Validation Concepts for Gravity Field Models from New Satellite Missions

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1. ABSTRACT

The new satellite missions CHAMP, GRACE and GOCE will provide significantly improved global gravity field information in terms of quality and spatial resolution. In order to quantify the quality of these gravity field models independently from the estimation procedure, new validation concepts are necessary using external information. Validation requires the processing of selected level 3 products from the satellite gravity missions, which further-on can be compared to independent data. A typical example of such an approach is the determination of the stationary sea surface topography using the geometric approach (mean sea surface minus the geoid) and comparison to oceanographically derived solutions. The paper summarises procedures for validation of gravity field models on different data levels and provides samples of validation results for the latest CHAMP and GRACE fields.

2. INTRODUCTION

Since the launches of CHAMP in July 2000 and GRACE in March 2002 several gravity field solutions based on these newly available data sets have been generated by different groups up to now. Some of them still must be regarded as first test results validating the system performance (specifically for GRACE), but what concerns CHAMP many of the models can be regarded as validated versions. A main issue now is to estimate the quality of these solutions with respect to that what was known before both missions. New tools have to be developed and new test data sets have to be acquired in order to perform these "external" testing. The development made here will also have major impact for the GOCE gravity field validation and should be regarded as a preparation step for that. In order to get a feeling for the error level to be expected from these new missions and what is claimed as current situation, Fig. 1 shows the cumulated geoid errors derived from mission error predictions as well as from coefficient errors resulting from the least squares data analysis.

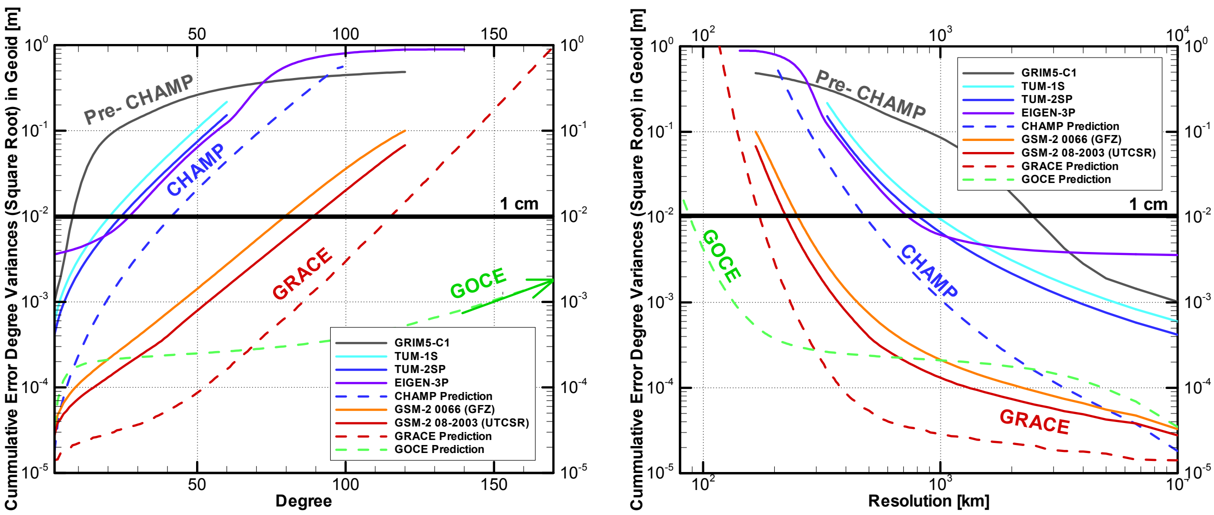

Figure 1: Cummulated error degree variances in different representations (resolution in half wavelengths)

From both figures it can be identified, that major progress has been made with CHAMP and GRACE, but that there is still room for further improvements under the assumption that the error predictions are really showing the theoretical system error level. Regarding the combined gravity field model GRIM5-C1 [1] as the pre-CHAMP sample we can identify that with the most recent CHAMP models EIGEN-3P [2] and TUM-1S / TUM-2SP [3] there is an improvement by a factor of 5 to 10 up to degree and order 60 corresponding to half wavelengths of about 350 km. From these models we know the geoid with cm accuracy with a resolution of about 700 km. But we also can identify that there is still room for improvements especially when more CHAMP data at lower satellite altitudes will be analysed in the near future. What concerns GRACE several models have been made available by the PI and Co-PI for validation purposes to our institute as member of the joint science team. For this reason they should be regarded as preliminary solutions showing a snapshot of that what might be possible with GRACE data. The two models regarded here are a monthly solution for August 2003 from UTCSR (named here as GSM-2 08-2003) and a solution from 66 days GRACE data from GFZ (named here GSM-2 0066) [4]. Both models show a similar error behaviour as a result of the least squares solution. They claim an improvement by a factor of 10 to 100 with respect to CHAMP and pre-CHAMP solutions up to degree and order 120. The resulting geoid can be determined at cm-level with a resolution of 300 km. As for CHAMP also for GRACE there is some room for further improvements when comparing the current situation with the error predictions. By further improving the analysis techniques and especially by using the range between both satellites as observations instead of the derived range-rates it can be expected that the resulting error curves get closer to the error predictions.

