The Future of Satellite Gravimetry

Report from the

Workshop on The Future of Satellite Gravimetry

12-13 April 2007, ESTEC, Noordwijk, The Netherlands

Radboud Koop and Reiner Rummel (Eds.)

IAS TUM Institute for Advanced Study

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Editors information:

Dr. Radboud Koop
Until 01/07/2007 at SRON Netherlands Institute for Space Research
From 01/07/2007 at NIVR Netherlands Agency for Aerospace Programmes
Email: r.koop@nivr.nl

Prof. Dr. Reiner Rummel
Institute for Astronomical and Physical Geodesy, Technische Universität München
Email: rummel@bv.tum.de

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1 Resolutions

On 12-13 April 2007 an International Workshop on The Future of Satellite Gravimetry took place at ESA/ESTEC, Noordwijk, The Netherlands. About 50 leaders from Earth sciences, fundamental physics and technology related to the field of satellite gravimetry participated. In a unanimous vote the workshop participants came to the following recommendations:

1 GRACE is demonstrating very successfully to provide monthly time series of changes in the Earth's gravity field. This adds a new – and very central – parameter set to the study of Global Change phenomena such as deglaciation in the large ice shields of Antarctica and Greenland or the variations of the global water cycle.

2 GOCE – to be launched 2008 – is expected to deliver the global static gravity field and geoid with unprecedented precision and spatial resolution. It will in particular serve as reference for global ocean circulation studies by altimetry.

3a In view of science achievements and the current performance of GRACE the participants of the workshop strongly support the idea of a GRACE follow-on mission based on the present configuration, with emphasis on the uninterrupted continuation of time series of global gravity changes. This should be short-term (Launch ~2011 TBD) priority one.

3b In parallel, investigations into the reduction of the aliasing problem offers even greater science benefits by increased spatial resolution and accuracy and should therefore have high priority.

4 Medium term priority should be focused on higher precision and higher resolution in space and time. This step requires (1) the reduction of the current level of aliasing (of high frequency phenomena, in particular tides, into the time series), (2) the elimination of systematic distortions (caused by the peculiar non-isotropic sensitivity of a single pair low-low SST), and (3) the improvement of the separability of the observed geophysical signals.

Elements of a strategy in this direction are configuration flights, multi-satellite systems, improved data processing methodologies and improved and comprehensive Earth System modeling.

This will open the door to a more efficient use of improved sensor systems, such as optical ranging systems, quantum gravity sensors, and active angular and drag-free control.

5 The long term strategy should include the gravimetric use of advanced clocks (ground based and flying clocks), micro-satellite systems, and space-qualified quantum gravity sensors.

6 The participants of the workshop support the activities and developments towards a future satellite gravity mission.

7 The workshop results will be offered to national and international space agencies and other relevant institutions.

8 The initiative will be taken to set up an international steering/working group or platform to coordinate the future activities and actions in this field.

9 Links between the geodetic and Earth science community with the communities from fundamental physics will be strengthened and/or established.

2 Introduction

By Radboud Koop and Reiner Rummel

With CHAMP and GRACE successfully in operation and with the GOCE launch shortly ahead, remarkable progress in scientific fields exploiting the strongly improved global gravity field knowledge is currently being made.
At the same time new and improved technologies – like laser metrology, accelerometry, position sensing, micro-propulsion systems – are currently under development, most noticeable related to the LISA, LISA Pathfinder, GRACE follow-on and Laser Doppler Interferometry (LDI) mission proposals.

Although the technologies to be implemented in a future gravity mission are still subject of ongoing discussion, development and selection, it can be expected (and it is actually the aim to achieve) that the data coming from such a mission will be of very high quality, having a very high spatial and temporal resolution and a very high accuracy.
Major achievements in the fields of hydrology, solid Earth geophysics, oceanography, glaciology and geodesy are within reach as the user community exploits these data to the fullest extent possible.

Over the years the scientific community has clearly identified what are the most important requirements for future progress in this field, related to geoscientific modeling, data processing, analysis, methodology and interpretation. This includes questions related to topics like the separation of geophysical signals in the gravity data, temporal and spatial de-aliasing, availability of complementary data and models, etc.
This challenging scientific progress is a necessary step towards the definition of realistic scientific and mission requirements for a future gravity mission. The establishment of such requirements, that are to be aligned with the system and sub-system requirements, is a natural starting point for the preparation of a mission proposal.

It is clear that the chances for realization of a future Earth gravity mission will be enhanced by a solid support from the scientific community, just as by the ongoing technological developments. While at several places research, programmatic and development activities have already started, a coordinated effort in these fields (including geoscientists, representatives from space agencies and representatives from the technology development organizations) could prove to be of additional value.

Therefore a 2-day “Workshop on the Future of Satellite Gravimetry” was held on 12 and 13 April 2007 at ESA/ESTEC in Noordwijk, The Netherlands. We gratefully acknowledge ESA/ESTEC, and in particular the local organizers Michael Kern, Roger Haagmans and Pierluigi Silvestrin, for their support and effort in the planning and organization of this workshop.
The workshop was attended by a selected number of key players from related scientific and technological fields (see Appendix 1).

The goals for the workshop were:

- to identify the open scientific issues and challenges in the fields of:
    - the use of satellite gravity field data in a broad range of geo-scientific applications (both existing fields of application as well as new fields),
    - geophysical modeling of the gravity field,
    - satellite gravity field data processing (pre-processing, calibration, corrections, etc.);
- to evaluate the status of the technological developments towards the new instrumentation for a future gravity mission, including the role of the synergy with space science missions;

- to draft a “shopping-list” of topics and issues, related to the development of a new Earth gravity mission, that need to be addressed in the following years;
- to devise a “roadmap” towards the realization of a future mission concept, showing all major milestones to be achieved by both the scientific as well as the technical communities.

