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Temporal gravity field variations from oceanic, atmospheric and inner core mass redistributions and their sensitivity to new gravity missions CHAMP and GRACE

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Abstract. Temporal gravity field variations are caused by mass redistributions in the atmosphere, on the Earth's surface and in the Earth's interior. With the upcoming new gravity missions CHAMP and GRACE, for the first time such variations can be measured from space on a global scale. To estimate the time variable gravity signals and their sensitivity to the new missions, simulation studies for specific gravity variation sources in all three areas are performed. Starting from a long series of monthly mean atmospheric air pressure data from 1900 to 1988, monthly atmospheric density variations with respect to the long-term mean are computed and transformed into monthly gravity coefficients. A similar approach was used to estimate monthly gravity field coefficients from oceanic mass redistributions. For an 8-year period, monthly spherical harmonic series up to degree and order 6 from ocean bottom pressure fields, derived from the POCM ocean circulation model, are estimated. Another method for estimating the impact of ocean mass redistributions on the gravity field is based on three-year monthly residual sea-surface models from altimetry, which are corrected for the thermal water expansion. Attraction of these residual water masses is transformed into monthly gravity field coefficients up to degree and order 100. Finally, gravity changes caused by the precession of the inner with respect to the outer core and their density differences are predicted for a long time series from 1900 to 1991. Half-yearly gravity coefficients are estimated up to degree 2. Time series for all gravity field coefficients from these different sources are then analyzed to detect their amplitudes and phase lags. All calculated gravity signals are compared to the expected sensitivity of the CHAMP and GRACE missions.

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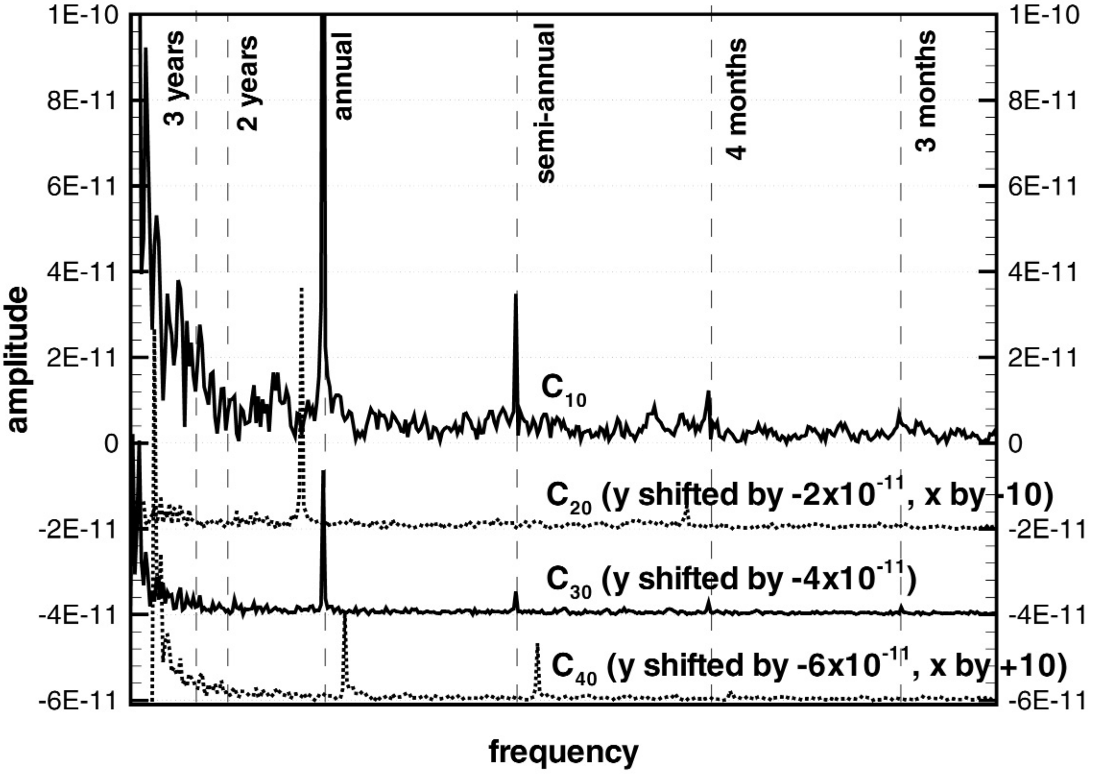

Fig. 1 - Amplitude spectra for gravity zonal harmonics from air pressure data.

