Assessment of a Next Generation Gravity Mission (NGGM) for monitoring the Variation of the Earth's Gravity Field

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WP 1100: Requirement Analysis

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2 Introduction

This document is the WP1100 report for ESA Study "NEXT GENERATION GRAVITY MISSION (NGGM)-Assessment of a Next Generation Gravity Mission for monitoring the variations of Earth's gravity". This document is submitted in satisfaction of the WP1100 formal contractual deliverables.

Work Package 1100 of the study contains the analysis and critical review of the different sets of requirements and constraints that could apply to a mission to monitor the variations of the Earth gravity field at high resolution. This WP involves reviewing the scientific questions that can be addressed by satellite gravity in general, evaluating what has been achieved (i.e. what has been accomplished with available missions), and determining what gaps remain between the science questions and time variable gravity observations. Further, and more importantly, the output of this WP should result in a prioritization of those unanswered science questions in terms of required accuracy, spatial resolution, geographic coverage, temporal resolution, and mission duration.

To a large extent, this report is based on an extensive literature review. However, this report also represents an assimilation of 1) the practical experience and knowledge gained by the NGGM Science Team within previous ESA studies (e.g. the studies *Enabling Observation Techniques for Future Solid-Earth Missions* and Monitoring and *Modelling Individual Sources of Mass Distribution and Transport in the Earth System by Means of Satellites (MTS)*), 2) from published scientific results of the analysis of spatially derived time variable gravity data, and 3) recent scientific workshops on this topic. The report identifies the most important sources and processes of mass distribution and transport in the Earth system.

In Section 2, we describe the parameters, which are required to define the mission requirements, i.e. accuracy, spatial and temporal resolution, geographic coverage, etc. However, experience has demonstrated that improvements in one parameter, sometimes results in degradations of others. Thus, in Section 3, we discuss the trade-offs between the parameters introduced in Section 2. In Section 4 we elaborate on the science questions that could be addressed by improving the accuracy, the temporal resolution and or the spatial resolution of observations of the time variable gravity field. Please note that what is presented in this Section is a scientific "wish list", i.e. no attempt at prioritization has been undertaken at this point. In Section 5, we review the main results of the ESA study, *Modelling Individual Sources of Mass Distribution and Transport in the Earth System by Means of Satellites*, which have a bearing on the present study. In Section 6, we briefly discuss the effects that inaccurate background models, aliasing, and our inability to separate different mass signals, have on our ability to observe mass transport phenomena. In Section 7, we attempt to prioritize the scientific questions in terms of the mission requirements. Finally we present the conclusions in Section 8.

3 Parameters Defining the Mission Requirements

Mass transport in the Earth's system takes place in several layers located above, at, and below the Earth's surface:

- Atmosphere (0-10 km above the Earth's surface)
- Hydrosphere and Cryosphere (at the Earth's surface)
- Solid-Earth (below the Earth's surface)

Satellite gravimetry observations of mass transport essentially lack vertical resolution. Observed gravity signals can be explained by mass variations in any of these layers. In addition, different types of mass transport may take place within any single layer at the same time. For a proper interpretation of observed mass variations, a priori knowledge of mass transport processes has to be incorporated. The most straightforward approach is to clean the observations for less relevant signals, by applying appropriate models of mass motion. Because the accuracy of such models is sometimes insufficient, the "clean" gravity residuals are still contaminated by nuisance signals or noise. Thus, other approaches are required in order to extract information about the mass transport processes of interest. For instance, the nuisance signals can be co-estimated together with the signals of interest. Alternatively, residual nuisance signals can be suppressed by a Wiener-type filtering in the frequency domain or by proper averaging of a sufficient number of observations in the time domain.

The requirements for mass transport observation missions must be defined in such a way that the observations contain sufficient information to:

- Quantify the process(es) of interest;
- Suppress the influence of residual nuisance signals.

The defined requirements will depend on the procedure that will be used for the elimination of the nuisance signals.

The following mission requirements will be discussed in the following sub-sections:

- Accuracy
- Spatial resolution
- Spatial coverage
- Temporal resolution
- Temporal coverage (duration of the observation period)

3.1 Accuracy

Obviously, the accuracy of observed gravity must be sufficient to observe the process of interest. Ideally, the observation errors must be several times less than the signal (depending on the adopted signal-to-noise ratio). The minimum requirement is that the expected noise level does not exceed the signal.

There are different ways to quantify mass transport signals. In most cases, this is done in terms of equivalent water layer thickness. If a mass variation is caused by a changing water level in an open water body, variations of equivalent water layer thickness essentially coincide with actual variations of the water level, provided that the water temperature and salinity remain constant. Alternatively, mass transport can be quantified in terms of geoid heights or in terms of gravity anomalies. Throughout the rest of this document, we will predominantly quantify the accuracy of mass transport estimations in terms of geoid heights and equivalent water layer thickness.

In the table below, we try to provide some idea of the useful accuracy required by some applications.

Table 3-1: Accuracy requirement of mass changes expressed as the thickness of a thin layer of water (mm). Values in the form 0.5(0.1) indicate a minimum useful accuracy, and a desired or target accuracy.

Application	mm H_2O
Hydrologic basin total water change	20(10)
Glacier mass loss	2(1)
Ice sheet mass loss	20(5)
Oceanic gyers spin up or down	4(1)
Global sea-level rise; thermostatic/eustatic	1(03)
Glacial isostatic adjustment	0.5(0.2)

3.2 Spatial resolution

Natural mass transport processes span a wide range of spatial scales. The upper bound is the size of the planet Earth itself. Defining the lower bound for many mass transport processes is not so easy because the signal amplitude diminishes gradually as the spatial scale reduces. In defining the spatial resolution requirement, it is important to ensure that at least the most essential features of the target process are captured.

Technically, the spatial resolution is typically defined as the spatial wavelength λ, which is a characteristic of a particular base function in the spherical harmonic expansion. It is related to the spherical harmonic degree l according to the following rule-of-a-thumb expression: $\lambda = L/l$, where $L = 40{,}000$ km (the length of the Earth's equator). Sometimes, the spatial resolution is defined in terms of half-wavelengths, i.e. as $\lambda_2 = L/2l$. In the rest of the report, we will define the spatial resolution in terms of both degree of the spherical harmonic expansion l, and wavelength, λ.

3.3 Spatial coverage

A number of mass transport processes take place only in selected geographical areas. For instance, ice sheet melting is predominantly limited to polar-regions, whereas mass transport of hydrological origin is limited to land areas (excluding the Antarctica). The spatial behaviour of a process should be taken into account when a satellite mission is designed. For example, a nearly polar orbit is a must, if ice sheet melting is to be investigated. At the same time, a non-polar orbit (and, consequently, the presence of polar gaps) is acceptable if the mission is focused on hydrological processes. In Figure 3-1, we show the RMS of the real Earth system model determined within the MTS.

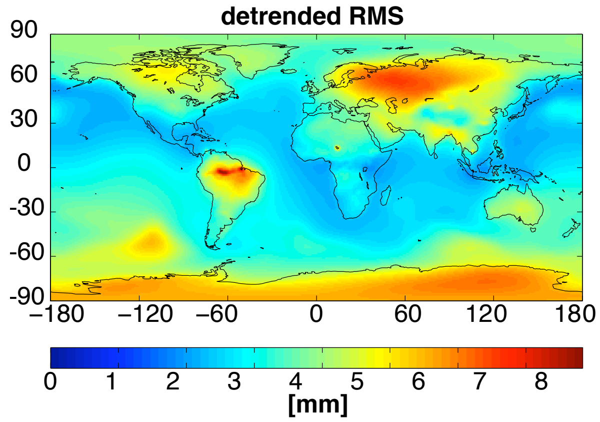

Figure 3-1: RMS of mass trasport processes as determined in the MTS.

3.4 Temporal resolution

Different mass transport processes show a very different behaviour in the time domain. For instance, mass transport in the atmosphere (associated with a changing atmospheric pressure) predominantly takes place with periods between several hours and 1 year. Mass transport in the solid-Earth is typically a slow process, so that it manifests itself mostly in the form of linear trends within the time interval of a few years to 100's of years. Conversely signals in hydrosphere cover a very wide range of periods: from hours (ocean tides) to infinity (melting of ice sheets).

The required temporal resolution, therefore, must be sufficient to capture most of the spectrum of the target processes or to estimate a linear trend (if the rate of a long-term mass change is studied). At the same time, it is important to consider the spectral behaviour of residual nuisance signals, e.g. aliased ocean tides. If the spectral content of these signals is significantly different from that of the target signal, an efficient separation of the signals in the frequency domain is possible. To facilitate this separations, however, the mission must be designed in such a way that the spectral contents of the residual nuisance signals is also captured, otherwise they may alias into the frequency range occupied by the target process, making the separation in the frequency domain impossible.

3.5 Temporal coverage

In the case of operational monitoring of natural mass transport, e.g. verifying mass changes associated with global warming, the added value of the mission is proportional to its duration. Therefore, the optimal mission duration is dictated rather by economic or technical considerations rather than by scientific ones. The situation is different, however, when a regular process (a periodic one or a linear trend) is investigated. Obviously, the minimum requirement is to collect sufficient information to quantify the process itself (e.g. to cover at least one full period of a periodic process or to cover the period in which a measurable mass change takes place in the case of a linear process). However, this may not be sufficient in practice. Firstly, this is due to the presence of nuisance signals. The mission duration must facilitate an efficient suppression of such signals. Secondly, the target processes themselves may deviate from an "ideal" behaviour. For instance, the rate of ice sheet melting may show significant variations from year to year, or even accelerations. In the ideal case, the mission duration must be sufficient to provide representative information about the target processes, such that these natural variations can be observed.

3.6 Summary

In this section, we have the parameters that need to be considered, from a geophysical perspective, in defining an Earth observing system. In the next section we discuss the interaction and the trade-off relationships between these parameters.

4 Trade-off Between Requirements

In defining the mission requirements, it is important to keep in mind that the requirements themselves are not independent. Improving the mission performance or increasing the quality of one requirement parameter almost inevitably causes degradation of other criteria. In this Section, we discuss the most obvious trade-offs and inter-dependencies between the requirements. This Section makes it clear that the primary scientific objectives of the NGGM must be defined as specifically as possible, so that the mission requirements can be tuned in order to maximize the mission performance, while at the same time, to minimize the conflicts between the requirements.

4.1 Spatial Resolution Versus Accuracy

Measurement accuracy defines the time variable mass signals observable by a satellite. In contrast to other Earth observation sensors, which provide point-wise information at a specific time and location (e.g. satellite altimetry), gravity sensors observe the integrated signal of the three dimensional mass distribution seen from a specific location at a specific time. In principle such a sensor observes mass distribution for the whole Earth, because any mass element of the Earth influences the observation. Therefore, processing of the whole data set collected within a given time interval is needed in order to enhance the spatial resolution. However, the spatial resolution cannot be increased infinitely. The gravity field signal associated with a given spherical harmonic degree, *l,* attenuates with altitude *h* $attenuation = \left[\frac{R_E}{(R_E + h)}\right]^{l+2}$, where R is the Earth's radius. Thus, the smaller the spatial scale, the higher the signal attenuation. At a given spherical harmonic degree, some signals will be smaller than the scatter in the noise, which means that those signals cannot be recovered, no matter which processing technique is applied. This means that there is always a trade-off between the spatial resolution of a model and the amplitude of the observable signals: the smaller the spatial scale, the higher the required signal amplitude.

A typical relationship between the spatial resolution and the errors of gravity field models (here in terms of (error) degree-RMS) driven by the sensor accuracy (here GRACE-like ll-SST) is shown in Figure 4-1. The decrease of the gravity field signal with higher resolution (larger degree l) and the previously mentioned increase in the gravity field errors with higher resolution due to signal attenuation can clearly be observed. In general, the intersection point (at degree l with spatial resolution λ = 40000/l km) between the signal and error degree-RMS can be defined as the spatial resolution. Obviously, this intersection point and thus the resolution can be enhanced if a sensor of higher quality/accuracy is flown. For a GRACE-like orbit altitude (h = 450 km) in this example, a gain of 20-30 degrees spatial resolution is achieved for a sensor improvement of 1 magnitude. For a lower orbit with less signal attenuation, the gain would even be larger.

4.2 Spatial Resolution Versus Temporal Resolution

Unlike electromagnetic sensors, gravity sensors cannot be directed to a particular area at the Earth's surface. This means that the spatial coverage of a satellite gravity mission is almost fully determined by the spatial pattern of satellite ground tracks. To achieve a high spatial resolution, (i) the observation period must be sufficiently long (typically, a few weeks) and (ii) the satellite orbit must not be characterized by a short repeat period. This of course contradicts the requirements of a high temporal resolution driven by a short repeat periods. This shows that there is a strong trade-off between temporal and spatial resolution.

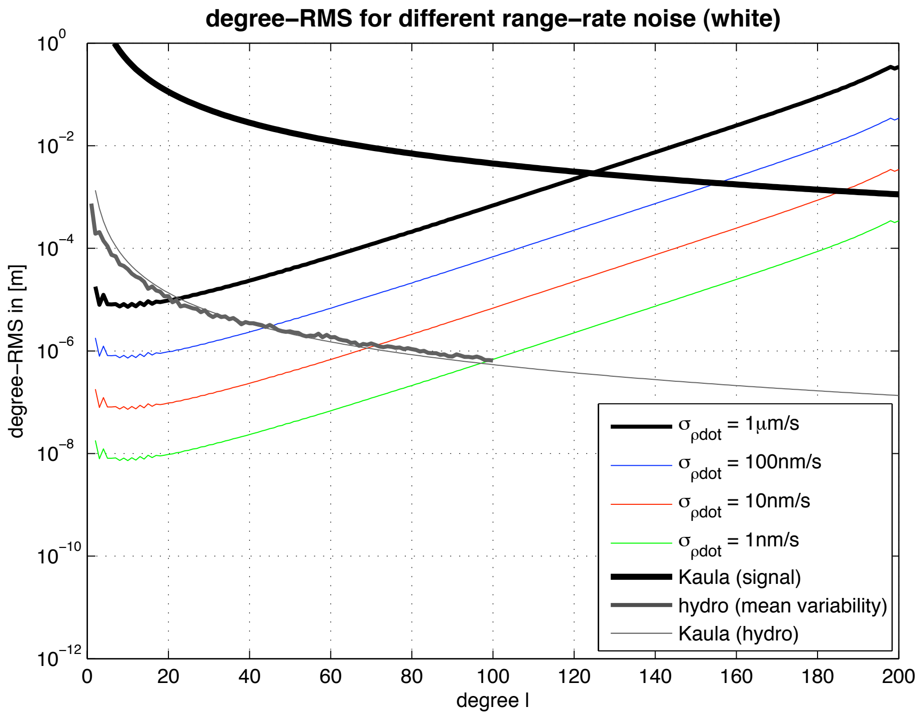

Figure 4-1: Dependence of the spatial resolution on the accuracy of the sensor system (here: k-band/laser ranging).

The relation between spatial and temporal resolution can be described most suitably for a (β/α)-repeat-orbit (β revolutions in α days). The minimum spatial and temporal scales that can be captured from a satellite (or satellite pair) flying on a (β/α)-repeat-orbit is (in a worst case scenario) $D_{space} = 2\pi / \beta\,[rad]$ (or $D_{space} = 40{,}000 / \beta\,[km]$ groundtrack-spacing) and $D_{time} = \alpha$ [days]. Since the ratio β/α of a repeat orbit is almost constant for a LEO ($\beta/\alpha \approx 15.6$), the product between the minimum temporal and spatial scales is also almost constant, which can be regarded as the "Heisenberg rule of thumb" $D_{space} \times D_{time} = c$ of the spatio-temporal sampling. This is depicted in Figure 4-2 as a hyperbola between the spatial and temporal resolution. In particular this means the higher the temporal resolution of a repeat orbit (smaller α), the lower the spatial resolution l_{max} (smaller β) and vice versa (here the maximum spherical harmonic degree l_{max} is connected to β by the Nyquist rule of thumb $\beta \geq$

$2l_{max}$ (or $\beta \geq 2m_{max}$)). In particular this also means that a higher spatial resolution achieved by a longer repeat period α would not only reduce the temporal resolution $D_{time} = \alpha$ [days] which can be achieved, it also would cause aliasing of undersampled temporal signals with scales ΔT < α [days] on scales ΔT ≥ α. Likewise, a higher temporal resolution achieved by a smaller repeat period α not only reduces the temporal scales D_{space} to be observed, it also causes spatial aliasing of the spatially undersampled structures of scale < D_{space} onto the larger scales ≥ D_{space}.

As a consequence from the Heisenberg-rule of thumb, a higher spatial resolution can be attained without affecting the temporal resolution only by adding further satellite (pairs) on interleaved orbits, the so-called Δλ-shift. A higher temporal resolution can be attained without influencing the spatial resolution by adding satellite (pairs) onto the same groundtrack with a time-shift (Δt-shift). The basics of spatio-temporal sampling are described in more details e.g. in *Reubelt et al.* [2009].

