

# **Roadmap Towards Future Satellite Gravity Missions in Support of Monitoring of Mass Redistribution, Global Change, and Natural Hazards**

## **STRATEGIC TARGET**

A multi-decade, continuous series of space-based observations of changes in the Earth's gravity field begun with the GRACE mission, and leading, before 2020, to satellite systems capable of global determination of changes in the Earth's gravity field from global down to regional spatial scales and on time scales of two weeks or shorter, as a contribution to an integrated, sustained operational observing system for mass redistribution, global change, and natural hazards, and in support of global water management, the understanding of climate variations, and the characterization and early detection of natural hazards.

## **PREAMBLE**

The success of recent satellite gravity missions has demonstrated that mass-transport observations are critical for monitoring key climate indicators such as ice-sheet mass balance, terrestrial water-storage change, sea-level rise, and ocean circulation. This roadmap recommends goals for future missions and identifies scientific and technological developments consistent with these goals. It describes activities that could lead from these first pioneering satellite gravity missions to a future where operational constellations of satellite gravity missions are a core element in a comprehensive Earth system monitoring system that serves both science and societal applications. The road to such a monitoring system requires scientific and technological development in many areas ranging from geophysical models used in interpretation of data, to processing algorithms, to mission design and instrument technology. The potential scientific and societal benefits of such a monitoring system are high, and they can only be achieved with gravity missions.

This roadmap is addressed to the Member Countries and Participating Organizations of the Group on Earth Observations (GEO). For GEO, it provides the framework for coordination of national programs and activities of the Participating Organizations to facilitate progress towards the common goals described in this roadmap.

The roadmap specifies activities that will inform the space agencies about the requirements for satellite gravity missions, and it signals the commitment of scientific and technological communities to take a leading role in the necessary research and development required for the mission definition, processing algorithms, models, and applications.

The roadmap involves science and technology communities whose active participation is needed in order to reach from today's position to the envisaged future. For these communities, the roadmap provides guidance and the context for necessary activities. Achieving significantly improved satellite gravity missions requires co-operation of multi-disciplinary teams in different countries in joint and coherent activities. The roadmap aims at facilitating the coordination of these activities, in particular across national and disciplinary boundaries.

## **ORIGIN OF THE ROADMAP**

This roadmap is the result of the Workshop “Towards a Roadmap for Future Satellite Gravity

Missions,” which was held on September 30 – October 2, 2009, at the Graz University of Technology, Graz, Austria. This workshop was jointly organized by the Group on Earth Observations (GEO), the International Association of Geodesy (IAG), the Global Geodetic Observing System (GGOS), the International Geoscience Program (IGCP) 565 Project, the National Aeronautics and Space Administration (NASA), and the European Space Agency (ESA). The workshop built on the results and recommendations of the previous user-community workshop “The Future of Satellite Gravimetry” held in April 2007 in Noordwijk, The Netherlands.

The workshop brought together 56 scientists from 11 countries and three continents representing scientific organizations, space agencies, research institutions, and universities. Full documentation of the workshop is available at <http://www.iag-ggos.org/workshops/Graz>.

## INTRODUCTION

### ***Why gravity? A unique quantity related to mass redistribution in the Earth system***

The Earth's gravity field is the result of the mass distribution in the complete Earth system, including solid Earth, oceans, atmosphere, ice, land, and biosphere. Mass redistribution in any of the Earth subsystems changes the gravity field. Satellite gravity missions provide integral measurements of mass redistribution and transport from the whole Earth system including all subsystems from the outer atmosphere to the center of the Earth. Satellite gravity measurements therefore establish a key element of Earth observation. They offer the possibility of closing the Earth mass budget comprising the effect of various interacting processes within the Earth System. With a global view of mass transport, they provide a unique framework in which the results from other missions for observations of Earth subsystems can be related to each other.

