MASS TRANSPORT AND MASS DISTRIBUTION IN THE EARTH SYSTEM

Jakob Flury$^{(1)}$ **and Reiner Rummel**$^{(1)}$

$^{(1)}$ *German GOCE Project Bureau*
Institute for Astronomical and Physical Geodesy
Technische Universität München, D-80290 München
flury@bv.tum.de, rummel@bv.tum.de

1 INTRODUCTION

In 2001 a German GOCE project bureau has been established, funded by the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt DLR). Its main objectives are (1) to promote research on the scientific use of the products to be delivered by GOCE, (2) to maintain close contact with industry and institutions involved in GOCE, (3) to inform the public about the progress of the GOCE mission and (4) to organize regular workshops for the scientific user community. For more details it is referred to [1] and `http://www.goce-projektbuero.de`. In this article we focus on a very recent activity. In a joint effort, a group of German Earth scientists formulated and submitted a proposal ”Mass Transport and Mass Distribution in the Earth System” for a so-called German Priority Research Program to the Deutsche Forschungsgemeinschaft (DFG), see [2].

2 SCIENTIFIC RATIONALE

GOCE has been selected as the first explorer mission of ESA’s ”Living Planet Programme” [3]. The program is based on an Earth system approach. Its aim is to advance the quantitative knowledge of processes within the various Earth system components and of their interrelations and to increase the overall understanding of the system in order to allow timely responses. The missions are selected on the basis of the contribution that can be expected towards these goals. Before this background, it is expected that GOCE, in particular, and satellite gravimetric missions, in general, can play an important and a very unique role in Earth system research. Our basic hypothesis is the following: ”From a combination of surface geometry and surface geometry changes with gravity it will be possible to quantify mass anomalies, mass transport, mass exchange and ultimately mass balance in the Earth system”. It will be a very fundamental contribution to the establishment of the energy budget inside the Earth system.

What is the role of the measurement of gravity and of the geoid with high spatial and temporal resolution in this? One can distinguish three principal fields of application. The first one is the comparison of the measured gravity or geoid with the corresponding quantity of an Earth model, e.g. a model co-rotating with the Earth and in hydrostatic equilibrium, see e.g. [4]. The deviation is referred to as anomaly. It is a direct measure of the imperfection of the Earth model and ultimately of unmodelled dynamics. This approach is as old as geodesy itself, already Huygens proposed to derive the Earth’s flattening from pendulum measurements. Nowadays Earth models are very refined. An excellent example of a forward modelling of the long-wavelength part of the geoid, up to spherical harmonic degree and order 15, with a 92% agreement between measured and modelled geoid is given in [5]. Modern Earth models of crust and mantle are based on a large variety of geophysical evidence, such as seismic tomography, topography, tectonic velocities or laboratory studies of material properties. The future trend will be a joint modelling taking into account gravity and geoid as well as all other geophysical sources. The second application is of much more recent date. The geoid is defined as the equipotential surface of the gravity field at mean sea level. It is reference surface of all topographic heights, those of the topographic terrain as well as those of ocean topography. In ocean areas, the geoid represents the surface of a hypothetical ocean at rest. The ocean topography is very small, typically smaller than 1 m. Thus, its determination very much depends on the precision with which the geoid and the ocean surface are known. With the geometric shape of the actual mean ocean surface measured by satellite altimetry and the geometric shape of the geoid computed from the measured gravity field, dynamic ocean topography can be determined. Under the assumption of geostrophic balance the latter translates directly into ocean surface circulation. The spatial scales of interest range from several thousand kilometres to scales between 30 and 70 km. The principle of this method dates back to the comparison of geodetic and oceanic levelling along coast lines, compare e.g. [6], [7]. With the advent of ocean altimetry and with the availability of more precise geoid models in the eighties the method became applicable on a global scale. Dynamic ocean topography is a key quantity for ocean studies, including the study of mass and heat transport in the oceans. The third field of application is the most evident albeit most challenging one. Any redistribution of mass inside Earth system results in temporal variations of gravity and geoid. This may be redistribution of mass inside of a component, such as solid Earth or the ocean, or mass exchange between components, e.g. between atmosphere, ocean and ice. Dependent of the material and its physical state (gas, liquid or solid) there exists a wide range of temporal and spatial scales. In general, temporal variations are very small and therefore difficult to measure. However, their measurement should allow, for example, the distinction between thermal expansion and mass surplus in sea level rise, see e.g. [8], or the transport of water through Earth system. Absolute gravimetry or superconducting relative gravimetry are very precise and are easily capable of detecting temporal gravity changes. However it is very difficult if not impossible to discern the various individual global, regional and local contributions in the sum of the measured signal. The effect of vertical crustal movements of the stations poses an additional problem. Gravimetric satellites, on the other hand, sense the effect of temporal variations integrated over large areas, so that even very tiny signals, e.g. due to variations in snow cover, become detectable. Very successful is the measurement of temporal variations in J_2 and in a few additional low degree zonal coefficients, and currently a very exciting debate is going on about their interpretation; see e.g. [9], [10], [11]. The separation of the individual contributions to the measured signal is a great challenge.