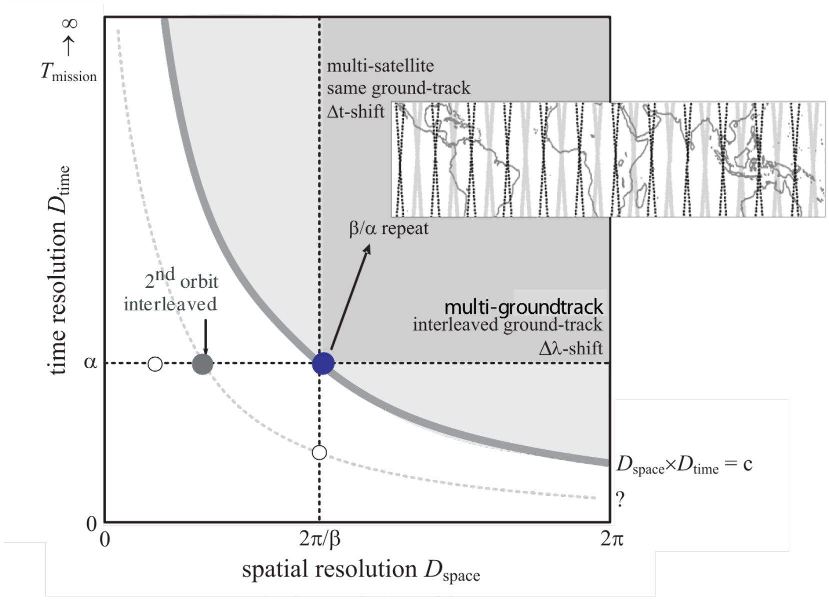

Figure 4-2: Space-time-sampling of satellite configurations.

4.3 Accuracy Versus Observation Period

It is likely that one of the primary goals of future satellite gravity missions will be to quantify certain regular processes, e.g. long-term trends. However, actual mass variations never show a perfectly regular behavior. The only way to determine whether the multiyear trends are representative of long-term changes in mass balance is to extend the length of the observations. The desired improvement in spatial resolution of future gravity missions and the continuation of the extended observation record would provide invaluable observations of long-term climate-related changes in the mass of the Antarctic and Greenland ice sheets and large Arctic ice caps. Longer records would also allow for better characterization of interannual changes in soil moisture and groundwater storage for use by hydrologists in global land surface models (although if the coarse spatial resolution cannot simultaneously be improved, it will continue to be a critical constraint on these types of observations).

The consensus within the scientific community seems to be, that a long term monitoring mission (at a somewhat better accuracy than GRACE) has priority over a quantum- leap-accuracy improvement.

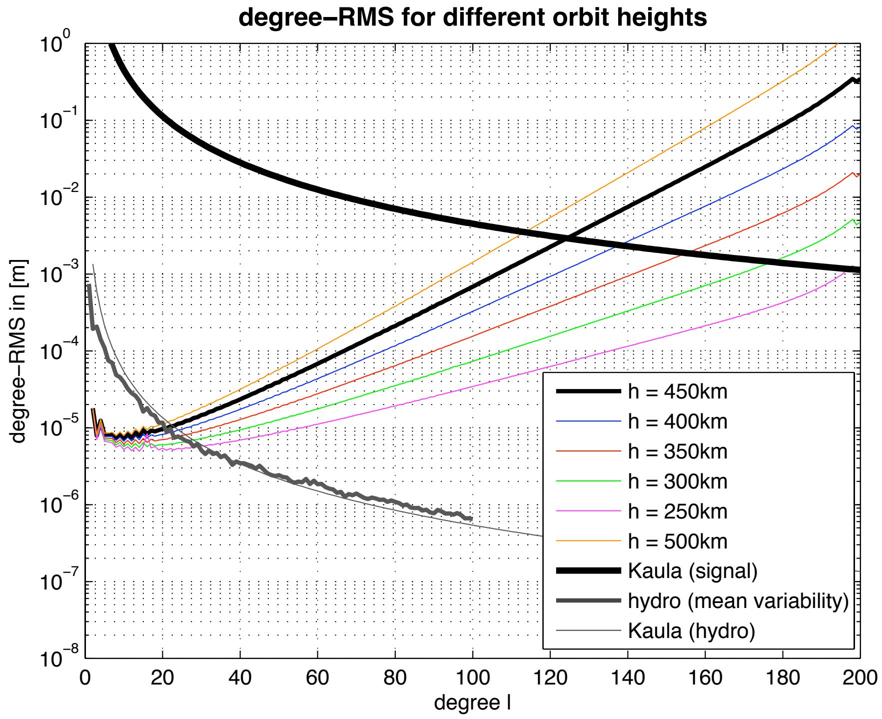

Figure 4-3: Dependence of the gravity field accuracy (degree-RMS) on the orbit height.

4.4 Accuracy Versus Mission Lifetime/Altitude

As was mentioned in Section 3.1, the gravitational signal to be observed from space attenuates with the altitude. The attenuation rate depends on the wavelength of the signal: signals of shorter wavelengths decrease faster than those of longer wavelengths (see Figure 4-3). This implies, that by going to higher orbits above the Earth's surface a more accurate measurement system is needed in order to observe mass distribution at a specific location and at a specific time with a predefined spatial resolution and accuracy (see Figure 4-4). By going to lower orbits, one could benefit from lower signal attenuation and relax the requirements on observation system accuracy somehow in order to reach similar resolution and accuracy (disregarding more stringent satellite system requirements for maintaining very low orbits). Higher orbits have some significant advantages related to the possible mission lifetime and the satellite system requirements. Thus, when defining an optimal mission scenario some trade-off between the chosen satellite altitude and the observation system performance has to be considered. This trade-off is driven primarily by the amplitude of the mass transport signals, as well as by the spatial resolution at which scientists require observations. In general one can state, that many applications need an observation time series as long as possible in order to monitor and understand the ongoing processes. So in this context a higher orbit is preferable. But, a higher orbit only makes sense if the sensor system is capable of observing the desired signals.

In conclusion, one should derive the orbit altitude from the science requirements (in terms of sensitivity and resolution) and the capabilities of the sensor system (in terms of accuracy).

4.5 Spatial Resolution Versus Signal-to-Noise Ratio

It is very likely that future gravity field missions will exploit the inter-satellite ranging technique, as is the case for the GRACE mission. An increase in the signal-to-noise ratio of the observations (and, therefore, the accuracy of the resulting models), can be attained by increasing the inter-satellite distance. The dependence of the gravity field accuracy (in terms of degree-RMS) on the inter-satellite separation is shown in Figure 4-4, where we have assumed a GRACE-type orbit/formation and k-band accuracy, $\sigma_p = 1\,\mu m/\sec$. However, it is important to note that the horizontal separation of the satellites limits the spatial resolution of observations. Signals of wavelength λ cannot be sensed by a pair of satellites with an inter-satellite separation greater than or equal to λ. For instance, the horizontal separation of GRACE satellite is about 200 km, which limits the spatial resolution of this mission to spherical harmonic degree 200, irrespectively of its accuracy. Thus, all other parameters being constant, if future missions must yield an even higher spatial resolution, the horizontal separation between the satellites must less than in the case of the GRACE mission.

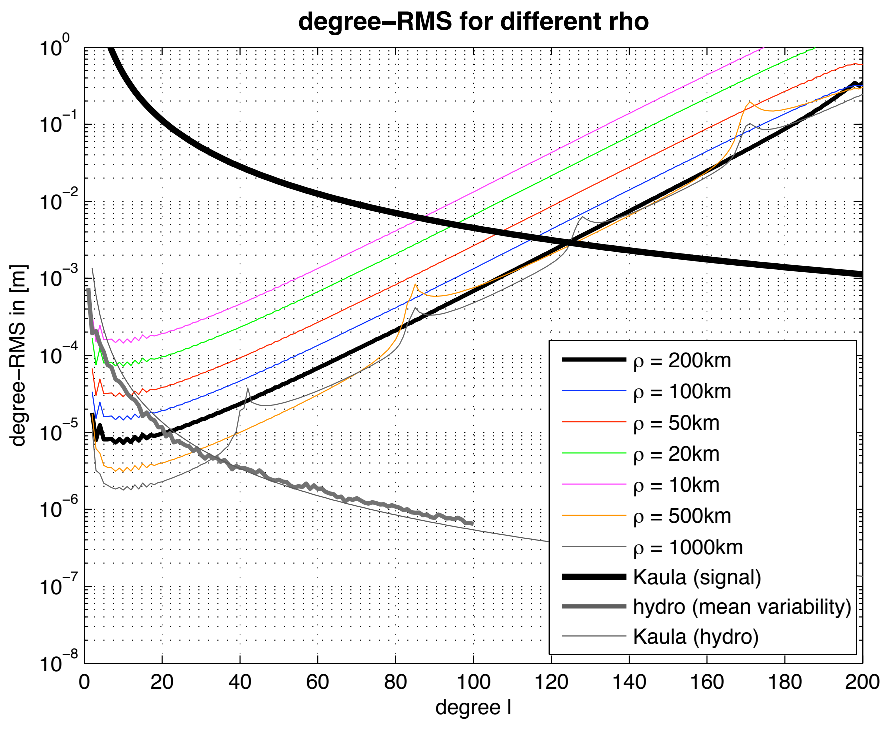

Figure 4-4: Dependence of the gravity field accuracy on the inter-satellite separation distance, ρ.

However, it is possible that range-rates determined over shorter distances might be determined with higher accuracy. If an improved accuracy over shorter satellite separations could be established, then the signal-to-noise ratio would not necessarily decrease by reducing the inter-satellite distance.

The same considerations are also valid for the proof-masses of gradiometry. However, in this case the measurement is performed over a different distance range (dm - m).

4.6 Orbit Inclination and Spatial Coverage Versus Accuracy

One of the limitations of the GRACE mission is its strongly anisotropic sensitivity. Essentially, the inter-satellite ranging data acquired by this mission contain information about gravity differences between the satellite locations. Since the GRACE satellites follow each other in a nearly polar orbit, they are located (most of the time) at nearly the same meridian. Consequently, the observations describe North-South variations of the gravitational field (and mass transport) much better than East-West variations. This anisotropic signal structure leads to the well-known North-South striations in the GRACE solutions. As shown by simulations, other types of satellite formations (e.g. Pendulum, Cartwheel, LISA) are able to reduce anisotropy and lead to higher signal sensitivity. While a Pendulum mainly captures cross-track and radial signals, and Cartwheels capture along-track and radial signals a LISA-type formation might be able to measure signals in all directions. Although such complicated formations are advantageous for gravity field determination, they impose high demands on satellite/instrument design, orbit/attitude control and mission costs.

Another way to increase isotropy and accuracy might be to opt for non-polar orbits, so that the ground tracks would intersect the Earth's meridians at larger angles. However, this would result in polar gaps, i.e. a reduced geographic coverage, which is undesirable for ice mass studies.

In addition to measurement accuracy and isotropy, another issue, which affects the total accuracy of a gravity field model, is spatio-temporal aliasing, (Section 3.2). A particular orbit always has an associated spatio-temporal sampling, which leads to spatio-temporal aliasing of undersampled signals. Aliasing can be avoided by adding further satellite pairs, either on the same groundtrack in order to improve temporal sampling or on interleaved groundtracks in order to enhance spatial sampling (see subsection 3.2). Another possibility for improving the spatio-temporal sampling is the so-called Pete Bender design, where an additional satellite pair is added on an orbit with low inclination. Using this type of design, the large equatorial groundtrack spacing of polar orbits can be reduced and, a higher isotropy due to the larger intersection angles of the groundtracks with the meridians can be achieved. Of course, the mission costs will rise if more satellite pairs are flown, in particular if different inclinations are desired different launchers will become necessary.

4.7 Summary

In this section we have discussed the trade offs between the various parameters defining an Earth observing mission.

5 Review of Science that can developed with TVG

Time Variable Gravity (TVG) has and is contributing significantly to our understanding of mass transport within the Earth system (oceans + atmosphere + cryosphere + hydrosphere + solid earth). Because most physical geodesists responsible for developing space missions or processing the raw time variable data are not necessarily also specialists in solid-Earth, hydrologic, atmospheric, oceanographic, or cryospheric sciences, it is not always obvious the extent to which TVG can contribute to the advancement of the science within a particular discipline. Similarly, it has historically been difficult for scientists with no background in physical geodesy to grasp the contribution that TVG can have to their understanding of the processes within their area of expertise. In fact, it is only been recently through the successes of the GRACE mission that non-geodetic scientists, particularly hydrologists and cryospheric scientists have started to embrace the possibilities offered by TVG. Thus, it has taken some time for specialists from the different groups to establish and agree on a list of scientific requirements for the NGGM.

This section presents a summary of the science that can be developed and improved with TVG (although some applications resulting from the improvement of the static gravity field are also mentioned). We start by reviewing the chronological milestones that have contributed to developing a scientific "wish list". These milestones are presented in the form of tables that have been refined and updated. In Section 4.5 we review the scientific questions and discuss how present missions have or are contributing to addressing these issues.

Please note, that at this point, no prioritization of the scientific objectives has been established. Scientific priorities will be established in Section 7 of this report.

5.1 Enabling Observation Techniques for Future Solid-Earth Missions [*Rummel et al.*, 2003]

Any review of the scientific requirements for a future gravity mission must begin with one of the first comprehensive analyses of the mass transport signals on the surface of and within the Earth. The ESA study ""Enabling Observation Techniques for Future Solid-Earth Missions" conducted by *Rummel et al.* [2003] quantified the components of the TVG and static gravity field in terms of geoid signal, characteristic spatial scale and fundamental periods.

After *Rummel et al.* [2003], a workshop was organized at the International Space Science Institute in Bern, Switzerland where a group of Earth scientists exchanged ideas with the objective of assessing the future needs in the Earth sciences for more precise and refined gravity models. The outcomes of the workshop were published in a book edited by J. Flury and *R. Rummel* [2005]. Table I from the *Sneeuw, Flury and Rummel* [2005] contribution to the book is reproduced here as Table 5-1. For those more accustomed to thinking of the signal precision in terms of "an equivalent layer of water of thickness (EWT)", the conversion between geoid signal and EWT is approximately 1 cm geoid = 10 cm EWT.

Table 5-1: Adapted from Table 1 of *Sneeuw et al.* [2005], Synopsis of future science requirements in terms of geoid and gravity field knowledge.

Science area Theme	Required Resolution (km)	Main periods	Required accuracy Geoid or gravity	Comment
Solid-Earth				
GIA	> 200	10,000 – 100,000 y	1 – 10 μm/y	Total geoid effect: 1-2 mm/y
Co-/post-seismic deformation Slow/silent earthquakes	Regional	Instantaneous – decadal	Sub-mm	Requires monitoring mission
Plate tectonics, mantle convection, volcanoes	> 10	Secular, instantaneous	< 1 mm/y	Requires monitoring mission
Core motion (nutation, Slichter), seismic normal modes	> 5000	10 s – 18 y	1 nGal – 1 μGal	
Ice				
Ice mass balance	100 – 4000	Seasonal – secular	< 0.01 mm/y	Monitoring mission desired
Bottom topography, ice compaction	20 – 50	Quasi-static	0.01-0.1 mGal	
Geoid for sea ice thickness	10 – 100	Static	100 mm	
Hydrology				
Snow, precipitation, ground water, dams, soil moisture, run-off, evapo-transpiration	10 – 5000	1 h – secular	0.5 – 1 mm monthly	High spatial resolution more important than accuracy
Ocean				
Mean flow: narrow current, topographic control	20 – 50	Quasi-static	5 – 10 mm	
Coastal current along shelf edges	10 – 50	Quasi-static	5 – 10 mm	
Interaction mean and eddy flow, ocean fronts position	10 – 100	Quasi-static	5 – 10 mm	
Bathymetry	1 – 10	Static		
Basin scale mass change, deep water formation	1000 – 5000	Months – decades	10 mm	Sea level, oscillations
Bottom currents	10 – 200	Months – decades	0.1 – 1 mm	
Sea level				
Global sea level change monitoring	> 2000	Interannual, secular	0.1 mm/y	Monitoring mission desired
Geodesy				
Precise heights for engineering, GNSS, leveling, coastal height reference, sea level monitoring	20 – 50	Static	5 – 20 mm	For some areas also geoid time variation
Inertial navigation	5 – 10	Static	0.1 mGal, 0''1 deflection of vertical	Combination with terrestrial data required
Atmosphere	Gravity field improvement may be interesting for future atmospheric modeling			
Planets	Dedicated autonomous gravity field missions with very high spatial resolution			

5.2 The Future of Satellite Gravimetry [*Koop and Rummel*, 2007]

A workshop entitled "The Future of Satellite Gravimetry" was held at ESTEC in April of 2007. Participants included about 50 scientists with expertise in the areas of Earth science, oceanography, the cryosphere, the atmosphere, continental hydrology, fundamental physics, and technology related to the field of satellite gravimetry. The scientific requirements for a time variable gravity mission were again evaluated. The authors of the Section *Geophysical Applications* of the Workshop Report state that

"Table 3-1, from *Rummel* [2005] summarizes the GOCE requirements, which are still the most useful targets for the time-averaged gravity field." That table is reproduced here as Table 5-2.

