Towards the Definitive Space Gravity Mission

P. L. Woodworth, J. Johannessen, P. Le Grand, C. Le Provost, G. Balmino, R. Rummel, R. Sabadini, H. Sünkel, C. C. Tscherning, and P. Visser, Members of the GOCE Mission Advisory Group. plw@pol.ac.uk

For many years, a large part of the geophysics community, including oceanography, has been lobbying for a space gravity mission which would provide a precise description of the Earth's gravity field and geoid independent of the quasi-geoid information provided by altimetry. Proposals such as GRM, Gravsat, GAMES, Gradio and Aristoteles have come and gone, killed off either by budget reductions or international politics.

It was recognised twenty years ago that space gravity would be an essential complement of precise altimetry. In the original TOPEX 'grey book' proposal (TOPEX, 1981), it was assumed that Gravsat would fly at more or less the same time as TOPEX, thereby providing gravity field models which would improve significantly the altimeter orbit errors achievable at that time. The 'grey book' also pointed to the fact that mean sea surface (MSS) height minus geoid height would supply oceanographers with the ocean dynamic topography, freeing them from having to make assumptions on 'levels of no motion' in hydrography. Wunsch and Gaposchkin (1980) had shown how a formalism could be constructed for including estimated geoid errors, and errors in MSS and hydrographic fields, in computations of dynamic topography.

Interestingly, now that TOPEX/POSEIDON has achieved excellent orbit error reductions, via a programme of gradual but sustained gravity field improvement by conventional methods together with the development of advanced forms of tracking (DORIS, GPS), the oceanographic justification for a gravity mission is stronger than ever. There are three main reasons:

1. To take advantage of the centimetric accuracy MSS fields now available by provision of centimetric geoids. One could have argued that the poorer MSS fields available some years ago would not have justified expenditure on a gravity mission in this way.
2. To further reduce orbit errors of the lower flying altimeter satellites (ERS-1/2, Envisat, Geosat Follow On) to the level achieved for TOPEX/POSEIDON. Residual gravity model errors are still major factors in orbit determination for the lower flying missions, even given near-global tracking.
3. To take advantage of the synergy of scientific knowledge which will be obtained by such missions now that, twenty years later, they are cheaper and technically more feasible. For example, knowledge of processes in the solid Earth such as Post-Glacial Rebound obtained from a mission such as the European Space Agency's GOCE (Gravity field and steady-state Ocean Circulation Explorer, see ESA, 1996) will benefit oceanographers and climatologists interested in global sea level change. In addition, knowledge of the temporal dependence of the gravity field obtained from the US-German GRACE (Gravity Recovery And Climate Experiment, see NASA, 1996) will provide data on movements of mass in the ocean, in the ice caps and on land which will have a wide range of application across geophysics.

The reader may know that three space gravity missions, the German CHAMP (CHAllenging Mini-satellite Payload, see Reigber et al., 1996) mission as well as GRACE and GOCE, are currently proposed for launch within the next 5 years. This much improved situation may stimulate the reader, who is probably an oceanographer and also a tax-payer, to ask why three are needed when oceanography seems to have been rubbing along fairly well for so long without one. For the detailed scientific arguments, we refer the reader to ESA (1996), NRC (1997) and Dickey et al. (1998); we believe the arguments will be convincing. We shall concentrate in this note on the topic of providing a precise, high resolution gravity field or geoid. (For discussion of monitoring temporal changes in gravity with long duration missions such as CHAMP and GRACE, see NRC, 1997).

The purpose in writing this note is to emphasise the unique contribution to the recovery of the gravity field and geoid from GOCE, as well as to document the complementarity with GRACE and CHAMP. In particular, the three missions offer major differences in the recovered resolution and accuracy of the gravity field spectrum. However, we do want all three. In addition, to be realistic, we know that there will inevitably be a learning curve between missions in space gravity (as there was in altimetry). No oceanographer would have settled for the Seasat data set if he had known TOPEX/POSEIDON was a few years away. Space gravity over the next few years will culminate in what will be, in our opinion, the definitive GOCE mission.