1. Introduction

Besides the Earth's magnetic field and climate research, the main objective of the upcoming small-satellite missions CHAMP (Challenging Mini-Satellite Payload for Geophysical Research and Application) (Reigber et al., 1997) and GRACE (Gravity Recovery and Climate Experiment) (Tapley, 1997) is the high-precision global gravity field determination. Both mission concepts use the satellites in a low orbit as proof masses with inter-satellite measurements to the GPS satellites (in case of CHAMP) or inter-satellite measurements between two LEO-satellites (in the case of GRACE). With a long-mission duration of 5 years each, and thanks to the continuous tracking information and the on-board accelerometers to measure the non-gravitational forces of both satellites, a homogeneous sequence of gravity field models will be available, with accuracy improvements of one order of magnitude and more with respect to current models. By analyzing the gravity field sequence (e.g. monthly solutions), an overall signal of mass variations from a variety of sources can be determined. The separation of this signal into contributions from individual sources will be one of the future challenges in gravity field research. This investigation quantifies gravity variations from three individual mass redistribution sources and determines the

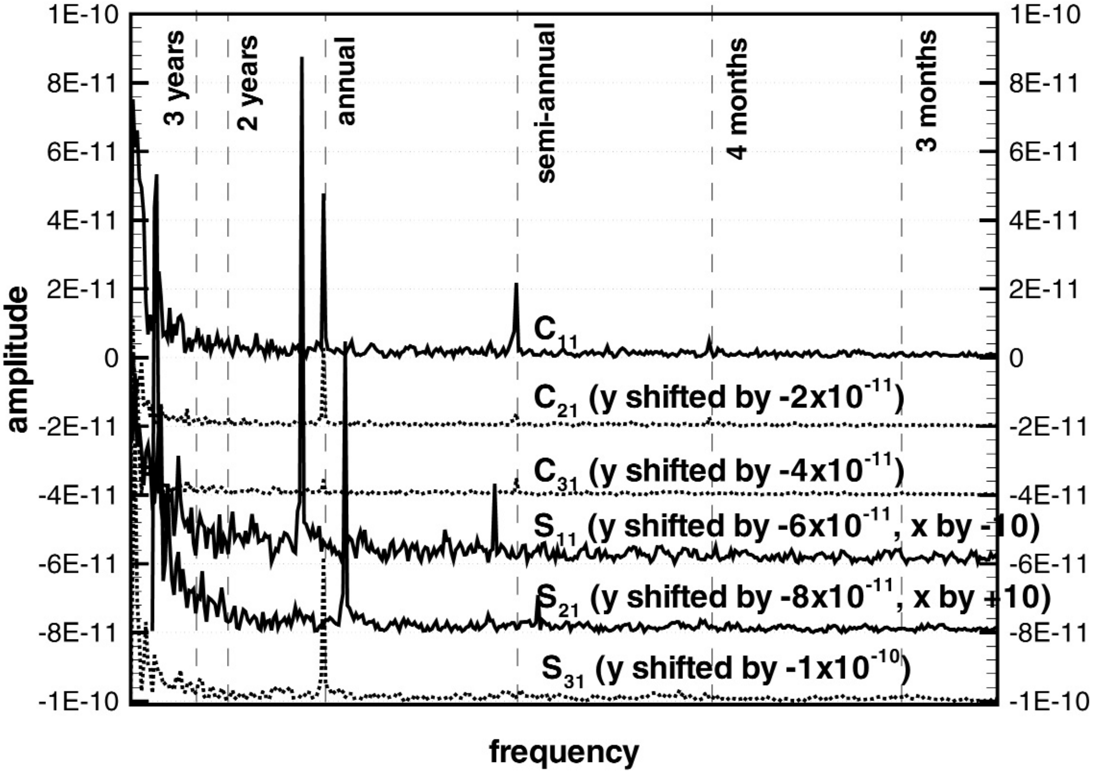

Fig. 2 - Amplitude spectra for order 1 gravity harmonics from air pressure data.

expected amplitudes and frequencies by analyzing data from different sources. Comparing these individual signals with the expected performances for both missions (Bettadpur et al., 1998) the sensitivity of each signal to CHAMP and GRACE can be determined.