One important contribution to defining the scientific requirements was the added factor of minimum accuracy/resolution. The "minimum requirements" are values below which a problem cannot be investigated. For each time varying scientific target, the minimum accuracy/resolution requirements are provided in Table 5-3. The averaging radii assume a lower threshold of 300 km; many signals of interest with shorter scales exist.

Table 5-2: Static gravity field, scientific requirements in preparation for GOCE, from Rummel [2005].

Application			**Accuracy**		**Spatial resolution half-wavelength D [km]**
			Geoid (cm)	**Gravity (mgal)**	
Solid-Earth	Lithosphere/upper mantle density			1-2	100
	Continental Lithosphere	Sedimentary		1-2	50-100
		Basin 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
	Basin Scale		~0.1		1000
Ice Sheets	Rock Basement			1-5	50-100
	Ice Vertical Movements		2		100-1000
Geodesy	Levelling by GPS		1		100-200000
			1		
			1	~1.5	100-1000
Sea level			Many of the above applications, with their specific requirements are relevant to studies of sea level change		

Table 5-3: Accuracy requirements, from *Koop and Rummel*, 2007. The mass change trends are expressed as the thickness of a thin layer of water. Values in for form 0.5(0.1) indicate a minimum useful accuracy, and a desired or target accuracy.

Application	**mm(H_2O)/mon**	**mm(H_2O)/yr**	**smoothing radius**	**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)	1000	
Oceanic gyers spin up or down		4(1)	700	interannual
Global Sea-level rise; thermostatic/eustatic		1(0.3)	5000	seasonal, interannual
Glacial Isostatic Adjustment		0.5(0.2)	1000	5-10 years

5.3 Monitoring and Modelling individual Sources of Mass Distribution and Transport in the Earth System by Means of Satellites [*van Dam et al.*, 2008]

The scientific requirements for a future gravity mission were revisited in the ESA study "Monitoring and modelling individual sources of mass distribution and transport in the Earth system by means of satellites" [*van Dam et al.*, 2008]. An updated version of Table 1 was presented in *van Dam et al.* [2008] and is reproduced here as Table 5-4.

Table 5-4: Requirements for a future gravity mission (taken from van Dam et al. [2008].
The colored table cells indicate:
Feasibility: Medium term=after GOCE; Long term=in the next 10-25 years
Priority: +, ++, or +++ (more +, higher Priority)

A) Solid-Earth Geophysics

A.I GIA		Medium term	+++ key theme
Total geoid effect:	1 mm/y – 2 mm/y		
Spatial scale:	~500 km		
Time scale:	10000 – 10000 y		
Accuracy requirement:	0.01 – 0.001 mm/y @ 100 – 200 km		
Geographic location:	Canada, Antarctica, Scandinavia, with global impact		
Mission duration:	> 5 y		
Mission considerations:			
Additional data and models:	GNSS, tide gauges, absolute gravimetry, levelling, ice models, preliminary Earth model		
A.II Co-seismic and post-seismic deformation, slow and silent earthquakes		Medium term	+++
Geoid effect:	Sub-mm		
Spatial scale:	Regional		
Time scale:	Instantaneous to decadal		
Geographic location:	Typically earthquake zones		
Mission duration:	Scientific monitoring mission		
Mission considerations:			
Additional data and models:	GNSS, INSAR, gravimetry, levelling, seismic data, preliminary Earth model		
A.III Plate tectonics, mantle convection, volcanoes		Medium term	++
Geoid effect:	Up to mm/y; volcanoes: sub-mm		
Spatial scale:	Global down to 10 km		
Time scale:	Secular; volcanoes: instantaneous		
Geographic location:	Typically earthquake zones		
Mission duration:	> 5 y; volcanoes: scientific monitoring mission		
Mission considerations:			
Additional data and models:	GNSS, INSAR, gravimetry, levelling, seismic data, preliminary Earth model		
A.IV Core motion (nutation, core modes, Slichter modes), seismic normal modes		Medium term	++
Gravity effect:	1 nGal – 1 μGal (for well defined frequencies		
Spatial scale:	long wavelengths		
Time scale:	10 sec – 18.6 y		
Geographic location:	global		
Mission duration:	?		
Mission considerations:			
Additional data and models:	superconducting gravimeters, Earth orientation parameters, magnetometry, long period seismometers		
B) Hydrology			
Snow / precipitation / groundwater / dams / soil moisture / run-off / evapo-transpiration		Medium term	+++ key theme
Geoid / gravity effect:	2 – 6 cm / 1 – 10 μGal		
Spatial scale:	1000's km to 10 km; high spatial resolution is particularly important		
Time scale:	1 h to secular (seasonal)		
Geographic location:	catchments / continents		
Mission duration:	1-5 y		
Mission considerations:			
Additional data and models:	hydrology data (e.g. river monitoring, dam data, soil moisture, groundwater, …), meteorological data; models of hydrological cycle		
Complementary precipitation and soil moisture missions will fly in the near future			
C) Ocean			
C.I to C.IV: Static gravity field improvement			

C.I Narrow scale components of global ocean circulation, topographic control of mean flow		Medium term	+
Geoid accuracy:	5 – 10 mm		
Spatial scale:	20 – 50 km (Rossby radius), structures up to 200 km		
Geographic location:	ocean straits, ocean basins		
Mission duration:	1 y		
Mission considerations:			
Additional data and models:	satellite altimetry (high spatial resolution), swath altimetry, in situ salinity, temperature, pressure, wind stress (scatterometer); Ekman transport		
C.II Coastal currents along shelf edges		Medium term	+++
Geoid accuracy:	5 – 10 mm		
Spatial scale:	10 – 50 km (width of continental slope)		
Geographic location:	continental shelf slopes		
Mission duration:	1 y		
Mission considerations:			
Additional data and models:	local gravity, current meters, tide gauges, altimetry, bathymetry (in unsurveyed areas); tidal models (critical)		
C.III Interaction mean flow – eddy flow, position of ocean fronts		Medium term	+
Geoid accuracy:	5 – 10 mm		
Spatial scale:	10 – 100 km		
Geographic location:	major current systems, Southern Ocean		
Mission duration:	1 y		
Mission considerations:			
Additional data and models:	satellite altimetry, thermal infrared data		
C.IV Bathymetry		Medium term	+
Bathymetry accuracy:	10 cm		
Spatial scale:	10 km for deep ocean, 1 km for coastal areas		
Geographic location:	oceans		
Mission duration:	1 y		
Mission considerations:			
Additional data and models:	high resolution satellite altimetry, marine gravimetry		
C.V to C.VI: Time variable gravity field			
C.V Basin scale mass changes		Medium term	++ to +++
Geoid effect:	1 cm		
Spatial scale:	1000 – 5000 km		
Time scale:	(days -) months – decades		
Geographic location:	ocean basins		
Mission duration:	multi-year to scientific monitoring		
Mission considerations:			
Additional data and models:	atmospheric pressure; improved tidal models, storm surge models, GIA models		
Points of interest: major shifts in extratropical oceans, relation to ENSO, major oscillation modes, deep water formation and spreading, sea level (mass vs. expansion)			
C.VI Bottom currents		Long term	+++ key theme
Geoid accuracy:	0.1 – 1 mm		
Spatial scale:	10 – 200 km		
Time scale:	(days -) months – decades		
Geographic location:	ocean basins, especially near steep topography		
Mission duration:	multi-year to scientific monitoring		

Mission considerations:			
Additional data and models:	atmospheric pressure; improved tidal models, storm surge models, GIA models		
Points of interest: deep WBC's, dynamics of thermohaline circulation, much more information and understanding than from C.V			
D) Global sea level change monitoring		Medium term	+++ key theme
Water equivalent effect:	1 mm/y		
Geoid accuracy:	0.1 mm/y		
Spatial scale:	global to basin scale		
Time scale:	interannual, secular		
Geographic location:	ocean basins		
Mission duration:	as long as possible		
Mission considerations:			
Additional data and models:	altimetry, tide gauges; climate models		
E) Ice			
E.I Ice mass balance (seasonal to secular)		Long term	+++
Geoid accuracy:	< 0.01 mm/y		
Spatial scale:	100 – 4000 km		
Time scale:	seasonal – secular		
Geographic location:	ice sheets (Antarctica, Greenland), glaciers		
Mission duration:	> 10 y		
Mission considerations:			
Additional data and models:	ice altimetry, GNSS, gravimetry, INSAR, meteorological data; ice models, GIA models, ocean models, meteorological models		
E.II Bottom topography, ice compaction (static gravity field)		Medium term	+
Gravity accuracy:	0.01 – 0.1 mGal		
Spatial scale:	20 – 50 km		
Geographic location:	ice sheets (Antarctica, Greenland), glaciers		
Mission duration:	1 y		
Mission considerations:			
Additional data and models:	ice altimetry, penetrating radar, gravimetry; ice models		
E.III Sea ice thickness (static gravity field)		Medium term	++
Geoid accuracy:	10 cm		
Spatial scale:	10 – 100 km		
Geographic location:	polar areas, ice shelves		
Mission duration:	1 y		
Mission considerations:			
Additional data and models:	ice altimetry, echo sounders (upwards); ocean circulation models		
F) Geodesy			
F.I Heights (civil engineering, coastal height reference, sea level height monitoring, GNSS levelling)		Medium term	++
Geoid accuracy:	*Static*: in combination with local terrestrial data 0.5 cm (long term) to 2 cm, without local data 5 cm (long term) to 15 cm; *Time variable*: 0.1 mm/y		
Spatial scale:	20 – 50 km (time variable: 200 km)		
Time scale:	static – secular		
Geographic location:	continents (time variable: Canada, Scandinavia, Antarctica)		
Mission duration:	1 y (time variable: 5 y)		
Mission considerations:			
Additional data and models:	local/airborne gravity, digital terrain models, density models		

F.II Inertial navigation	Medium – long term	+
Gravity / DOV accuracy: 1 mGal / 0.1 arcsec (incl. Omission error) Spatial scale: resolution as high as possible (few km) Geographic location: global Mission duration: 2 y Mission considerations: Additional data and models: terrestrial / airborne gravity, digital terrain models		
Improvement of autonomous navigation: submarine, borehole, tunnels; Reduction of systematic navigation errors: aircraft, missile, and vehicle navigation.		
F.III Satellite orbits		
After GOCE little margin		
G) Atmosphere		
At present there are no specific geoid or gravity requirements from atmosphere scientists. However, future atmospheric model improvements may impose such requirements in a number of areas (topographic gradients, independent detection of mass changes, barotropic circulation).		
H) Planets	Medium – long term	+++ key theme
Dedicated gravity gradiometry mission for Moon – Mars – Venus - … for scientific understanding		

5.4 Towards a Roadmap for Future Satellite Gravity Missions [*Graz*, 2009]

We also mention a recent meeting sponsored by the Global Geodetic Observing System, GGOS, entitled “Towards a Roadmap for Future Satellite Gravity Missions”, which was held on September 30 - October 2, 2009, in Graz, Austria (hereafter referred to as the Graz Workshop, 2009). The goal of the meeting was to establish a roadmap, addressed to the Member Countries and Participating Organizations of the Group on Earth Observations (GEO). The roadmap provides the framework for coordination of national programs and activities of the Participating Organizations to facilitate progress towards the common goals described the roadmap.

The roadmap contains the following text, written in response to the question, “Where do 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.”

The final declaration from the meeting [*Plag et al.*, 2009] is reproduced in the Appendix. It emphasizes the need for “a long and uninterrupted series of satellite gravity mission with accuracies and resolutions at least as good as GRACE…to adequately monitor the global water cycle and to improve our understanding of the processes and consequences of change.”.

The scientific objectives of a GRACE follow on were also discussed. The working group tasked to define the scientific priorities, reintroduced the Scientific Requirements defined in *Sneeuw et al.* [2005].

Specific requests for a follow-on mission were articulated by J. Famiglietti and M. Rodell, representatives of the Hydrologic Science community to the workshop. They requested spatial resolutions of 100 km x 100 km and temporal resolutions of 10-15 days for the NGGM.

5.5 Review of Mass Transport in the Earth System

In this section, we identify the most relevant sources and process of mass distribution and transport in the Earth system. We describe the state-of-the-art results as well as limitation of the current missions.

This section also focuses on the results and limitations of GRACE. At present, the GRACE mission has provided more insight into time variable Earth mass process than any previous gravity mission. As a result, an overview of the GRACE results here will provide a benchmark of the current limitations of satellite gravity in general, i.e. those problems that cannot be addressed today due to insufficient spatial and temporal sampling of the mass field.

5.5.1 Solid-Earth

The four largest areas of solid-Earth contributions to the time variable mass field can be distinguished as: Glacial Isostatic Adjustment (GIA) due to long-term continental ice mass changes and concomitant sea-level variations; co- and post-seismic solid-Earth deformation; mantle convection and plate tectonics; and core motions and seismic modes. The temporal and spatial characteristics of these signals are given in Figure 1-1 of *van Dam et al.* [2008].

5.5.1.1 Glacial Isostatic Adjustment

GIA is the global response of the solid-Earth to changes in ice load following the melting of the Pleistocene glaciers. GIA alters the Earth’s gravitational field as a consequence of mass redistribution within the Earth’s mantle, as well as by deforming the Earth’s surface. The amplitude of the response varies depending on location. In some geographical regions, the corresponding uplift of the Earth’s surface reaches 10 mm/year. Ground motion trends of this amplitude will certainly have an effect on geodetic measurements. Research to investigate present day ice mass or volume change requires accurate models of GIA.

Models are usually poor in polar-regions where a global gravity mission can provide valuable data.

GIA is also an important contributor to sea level change. The retreat of a continent based ice sheet causes land uplift, whereas the water discharged into the ocean causes subsidence of the ocean floor. The redistribution of water into the oceans is geographically dependent. The additional water does not increase sea-level uniformly over all the ocean basins.

Tide gauges provide reliable measurements of sea level [*Douglas*, 1991]. However, precise measurements of sea-level rise have been obtained with satellite altimetry for more than a decade [*Bindoff et al.*, 2007]. Interpretation of these data in terms of present day climate change versus the normal heating and cooling cycles requires that we model the GIA effect accurately.

5.5.1.2 Co- and Post-Seismic Solid-Earth Deformation and Volcanoes

The continual evolution of the solid-Earth on a wide variety of timescales necessitates the use of global observations to develop the knowledge necessary for mitigation of natural hazards. The earthquake cycle in seismically active regions has characteristic timescales of centuries to millennia. Thus, observations at one place over intervals of days to decades, or even over a century only capture a tiny fraction of the cycle. However, when studied over the whole globe, the frequency of events is high, and the study of events at one location can provide the knowledge needed to protect lives in other regions. For example, observations of tsunamis generated by earthquakes in Indonesia and South America help improve the assessment of earthquakes and tsunami risk in the Pacific Northwest of the United States. Observations of landslides in Pakistan and of volcanic eruptions and their precursors in Kamchatka and the Philippines help to improve our understanding of similar risks in other regions of the globe.

The conclusion of the Solid-Earth Hazards, Natural Resources, and Dynamics Panel of the National Research Council (NRC) study, Earth Science and Applications from Space [*NRC*, 2007], concluded that what is slowing progress toward our capability to predict natural hazards is sufficient quantitative observation of the relevant physical processes. By combining such observations with realistic parameterizations of Earth material properties over the spatial scales needed to understand events that trigger catastrophic hazards, as well as the processes that unfold after initiation, it will be possible to improve forecasting for protection of property and human life.

As a result the NRC Solid-Earth Panel recommended as a first priority for solid-Earth science a mission to observe and characterized sub-centimetre level vector-displacements of Earth's surface. Surface deformation is a visible response to processes at depth that drive seismic activity, volcanism and landslides. If the surface deformation is associated with a mass redistribution, gravity can be used as a proxy to surface deformation observations, and thus can provide us with information about the earthquake process.

Clearly, the requirement of sub-centimetre level displacements of the Earth's surface is not directly applicable to NGGM. Nonetheless, GRACE has already demonstrated the ability to observe co- and post-seismic gravity changes associated with the 2004 Sumatra-Adaman Earthquake [*Han et al.*, 2006]. What is significant about the GRACE contribution here is that the observations constrained the co- and post-seismic mass movement where observations of surface displacement were unavailable, i.e. the displacement was under the ocean.

The topic of core motions and seismic normal modes will not be considered in the context of this report as these signals are currently better observed using ground based techniques.