The different missions

There are three missions planned: CHAMP, GRACE and GOCE.

CHAMP is a low cost, multi-payload, small satellite mission, providing a gravity field intermediate between our present knowledge and oceanographic requirements (which are summarised below). Launch is planned for late 1999 with the mission lasting 4–5 years. Altitude will be approximately 470 km initially, reducing with air drag to 300 km.

GRACE is a more advanced mission, especially aimed at monitoring the time variations of the gravity field at long wavelengths (i.e. 500 km and longer). It consists of two CHAMP-like satellites about 250 km apart connected by a satellite-to-satellite (SST) microwave link. The altitude

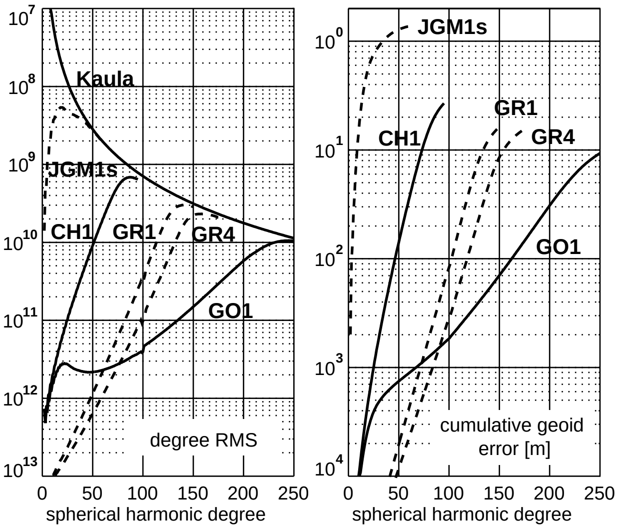

Figure 1. Spectral error results of the baseline missions: dimensionless degree RMS curves (left) and cumulative geoid errors, or commission errors (right). From ESA (1998).

will initially be around 470 km decaying towards 320 km at the end of the mission. Launch is planned for mid-2001 with the mission lasting 3–5 years.

GOCE is a high resolution gravity field mission and will open a completely new range of spatial scales (order of 100 km) of the gravity field spectrum to the research community. It consists of a single satellite of high mass-to-area ratio, with either a 'room temperature' (capacitive) or superconducting (inductive) three-axes gradiometer. Launch is planned for 2003 with the mission lasting 8 months. Altitude will be kept at about 250 km.

All three missions will have a near-polar orbit. Each will use GPS (or GPS/GLONASS for GOCE) high-low SST, providing the longer wavelength components of the gravity field. The two GRACE satellites also employ SST in low-low mode to recover the shorter wavelength components. GOCE employs gradiometry to provide the latter. CHAMP and GRACE will use accelerometers to measure the non-conservative forces (drag) operating on the spacecraft; GOCE will use the 'common-mode' capability of the gradiometer to measure the remaining non-conservative forces after its Drag Free Control has compensated for most of them.

It has proved extremely difficult to make simulations which might provide meaningful comparisons between the different missions with regard to achievable gravity field recovery. For example, not only are the different satellites planned to fly at different altitudes and at different points in the solar cycle, but the altitudes of CHAMP and GRACE will reduce during their missions, with, in principle, greater precision being obtained in the later stages. Therefore, one has to assume that the satellites will have lifetimes as anticipated. In addition, GRACE and GOCE will be using technologies which have never been used in space before, and the estimation of instrument performance (microwave SST link for GRACE, gradiometer for GOCE) is critical to the simulations: should one assume target errors for these technologies or be conservative?

In spite of these reservations, a set of simulations has been carried out recently in order to identify the strengths and weaknesses of the different proposals (Balmino et al., 1998). First, a set of 'normalised mission concepts' was constructed. These simulate idealised missions of the same duration (30 days) and precise polar orbit, and with nominal accuracies for GPS differential positioning, GRACE-like SST, and GOCE-like capacitive or inductive gradiometry. The results confirm what has been known for some time, that GRACE-like SST is superior to GOCE-like gradiometry in the lower harmonics below degree and order typically 50–60 (equivalent half-wavelength of approximately 400 km), making a GRACE-like mission optimal for studying time dependent gravity errors at long to moderate wavelengths. Gradiometry, on the other hand, is superior for studying high spatial resolution features as small as 100 km half-wavelength, and especially those which are not time dependent.