2. Atmospheric mass redistributions

Atmospheric circulation is expected to cause mass redistributions in the atmosphere; a source of gravity field variations. These mass redistributions are related to the temporally and locally changing air pressure. Monthly mean values of air pressure data, published by Vose et al. (1992) ,were used to evaluate Stokes' coefficients for the period 1900 -1989. The Earth's surface was divided into 32 × 64 compartments. For each compartment a mean pressure value was calculated with the data provided by the meteorologic observatories of each relevant compartment. Air pressure data from a theoretical climate model were introduced into compartments containing no-pressure observations. From these data the Stokes' coefficients were estimated taking into account the inverted barometer principle. This principle can determine the locally independent

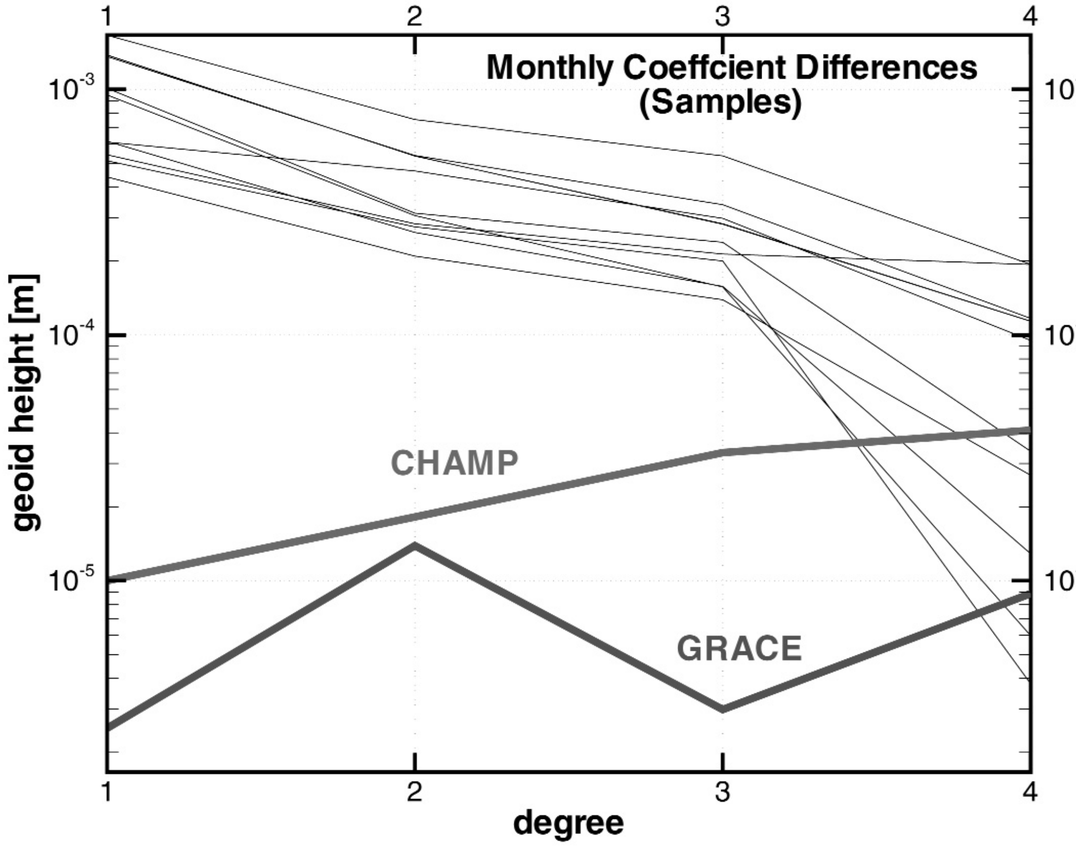

Fig. 3 - Square root of degree variances in geoid hights from coefficient differences of monthly separated models compared with expected gravity mission errors.

load variations at sea through air pressure data on the continents, taking into consideration the conservation of mass. Since in the early years of this century, the air pressure observations were not well distributed on the Earth's surface, our estimates, for one year, of the variations of Stokes' coefficients, were compared with the results of modern estimations, so that our calculations could be checked. It was found that both estimations are sufficiently in agreement. The properties of the variations of Stokes' coefficients were studied by computing their amplitude spectra. From these it followed that the annual periods are dominating. For the zonal harmonics, up to the fourth degree, the amplitudes of the annual periods amount to 10^{-10} (Fig. 1). The same applies for the second degree tesseral harmonics (Fig. 2). Besides the annual periods, a number of periods are indicated which could be identified as climate cycles. The amplitudes of these cycles are partly in the same order of magnitude as those of the annual terms.