The workshop, having the character of a “round-table discussion” rather than a “symposium”, was organized around 4 main topics:

1. Geophysical Applications,
2. Separability and De-aliasing,
3. Future Mission Concepts,
4. Candidate Technology.

Each topic was introduced by one or more short lectures, intended to give an overview of the topic and to stimulate the subsequent discussions. The speakers of these lectures were:

1. Geophysical Applications: Georges Balmino
2. Separability and De-aliasing: Srinivas Bettadpur
3. Future Mission Concepts: Nico Sneeuw
4. Candidate Technology: Pierluigi Silvestrin, Michael Watkins, Steve Nerem, Stefano Cesare, Ernst Rasel, Gerhard Heinzel, Stephan Schiller.

A closing talk was kindly provided by Mark Drinkwater. The contribution of all the speakers is gratefully acknowledged. A copy of all presentation material can is available on request by contacting the editors of this report.

We also would like to acknowledge the contribution of the following participants who acted as chair of the discussions:

1. Geophysical Applications: Bert Vermeersen
2. Separability and De-aliasing: Victor Zlotnicki
3. Future Mission Concepts: Roger Haagmans
4. Candidate Technology: Steve Nerem

This document is the report of the workshop. For each theme, a writing team – consisting of two workshop participants – was invited to minute the discussion and write a summarizing report that constitutes the input for the subsequent chapters of this document. We gratefully acknowledge the effort of these writing teams.

We would like to thank all participants, speakers, session chairs, writing teams and (local) organizers for their efforts and contributions in making this workshop a success.

3 Geophysical Applications

By Victor Zlotnicki and Tonie van Dam.

3.1 Introduction

The water cycle, the circulation of the oceans, the circulation of the atmosphere, shrinking ice caps, all have in common large-scale redistribution of masses as a function of time, especially from season to season and year to year. The continuing rebound of the lithosphere following the retreat of the large continental ice sheets, some 10,000 years ago, causes large-scale mass redistribution with time scales much longer than a few years. Tectonic plates sinking into the mantle under subduction zones and the topography of the core-mantle boundary are but two examples of departures of the Earth's mass field from a hypothetical hydrostatic equilibrium, even if time change is not involved (or is much longer than centuries). All such mass redistributions produce an associated signal in the gravity field, whether in its time variation or in its departure from some ideal shape.

As a consequence, measurements of the gravity field constrain these processes in ways useful to model them.
Consider these very few examples:

- The Earth's flattening reflects the fact that the equatorial radius is approximately 23 km longer than the polar radius (the actual definition of 'J2' is in terms of the 3 principal moments of inertia and a mean mass and radius). It directly affects the orbit of a satellite. Starting with Sputnik the value of J2 has been refined by studying the orbits of 'artificial' satellites, time changes in J2 noted, signals at 18.6 and 9.3 years identified and explained in terms of ocean tides, superimposed on a steady decrease of J2 explained in terms of post glacial rebound. In the last few years, interannual departures from the steady decrease have been explained in terms of ocean and cryospheric signals (Cox and Chao, 2002; Committee on Earth Gravity from Space, 1997).
- The relation between long-wavelength geoid highs with subduction zones and with 'hotspots' was established from crude gravity models, leading to physical models linking the variation of lateral mantle viscosity with gravity signals (Richards and Hager, 1989). Higher accuracy and resolution gravity can constrain such physical models.
- A combination of ocean surface drifter data, time-averaged altimetric sea surface height, and a GRACE derived time-averaged ('static') geoid has produced the most detailed and accurate description of the time-mean surface currents in the world's oceans over a broad range of length scales ever produced (Niiler et al., 2003)
- GRACE data identified a significant mass loss in total water storage between 2002 and 2006 in the Congo river basin in Africa. (Crowley et al, 2006).
- Sea level rise includes a component due to thermal expansion (thermosteric) and one due to mass addition by melting ice (eustatic), plus a smaller one due to salinity changes. As mentioned earlier, Lombard et al 2007 computed such a partition from a combination of satellite altimetry, gravimetry and in-situ data. What is more, the discrepancy between the in-situ and satellite versions of this curve has now been resolved – pinpointing an error in a subset of (in-situ) ARGO floats deployed since 2003 (J. Willis, 2007, pers. comm.).
- Perhaps the most striking example of the value of time-varying gravity data have been the estimates of mass loss in Greenland and Antarctica using GRACE (eg, Velicogna I. and J. Wahr, 2006; Chen, et al, 2006). While these estimates continue being refined, there is now little doubt that they contribute significantly to the current analysis of the climatic changes in our planet.

Dedicated gravity missions have included CHAMP (launched in 2000), GRACE (launched 2002), and the upcoming GOCE (to be launched 2008). Combined, these missions will give us by 2010 the most detailed view of signals such as those exemplified above that humans have ever obtained.

This information cannot come at a better time. Humankind is changing our planet in ways whose consequences we have difficulty in foreseeing due to the complex interactions among processes. For example, quoting from the fourth Assessment Report of the International Panel on Climate Change (IPCC 2007, http://www.ipcc.ch): “Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global mean sea level”. This warming has many consequences, one of which is sea level rise and the risks it poses to coastal communities. How much this warming will accelerate sea level rise depends critically on its effect on ice sheet flow: “Models used to date do not include uncertainties in climate-carbon cycle feedback nor do they include the full effects of changes in ice sheet flow, because a basis in published literature is lacking.” (IPCC 2007). Mass loss due to increased ice-sheet flow is precisely one of the quantities measured by precision time-varying gravity field estimates. Models that forecast the evolution of our climate must be able to reproduce the partition of sea level rise into the component due to thermal expansion (thermosteric) and due to mass addition by melting ice (eustatic); information on this crucial time series is also being provided, for the first time, by a combination of satellite altimetry (TOPEX/POSEIDON, JASON, ERS-1,2, Envisat, GFO), satellite gravimetry from GRACE, and in-situ measurements of ocean temperature and salinity.