Our studies then progressed to perform specific CHAMP, GRACE and GOCE simulations using a range of instrument performance characteristics, non-polar inclination orbits and altitudes. The results are summarised in Fig. 1 wherein JGM1s refers to the estimated accuracy of the currently available JGM1s model based purely on orbit information; CH1 refers to CHAMP; GR1 and GR4 refer to GRACE with a 400 and 320 km altitude respectively; and GO1 refers to GOCE with the non-superconducting gradiometry. (See Balmino et al., 1998 for full details of parameter values adopted in the simulations.)

From Fig. 1, it is again obvious that GRACE is superior for the low degrees, say up to 50. This is not strictly an intrinsic feature of SST low-low, but is rather a result of the extraordinarily high assumed system performance advertised by the mission.

GOCE, on the other hand, outperforms all other missions in the higher degrees up to degree 250, with the error curves for GRACE and GOCE crossing between degrees 60 and 80, depending of course on the specific mission parameters. A lower orbit, or better measurement accuracy, or scaling of the mission duration would push the GRACE curve downwards. However, since the curves are steep, the cross-over point would shift to the right hand side by a relatively small amount.

The oceanographic requirements

It is clear that each of these missions will result in major gains in knowledge of the gravity field and geoid, but what requirements do oceanographers really have?

Most oceanographers will know that at present an altimetric MSS is distinguishable from the best model of the geoid up to degree 15 or so (or wavelengths of approximately 2000 km); at shorter scales the errors in the geoid models render such subtractions imprecise (see ESA, 1996 for a review). Recent studies, which do not differ qualitatively from others performed over the last 20 years, have expressed geoid measurement error requirements as a spectrum of magnitude approximately 2 cm averaged over wavelengths of 100 km; 0.2 cm over 200 km wavelengths; through to less than 0.1 cm at 1000 km wavelength (the ‘basin scale’). The short 100 km scale is often referred to, perhaps inappropriately, as the ‘mesoscale’; it is intended to represent essentially the Rossby radius. Fig. 2 indicates schematically the signals in the dynamic topography which we wish to identify via studies of MSS minus geoid. These vary from short wavelength features such as through-flow currents, coastal currents and deep ocean fronts to the large scale ocean gyres.

For example, Wunsch (quoted in ESA, 1996) has shown that an error of 1 cm in the geoid height difference (or altimetric MSS height difference) across the North Atlantic at 30°N corresponds to a volume transport of 7 Sv (if interpreted in a barotropic sense) and approximately 10^{14} W in meridional heat transport. These are large numbers but measurements to this accuracy would represent significant improvements compared to present uncertainties. It is clear that one has to do better than 1 cm at these scales, hence the 0.1 cm requirement at 1000 km wavelength.

Developments for merging such information at this scale, which will be obtained by both GRACE and GOCE, into ocean models have recently been discussed by Gannachaud et al. (1997), Wunsch and Stammer (1998) and Le Grand and Minster (1998). Fig. 3 illustrates an example of such work using a coarse (4.5°) inverse model. The figure shows transport uncertainties (Sv) estimated by the model using the EGM96 and GOCE error budgets (dark and light grey respectively). The left hand panels show uncertainties associated with zonally integrated transports across 24°N, 36°N, and 48°N, while the right hand panels show the uncertainties associated with meridional transports across 36°N in the region of the Gulf Stream between 75°W and 72.5°W. From top to bottom, the panels show transport uncertainties integrated from the surface to the ocean bottom, from the surface to 100 m depth, from the surface to 1000 m depth, and from 3000 m to 4000 m depth. The reduction in uncertainty obtained at 48°N section when the GOCE error budget is used is shown in percent. Uncertainties corresponding to EGM96 and GOCE error budgets are not significantly different for surface to bottom transports (top panels), and for deep ocean transports (bottom panels). However, they are significantly different for transports in the upper ocean (middle panels), especially for the 48°N section. In this section, the uncertainty in transports in the upper 100 m of the ocean is reduced by 26% when the GOCE error budget is used. The corresponding volume transport uncertainty reduction is about 0.2 Sv, which translates into a heat transport uncertainty reduction of about 10^{13} W.

