A quality assessment of the GRACE monthly geoid solutions in view of tide and air pressure modelling errors.

E.J.O. Schrama,
Department of Geodesy, TU Delft, The Netherlands
e-mail: schrama@geo.tudelft.nl

Proceedings JLG meeting 4-6 Nov 2002 Luxembourg

1 Introduction

The GRACE gravity mission currently provides data whereby the geoid map is represented with the unprecedented precision of about 2 cm for spherical harmonics up to degree and order 120, see also [13]. The accuracy of the gravity field is expected to improve when more GRACE data become available from this unique gravity mapping project. The outlook is that GRACE will be able to recover temporal changes in the gravity field in order to detect geophysical signals caused by mass variations as a result of continental hydrology or oceanic processes, for more details see [1].

During the reduction of data from GRACE it will be necessary to apply a number of instrumental and geophysical corrections, of which two are reviewed here. We focus on the quality of the air pressure and the ocean tide corrections which both determine the accuracy of the monthly geoid maps recovered from GRACE. For both cases we simulate geoid errors as a result of the differences between existing ocean tide models enhanced by TOPEX/POSEIDON altimetry and air pressure fields of the ECMWF and NCEP reanalysis data. From the characteristics of both error signals we conclude that significant geoid effects remain. The consequences of these simulated errors in view of the GRACE mission objectives are the central scope of this paper.

A part of the material in this paper was presented at the ISSI workshop in Bern, see also [12].

2 Decade of the geopotentials

GRACE is a low-low satellite to satellite tracking mission launched on March 17, 2002 from Plesetsk Cosmodrome in Northern Russia using the ROCKOT launch vehicle. The principle of GRACE is to observe range variations between two low Earth orbiters to within approximately 1 $\mu m/s$ while both satellites are adjusted by small thrusts about every 2 minutes to maintain a baseline orbit. The accelerometers on both GRACE spacecrafts are intended for mapping the drag experienced by both satellites including those caused by small thrusts. The GRACE mission is the second in a series of three missions that will continue to improve our knowledge of the Earth's gravity field. GRACE was preceeded by CHAMP launched in the summer of 2000. In order to map the gravity field CHAMP contains as primary instruments a spaceborn GPS receiver and an accelerometer similar to that on GRACE, see also [9]. Another future experiment is that of GOCE, see also [2] which is based upon a pair of accelerometers forming a gradiometer in a 270 km orbit. The latter mission is expected to complement GRACE by observing the gravity field out till spherical harmonic degree and order 240.

The expected sensitivity of GRACE and GOCE with respect the spherical harmonic coefficients are shown in figure 1 and 2. In figure 1 we show the cumulative geoid errors of EGM-96 (see [6]), GOCE and GRACE under the assumption that a continuous stream of observation data is collected over a period of 1 year. Specifications with regard to the instrument accuracy and sampling rate etc. can be found in [1] and [2]. From figure 1 it can be seen that the EGM-96 geoid error largely exceeds the projected geoid errors that follow from GOCE and GRACE. In figure 2 we have introduced worst-best case scenarios for both missions. The worst case scenario for GOCE assumes a gradiometer only solution that is not improved by the GPS tracking data information that is contained in our best case. The worst case scenario of GRACE refers to a 30 day solution, the best case refers to a 5 year solution.

For CHAMP there exists an EIGEN-1S / GRIM5 combination solution that was recently computed by [9]. This is a noticable improvement compared to the EGM-96 solution. The error degree variances (not shown in figures 1 and 2) for this gravity solution suggest a cumulative geoid error of 1,5 cm at $l = 20$ which is more than factor 2 better.

A caveat emptor on the projections of the GRACE and GOCE geoid errors and degree rms values shown in figure 1 and 2 is that we have never inverted a system of normal equations built from real observation data. Instead we rely on semi-analytical techniques such as described in [10] whereby the data are assumed on a specified nominal orbit and sampled at a regu-

