IMPACT OF NEW GRAVITY FIELD MISSIONS FOR SEA SURFACE TOPOGRAPHY DETERMINATION

Th. Gruber, P. Steigenberger
Institut für Astronomische und Physikalische Geodäsie (IAPG)
Technische Universität München, 80290 München, Germany
e-mail: Thomas.Gruber@bv.tu-muenchen.de

Abstract. The determination of the stationary part of the sea surface topography, by subtraction of the oceanic geoid from altimetry derived mean sea surfaces (altimetric approach), has suffered since the beginning of altimetry from uncertainties in the global gravity field models. On the other hand sea surface topography models, determined with oceanographic methods (e.g. steric levelling, oceanic circulation models), do not refer to an equipotential surface and strongly depend on the quality of the ocean model. For many years scientists from the geodetic and oceanographic communities have tried to overcome the various problems without reaching satisfactory results. With the new dedicated gravity field missions CHAMP, GRACE and GOCE a major step towards a high precision determination of the absolute stationary sea surface topography by the altimetric approach is possible. The predicted geoid error will be reduced with CHAMP and GRACE by 1-2 orders of magnitudes for the long wavelengths (500 km and larger) and with the GOCE gradiometric mission it will be possible to determine the geoid with an accuracy of better than 1 cm with much higher spatial resolution (about 160 km full wavelengths). With the availability of the first CHAMP based long wavelength gravity field models (EIGEN-1S from GeoForschungsZentrum Potsdam and TEG-4 from Center for Space Research at University of Texas in Austin) the current situation has changed rapidly. Both new models provide significant improvements for the low degree spherical harmonics, which are strongly influenced by the CHAMP GPS satellite-to-satellite tracking data. Sea surface topography models computed with these gravity models already show major improvements with respect to the pre-CHAMP era. Oceanic features like the major ocean currents now can be much better identified than in previous solutions and the long wavelength vertical reference is precisely defined.

We briefly review the state of the art of sea surface topography determination in the pre-CHAMP era and then focus on results based on the CHAMP gravity field models. Several models with different mean sea surfaces are computed and compared with oceanographic derived models. Analyses are performed in the space and spectral domains in order to identify which model best represents reality.

Keywords. Sea surface topography, CHAMP gravity field model

1. Introduction

One decade ago, with the beginning of operational altimetry by the ERS-1 and Topex-Poseidon satellite missions, first models of the stationary sea surface topography were estimated by subtraction of the oceanic geoid from the mean sea surface. These models were strongly influenced by errors in the altimetric mean sea surfaces (like radial orbit errors or uncertainties in the corrections for the altimetric range) and mainly by the insufficient knowledge of the marine gravity field. While mean sea surfaces became more and more accurate, with the availability of more data and with the development of new models and techniques for variability reduction (e.g. tide models, radial orbit error reduction), gravity field models, derived only from satellite tracking observations, remained at a certain low-accuracy level. Their errors at short wavelengths dominated the estimated sea surface topography solutions. To overcome the errors in satellite-only gravity field solutions, combined models incorporating surface gravity and altimeter data were developed. These models could improve the estimated sea surface topography solutions only by including preconditions for the sea surface topography, which were derived from oceanographic observations and models or by using sparse marine gravity observations of relatively poor quality. This means the altimetric method for sea surface topography determination was strongly dependent on oceanographic modeling techniques aiming in the same quantity. One can say that these models were biased by oceanographic a-priori information.

With the launches of CHAMP (Reigber at al, 1999, 2000) in July 2000 and GRACE (Tapley and Reigber, 1999, 2000) in March 2002 for the first time satellite-only gravity field models of adequate accuracy are and will be available for determination of the long wavelength stationary sea surface topography. These solutions will not be anymore dominated by the geoid error. As a secondary effect, it can also be expected that the orbit accuracy of the altimeter satellites will increase significantly with the usage of these new gravity field solutions. The geographically correlated radial geoid error for these satellites, which can not be reduced by crossover techniques, will be eliminated almost completely. With the ESA gradiometry mission GOCE (ESA, 1999), scheduled for launch in early 2006, the spatial geoid resolution and the accuracy for higher frequency terms can also be increased significantly, such that at this time also medium scales of the sea surface topography can be determined with sufficient accuracy by the altimetric method. Also the oceanographic methods for sea surface topography estimation will gain a lot of accuracy by the assimilation of the new gravity field solutions into their estimation scheme. Both methods should converge to a singular sea surface topography solution.