At time scales from hours to several decades, mass relocation in and among the various reservoirs of the water cycle is one of the main contributions to mass redistribution. Climate change and human interference are changing the water cycle at all levels, from local to global scales, seasonal and longer time scales, including sudden, extreme events. Sufficient access to water for human and animal consumption, for agriculture, energy production, industrial processes, and urban life is a key element of sustainable development. Today, more than one billion people are without access to sufficient clean drinking water, and worldwide, water resources are under increasing pressure from competing and often conflicting usage. As emphasized by the 2<sup>nd</sup> United Nations Water Report, water shortage is mainly a problem of poor governance, often caused or worsened by insufficient scientific understanding and quantitative knowledge of the water resources and their changes over time. Clearly, understanding the water cycle and related global changes currently witnessed all over the world is a crucial task for the world community, and one that would be greatly facilitated by establishing a dedicated monitoring system.

The potential of satellite gravity missions to monitor geodynamic processes has been demonstrated. These processes include coseismic, post-seismic, and potentially inter-seismic signals and large-scale geodynamic processes including glacial isostatic adjustment. It has also been demonstrated that satellite gravity missions have a *unique* capability to measure ice sheet and glacier mass ablation or accumulation, terrestrial water storage change, and ocean mass variations. Satellite gravimetry is the only space-based technology able to observe mass variability beneath the top few centimetres of the Earth's surface, exemplified most recently by the detection of a decline in the water table in northwestern India between 2002 and 2008 of about 33 cm/yr due to groundwater withdrawals for

irrigation; also exemplified by its measurement of net decreases in the masses of ice stored in Greenland, certain regions of Antarctica, and Alaskan glaciers, over the same time period. These measurements directly provide quantifications of anthropogenic and climate change impacts and of geophysical causes of global sea-level rise.

**Satellite gravity missions are a unique observational system for monitoring mass redistribution in the complete Earth system – no other sensors could do the same.**

### ***Where we want to go? The goal***

The goal is to establish a worldwide satellite-based system (or system of systems) to monitor mass redistribution in the Earth system. The mass-variation and mass-redistribution products generated by such a monitoring system constitute essential variables for the improved understanding of global change and climate evolution, and also provide a much refined framework for assessment and analysis of natural hazards and related mitigation measures that serve both science and societal applications.

Measuring mass redistribution on a range of spatial scales and consistently over decades is arguably one of the most valuable products for climate and global change research, and earth sciences in general, and this product is currently missing in the Earth observation database. Only long and continuous records enable us to exploit the signal content to its maximum extent.

### ***Where do we stand?***

The Gravity Recovery And Climate Experiment (GRACE) mission provides the most accurate measurements of temporal changes in the Earth's gravity field. This mission has a designed lifetime of 5 years, and it is currently in its 8<sup>th</sup> year of operation. It may be difficult for GRACE to last until 2013, more than twice its designed lifetime, and presently no follow-on mission has been decided upon. Current agency plans leave a potentially large gap between the end of GRACE and a follow-on mission. If no such follow-on mission can be implemented in a timely manner, science would lose a key component in the observing system for the water cycle. This would interrupt, potentially for years, the recent progress in understanding the water cycle facilitated to a large extent by GRACE, and make difficult, if not impossible, the connection of the critical GRACE time series with later missions. Moreover, in times when we can expect that climate change and increasing human interference will cause significant changes in the water cycle with potentially dire and unexpected consequences, a significant reduction in the observation system of this crucial mass and energy cycle would be unacceptable. Thus, a follow-on mission, launched before the middle of the next decade, with accuracy and resolution at least as good as GRACE's is essential.

With the Gravity field and steady-state Ocean Circulation Explorer (GOCE), which was launched in March 2009 and has a designed lifetime of 20 months, the accuracy of the static gravity field is expected to be improved significantly and to reach 1-2 cm at wavelengths of 100 km or better. A high-resolution static gravity field provides a unique physical reference surface for diverse geophysical processes, including the time-variability. This will in turn have considerable impact on our understanding of ocean dynamic topography, mass and energy circulation and distribution in the oceans, and also on our ability to understand and model geophysical processes taking place on the Earth's surface, including sea level rise. Spatially detailed gravity anomalies at 1 mGal accuracy and at the same resolution will furthermore lead to a much-improved understanding of geophysical processes taking place within the Earth, such as post-glacial adjustment and post-seismic deformations.