Comparing the amplitudes of the periodic terms of the temporal variable of Stokes' coefficients, it is seen that the amplitudes of the annual periods decrease with the increasing degree of spherical harmonics, which shows that these periods are caused by a mass redistribution between the northern and southern hemispheres of the Earth. This global property

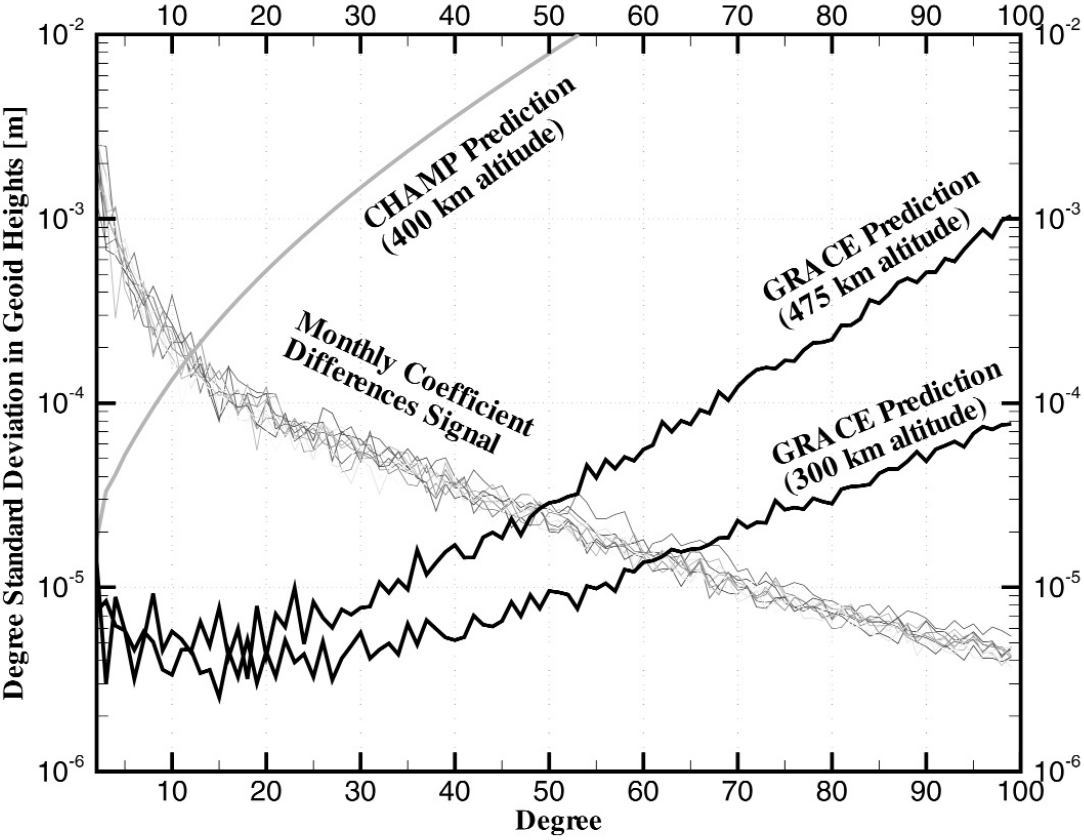

Fig. 4 - Monthly altimetric oceanic signal versus mission sensitivity.

of the annual terms is not so evident for climatic cycles, however, their decreasing amplitudes with the increasing degree of tesseral and sectorial harmonic shows that these cycles are also related to global processes. This discussion shows that another source for proxi data of global change is obtained with an improved accuracy of global gravity field determinations in the future. By comparing the gravity variation signal coming from atmospheric mass redistributions with the predicted mission performances, it can be seen that the signal up to degree 3 is, by a factor of 10 and more, larger than the geoid height errors (Fig. 3) for CHAMP and GRACE. For degree 4 a rapid decrease of the signal is visible. The reason for this is, because only the zonal coefficient for degree 4 was estimated and because the degree variance is computed only by this coefficient. If all degree 4 coefficients had been estimated, a much larger signal would have been detected. Summarizing, it became clear that to determine the full sensitivity of the new missions to atmospheric mass redistributions, gravity coefficients to a much higher degree have to be estimated from such data sources.