This present impact estimate, which is based on available data and error budgets only, is a conservative one for several reasons:

(i) Uncertainties in Ekman transports will be reduced in the near future using new scatterometer data. Neglecting Ekman transport uncertainties doubles the impact of GOCE on volume flux uncertainty reduction at 48°N (52 instead of 26% reduction).

(ii) Ganachaud et al. (1997) showed that the North Atlantic is the ocean basin where gravity missions will have the smallest impact.

(iii) The calculations use estimates of mean dynamic topography averaged over 4.5°, and the present study therefore underestimates the impact of GOCE on the determination of transports along sharp fronts like the Gulf Stream.

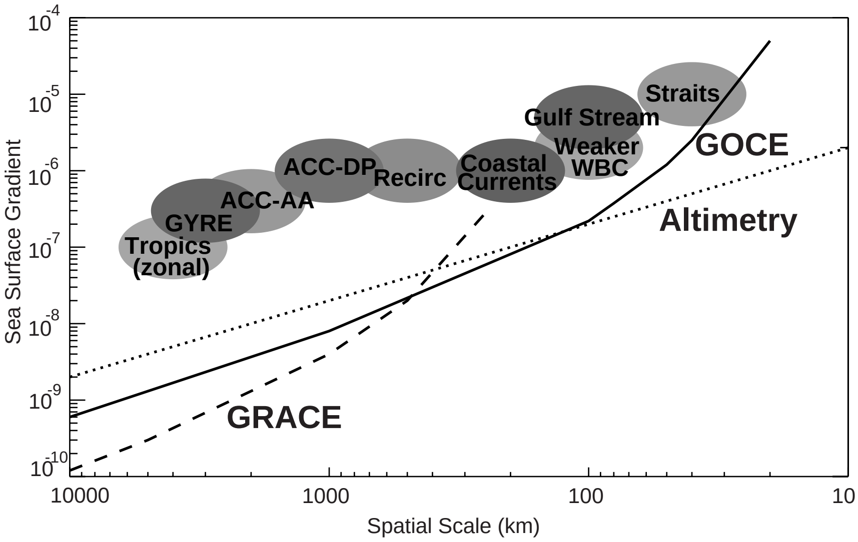

Figure 2. Highly schematic illustration of sea surface gradients (relative to the geoid) of several components of the ocean topography compared to MSS slope accuracy from altimetry (dotted line) and to geoid slope accuracy from space gravity missions such as GOCE (solid line) and GRACE (dashed line). ‘Gulf Stream’ represents the stronger deep ocean fronts including those of the Gulf Stream itself and of, for example, the Antarctic Circumpolar Current. ‘Recirc’ represents the Gulf Stream recirculation. ‘Weaker WBC’ represents the weaker Western Boundary Currents (e.g Brazil Current) with spatial scales of order 100 km and gradients of order 10^{-6}. ‘ACC-DP’ and ‘ACC-AA’ represent a major current such as the ACC at Drake Passage or at the wider African and Australian choke points respectively. ‘GYRE’ represents a typical 1 m ocean gyre over 3000 km scale. ‘Coastal Currents’ represents the myriad of coastal currents, flows through longer straits and meridional equatorial signals with space scales of order 100 km and gradients of 10^{-6}. ‘Straits’ represents flows through short straits which are at the limit of spatial resolution. GOCE will be needed to resolve all these signals. Note that at very long wavelengths, where GRACE accuracy is superior to that of GOCE, remaining altimeter orbit and other systematic uncertainties are still significant.