In summary, there are three ways in which gravity and geoid information can be used. Gravity and geoid anomalies are the difference between the measured gravity or geoid and the corresponding quantities of a model Earth. They reflect unmodelled mass heterogeneities. Ocean topography is the difference between an altimetrically derived mean ocean surface and the geoid. The geoid takes here the role of the model, i.e. the model of a hypothetical ocean at rest. Via the geostrophic balance ocean topography can be translated in ocean surface circulation. Temporal variations of gravity and geoid result from mass redistribution inside the Earth system.

3 MASS TRANSPORT IN THE EARTH SYSTEM

Based on the applications described above, a group of German Earth scientists has formulated a proposal for an interdisciplinary research program. Its title is ”Mass Transport and Mass Distribution in the Earth System – Contribution of the New Generation of Satellite Gravity and Altimetry Missions to Geosciences”. The proposal has recently been submitted to the DFG in order to establish a German Priority Research Program. The implementation of the program is still uncertain, because only about 20% of the submitted proposals are granted.

The objective of this project is the comprehensive study of mass anomalies, mass transport, mass exchange and mass balance in the Earth system. In particular, the dynamics of the Earth’s crust and mantle, ice mass balance and sea level, the hydrological cycle and ocean transport as well as their interactions will be investigated. Mass transport in the atmosphere and mass exchange between atmosphere and hydrosphere are of importance, too, and will be taken into account employing the best available atmospheric models. However, our expectation is that at this point an improved modeling of atmospheric mass changes is not feasible based on gravity data. All mass phenomena are derived from the combination of geometric and gravimetric satellite missions. We denote geometric satellite missions those which provide the shape and changes of shape of ocean, ice and land surfaces as well as ice and tectonic velocities. The corresponding techniques are ocean and ice altimetry, interferometric SAR of ice and land areas as well as point positioning by GNSS (GPS, GLONASS, GALILEO). Their combination with the gravity and geoid data produced by gravimetric satellite mission yields the required mass signals. The project takes advantage of a unique constellation of geometric and gravimetric satellite missions, partly already in orbit now and partly to be launched in the near future. Only because of this unique constellation this research project becomes feasible at all. An overview is given in Fig. 1.

Fig. 1 shows on the left hand side a selection of the satellite configuration on which this project is based. The new generation of dedicated gravimetric missions CHAMP, GRACE and GOCE will provide, in their combination, the global gravity field and geoid with unprecedented precision and spatial as well as temporal resolution. These three missions are the key for the determination of gravity and geoid anomalies, ocean topography and temporal changes of gravity and geoid with much higher detail and accuracy than ever before. As a selection the altimetric missions Envisat, Jason-1, CryoSat and ICESat are shown, too. In addition, there are missions that deliver complementary data such as land and ice

