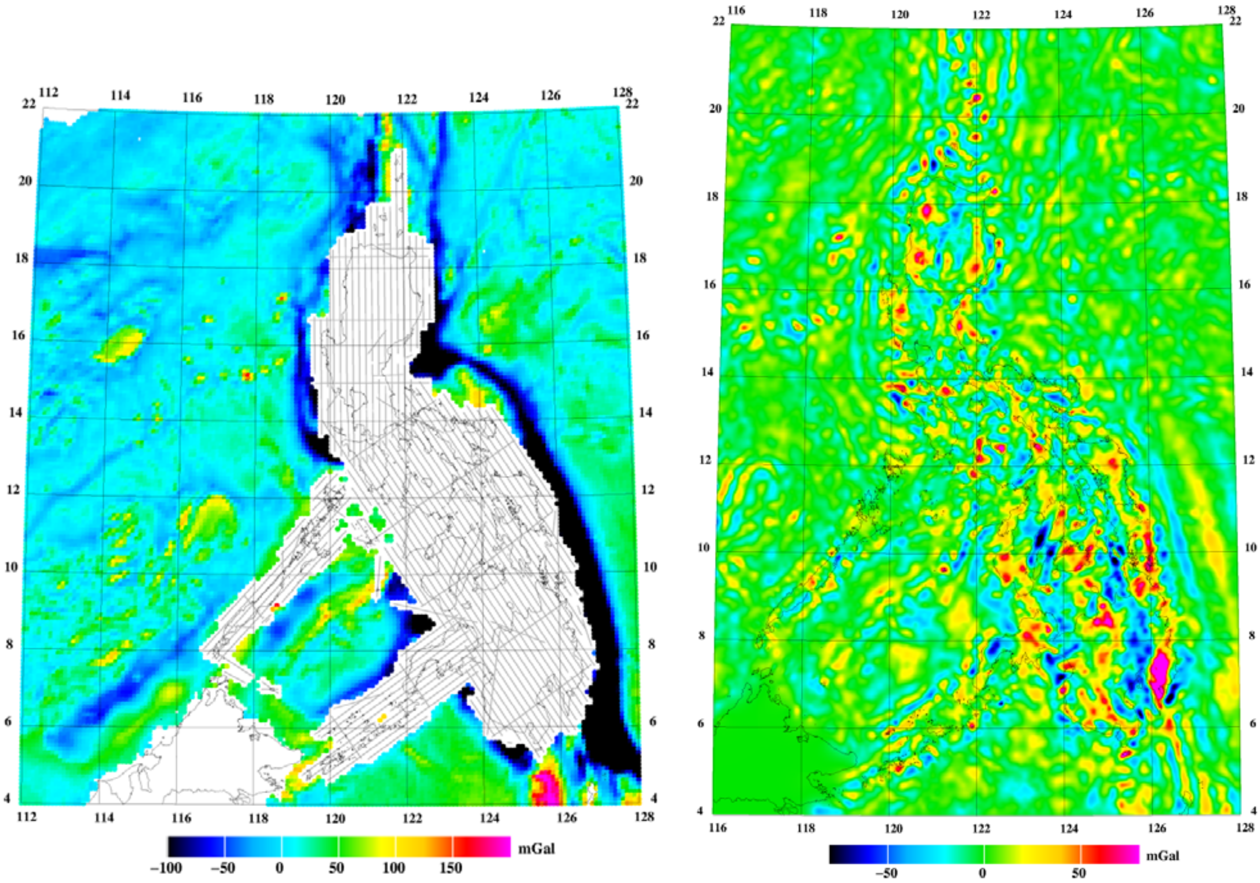

Fig. 5.The used DTU-10 satellite gravity (left), and the collocation downward continued merged grid (right)

Geoid processing results

The plots in the sequel shows the intermediate results of the final remove-restore geoid processing (*"geoid.gri")*, computed with full 3-dimensional modelling, going via the quasigeoid to the classical, final geoid.

The final geoid covers the region 4-22°N, 112-128°E, and has a resolution of 0.025° x 0.025°. The airborne and surface gravity data were gridded by spatial least squares collocation (*gpcol1, using covariance parameters* $\sqrt{C_0} = 18$ *mgal,* $D = 6$ *km,* $T = 30$ *km*). A priori errors assumed were 2 mGal for both the airborne data and the surface data (averaged in 0.025° blocks), and 5 mGal for DTU-10. The collocation downward continuation was done in 1° x 1° blocks, with 0.6° overlaps.

