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IMPACT OF LIMITATIONS IN GEOPHYSICAL BACKGROUND MODELS ON FOLLOW-ON GRAVITY MISSIONS

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Abstract. Purpose of this article is to demonstrate the effect of background geophysical corrections on a follow-on gravity mission. We investigate the quality of two effects, tides and atmospheric pressure variations, which both act as a surface load on the lithosphere. In both cases direct gravitational attraction of the mass variations and the secondary potential caused by the deformation of the lithosphere are sensed by a gravity mission. In order to assess the current situation we have simulated GRACE range-rate errors which are caused by differences in present day tide and atmospheric pressure correction models. Both geophysical correction models are capable of generating range-rate errors up to 10 μm/s and affect the quality of the recovered temporal and static gravity fields. Unlike missions such as TOPEX/Poseidon where tides can be estimated with the altimeter, current gravity missions are only to some degree capable of resolving these (geo)physical limitations. One of the reasons is the use of high inclination low earth orbits without a repeating ground track strategy. The consequence is that we will face a contamination of the gravity solution, both in the static and the time variable part. In the conclusions of this paper we provide suggestions for improving this situation, in particular in view of follow-on gravity missions after GRACE and GOCE, which claim an improved capability of estimating temporal variations in the Earth's gravity field.

1. Introduction

Any gravity mission designed to map the temporal gravity field will inherently face the fact that oceanic tides and atmospheric pressure signals must be compensated for during the set-up of the normal equations containing the gravity parameters. Purpose of this article is to assess the consequence of this assumption, since the background corrections contain errors. In Section 2 it is explained that oceanic processes are not a primary objective of the GRACE mission, during the GRACE data processing all atmospheric pressure variations and oceanic mass variations due to tides are removed so that the continental hydrology signal remains as a primary signal to observe. In Section 3 we provide background information with respect to both background corrections. In Section 4 we will show that the accuracy of background models is insufficient to guarantee a full removal from the gravity solution (regardless whether it is static or temporal). A more rigorous approach is shown in Section 5 where we carry out a full simulation of both errors on the GRACE mission. In Section 6 we present our conclusions and recommendations.

2. The GRACE Mission

GRACE is designed to measure inter-satellite range-rates with an accuracy better than 10 μms^{-1} Hz$^{-1/2}$, for more details on the GRACE system and its ancestors (see Colombo, 1986; Dickey, 1997; Reigber et al., 2002) and the recent article by Tapley et al. (2004). The primary observation of the GRACE system is an integrated Doppler observation in the K band equivalent to that of a GPS carrier phase observation. This is equivalent to a biased range observation. In the near future the geodetic community will hopefully get access to data from another gravity mission, GOCE (cf. ESA, 1999), which is based on a different concept involving a gravity gradiometer. The goal of both missions is to map the Earth's gravity field whereby. GRACE will allow one to map the lower degree and orders of the field up to degree and order 120 while GOCE will be able to extend the resolution of this field to degree and order 250. The accuracy of the geoid obtained by both concepts depends on the length of the observation series that is used to create a gravity solution. GRACE has demonstrated a geoid accurate to about 3 mm which can be provided on a monthly basis according to Tapley et al. (2004). At the moment of writing GOCE is built by Astrium under contract from ESA, and the performance of this mission is assessed with analytical techniques as described in Schrama (1991).

Space born GPS receivers are a necessity for all gravity mapping missions. In the data processing scheme GPS tracking data is required to stabilize the least squares solution in the lower degrees. GPS information has to be weighted in some optimal way together with gradiometric or inter-satellite range-rate measurements. An example of a GPS-only tracking mission is CHAMP; in this case GPS is combined with accelerometry to map non-conservative forces caused by air drag, solar radiation pressure or other effects acting on the skin of the satellite. The CHAMP mission alone yields a significant improvement compared to earlier gravity solutions but is by far not capable of achieving the level attained by GRACE and GOCE where the performance is driven by the KBR instrument and the gradiometer respectively, (See also Reigber et al., 2002). During data reduction, i.e. all steps where normal equations of least squares systems are constructed, one will apply geophysical models to correct for known effects. The observation equations included in the normal matrices will be corrected for gravity, tidal effects, atmospheric pressure loading, measurement delay and offsets, and many other parameters. The differential improvement after inversion is then used to update our knowledge of parameters in the problem.

In the study presented here it is assumed that a follow-on gravity mission will be like the GRACE mission and that its focus will be on estimating temporal variations in the gravity field rather than the static field. For this purpose we will select two geophysical background models of which it is known that they are sufficiently large and where there are strong indications that the signal can not be fully represented by the model. Oceanic tides and atmospheric air pressure loading are suitable candidates for such models. The physics of both processes is well understood and it is likely that both will act as nuisance factors during data reduction. The actual scientific objectives of a follow-on gravity mission are very likely a study of the continental water balance (which is the largest signal) or variations of mass in the ocean interior or mass variations closer to the continental shelf margin, (See also Wahr et al., 1998).

Our starting point in the discussion is that ocean tide and atmospheric pressure models contain errors that propagate as systematic noise in the observations. Both processes have in common that they take place on time scales much shorter than the typical temporal resolution of the expected gravity field solution intervals (a month for GRACE). And for this reason it is expected that aliasing by background model errors will affect the performance of any follow-on gravity mission. If this assumption is true then the design criteria of a follow-on mission may need to be reviewed possibly in order to optimize or potentially benefit from a modified sampling strategy. Although the latter is perhaps desirable for the actual design of a future mission we will only provide suggestions in our conclusions.