Thus, the time to plan for future satellite gravimetric missions is now. Neither GRACE nor GOCE are likely to be flying by 2012, and it takes several years for a gravimetric mission to be studied, approved, designed, built, tested, and readied for launch. ***Satellite gravimetry has already proved its value, a value that increases with each annual cycle of data***.

3.2 Scientific Focus

It is necessary to describe the signals to be detected and the necessary accuracies and resolutions in time and space in order to design a mission. Many of these numbers are informed by what seems to be technologically feasible: a satellite system flying a few hundred km above the surface of the Earth will not retrieve signals over . For each problem one must have a minimum accuracy / resolution below which the problem cannot be addressed, and ideal values that the missions should target: these are the difference between ‘requirements’ and ‘targets’ or ‘desired values’. Furthermore, it is not necessary to be ‘exhaustive’ by attempting to foresee every possible class of signal that can be detected. In terms of providing mission designers with enough information to design and build a mission, it is sufficient to identify the most challenging scientific objectives to be attained, those most challenging from a technical point of view and most rewarding from a scientific and societal point of view.

For time-averaged gravity, the appropriate unit is a geoid height (mm) or a gravity acceleration (mgal). For time-varying gravity, the most useful unit is not one of gravity itself (geoid height or gravity acceleration) but one of mass change. Since Wahr et al (1998), that unit has been the thickness of a layer of water, assumed to drape the Earth’s surface, with a horizontal extent given by whatever spatial filter is applied (a regional average over Greenland, a localized area average such as a Gaussian filter, etc). That unit of mass is here labeled cm_{H2O} and reads as ‘cm of equivalent water thickness’, to distinguish it from geoid height; its relation to geopotential coefficients is given in Wahr et al (1998).

3.2.1 Time-averaged gravity field

Briefly, improved time-averaged gravity data will constrain the planform of mantle convection, the structure of the deep crust and upper mantle, and the nature plate tectonic processes, including, ridges, trenches and mountain building. For ocean circulation, gravity data are needed to determine the absolute surface geostrophic circulation from satellite radar altimetry.

Table 3-1, from Rummel (2005) summarizes the GOCE requirements, which are still the most useful targets for the time-averaged gravity field retrieval.

Table 3-1: Static gravity field, scientific requirements in preparation for GOCE, from: Rummel (2005).

Static gravity field, scientific requirements in reparation for GOCE					
Application			Accuracy		Spatial resolution
			Geoid [cm]	Gravity [mGal]	Half wavelength D [km]
Solid Earth	Lithosphere/upper mantle density			1-2	100
	Continental lithosphere	Sedimentary		1-2	50-100
		Basins rifts		1-2	20-100
		Tectonic motions		1-2	100-500
	Seismic hazards			1	100
	Ocean lithosphere/asthenosphere			0.5	100-200
Oceanography	Short scale		1-2		100
			0.2		200
	Basin scale		~0.1		1000
Ice sheets	Rock basement			1-5	50-100
	Ice vertical movements		2		100-1000
Geodesy	Levelling by GPS		1		100-1000
	Unified height system		1		100-20000
	INS			~1-5	100-1000
	Orbits			~1-3	100-1000
Sea level change			Many of the above applications, with their specific requirements, are relevant to studies of sea level change.		

3.2.2 Time varying gravity field

Improved measurements of the time-varying field help determine seasonal, interannual and long-term trends in ice sheet masses, hydrologic basins, ocean current transports, and changes in overall ocean mass. Such changes are better expressed in terms of the changes in mass that cause the change in gravity. The mass change is then expressed thickness of a thin layer of water draped over the surface of the Earth, a thickness allowed to vary with position.

The following table gives needed accuracies in terms of rates of change in mass, either averaged over 1 year or over 1 month. The averaging radii assume a lower threshold of 300 km: many signals of interest with shorter scales exist, but they are better measured with non-global observations. Values in the form 0.5 (0.1) indicate a minimum useful accuracy, and a desired or target accuracy.

Table 3-2: Accuracy requirements.

Application	**mm_{H2O}/mon**	**mm_{H2O}/yr**	**smoothing radius (km) ≥ 300**	**Timescales and Notes**
Hydrologic basin total water change	10	20 (10)	400	days to decades
Glacier mass loss		2 (1)	300	seasonal, interannual
Ice sheet mass loss		20 (5)	1,000	
Oceanic gyres spinup or down		4 (1)	700	interannual
Global Sea level rise: thermosteric / eustatic		1 (0.3)	5,000	seasonal, interannual
Glacial Isostatic Adjustment		0.5 (0.1)	1,000	5-10 years

3.2.3 Complementary Data, Separability, Aliasing, Modeling

These topics deserve an entirely separate section and will be addressed later. However, it is important to note here that gravity is a powerful integrator: it ‘senses’ the combined changes due to many effects, and it helps eliminate unphysical estimates or models of the processes involved. As GRACE and CHAMP have shown, time changes in the gravity field with time scales shorter than the monthly or longer averaging estimate, alias into longer period components. All these issues indicate the need for (a) additional data types to help separate the various contributions to the gravity signal; (b) accurate models of the shorter time scales of the gravity field; (c) improved Earth models to take advantage of the new gravity data.

Examples of (a) include: radar altimetry to measure the slope of sea surface with respect to the horizontal provided by a gravity mission or the time variations in both; laser altimetry to measure ice sheet changes. Examples of (b) include the European Center Medium Range Weather Forecast’s model of the global atmosphere and models of ocean and hydrologic changes accurate over at least short time scales (eg, Dobslaw and Thomas, 2005; Rodell et al., 2004). Examples of (c), models capable of assimilating the data from these gravity missions together with other data, include Rodell et al (2004), Kim et al (2004), Stammer et al 2002, etc.

