Using satellite altimetry data for regional marine gravity field modeling

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Introduction

Measurements from radar altimetry missions are the primary source for high resolution marine gravity field modeling. Particularly, the geodetic mission phases with its dense ground track pattern can provide valuable information. In addition to the elder data from GEOSAT and ERS-1, new measurements are available today: Jason-1 was flying on a geodetic orbit between May 2012 and February 2013; Cryosat-2 was launched in 2010 with a long repeat-cycle of 369 days.
The modeling approach presented here directly uses absolute sea surface height measurements along the ground tracks of these missions instead of the commonly used relative and/or gridded products.

Modeling Approach

The model is set up as a series expansion in spherical basis functions, i.e. spherical scaling functions ϕ_{J+1} (Schmidt et al. 2007) whose unknown coefficients $d_{J,q}$ are estimated in an adjustment procedure. In order to get rid of the low-frequency signal parts -which cannot be determined from regional data- signal differences to a given background model (e.g. GOCO03S) are computed. Within the adjustment process a variance component estimation (VCE) is used to ensure an appropriate relative weighting between the different altimeter missions (and other input data types, if desired). The estimation of the gravitational potential V enables deriving not only geoid undulations N but any functional of interest, e.g. gravity anomalies Δg or gravity gradients T_{rr}.

$$V = \sum_{q=1}^{q_{max}} d_{J,q}\phi_{J+1} \qquad \phi_{J+1} = \sum_{l=0}^{l_{max}} \frac{2l+1}{4\pi}\left(\frac{R}{r}\right)^{l+1} \Phi_{J+1,l} P_l(\cos\psi)$$

j	resolution level
J	maximum resolution level ($j \le J$)
q_{max}	total number of Reuter grid points
l_{max}	maximum degree
$P_l(\cos\psi)$	Legendre polynomials
ψ	spherical distance angle (between observation point and Reuter grid point)

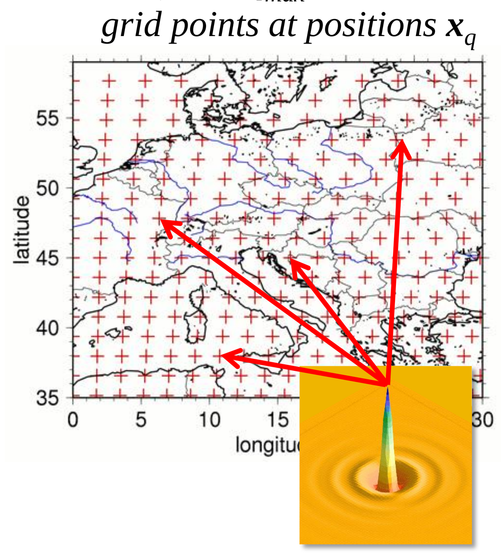


Fig. 1: Scaling function ϕ_{J+1} for level j=4 (basis b=2) and q_{max} Reuter grid points at positions $\mathbf{x}_q$

Tab. 1: Parameter of scaling functions and resulting model resolution

b	2	1.8	1.5	1.545	1.7	1.5	1.8	2
j	11	13	19	18	15	20	14	12
l_{max}	2047	2081	2216	2515	2861	3324	3737	4095
r [km]	9.8	9.6	9.0	8.0	7.0	6.0	5.3	4.9

$$l_{max} = b^j - 1$$

The model resolution is defined by the level j of the scaling functions and its basis b. The higher j the better the spatial resolution. Tab.1 gives the relation between j, the corresponding max. degree of the expansion l_{max} and the spatial resolution r.