For the spherical FFT transformation of gravity to geoid, 3 reference bands were used. Fig. 6-7 below shows the primary data grids done in connection with the geoid processing.

The final geoid "restore" statistics is shown in Table 2.

Table 2. Statistics of the restore quantities on the geoid

Unit: m	Mean	Std.dev.	Min.	Max.
Reduced geoid (after spherical FFT)	0.00	0.25	-1.61	2.88
RTM restore effects (computed by FFT)	0.00	0.04	-0.23	0.74
Final gravimetric geoid statistics	39.06	18.36	-9.02	76.43

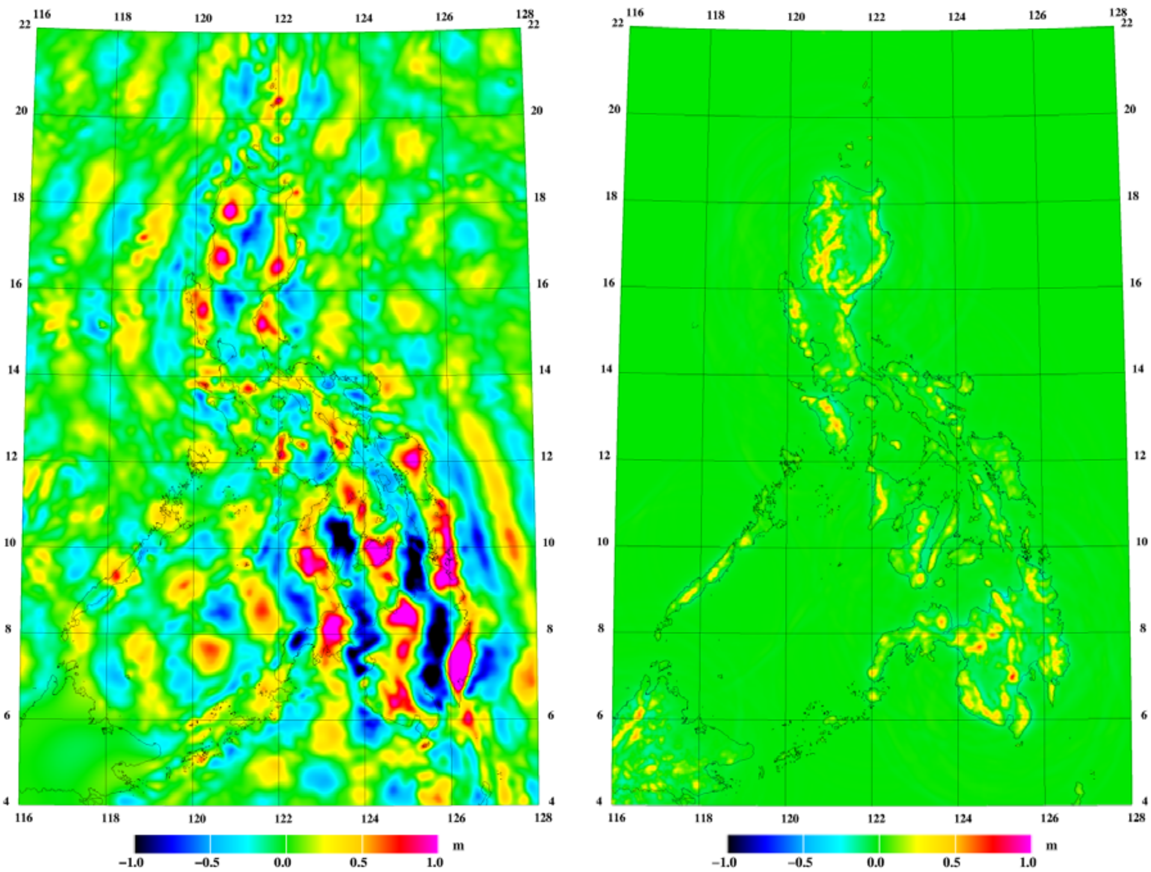

Fig. 6. Left: Reduced geoid (after spherical FFT transformation); right: RTM terrain effect on geoid.