2. Sea Surface Topography Determination – State of the Art

As mentioned above, two different approaches with different methodologies have been used in the past for estimation of the stationary sea surface topography. In the following a review of these methods (without claiming completeness) with pro's and con's is provided (Table 1).

Table 1: Review of approaches for sea surface topography determination and comparison with advantages and disadvantages.

Method	Pro's	Con's
Altimetric		
Gravity field, satellite orbits & sea surface topography simultaneously	• no hypothesis • simultaneous estimation	• strong correlation • only long wavelengths
Mean sea surface minus geoid & filtering	• no hypothesis • simple computation	• full geoid & orbit error • filter design dependent
Oceanographic		
Steric leveling	• higher resolution • good relative accuracy	• level of no motion hypothesis • only long term data useful
Ocean circulation model	• higher resolution • good relative accuracy	• ocean model errors fully in solution
Inverse methods	• assimilation of altimetry • higher resolution • good relative accuracy	• assimilation theory not yet fully developed

Generally one can say, that oceanographic derived models have better relative accuracy and a higher spatial resolution. But these solutions are strongly dependent on the quality of oceanographic models and, in case of steric leveling, they depend on a hypothesis for the level of no motion surface. On the other hand the altimetric approaches are relatively simple and do not have to rely on a hypothesis if the oceanic geoid is determined from satellite-only gravity field models. (This is not true if combined satellite and surface gravity field models are used, which include an a-priori assumption on the sea surface topography). But altimetric sea surface topography models are strongly influenced by the geoid and orbit errors, which are directly related to the gravity field errors. Also the filtering of the pointwise differences between mean sea surface and the oceanic geoid by spherical harmonmics is tricky, because of the missing land areas. Strong aliasing effects and Gibb's phenomena can influence the result significantly.

Figure 1 shows one of the first sea surface topography solutions from steric leveling using sea surface temperature and salinity (Levitus, 1982). The model shows very well the geostrophic ocean currents, like the Antarctic Circumpolar Current, the South Equatorial Current, the Kuroshio with the North Pacific Current and also a little bit less clear the Agulhas, the Brazil Current and the Gulf Stream. The model (at least in a relative sense) can be regarded as a reference for all newer solutions.

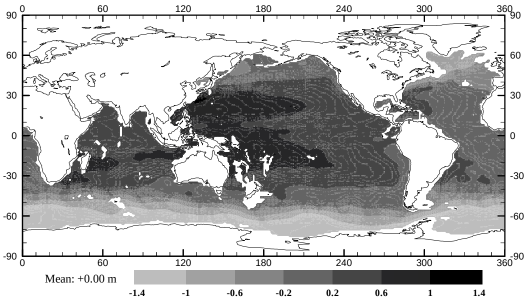

Figure 1: Sea Surface Topography from Levitus Climatology (1982); Data time span from 1900 to time of computation (centered around mean) [m].

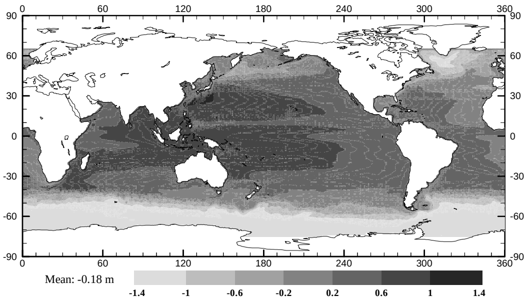

Figure 2: Sea Surface Topography from Parallel Ocean Climate Model (POCM); Model time span 32,5 years (centered around mean) [m].

