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CHAMP, GRACE and GOCE: mission concepts and simulations

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Abstract. For the first time in satellite geodesy, three gravity missions have the potential of being realized: (1) CHAMP is a low-cost mission, an intermediate step between our present knowledge and the ambitious goals that are formulated by geodesists, solid Earth geophysicists and oceanographers; (2) GRACE is planned as being a more advanced mission, especially aimed at monitoring long wavelength time variations of the gravity field; (3) GOCE will open a completely new range of spatial scales (in order of 100 km) of the geopotential spectrum to research. The three missions are based on different space segments which have in common the high-low satellite-to-satellite tracking (SST) from GPS; other common parts being the low-low SST in the case of the two co-orbiters of GRACE, and gradiometry on board the GOCE spacecraft. Many new numerical simulations have been conducted in a unified effort in order to:

1. compare the concepts in terms of idealized (e.g. polar) missions using only one technique at a time;
2. estimate the capabilities of more realistic missions, closer to the planned scenarios of GOCE, GRACE and CHAMP with instrument, orbit and mission parameters that will allow an easy scaling to the actual cases. The most significant results are reported in this paper.

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1. Introduction

We are at the dawn of a revolution in the Earth's gravity field modeling capabilities and their consequences. Three dedicated space missions are potentially in the making of being realized: (I) CHAMP will be launched in December 1999 and wants to improve our knowledge concerning the global gravity field, homogeneously, by about a factor two in resolution and a factor 5 to 10 in precision (depending on the resolution); it will reach an intermediate objective of the geodetic and geophysical community, in a relatively simple manner, and at a low cost (Reigber et al., 1996); (II) GRACE is a new project, recently conceived and approved, whose aim is to monitor on a monthly to annual (even inter-annual) basis time variations of the long wavelength part of the gravity field (Tapley, 1998), and if the mission (to be launched in mid-2001) completes its planned four-to five year life-span, it should also yield a very good stationary gravity field at long to moderate spatial scales; (III) GOCE is an advanced satellite mission that will provide a completely new range of spatial scales (in the order of 100 km) of the Earth's gravity field with unprecedented accuracy (ESA, 1996); GOCE has been proposed and designed as one of the Explorer missions to provide the best snapshot of the gravity lateral variations and of the geoid surface, globally, to constrain models of our planet Earth's system: time-wise boundary conditions contributing (together with results of other missions) to the description of the temporal evolution of some phenomena, and space-wise boundary conditions to a better understanding of the Earth's structure, of its oceans and their movements.

This paper presents the results of a new set of simulations whose objective was to make a fair comparison of the three missions capability of recovering the Earth's gravity field, in an unified framework, and by using carefully tested tools designed by various groups that have been dealing with these matters for years. In particular, the spacewise and the spectral approach software were inter-compared all along during these studies, and the agreement between them was deemed satisfactory. Details of the procedures can be found in the ESA (1998) report.

The results are of course based on assumed instrument and system specifications provided by mission documents made available to us. The characteristics of the three missions, their on-board instrumentation and their life span are so different (they fulfil different objectives in line with their designs) that we felt necessary to perform a first set of simulations of so-called conceptual and normalized (e.g. polar) missions which would use only one of the following techniques at a time: satellite-to-satellite tracking (SST) in the high-low mode, SST in the low-low mode, or satellite gravity gradiometry (SGG). This approach was then extended by comparing it to more realistic missions, closer to the planned scenarios of GOCE, GRACE and CHAMP with instrument, orbit and mission parameters which allow easy scaling to the actual cases.

2. Comparison of mission concepts

The three concepts considered here are satellite-to-satellite tracking in the high-low mode (SST hi-lo), satellite-to-satellite tracking in the low-low mode (SST lo-lo) and satellite gradiometry. Representatives of these three concepts are: CHAMP, for SST hi-lo, GRACE for SST lo-lo (combined with SST hi-lo) and GOCE for gradiometry (combined with SST hi-lo). Common to all three concepts is that the determination of the Earth's gravity field is based upon the measurement of the relative motion (in the Earth's gravity field) of the test masses.