3. EXTERNAL GRAVITY FIELD VALIDATION TOOLS

As the gravity field model error curves (shown in Fig. 1) all are derived from error estimates as a result of a least squares solution, they shall be regarded as "internal" error estimates. The difficulty and challenge now is to estimate the so-called "external" accuracy, what means the real geoid or gravity error of these models. There are several tools and data sets available, which can be applied for that purpose. Table 1 summarises these tools and data sets and tries to provide some estimates for what frequency range these tests are applicable and what are the problems with these tests. We always have to have in mind, that we want to compare high quality global gravity field models limited to a specific resolution with independent gravity field and orbit observations for which often their quality is not very well known and which usually contain the full gravity field signal.

Table 1: Tools and test data sets usable for gravity field validation

Tool	Test Data Sets	Range of Test	Quality Parameters	Problems
Precise orbit determination of geodetic and altimeter satellites with a variety of orbit parameters.	Satellite tracking data: Laser, DORIS, PRARE, GPS, Altimetry.	Long wavelengths: Degree: 0-70 Resolution: 300-20000 km	Residuals with Respect to Tracking Data in Space and Frequency Domain; Altimeter Crossover Differences for Computed Orbits.	Independent Tracking Data; Quality of Altimeter Observations; Sensitivity of Satellites for Gravity Field; Non- gravitational Disturbances.
Comparison with independent geoid and gravity information.	GPS-levelling geoid heights; Point-, mean gravity anomalies.	Medium to short wavelengths: Degree: 50-250 Resolution: 80-400 km	RMS and mean of geoid height and gravity anomalies differences at the points of comparison and slopes.	Treatment of omission error; Filter model; Impact of long wavelengths.
Analysis of sea surface topography solutions.	Mean sea surfaces from altimetry; Oceanographic sea surface topography solutions.	Long to short wavelengths: Degree: 10-250 Resolution: 80-2000 km	Differences between geodetic and oceanographic solutions; Test for remaining oceanographic signals.	Quality of mean sea surfaces and oceanographic sea surface topography models; Filtering; Ocean boundaries.

Orbit test are a tool for testing the long wavelength components of the gravity field model. By computing orbits to a variety of high and low flying geodetic and altimetric satellites with different orbit parameters in a dynamic (reduced dynamic) approach and by analysing residuals for available tracking data to these satellites we can get a picture about the quality of the orbits and indirectly about the quality of the used gravity field model, if all other force models are not changed. In [4] first results for the GRACE models are shown. These results imply that some improvements are visible in the tracking data residuals. But it also can be noticed, that only a minor improvement of about 10% could be reached, even if the gravity field is improved by, lets say, 90% in this frequency range. The reason for that is, that other models used for the time-variable gravitational (e.g. tides) and non-gravitational forces as well as the tracking data are somehow limited in accuracy and fully overlay the induced gravity field errors. Also the attenuation of the gravity signal with satellite height plays a role in this analysis. In summary it might be the case that the gravity field is perfect for that orbits, but that all other sources sum up to the remaining residuals. It is extremely difficult to distinguish the individual error sources from the overall residuals statistics. A detailed analysis of tracking data residuals might help to identify at least some of the sources and is recommended here.

Observed geoid heights and gravity anomalies can be used for gravity field validation. In this context GPS-levelling derived geoid heights and national gravity networks can play a prominent role for validation purposes. These data contain the full gravity signal as it is observed at the Earth surface. Because these data usually are connected to national height datums, long wavelength errors might be present in the data sets. All this has to be taken into consideration when comparing them to model derived geoid heights and gravity anomalies. That means these data can be used for medium to short wavelength tests of the global gravity field solutions. Before comparing the two data sets a low-pass filtering of the surface observations has to be done in order to take into account the omission error in the global fields. Several techniques are possible to do that filtering. In order to optimally prepare the surface data the filter has to be designed very carefully taking into account the specific attributes of these data. A sample for the filtering using a very simple approach is shown in the next chapter.