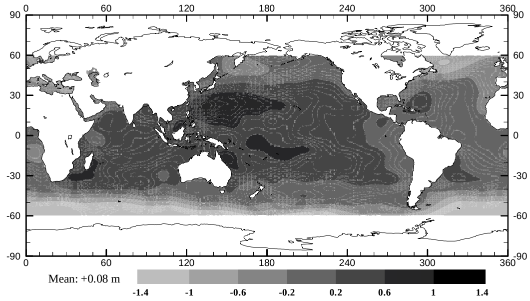

Figure 3: EGM96 Sea Surface Topography Solution (centered around mean) [m].

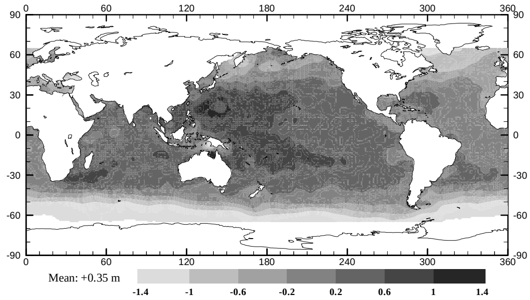

Figure 4: IAPG Sea Surface Topography Solution from Topex Altimetry (centered around mean) [m].

Figure 2 shows a sea surface topography solution from a coupled ocean-climate model (Semtner et al, 1992). Comparing the figures 1 and 2 one clearly can see, that the ocean-climate model does not show as many details as the Levitus model from steric leveling. Especially the smaller curents like the Gulf Stream, the Agulhas and the Brazil Current are nearly not visible. Figure 3 shows the EGM96 sea surface topography solution (Lemoine et al, 1998). This model was computed simultaneously with the EGM96 gravity field model with the altimetric approach by including marine gravity data as additional observations. The model was provided as spherical harmonic series up to degree and order 20. Comparing figure 3 with figure 1 it can be seen that this model only contains the main structures of oceanic topography. Finally, figure 4 shows a sample sea surface topography solution from IAPG, computed for this study from Topex altimeter sea surface heights and the JGM-3/OSU91a geoid model, which is included in the Topex-Poseidon geophysical data records. The model was computed by a gridding of the individual 1 seconds sea surface topography heights. Comparing it to the Levitus climatology (figure 1) it can be seen that most of the main ocean currents are visible with a relatively high spatial resolution. It has to be clarified to what extent the higher frequencies contain a real sea surface topography signal or if they are caused by the gridding algorithm. It should be noted here again, that this model is dependent on an a-priori sea surface topography solution, which was used for the JGM-3 gravity field determination to condition the satellite altimeter heights initially.

3. CHAMP Gravity Field Models

The first gravity field solutions using a set of CHAMP GPS satellite-to-satellite tracking data in the high-low mode were computed by GFZ Potsdam in the EIGEN-1S model (Reigber et al, 2002) and Center for Space Research in the TEG-4 model (Tapley et al, 2001). The EIGEN-1S satellite-only model is an upgrade of the GRIM5-S1 model (Biancale et. al, 2000) plus additional SLR observations to Lageos 1 and 2, Starlette and Stella. 88 days of CHAMP SST data and accelerometer data for surface force reduction were used for the model. EIGEN-1S is complete to degree and order 100 with higher degree terms up to a maximum degree 119 for CHAMP-sensitive and resonant orders. TEG-4 is a combined gravity field model complete to degree and order 200, including multi satellite tracking data, surface gravity data and ocean geoid heights, which were derived from altimetry and an a-proiri sea surface topography solution. Additionally 80 days of CHAMP GPS-SST data were included. Because an a-priori assumption for the sea surface topography was introduced in the TEG-4 estimation scheme, the model is somehow dependent by this assumption. This has to be kept in mind when the TEG-4 geoid is used for determination of the sea surface topography.