5.5.1.3 Solid-Earth Studies and GRACE

Differences in mantle viscosity and lithospheric thickness are expected to become discernable from GRACE data up until ~ degree 15, where lower mantle viscosity exhibits the highest sensitivity. *Wahr and Davis* [2002] show that in the pre-launch error estimates for GRACE, that GRACE should be able to detect GIA motions and present-day Antarctic and Greenland Ice mass decay up to harmonic degree 40, and might be able to distinguish mantle viscosity and lithosphere thickness in solid-Earth models up to harmonic degree 15. Furthermore *Wahr and Davis* [2002] demonstrated that if the pre-launch GRACE error curve could be lowered for harmonic degrees above 15, additional information would become available, particularly on lithospheric thickness and shallow mantle viscosity.

Current GRACE data sets indicate that the late-Pleistocene ice sheet above Canada must have consisted of at least two major domes [*Tamisiea et al*., 2007]. Combining the GRACE trends with the static free-air gravity data from the region, the authors find that the determined rates contribute ~25-45% to the observed static gravity field. This finding represents an important boundary condition on the buoyancy of the continental tectosphere.

As mentioned above, *Han et al.* [2006] used the GRACE fields to extract the gravity change signal associated with the Sumatra-Adaman Earthquake. The post-seismic signal has been detected as well [*Chen et al*., 2007; *de Lineage et al*., 2009]. These studies are particularly important because they have provided information, which has been used to infer crustal displacement on the fault. As the fault is under water, there is no other way to determine this quantity. These results are also important for providing information on the post-seismic relaxation and on the mass redistribution. If the spatial and temporal sampling were improved, smaller more typical earthquakes could be studied, providing more information on the earthquake cycle.

5.5.2 Oceans

Oceanography is a field where improved satellite gravity observations could have a tremendous impact.

Improved knowledge of absolute surface currents based on satellite altimetry is expected in the near future with precise measurements of the static geoid (GOCE). A high spatial-resolution static gravity field in combination with similarly high resolution altimetry can be used to improve our understanding of the topographic control of mean ocean circulation, coastal currents along shelf edges, eddy flow, the positioning of ocean fronts, and the ocean bathymetry.

Observations of temporal gravity field variations are of great importance for oceanography as well. Satellite altimetry cannot distinguish between sea-level changes from steric effects (temperature and salinity-induced) and those from water-mass effects. However, the separation is possible by combining altimetry with GRACE, which measures the ocean mass component only. Such a separation allows an independent estimate of basin scale sea-level changes, provided that *in situ* measurements of the water temperature and salinity are interpreted simultaneously.

Unfortunately, the current GRACE mission has a low signal-to-noise ratio over the oceans. An NGGM should provide more precise estimates of the vertically integrated ocean mass (or equivalent bottom pressure) variations associated with ocean currents. Assimilation of data from satellite altimetry and NGGM gravity data into general circulation models would allow for the determination of the vertical structure of the ocean circulation.

5.5.2.1 Ocean Studies and GRACE

Most ocean studies to date using the GRACE data have focused on the longer wavelength signals such as seasonal steric sea level variations [*Chambers*, 2006], global ocean mass variations [*Chambers et al.*, 2004; *Kuo et al*., 2008; *Morison et al*., 2007], large-scale ocean bottom pressure variability [*Chambers and Willis*, 2008; *Kanzow et al*., 2005; *Ponte et al.*, 2007], and diurnal ocean tides [*Han et al.*, 2005; *Han et al*., 2007; *King et al*., 2005; *Knudsen*, 2003; *Ray et al*., 2006].

Other studies have used the static field to derive the mean surface topography and geostrophic ocean surface velocities [*Dobslaw et al*., 2004; *Thompson et al*., 2009]. *Thompson* concluded that GRACE was only able to provide information on the ocean surface velocities down to about 1000 km.

Investigations into ocean circulation of the North Atlantic Ocean [*Jayne*, 2006] and the Antarctic Circumpolar Current [*Zlotnicki et al.*, 2007] using GRACE data have been very successful. However, problems with the monthly averaging of the GRACE data make direct comparisons with altimetric observations difficult. Further, the spatial resolution of the GRACE spherical harmonic data is several hundred km, whereas in the case of the North Atlantic Study [*Jayne*, 2006], spatial sampling, on the order of 50 km is required to study the Gulf Stream.

One of the largest error sources in interpreting the GRACE data in terms of oceanographic variability is the leakage of mass change signals from the nearby continents into the ocean mass signals. This problem could also be mitigated, with higher spatial resolution of the gravity field.

5.5.3 Hydrology

5.5.3.1 Surface Water

The change in water stored in lakes, reservoirs, wetlands, and stream channels, and the discharge of streams and rivers, are major terms in the water balance of global land areas. Both terms are poorly observed globally. Observations of these variables are now provided by in situ networks, whose quality and spatial distribution vary greatly from country to country. Even where point data are high, they are unable to capture the spatial dynamics of wetlands and flooding rivers.

5.5.3.2 Snow

Over most of the northern hemisphere land areas and the high-elevation areas of the southern hemisphere snow is a key component of the water cycle. The discharge of the major Arctic rivers originates almost entirely as snowmelt. The challenge is to be able to separate snow mass from other mass sources. In addition, evolving snow cover affects atmospheric circulation and climate on local to regional and global scales.

5.5.3.3 Groundwater Storage

Groundwater storage is an essential component of the hydrologic cycle. GRACE has successfully demonstrated the feasibility of space-based gravity measurements for global land hydrology. Even though its relatively coarse spatial resolution (effectively ~500 km, although the spatial resolution of GRACE has to be interpreted carefully) has limited its use to large regional-scale observations, breakthrough science has resulted, including observations of seasonal and multiyear variations in the groundwater stored in the underground reservoirs in the Indian areas encompassed by Rajasthan, Punjab, and Haryana [*Rodell et al.*, 2009].

5.5.3.4 Soil Moisture

Soil moisture is a key determinant of evapotranspiration. Extracting the soil moisture component from the cumulative mass change signal would require additional data sets.

5.5.3.5 Hydrological Mass Change Trends

The only way to determine whether the multiyear trends are representative of long-term changes in mass balance is to extend the length of the observations. Other hydrologic measures, such as mean river-basin evapotranspiration, may also be inferred for large river basins but are likewise constrained by the short data record. The somewhat improved spatial resolution of an NGGM and the continuation of the GRACE observation record would provide invaluable observations of long-term climate-related changes in the hydrology mass fields. Longer records would improve the characterization of interannual changes in soil moisture and groundwater storage, which are used by hydrologists for understanding drought and flooding.

5.5.4 Hydrology and Global Change

With regards to a future gravity mission, the hydrologists at the Graz Workshop 2009 indicated that an NGGM should be designed to address the following questions:

- Is the water cycle accelerating? Are floods increasing? Is drought increasing? In a warming climate we can expect more evaporation and thus more precipitation and runoff, i.e. bigger exchanges or more cycling of water in the water cycle. Models suggest and observations are beginning to indicate that the magnitude and frequency of hydrologic extremes of flooding and drought will also increase. GRACE is beginning to contribute to these studies. A future mission should enhance the spatial and temporal resolution of observations and provide the longer record required.
- What are the land contributions to global mean sea level rise? Currently these contributions to sea level rise are unclear [*Church et al.*, 2001]. This question can be addressed by higher temporal and spatial resolution of the water-storage field over land.
- Are the observed trends real and are they representative of the long-term trends? Again any future mission must have a minimum decadal mission life to address this question.

5.5.4.1 Hydrology and GRACE

Hydrology represents the field where GRACE has probably contributed the most. In the early history of GRACE many papers were published on the long-wavelength seasonal changes in continental hydrology [See for example *Tapley et al.*, 2004; *Wahr et al.*, 2004; *Swenson et al.*, 2003; *Chen et al.*, 2005; *Ramillen et al*. 2004; *Ramillen et al.*, 2005; etc.].

Since about 2004, more and more studies have begun to focus on basin scale estimates of total water storage change, for example the Congo Basin [*Crowley et al.*, 2008], Lake Victoria [*Awange et al.*, 2008; *Swenson and Wahr*, 2009], and Three Gorges [*Wang et al.*, 2007]. These studies often compare GRACE observations with in situ data and demonstrate the value of TVG at spatial scales on the order of 200 km.

In addition to these studies of the total water storage, specific components, such as, evapotranspiration [*Rodell et al.,* 2004; *Ramillien et al.* 2006a] groundwater storage [*Rodell et al.*, 2007; *Strassberg et al.*, 2007], precipitation [*Crowley et al.*, 2008] have been derived for regional scales from the GRACE data. This fact points to the ability to separate the different mass components using outside data sets in combination with GRACE.

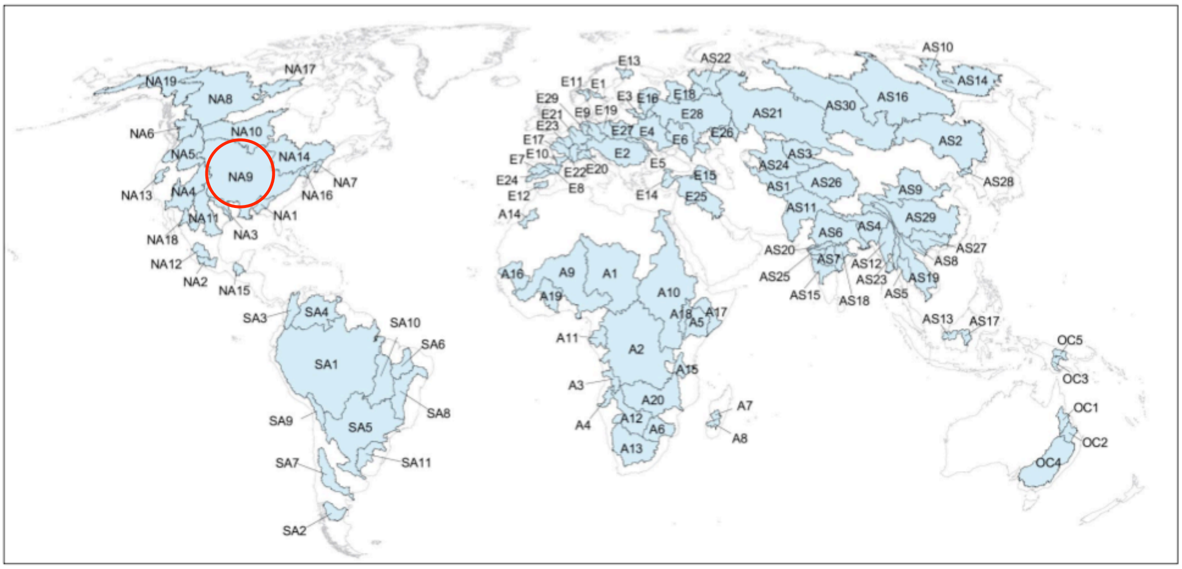

Figure 5-1: Distribution and relative size of the global river basins. The red circle in the figure shows the spatial resolution of GRACE.

In summary, while GRACE is proving invaluable to our understanding of continental water mass transport, TVG would be even more valuable at higher resolutions in time and space. This is evident by Figure 5-1, which shows the global distribution of the world's river basins. The red circle shows the average spatial resolution of GRACE. Please note the number of basins (conservatively about 50%) in the figure that cover a smaller area than the GRACE footprint and are thus not currently observable with GRACE. Wetlands, lakes, streams, and groundwater reservoirs are in general also much smaller than the GRACE footprint and are also thus not adequately resolved.

The demand for finer spatial resolution is also evident in the recommendations from the NRC Panel on Water Resources and the Global Hydrologic Cycle [NRC, 2007], who state that global measurements of surface water, soil moisture, and groundwater are required at spatial resolutions of 100 km. Further, at the recent Graz Workshop, 2009, J. Famiglietti and M. Rodell, as representatives of the Hydrologic Science community called for spatial resolutions of 100 km x 100 km and temporal resolutions of 10-15 days.

5.5.5 Polar Ice and Glaciers

Mass balance of the ice sheets and their contributions to sea level are key issues in climate variability and change. The relationships between sea level and climate have been identified as critical subjects in the Intergovernmental Panel on Climate Change (IPCC) assessments. However the relative contributions of the different components remains highly debatable. Because much of the past and future behaviour of ice sheets is manifested in their mass, accurate and high spatial sampling of ice mass change is essential for understanding their contribution to sea-level rise.

The NRC Panel on Climate variability and Change [*NRC*, 2007] state that "as climate change continues, ongoing frequent measurement of both land ice (monthly) and sea ice (daily) will be needed to determine trends, update assessments, and test climate models…Combining altimetry with a gravity measurement at a higher precision than GRACE would optimally measure change in ice sheet volume and mass and contribute directly to determining the ice sheet contribution to sea-level rise."

5.5.5.1 GRACE and Ice Mass Change estimates

Spectacular results have been achieved with GRACE Stokes coefficients including regional estimates of ice mass change trends over Greenland [*Velicogna and Wahr*, 2006a; Chen et al., 2006a] and Antarctica [*Velicogna and Wahr*, 2006b; *Chen et al*., 2006b]. Finer resolution estimates of mass change have also been derived using the so-called *mascons* [*Luthcke et al*., 2006; *Luthcke et al*., 2008]. Nonetheless, the spatial resolution remains too coarse to allow us to distinguish between mass loss due to ice sheet melting or glacial dynamics.

An additional problem for interpreting change on the large ice sheets is that the mass change trend estimates differ considerably among the investigations. Compare, for example, the trend estimate of (-139 $\pm$ 73) Gt/yr for the period 04/2002-08/2005 by *Velicogna and Wahr* [2006b] with the estimate of (-40 $\pm$ 36) Gt/yr for the period 07/2002-03/2005 by *Ramillien et al.* [2006b]. As noted by *Horwath and Dietrich* [2009], interannual ice mass variations are one cause of the differences. However, even restricting the analysis to identical time intervals, very different results can arise from different releases of monthly solutions or from different methods of analyzing one set of monthly solutions. A significant contribution to interpreting the GRACE data over Antarctica has recently been published by *Horwath and Dietrich* [2009]. In the paper they investigate methods and errors of mass change inferences from GRACE monthly solutions given in the spherical harmonic representation. Their conclusions reinforce the need for an improvement in background models, as well as the need for the application of more realistic error models for the GRACE solutions.

6 Results from the ESA Mass Transport Study (MTS)

The stated goal of the ESA sponsored study "Monitoring and Modelling Individual Sources of Mass Distribution and Transport in the Earth System by Means of Satellites" was to "…find means to monitor and model individual sources of mass distribution and transport in the Earth system." The tasks included 1) identifying and modelling the major mass transport processes in the Earth system; 2) determining a limited number of initial orbit scenarios for observing the mass transport; 3) the development of a simulation tool to generate synthetic gravity fields from the various orbit scenarios; and finally, 4) retrieving the initial hydrology field from the synthetic gravity retrievals.

This section highlights the most important results obtained in that study and which are pertinent to the current study. In particular, we discuss:

- The frequency-spectral content of the mass-transport model developed in the MTS.
- The process the study team used to select the mission designs used in the simulations in that study;
- The mission designs themselves;
- The closed-loop gravity field retrieval;
- And the study conclusions.

6.1 Modelling the Major Mass Transport Processes

The study team selected representative source models in the fields of solid-Earth geophysics (S), oceanography (O), tides, ice (I), hydrology (H), and atmospheric pressure (A). In the interest of brevity, each individual mass-transport component, which contributed to the mass-transport model, is described in the Appendix.

6.1.1 Frequency Spectral Analysis of the Mass Fields

The individual data files were interpolated to 1 x 1 degree grid at 6 hourly time steps. All the source models were converted to spherical harmonic expansions complete to degree and order 180. The RMS of the degree amplitudes for a single year for the combined model (AOHIS) is displayed in Figure 6-1.

The gravity field mission scenarios that were investigated aimed at resolving temporal gravity, i.e. in the analyses the gravity field solutions were determined with respect to the mean of the specific year that has been selected. It can be seen that the atmospheric, ocean and hydrology mass change signals have the same order of magnitude for the low spherical harmonic degrees (1-15). The hydrological mass change signals starts to dominate the other signals beyond degree 20.

One has to be careful when regarding degree-amplitudes of spherical harmonics converted to mass fields. As this is a global representation, the signal is underestimated when only regional data sets are used. For example, ice contributes only in Greenland and Antarctica. Everywhere else the signal is set to 0. After conversion to spherical harmonics, we obtain some mean signal per frequency, which could be strongly influenced by the zero values (signal is decreased). So in reality the signal strength could be much stronger in such a case over the region where the signal exists. One should take this into account when comparing mass signals in spherical harmonic representations versus gravity field errors from simulations.