2.1. Satellite-to-satellite tracking

In the case of **SST hi-lo** the low flying test mass is a low Earth orbiter (LEO) and the high flying test masses are the satellites of the Global Positioning System (GPS). As the GPS-receiver, mounted on the LEO always “sees” six or even more of the GPS satellites, the relative motion of the LEO can be monitored in a three dimensional manner, i.e. in all three coordinate directions. The lower the orbit of the LEO, the higher its sensitivity with respect to the spatial variations of the gravitational field. Since the LEO's orbit is not only determined by the integral effect of all gravitational forces but by skin forces as well (atmospheric drag, solar radiation, albedo etc.), the latter must either be compensated for by a drag-free mechanism or, like for CHAMP, measured by a three-axis accelerometer. The high orbiters, as well as the GPS satellites are affected by non-gravitational forces. However (1) the latter are modeled pretty well anyway, (2) they mainly affect the very long spatial scales and (3) to a large extent their effect averages out. In addition, the ephemerides of the GPS satellites are determined very accurately by the large network of ground stations of the International Geodynamic GPS Service (IGS).

In the case of **SST lo-lo** the relative motion between two LEO's, chasing each other, is measured with highest precision. The quantity of interest is the relative motion of the center of mass of the two satellites. Again the effect of non-gravitational forces on the two spacecraft either has to be compensated actively or measured (GRACE). Low orbit means high gravity sensitivity.

2.2. Satellite gradiometry

This technique entails the measuring of the relative acceleration; not between free-falling test masses like satellites, but of test masses at different locations inside one satellite. Each test mass is enclosed in an individual housing and kept levitated (floating, without ever touching the walls) by a capacitive or inductive feedback mechanism. The difference in feedback signals between the two test masses is proportional to their relative acceleration and exerted purely by the differential gravitational field. Non-gravitational acceleration of the spacecraft affects all accelerometers inside the satellite in the same manner and ideally drops out when differencing. The rotational motion of the satellite affects the measured differences. The rotational signal (angular velocities and accelerations) can be separated from the gravitational signal, if acceleration differences are taken in all possible (spatial) combinations (= full tensor gradiometer). Again low orbit means high sensitivity.

2.3. Comparison of normalized missions

For a comparison of the mission concepts the following baseline parameters are adopted

Table 1 - Mission concepts comparison. PSD=power spectral density (includes satellite and system errors), I=inclination, h=satellite altitude, T=mission duration, L=highest spherical harmonic degree in adjustment process, ρ_0=inter-satellite distance, 1mE=1 milli-Eötvös where 1 Eötvös=10^{-9} m/s^2 per meter=10^{-9} s^{-2} .

Mission	obs.	$\sqrt{(PSD)}$	*I* [deg]	*h* [km]	*T*	*L*	ρ_0 [km]
SGG1	T_{xx}, T_{yy}, T_{zz}	1mE/$\sqrt{Hz}$	90	250	30 d	275	-
SGG2	T_{xx}, T_{yy}, T_{zz}	5mE/$\sqrt{Hz}$	90	250	30 d	275	-
SST1	Δρ	10 µm/$\sqrt{Hz}$	90	350	30 d	175	300
SST2	ΔρY	1 µm/s/$\sqrt{Hz}$	90	350	30 d	175	300
DXYZ	Δx	1 cm	90	350	30 d	100	-

(Table 1). To exclude misunderstandings, this is not a comparison of actual mission parameters but of so-to-say **normalized missions**.