### ***What is needed in order to get from here to there?***

In order to meet the goal of ensuring a long sequence of satellite gravity missions, a follow-on mission for GRACE needs to be decided on, planned and implemented in a timely manner to avoid an undesirable gap in the record of Earth gravity changes.

In order to serve the current and emerging requirements for science and applications, the science and technology developments required to build improved satellite gravity missions, potentially based on novel principles or novel sensors, have to be carried out. The limitations of the current missions provide a solid basis for the development of new mission concepts and designs as well as improved or new sensors, which would allow us to overcome these limitations and to push the accuracy, spatial and temporal resolution, and latency of the results to unprecedented levels. However, in order to use resources effectively and progress in a timely manner, both research and technological developments need to be coordinated and focused (including processing, modeling, applications, principles, sensors, and mission design). Support and coordination across national borders is needed, and coordination of missions, including the development of multi-mission plans, is essential. This is an effort in which both geoscientists and state-of-the-art technology developers from research institutes and industry should work closely together.

#### **THE WAY FORWARD: THE MAP**

##### **Activity 1: Science developments**

###### *1.1 Identifying the guiding science questions and application*

Many scientific studies and practical applications benefit from knowledge of mass redistribution in the Earth system and its subcomponents. Scientific disciplines that could benefit include solid Earth physics (e.g., glacial isostatic adjustment, co-/post-seismic deformation, slow/silent earthquakes, plate tectonics, mantle convection, volcanoes, and core motion); hydrology (e.g., directly through observation of water stored on land including groundwater, soil moisture, snow, and surface waters, and indirectly by constraining fluxes including precipitation, evapotranspiration, and runoff); glaciology (e.g., ice mass balance, bottom topography, ice compaction, and geoid for sea-ice thickness); oceanography (e.g., mean flow, narrow currents, topographic control, coastal currents along shelf edges, interaction between mean and eddy flow, positions of ocean fronts, bathymetry, basin-scale mass change, deep water formation, and bottom currents); sea level (e.g., separation of steric and non-steric sea-level changes and global sea-level change monitoring); geodesy (e.g., a unified global vertical reference); and climate change (e.g., quantifying and understanding the global water and energy cycle). Emerging practical applications of satellite gravimetry are regional water management, drought monitoring, seasonal snow-pack and stream-flow forecasting, and mitigation of natural disasters such as floods.

Only a dedicated effort will ensure that a concise overview of the relevant science and societal problems benefiting from gravity missions is readily available. This overview will help to ensure that user and mission requirements can evolve in order to maintain relevance to the emerging scientific questions and priorities, as well as practical applications, that could benefit from improved knowledge of the gravity field and its temporal variability.

## *1.2 Consolidating and reviewing user and mission requirements*

Over the past decades, requirements of users in science and practical areas concerning the knowledge of the Earth's gravity field and its changes have evolved considerably, impacted by progress in our understanding of Earth-system processes, technological developments in various areas, changing needs for applications depending on knowledge of gravity changes, emergence of sophisticated decision support systems, and changing societal priorities. It is likely that the recent rapid development in requirements will continue. In order to plan and implement efficient satellite gravity missions that will meet the requirements during their lifetime, it will be necessary to periodically review the user requirements and to derive mission requirements consistent with technological and mission-cost limitations. These requirements will have to consider both the static and the time-variable parts of the gravity field. For both parts, observational requirements will have to be specified in terms of observation time span, spatial resolution, temporal resolution, accuracy, and latency. The level of scientific consolidation of the geophysical requirements has to be assessed, and those themes that need new sensitivity studies have to be identified. These activities will lead to a more comprehensive set of geophysical requirements that can be used to derive mission requirements.