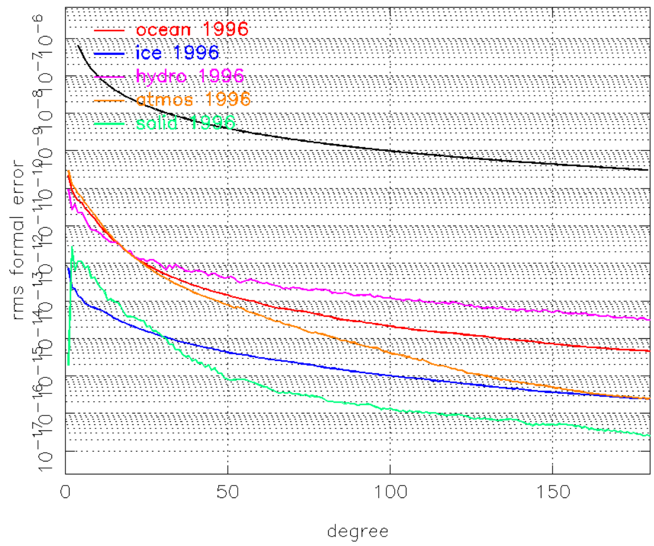

Figure 6-1: RMS about the mean of spherical harmonic coefficients of the source models as a function of degree.

In the following sections we analyze the frequency spectral distribution of power in the mass fields. This type of analysis provides some indication of the frequency and wavelength where power exists in the model. Please note, that the study attempted to capture as much of the real mass transport dynamics in the models generated as possible. Nonetheless, there is the possibility that some real signal may have been missed. Thus, the results presented here should be interpreted with a small degree of scepticism.

Further, several unrealistic features were discovered in the model. These limitations are discussed in the Appendix.

6.1.1.1 Total Mass Field

Figure 6-2 shows the degree amplitude of the combined mass signal (for the year 1995) versus the sensitivity of various existing or proposed satellite gravity missions, e.g. CHAMP, GRACE, GOCE, and potential future gravity mission scenarios, e.g. GRACE-like with 10 times more sensitivity (GRACE10), and GRACE-like with 100 times more sensitivity (GRACE100). In this figure, we see that GRACE is sensitive to variability in mass variability up to degree l=15 (a spatial wavelength of 2700 km). (However, post-processing techniques have allowed for an even higher spatial resolution of the GRACE data in reality.) Improving the sensitivity of a GRACE-like mission by a factor of 100 would increase the maximum wavelength of the signals currently observable by GRACE (the most sensitive gravity mission to date) from approximately 2700 km (l=15) to 620 km (l=65).

In Figure 6-3a, we show the power spectral density of the 1995 combined data as a function of degree and frequency. This plot demonstrates that most of the power in the mass field is due to low frequency variations from large spatial scale events. There is an obvious signal at all degrees at one cycle/day (365 cy/yr). The detrended RMS of the combined signal is shown in Figure 6-3b. The bulk of the scatter comes from the high latitudes (> ±35°). However, some equatorial signals are evident due to annual hydrological variability in the Amazon and South-East Asia.

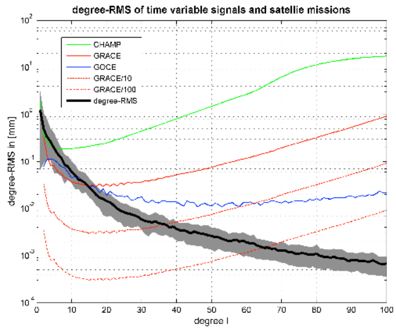

Figure 6-2**:** The degree amplitude of combined mass signal versus several existing, and planned gravity missions, as well as 2 potential missions having the 10 and 100 times the sensitivity of GRACE. This plot was generated for the data from 1995.

The information in Figure 6-3 is incomplete. While we know which degrees have power at which frequencies (Figure 6-3a), this Figure does not indicate at which bandwidths the power is found. In Figure 6-4 we compare the RMS of the total combined mass signal (for 1995) at various temporal bandwidths. This type of analysis demonstrates which temporal periods contribute to the scatter of the spatial mass field. These images are generated by first converting the spherical harmonic data into 6-hourly gridded global data. The time series at each point is then demeaned (using the 1995 data), de-trended, bandpass filtered and the RMS of that time series is determined. The largest spatial variability is observed at periods between 2 and 30 days.

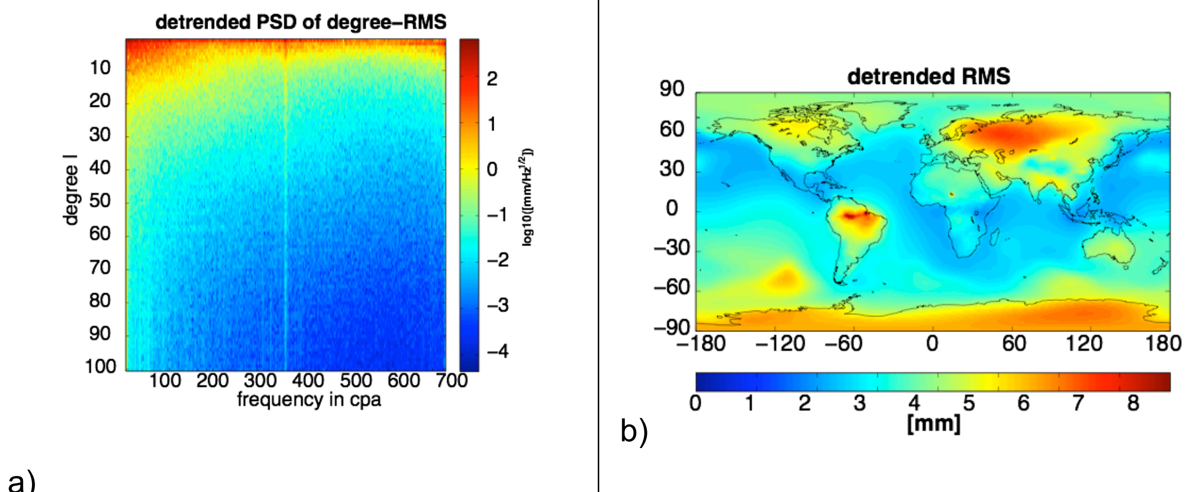

Figure 6-3: a) Frequency-spectral analysis of the Atmosphere + Ocean + Hydrology + Ice + Solid-Earth Mass field combination for 1995; b) RMS of the geoid height of Atmosphere + Ocean + Hydrology + Ice + Solid-Earth Mass field combination for 1995.

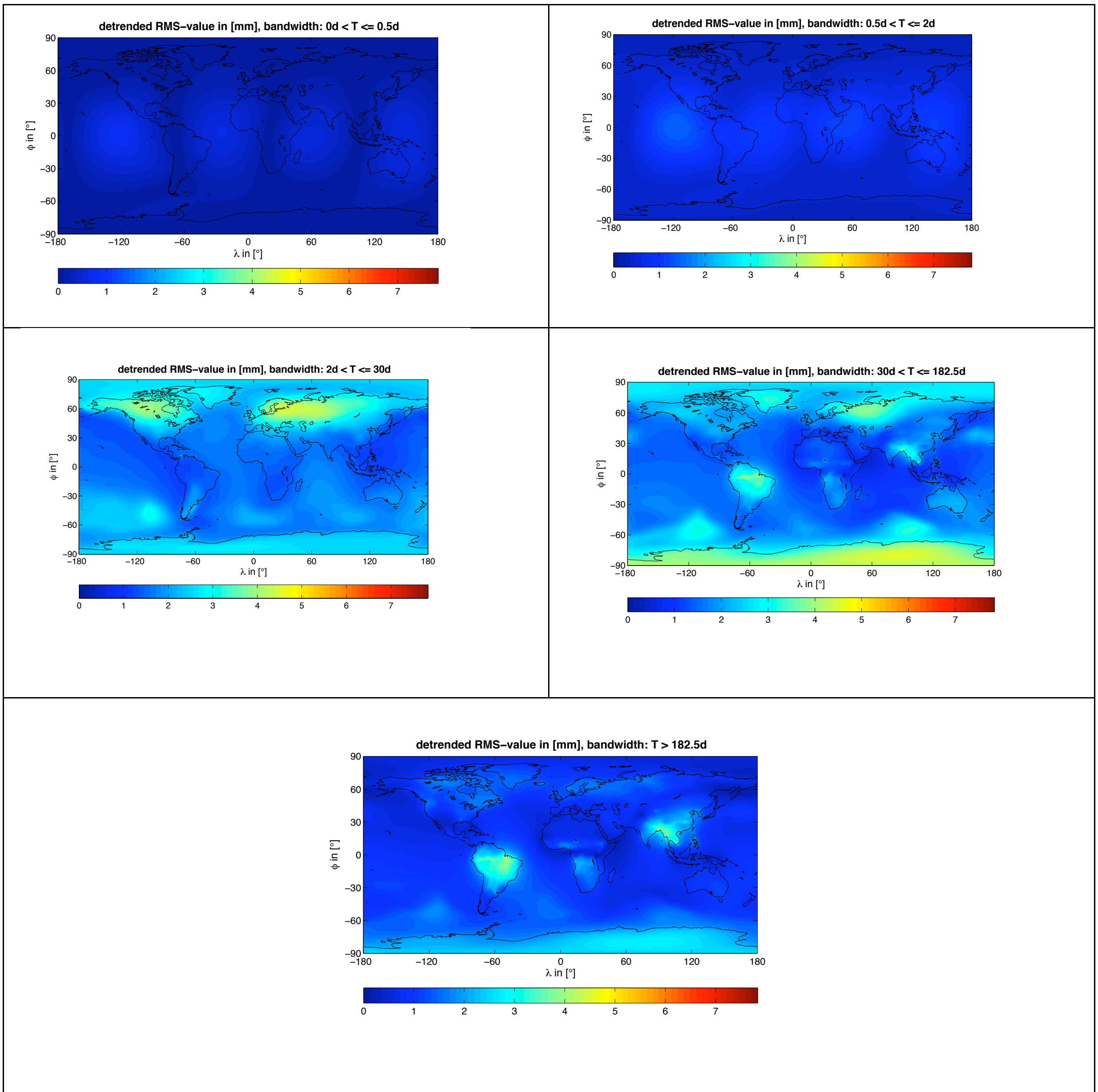

Figure 6-4: RMS summary of the geoid height by bandwidth for the Atmosphere + Ocean + Hydrology + Ice + Solid-Earth mass field, 1995 data. The largest spatial variability is observed at periods between 2 and 30 days.

6.1.1.2 Atmosphere + Ocean

A spectral-frequency analysis of the 1995 atmosphere-ocean (AO) data, Figure 6-5a, indicate that most of the signal has a spatial resolution of 1 ≤ l ≤ 10 (a corresponding spatial half-wavelength of 20,000 km ≤ λ/2 ≤ 2000 km), with temporal power at frequencies from 365 to 1 cycles/yr. Figure 6-5b shows the RMS of the AO data. Most of the variability occurs in the regions outside the latitude range of ± 30 degrees of the equator. The atmospheric signal is compensated over most of the oceans, excluding the extreme southern ocean.

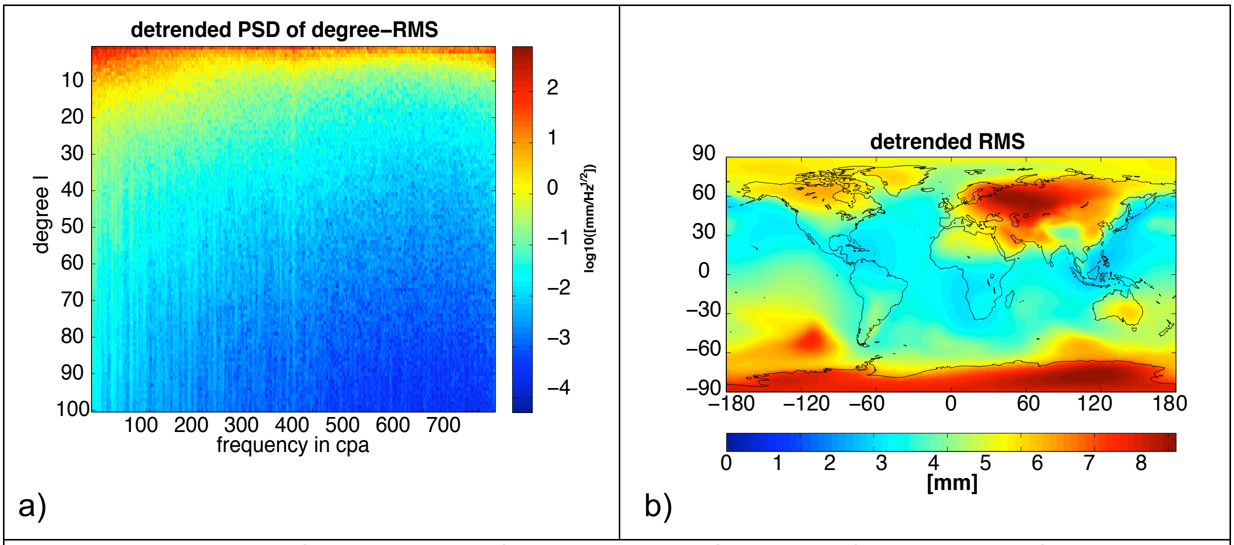

Figure 6-5: a) Frequency-Spectral analysis of the Atmosphere + Ocean Mass field combination for 1995. b) RMS of the geoid height of the Atmosphere + Ocean Mass field combination for 1995.

Additional bandpass analyses of the RMS data (not shown) indicate that the scatter in the AO is primarily driven by signals with frequencies between 30 and 182 days. However, some scatter is observable in the range 0.5-2 days and also the range 2-30 days. These results indicate that if recovery of the AO-signals by future satellite missions was determined to be a primary objective, a temporal sampling of the AO at of 1 day or even 12 hours with a polar orbiting satellite should specified at part of the mission definitions. In the MTS, high frequency AO signals are considered nuisance signals and are handled as background models in the gravity field modelling.

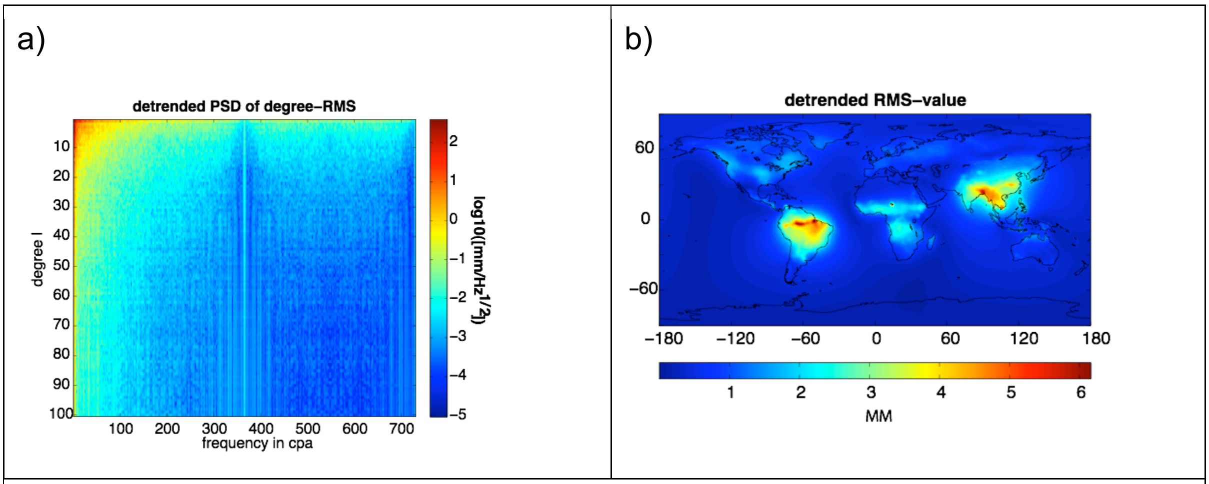

Figure 6-6: a) Frequency-Spectral analysis of the Hydrology Mass field combination for 1995. b) RMS of the geoid height of the Hydrology Mass field combination for 1995.

6.1.1.3 Hydrology

The spectral-degree decomposition of the hydrology mass signal (Figure 6-6a) indicates that the hydrological mass signal is dominated by signals with a frequency between 1 and 50 cycles/yr (or 6 days to 1 year) with long spatial wavelengths, $1 \leq l \leq 20$, (a corresponding spatial half-wavelength of 20,000 km $\leq \lambda/2 \leq$ 1000 km). The

RMS values (Figure 6-6b) of the geoid height can reach up to 4-8 mm in the Amazon, Central Africa, and South-East Asia. A band-pass analysis of the gridded RMS data (not shown) indicates that the RMS is controlled by changes in water mass at periods between monthly and annual. Future missions should aim for a spatial resolution of l=60-70 and a temporal sampling of 14-30 days to reliably capture hydrological variability.

6.1.1.4 Ice + Solid-Earth

The low degree coefficients from this data display a drift (not shown). This is expected from the mass trends due to long-term ice melting at the poles and due to the glacial isostatic adjustment of regions near Fennoscandia and Canada. These trends should be observable with a satellite with a long measurement period (5-10 years).