SGG represents a gradiometric mission (such as GOCE) with either a superconducting inductive instrument (SGG1) or a capacitive one (SGG2). Drag-free compensation is assumed and only the three diagonal terms of the gravity gradient tensor are employed for gravity analysis. SST represents a low-low satellite-to-satellite tracking mission. Measured are either range ($\Delta\rho$) or range-rate ($\Delta\dot{\rho}$). The given PSD numbers correspond to those discussed for GRACE. The PSD accelerometer has not been taken into account. A height of 350 km is chosen, since it is assumed that the satellites do not to fly drag free. In that case, 350 km is already rather low. An intersatellite distance of 300 km is chosen so that no "common-mode" attenuation effects occur. DXYZ represents a high-low satellite-to-satellite tracking mission of the CHAMP type. This can also be viewed as orbitography, i.e. the observable is the 3-D orbit perturbation of the LEO as tracked by the GPS. No regularization (i.e. no stabilization of the final system of eqs. to be inverted) is applied. In addition, SST and SGG are not aided by GPS in these simulations. As will be seen, SGG benefits very much from GPS in the very low degrees.

The results of the error simulations are presented in Figs. 1a and 1b., Figure 1a shows the degree root mean square (RMS) values of the expected error of the spherical harmonic coefficients for the five-mission concepts of Table 1. The "Kaula" curve shows the expected signal degree RMS values and allows to define spectral, i.e. also spatial, resolution. Fig. 1b expresses the same results but translated into the cumulative expected geoid error: the very low plateau for SGG, up to degrees 100, would decrease to an even lower value with the inclusion of GPS (see next section).

The results confirm that SST is superior in the lower harmonics, below degree and order 50-60, making a GRACE-like mission optimal for studying time-varying gravity effects, provided the mission is long enough, i.e. is several years. Gradiometry, on the other hand, is superior for obtaining a high spatial resolution and for such a purpose does not require a long-mission duration. As a general rule one should note that the increase of measurement precision or decrease in altitude corresponds essentially to a shift of the error spectrum curve along the

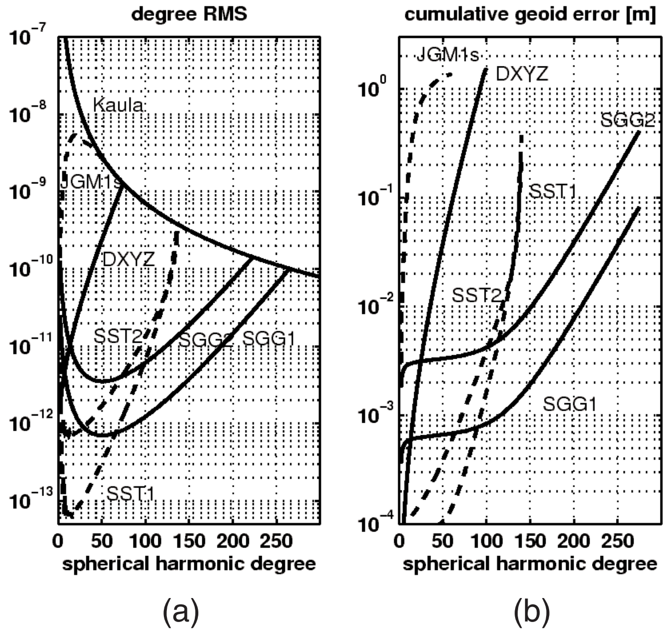

Fig. 1 - Principal character of the gravity satellite mission concepts. Also included are errors per degree of one of the best available gravity potential models (JGM 1 S) based purely on orbit information. The average signal behavior is indicated by the “Kaula” curve. The crossing between signal and error curve defines the maximum resolution.

vertical axis in Fig. 1. Due to the steep slope of the curve, in the case of SST lo-lo, the corresponding increase in spatial resolution is rather moderate. The slope of the gradiometry curve is, in contrast, much slower, therefore the gain in spatial resolution is very high in this case. Only if SST is flown very low, thus requiring a drag-free approach, would it be able to attain a similar resolution. The DXYZ curve shows that a space-borne GPS receiver achieves a gravity field improvement of, say, one order of magnitude over current knowledge.

3. GOCE, GRACE and CHAMP simulations

The missions, especially their purposes, are not directly comparable. GRACE focuses on time-varying parts of the gravity field, especially at medium range degrees, thus a long mission duration is required. GOCE focuses on the highest possible spatial resolution of the static field, the mission can be shorter but the orbit has to be low, thus requiring drag compensation.