3. Geophysical Effects

3.1. Tides

Tides are the result of the gravitational attraction of Sun and Moon on the Earth itself, the relation to gravity missions is extensively described in Schrama (1995) where three tidal phenomena are identified.

Following the discussion in Schrama (1995), there is a direct tidal effect caused by the gravitational working of Moon or Sun directly on the satellite. This is the most straightforward part of the model and the accuracy of the correction depends on gravitational constants of the Earth and external bodies, relative position knowledge of these bodies, including position knowledge of the satellite. The relative accuracy of the direct tide effect is better than 10^{-8} so that direct tide model errors are not relevant for our study since we don't expect that planetary positions or their gravitational constants will be adjusted during data reduction.

In Schrama (1995) it is mentioned that there are two indirect tide effects which are caused by the deformation of the fluid and solid earth as a result of the direct tidal effect. A first indirect tide effect is the solid earth tide deformation model whereby we need to specify Love numbers k_n and h_n for $n = 2$ and 3 describing the elastic solid Earth response to external forcing. If horizontal site displacement must be adjusted then Love number l_n may need to be included in the model. Also for this part we expect no significant show stoppers albeit that a few Love numbers may need adjustment during data reduction of a new gravity mission.

The second indirect-tidal effect is related to ocean tide loading. This effect is far more difficult to model because a hydrodynamical model enters in the discussion. Ocean tide models contain many more parameters to specify the geographic response function which is now local rather than global. Significant progress has been made with the aid of the TOPEX/Poseidon altimetry (see also Schrama and Ray, 1994; Fu and Cazenave, 2001). As a result ocean tides are mapped to within 1.5 cm rms for the largest tidal constituent M_2 while the remaining constituents add less than 1.0 cm noise. The total rms. of the ocean tide signal is better than 3.0 cm rms in the deep oceans (see also Schrama and Ray, 1994). Yet the ocean tide model accuracy deteriorates on continental shelves and at latitudes beyond 66N or 66S because of the inclination of the TOPEX/Poseidon orbit. In Fu and Cazenave (2001) it is shown that M_2 errors in excess of 10 cm rms exist in coastal seas. In addition it is known that energy transfers from main tidal lines to parasitic ones as a result of non-linearity in the hydrodynamic equations in the quadratic bottom friction. Another reason is the presence of advective terms. Advection and bottom friction become relevant near the coast (see also Fu and Cazenave, 2001)

3.2. Atmospheric loading

Another correction that needs to be applied during data reduction deals with the weight of air masses that load on the Earth's surface. In earlier studies such as Velicogna et al. (2001) it is recognized that this effect is sufficiently large to be sensed by all gravity missions. The local weight of an air column is proportional to the terrain level pressure over continental areas. Over oceanic areas it is expected that the effect is compensated because of the inverted barometer (IB) mechanism. An algorithm more realistic than the IB model would include wind-stresses and air pressure forcing in a global hydrodynamic model. This method would modify the standard IB theory which after all assumes that there is an instantaneous -1 cm/mbar response of the sea level to air pressure variations. It is known that the global atmospheric pressure loading effect typically takes place on time scales of about 12 h and beyond and that the IB law becomes effective at time scales longer than three days (see also Mathers and Woodworth, 2001)

For all continental atmospheric loading calculations we have made an approximation for the weight of the air column loading the Earth's surface. The study of Verhagen (2001) has shown that radiosonde data can be approximated with an exponential decay law whereby we need as input the mean sea level pressure and the Earth's topography. For our purpose the largest uncertainty in the air pressure loading calculation comes from the accuracy of meteorologic models, and not so much the vertical distribution of mass in the air column which occurs between terrain level and the top of the atmosphere.

The largest input from the atmospheric loading effect on GRACE is expected over continental areas and not from incomplete compensation over oceanic areas. Meteorologic pressure models must be used during data reduction, well known meteorologic models are the NCAR reanalysis product and the ECMWF product. Both products are the result of a dynamic weather model in which meteorologic data as well as remote sensing data is assimilated. The accuracy by which the models differ is approximately 1.5 mbar, which is equivalent to a water layer of 15 mm (see also Velicogna, 2001). Atmospheric pressure loading errors typically occur on time scales less than the update interval of individual gravity solutions of a follow-on gravity mission. And therefore it is expected that some level of aliasing will take place as a result of the atmospheric pressure loading problem (see also Verhagen, 2001).

4. Degree Variance Signal and Error Spectra

Purpose of this section is to show degree variance spectra for air pressure variations and ocean tide variations and to convolve these input mass fields towards temporal changes in the geoid.

4.1. Tides

To compute the degree variances of the ocean tide fields convoluted towards the geoid under the assumption of a self attraction formulation that includes lithospheric deformation we assume that tides are prescribed by (See also Cartwright, 1993).