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4 Separability and de-aliasing

By Pieter Visser and Erricos Pavlis.

4.1 Introduction

It was concluded that clear definitions are required for separability and (de-)aliasing. The following definitions were discussed:

1. Aliasing: mapping of signal from higher frequencies onto lower frequencies due to under-sampling;
2. Distortion (striations, stripes): geographic systematic effects resulting from the propagation of – errors in the observations due to – the sampling configuration (non-isotropy, (near-) polar orbit, resonances, inhomogeneous ground-track pattern, etc.);
3. Separation: unraveling into its individual contributions the superposition of all possible gravity effects that the measurement system intrinsically measures.

In fact, a distinction has to be made between separability, coarse and fine spatial aliasing, and distortion. Based on GRACE results, an example of coarse spatial aliasing is the relatively low-precision C_{20} time series, an example of fine spatial aliasing are the gravity field maps displaying localized excursions, and an example of distortions are the "striations" (or trackiness) in the gravity solutions. Apart from the fact that these errors appear to be related to processing methodologies as well, in the case of GRACE the distortions can be caused by any systematic error that manifests itself predominantly at the resonances (e.g. affecting spherical harmonic order 15 coefficients) and the group of spherical harmonic coefficients with n ≈ m and n rather high.

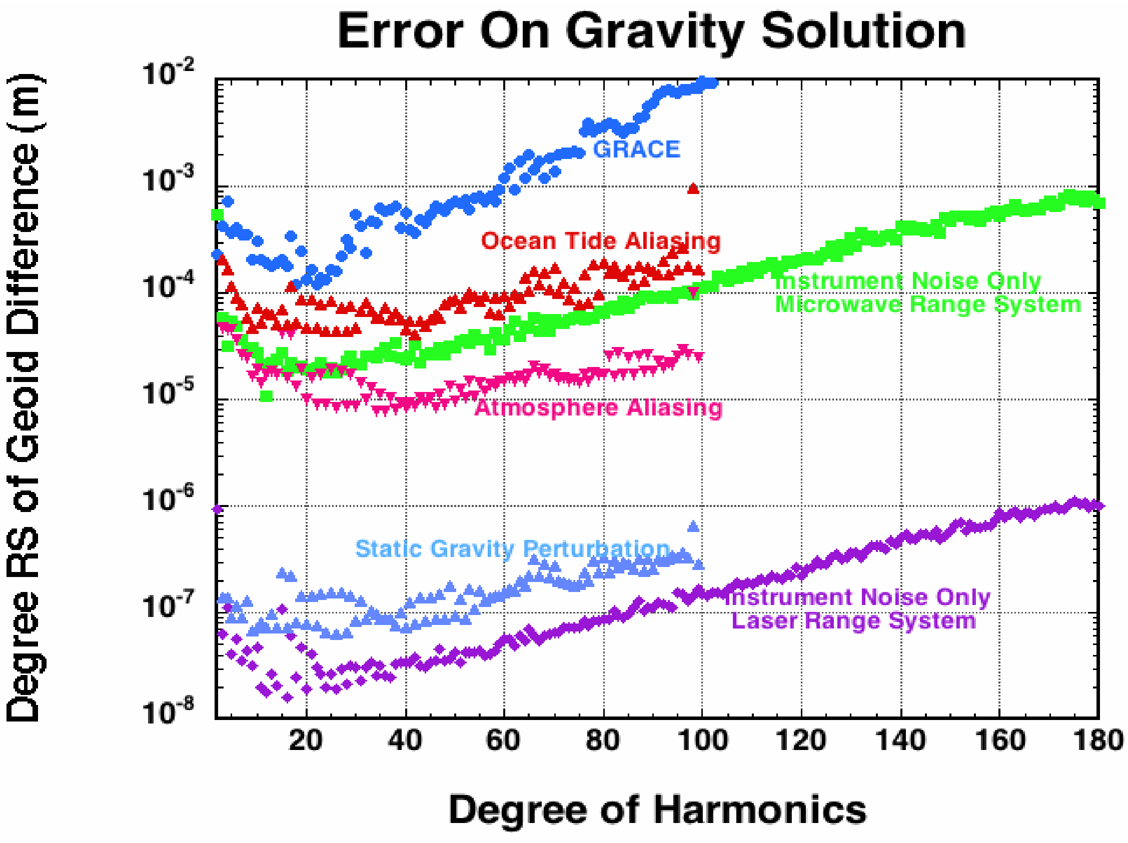

Figure 4-1: Error on gravity solution. Courtesy: M. Watkins, 2007.

In principle, instruments on board of gravity-mapping satellites observe the integrated effect of the total gravity field (static and temporally varying), which is composed of many sources (pseudo-static gravity field, solid Earth and ocean tides, atmospheric, hydrologic, polar ice mass changes, “non-tidal” ocean mass transfer, etc.). Recent experiences with GRACE demonstrate a well-known theoretical principle, that is, the accuracy of derived gravity field products is not only limited by the precision of the satellite observing system, but also – or especially – by the ability to separate the different contributors. In general, this separation is attempted by reducing the signal size of the observations by so-called background or de-aliasing models typically for taking into account atmospheric and ocean tidal mass redistributions. In recent years, such models have been improved significantly, but their accuracy still seems to be insufficient to fully exploit the information content of the observations. It is expected that this become the fundamental limitation for more precise, second generation space-borne gravity observing systems that are currently being proposed and investigated, despite the parallel improvements of these background and de-aliasing models by better data from other remote sensing techniques. For example, when nm-precision low-low SST would be possible in low Earth orbits (altitude 250 km) the ocean tide aliasing errors will be three orders of magnitude larger than gravity recovery error caused by observation noise, cf. Figure 4-1.