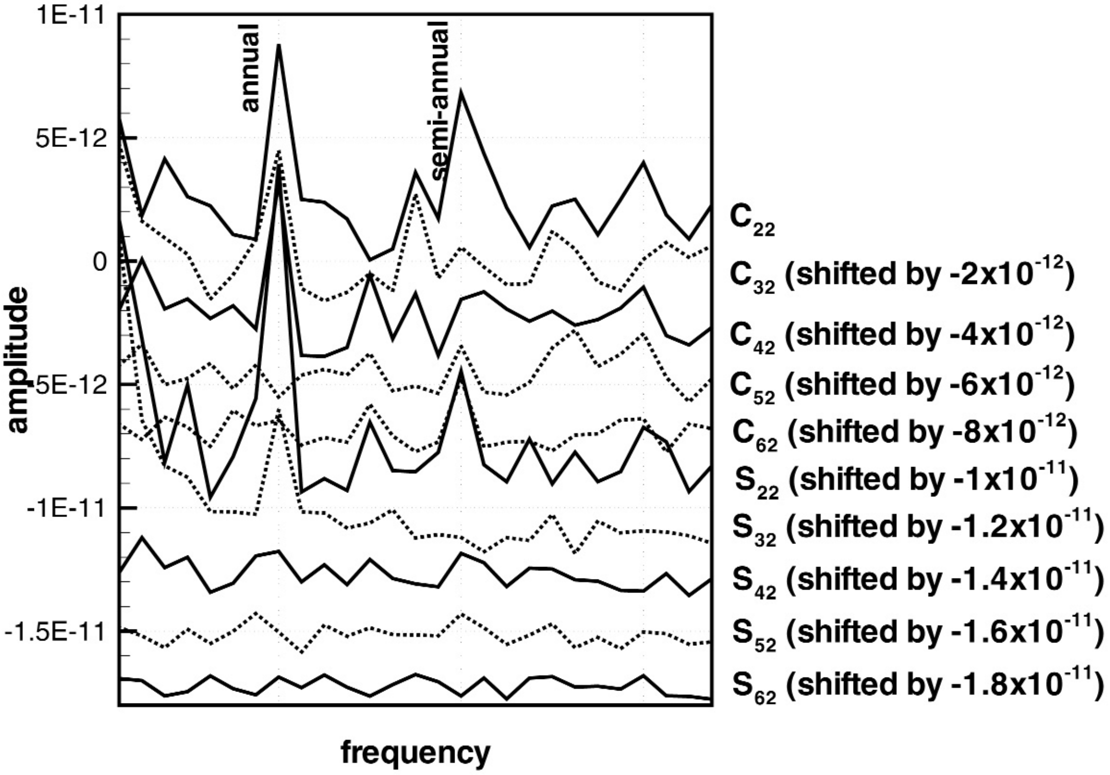

Fig. 5 - Amplitude spectra POCM gravity coefficients of order 2.

3. Oceanic mass redistribution

Water mass redistributions can be independently estimated from satellite altimetry and ocean circulation models. Estimates from both data types were calculated and finally compared to each other. From reprocessed ERS-1 altimeter data, monthly sea-surface height models for the period April 1992 to March 1995 were computed (Anzenhofer et al., 1998). Residual sea-surface heights with respect to the three year mean, together with residual sea-surface temperatures, which were calculated from the monthly U.S. National Meteorological Center (NMC) temperature fields, were used to estimate the thermal expansion component in the residual sea heights. To compute the thermal expansion, monthly correlations between both data sets were performed after an additional data editing and smoothing. The mean of these monthly gradient fields was finally multiplied with the residual temperature fields to remove the thermal expansion component from each monthly residual sea-surface height field. Assuming that the remaining signal is exclusively from oceanic water mass redistributions, the residual attraction, in terms of gravity, is calculated from the water volumes. For this, a standard ocean water density of 1028 kg/m^3 was used. From each monthly residual gravity signal a spherical harmonic series up to