Input Data

In our modeling approach we use 1 Hz absolute sea surface height (SSH) measurements from various altimetry missions (see Tab. 2) together with instantaneous dynamic ocean topography DOT (Bosch et al. 2013) to estimate perturbation potential T in ocean areas with high spatial resolution. The consistency of the different altimeter missions is obtained by a pre-processing crossover analysis (Dettmering & Bosch 2013) which also ensures that long-wavelength errors such as orbit errors are eliminated beforehand. Moreover, a background model (GOCO03S up to d/o 180) is used for providing the low-frequency signals T_{back} and to ensure stability of the adjustment system.

$$T = \gamma \cdot N = \gamma \cdot (SSH - DOT) \qquad \gamma\text{: normal gravity}$$

The observation equation for each observation i with measurement error e at position $\boldsymbol{x}^i$ reads:

$$T(\boldsymbol{x}^i) + e(\boldsymbol{x}^i) = T_{back}(\boldsymbol{x}^i) + \sum_{q=1}^{q_{max}} d_{J,q}\,\phi_{J+1}(\boldsymbol{x}^i, \boldsymbol{x}_q)$$

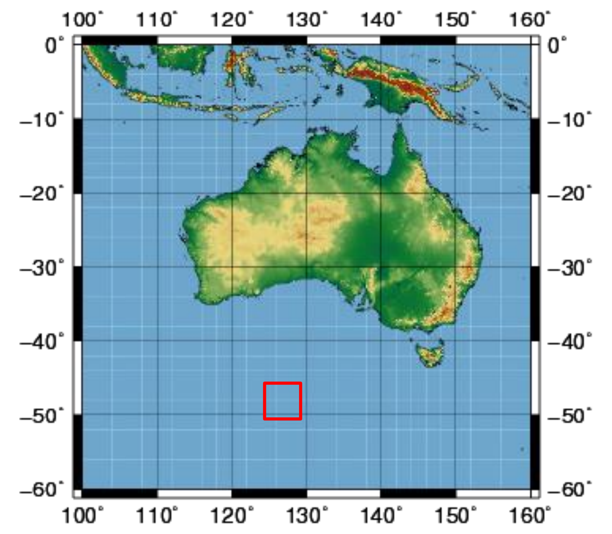


Fig. 2: Study area south of Australia (5°x5°, red box)

	ERS-1 GM	Cryosat	Jason-1 GM
Repeat cycle [days]	168	369	406
Track separation [km]	8 (16/2)	7.7	7.7
Time period	Apr. 1994 – Mar. 1995	Jul 2010 – Dec. 2012	May 2012 – Feb. 2013

Tab. 2: Altimeter missions used in this study

In the study area of 5°x 5° the three altimeter missions provide 51,269 observations with an averaged distance of about 3' (5.5 km) and a nearly uniform spatial distribution (along-track resolution is not significant better than cross-track resolution).
A combination with other input data types, such as GOCE gravitational gradients, is also possible in order to stabilize the results in the lower frequency band.

Results

Based on the estimated scaling coefficients any gravitational functional of interest can be derived. We use Blackman scaling functions (Schmidt et al, 2007) to compute free-air anomalies Δg. Figure 3 shows the gravity anomalies *(a)* and its formal errors *(b)*. The model parameters are set to level 20 with basis 1.5 (≈ 6 km, see Tab.1) as this resolution fits best to the observation distribution. For this resolution $q_{max} = 9855$ model coefficients are estimated.