Fortunately, part of the ocean tide signal is separable due to the fact that they are coherent signals at well-known frequencies. Other parts, e.g. ocean tides in coastal waters, are highly non-linear and difficult to model. There are other signals though which produce gravitational signals (temporarily varying), which are very difficult to separate from pure gravitational change, since the physics and the mechanism behind them are still not well understood (e.g. soil moisture, atmospheric water, etc.).

The question of how to separate the different components of the gravity field is related to how the satellite observing system samples the gravity field in space (1) and time (2). In addition, it is always required to assess whether use can be made of complementary sensor systems (3) and complementary terrestrial, airborne and other satellite data (4), and – as already mentioned above – background models.

4.2 Sampling in space

The achievable spatial resolution depends strongly on the geographical coverage of each space-borne observing system. Results based on GRACE show for example that the quality of monthly solutions is not homogeneous because of changing – and sometimes unfavourable – ground track patterns. It might be argued that a more stringent (repeat) orbit control would lead to better performance. An important issue concerns the observing technique itself, for example one-dimensional (“one-arm” low-low satellite-to-satellite tracking (SST)) vs. multi-dimensional (“three-arm” gradiometry or special satellite formations) observations. The question is whether multi-dimensional observing techniques will reduce for example distortions. In addition, the differences in how aliasing affects observations that require orbit integration (e.g. SST) versus “in situ” observations (e.g. gradiometry) should be studied in depth.

4.3 Sampling in time

Just like with other Earth observing satellites, it is obvious that for gravity mapping satellites a trade-off has to be made between temporal and spatial resolution. It was noted that current space-borne observing systems are sensitive to temporal gravity changes with periods as small as 12 hours (e.g. background models seem to reduce the signal level of GRACE observations at these time scales). Temporal resolution at such level can not be achieved globally by a single gravity mission. Simulation studies have been carried out to assess the performance of proposed future missions such as, for example, two GRACE-type missions flying simultaneously, one in a non-repeat orbit and one with a very short repeat period. Results are so far inconclusive and more investigations are required before concrete conclusions can be drawn.

4.4 Complementary sensor systems

Strong synergies can be identified between satellite gravity missions and other satellite missions. For example, altimeter satellites have provided the information for high-precision ocean tide and ocean current models. However, there is still room for improvement, and ocean tide models in particular still require improvement for use as background models of gravity reductions. Recently, GNSS radio occultation observations (limb sounding) provide valuable information on mass changes in the atmosphere. Synergies can, or have been, identified with missions such as ICESAT, CRYOSAT and SMOS missions.

4.5 Complementary terrestrial, airborne and satellite data

It has been noted that certain parts of the gravity field are, or can be, better observed with terrestrial systems. For example, core motion and seismic events are already being accurately observed better by superconducting gravimeters. In addition, an enormous amount of terrestrial and airborne gravity data sets have been collected that can be used in support of the space-based gravimetric data in terms of calibration, validation and regional densification. An open question is what kind of other satellite missions (existing, as well as those envisioned in the near future) might support, complement, and/or enhance the products of future gravity mapping missions.

4.6 Models

It has been extensively discussed that the quality of background models (ocean tides, atmosphere, hydrology, etc.) is crucial for taking full advantage of space-borne gravity field observing systems, and in fact these might be limiting factors. Different philosophies might be pursued: further improvement on the basis of other data (existing and future), co-estimation (e.g. tidal coefficients), and/or the combination of the two. For GRACE-type missions, simulations indicate that in general the influence of various geophysical phenomena on the observations was underestimated (which can again be considered as a strength and weakness). To take advantage of the high sensitivity of such satellite gravimetry to phenomena that manifest themselves as gravity changes, further investigations are required in the near future.

4.7 Key issues

In summary, the following issues have been identified during the workshop as key issues for further discussion:

- Proper definition of separability, aliasing, distortion
- Sampling in space:
    - Orbit design/control: repeat, non-repeat
    - Observation technique: “one-arm” vs. “multi-dimensional arm”, “integrated” vs. “in-situ”, satellite formations
- Sampling in time:
    - Observing systems are sensitive to high-frequency temporal variations (<12 hr): simultaneous missions, formations
- Complementary sensor systems:
    - Synergy with other satellites data: altimetry, GNSS radio occultation, ocean temperature etc.
- Complementary terrestrial, airborne and satellite data:

  - Gravity contributors already being observed
  - Supporting data sets: calibration, validation, regional enhancement, higher frequency gravitational signal modelling (above degree ~250)
- Models:
  - Quality of background models: achievable improvement and limitations
  - Modelling and/or co-estimation (e.g. ocean tides)
  - Which gravity sources are significant and need to be taken into account?

4.8 Recommendations

In summary, the following issues have been identified during the workshop as main recommendations:
Short term:

- Additional studies:
  - Simulations of different processing strategies for GRACE data, e.g. co-estimation of more temporal gravity sources such as ocean tides
  - Further assessment of synergies with other sensors/satellite missions

Medium term:

- Requirement for continued observations by gravity missions such as GRACE in order to allow the retrieval and study of more temporal gravity sources

Long term:

- Mission scenarios for enhanced temporal and spatial sampling of the gravity field

5 Future Mission Concepts

By Jürgen Kusche and Roland Pail.

5.1 Introduction

The participants of the workshop acknowledge the great scientific advancements that has been achieved through current exploitation of the GRACE data Further improvements are anticipated from reprocessing GRACE data in the future when improved models and procedures for de-aliasing, signal separation and data analysis are available. Also GOCE will lead to greatly improved models of the Earth's mean gravitational field with medium to high resolution in the near future.