The EIGEN-1S model shows major improvements in terms of geoid accuracy compared to the previous GRIM5-S1 satellite-only gravity field model. This can be seen by the signal and error degree variances (see figure 5) and by geoid height comparisons at GPS-leveling stations (see figure 6). Comparing degree and error degree variances (square root) for GRIM5-S1 and EIGEN-1S, it becomes immediately visible, that EIGEN-1S has more signal for degree 25 and higher and that the errors (based on the coefficient variances) are much smaller (except for the very low degrees). This means, that the additional data in EIGEN-1S really improve the model, at least regarding the internal errors, compared to the GRIM5-S1 base model.

Looking to the intersection of the sea surface topography signal degree variances (computed by spherical harmonic analysis of the POCM model) and the gravity field error degree variances, it becomes immediately clear that EIGEN-1S is much better suited for sea surface topography estimation. From figure 5 we can read that the sea surface topography can be estimated up to degree 26 when EIGEN-1S is used compared to degree 14 with GRIM5-S1. This will be taken into consideration in the next chapter when EIGEN-1S based sea surface topography solutions are computed.

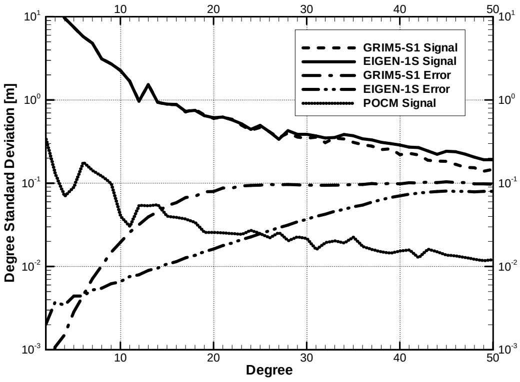

Figure 5: Degree and Error Degree Variances (Square Root) in Terms of Geoid Heights for EIGEN-1S and Signal of POCM Sea Surface Topography.

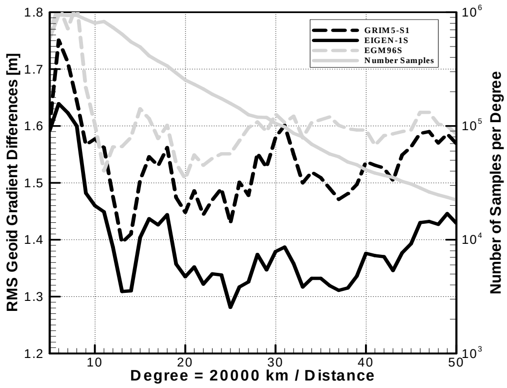

Figure 6: Residuals of Geoid Height Differences between US GPS Stations from Levelling plus GPS and Geoid Models (5168 Points).

While degree variances in figure 5 only show the internal quality of the gravity model, resulting in an improved variance-covariance matrix, comparisons to independently observed geoid heights at GPS leveling stations provide an external quality estimate. For this the US GPS on benchmark data set with 5168 sample points is well suited (Milbert, 1998). Comparing the absolute geoid heights from the model (up to degree 50) and the GPS leveling data set a RMS-reduction from 1.094 m for GRIM5-S1 to 1.021 m for EIGEN-1S can be reached. This is a significant improvement in geoid quality for the long wavelengths. A closer look to the geoid quality provides the statistic of geoid gradient differences. These are the differences between the model geoid height differences and reference point geoid differences dependent on the distance of the reference points, which is further mapped to the spherical harmonic degree (for more details on the geoid gradient test see Gruber, 2001). The large number of sample values for the statistical analysis is due to the computation of differences for every station with any other station in the US network. This enables a significant statistical analysis. Up to degree 50, corresponding to a point distance of 400 km, the RMS value of geoid gradient differences is reduced between a few centimeters and 1 dm. Results in figure 6 show significant improvements for the low degree spherical harmonic coefficients of the EIGEN-1S model with respect to GRIM5-S1 and EGM96S. Using the full model resolution further improvements can be reached also for higher degree and order terms. It should be noted that in similarity also the TEG-4 model was slightly improved with respect to the previous TEG-3 solution by inclusion of CHAMP data, but by a smaller factor, which is due to the large impact of the surface gravity and altimeter data in TEG-4.