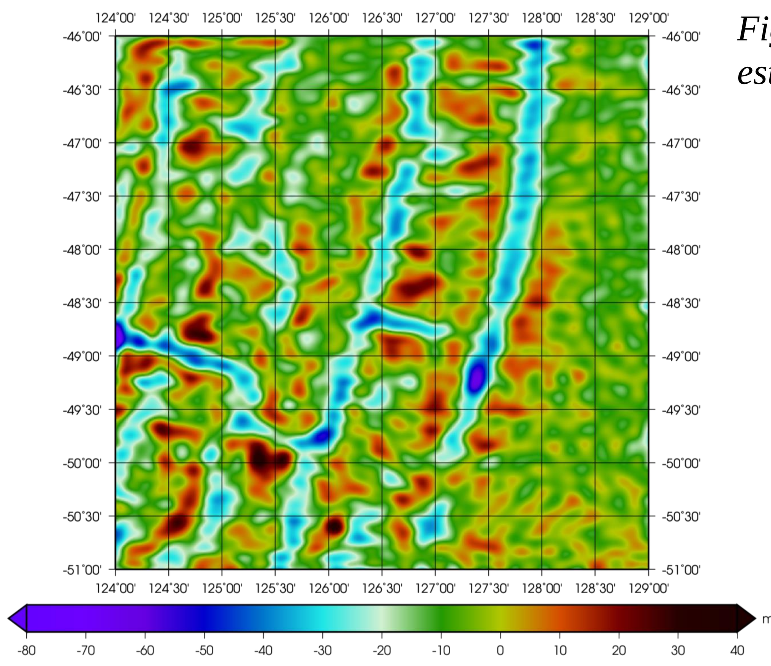


Fig. 3a: Gravity anomalies in [mGal] for level j=20 (b=1.5) estimated from altimeter SSH.

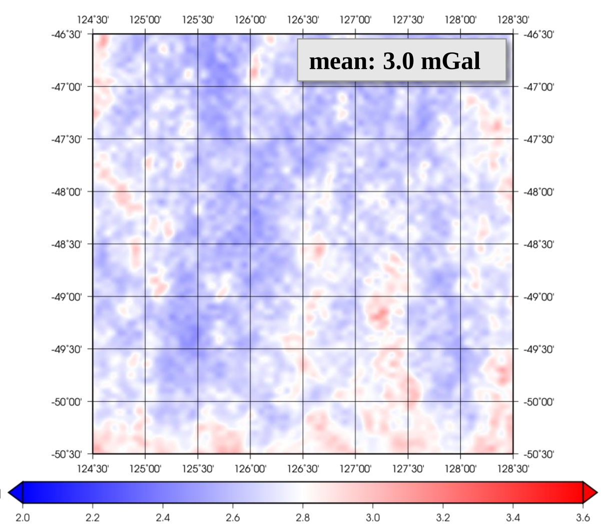


Fig. 3b: Corresponding formal errors (only for the inner region). The standard deviation at the margins exceeds 10 mGal.

Comparison to EGM2008

To get a first impression on the model accuracy differences to EGM2008 are build.

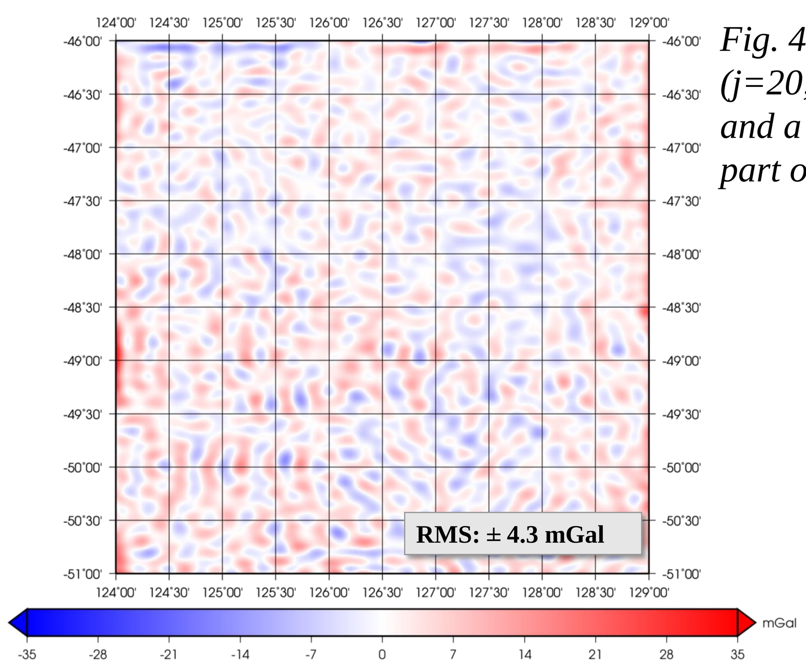


Fig. 4: Differences to EGM2008 (d/o 2190). The model differences (j=20, b=1.5) are randomly distributed with an RMS of 4.3 mGal and a maximum of 35 mGal. The consistency is better in the central part of the area: 3.6 mGal RMS and 15 mGal maximum.