A very powerful tool for gravity field validation could be the comparison of geometrically and oceanographically derived sea surface topography solutions. For the geometrical or also called geodetic approach the oceanic geoid computed from the gravity model is subtracted from an altimetry derived mean sea surface. This again implies some processing steps, which should be carefully analysed. First, the altimetric mean sea surface has to be determined. Depending on the data to be used for computation of the mean sea surface a representative equally accurate surface has to be determined. Any systematic error in the altimeter data fully is contained in the derived mean sea surface. By combination of different altimeter missions systematic errors in one mission with respect to the other can be identified, but not in an absolute sense. In addition any mission combination introduces new problems and computational efforts due to the usage of different correction models in the altimeter observations. The surface also has to be low-pass filtered in order to take into account the omission error in the gravity field model. If all that can be done in an efficient an accurate way the derived sea surface topography can be compared to oceanographically derived solutions. By doing that one has to take also into account possible errors in the oceanographic model. A close cooperation between oceanographers and geodesists is required to analyse the results and draw the right conclusions. In the next chapter a sample for such a test using spherical harmonics for filtering is shown.

4. VALIDATION OF PRE-CHAMP, CHAMP AND GRACE MODELS

4.1 Comparison with GPS-Levelling Data

Several GPS-levelling data sets are available in our institute. All of them have been used for testing the new CHAMP and GRACE fields in comparison to the pre-CHAMP solution GRIM5-C1. Cut-off frequency for this test was degree and order 60, because our assumption was that this is the current natural limit for the CHAMP models. For taking into account the omission error geoid heights computed from the GPM98A model [5] from degree 61 to 720 were subtracted from the GPS-levelling geoid height data sets. The GPM98A model is mainly based on a global topography model and somehow represents the full signal (even if we can assume that various uncertainties are present in this model). Table 2 shows the RMS values of the differences around the mean value between the filtered GPS-levelling and model geoid heights for different continental areas.

Table 2: RMS in [m] of differences between GPS-levelling and model geoid heights (degree 0-60)

GPS-Levelling Data Set	Number Points	GRIM5-C1	TUM-1S	TUM-2SP	EIGEN-3P	GSM-2 0066 (GFZ)	GSM-2 08-2003 (UTCSR)
USA	5168	0.453	0.641	0.471	0.421	0.416	0.410
Canada	1587	0.549	0.609	0.600	0.528	0.522	0.524
Europe	180	0.397	0.564	0.331	0.296	0.283	0.280
Germany	675	0.303	0.526	0.257	0.194	0.195	0.194
Australia	197	0.543	0.633	0.527	0.532	0.502	0.501
Japan	837	0.594	0.655	0.548	0.502	0.515	0.514

Table 2 shows, that the GRACE models perform best, but also that the CHAMP EIGEN-3P model (based on 3 years of CHAMP data) also is very close to that results. This is in contradiction to the internal error estimates shown in Fig. 1. But, except for the TUM-1S model, we can identify a significant improvement with respect to the pre-CHAMP model. The TUM-1S model is based on 6 months of CHAMP data using a new estimation technique [3]. Because of the limited data set and some problems in the new technique it performs worse than the other models. By adding more data and improving the technique results could be significantly improved (see TUM-2SP). The size of the differences of a few decimeters indicate that the quality of the comparison data sets is not sufficient and/or that the filter method is not adequate. Both have to be investigated more detailed in order to enable a qualified analysis of these differences.

An interesting tool to further analyse the geoid differences at GPS-levelling points is the computation of geoid slopes between all possible observation points and compare them to the slopes derived from the gravity field model in dependency of their distance. Using the USA data set we get more than 1 million differences, which can be classified according to their distance. A simple statistic of the differences per distance class finally can be computed and visualised. This is shown in Fig. 2 on the right hand side for all the models discussed above. What we can read from that figure is, that it corresponds very well to the results in table 2. The GRACE fields show some improvement with respect to the 3 years CHAMP solutions, but not drastically. We also can see that the test performs much poorer for the longer distances (i.e the long wavelengths) as it was discussed in chapter 3.