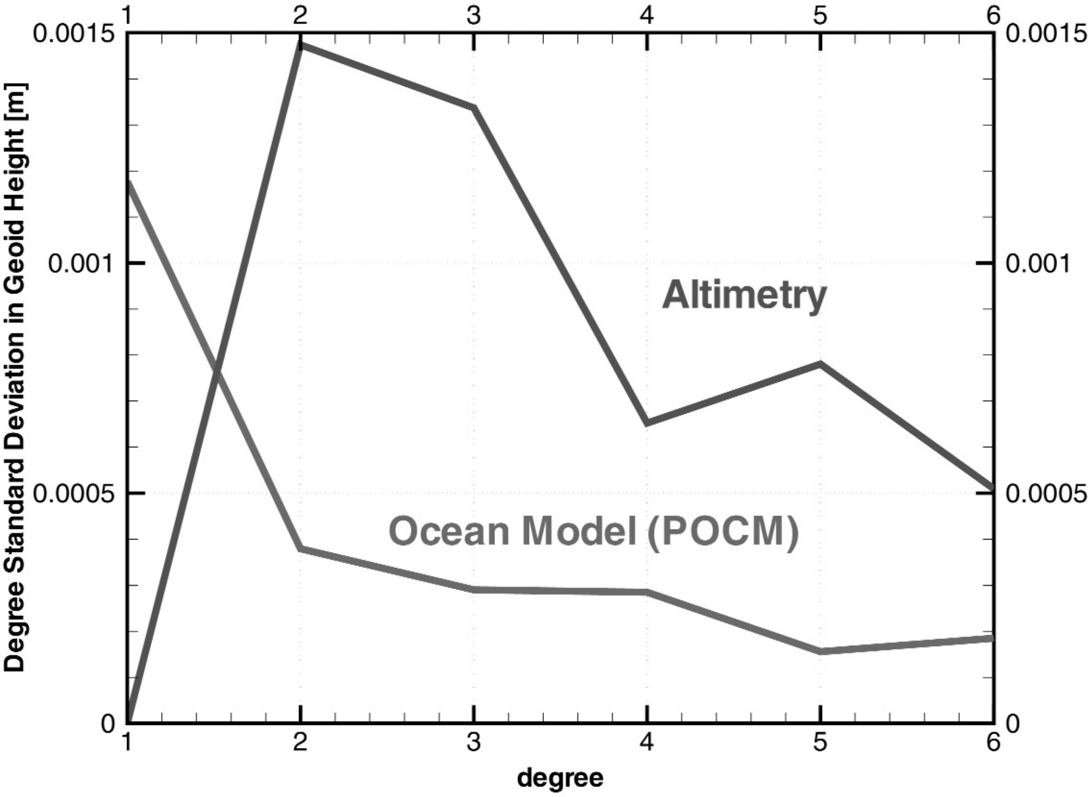

Fig. 6 - Ocean mass distribution signals from POCM and altimetry.

degree and order 100 was computed by a block-diagonal least-squares approach (Colombo, 1981). Each series represents a residual gravity field with respect to the three year mean. By analyzing the sequence of these residual gravity fields, in terms of monthly coefficient differences, the impact of oceanic mass redistribution from month to month onto the gravity coefficients can be determined. Finally, by analyzing the signal degree variances of the monthly coefficient differences together with the error spectra of the new gravity missions, and by performing a spectral analysis of individual coefficient time series, the sensitivity of the new missions and the major frequencies of the signal can be determined. Fig. 4 shows the square root of monthly coefficient difference degree variances of the oceanic signal and the error spectra for CHAMP and GRACE in terms of geoid heights. We can expect a signal up to degree 12 from oceanic water mass redistributions in CHAMP gravity field solutions and up to degree 50 or 60 (depending on the satellite altitude) in GRACE gravity field models. From the spectral analysis of the coefficient time series it was found, that the largest amplitudes are from annual signals and that slightly increased amplitudes with respect to the noise level can be identified for semi-annual signals. Other frequencies are generally on the same amplitude level.

As a second source, gravity coefficient time series derived from ocean bottom pressure fields computed from the Parallel Ocean and Climate Model (POCM) (Semtner et al., 1992) were used.