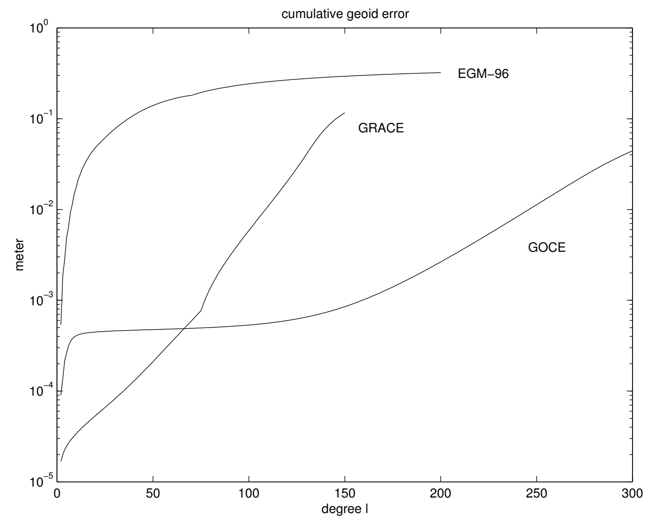

Figure 1: Cumulative geoid errors inferred from the EGM-96 model, worst and best case scenarios for GOCE and GRACE, Units: spherical harmonic degree and meters

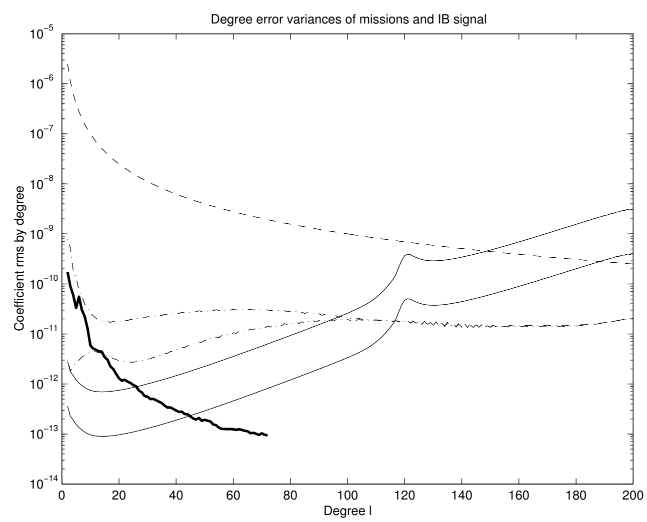

Figure 2: The rms by coefficient by degree for GOCE (dash-dotted line) and GRACE (solid line), mean signal rms according to Kaula's rule of thumb (dashed line) and the air pressure loading signal (thick line). Units: spherical harmonic degree against dimensionless coefficients.

lar interval and an observation noise power density spectrum according to instrument specification. In the real world one will face the problem of observation outages (not polar gaps due to sun synchrous orbit etc) or datasets that are shorter than planned etc.

It is therefor not surprising that the most recent GRACE derived geoid model errors are still a factor 10 larger than the monthly geoid solutions shown in figure 2. In addition the formal error characteristics of either mission should formally be specified by a full covariance matrix or a representation as geoid error grids.

3 Observation of temporal gravity

The observation of temporal changes in the gravity field is one of the exiting new ideas that can hopefully be realized by the GRACE mission. This mission should be able to perform this task thanks to its extreme sensitivity below degree and order 50, see figure 2 and [16]. The term "temporal gravity" should be interpreted as the gravitational effect of mass changes due to geophysical processes. Several candidates are mentioned in [1], the list includes mass changes as a result of ocean tides, atmospheric effects, continental hydrology, ice volume changes, sea level changes unrelated to temperature, post glacial rebound, earthquakes, mantle convection, tectonic processes, and processes in the Earth's core and mantle.

In order to observe the mentioned effects it will be necessary to correct the observed inter-satellite range rates for known geophysical effects which are not in the direct scientific interest of the GRACE project. Such corrections are made with existing models which each come with their own inherent accuracy label. It is expected that GRACE temporal geoid maps are affected by the quality of both corrections. Here we will try to address this question by considering simulated errors of existing ocean tide models and atmospheric pressure models which are two large contributors in the GRACE data reduction scheme. (ie. modelling activities before the monthly geoid maps are provided to the scientific community).