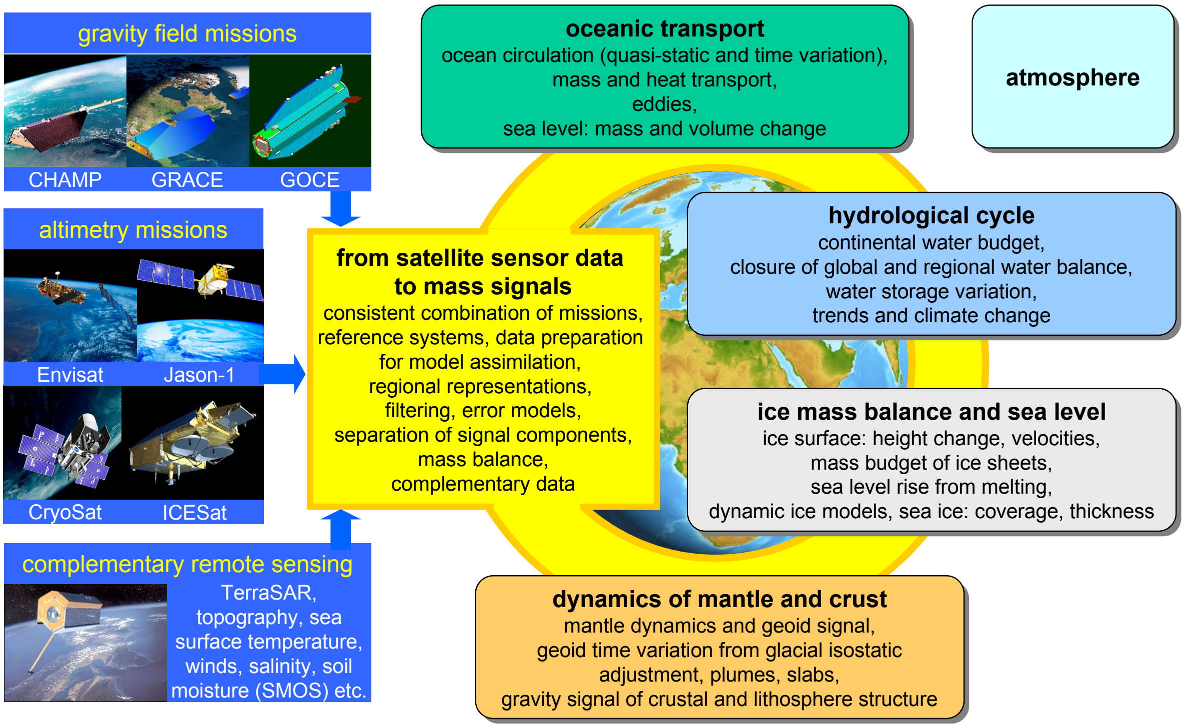


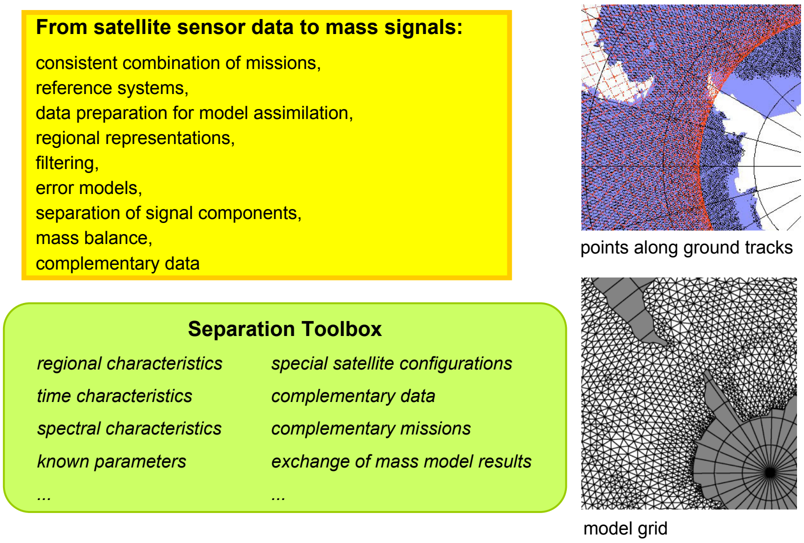
Fig. 1: Structure and themes of the program ”Mass transport and mass distribution in the Earth system”.

shape and velocities, sea surface temperature, winds, salinity, soil moisture a.s.o.

Fig. 1 shows also the four research fields: dynamics of mantle and crust, ice mass balance and sea level, hydrological cycle, ocean transport (mass and heat). The respective uses of the gravity and geoid information are indicated, too. The link between the various satellite sensor data and their geophysical application is established by the research theme ”from satellite sensor data to mass signals”.

As shown in Fig. 2, this interface theme is very challenging. Mass anomalies and mass transport signals are very small and they have to be deduced from a combination of geometric and gravimetric sensor data. This is very difficult by definition. It will only be feasible if all involved satellite sensor systems operate as one Earth encompassing global instrument. This implies that all satellite systems have to be integrated into one terrestrial reference system, with a relative precision of one part-per-billion, free of systematic distortions and stable over decades. The International Association of Geodesy (IAG) has initiated the pilot project ”Integrated Global Geodetic Observing System” (IGGOS) with this goal. Here one has to deal with its realisation for all used satellite systems. In a further step the geometric and gravimetric products have to be prepared for data assimilation into Earth models. Thus, on the one hand, their mathematical representation has to be compatible with the assimilation model; on the other hand, a complete stochastic model has to be developed that takes into account the stochastic properties of the sensor data, their propagation to the assimilation model, an appropriate sampling strategy in space and time as well as the size and character of omission errors. The third area of research, related to this theme, is the separation of the measured mass signals into all individual effects. For this purpose a comprehensive separation strategy has to be developed, see Fig. 2 (lower part).