## *1.3 Meeting the scientific challenges on the road to future gravity missions*

Time-variable gravity field observations include contributions from mass relocations related to all geophysical phenomena. The separation of the sources of mass redistribution is an ongoing topic of scientific research. The most promising techniques use complementary (geodetic and non-geodetic) observations and our knowledge of Earth-system processes as represented in sophisticated numerical models in order to disaggregate the components in a physically consistent manner. Improvements of these models require a joint effort in Earth-system modeling, in particular since various processes are interacting across the boundaries of subsystems. The consistent integration of gravity observations with those of surface displacements of the solid Earth and changes in Earth's rotation are one step towards improved inversions.

## **Activity 2: Technology developments**

### *2.1 Short-term developments*

In the short term, highest priority has to be on preventing or minimizing gaps in the observation time series and to ensure continuation at least with the performance presently available from GRACE. For a short-term mission implementation, no significant advance in technological development is needed, but based on GRACE heritage and in-flight experience, some incremental improvements of the instruments and subsystems used in GRACE have to be performed. These include microwave ranging, electrostatic accelerometers, and thermal, attitude, and spacecraft control. Novel techniques such as Laser interferometry are not mandatory, but could be added as demonstration packages.

### *2.2 Medium-term developments*

For the medium term, the main goal is to increase the performances in terms of lifetime, spatial resolution, temporal resolution, and accuracy, as well as to provide complementary observations. This goal requires the development of more advanced technologies. Anticipated developments include inter-satellite laser ranging with emphasis on fine laser beam pointing control, advanced electrostatic

accelerometers (with capacitive or optical sensing), active compensation of drag forces, refined attitude control, and enhanced platforms with high-dimensional and thermal stability. The added value of complementary measurement instruments (e.g., altimeters, GNSS reflectometry) should be investigated in parallel.

Important elements of a strategy to achieve the medium-term goals are configuration flights and multi-satellite systems. Consequently, in parallel to the technological developments, a concise evaluation and assessment of these different sensor systems and multi-satellite constellations in terms of a matrix of generalized mission concepts is indispensable. At present, two or more pairs are preferred, with one pair probably in a moderate inclination orbit.

### *2.3 Long-term developments*

In the long term, the goal is to increase the accuracy and resolution of gravity satellite missions by studying novel measurement principles and techniques as an alternative to already established technologies. Employing such new sensing techniques and benefiting from general technological advancements, new missions designs in the direction of configuration flights, multi-satellite systems, and constellations will become attainable.

### *2.4 Matrix of mission concepts*

A matrix of mission concepts as a consistent overview of the considered concepts should be maintained. This table should address at least the following characteristics for all mission concepts: mission (user) requirements; expected performance; strengths and weaknesses of the mission concept; level of technological maturity; expected qualification time; activities needed to reach technological maturity; level of readiness of supporting science; remaining scientific challenges and expected solution time; complementarity with, and need of, external data sources; cost estimates; and preliminary ranking.

## **Activity 3: Mission implementation**

### *3.1 Facilitate the international coordination of science and technology activities*

Success of the activities described in this roadmap depends strongly on sufficient international cooperation. There are a number of existing international organizations that could provide forums for such coordination. Potentially, the creation of a dedicated multi-organization working group with participation of the relevant scientific and intergovernmental organizations, and with links to relevant users could be an efficient avenue. Since gravity missions need to be developed in very close cooperation between science and technology, a strong contribution of technology communities to this working group is pivotal. The goal of such a working group would be to support the development of long-term plans for the implementation of the roadmap.

In order to have a clear mandate from relevant organizations and countries, this working group could be integrated in the frame of GEO, or it could be associated with an appropriate United Nations agency. A first step should be the evaluation of various options for the creation of such a forum for international cooperation.

### *3.2 Develop a proposal for a virtual constellation for mass redistribution*

Space agencies, particularly in the frame of GEO, have started to implement the concept of virtual constellations. A virtual constellation for mass redistribution in the fluid envelop of the solid Earth would respond to many urgent scientific problems and practical applications. Among other sensors, such a virtual constellation would have to include a set of gravity missions. Therefore, a dialog with GEO and the Committee on Earth Observation Satellites (CEOS) should be initiated with the goal to develop a proposal for a virtual constellation for mass redistribution.