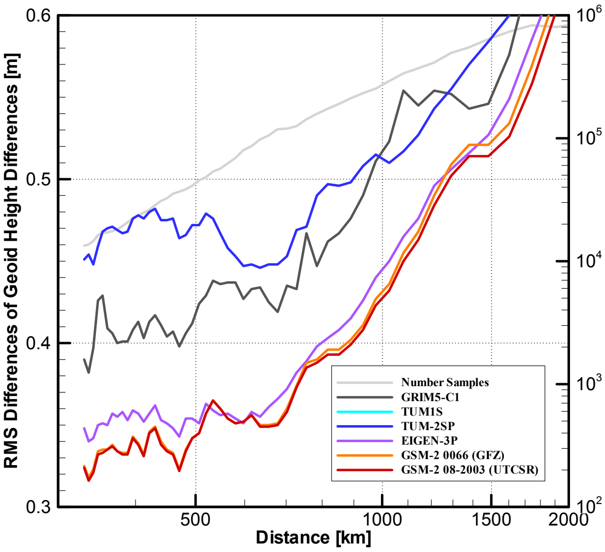

Figure 2: Geoid slope differences for USA GPS-levelling data set and gravity models

4.2 Sea Surface Topography Models

Sea surface topography solutions for the North Atlantic were computed using several gravity field models. Again as cut-off frequency degree and order 60 was used. As mean sea surface the GSFC mean sea surface model was used [6]. For filtering the model a spherical harmonic analysis of the mean sea surface was done. Continental and not covered areas were filled with geoid heights computed from the EGM96 gravity field model [7] up to degree and order 360 in order to avoid spectral leakage. Finally a spherical harmonic synthesis up to degree 60 was done before the differences to the geoid heights from the gravity field model were computed. Fig. 3 below shows the results for three models together with an oceanographically derived model from LeGrand [8].

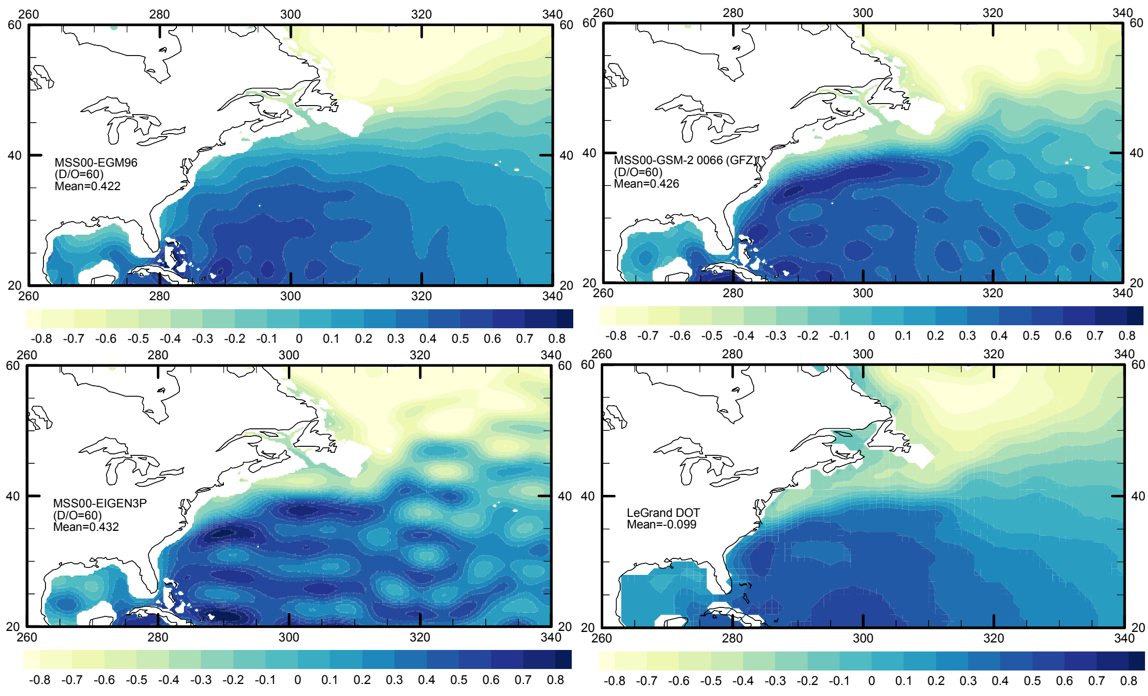

Figure 3: Sea surface topography solutions in the North Atlantic with EGM96 (upper left), EIGEN-3P (lower left), a GRACE Model (upper right) and from an oceanographic approach from LeGrand (lower right) [m].