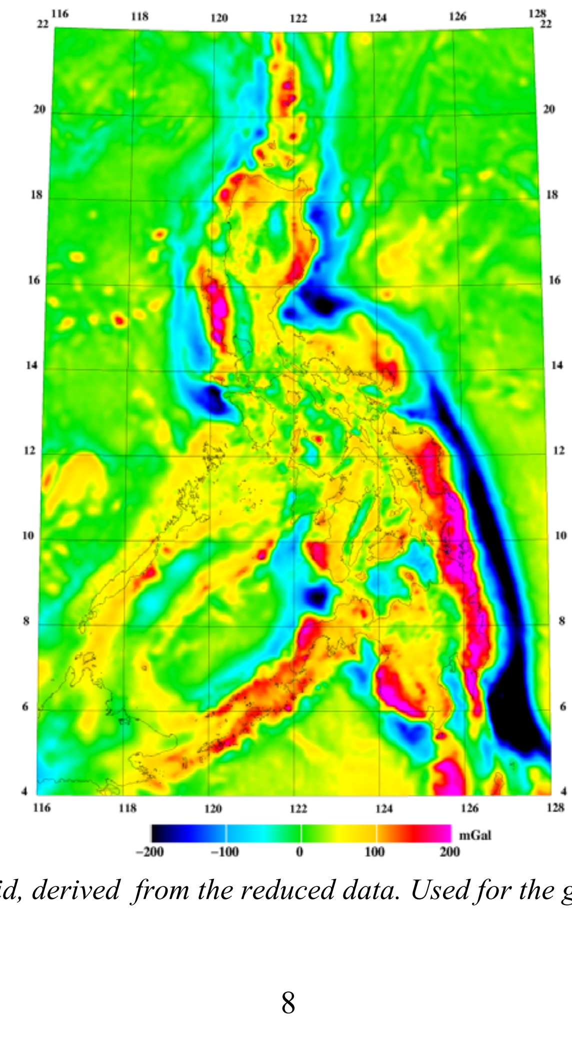

Fig. 7. Bouguer anomaly grid, derived from the reduced data. Used for the geoid-quasigeoid estimation..

GPS data comparison and final geoid

A set of 190 GPS data in ITRF2005 levelling benchmarks was available from Geodesy Division of NAMRIA. These GPS data showed a relatively large error relative to the geoid, with large outliers in some regions, likely due to a combination of geodynamic effects and levelling or GPS errors. The rms fit is 0.5 m; it is therefore not possible to use these data for validation of the geoid. Fig. 8 shows the offset values, and the geoid correction surface for a fitted geoid *ph_geoid_fit* (corrector surface gridded with 80 km correlation length, and GPS-levelling apriori error of 10 cm). Fig. 9 shows the comparison to EGM2008; large improvements are seen, especially in the south. Fig. 10 shows a comparison to the DTU10-MSS, i.e. the MDT, shifted by -91 cm to take into account the different reference systems.