The output of this interface theme are mass signal data, fully assessed and prepared for data assimilation. The theme ”dynamics of mantle and crust” will deal with modelling of the crustal and lithospheric structure, mantle dynamics, mantle plumes, subducting slabs, and glacial isostatic adjustment. It will exchange information on postglacial rebound with the theme ”ice mass balance and sea level”. Here the aim will be the improvement of dynamic ice models and mass budget. For the first time it will be possible to determine the ice mass balance of the polar areas directly, based on geometric information about changes of ice cover and ice velocity, crustal motion and gravimetrically measured mass changes. This will, for example, give an answer to the open question, whether the Antarctic ice sheet is loosing mass or not. A key challenge is the separation from vertical land movements. Sea level change is a link to the oceanographic



From satellite sensor data to mass signals:

consistent combination of missions,
reference systems,
data preparation for model assimilation,
regional representations,
filtering,
error models,
separation of signal components,
mass balance,
complementary data

Separation Toolbox

regional characteristics	*special satellite configurations*
time characteristics	*complementary data*
spectral characteristics	*complementary missions*
known parameters	*exchange of mass model results*
...	...

points along ground tracks

model grid

Fig. 2: Challenges for geodesy: consistent combination of missions, combination of different representations (e.g. points along tracks with triangular mesh models, see the examples to the right), and separation strategies.

Table 1: Core team for the proposed priority program on mass transport and mass distribution in the Earth system

Prof. H. Schmeling	Univ. Frankfurt/M	mantle dynamics
Prof. D. Wolf	GFZ Potsdam	mantle dynamics
Prof. H. J. Götze	FU Berlin	crust dynamics
Prof. R. Dietrich	TU Dresden	ice mass balance
Prof. H. Miller	AWI Bremerhaven	ice mass balance
Dr. C. Haas	AWI Bremerhaven	ice mass balance
Dr. Ph. Huybrechts	AWI Bremerhaven	ice mass balance
Prof. D. Stammer	Univ. Hamburg	oceanic transport
Prof. W. Zahel	Univ. Hamburg	oceanic transport
Dr. J. Schröter	AWI Bremerhaven	oceanic transport
Prof. A. Bardossy	Univ. Stuttgart	continental hydrology
Dr. J. Riegger	Univ. Stuttgart	continental hydrology
Dr. B. Merz	GFZ Potsdam	continental hydrology
Dr. A. Güntner	GFZ Potsdam	continental hydrology
Prof. K. H. Ilk	Univ. Bonn	gravity field, coordination
Dr. P. Schwintzer	GFZ Potsdam	gravity field
Prof. Reigber	GFZ Potsdam	gravity field
Prof. R. Rummel	TU München	gravity field
Dr. J. Flury	TU München	gravity field, coordination
Dr. W. Bosch	DGFI München	altimetry

part of the project where the separation of the steric and mass related component of sea level variations is addressed. The theme ”hydrological cycle” is a first attempt to employ global mass movements as large scale constraints for continental water budget and for global and regional water balance, for storage variation, trends in evapotranspiration and ultimately climate change. As large parts of the continents are very sparsely covered by hydrological in-situ data, the satellite data could enable considerable improvements for hydrological modelling, due to the global coverage. The ocean theme will concentrate on ”ocean transport”. Here dynamic ocean topography as derived from altimetry and geoid will yield global ocean surface circulation. Oceanographers are waiting in particular for the so-called barotropic component of circulation, which could not be measured so far. On the other hand, gravity changes can be related to bottom pressure variations and to deep ocean circulation. Thus, it is to be seen what the effect of these new types of global data will be on ocean modelling.

A detailed description of this research proposal is given in [2]. The list of core group members is given in Table 1. Coordinators are Prof. K.-H. Ilk and Dr. J. Flury.