$$\zeta = \sum_{v} H^{v} \cos(X^{v} - G^{v}), \tag{1}$$

where the in-phase and quadrature components of each wave with index v are:

$$P^v = H^v \cos(G^v), \tag{2}$$

$$Q^v = H^v \sin(G^v). \tag{3}$$

For each constituent v the maps P^v and Q^v are approximated in spherical harmonics (now dropping index v):

$$P = \sum_{nma} A_{nma} Y_{nma}(\theta, \lambda), \tag{4}$$

$$Q = \sum_{nma} B_{nma} Y_{nma}(\theta, \lambda), \tag{5}$$

where the dimension of P and Q and hence A and B is meters. The corresponding convolution towards geoid heights yields the spherical harmonic coefficients C and D (cf. Schrama, 1997)

$$\begin{Bmatrix} C_{nma} \\ D_{nma} \end{Bmatrix} = g^{-1} \frac{3\mu(\rho_w/\rho_e)}{a_e^2(2n+1)} (1 + k_n') \begin{Bmatrix} A_{nma} \\ B_{nma} \end{Bmatrix}, \tag{6}$$

where g is the gravitational acceleration, μ the gravitational constant, ρ_w and ρ_e are the density of sea water and the mean density of the Earth, k_n' are load Love numbers, and a_e is the mean equatorial radius. The degree variances for the geoid are

$$E_n^2 = \frac{1}{(2n+1)} \sum_{ma} [C_{nma}^2 + D_{nma}^2]. \tag{7}$$

For the simulation of tide model errors we difference the coefficients C and D from two ocean tide models to obtain δC and δD. The simulated tide model error degree variance δE_n^2 is then

$$\delta E_n^2 = \frac{1}{(2n+1)} \sum_{ma} [\delta C_{nma}^2 + \delta D_{nma}^2]. \tag{8}$$

4.2. Atmospheric pressure variatons

In order to compute the average degree variance of a sequence of equivalent water height fields that follow from an IB model including an error assessment of this average we proceed as follows. Water level variations as a result of air pressure variances are simplified by (see Gill, 1982)

$$\zeta = \frac{-1}{gp}(P - P_0), \tag{9}$$

where P_0 is some reference pressure value. Here P_0 is 1013.3 h Pa while g is the gravity acceleration (9.81 m/s^2) and $\rho = 1026$ kg/m^3. P follows from a meteorologic model, for which we have used the ECMWF and the NCAR reanalysis model which come as daily grids during 1992. In this case the values of ζ only exist on land, and the air pressure difference term $(P - P_0)$ is scaled down by an exponential law from the sea level to the terrain level (see Verhagen, 2001). Over sea the ζ values are set to zero and full mass compensation is assumed in agreement with the inverse barometer law.

The convolution of ζ (now provided as a spherical harmonic coefficient set in terms of coefficients A_{nma} at time step i) to geoid heights is similar to that of tides (see Schrama, 1997)

$$C_{nma,i} = g^{-1}\frac{3\mu(\rho_w/\rho_e)}{a_e^2(2n+1)}(1 + k_n')A_{nma,i}, \tag{10}$$

whereby geoid heights are calculated on the Earth's surface. The degree variances for the geoid are now computed as

$$E_{ni}^2 = \frac{1}{(2n+1)}\sum_{ma} C_{nma,i}^2. \tag{11}$$

At this point we define the average degree variance of a sequence of $I_{\max}$ pressure grids as follows

$$E_n = \frac{1}{I_{\max}}\sum_{i=1}^{I_{\max}} E_{ni}. \tag{12}$$

For the simulation of model errors (and then the self attraction and loading representation) we difference the coefficients A in Equation (10) from two models to replace them by δA.

4.3. Results

The computed degree variances for the tide calculation involves the models FES99 and GOT99.2. We are aware of the fact that newer versions of such models will continue to evolve from the tidal community. For the scope of this study we do not expect that the results significally change because the set of observed tidal constants is heavily biased towards the same TOPEX/Poseidon observations. For the meteorologic models we have used ECMWF and NCAR reanalyis daily pressure grids in 1992. Also here we are aware of the fact that 1992 is taken as a reference year and that more modern versions exist. For a simulation study such as this we have no indication that our conclusions are significantly affected. Square roots of degree variances of all relevant data are shown in Figure 1. The conclusion of this calculation is that below degree and order 50 the degree variance errors of both tides and air pressures are larger than the initially advertised performance noise of GRACE, which is about 0.01 mm at the lowest degrees according to the prelaunch estimates (see also Dickey, 1997). The same problem will also play a role with any follow-on gravity mission declicated to the observation of temporal gravity. Tide and atmosphere errors are at the moment of writing a limiting factor up to degree and order 10–15, a region in the gravity field where many geophysical signals leave their signature. Discussion on basis of degree variance spectra:

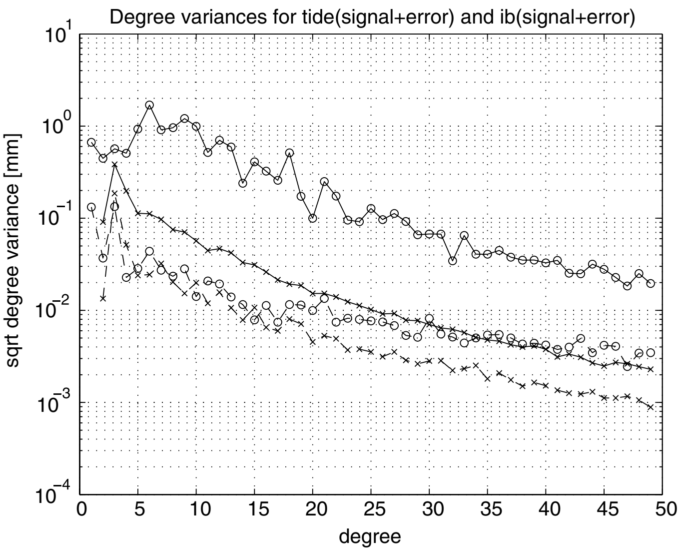

Figure 1. Square root of degree variances of tides and atmospheric pressure loading and simulated errors, horizontal axis degrees, vertical axis: meter geoid change. The solid line with circles represents tide signal and the dashed line with circles are tide errors. The solid lines with crosses represents atmospheric pressure, and the dashed line with crosses follow from the simulated atmospheric error.