3.1. Simulation parameters

Three points, often of concern, have been investigated by varying certain simulation parameters, by analyzing the spatial behavior of the error, or by scaling the results under a certain assumption:

Table 2 - Simulation parameters. (Quantities are as in Table 1; FP stands for Félix Perosanz model, explained in the text.

Mission	obs.	$\sqrt{(PSD)}$	I(deg)	h [km]	T	L	ρ_0 [km]
GO1	T_{xx}, T_{yy}, T_{zz}	[5 mE/ $\sqrt{Hz}$5]	96.5	260	3 mo	250	-
	$\Delta\underline{x}$	FP					
GO2	T_{xx}, T_{yy}, T_{zz}	[5 mE/$\sqrt{Hz}$5]	96.5	260	3 mo	150	
	$\Delta\underline{x}$	FP				100	-
GR1	$\Delta\rho$	50 µm/$\sqrt{Hz}$	83	400	3 mo	150	300
	$\Delta\underline{x}$	FP				100	
GR2	$\Delta\dot{\rho}$	5 µm/s $\sqrt{Hz}$	83	400	3 mo	150	300
	$\Delta\underline{x}$	FP				100	
GR3	$\Delta\rho$	50 µm/$\sqrt{Hz}$	83	400	3 mo	150	150
	$\Delta\underline{x}$	FP				100	
GR4	$\Delta\rho$	50 µm/ $\sqrt{Hz}$	83	320	3 mo	175	300
	$\Delta\underline{x}$	FP				100	
GR5	$\Delta\rho$	[50 µm/$\sqrt{Hz}$4]	83	400	3 mo	150	300
	$\Delta\underline{x}$	FP				100	
GR6	$\Delta\rho$	500 µm/$\sqrt{Hz}$	83	400	3 mo	150	300
	$\Delta\underline{x}$	FP				100	
CH1	$\Delta\underline{x}$	FP	83	400	3 mo	100	-
CH2	$\Delta\underline{x}$	9;6;3 cm/$\sqrt{Hz}$	83	400	3 mo	100	-

1. Polar orbit or not: it is important to distinguish whether the chosen orbit is really polar or only sun-synchronous ($I \approx 97°$), but only in the narrow sense; with a polar orbit the entire Earth is mapped, with a sun-synchronous orbit the pole caps are missing;
2. mission duration: in the case of a white noise error spectrum the results can be easily scaled;
3. altitude: the mission altitude is decisive for the performance since the sensitivity decreases quasi-exponentially with increasing altitude. The errors are also exponentially amplified with respect to the altitude in the downward continuation process.

To make the missions comparable the following assumptions have been introduced: the time-varying part of the gravity field was not considered; similar polar data gaps were assumed: GOCE because of its sun-synchronicity ($I \approx 97°$), GRACE and CHAMP because of the choice of the launch site ($I \approx 83°$, may be increased to 87° in the case of GRACE); the same (arbitrary) mission duration of 3 months was chosen (rescaling the simulation results to actual mission duration requires a simple rule-of-thumb calculation); orbital heights are constant. The impact of decaying orbit height (as will be the case of GRACE and CHAMP) was not directly accounted for, but some simulations were carried out with decreasing altitudes to simulate the effect indirectly.

Parameters of the main simulations are given in Table 2. GO stands for GOCE, GR for GRACE and CH for CHAMP. GOCE's basic observables are the diagonal components of the gravity gradient tensor (T_{xx}, T_{yy}, T_{zz}). For GOCE we to the conservative side and adopted the PSD value for the capacitive instrument. For GRACE, it is unclear what the basic observable will be: range ($\Delta\rho$) or range-rate ($\Delta\dot{\rho}$), or if both, whether they will be uncorrelated.

Therefore, both range and range-rate are simulated separately. Both missions are aided by GPS-based orbit determination, denoted by $\Delta \underline{x}$. Thus, in terms of the normalized mission concepts studied previously, the GOs are combinations of SGGs and DXYZ and the GRs are combinations of SSTs and DXYZ. For CHAMP $\Delta \underline{x}$ is the basic observable. All simulations assume regularization by the JGM-1S error spectrum and Kaula's rule (JGM-1S is not the most recent satellite-only gravity model anymore, but serves its purpose as reference for low order regularization well enough). GO1, GR1 and CH1 are considered as baseline scenarios. All other cases are defined so as to study the change in a certain parameter. GO2 and CH2 are used for control purposes.