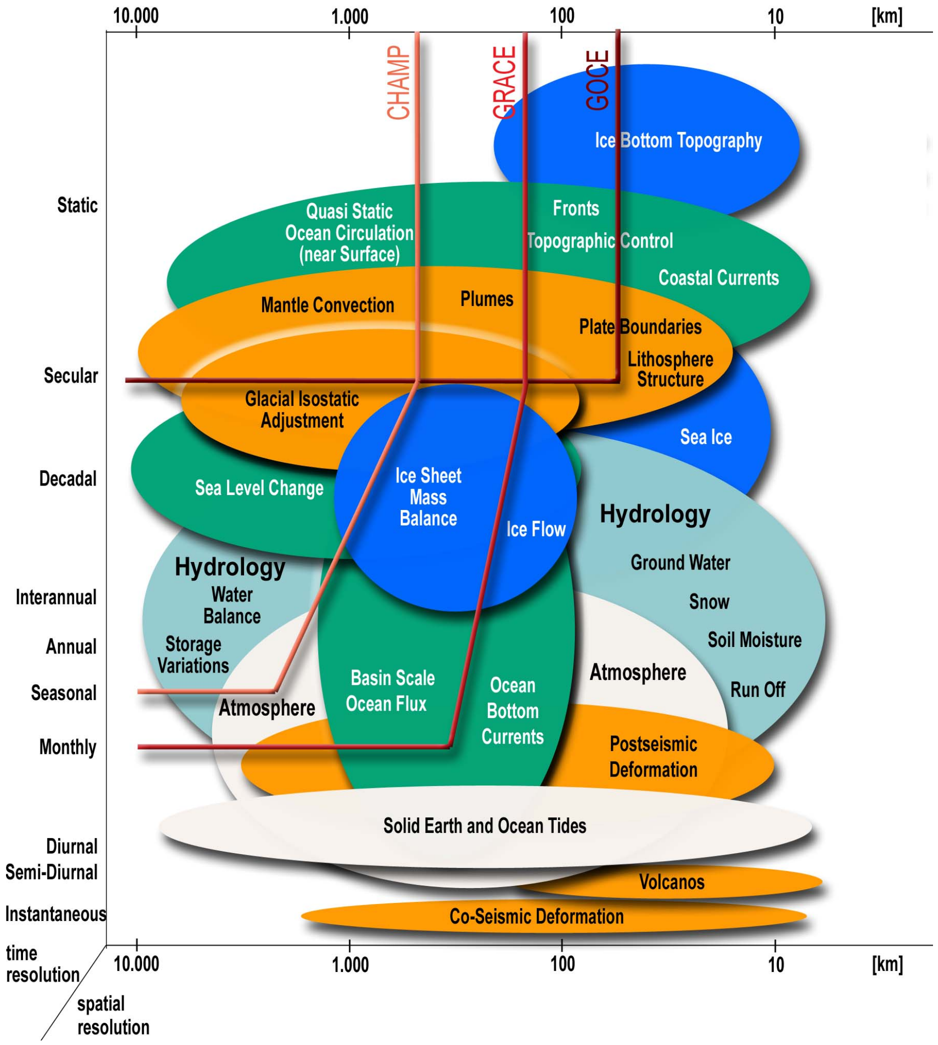


Fig. 3: Temporal and spatial scales of geoid signals associated to solid Earth (orange), ocean (green), ice (dark blue) and continental hydrology (light blue) processes. The red lines show the spatial and temporal resolution limits of the CHAMP, GRACE and GOCE missions. From [2].

4 THE FUTURE

It has been pointed out that the above research and similar research initiatives on an international level are based on this unique and excellent constellation of geometric and gravimetric satellite missions. Thus, the question arises whether these missions and the related research projects are able to answer all questions concerning mass transport in the Earth system. Of course the answer is in the negative. For this reason, an assessment has recently been carried out about the need of future gravimetric satellite missions. This investigation has been done in the context of a study to ESA on ”Scientific Objectives for Future Geopotential Missions” [12]. Fig. 3 summarizes the state of affairs after CHAMP, GRACE and GOCE. It can be seen that the emphasis of future missions has to be on the accurate and much more detailed determination of temporal variations of gravity and geoid. The temporal resolution should aim at monthly variations, the spatial resolution on typically half-wavelengths of 100 km or shorter. This is difficult to achieve. Only very sophisticated low-low SST links in very low orbit and based on laser tracking or new concepts of satellite gravity gradiometry may be able to meet these challenges. In a workshop at the International Space Science Institute in Bern, Switzerland, in 2002, compare [13], a group of invited participants discussed future concepts of gravimetric satellite systems and their use in Earth science. What is needed now is the formulation of a mission proposal for a next generation gravimetric satellite mission as well as a comprehensive and conclusive scientific rationale.

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