- Usually the T/P tide model accuracy specifications are based on deep water comparisons to tide gauges where nowadays a 3 cm rms total error is found. Over continental shelves localized errors still exist and the models are some-times up to 15 cm or higher in error. In polar regions there is no T/P coverage and the realism of the model depends on hydrodynamic models such as FES99. Overall tide model errors are greater than air pressure errors as far as temporal changes in the geoid are concerned (see also Figure 1).
- There exists a coupling mechanism between tides and air pressure in the form of atmospheric tides. This effect is the consequence of the atmosphere being forced as an air mass layer that experiences gravitation forcing in the same way as the oceans. Aliasing of S_1/S_2 oceanic and air tides is relevant for sun-synchronous orbits which are considered for GOCE (but not for CHAMP and GRACE). This effect will result in a pseudo static field mapping along on the ground tracks of GOCE. Errors in S_1 or S_2 models, either oceanic or atmospheric, will therefore alias into a static gravity field error (see also Schrama, 1995).
- For the non-tidal air pressure signal we know that the in-situ point wise now-cast error for calm or normal weather condition is approximately 1–1.5 mbar. This value is typical for both ECMWF and NCAR reanalysis data (Velicogna, 2001) Averaging over space and time helps to drive down this error, but levels better than 0.3 mbar are unlikely at the moment of writing according to Velicogna (2001). Yet meteorologic models have heterogeneous error characteristics and we know that some regions are more poorly represented than others. Antarctica is a typical region where NCEP reanalysis data and ECMWF data significantly differ, ie. the errors will be larger. We ignored these effects in the computation of our degree variances by cutting out all latitudes pole wards of 70N and 70S.
- It was found in separate studies that meteorologic models use their own topography (or orography) which is adapted to the numerical scheme for solving the differential equations. This effect becomes visible as a difference between meteorologic models and is correlated with topographic height.
- More serious is the conclusion that meteorologic pressure grids are provided on a 3 hourly to daily basis while the temporal gravity solution interval is typically 10 days to a month (for GRACE 6 hourly fields are used). This means that errors in the atmospheric pressure variations will alias into the gravity solution.
- Finally it should be remarked that oceanic responses are modelled such that they behave like an inverted barometer, i.e. masses are fully compensated over the ocean and in reality we know that this is not the case, see for instance (Mathers and Woodworth, 2001). The IB model may contain

errors up to 20% for periods up to a day and there exist resonance regions in the Southern hemisphere that cause systematic errors of a few percent. The GRACE team relies on an alternative IB barotropic model forced by air pressure and wind that is used during data reduction.

- From the degree variance spectra it is clear that the noise level of the projected gravity fields (i.e. projected with analytical propagation techniques as discussed in Dickey (1997), ESA (1999) and Schrama (1991)) will be too optimistic. At least one reason is the existence of model noise from two main geophysical corrections which must be applied during data reduction of either GRACE or a follow-on gravity mission. The analytical propagation techniques on which the results in Dickey (1997) and ESA (1999) are biased in this sense and do not include these effects. Hence we conclude that these analytical gravity mission performance curves are probably too optimistic in the lower degrees. This may also partially explain why all GRACE hydrology results as shown in Tapley et al. (2004) avoid the use of degree 2 spherical harmonics and the fact that Gaussian smoothing with a 400 km averaging radius is required to suppress noise in their gravity solutions.

5. GRACE Simulation Experiment

In order to simulate the inter-satellite range-rate signal as a result of geophysical model errors we use the existing GRACE gravity mission trajectory along which suitable potential functions are simulated. The following sections describe the choice of the baseline orbit and the simulation experiment.

5.1. Choice of the gravity mission baseline orbit

The simulations depend on the choice of a reference trajectory for which we have chosen the nominal GRACE trajectory. Initial orbital elements have been selected from the GRACE web site at the university of Texas at Austin, Center of Space Research: $a = 6861124.723$ m, $e = 0.001687$, $I = 89.001°$, $\Omega = 307.659°$, $\omega = 17.338°$ and $f = 307.052°$ on 7/3/2003 14:37:00. For the gravity model we have used the EGM-96 model (see Lemoine et al; 1998), complete to degree and order 70. Furthermore direct astronomical and indirect solid Earth tides have been modelled where JPL's DE200/LE200 model provides planetary and lunar locations; in addition relativistic effects are also taken into account while IERS bulletin B values are used for the definition of pole positions.

Although in reality the GRACE satellites will go through various orbit regimes this simulation relies on a baseline trajectory which gives a reasonable track coverage in about 9 days. In fact, the simulated ground tracks repeat within 1 degree longitude variation in the ascending node every 8.9747 days when the GRACE system completes 137 orbits. To simplify the discussion it is assumed that this ground track pattern is repeated every 137 orbital periods. The obtained sampling characteristics are used in the tidal aliasing experiment.