### *3.3 Inter-agency coordination*

The need for a long series of satellite gravity missions requires coordination of plans between different space agencies and agencies with operational monitoring satellites. A dialog should be initiated on the CEOS level with the goal to promote inter-agency coordination of plans and missions consistent with the goals of this roadmap.

### *3.4 Agency plans including operation*

In particular, the development of future improved satellite gravity missions and the development of versatile products requires support from scientific and technological communities outside of the space agencies. This support should be facilitated through participation of representatives of the relevant science and technology communities in the development of mission plans and the processing of observations, e.g. by working with agency representatives and on advisory boards.

## **Activity 4: Processing, modeling, and applications**

### *4.1 Processing*

The current achievements and limitations of results obtained, based on GRACE observations, indicate a need for new conceptual definitions and practical representations of the time variable and the static gravity field. Alternative representations of the time-variable gravity field are under investigation, and it is expected that these would improve the space geodetic and geophysical applicability of the measurements.

Separation of the sources of time-variable gravity is a major issue, for example, the separation of atmospheric, terrestrial water storage, and oceanic signals. Although mission design can improve separability, much depends on the data processing. Methodologies that favor separability need to be developed. Separation may be achieved by use of the space-time variable “fingerprints” determined from complementary measured or modeled data, which could be used as empirical space-time functions for the separation. The combination of observations of surface deformation and Earth’s rotation variations with time-variable gravity observations is another avenue to better separability as the “fingerprints” in these three types of observations differ significantly. Availability of ancillary satellite data (e.g., altimetry) is crucial for validation, combination, and creation of standard and cross-products.

### *4.2 Geophysical modeling*

Both the present GRACE mission and future gravity missions will significantly benefit from improve

geophysical background models in the high-frequency spectrum, particularly for oceanic and atmospheric mass relocation (including tides). Improvements will require modeling efforts in the atmospheric and oceanographic community as well as in the data used to force these models. It is likely that these models need to be provided at higher temporal (down to 1 hour) and spatial resolution. Assimilation of altimetry data in tide models and hydrodynamic models forced by the atmosphere will provide a better description of these rapidly varying phenomena. Assimilation of GPS/Galileo meteorological data in atmospheric global circulation models (GCMs) will also contribute to tracking the water vapor in the atmosphere.

A special effort has to be made to ensure consistency of complementary geophysical models of subsystems inside a comprehensive Earth-system model, which would provide the framework for coherently merging various sources of information. In particular, stability of the submodels in terms of mass budget and fluxes needs to be improved.

On longer time scales, improved models for secular contributions from geophysical phenomena impacting the gravity field such as glacial isostatic adjustment are required, in particular for the determination of mass balance in other slowly changing reservoirs, such as the ice sheets and glaciers.

#### *4.3 Supporting science and societal applications through a dedicated service*

Future gravity missions will have to provide user-friendly, short-latency, and standardized products. This will require that more resources be dedicated to the delivery of end products which are easily accessible, understandable, and usable by a wide range of users. Scientists and decision makers in, for example, hydrology, oceanography, meteorology, glaciology, climatology, and water resource management would be able to fully utilize the potential of satellite gravimetry products if they were ready for use with minimal additional processing required. Current publicly available products are rarely optimal for the user's objectives, and exploitation of the GRACE observations would benefit if a standard set of optimal gravimetry products could be made easily obtainable with end-users in mind.

Establishing an IAG Service for satellite gravity products, including mass variations in different components of the Earth system, would be a step towards such products. This service would have to include the main processing centers of satellite gravity measurements, and it would provide multiple combined, standard gravity products that would not require post-processing by the users. The service would also provide the framework to deal with technical aspects of the combination of different products, and thus not bother the users with these details. The products would serve different user needs (gravity anomalies, equivalent water heights), and the products could be tailored for geophysical, climatological, hydrological and/or other societally-relevant applications.

A satellite gravity service should also develop a public domain framework for studies of major science challenges that could use the gravity observations and products for research. In particular, a framework for the interpretation of mass redistribution in terms of climate change would greatly enhance the usability of the gravity observations.



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