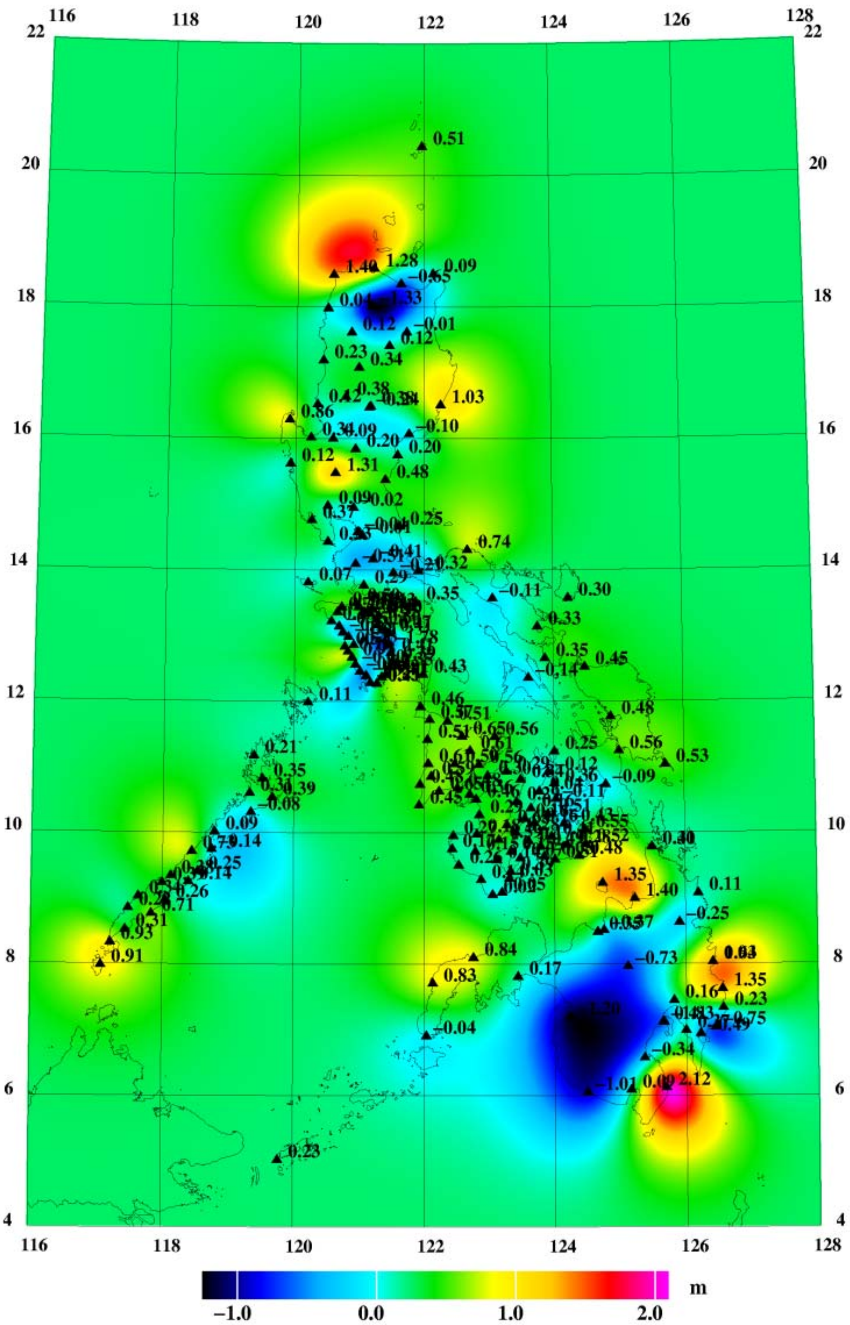

Fig. 8. Location of GPS-levelling data. Colour show the correction surface for the fitted geoid.