5.2. Simulation model for tides

In this section we will discuss a quick diagnostic model to explain inter-satellite variations on the GRACE system as a result of geophysical model noise. In all computations we will assume that both systems are separated by about 30 s so that the inter-satellite separation distance is about 230 km. To simulate this inter-satellite range-rate effect we assume for simplicity: (1) the total energy being the sum of potential and kinetic energy is conserved for GRACE 1 and 2, i.e. the non-conservative forces acting on GRACE 1 and 2 are ignored,(2) both GRACE satellites follow the same trajectory and are only separated in time,(3) the along track velocity component is differenced between both satellites to simulate inter-satellite range-rate variations,(4) both satellites move with an average velocity v_0, (5) there are no coupling terms to earth rotation. Under these assumptions the inter-satellite velocity variations between GRACE 1 and 2 are equal to the difference of the simulated error in the potential ΔU's of each satellite

$$\Delta v(t_1, t_2) = v_0^{-1}(\Delta U(t_2) - \Delta U(t_1)), \tag{13}$$

where v_0 is local velocity at the reference orbit. For the ocean tide model we have the following relation:

$$U(r, \phi, \lambda, t) = \sum_i A_i(r, \phi, \lambda) f_i \cos(\chi_i + u_i) + B_i(r, \phi, \lambda) f_i \sin(\chi_i + u_i), \tag{14}$$

where i is a running index over tidal waves in the model, χ_i f_i and u_i are astronomically defined quantities related to the definition of these waves (see Cartwright, 1993), while A_i and B_i denote in-phase and quadrature terms which are defined as follows

$$A_i(r, \phi, \lambda) = \sum_{nma} \frac{3\mu(\rho_w/\rho_e)}{a_e^2(2n+1)}(1 + k_n')\left(\frac{a_e}{r}\right)^{n+1} A_{nma,i} Y_{nma}(\phi, \lambda), \tag{15}$$

$$B_i(r, \phi, \lambda) = \sum_{nma} \frac{3\mu(\rho_w/\rho_e)}{a_e^2(2n+1)}(1 + k_n')\left(\frac{a_e}{r}\right)^{n+1} B_{nma,i} Y_{nma}(\phi, \lambda). \tag{16}$$

In these expressions μ is the Earth's gravitational constant, ρ_w is the mean density of sea water, ρ_e is the mean density of rock, a_e is the Earth's equatorial radius, k'_n are elastic load Love numbers, Y_{nma} are normalized spherical harmonic functions, index a selects the combination cos $m\lambda\bar{P}_{nm}(\sin\phi)$ or sin $m\lambda\bar{P}_{nm}(\sin\phi)$ with $\bar{P}_{nm}$ representing normalized associated Legendre functions (see also Ray et al., 2003). The terms $A_{nma,i}$ and $B_{nma,i}$ follow directly from a spherical harmonic analysis of ocean tide model maps. To simulate tide model errors we have used the FES99 and the GOT99.2 models (see Ray et al., 1999; Lefèvre, 2002) to construct the corresponding spherical harmonic coefficients. It obtain ΔU that represents tide model errors we differenced U(FES99) and U(GOT99.2).

5.3. Simulation results

Equation (13) in combination with the definition of the ocean tide error potential gives a series of Δv values along the baseline orbit. In fact, Δv is now easily projected ahead in time because it is a harmonic function; whereby we assume a repeat cycle length of 8.9747 days. For this purpose our simulation program works in two steps. We start by computing the harmonic coefficients for all selected tidal waves (only 8 are used) and we implement these harmonic coefficients in a time series generation algorithm provided by R.D. Ray.

A first result is to find extreme excursions over each $1° \times 1°$ block over the sphere; this is shown in Figure 2. From this Figure we observe that most parts of the globe experience velocity errors less than 1 μm/s. In quiet coastal zones we see that the velocity variations are of the order of 1–2 μm/s and in certain noisy regions we see very localized errors of 10 μm/s or more. Such phenomena happen over certain continental shelves where it is known that the global ocean tide models are inaccurate. A moderate smearing of this phenomenon takes place because of the upward continuation from the Earth's surface to the potential function at satellite height. Similar large excursions are observed at latitudes beyond 66N and 66S which are in our opinion due to the quality of tide models beyond the TOPEX/Poseidon inclination latitude.

5.4. Strategy for error suppression

It is evident from the result in Figure 2 that GRACE velocity data can easily contain errors caused by tidal modelling that exceed the measurement accuracy. The question is now whether one can accept such errors or whether additional nuisance parameters need to be defined. The answer to this

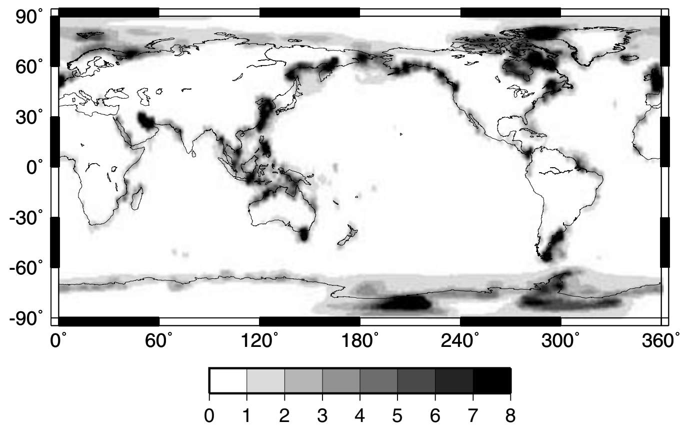

Figure 2. Extreme velocity variation observed in the simulation set where velocity errors are projected using the energy conservation approach from simulated ocean tide model errors. Scale: μm/s.

question is probably that it is desirable to estimate suitable nuisance parameters, i.e. it is realistic to assume that future activities will concentrate on the estimation of unmodelled tidal effects. But we will also warn that modelling tide errors in GRACE is far from trivial due to unfavorable sampling of short periodic tides compared to the, relative long repeat cycle of GRACE. (In reality GRACE doesn't have a repeat cycle, the longitudes of the nodes of the ascending ground tracks coincide to within 1° in a 8.9747 day mapping cycle)

Figure 3 shows for instance the history of all collected velocity residuals in a radius of 1° around bin 65N 80W, which is in the Hudson bay. If the Δv signal were favorably mapped then we would easily recognize periodic features in this series, instead we get to see that the velocity errors appear in local clusters that seem to alternate every 9 days in sign. In fact, in order to be able to recognize an aliased beat signal due to unmodelled tides, it is necessary to extend this experiment over many more repeat cycles.