4. Impact of CHAMP on Sea Surface Topography Determination

As shown in the previous chapter, the EIGEN-1S model shows significant improvements in terms of geoid heights over continents. Now we ask to what extent the CHAMP based gravity field models also improve the geoid over the oceans. For this purpose several mean sea surface models, CLS2001 (Hernandez, 2002), CSR1995 (Tapley and Kim, 2000), GFZ1993 (Anzenhofer et al, 1995), GSFC00.2 (Wang, 2001), KMS2001 (Knudsen et al, 1998), OSU1995 (Yi, 1995) and the GRIM5-S1, EIGEN-1S, EGM96S (Lemoine et al, 1998), TEG-3 and TEG-4 gravity field models were used to determine the long wavelength sea surface topography by subtraction and filtering. As it was shown in figure 5 the propagated EIGEN-1S geoid height errors are below the sea surface topography signal up to approximately degree 26. Therefore the filter was designed that frequencies above degree 30 are removed from the sea surface topography solutions. Figure 7 shows the flow chart, which was used for the subsequent sea surface topography computation.

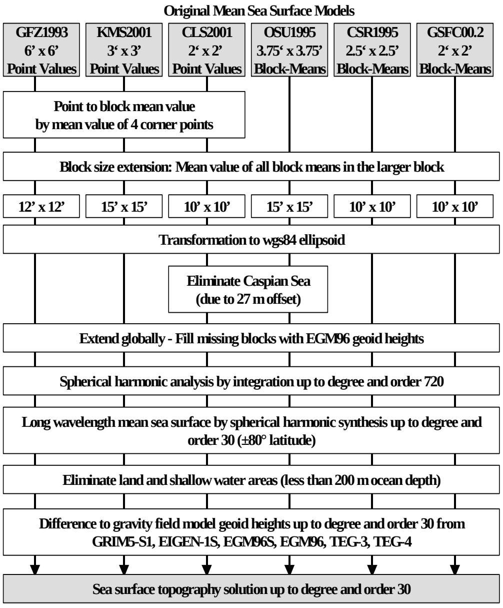

Figure 7: Flow Chart of Sea Surface Topography Determination with Filtering by Spherical Harmonics.

The filtering was performed by spherical harmonic analysis and elimination of all coefficients above degree and order 30. In order to avoid Gibb's phenomena and aliasing effects at the ocean-continent boundaries, in all areas, where the mean sea surface model is not defined, EGM96 geoid heights with the same resolution were included. This ensures that globally defined data sets were used for the spherical harmonic analysis. Figures 8, 9, 10 and 11 show as samples the resulting sea surface topography solutions up to degree and order 30 from the Goddard mean sea surface model GSFC00.2 and the satellite-only gravity field models GRIM5-S1, EGM96S, EIGEN-1S and the combined solution TEG-4. Solutions with the other mean sea surfaces generally look very similar and are therefore not shown here.

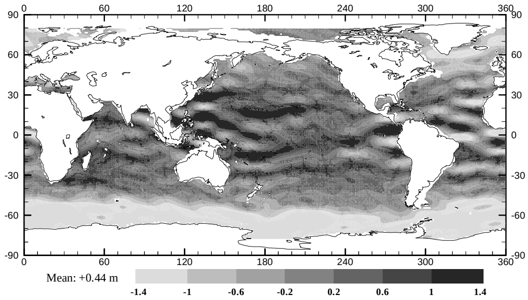

Figure 8: Sea Surface Topography Solution from GSFC00.2 Mean Sea Surface and GRIM5-S1 Geoid (centered around mean) [m].