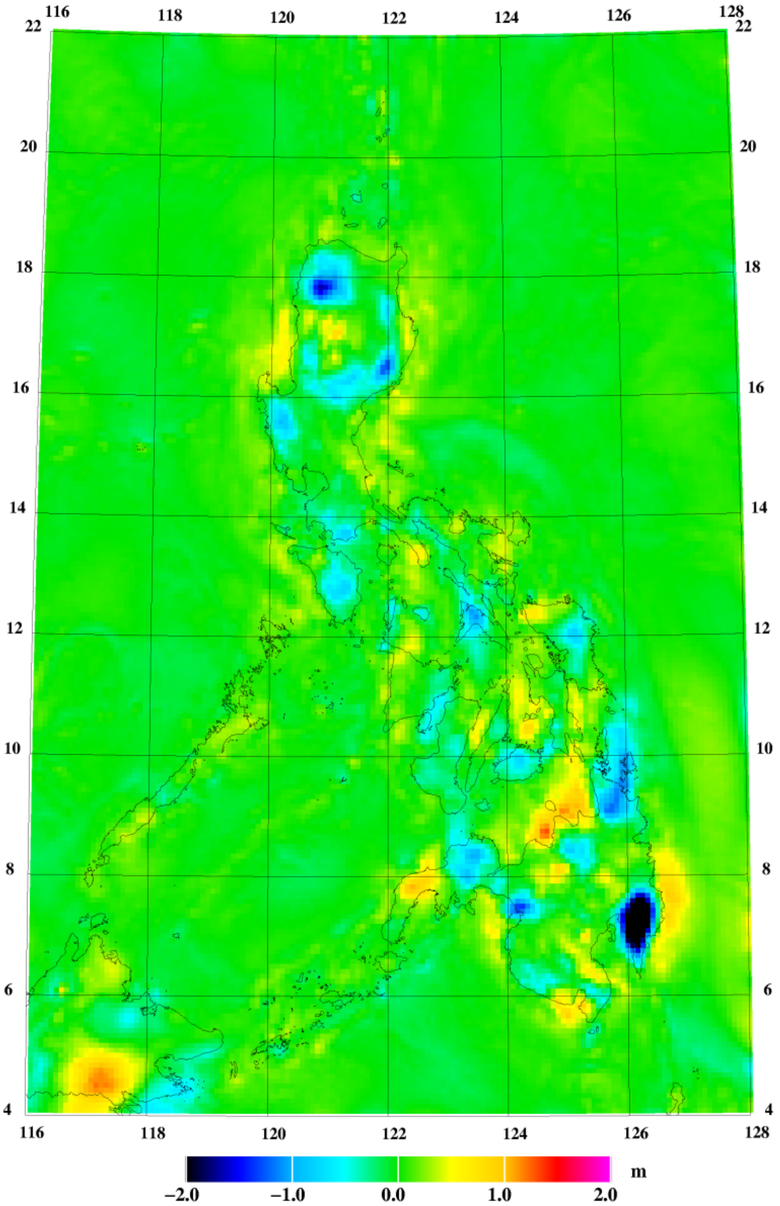

Fig. 9. Differences between the new Philippines geoid and EGM2008

The final geoids are given as *GRAVSOFT* grids, and can be interpolated by the GUI program *grid_int* (or the command line program *"geoid"*), provided to NAMRIA as part of the computations, along with the general software and geoid job setups (Appendix 1).

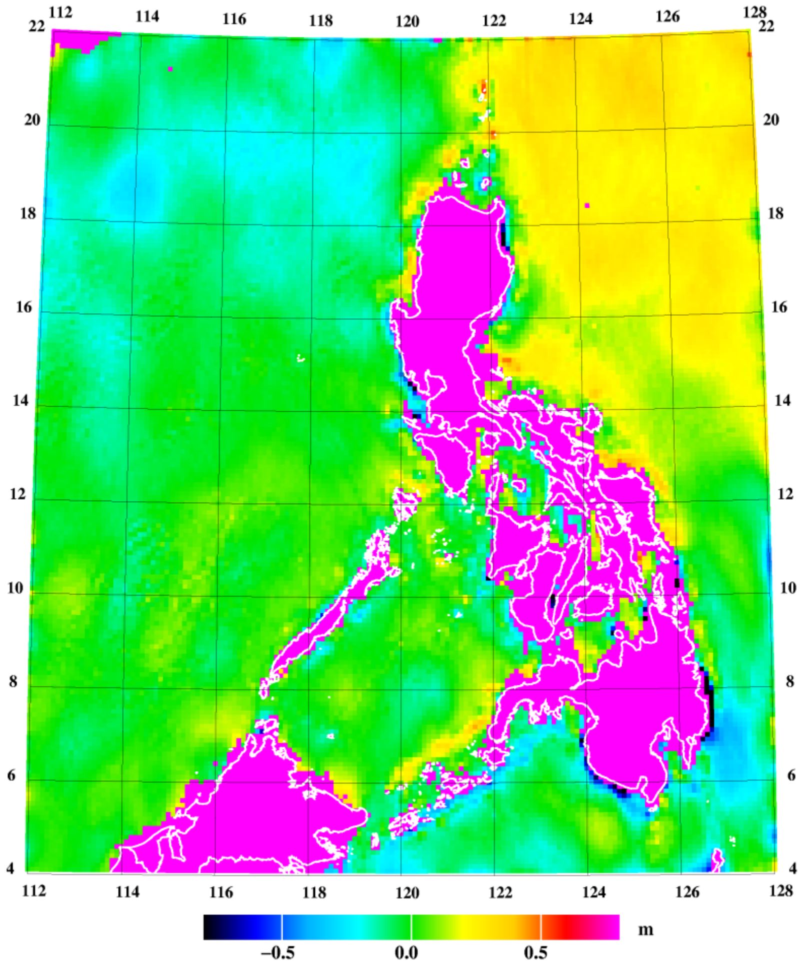

Fig. 10. Mean dynamic ocean topography (MDT) from DTU10 mean sea surface (shifted by 91 cm)