The Ice + Solid-Earth signals are quite small in comparison to the Hydrology and the Atmosphere + Ocean mass signals. The largest signals are restricted to regions that are currently covered with ice, e.g. Greenland and Antarctica. Spectral degree-frequency analysis of the de-trended data (Figure 6-7a) indicates that there is power at the annual and longer periods. The RMS of the de-trended data is confined to Antarctica and Greenland (Figure 6-7b).

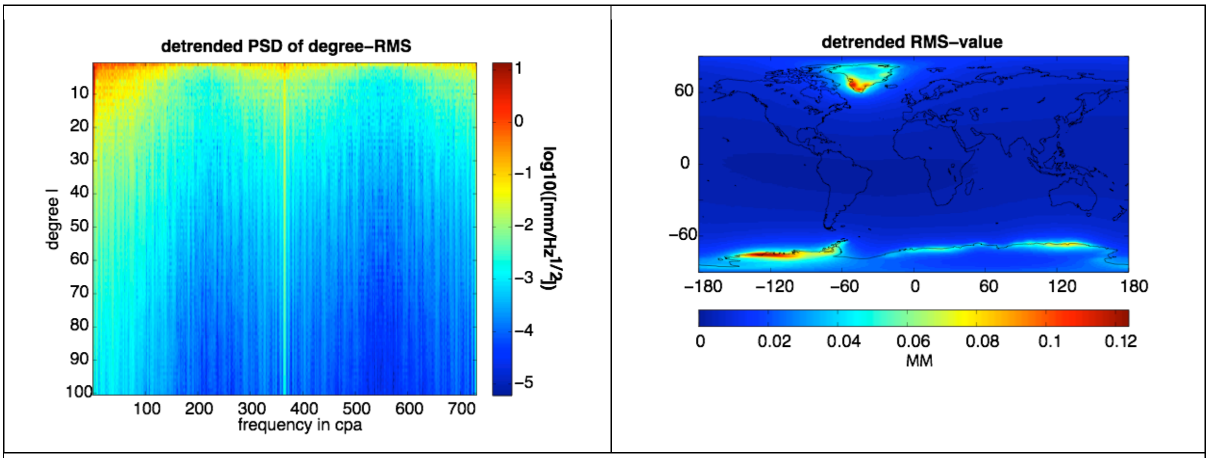

Figure 6-7: a) Frequency-Spectral analysis of the Ice + Solid-Earth Mass field combination for 1995. b) RMS of the geoid height of the Ice + Solid-Earth Mass field combination for 1995.

6.1.1.5 Summary

These analyses of the power content of the MTS mass transport model in terms of frequency, wavelength, spatial distribution, and bandwidth can be summarized as follows:

- Ice and solid-Earth signals are primarily characterized by long terms trends and they are concentrated in very specific regions, i.e. Greenland and Antarctica.
- Hydrology signals have power primarily at annual and secular periods with spatial wavelengths between l=1 and l=60. The scatter is geographically limited to continents, primarily large ocean basins. The RMS in the bandpass analysis indicates that the largest variability occurs in the range of 30 days to 1 year.

- The atmosphere and ocean has power at a wide range of frequencies. Most of the power comes from the high latitudes.
- The total mass model shows that most of the power comes from transport with large spatial scales. The bulk of the signal comes from the high latitudes as well as from known large hydrological basins. The bandpass analysis indicates that the largest variability occurs between 2 and 30 days.

6.2 Mission Design and Selection

Figure 6-4 shows that the total AOHIS mass variation contains signals at all frequencies. The hydrology (H) is dominant at low frequencies with periods near the annual (see Figure 6-6). The AOHIS is dominated at periods greater than 182 days by the hydrology signal, particularly those in the Amazon River basin. The atmosphere + ocean (AO) signal dominates the RMS at the higher frequencies (2 days < T < 182 days) and primarily acts over the high latitudes (the Arctic and Antarctic).

The ocean tide model is dominant in the period between 0 and 2 days. The tides cover the oceans with a well-known structure. The tidal signal amounts to ~ 3 cm of geoid height and is very large compared to hydrology and AO.

The ice+ solid (IS) Earth signal is dominated by a trend (due to post-glacial uplift over Canada and Fennoscandia and due to ice-mass loss over Greenland and Antarctica).

To determine the initial orbit scenarios, it was necessary to decide which signals were to be recovered from the simulations. The MTS study team decided to focus on the recovery of the hydrology and the trends in the ice/solid-Earth signals. To capture the hydrological signal, weekly or even monthly solutions with good ground-track coverage of the Earth at near equatorial areas appeared sufficient. For the IS trends, a long mission duration and polar or near polar orbits were deemed important.

Nevertheless, the H and IS solutions will be perturbed by the high frequency and strong signals of the atmosphere/ocean and especially the ocean tides, if they are not removed correctly by: 1) AO de-aliasing products; 2) co-estimation; or 3) sampled correctly by the satellite mission. In general, the AO signal and the tides will alias into the long wavelengths and spatial distribution of the hydrology solution due to temporal and spatial under-sampling. The aim is to find a satellite mission, which mitigates such aliasing effects due to an improved spatio-temporal sampling. For the reduction of the tidal aliasing, alternative possibilities may exist since their signal is strictly periodic. If the satellite orbit is known, the tidal aliasing periods can be determined a priori and the tidal effects thus might be estimated or reduced from the satellite data or solutions. Also vice-versa, the satellite orbit can be designed in such a way that it produces predictable aliasing frequencies.

For the mission selection only (β/α) repeat orbits were regarded in order to mitigate the effects due to time-variable ground-tracks (See Section 3.2).

The sensitivity of the mission and the required temporal sampling were regarded as given quantities. For the recovery of hydrology gravity change signals, 8-day solutions (ΔT = 8 days) seemed to be sufficient. The spatial resolution is then determined by the mission sensitivity and the signal strength of the mass fields. The potential sensitivity of the mission is mainly driven by the measurement accuracy and the selected satellite formation. The comparison of the mission sensitivity and the time variable signals to be recovered leads to a maximum spherical harmonic degree l_{max}. Figure 6-2 shows degree-RMS-curves of the time-variable signal (hydrology) and GRACE errors for the year 1995. The GRACE10 and the GRACE100 error curves for an improved mission (factor of 10 or 100) are predicted from GGM02S [*Tapley et al*., 2005]. Thus, a recovery of the hydrology signal up to degree l_{max} = 40 - 70 should be possible by an improved GRACE-like mission, provided that the aliasing problem can be overcome.

Six initial orbit scenarios were developed. The first scenario came about by considering a GRACE-like formation (sensor) having an improved, measurement accuracy for the range rates. The favoured temporal sampling of 8 days led to l_{max} = 60. A single-ground track strategy was adopted, which led to a minimum of 120 revolutions and a repeat orbit of ~ 16 days (SC1 which represents 2 tandems).

For scenario two, SC12, we tried to reduce the aliasing periods such that the temporal sampling was 4 nodal days. This was accomplished by placing a second satellite pair on the same ground track as Scenario 1 with a time shift.

For scenario three, SC1234, the aliasing was reduced by placing 4 additional tandems on the same ground track and resulted in a temporal sampling of 2 days.

In addition to these homogeneous strategies, heterogeneous strategies, i.e. ground-tracks in different repeat modes and with different inclination were also considered. As an additional mission, a so-called Bender configuration (mission BEN12) with sensors in 79/5-repeat modes (I = 90°, BEN1) and 360/23-repeat modes (I = 117.4°, BEN2) is investigated [*Bender et al*., 2008]. By adding a second sensor with different repeat mode and inclination, both the temporal and spatial sampling can be improved.

The relevant orbit parameters of the satellites are shown in **Table 6-1** and **Table 6-2**.

Table 6-1: Satellite tandems (ψ represents the distance between the leading and trailing satellite of each tandem in terms of orbit angle).

Pair	a [km]	I [deg]	Separation ψ [°]	Repeat period	
				days	rev
1 SC1 - 4	6746.3	90.0	1.958	8/7.98	125
2 BEN1	6696.4	90.0	1.958	5/4.99	79
3 BEN2	6784.8	117.4	1.958	23/23.17	360

Table 6-2: true anomaly ν_0 of satellites SC1-4 (leader satellite of the tandem); I = 90°, a = 6746.3 km, e = 0, ω = 0°, Ω = 0°

Kepler element	SC1	SC2	SC3	SC4
true anomaly ν_0 [°]	0	180	270	90

6.3 Closed–loop Gravity Field Retrieval

This Chapter includes a brief summary of the setup that was used for the closed-loop gravity field retrieval simulations and a selection of representative results. The analysis of the results has been enhanced by zooming in on selected geographical areas in South-America, Africa and the Arctic.

The observation of gravity field changes due to hydrology has been investigated in the most detail (of all source mass models) to assess the impact of mission parameters, sensor error levels, errors in modelling of certain gravity field sources, etc.. In addition, attention has been paid to the observation of gravity field changes due to the Sumatra earthquake in 2004, and due to oceanography either separately or in combination with hydrology.

6.3.1 Representing the Real-World

The real-world gravity field was compiled by taking into account a static background model, i.e. GGM01S, and the modelled time-varying mass changes caused by hydrology, oceanography, atmosphere, solid-Earth and ice. Use was made of 6-hourly piecewise-linear spherical harmonic expansions complete to degree and order 50, commensurate with a spatial resolution of about 400 km thereby including the dominant part of the associated signals. In addition, the time-varying gravity field due to ocean tides was taken into account, including again spherical harmonic expansions complete to degree and order 50 for the 8 major tidal constituents.

6.3.2 Mission Scenarios and Observations

The satellite constellations that have been selected are missions based on 1, 2 and 4 polar satellite pairs, and the Bender-type missions consisting of two pairs in orbits with different inclination (**Table 6-1**). A comprehensive and detailed software system has been used for simulating satellite orbits and observations, a system that is in use for processing real observations for gravity field determination as well. The choice for this study has been to conduct closed-loop gravity field retrieval simulations for GRACE-type missions only, i.e. the observables consist of low-low Satellite-to-Satellite Tracking (ll-SST) observations and time series of orbital positions (thought to be derived from e.g. GPS high-low SST observations). The ll-SST concept is considered to be the most feasible for observing time-varying gravity.

6.3.3 Gravity Field Estimation

The closed-loop gravity field retrieval approach is outlined in flow chart found in **Figure 6-8** (more detail can also be found in *Visser and Schrama*, [2005]). Benchmark gravity field retrieval simulations were conducted with two different methods, referred to as the *variational approach* and *acceleration approach*, respectively. The two methods led to consistent results. Since the implementation of the *variational approach* has the capability to simulate all steps for closed-loop gravity field retrievals, this method was chosen as the baseline method.

The closed-loop approach allows for the assessment of the impact of different choices for mission scenarios, different sensors and in association sensor noise levels/profiles, errors in the modelling of specific gravity field sources, etc.

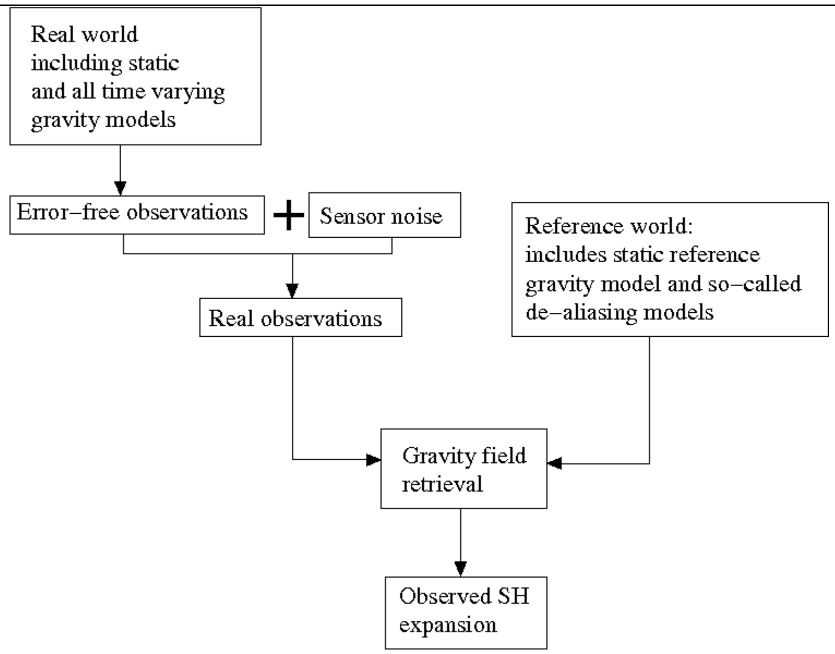

Figure 6-8: Flow chart for closed-loop gravity field retrieval.

Error sources were also considered in the gravity field retrievals. A summary of the error sources that were considered is provided in **Table 6-3**. Extensive retrieval results were presented in the Task 4 report of the MTS study and will not be reproduced here.

Table 6-3: Overview of error sources that can be used to assess their impact on the retrieval of mass changes due to hydrology.

Error sources	Defined amplitude
- sensor noise	High noise: Gaussian 1 cm for orbit position coordinates & 1 µm/s for ll-SST @ 0.05Hz Low noise: Gaussian 1 cm for orbit position coordinates & 10 nm/s for ll-SST @ 0.05 Hz
- accelerometer	High noise: 10^{-10} m/s^2 @ 0.05 Hz Low noise: 10^{-11} m/s^2 @ 0.05 Hz*
- solid-Earth	Switched-off
- ice	Switched-off
- atmosphere	10% of signal
- oceans	10% of signal
- ocean tides	FES2004 vs. TPX06.2
- static gravity	GGM01s claimed coefficient errors

*This noise floor just served as an example. In fact any noise floor can be specified for the tools that we use.

6.4 Conclusions of the MTS

In this section, we present the main conclusions of the MTS that have a bearing on the present NGGM study.

Temporal aliasing is intrinsic to observing gravity field changes by satellites, but e.g. leads to relatively smaller distortions for hydrology than for oceanography.

The combination of ll-SST and orbit observables does not allow for the precise determination of the spherical harmonic degree-1 terms or geo-centre variations. These terms have to be derived by other means, e.g. by Satellite Laser Ranging (SLR).

As soon as sensor noise levels are sufficiently low, temporal aliasing leads to larger uncertainties in the observation of gravity field changes due to mass transports rather than sensor errors. The impact of temporal aliasing also depends on the choice of the satellite constellation and their associated orbital parameters.

In the case of high sensor noise levels, flying more pairs of satellites significantly reduces the gravity field retrieval errors. However, a much bigger improvement can be achieved by lowering the noise levels of the sensor systems. Also, when flying more pairs of satellites, great care has to be taken with the choice of orbital parameters.

Single polar satellite pairs provide better performance at high latitudes (or polar areas), even at high sensor noise levels. The observation and study of mass changes due to for example the melt of the Greenland ice cap [*Wouters et al*., 2008] would already benefit by flying a GRACE follow-on mission with the same instrumentation.

When processing space-borne gravimetric observations for retrieving mass changes due to a certain physical phenomenon, it is best to include as much as possible prior knowledge in the background gravity model. This background model was used to reduce the observations to residuals from which the signal of interest is to be retrieved.

In the presence of systematic errors, such as errors in gravity field background models (e.g. ocean tides, atmosphere), assigning weights to different observables (e.g. orbit coordinates, ll-SST observations) is a complicated optimization process. Also, the estimation of absorption/nuisance parameters in addition to the gravity field coefficients can help to mitigate the effect of such systematic errors.

6.4.1 Hydrology

The aliasing of ocean tides can be mitigated significantly by selecting appropriate orbital parameters. In addition, improvements can be obtained by tuning the weighting of different observables in the gravity estimation process and/or by co-estimating ocean tidal functions.

Performance can be different for different geographical regions. For lower latitudes, a Bender satellite constellation can lead to a significant improvement in the observation of mass changes.

6.4.2 Solid-Earth

Many solid-Earth processes lead to very slow changes of the Earth's gravity field, typically at time scales that are orders of magnitude longer than the duration of satellite missions. It can be stated that such processes lead to contributions to the gravity field that can be considered pseudo-constant. The focus of this study has been on the observation of time-varying gravity, but it is fair to assume that future gravity field missions will allow for the observation of small-scale spatial structures (< 100 km) of the static gravity field. An open issue for research is how such structures can be separated from other contributions. Such separation will provide insight into the physical properties of the solid-Earth.

The potential for observing gravity field changes due to large earthquakes by a GRACE like mission was verified by the gravity field retrieval simulations.

6.4.3 Oceanography

Ocean signals dominate on short time scales in this study. Therefore ocean signals are prone to temporal aliasing effects in satellite observations. Due to this temporal aliasing, the observation of mass changes at low latitudes by satellites is very unreliable. Many satellite pairs are required to obtain reliable estimates. With spatial smoothing, long wavelength components of the signals can be observed at the obvious cost of loosing part of the signal in the process.