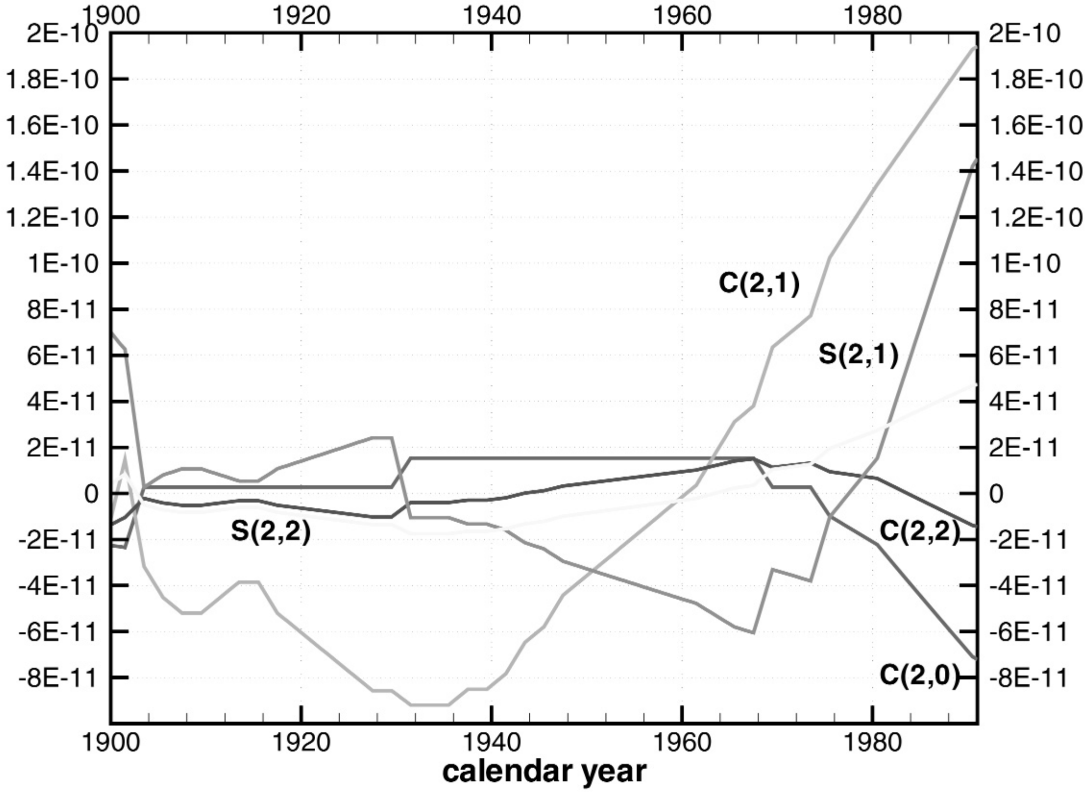

Fig. 7 - Predicted temporal variations of the geopotential due to precession of the ellipsoidal and oblique inner core in terms of spherical harmonic coefficients of degree 2 (plotted with respect to their mean value).

The 1×1 degree gridded bottom pressure fields were derived from all 20 levels of ocean temperature and salinity for an 8-year period (1988-1995) with a resolution of 6 days. Gravity coefficients from these fields up to degree and order 6 were inverted by Tom Johnson from the Center for Space Research at the University of Texas in Austin and further analyzed by us. Fig. 5 shows, as sample, the coefficient amplitude spectra of the coefficients of order 2. The annual and semi-annual peaks of the altimetry approach can be identified. In addition, slightly increased amplitudes with respect to the noise level can also be seen for some higher frequencies, which cannot be addressed by specific seasonal phenomena.

Comparing signals from the altimetry and the POCM approach it can be seen (by considering the degree variances (Fig. 6)), that for the low-degree harmonics the ocean model approach provides smaller signals than the altimetry derived coefficients. The reason for this difference has to be attributed to both approaches. On the one hand there are indications that the POCM is underestimating the amplitudes of ocean variability by a factor of 2 to 4 (Stammer et al., 1996),

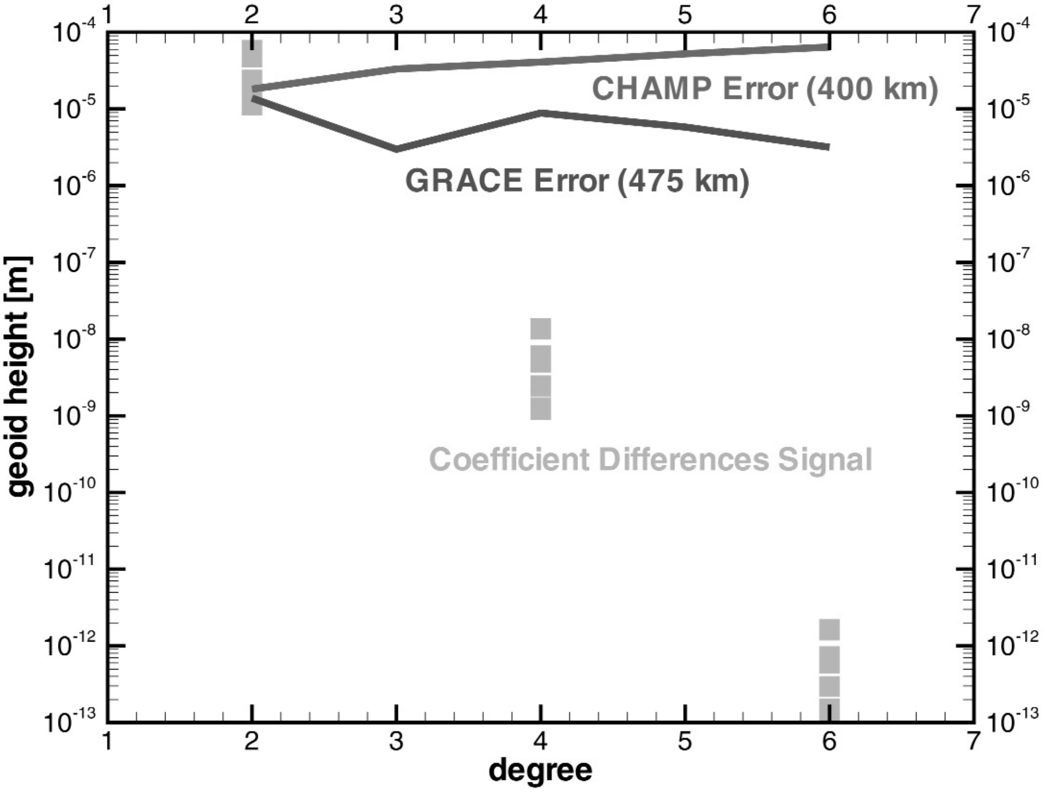

Fig. 8 - Square root of degree variances in geoid hights from coefficient differences of subsequent half-yearly models compared with expected gravity mission errors.