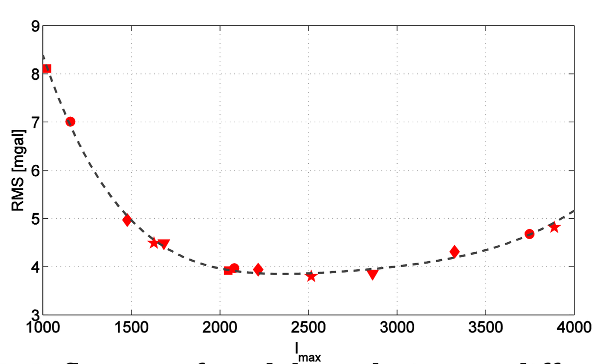


Fig. 5: Influence of model resolution on differences to EGM2008. The smallest differences to EGM can be reached using a similar spatial resolution.

The choice of the level defines the spatial model resolution and influences the consistency to EGM2008 (which is developed up to l_{max}=2190). The smallest differences to EGM can be reached with j=18 (b=1.545), since the resolution (l_{max}≈2500) of the models is akin in this case (keeping in mind the spatial smoothing characteristics of Blackman functions). The differences to EGM reach 3.8 mGal RMS for this model (see Fig. 5).

Validation

For model validation ship-borne free-air gravity anomalies from NOAA's NGDC are used. In the study area, 12 different surveys provide measurements. As the data has not been pre-processed and harmonized, model differences (RMS) and correlation coefficients ρ are computed for each campaign independently.

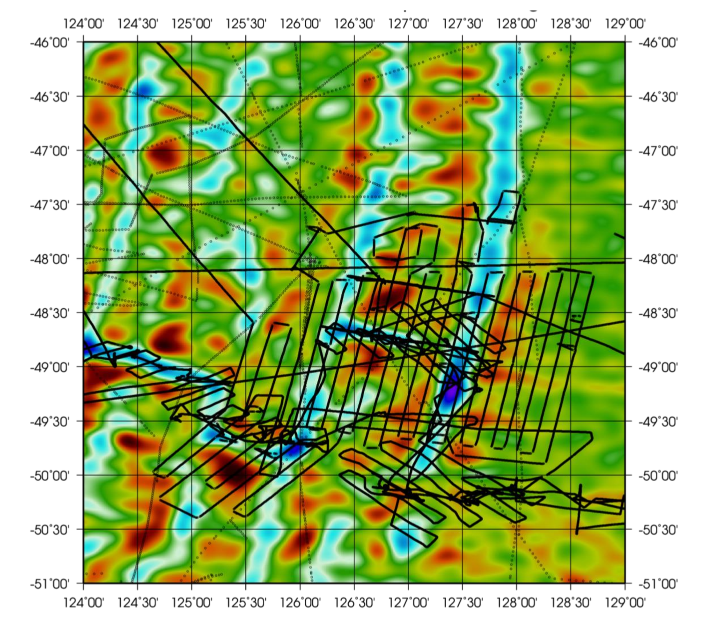
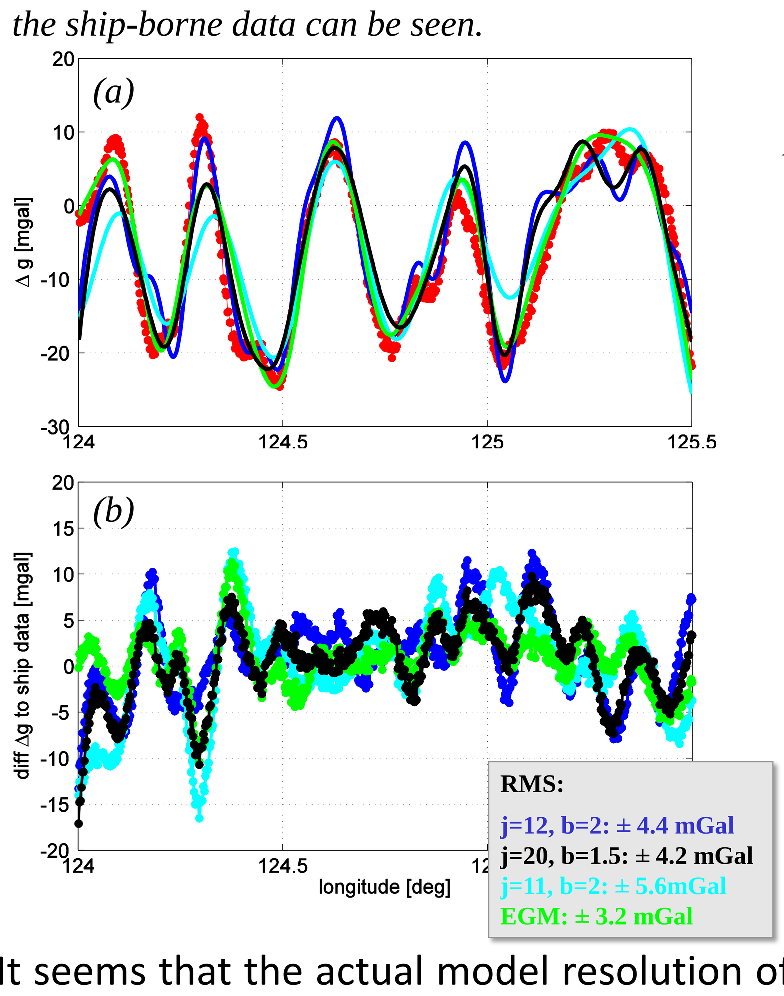