More evidence for this observation is provided in Figure 4 where an attempt is made to recover by means of a least squares filter tidal amplitudes and phases for each $1° \times 1°$ bin where 200 repeat cycles are used. After correcting the GRACE data for all solved for corrections per bin we are able to present the velocity excursions in the same way as in Figure 2. But even after this filtering step it is obvious that we are not able to suppress all tidal errors, i.e. significant residuals remain visible in Figure 4 which is a likely indicator that it will be difficult to undo the GRACE data set from tidal modelling errors. Similar results are presented in Knudsen and Andersen (2002) and Ray et al. (2003).

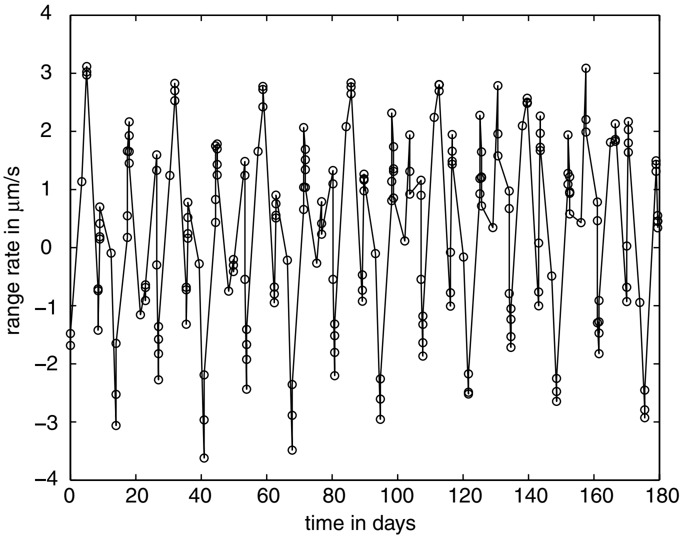

Figure 3. History of velocity variations observed over the Hudson bay 65N 80W, along the x-axis the time is shown in days, along the y-axis the inter-satellite velocity variations are shown in μm/s.

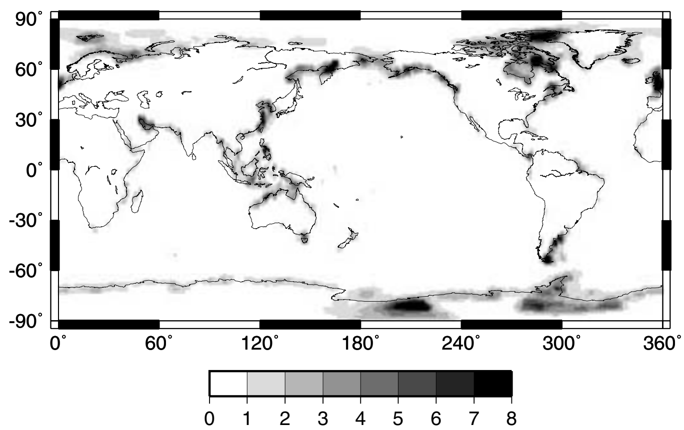

Figure 4. Extreme velocity variations observed in the simulation set after we took care of removing a 16 parameter function for each $1° \times 1°$ bin. Scale: μm/s.

5.5. How realistic is the energy conservation approach

As was pointed out, the here described energy conservation approach with statistics displayed in Figure 2 is an approximation. A better method is to simulate range-rate errors by means of the GEODYN orbit computation program whereby a 10 day trajectory was integrated once using the GOT992 ocean tide model. During data reduction, whereby initial state vectors of both GRACE's are solved for, it is assumed that the inter-satellite range-rate and position) knowledge of the two orbiters are observations. In this second (iterative) orbit adjustment process the FES99 model is used as a forcing model. No effort was undertaken to model skin accelerations on both GRACE satellites during this run. The inter-satellite range- rate observations are binned in $1^\circ \times 1^\circ$ blocks in the same manner as Figure 2.

In Figure 5 we observe an abundance of low frequency variations in the Δv's which don't seem to correspond to the earlier results obtained with the energy conservation approach where we found localized velocity excursions around geographic regions where coastal tide model errors occur.

An obvious explanation of this phenomenon follows from the orbit dynamics experienced by two satellites that translates itself in an inter-satellite range-rate at once and twice per orbital period. A GEODYN simulation will also reveal that the leading GRACE satellite experiences velocities and accelerations along a slightly different flight path compared to the trailing GRACE satellite. Furthermore in this simulation the velocity vector of each satellite doesn't project directly on the inter-satellite range. Our simplified energy conservation approach does not include all complexities which are part of the GEODYN simulation and ignores the long wavelength effect visible in Figure 5.