However, limitations of the current mission GRACE and also of the upcoming mission GOCE exist. They are due to lifetime, temporal and spectral resolution, the "aliasing" problem, the problem of separability of sources, and in the case of SST of the error anisotropy of the recovered fields.

Regarding the workshop theme "Future Mission Concepts", the rationale for three development phases of future missions have been identified:

- On the short time scale, it would be desirable to have a continuation of the current observation series of temporal gravity changes with GRACE, thus avoiding a gap after the GRACE lifetime expires. The only realistic option to be considered is a near-rebuild of the GRACE spacecraft and mission concept. A possible improvement of the orbital characteristics should be investigated.
- On the medium time scale, the workshop participants expressed the expectation that new mission concepts will overcome the limitations of the current mission concepts. Several candidate mission concepts (including but not limited to single or multiple pairs of GRACE-type formations, equipped with microwave or laser inter-satellite link, single or multiple pairs of pendulum or cartwheel formation, GRACE follow-on missions equipped with an across-track gradiometer) have been discussed (cf. Figure 5-1). It is felt that already now, in parallel with efforts towards a GRACE continuation mission, the community should continue investigations aiming at improved sensor systems and mission concepts.
- On the longer time scales, it appears that "new" technologies such as atom interferometry or ultra-precise clocks, which are really new in the field of gravity field research, may become part of future mission concepts. It became obvious from the workshop that the space gravimetry community should monitor closely the technology developments in these fields. It is recommended that the links to the instrument development in the field of fundamental physics be strengthened.

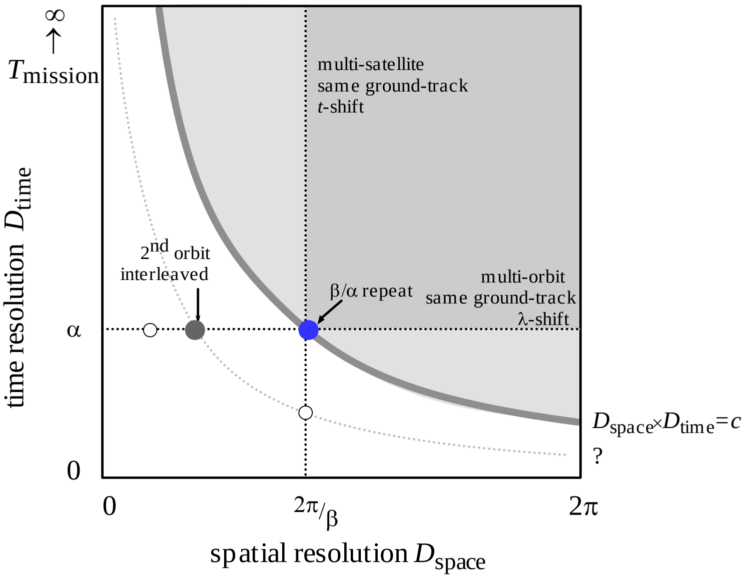

Figure 5-1: Resolution space: spatial (horizontal axis) versus temporal resolution (vertical axis) for a single β/α repeat orbit. The product of space and time resolution is constant. Thus, the single-satellite concept can never perform better in resolution space than the hyperbola. Multi-satellite and multi-orbit concepts can reach resolution space at the lower left of the hyperbola.
Courtesy : N. Sneeuw, 2007.

5.2 Recommendations

Regarding the medium timescale, the recommendation was expressed towards the space agencies to initiate studies aiming at future mission concepts already now, as a first step of a roadmap that eventually should lead to the definition of a gravity mission that overcomes present limitations. Specifically, it is proposed:

- To formulate a matrix or table, indicating in how far a set of generalized mission concepts addresses evaluation criteria such as
    - relevance to the (possibly updated) research objectives of future gravity missions
    - addressing the aliasing problem
    - uniqueness and innovation
    - complementarity with other data sources
    - level of technological maturity
    - timeliness
    - costs

  in a qualitative way.
- carrying out numerical simulations in a generalized setup regarding at least the following evaluation criteria
    - measurement accuracy and error anisotropy structure
    - mitigation of aliasing
    - temporal and spatial resolution
    - mission lifetime, detection of trends
    - stability of formation

6 Candidate Technology

By Sean Bruinsma and Jürgen Müller.
(with remarks by Peter Bender, Pierre Touboul and Pierluigi Silvestrin)

This section gives an overview of existing (i.e. flight qualified or proven) and candidate technology with respect to future Earth gravity field mapping missions. The overview is not restricted to the gravity sensor per se, but also considers supporting technology that is imperative to the optimal operation and usage of such a device.

Table 6-1 presents the gravity sensors and their present status of development, using the NASA and ESA terminology 'Technology Readiness Level' (TRL).

Table 6-1: Gravity Sensors and Their Status of Development.

	Status	**Expected qualification time***
Microwave interferometer	Flight proven (TRL9)	-
Inter-spacecraft Laser interferometer: Master-slave (2 lasers) Master+retro-reflector(1 laser)	 Qualified prototype (TRL6) Breadboard (TRL4)	 1-2 years 2-4 years
Gradiometer: Electro-static LTP Optical test mass readout Quantum Cryogenic	 Flight qualified (TRL8) Launch in 2010 (TRL7) Breadboard (TRL3) Breadboard (TRL3)	 - 1 year 15 years undefined (unfit for mission)
Drag-free low-low SST: LTP Gravity Reference Sensor One-axis Ion Thrusters 5-DoF FEEP Thrusters	 Launch in 2009 (TRL7) Flight Proven (TRL 9) Launch in 2009 (TRL 5)	 1 year - 3 years
Optical clock	Qualified prototype (TRL6)	15 years

* This is the estimated time necessary for the technology to attain the required accuracy for a gravity monitoring mission.