There are two main limitations in this study that are related to the ocean model:

- The current ocean model resolution excludes explicit eddy variability but parameterized eddy fluxes; the effect on mass redistribution is unclear (but it may be small).
- The representation of non-global source models such as the ocean model and hydrology model in global (spherical harmonics) functions to a finite degree excludes error sources that are introduced by limited resolution.

Further, the analysis was restricted to one year due to study time constraints. Therefore no analysis of trends in the retrieval system was possible.

6.4.4 Oceanography and Hydrology

The simultaneous retrieval of gravity changes due to oceanography and hydrology was limited by the accuracy of the background models and the spatio-temporal resolution of the retrieval. Spatial smoothing is required to identify and separate mass changes due to hydrology over land areas and due to oceanography over the ocean areas. After smoothing, the hydrology and ocean signal can be separated geographically and by spectral bands. However, the atmospheric correction, in particular, needs to be accurate for an accurate ocean-signal retrieval because of the inverted barometer effect.

6.4.5 Strategies for the Reduction of Tidal Aliasing

Tidal aliasing was demonstrated to be one of the largest error sources in the gravity retrievals. A summary of the techniques used to mitigate the tidal aliasing and the conclusions from those experiments are presented here:

1. Temporal filtering of the time variable gravitational fields

   a. Advantage:
      i. Band-pass filtering for the aliasing periods $T \cong T_{alias}$
      ii. High-pass filtering of scatter at short periods (T < 30-60 days); this is possible in the case of long periodic signals in H
   b. Problems:
      i. Aliasing periods in this case should not coincide with signals of interest
      ii. The scatter of the signal outside the aliasing periods, due to the remaining spatio-temporal aliasing impact, is limited (see Section 6.1.1)
2. Correct sampling of the tidal periods. This means, that for a spatial resolution of l_{max} = 50 altogether 32 or 33 satellites (depending on the inclination) are necessary
   a. Advantage:
      i. temporal aliasing is reduced/avoided
      ii. tides can be estimated within adjustment
   b. Problem: too expensive
3. Find a mission whose tidal aliasing periods are $T_{alias} = \infty$ or at least $T_{alias} >> T_{mission}$.
   a. Advantage: the tides will appear as a static field and will not enter into the time variable solutions
   b. Problem: It appears to be impossible to find such an orbit or mission (see TR5)
4. Since the aliasing periods are known, the tides can be parameterized and estimated within the adjustment
   a. Problems:
      i. Huge system of equations and number of unknowns since time variable solutions are correlated with the tides
      ii. Find a mission which separates the aliasing periods
         1. Low inclination as for TOPEX
         2. Heterogeneous orbits (Bender-type mission)
      iii. Aliasing periods should not coincide with the periods of the signal to be recovered (for H: 0.5 y ≤ T ≤ 1 y)
      iv. Due to remaining spatio-temporal aliasing and correlations among each other and with other signals the estimation and reduction of tides may still be imperfect.

7 Spatial and Temporal Sampling and their Impact on Observability

In this section we discuss what effects limited spatial and temporal sampling have on the time variable mass signals we are trying to capture from existing gravity missions.

Much of the following discussion is taken directly from “The Future of Satellite Gravimetry Workshop Report“ [*Koop and Rummel*, 2007].

At this point in the study, we have adopted a somewhat different philosophy towards separability than that held by the community at the time the following report was written. Separability of the various components of the mass transport system is not a high a priority for this study. However, the precise measurement of a true mass change signal, independent of what the cause is a priority. The motivation for this change in attitude is driven by the availability (or imminent availability) of satellite-based observations that would measure certain components of the mass field separately, e.g. SMOS to observe soil moisture. Nonetheless, for completeness we retain the discussion of separability.

7.1 Separability and de-aliasing

At “The Future of Satellite Gravimetry Workshop” [*Koop and Rummel*, 2007], it was concluded that clear definitions are required for (de-) aliasing, distortion, and separation. From the Workshop report the following definitions were provided:

1 Aliasing: mapping of signal from higher frequency onto lower frequency 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: unravelling into its individual contributions the superposition of all possible gravity effects that the measurement system intrinsically measures.

A well-known example of tidal aliasing is shown in Figure 7-1a. The figure, reproduced from *Chen et al.*, [2008], shows the manifestation of the 161 day aliasing of S_2 semi-diurnal solar atmospheric tide into the Center for Space Research (CSR) RL01 GRACE monthly gravity fields. While analysis of the 161-day S_2 alias is relatively straight forward, it is more difficult to estimate errors from other constituents, such as K1 and K2. Their aliases have much longer periods around (7.46 and 3.73 years) and may contaminate estimates of trends in Antarctic ice mass balance derived from the 6-year period of Grace observations [*Moore and King*, 2008].

An example of distortion can be observed in Figure 7-2, which is reproduced from *Swenson and Wahr* [2006].

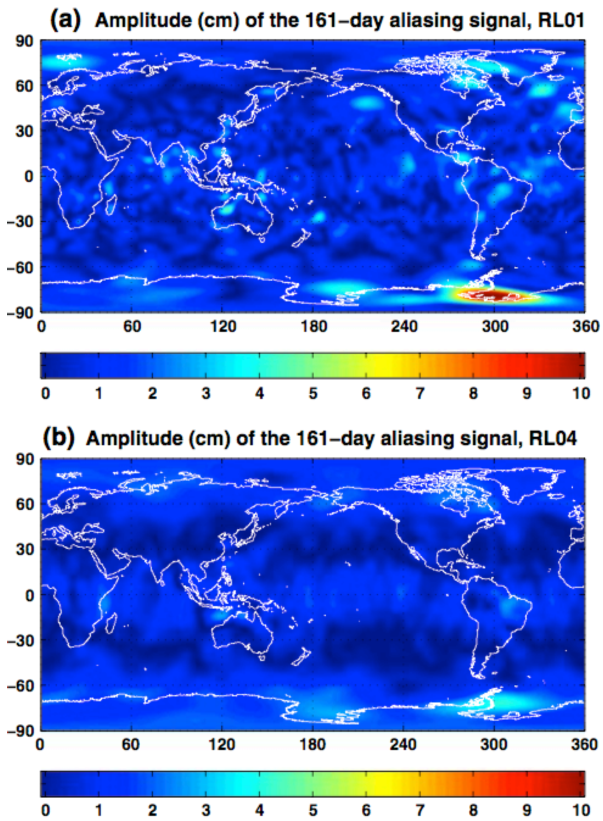

Figure 7-1: S2 tidal aliasing in GRACE time-variable gravity solutions. a) Least square fit amplitude (cm of equivalent water height) of the 161-day S_2 alias from the 53 monthly GRACE solutions in RL01. b**)** As in a**)** but for RL04. (Reproduced from *Chen et al*., [2008].)

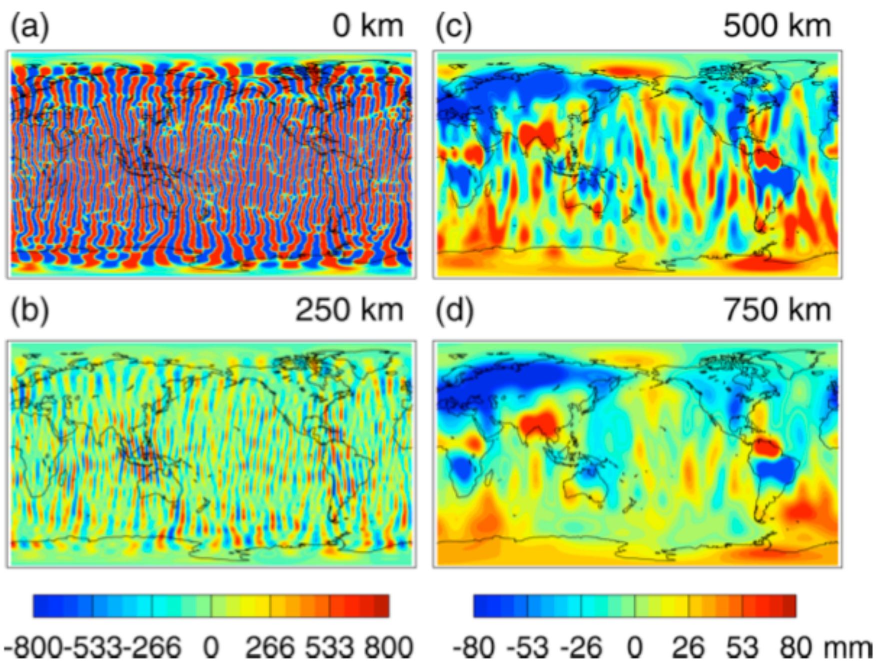

Figure 7-2: a) Original grace mass field; b) mass field in a) smoothed using a Gaussian smoothing filter with a radius of 250 km; c) same as in b) but with a 500 km radius; d) same as in b) but with a 750 km filtering radius. The north-south stripes are what is referred to here as distortions. (Reproduced from Swenson and Wahr, [2006]).

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 $n \approx m$ and n rather high [*Swenson and Wahr*, 2006].

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. At long periods signals are separated in post-processing using models or observations of the individual mass transport components.

At high frequencies (periods shorter than a month), 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 (compare Figure 7-1a and Figure 7-1b), but their accuracy still seems to be insufficient to fully exploit the information content of the observations. It has been demonstrated that this tidal aliasing remains 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, as shown in Figure 7-3.

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.

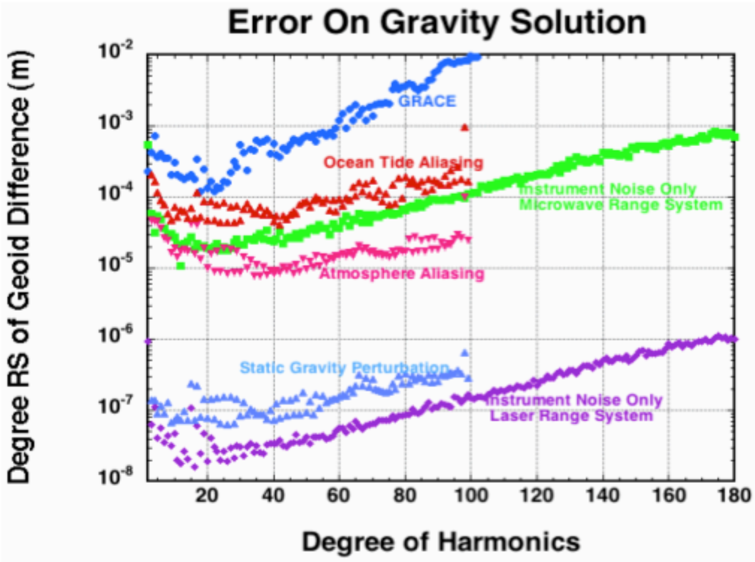

Figure 4-1: Error on gravity solution. Courtesy: M. Watkins, 2007.

Figure 7-3: Error on gravity solution. Courtesy: M Watkins, 2007.

7.1.1 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.

Some preparatory work was carried out during the MTS to investigate if multi-dimensional observing techniques could potentially reduce distortions. However, no in depth analysis has been carried out. The science team hopes to undertake this type of analysis within the context of the present study.

7.1.2 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 a level cannot 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.

7.1.3 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.

7.1.3.1 Solid-Earth Geophysics

Typically, gravity field changes due to ocean tides, ocean and atmospheric mass redistributions are provided as (temporal) spherical harmonic expansions. The errors in existing static gravity field models that are used for correcting the time variable component (the so-called de-aliasing products) start to detrimentally affect the study of mentioned (temporal) Solid-Earth gravity field sources for spherical harmonic degrees above 15. This is the ‘geographical aliasing’ described above. This problem may be mitigated, by using more reliable and higher-resolution static gravity fields.

7.1.3.2 Atmosphere & Ocean

When we consider the GRACE mission, the philosophy from the beginning was that the high frequency motions of the atmospheres and the oceans were generally not signals of interest for this satellite-gravimetric mission. The mass focus for GRACE was hydrology and ice. This is not to say that future missions should also consider the atmosphere and oceans as noise. In fact, without financial constraints we would probably like to launch several GRACE type missions to determine the full unaliased time-variable gravity signal without any background models. That being said, here we discuss the procedure for removing the short period variability of the oceans and atmosphere from the GRACE data.

The aliasing issue for the atmosphere and oceans is twofold. First there is the tidal effect, any errors in the background models will manifest themselves as the striping type of aliasing error. The second issue is the fact that the atmospheric and oceanic masses are constantly in non-tidal motion. This means that a satellite might go over a mass anomaly on one pass. However as the mass is moving, it may also be sampled in a different location on another pass. For the GRACE 30-day gravity fields, the motion of these mass anomalies must be modelled at shorter periods or they will alias into the gravity solution.

For de-aliasing of the atmospheric and oceanic masses the following processing sequence is performed for each 6-hourly time step, for which updated atmospheric parameters are available. The gravitational impact of the atmosphere on the satellite depends on the centre of gravity of the atmospheric column below the satellite.

Therefore, the centre of gravity of the atmospheric column is determined from temperature and specific humidity distributions, which are operationally provided by ECMWF at 91 levels (before January 2006 for 61 levels). In order to compute the centre of gravity a vertical integration using these parameters is performed. The vertically integrated atmospheric pressure is combined with the oceanic bottom pressure as it comes out from the OMCT model. Implicitly the inverse barometer effect is taken into account by adding both components over the ocean. In a second step gravity field coefficients for the combined atmosphere and ocean are determined every 6 hours by a spherical harmonic analysis.

Known limitations:

- For atmospheric de-aliasing of GRACE the ECMWF and the OMCT models are applied on a 6 hourly basis. As reference for both a bi-yearly mean over 2001 & 2002 is used. This means all signals with respect to this mean are intrinsically removed during processing of the monthly GRACE gravity field solutions. If both models are regarded as error-free the GRACE gravity field time series only contains mass variation effects from hydrology, ice masses and any other un-modelled effect.
- There are some significant differences between atmospheric models specifically in areas with sparse in-situ observations of atmospheric parameters. These are the polar areas (and here mainly Antarctica) as well as the large oceans (and here mainly the Southern oceans). The differences between the two models for a specific time stamp can reach up to 1-1.5 hPa RMS in terms of surface pressure. This is well above the sensitivity of the gravity field missions. Thus there are some uncertainties in the global models, which could have impact on the atmospheric de-aliasing accuracy.
- GRACE de-aliasing is restricted to the 6 hourly time steps available from the atmospheric model applied. Any shorter period mass variations cannot be modelled due to this sampling.

7.1.4 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?

7.1.5 Recommendations

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

7.1.5.1 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

7.1.5.2 Medium term

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

7.1.5.3 Long term

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

7.2 Spatial Aliasing.

Spatial aliasing occurs when a true mass signal has power in the higher degrees (large l) over and above the resolution of the gravity solution. For example the background static gravity field contains information at degrees $2 \le l \le 200$. However, the gravity field solutions for GRACE only go to degree l_{max}= 120. As a result, the information in the static gravity field for $121 \le l \le 200$ will be spatially aliased into the GRACE gravity fields.

8 Prioritization

The goal of establishing the scientific priorities for the NGGM, is to provide mission designers with enough information to design and build a mission. Thus, it is sufficient to identify the

- Accuracy
- Spatial resolution
- Spatial coverage
- Temporal resolution
- Temporal coverage (duration of the observation period),

which will optimize the science/mission-complexity ratio.

A summary of all of the mass transport signals considered in Section 4 as a function of their spatial and temporal signatures is provided in Figure 8-1. (The figure is an adaptation of the Figure 12.1 from *Rummel et al.* [2003]). Please note that the spatial scale is logarithmic. The yellow bubbles are associated with the atmosphere and tides, mass variations that are not necessarily science priorities, but whose signature is contained in the gravity retrievals and needs to be accounted for. This representation illustrates which mass transport signals can be observed by defining the spatial and temporal resolution of an NGGM.

The solid and dashed red rectangles in the figure show the approximate spatial and temporal coverage currently provided by the GOCE and GRACE missions respectively. In terms of GRACE, we have been successful at observing mass changes down to scales of 500 km. By increasing the resolution of the NGGM, the number of mass transport signals that can be observed increases significantly.

Four types of mass transport processes can be identified as the primary focus for an NGGM:

- Ice
- Continental Water: at spatial scales
- Ocean Mass
- Solid-Earth

As explained in Section 4, a deeper understanding of these processes is important for scientific as well as societal reasons.

We must bear in mind that our interpretations of the science are hindered by aliasing caused by inadequate background models and by our ability to separate the various mass transport signals. Thus, the choice of mission parameters that allow for the mitigation of nuisance signals caused by poor background models is also a priority. Likewise, parameter choices that allow for the separation of the mass transport signals, is also highly desirable.