In an attempt to suppress long wavelength contamination we implemented a high pass filter with a cut-off frequency at 3000 s. After implementation of this filter the Δv's show a behavior as in Figure 6. These results show similar characteristics as obtained with our energy conservation approach, i.e. the Δv effect is increased over regions where there are large tidal modelling errors. Nevertheless there remain some remarkable differences which we blame for

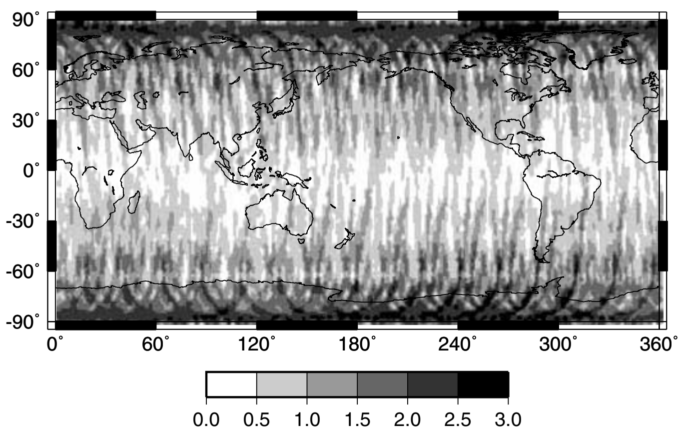

Figure 5. Extreme velocity variations observed in the GEODYN simulation set. Scale: μm/s.

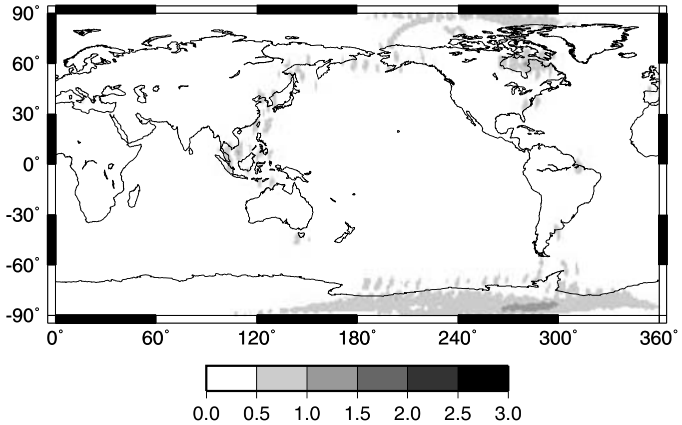

Figure 6. Extreme velocity variations observed in the GEODYN simulation set after application of a 3000 s high pass filter.

the moment to the realism put into the GEODYN simulation where the simulation runs over 10 days and ocean tide spherical harmonic coefficients to represent FES99 and GOT992 are truncated at degree and order 35. These limitations suppress localized excursions of the tides in shallow seas and avoid that the ocean tide signal is mapped over more cycles.

5.6. Simulation model for air pressure variations

In order to study air pressure variations it is necessary that we evaluate the effect of air pressure changes and its direct consequence on a follow-on gravity mission. Here we remind that the realism of such a study depends on the specification of meteorologic model errors which are on the one hand difficult to quantify largely because similar techniques and observation data are used by different meteorologic centers. On the other hand we know that there are geographical regions such as the Antarctic where both pressure fields are substantially different and where one or both models have significant limitations (see also Verhagen, 2001). Estimates for meteorologic pressure errors can be found in Velicogna (2001), and a more complete simulation of the effect on GRACE including a full formal assessment of such errors in the recovery of science signals from GRACE such as discussed by Wahr et al. (1998) does in our opinion not yet exist. The approach used here is to evaluate the difference between the NCAR reanalysis surface pressure models and the ECMWF surface pressure model whereby the atmospheric loading is contained in continental areas and where an exponential decay law, for detail (see Velicogna, 2001) is used to convert sea level pressures into terrain level pressures. Mass variations as a result of the simulated air pressure differences are then converted into equivalent water height. It is the gravitational effect of this layer and the application of relations similar to Equations (15) and (16) that yield a potential ΔU to be substituted in Equation (13).

Figure 7 shows extreme velocity variations observed over one by one degree bins on the globe as they are encountered in a GRACE simulation set with a length of 1 year. From this Figure we conclude that the differences between the models reach 3 μm/s; such errors will be significant for GRACE or any follow on gravity mission. Moreover we observe that the Δv error pattern is geographically constrained to Asia, North America, and the Antarctic. In our calculations we ignored meteorologic pressure difference at latitudes beyond 70N and 70S due to unrealistically large meteorologic modelling errors as discussed in Verhagen (2001).

Any effort to reduce air pressure errors will require to design filters that are even more complicated than to reduce periodic modelling errors such as for tides. The design of such filters could exploit geographical or temporal properties of the signal. Geographical interpretation: Evidently, Figure 7 shows that meteorologic errors are not only constrained to the coastal zones as is the case with ocean tide errors, but rather that the error appears to be correlated to land topography. Furthermore it is evident that variations in the tropics are less than those at higher latitudes. Temporal interpretation: Air pressure variations and their errors do contain daily and seasonal signals but lack for a significant part astronomic periodicity. At best averaging procedures will therefore help to suppress the errors (see also Velicogna et al., 2001).