and on the other hand the block-diagonal approach for gravity field estimation could cause an overestimation, especially in the low-degree harmonics due to the land-ocean distribution.

4. Gravity variations due to core rotation

If the inner core has no spherical symmetry and its figure axis moves relatively to the Earth, then this relative movement in connection with the density jump between inner and outer core causes time variations of the Earth's gravity field. The following hypotheses were discussed first in Smylie et al. (1984) and then in Szeto and Smylie (1984, 1989):

- the inner core rotates around its figure axis relatively to the outer core and the mantle;
- the figure axis of the inner core is oblique with respect to the symmetry axis of the Earth;
- the inner core is oblate (ellipsoid of revolution) and its figure axis performs a relative precessional motion.

Using simplified models, Schmutzer (1977, 1978) and Greiner-Mai (1997) showed that the relative rotation of the inner core can induce an alignment of the geomagnetic dipole axis with the figure axis of the inner core. With these assumptions one can identify the observed variation of the dipole axis (mainly the westward drift) with that of the inner core axis. These hypotheses are supported by the fact that Jochmann (1989) investigated its consequences on polar motion and found that the observed 18-, 25-, 35-, and 70-year periods are mainly caused by this assumed inner core wobble. Recent seismological investigations (Song and Richards, 1996) have also suggested that the axis of seismic anisotropy of the inner core is moving relative to the mantle.

To estimate the influence of the precession of a flat and oblique inner core on the Earth's gravity field we developed the gravity field of the inner core into spherical harmonics with respect to the inner core axis and transformed it into a mantle fixed coordinate system. The details are described in (Greiner-Mai et al., 1998) and could be summarized as follows:

- it is sufficient to approximate the gravity field of the inner core by the field of an ellipsoid of revolution filled with a constant (relative) mass density according to the density jump between inner and outer core. With respect to the figure axis of the inner core, only zonal spherical harmonic coefficients of even degree occur;
- the density jump and the major semi-axis of the inner core were taken from Dziewonski and Anderson (1981) and for the flattening of the inner core Smylie et al.'s (1984) solution of Clairaut's equation was assumed;
- the time-dependent coordinate transformation is based on the direction of the geomagnetic dipole axis derived from the observed geomagnetic field (Hodder, 1981).

Fig. 7 shows the calculated time variation of the normalized harmonic coefficients after the coordinate transformation with respect to their mean values. Because the influence on the coefficients of higher degree is very small, the variation of degree 2 coefficients are only plotted. If we compare these values with the expected accuracy of the planned CHAMP and GRACE missions (Fig. 8), it may be possible in the next decade to check the hypotheses mentioned above. Nevertheless, the problem of separating the different influences on the low-degree harmonic coefficients has to be solved.

5. Conclusions

In concluding this investigation, the following statements can be made:

- for the first time, small gravity variation signals can be measured from space on a global scale up to wavelengths of 600 km with CHAMP and GRACE;
- gravity coefficient changes caused by atmospheric mass redistributions were computed up to degree 4. The signal shows large annual and semi-annual amplitudes. Signal degree variances are by a factor of 10 and more larger than expected mission errors. Sensitivity to higher degrees is expected and has to be further analyzed;
- the signal of ocean mass redistribution is analyzed from altimeter data and an ocean circulation model. Annual and semi-annual amplitudes were identified as a main signal. Gravity coefficient amplitudes and degree variances differ significantly in both approaches. The POCM ocean model seems to underestimate ocean variability, whereas for altimetry, incomplete thermal reduction could overestimate the ocean mass contribution. Missions are

sensitive up to degree 10-12 for CHAMP and up to degree 40-60 for GRACE;

- the gravity signal from the inner core rotation shows small amplitude-peaks for frequencies of 3 years and longer. Both missions are sensitive to degree 2 terms of this signal. Degree 4 and 6 terms have very small signals;
- one of the major tasks of future gravity field research will be the separation of the overall signal, measured by the new gravity missions into single contributions for different gravity variation sources.

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