3.1 Ocean tides errors in GRACE geoid maps

In order to compute the geoid effect caused by an ocean tide signal during the GRACE data reduction we consider recent ocean tide models which are enhanced by TOPEX/Poseidon altimetry data, see also [3]. To simulate a geoid model error as a result of still remaining ocean tide model errors we have assumed that the mass layer input function becomes the difference between the GOT99.2 and the FES99 model developed by [7] and [5] respectively. By means of convolution operators that contain a Newtonian and an elastic loading term and that operate on the thin mass layer we obtain the simulated geoid error as a result of GOT99.2 relative to FES99. The amplitude maps of the simulated geoid effect are shown in figure 3 for the tidal constituents M_2 S_2 O_1 and K_1. It can be seen that the simulated geoid error is less than 0.5 mm in the open oceans. In polar regions and on continental shelf areas there are more significant differences that reach the 3 mm level. These geoid errors are caused by the fact that the T/P inclination of 66 degrees limits the altimeter mapping range. Moreover in shallow water the altimeter track spacing is too coarse to map the finer details of the shallow water tides.

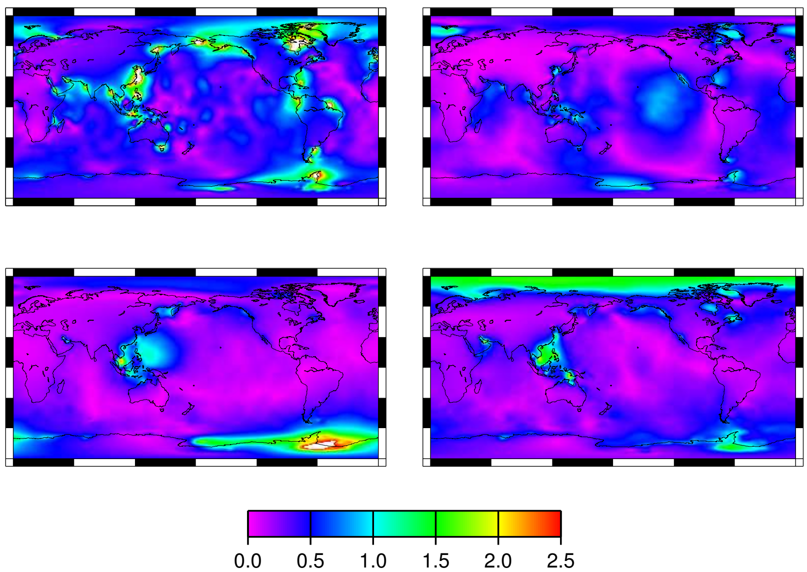

Figure 3: Simulated geoid errors as a result of the difference between the ocean tide models GOT99.2 and FES99, the range of the color scale goes from 0 to 3 mm. Upper left M_2, upper right S_2, lower left O_1, lower right K_1.

Attempts to design methods for assessing the tide model error contamination are discussed by [4] [8] and [11]. The aliasing problem for a gravity mission is far more difficult to comprehend than the way tidal modelling errors map along repeating T/P altimeter ground tracks. According to [8] an important factor is the rate of change of the orbital plane of GRACE compared to the rate of change of the tide generating potential at a specified constituent. The tidal aliasing periods mentioned in [8] are that K_1 maps at 7.48 years while S_2 maps at 161 days. Tidal aliasing justifies further research on the propagation of the simulated tide model errors in the adopted data reduction procedures implemented for GRACE.

3.2 Air pressure errors in GRACE geoid maps

The motivation for studying the self attraction geoid effect that follows from the air pressure signal is provided in figure 2. In this case the thick line is representing the total contribution of the air pressure correction of the NCEP (National Centers for Environmental Prediction) reanalysis data in 1992. Interestingly enough, the magnitude of this correction is up to a factor 100 larger than the best GRACE curve and the natural question arises whether air pressure can be modelled with sufficient accuracy to fully exploit the GRACE sensitivity at lower degrees.

The validity of the atmospheric pressure correction algorithm is addressed in [14] where it is stated that the pointwise accuracy of global models is of the order of 1.0 to 1.5 mbar. They conclude this from a comparison of ECMWF data (European Center for Medium Range Weather Forecasts), NCEP reanalysis data and in-situ air pressure data. In [14] it is also suggested that the accuracy of surface pressure corrections may be improved after spatial and temporal smoothing of the input data. They show examples where the air pressure error is reduced to about 0.3 to 0.5 mbar (in remote deserts) when the average field is computed over a period of a month. The conclusion of [14] is that regional improvement by in-situ air pressure measurements appears to be sufficient to remove the air pressure effect from GRACE data.