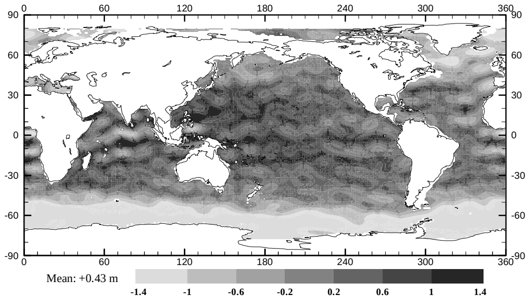

Figure 9: Sea Surface Topography Solution from GSFC00.2 Mean Sea Surface and EGM96S Geoid (centered around mean) [m].

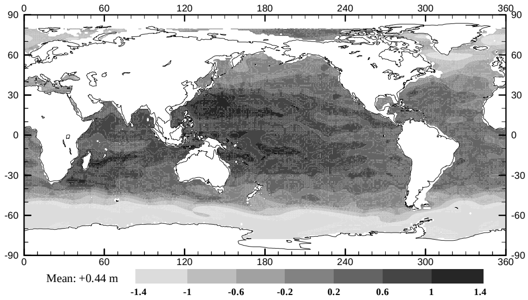

Figure 10: Sea Surface Topography Solution from GSFC00.2 Mean Sea Surface and EIGEN-1S Geoid (centered around mean) [m].

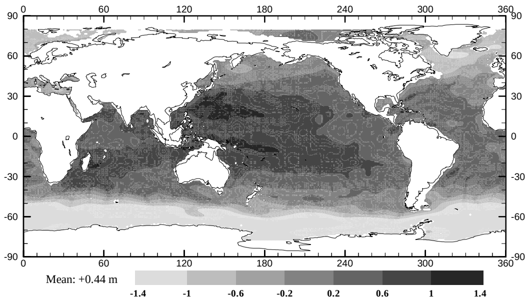

Figure 11: Sea Surface Topography Solution from GSFC00.2 Mean Sea Surface and TEG-4 Geoid (centered around mean) [m].

The results shown above clearly indicate, that with EIGEN-1S a major improvement of the geoid accuracy could be reached also over the oceans. While for the GRIM5-S1 and EGM96S solutions unrealistic features in the sea surface topography are visible (e.g. waves around the equator) for the EIGEN-1S solution the structures of the main ocean currents are now visible. This is the first time that an "un-biased" gravity field model geoid is applicable for sea surface topography determination. For comparison purposes also the TEG-4 solution, which contains altimetry and a-priori estimates for the sea surface topography, is shown in figure 11. Comparing it to figure 10 (EIGEN-1S solution) it can be seen, that the main features look very similar. This means, that the EIGEN-1S geoid is, for the long wavelengths, at the same accuracy level as the combined solutions. The EIGEN-1S sea surface topography solution also looks similar to the oceanographic models for the main ocean currents (see figures 1 and 2). It can be stated that by using EIGEN-1S the oceanographic and altimetric approaches for sea surface topography determination provide similar results.

5. Conclusions

Several mean sea surface and gravity field models without and with CHAMP data were used to determine the long wavelength features of the sea surface topography. From the results shown above it can be concluded, that with the availability of CHAMP based gravity field models a revival of the altimetric method for sea surface topography determination is now possible. Therefore the conclusions are separated into a pre-CHAMP and post CHAMP section.

Pre-CHAMP:

- Satellite-only gravity field models can not be used for sea surface topography determination with the altimetric approach (e.g. fig. 8).
- Combined gravity field models using altimetry in any form are biased by a-priori sea surface topography estimates included in the solution (usually from oceanography).

Post-CHAMP:

- Improvement of geoid quality for long wavelengths of about 10 cm over continents is visible. The same can be expected over the oceans.
- Strong improvement in EIGEN-1S based sea surface topography solutions with different mean sea surface models visible.
- Slight geoid improvement also visible in combined TEG-4 model by inclusion of CHAMP data (not shown here).
- Further improvement in sea surface topography can be expected by using more and reprocessed CHAMP data sets.
- With GRACE and later-on GOCE it is expected that the altimetric approach in future will be the best method for sea surface topography determination.

Generally we see now the first benefits from the new gravity field missions and we expect a lot of more in the near future.

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