The simulation of CH2 makes use of the "old" PSD model, which assumes a 9, 6 and 3 cm/$\sqrt{Hz}$ white noise. The GPS error spectrum or FP (Felix Perosanz)-model was derived from orbital error studies of the Topex/Poseidon satellite as tracked by the GPS constellation; it is roughly one order of magnitude better than the old modeling. GO2 is meant to check effects of choosing L, since it can be influential on the low order harmonics (i.e. for all degrees) due to the polar gap: some effect is seen here, though it is not very significant, the small differences being probably due to the effect of regularization of the coefficients affected by the polar gap. GO2 and CH2 will not show up in the graphics in the sequel. For GRACE a series of case studies was performed to study effects of the type of observable (GR2: $\Delta\rho$ vs. $\Delta\dot{\rho}$ Y), a shorter inter-satellite baseline ρ_0 (GR3), a lower orbit (GR4), accelerometer performance (GR5) and reduced accuracy (GR6).

The following remarks are made for the PSD modeling: (1) the given PSDs for GRACE may seem large. Integrated over the band-width of the internal digital low-pass filter (0.05 Hz), however, 50 $\mu m/\sqrt{Hz}$ and 5 $\mu m/s/\sqrt{Hz}$ yield the quoted 10 μm and 1 $\mu m/s$ for range and range-rate respectively; (2) the second number in the PSD denotes a corner frequency, below which the PSD degrades. For GOCE a $1/f$ degradation is assumed. GR5 employs $1/f^4$ to simulate an accelerometer of 10^{-9} $m/s^2/\sqrt{Hz}$ in the $\Delta\rho$-domain. The frequency is normalized with respect to the orbital frequency, in units of (cpr). A corner frequency e.g. of 5 cpr roughly equals 1 mHz; (3) the GPS error spectrum (FP-model) has peaks of 9, 6 and 3 cm for along-track, cross-track and radial direction respectively, around 1 cpr and additional smaller peaks around 2 cpr. The noise floor is only 0.5 cm; (4) all other PSDs are white.

3.2. Spectral results

They are presented in condensed form as degree RMS curves, cf. Fig. 2a. To be precise, the *median* per degree is taken. The median per degree equals, loosely speaking, the degree RMS if the orbit had been polar. This way the spectral distortion, due to the polar gap, is eliminated. Still the numbers are representative for the global field outside the polar gaps. The cumulative geoid error curves (Fig. 2b) are also computed this way.

It is obvious from Fig. 2a that GRACE is superior for the low degrees, say up to degree 75. This is not strictly an intrinsic feature of SST lo-lo, but also a result of the extraordinarily high system performance assumed. Taking into account the mission length, it makes GRACE the

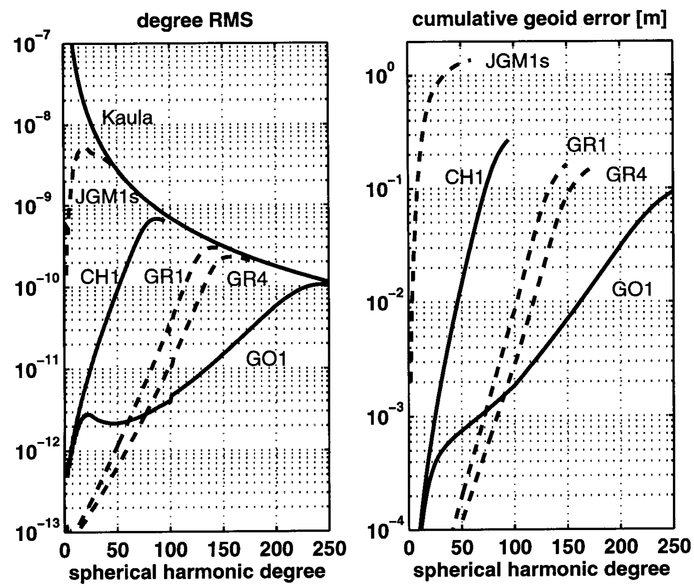

Fig. 2 - Spectral error results of the baseline missions: dimensionless degree RMS curves (a) and cumulative geoid errors, or commission errors (b).