Fig. 6: Ship tracks used for model validation. Each black dot indicates one ship-borne measurement. In the study area 56,690 measurements from 12 different campaigns are available.

Fig. 7: Gravity anomalies for part of campaign BMRG05MV (#625 obs.). Plot(a) shows the ship-borne data (in red) and 4 different model solutions. In plot (b) the model differences to the ship-borne data can be seen.



As it can be seen from Fig. 7, the quality of the model depends on the model resolution. In some areas the gravity signal cannot be described by model resolutions around 10 km (such as j=11, b=2 in cyan). The model with higher resolution (e.g. j=12, b=2, r ≈ 5 km in blue) performs better. However, this is different in other model areas where the data distribution is sometimes too sparse for a reliable estimation of higher levels. The black curve (j=20, b=1.5, r ≈ 6 km) is a compromise and performs best taking into account the whole study area.

It seems that the actual model resolution of about 6 km is not sufficient to describe all high-frequent signals available in the study area. However, the 1Hz data distribution is too sparse in some regions of the study area to reliably estimate higher levels.

Tab. 3: Model differences to ship-borne data set for various model resolutions (mean values from 12 campaigns; in the inner region). The best campaign gives an RMS of 4.1mGal, the worst 13.8 mGal.

j(b)	11(2)	13(1.8)	19(1.5)	20(1.5)	14(1.8)	12(2)	EGM
RMS	7.2	7.2	7.1	6.9	7.0	7.4	6.3
ρ	0.81	0.81	0.81	0.80	0.79	0.71	0.85

The best model reaches a similar consistency to the ship-borne data set than EGM2008. However, EGM behaves slightly better. The reason for this effect is still under investigation.

The quality of the ship-borne data is different for the campaigns. Comparing the model to the most reliable survey (BMRG05MV with about 15,000 observations) provides an RMS of about 4 mGal. This is in good coincidence with the estimated formal errors of about 3 mGal.

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Conclusions

The presented approach provides high-quality regional gravity models comparable to EGM2008. In order to further improve the model resolution the spatial distribution of input observations should be increased, e.g. by using preprocessed high-frequent altimeter data and data from GEOSAT geodetic mission phase.

IAG Scientific Assembly 2013, 1-6 September 2013, Potsdam, Germany