The K-band microwave ranging system is used in the GRACE mission. The precision of the range-rate measurements is 0.1μm/s. This instrument is sufficiently precise for a GRACE follow-on mission that primarily serves continuation of the currently established time series. Only if the level of aliasing and distortions can be reduced substantially full advantage can be taken from the second generation technology concepts discussed in the following.

The laser interferometer, using the master-slave concept, has a (demonstrated) precision of 1 nm/s and the potential to measure spacecraft relative attitudes via beam alignment with 100 nrad/Hz$^{1/2}$ noise. It requires low-power lasers (10-30 mW), which are already flight qualified, with a very high level of frequency stabilization (not space qualified yet, but under development for the LISA mission).

The single laser and retro-reflector concept, compared to that using two lasers, has the disadvantage of requiring a larger optical power for a given operating distance, though ≈ 100mW are sufficient for an inter-satellite distance of 10 km. The short intersatellite distance may prohibit monitoring of the very long wavelength temporal variations. On the other hand it is simple (just a single laser, single interferometer and phase meters), robust (the co-alignment of the retro-reflected beam is automatically ensured by the retro-reflector and does not need an active pointing system on the second satellite), and reliable (no simultaneous operation of two lasers, two interferometers and phase meters).

The gradiometer for the GOCE satellite uses six 3-axis electro-static accelerometers, the sensitive axes of which have a sensitivity of $2x10^{-12}$ $ms^{-2}Hz^{-1/2}$ (compared to 10^{-10} $ms^{-2}Hz^{-1/2}$ for the GRACE instruments) in a given measurement bandwidth. The capacitive readout has a noise level of about 6 $pm/Hz^{1/2}$. In this kind of instrument, test masses of the order of 0.07-0.32 kg are actively maintained in the center of the instrument cage through electro-static compensation. The precision in the measurement bandwidth of the GOCE gradiometer is a few 10^{-12} s^{-2}. The limit of resolution of the GOCE accelerometer (alone) is mainly due to the range of the digital conversion of the instrument analog output, which have to include as a minimum the DC gradient and its weak fluctuations. Improvement by a factor ten requires the availability of better electrical components, which seems unlikely in the near future. A factor 2 could be obtained by optimized operational conditions minimizing the margin in the maximum sustainable acceleration (the very high resolution of 10^{-15} ms^{-2} required for the microscope mission is obtained after averaging over a long period of time). In addition, the attitude control, the thermal control and the stiffness of the material used to construct and mount the instrument are extremely demanding, but they must be in step with enhanced instrument sensitivity.

Technology developed for LISA Pathfinder (launch in 2010) includes a drag-free system with inertial sensors around the 10^{-14} m/s^2 level – however designed for a very low perturbation orbit environment – and a local interferometric test mass readout with 10 $pm/Hz^{1/2}$ noise. Both of these instrument noise levels are about a factor of 100 lower than would be needed for a drag-free two spacecraft mission. This is because of the perhaps 50 km baseline between the two satellites. One main advantage of drag-free operation is being able to fly a two spacecraft mission at a lower altitude, as for gradiometers. The other is the removal of the scale factor calibration and stability requirements associated with accelerometers. A problem may be the associated shorter mission life time.

A quantum interferometer gravity gradiometer uses atomic particles, which are cooled to a few µK by laser, as free fall test masses. Its building blocks are atom-interferometer accelerometers. The projected achievable precision is comparable to that of the GOCE gradiometer, but the measurement bandwidth of such an instrument (GOCE: 5mHz to 0.1 Hz) is not yet known.

The cryogenic gradiometer has been added for completeness, but in fact is not adapted for missions exceeding 1-2 years due to the too large volume of liquid helium necessary to keep the instrument cooled.

In a wider sense also comparison of high precision clocks is related to space gravimetry. The optical clock technology offers the possibility to determine the difference in gravitational potential between clocks at different locations and therefore of establishing a unified global height datum. Such a system is required for several geodetic applications such as the global height synchronization of tide gauges for global sea level monitoring. This approach has the advantage of being independent of the satellite acceleration. However, a height change of about 1 mm at the Earth's surface necessitates a clock accuracy of 10^{-19}. Presently, 10^{-17} accuracy is reached after several hours. Thus in the foreseeable future, this techniques cannot be applied to in-situ gravitational potential difference measurement along orbits. A second complication of using clocks in orbit is the required altitude accuracy, namely 1 cm and 30 cm for LEO and geostationary orbits, respectively. Even for high precision height determination with ground based clocks, time synchronization by "orbiting clocks" has to reach a level of precision compatible with the above quoted numbers.

Table 6-2 presents the supporting technology required for gravity field missions and their present status of development. The first frame presents the tracking systems, of which only GPS is fully operational today. Using hybrid receivers on future LEO satellites is expected to improve orbit accuracy, in particular using the kinematic or highly-reduced dynamic orbit determination approaches.

Most future missions will require spacecraft that are drag compensated, with the exception of a nearly-identical GRACE follow-on. The main reason for this is the desirable low orbit altitude of 250-300 km of such a mission, which increases the sensitivity to the geopotential, but the atmospheric drag would lead to its decay in less than two years. Therefore, drag compensation is necessary for a targeted mission of five years or more. Highly controllable ion engines will be used on GOCE to compensate for drag in the along-track direction, in which it is largest by far. Solar cells, and batteries during the eclipses, can supply the electric power necessary to operate the ion engines.

Field Emission Electric Propulsion (FEEP) thrusters, which have very high specific impulse (I_{sp}), are developed for precise orbit and attitude control. The thrust range is of the order of 10^{-6} to 10^{-3} Newton. Presently their tested life time is too short for a future gravity monitoring mission, but intense work is ongoing for LPF, MICROSCOPE and LISA.