favorite mission for recovering time variations of the gravity field, and recovering the low degree static field. GOCE, on the other hand, outperforms all other missions in the higher degrees, i.e. high resolution determination of the static field, up to degree 250. Depending on the specific mission parameters, the error curves (also the cumulative ones) of GOCE and GRACE cross between degrees 60 and 80. A lower orbit, or better measurement accuracy or scaling from the mission duration would push the GRACE error curves downwards. However, since they are steep, the cross-over point would shift to the right hand side by a relatively little amount. Assuming that the GPS error spectrum (FP) also applies to low altitude orbits, GOCE would benefit much below degree 20. This becomes clear in Fig. 2a where CH1 and GO1 are equal at the lowest degrees.

3.3. Spatial results

The error characteristics of Fig. 2a are propagated onto the sphere, resulting in spatial error functions, in this case an RMS geoid error. It is seen in Fig. 3 that the errors are homogeneous, except for the polar gaps (7° radius), where the errors increase up to one order of magnitude. The level of the RMS curves is consistent with the cumulative errors, up to the specified maximum degree L, from Fig. 2a. Up to degree 150, GOCE yields a geoid error just below the centimeter level. At this resolution GRACE is at decimeter level already. Note that GRACE offers no information (of good enough quality) at L = 200 and above, and that CHAMP reaches the centimeter level already at degree 50.

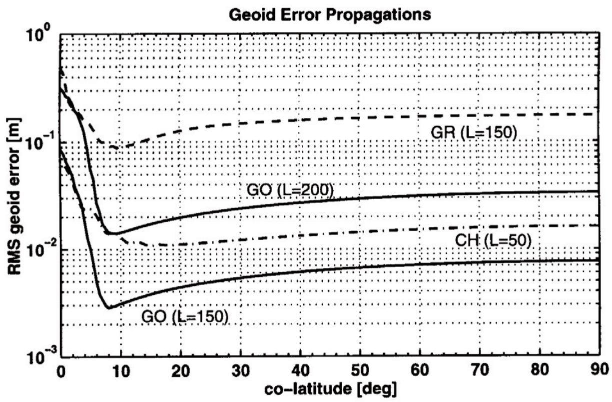

Fig. 3 - Spatial error results: RMS geoid errors as function of co-latitude.

3.4. GRACE case studies

Only two GRACE simulations (GR1, GR4) have been presented in Fig. 2, showing the baseline mission and a reduced height simulation. For a closer look into the GRACE case studies, ratios of degree error results have been computed (with GR1 as reference). Thus a ratio larger than one, denotes worse results compared to GR1, etc.. We summarize the main findings. In general the various GRACE simulations do not differ much in performance. Only a lower orbit (GR4) or a less accurate instrument (GR6) changes the picture considerably. An accuracy change shifts the degree RMS curve vertically, whereas orbit height changes its slope. In particular:

1. range (GR1) and range-rate (GR2) show more or less the same result as above about degree 50, GR1 remaining slightly better. At the lower degrees, GR2 can be much worse;
2. a smaller baseline (GR3) does not significantly improve the result over most of the spectrum. On the other hand, a larger baseline could deteriorate the result through "common-mode" attenuation;
3. the $1/f^4$ contribution to the PSD of $\Delta\rho$ (GR5 case), which simulates an accelerometer contribution, hardly affects the result. Only the lowest degrees are involved. This changes, of course, if the corner frequency becomes considerably larger than 4 cpr;
4. GR6 simulates an accuracy degradation by factor 10. This factor shows up in the ratio calculation as well, up to degree 100. After that, regularization takes over. Note also that if range and range-rate can be determined independently, indeed all the GRACE results above will roughly improve by a factor of $\sqrt{2}$.