In the following we simulate the air pressure model errors by the difference between the ECMWF and the NCEP reanalysis sea level pressure data provided as daily grids in 1992. In figure 4 we show the mean geoid error effect as a result of this model error; in this computation the sea level pressure changes are converted to equivalent water height values over land assuming a vertical air pressure gradient by an exponential decay law and 100% inverse barometric compensation over the oceans. Geoid error grids are then computed on a daily basis and averaged over a period of 12 months. The polar regions beyond 70 degrees latitudes were deliberately left out of this analysis since it is assumed that the discrepancy between the ECMWF and NCEP models is unrealistic, see also [15]. This computation shows that the error is non-uniform and that it is mostly contained in the Himalayas,

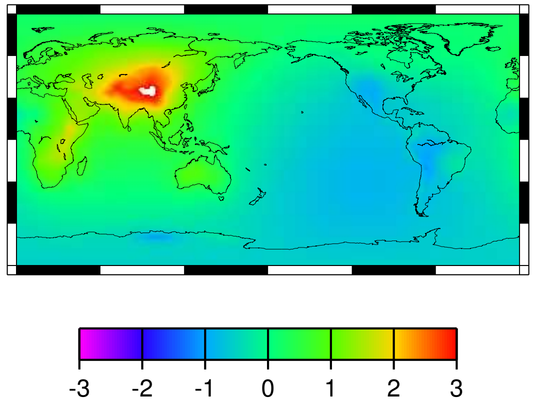

Figure 4: Mean geoid effect as the result of ECMWF vs NCEP pressure differences in the month of January 1992, the color scale runs from -3 to 3 mm.

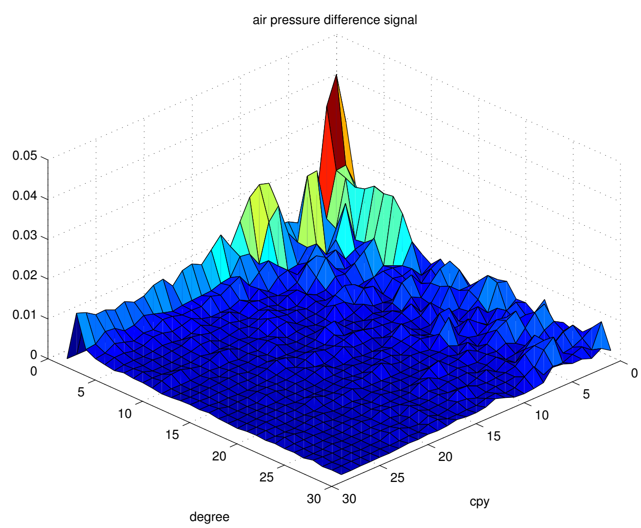

Figure 5: Wavenumber frequency difference spectrum of detrended air pressure in mbar for ECMWF vs NCEP over 1992, the left diagonal axis represent spherical harmonic degrees l, the right diagonal axis frequency in steps of cycles per year (cpy), the vertical axis represents mbar (formally mbar per square root of the spatial frequency and per square root of the temporal frequency).

in Africa and to a lesser extent in Australia. It is for this reason that we expect that air pressure contamination is significant and that it may show up as a systematic bias in a static gravity model.

A wavenumber frequency analysis of the simulated air pressure differences minus the average effect is shown in figure 5. This spectrum represents on one axis the spherical harmonic degree and on the other axis the frequency in cycles per year (cpy). It shows that systematic long wavelength spatial and temporal residuals between both meteorologic models exist. An integration in the wavenumber frequency spectrum learns that the signal contained at frequencies longer than two months (i.e. twice the monthly mapping cycle by GRACE) and over spherical harmonic degrees up to 20 results in an air pressure rms of 0.16 mbar. The magnitude of this modelling error appears to be significant in view of the anticipated accuracy of GRACE which promises a geoid to be mapped to within 0.03 mm below degree and order 20. Furthermore it should be mentioned that air pressure changes will occur within the GRACE mapping cycle. Also these signals will alias (or fold) into the monthly geoid maps. So far integration in the wavenumber frequency spectrum suggests that such effects are far smaller than the above mentioned effects. This analysis does not account for atmospheric tides, see also [8], due to the daily sampling rate of our input maps.