References

[1] Forsberg, R and C C Tscherning: Overview manual for the GRAVSOFT Geodetic Gravity Field Modelling Programs, 2nd Ed. Technical report, DTU-Space, August 2008.
[2] Forsberg, R., D. Solheim and J. Kaminskis: Geoid of the Nordic and Baltic area from gravimetry and satellite altimetry. Proc. Int. Symposium on Gravity, Geoid and Marine Geodesy, Tokyo, Sept. 1996, pp. 540-548, Springer Verlag IAG Series, 1996.
[3] Forsberg, R., G. Strykowski, J.C. Illife, M. Ziebart, P.A.Cross, C.C. Tscherning , P. Cruddace,
K. Stewart, C. Bray and O. Finch: OSGM02: A new geoid model of the British Isles. Proceedings of the 3rd meeting of the International Gravity and Geoid Comission, GG2002, Aug. 26 - 30, 2002, Thessaloniki, I. Tziavos (ed.), Editions Ziti, pp. 132-137, 2003.
[4] Forsberg, R. and A. Olesen: Forsberg, Airborne gravity field determination. In: G. Xu (ed): Sciences of Geodesy – I, Advances and Future Directions, pp. 83-104, Springer Verlag, 2010, ISBN 978-3-642-11741-1.

APPENDIX 1 – Directory structure and GRAVSOFT geoid jobs

Directory	Files	Comments
DATA	dtu-10_edited.fa	*DTU-10 free-air anomaly data*
	namria_edited.fa	*NAMRIA edited free-air anomalies*
	airborne.fa	*Airborne free-air data*
NAMRIA	namria.fa	*Original NAMRIA gravity data, reformatted from xls-files*
	gps-lev.dat	*Files with N from GPS-levelling*
	gps-lev-wgs84.dat	
DEM	ph_dem005.gri	*SRTM 15" file (30" used in Malaysia)*
	ph_dem025.gri	*Averaged file for remote zone computations + geoid*
	ph_demref.gri	*RTM mean elevation surface, made with* dem_ref.job
RD-TC	*Remove steps (run "jobs" in sequence)*	
	egm08goce5_720	*Spherical harmonic coefficients for EGM08GOCE model*
	geocol17.job	*Program to compute EGM08GOCE in grids for N and g*
	rd_surface.job	*EGM and terrain reduction of NAMRIA data*
	rd_air.job	*Reduction of airborne data, incl. terrain effect filtering*
	rd_dtu10.job	*Reduction of DTU-10*
	qc.job	*Geogrid job to make difference NAMRIA minus airborne g*
DOWNCONT	*Downward continuation and gridding*	
	gpcol1.job	*Collocation job, blockwise solutions*
	gpfit.job	*Simple covariance estimation, use only as rough guide*
GEOID	*FFT and restore steps for geoid*	
	bouguer.job	*Job for making land Bouguer anomaly from downward continued, reduced gravity grid file "downrd.gri"*
	n-zeta.job	*Difference of geoid and quasigeoid, from DEM & Bouguer*
	n_rtm.job	*RTM geoid terrain effect by prism integration (slow task!)*
	geoid.job	*Composite geoid job, doing FFT, add terrain effect, add EGM, apply corrections for quasigeoid -> "ph_geoid.gri"*
	geoip.job	*Difference to GPS-levelling data (statistics and dif-file)*
GPS-LEV	*Geoid fit files*	
	fitgeoid.job	*Fitting of geoid to GPS-lev file with collocation. Always plot the following files to judge fit of "ph_geoid_fit":* *- fitgeoid_dif.dat: point list with differences GPS-geoid* *- fitgeoid_dif.gri: corrector surface for fitted geoid*
Auxillary:	grid_int_ph.exe	*User-friendly interpolation program*
	se-asia.bna	*Coastline file for "surfer" graphics*

Note: to run GRAVSOFT on 64-bit Windows machines, check "job.bat" in GRAVSOFT directory for the following statement in line 2, it shoul read: `jobb64 <%1.job (job <%1.job for Win32)`