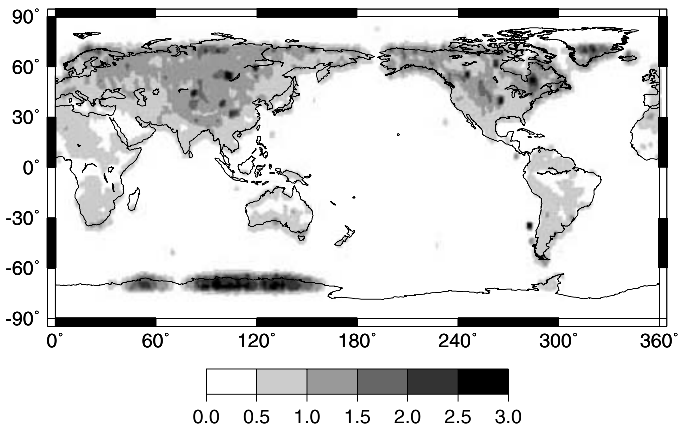

Figure 7. Extreme velocity variations observed in the simulation set as a result of the air pressure error simulated as the difference between ECMWF and NCAR reanalysis data. Scale: μm/s.

6. Conclusions and Recommendations

This article started with the scientific rationale of the GRACE mission, and the remark that certain geophysical corrections may pose a limitation for the interpretation of GRACE observation data. This conclusion follows directly from the degree variance spectra of signal and noise (see Figure 1) when they are overlaid on the gravity mission performance spectra such as shown in Dickey (1997) and ESA (1999). Both studies did not account for aliasing effects as a result of geophysical model errors.

During the GRACE data reduction a self attraction potential for air pressure and ocean tides will be computed during the procedure, ie. the gradients of Equation (14) or equivalent will be used in the orbit computation scheme. Purpose of this study is to focus on the consequences of modelling errors in such potentials on the inter-satellite range-rate variation between both GRACE satellites. Our study is diagnostic and merely intends to identify and characterize the nature of the inter-satellite range-rate errors. Furthermore we hope to draw conclusions from this study in order to assess the consequences for any possible follow-on gravity missions.

6.1. Conclusion from the GRACE simulation experiment

For tides we observe that velocity errors of the order of 1–10 μm/s occur which are caused by model differences in continental shelf areas and polar areas. One reason is the spatial resolution of the T/P altimeter data that was used in the construction of GOT99.2 and FES99 and the tendency of tidal surface waves to spatially narrow which depends on coastal geometry and bathymetry. The surface propagation speed of a tidal wave is equivalent to $\sqrt{gH}$, and for seas or channels with a depth H less than 5 m the depth integrated velocity times tidal period becomes less than the inter-track separation distance between two TOPEX/Poseidon ground tracks at the equator, i.e. there may be surface details in the tides which are too small to be observed by the altimeter. Another reason for tides to differ in these regions is that the models only contain astronomically defined frequencies while they miss overtones or mixed frequencies as would be the case when realistic dissipations due to bottom friction and advection were part of a dynamic tide model.

The simulation of air pressure errors and the upward continuation to a potential at satellite height was performed with the aid to ECMWF and NCAR reanalysis data. In this approach we have used the energy conservation approach and have simulated this effect over a 1 year period. For this effect we observe that the Δv error pattern leads to excursions of approximately 3 μm/s and that the error pattern is geographically constrained to

Asia, North America, and the Antarctic. In addition we see that there is a tendency for correlation of such errors with the local topography. No further attempts have been made to reduce this type of error with the aid of specifically designed filters for this problem.

6.2. The need for mitigation strategies

So far we conclude that tide errors for the main constituents could be estimated provided that gravity field mapping missions are designed such that the corresponding frequencies do not alias to infinite periods. Atmospheric tides like S_1 and S_2 are capable of adding a permanent contribution to the static gravity field. An example of a simulated tide error can be found in Schrama (2003), is shown for the S_2 tide on page 188, it is typical for a static contribution to the gravity field. To mitigate tide model errors it is necessary to optimize the baseline orbits for follow-on gravity missions. Another option is to include suitable nuisance parameters in data reduction scheme.

We can expect that tide and atmospheric pressure models will probably improve in the next decade. For atmospheric models we will probably see that GPS limb sounding could help to independently and globally map the-atmosphere and its density variances.

Finally we want to remark that scientific disciplines may develop their own feature extraction techniques to estimate their signals. Hydrology studies could focus on optimized anti-leakage techniques that drive the errors down outside selected river basins, moreover they could benefit from the presence of annual periodicity in the hydrologic cycle.

From the results so far shown by the GRACE science team we can expect that the annual hydrology signal in the geoid is larger than the geoid error to expect from this study. A propagation of tide model difference between FES99 and GOT99.2 results in geoid features no larger than about 5 mm. In Tapley et al. (2004) and during presentations of the GRACE science team at the EGU in Nice in 2004 it was demonstrated that the hydrology signals sensed by GRACE results in geoid signal of approximately 10 mm with a clear annual period. Spatial averaging to suppress trackiness in the GRACE geoid solutions is required to obtain the hydrologic signal (see Tapley et al., 2004; Wahr, 2004).

6.3. Future work

From the GRACE simulation we conclude that the energy conservation approach and the GEODYN approach resulted in different answers which are probably due to the realism put in the first approach. We intend to increase the level of realism that is put in our current GEODYN simulation, essentially by increasing the spherical harmonic expansions of the used ocean tide field and by increasing the length of the simulation data set. Similar plans need to be worked out for the air pressure error simulation where so far we have only relied on the energy conservation approach.

The identified error patterns of both geophysical effects are however significant and large enough to affect temporal solutions of the gravity field by GRACE, especially when one would attempt to recognize smaller signals. The consequences of geophysical background model errors and their effect on a gravity inversion is however not part of this study but is in progress (Visser and Schrama, 2004).

Another recommendation is to investigate alternative strategies that exploit the synergy of different gravity missions possibly in combination with auxiliary measurements.

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