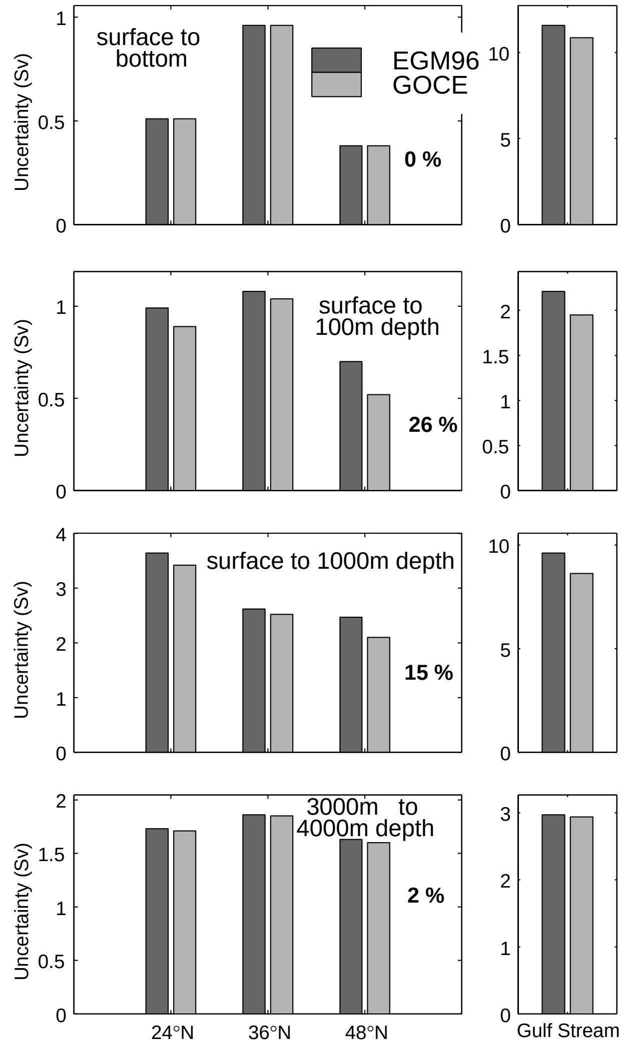

Figure 3. Estimates of reductions in transport uncertainties with the use of a gravity mission such as GOCE (see text for explanation).

(iv) Because the present study is a steady state one, it must account for the presence of noise in the density field caused by natural variability. New assimilation techniques (Hasselmann and Giering, 1997; Wunsch and Stammer, 1998), combined with precise estimates of the instantaneous density field from either better sampling of modelling, will circumvent this problem and allow the MSS - geoid information to reach deeper levels of the ocean.

Therefore, in summary, is it really necessary to resolve the small spatial scales with a gravity mission? Is their resolution essential to our understanding of the ocean circulation, and climate? Will not such small scale features become evident in models once the large scale flows are adjusted? These are questions which modellers involved in assimilating potential gravity fields into ocean models are endeavouring to answer. What is clear is that if one simply high-pass filters a dynamic topography from a long run of a numerical model (e.g. Semtner-Chervin) with a filter which preserves signals of degree 80 or more (i.e. the ‘GOCE-only-accessible’ part of the spectrum of Fig. 2), then many important short spatial scale features are evident (frontal signatures of the major currents; definition of narrower and smaller boundary currents; ACC jet banding; zonal equatorial signals) (Fig. 4, page 24), and such models cannot, of course, be claimed to be a complete representation of the ocean.

It is our belief that the correct scientific approach is to measure the shorter wavelength components of the gravity field spectrum if one has the means to do so (i.e. by means of a mission such as GOCE), rather than rely on their simulation via model constraints. We would appreciate receiving your views on this question.

It is also our belief that GRACE and GOCE together would provide an outstanding data set, covering all parts of the gravity field spectrum with unprecedented accuracy. This combination would really be the ‘definitive mission’. We hope that GRACE, GOCE and the pioneering CHAMP mission will all receive the support of the oceanographic community.

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