4 Conclusions

In this paper we focus on the problem of the error characteristics of gravity fields from CHAMP, GRACE and GOCE including the EGM-96 solution. The scientific interest in GRACE is in the recovery of gravity signals such as variations in the continental water balance. To accomplish this task reductions should be made for the variations caused by tides and air pressure variations. In order to quantify this problem we discuss the results of simulated errors as a result of tide model differences and air pressure model differences. Our conclusion is that tidal modelling errors occur with a magnitude up to 3 mm where the K_1 constituent is likely to map at a frequency that exceeds the planned 5 year length of the GRACE mission. From the air pressure error simulation we conclude that tides appear to be more significant than the errors introduced by the air pressure correction algorithm. The expected signal error in the simulated air pressure signal is estimated at 0.16 mbar for periods longer than 2 months and for spherical harmonic degrees less than 20. Such pressure errors appear to be significant in view of the anticipated GRACE sensitivity of 0.03 mm in the geoid below degree

20. Both issues justify future research with regard to the implementation of algorithms for separation of signal and noise from monthly GRACE solutions.

Acknowledgements

I thank Pieter Visser, Pascal le Grand, Johannes Bouman, Nico Sneew and Richard Ray for their helpful comments and/or data used in this paper. The ECMWF air pressure grids originate from Meteo France provided to TUD/DEOS through a cooperation with CNES/GRGS, Cathy Smith at NOAA/CDC assisted in getting access to their reanalysis data.

References

[1] Dickey, J.O., Satellite Gravity and the Geosphere, National Research Council Report, Nat. Acad. Washington D.C. 112 pp., 1997.

[2] ESA, Gravity field and steady state ocean circulation mission, ESA SP-1233, pp 217, July 1999.

[3] Fu L.L. and A. Cazenave, Satellite altimetry and Earth Sciences, A handbook of techniques and applications, International Geophysics Series, Vol 69, Academic press, 2001.

[4] Knudsen P. and O. Andersen, Correcting GRACE gravity fields for ocean tide effects, Geophysical Research Letters, Vol. 29, No.8, pp. 19.1 – 19.4, 2002.

[5] F. Lefèvre, F. Lyard, C. Le Provost, E. Schrama, FES99: A global tide finite element solution assimilating tide gauge and altimetric information, Journal of Atmospheric and Oceanic Technology, Vol 19, pp 1345 – 1356, 2002.

[6] Lemoine et al, The development of the joint NASA GSFC and NIMA geopotential model EGM-96 gravity model, NASA/TP–1998–206861, July 1998.

[7] Ray R. A Global Ocean Tidel Model from TOPEX/POSEIDON Altimetry: GOT99.2, NASA TM 1999-209478, 1999.

[8] Ray R., D. Rowlands, G. Egbert, Tidal models in a New Era of Satellite Gravimetry, ISSI workshop, Bern, 2002.

[9] Reigber et al, A High-Quality Global Gravity Field Model from CHAMP GPS Tracking Data and Accelerometry (EIGEN-1S), Geophysical Research Letters, Vol 29, No. 14, 10129/2002GL015064, 2002.

[10] Schrama E., Gravity Field Error Analysis: Applications of Global Positioning System Receivers and Gradiometers on Low Orbiting Platforms, Journal of Geophysical Research, Vol 96 No. B12, pp. 20,041 - 20,051, 1991.

[11] Schrama E, Gravity missions reviewed in the light of the indirect ocean tide potential. proceedings IAG symposia proceedings No 116, pp 131-140, Springer Verlag, 1995.

[12] Schrama E., Error Characteristics Estimated from CHAMP, GRACE and GOCE derived geoids and from Satellite Altimetry Derived Mean Dynamic Topography, ISSI workshop, Bern, 2002.

[13] Tapley B., The GRACE mission: Status and Performance Assessment, Presentation G12B-01 at AGU Fall Meeting, San Francisco, 2002.

[14] Velicogna I, J. Wahr and H. van den Dool, Can surface pressure be used to remove atmospheric contributions from GRACE data with sufficient accuracy to recover hydrological signals? JGR Vol 106, No B8, page 16415, 2001.

[15] Verhagen S., Time variations in the gravity field, the effect of the atmosphere, MSc report, 81 pages, TU Delft Geodesy, 2001.

[16] Wahr J., M. Molenaar, F Bryan, Time variability of the Earth's gravity field: Hydrological and oceanic effects and their possible detection using GRACE, JGR Vol 103, No. B12, pp 30205-30229, 1998.