3.5. The mission duration

A constant of three months was fixed for all simulations above so as to make sensible comparisons. Mission lengths might be extrapolated by adopting the simple rule-of-thumb, i.e. error results are inversely proportional to the square root of the mission length. This rule-of-thumb holds outside the regularization regime, which takes over in case of polar gap and near the maximum resolvable degree. An actual GOCE mission of nine months would thus rescale the given results downwards, i.e. will improve these by a factor of $\sqrt{3}$. A five-year GRACE mission would yield an improvement by a factor of $\sqrt{20}$ ≈4.5. GRACE, with respect to GOCE would therefore be underestimated by a factor of about 2.5 (reduced to 1.8 in the case of a GOCE mission of longer duration, of 18 months which has been shown to be feasible). As mentioned before, this does not change the resolution discussion. However, GRACE's main focus is to measure the time-varying gravity field, probably in the form of two-week to three-month *snapshots*. It shouldn't be seen as one long five-year mission. Moreover, its orbit will decay. The recovery of the static field during the last few months of its existence (cf. GR4) will outperform the results of the previous years.

4. Conclusions

GRACE is complementary to GOCE. For the first time the temporal variations of the Earth's gravity field (beyond the dynamical flattening and the pear-shape coefficient) will become visible on a global scale to a rather high spatial resolution. GRACE will measure gravity changes due to mass changes or mass motion related to sea level, hydrology, glaciology and solid Earth. A scientific challenge will be that of separating the observed total signal according to the temporal and spatial variability of the various sources.

The high spatial resolution of GOCE is essential for the determination of stationary dynamic topography in general, and for high resolution ocean circulation determination in particular, for leveling by GPS, navigation, continental lithosphere studies and for global unification of height systems allowing the establishment of a global sea level monitoring system.

Realistic comparisons of the performances in gravity field recovery of the GOCE, GRACE and CHAMP missions have been performed. The results obtained confirm earlier results obtained by European groups in support of GOCE: see, for instance, Balmino & Perosanz (1994), Rummel et al. (1995).

The crossing point of GOCE and GRACE performances will be somewhere close to the spherical harmonic degree 80 to 90 (at most) which corresponds to spatial scales of 450 to 500 km. The GRACE resolution may reach degree 150 (at best) but with degraded precision. The GOCE resolution will be at degree 250 (at least). In terms of the number of spectral lines (individual coefficients that are to be resolved) this corresponds to 63 000 coefficients at degree 250 as compared to 6500 to 8300 at degree 80 to 90 (a factor of ten).

Of little concern are the distortions in the spherical harmonic spectrum caused by a non-polar orbit, because these distortions are perfectly mapped back to the polar regions when going back to the space domain. Technical complications associated with the choice of a polar orbit or of an inclination of 83° may result from the unavoidable eclipses.

As a rough rule, an extension of mission length results in improvements of the performance level. A mission length of 27 months results in an improvement by a factor of 3 as compared to a 3-month mission, for a 9-month mission the improvement is $\sqrt{3}$. However, the GRACE mission, whose main goal is to obtain snapshots of the gravity field at intervals of a few weeks or months, should not be viewed as one long five-year mission.

The mission altitude is decisive to the performance, as this increases exponentially with decreasing altitude. This holds especially for the higher degrees, and, consequently the resolution benefits from reduced altitude.

Finally, let us remark that the GOCE instrument is three-dimensional (i.e. it simultaneously measures the gravitational field in all three spatial directions). Consequently, the errors of the resulting gravity parameters (gravity anomalies or geoid heights) exhibit no preferred direction. Apart from the redundancy, the errors are independent and isotropic. GRACE, on the other hand, measures the gravity field essentially in one direction (along track). Therefore, the errors will be decorrelated in one direction and correlated in the direction perpendicular to it. This non-isotropy of the error structure is a disadvantage, in particular, when the directional structure of the gravitational field is of importance as is the case in oceanography where slopes of dynamic topography are to be derived.

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