The performance of the star trackers required for attitude determination and control is at the level of 1” RMS today, a pointing accuracy of about 0.05” can be achieved in a few years (at significant cost) with a customized sensor tightly coupled with the instrument.. Depending on the mission design (inertial or Earth-pointing) and the combination with accelerometer angular acceleration measurements, this accuracy should be sufficient for future gravity field missions.

The status of the accelerometers was already given in the paragraph concerning electro-static gradiometers.

Table 6-2: Supporting Technology for Future Gravimetric Satellite Missions.

	Status	**Expected qualification time**
Tracking system:		
GPS	Flight proven (TRL9)	-
GLONASS	Flight proven (TRL9)	1-2 years *
GALILEO	Prototype (TRL5)	
Electric propulsion:		
Ion engine (high thrust)	Flight qualified (TRL8)	-
FEEP (low thrust)	Qualified prototype (TRL6)	2-4 years
Accelerometer 10^{-10} ms-2	Flight proven (TRL9)**	-
Accelerometer 10^{-12} ms-2	Flight qualified (TRL8)**	-
LISA/LTP inertial sensor 10^{-14} ms^{-2}	Launch in 2010 (TRL7)	1 year

* The constellation will be complete again.

** The CHAMP and GRACE accelerometers are flight proven; the GOCE instruments were qualified recently.

7 Appendix 1: List of Participants

Name		email	country
Miguel	Aguirre	Miguel.aguirre@esa.int	ESA
Georges	Balmino	Georges.balmino@orange.fr	France
Peter	Bender	pbender@jila.colorado.edu	US
Srinivas	Bettadpur	srinivas@csr.utexas.edu	US
Ben	Braam	Ben.Braam@tno.nl	Netherlands
Sean	Bruinsma	Sean.bruinsma@cnes.fr	France
Stefano	Cesare	Stefano.cesare@thalesaleniaspace.com	Italy
Tonie van	Dam	Tonie.vandam@uni.lu	Luxembourg
Karsten	Danzmann	danzmann@aei.mpg.de	Germany
Mark	Drinkwater	Mark.drinkwater@esa.int	ESA
Rune	Floberghagen	Rune.floberghagen@esa.int	ESA
Thomas	Gruber	Thomas.gruber@bv.tu-muenchen.de	Germany
Roger	Haagmans	Roger.haagmans@esa.int	ESA
Gerhard	Heinzel	Gerhard.heinzel@aei.mpg.de	Germany
Christian	Jentsch	Christian.jentsch@astrium.eads.net	Germany
Ulrich	Johann	Ulrich.johann@astrium.eads.net	Germany
Michael	Kern	Michael.kern@esa.int	ESA
Volker	Klein	Volker.klein@kayser-threde.com	Germany
Radboud	Koop	r.koop@nivr.nl	Netherlands
Jürgen	Kusche	jkusche@gfz-potsdam.de	Germany
Bruno	Leone	Bruno.leone@esa.int	ESA
Torsten	Mayer-Guerr	Mayer-guerr@geod.uni-bonn.de	Germany
Federica	Migliaccio	Federica.migliaccio@polimi.it	Italy
Jürgen	Müller	mueller@ife.uni-hannover.de	Germany
Eamonn	Murphy	Eamonn.murphy@esa.int	ESA
Danilo	Muzi	danilo.muzi@esa.int	ESA
Steve	Nerem	nerem@colorado.edu	US
Roland	Pail	pail@geomatics.tu-graz.ac.at	Austria
Erricos	Pavlis	epavlis@umbc.edu	US
Ernst	Rasel	rasel@iqo.uni-hannover.de	Germany
Markus	Rothacher	rothacher@gfz-potsdam.de	Germany
Reiner	Rummel	rummel@bv.tum.de	Germany
Fernando	Sansò	Fernando.sanso@polimi.it	Italy
Stephan	Schiller	Step.schiller@uni-duesseldorf.de	Germany
Ejo	Schrama	e.j.o.schrama@lr.tudelft.nl	Netherlands
Avri	Selig	a.selig@sron.nl	Netherlands
C.K.	Shum	ckshum@osu.edu	US
Pierluigi	Silvestrin	Pierluigi.silvestrin@esa.int	ESA
Nico	Sneeuw	n.sneeuw@gis.uni-stuttgart.de	Germany
Pierre	Touboul	touboul@onera.fr	France
Bert	Vermeersen	l.l.a.vermeersen@tudelft.nl	Netherlands
Pieter	Visser	p.n.a.m.visser@tudelft.nl	Netherlands
Michael	Watkins	mwatkins@jpl.nasa.gov	US
Remco	Wiegerink	r.j.wiegerink@ewi.utwente.nl	Netherlands
Ulrich	Wittrock	wittrock@fh-muenster.de	Germany
Victor	Zlotnicki	Victor.zlotnicki@jpl.nasa.gov	US

8 Appendix 2: Abbreviations and Acronyms

CHAMP	Challenging Mini-satellite Payload for Geophysical Research and Applications
DoF	Degree of Freedom
FEEP	Field Emission Electric Propulsion
GFO	Geosat Follow-on
GNSS	Global Navigation Satellite System
GOCE	Gravity Field and Steady-State Ocean Circulation Explorer
GPS	Global Positioning System
GRACE	Gravity Recovery and Climate Experiment
ICESAT	Ice, Cloud, and land Elevation Satellite
INS	Inertial navigation System
IPCC	Intergovernmental Panel on Climate Change
LDI	Laser Doppler Interferometry
LEO	Low Earth Orbit
LISA	Laser Interferometer Space Antenna
LPF	LISA Pathfinder
LTP	LISA Technology Package
SMOS	Soil Moisture and Ocean Salinity mission
SST	Satellite-to-Satellite Tracking
TBD	To Be Determined/Decided
TRL	Technology Readiness Level