From the results in Fig. 3 we can conclude that the GRACE derived sea surface topography recovers very well the Gulf stream, what is not the case for the CHAMP model. The EGM96 derived model fits very well to the oceanographic model, because during the EGM96 computation another oceanographic model was used as a-priori information. As it is also pointed out in [4] the main differences between the GRACE derived sea surface topography solution and the oceanographic solution can be addressed to problems in the oceanographic modelling. From this viewpoint it becomes obvious, that we are running into a chicken-egg problem. That means for improving the oceanographic modelling of the dynamic topography a high accurate ocean geoid is required. On the other hand for validating the gravity field model we compare geometrically derived sea surface topography solutions with existing oceanographic information. This means that both approaches can only be used in an iterative way and that we must be very careful in analysing these differences.

An additional feature, which is visible in the GRACE and especially in the CHAMP derived sea surface topography models are the bumps and holes, which appear regularly distributed. These are caused by the filtering approach using spherical harmonics. It becomes obvious that better filter approaches in the space domain have to be applied for low-pass filtering of the mean sea surface. Otherwise these artefacts become visible in the derived models. From the CHAMP based sea surface topography model we also can conclude, that we are at the edge of the CHAMP sensitivity. In this solution nearly no oceanographic features are visible, but only noise from the filtering approach. This also corresponds to our experiences when computing the TUM-1S and TUM-2SP CHAMP models [3].

5. CONCLUSIONS

From the results shown above we can draw several conclusions related to the validation of the new mission gravity field models. Generally we can say that the gravity field models from CHAMP and GRACE have reached such an accuracy level, that it is very difficult to estimate their absolute errors. Up to now we are only able to find some hints whether a model has been improved compared to other solutions. The list below points to some areas where improvements have to made. If these problems can be solved we might be able to come closer to a real absolute error estimation.

- From the least squares error estimates it becomes visible that for the CHAMP and GRACE gravity field models there is still some room for improvements compared to the error predictions. The reasons for not reaching the mission baselines could be: (1) The mission baseline is based on the complete mission duration. This means only after the satellites are flown in their lowest orbit the full predicted signal can be recovered. (2) The mission baselines have been estimated too optimistically. The simulation scenarios have to be repeated using the most up to date instrument performance estimates. The simulation scenarios have to be re-investigated in order to find out if they are still realistic. (3) For GRACE gravity field models up to now only range-rate observations have been used. By introducing the originally observed ranges between both satellites additional performance can be gained. As a drawback the unknown range bias has to be separately estimated.
- The internal error estimates have to be regarded very carefully and do not necessarily represent the real (external) geoid error.
- Tracking data residuals from orbital fits can only be used for assessing the long wavelength gravity field quality. As the residuals only slightly improve for the new gravity field models it can be assumed that other effects from modelling the (non-) gravitational forces are dominating the residuals. Also the quality of the tracking data themselves has to be taken into consideration.
- GPS-levelling geoid heights can be used for testing the medium to short wavelength components of the gravity field. GRACE error degree variances indicate a geoid quality at the level of 1 cm (or better) up to degree 60. The quality of the validation data sets is not fully known, but should be at the level of a few cm up to 1 dm. Long wavelength errors in GPS-levelling geoid heights could also affect the validation results (increasing RMS values for larger distances).
- For the comparison of GPS-levelling geoid heights or observed gravity anomalies with gravity models a filter is required in order to minimise the omission error. The filter design has strong impact on the results and has to be improved.
- Sea surface topography solutions can be used to test the gravity field over the full spectrum. The 'GRACE' based sea surface topography solution in the North Atlantic shows significant improvements with respect to the 'CHAMP' derived model. Oceanographic features are now clearly visible (Gulf- stream).
- The quality of the mean sea surface model determined from altimetry has to be carefully analysed. Specifically systematic effects in the altimeter observation system completely are reflected in these models.

- The mean sea surface model has to be filtered carefully in order to remove the higher frequency content. The spherical harmonic filter used in our approach shows artefacts, which have nothing to do with a sea surface topography signal. The need for an improved filter approach becomes obvious.
- The cut-off frequency at degree 60 for the sea surface topography model is close to the sensitivity limit of CHAMP. Therefore the CHAMP derived sea surface topography solution shows quasi no oceanographic signal.
- The quality of oceanographically derived dynamic topography models is partly influenced by the quality of introduced oceanic geoid information. Therefore, comparisons of sea surface topography solutions derived from both approaches should be analysed very carefully.

All what is said above for CHAMP and GRACE also holds in future for GOCE. Only due to the higher spatial resolution of the GOCE fields some of the test methods have to be implemented in a slightly different way.

6. REFERENCES

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