In the following subsections, we estimate what effects improvements in

- Accuracy

- Spatial resolution
- Spatial coverage
- Temporal resolution
- Temporal coverage (duration of the observation period),

will have on the observation mass transport processes.

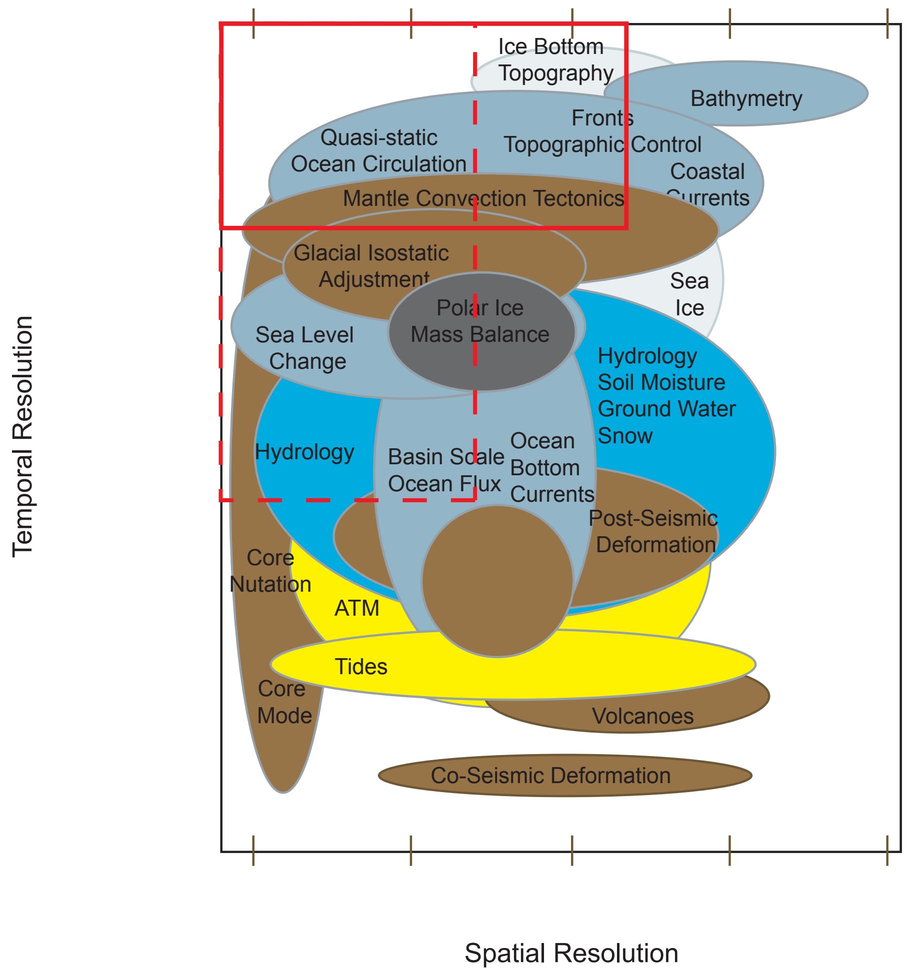

Figure 8-1: A summary of the mass transport signals and their spatial and temporal signatures, adapted from *Rummel et al.* [2003]

8.1 Spatial Scales

Currently, we can observe mass transport at spatial scales down to 500 km optimistically and maybe down to 700 realistically. While this resolution has provided tremendous insight into many mass transport processes, improving the resolution, would substantially increase the amount of science that could be undertaken. If we take, for the sake of argument, that the spatial scale of the NGGM will be 200-100 km the following advances in our understanding might be expected:

- Ice
  a. An understanding of how glacier dynamics contribute to ice mass loss;
  b. A separation of GIA, which tends to be long wavelength (> 500 km), from present day ice mass changes (50 – 500 km);

   c. A distinction between ice-mass changes over smaller regions;
- Continental Water
   a. The observed mass change at the basin scale of the large to medium sized river basins;
   b. The observation of continental glacier melting and other continental water and its effect on sea-level;
   c. The observation of mass change in continental reservoirs;
   d. The implementation of NGGM observations as input into land storage models;
   e. A reduction in the uncertainty due to leakage from ocean mass signals
   f. The separate climatic, physiographic and land use impacts on actual evapotranspiration;
   g. The ability to monitor continental water at scales valuable for water resources and agricultural applications;
   h. Transboundary water resources sharing;
   i. Drought monitoring over adequate wavelengths (~ 50-200 km);
   j. The development of sophisticated modelling of regional evapotranspiration leading to an improved understanding of the large scale characteristics of evapotranspiration;
- Ocean Mass
   a. An analysis of the Western Boundary Currents (spatial sampling on the order of 50 km is required to study the Eastern Boundary Currents);
- Solid-Earth
   a. Resolution of mass changes due to post-seismic deformation of smaller events leading to an improved understanding of the earthquake cycle (Currently only the largest earthquakes with large vertical displacements at long wavelengths generate signals observable in the GRACE data.);
- Dealiasing
   a. A reduction in dealiasing as the tidal signals could be more readily observed and subsequently modelled at these spatial scales (maybe even coestimated).

8.2 Temporal Scale

Currently we get information from GRACE at monthly intervals. This temporal sampling is sufficient for most scientific studies, e.g. ocean mass, solid-Earth, and ice. However, the monthly data is not a snapshot of the mass field at monthly intervals. It is an integrated image of the mass change over the month. Improvements in our understanding of the following issues could be expected with an increased temporal sampling of approximately 8 days, taken for the sake of discussion:

- Continental Water
   a. An improvement in our understanding of continental water transport as hydrological processes operate on hourly to weekly time scales;
   b. An improvement in our ability to update hydrological assessments for water resources and agricultural applications via climate models;
- Dealiasing

   a. A reduction in dealiasing as the tidal signals could be more readily observed and subsequently modelled at these temporal scales.

Please note that the sampling of 8 days used here was taken only as an example. We do not intend to claim that this length period is in any way optimal.

8.3 Spatial Coverage

Many of the signals associated with global climate change, e.g. polar ice mass balance, sea ice extent, deep/bottom water warming, are concentrated in the high latitudes. In addition, much of the GIA signal is located at the high-latitudes. Thus, it would be highly desirable for the NGGM to have a nearly polar orbit such that these global climate change processes will continue to be observed. However, a stated priority of polar observations does not minimize the need for continued observations at the mid- to low-latitudes where continental water storage observations and Earth dynamic processes tend to be concentrated.

- Ice
   a. to determine the geographical dependence of mass change on the polar ice sheets
   b. to determine the dynamics of polar glaciers and ice sheets and their contribution to sea level;
- Dealiasing
   a. Inadequate tidal models are particularly problematic near Antarctica and in the Arctic; improved spatial coverage in this region could potentially improve our background models of the tides here.

8.4 Temporal coverage

With regards to mission lifetime, the mission duration scales with the characteristic temporal scale of the mass transport signal of interest. For example, to reliably acquire polar ice mass trends, which have a temporal resolution of about a decade, would require at least 10 years of observations. In addition, many climate change trends have cycles on the order of a decade, reinforcing the requirement for long time series. The following list enumerates the importance of long time series for the various scientific targets:

- Ice
   a. Longer time series allow for the separation of present day mass changes from those associated with GIA as GIA trends would be constant over this period but ice mass variability would change;
- Continental Water
   a. A determination of the emerging trends in evapotranspiration;
   b. Long time series allow us to determine the secular trends in the water cycle, e.g. droughts, river-basin evapotranspiration, etc.;
   c. improved characterization of interannual changes in soil moisture and groundwater storage;
- Ocean Mass
   a. with altimetry, improvements in the mean dynamic topography at long wavelengths

   b. with altimetry, long time series could be used to monitor the deep ocean circulation-measuring slow changes in density as water moves from basin to basin
- Dealiasing
   a. A reduction in dealiasing as the tidal signals could be more readily observed and subsequently modelled at these spatial scales (maybe coestimated);
   b. The determination of secular trends in the geoid would improve the background modeling;
   c. Improvements in the geoid at longer scales.

8.5 Accuracy

Figure 8-2 (adapted from *Rummel et al.* [2003], Figure 12.2) provides an indication of the required geoid/gravity accuracies for the mass transport targets. In some cases, the necessary measurement precision is too high to be considered for an NGGM, e.g. core nutations and other core modes.

The MTS demonstrated that reducing sensor noise levels, has a much bigger impact on reducing errors in the gravity retrieval than flying more tandems. Referring to Figure 8-2 we see that reducing the noise on the sensor allows for the observation of shorter wavelength mass signals. As a reference, the precision of GRACE is often

It is clear that an improvement on the measurement precision would be a benefit the understanding of all mass transport signals and processes. In the following list, we enumerate just some of the science that can be achieved with improved sensor accuracy.

- Ice
   a. Reduce the error on mass balance and GIA estimates;
- Continental Water
   a. Allows for the resolution of smaller wavelength signals;
- Oceans
   a. A higher accuracy of the vertically integrated ocean mass variations associated with ocean currents will allow us to understand ocean circulation better;
- Solid-Earth
   a. Only earthquakes with magnitudes greater than 8 can be detected with the GRACE data [*De viron et al*., 2008] because of its accuracy. An improvement in the accuracy would allow us to discriminate mass changes due to smaller earthquakes. The more earthquakes that can be studied, the more we learn about the earthquake cycle.
   b. A mission 10 times more precise would allow for the detection of the accumulation of mass along active tectonic zones, discrimination of fault plane models, and the monitoring of asperities on locked seismic zones [*Mikhailov et al*., 2006].

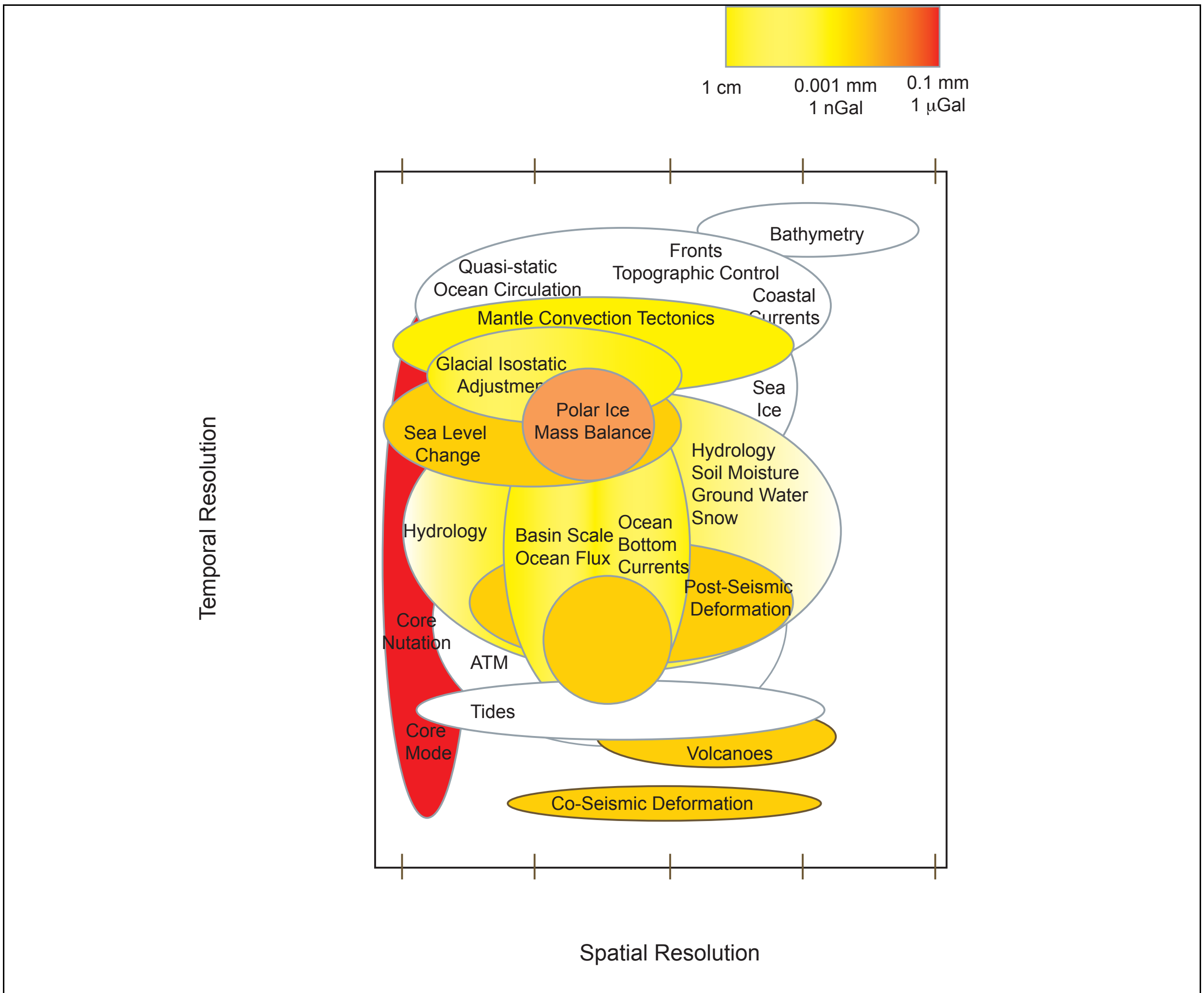

Figure 8-2: A summary of the required geoid/gravity accuracies of the mass transport signals, adapted from *Rummel et al.* [2003]

8.6 Prioritization

In the table below, an attempt is made to prioritise various mass transport processes. The second column, Observability, indicates whether the process is currently observable with GRACE. “Alternative Techniques”, indicates whether there is the possibility to observe the process with alternative techniques.

Mass Transport Process	**Observability: +, ++, or +++ (+++ easily observed with GRACE; ++ at the limit; + cannot be observed with GRACE)**	**Alternative techniques**	**Rating**
Solid-Earth			
GIA	+++	GNSS, absolute gravimetry, levelling, etc. (measure surface deformations)	++

Co-seismic deformation	++ (only the largest earthquakes are observable with GRACE)	Seismic data – globally; other techniques (GNSS, absolute gravimetry, levelling, etc.) – only in-land	++
Post-seismic deformation	++	In the oceanic areas – no; In-land: GNSS, absolute gravimetry, levelling, etc.	+++
Hydrology			
Ground water (antropogenic)	++	Only in-situ data (e.g. from hydrological wells)	+++
Ground water (natural)	+++	in-situ data, hydrological models based on in situ and meteorological data	++
Soil moisture	+++	In-situ data, microwave sensors, hydrological models, etc	+
Snow cover	+++	Satellite altimetry (only volume, not mass); hydrological models	++
Open water bodies	++/+	Satellite altimetry; in-situ data	+
Ice			
Melting of ice sheets	+++	Satellite altimetry (only volume, not mass); INSAR (indirectly)	+++
Melting of mountain glaciers	+	Satellite altimetry (only volume, not mass); INSAR (indirectly); in situ data	+
Ocean			
Non-steric component of sea-level variations (seasonal and shorter time scales)	++	Combination of satellite altimetry and in-situ data	+++
Non-steric component of long-term sea-level rise	+ (hardly separable from GIA)	Combination of satellite altimetry and in-situ data	++

Thus, 4 types of mass transport processes can be identified as the primary focus of future satellite gravimetry missions:

1. Post-seismic deformations (particularly, in the oceanic areas)
2. Depletion of ground water stocks for anthropogenic reasons
3. Melting of ice sheets
4. Non-steric component of sea-level variations at seasonal and shorter time scales.

Monitoring of these processes is important for scientific or/and practical reasons; other observation techniques are suitable for that only partly or even not suitable at.

Studying post-seismic deformations is important for better understanding of the tectonic processes and a quantification of rheological properties of the mantle. A number of observation techniques can be used for that purpose in-land (GNSS, absolute gravimetry, levelling, etc). However, satellite gravimetry is the only technique that allows monitoring post-seismic deformations in the oceanic areas.

Overexploitation of ground water resources is the subject of great concern nowadays, especially in arid and semi-arid areas. Traditionally, depletion of ground water stocks is monitored with in situ observations (e.g. in hydrological wells). However, the results obtained in this way may not be sufficiently accurate due to a large spatial variability of hydrological properties and a limited number of observations (especially, in developing countries). Hydrological models may not be applicable as well, since they are mostly limited to *natural* processes. As far as electro-magnetic (hydrology-oriented) remote sensing techniques are concerned, their penetration depth typically does not exceed a few tens of cm. Thus, satellite gravimetry is the only technique that allows a depletion of ground water stocks to be observed remotely. A recent example of a successful application of GRACE data for that purpose is a quantification of ground water losses in India [reference].

Measuring the rate of ice sheet melting is of great importance for understanding the process of global climate change and its potential consequences, including global sea level rise. Satellite gravimetry is the only observation technique that allows ice mass balance to be quantified directly. Alternative techniques (e.g. satellite laser altimetry) can only measure volume changes. Then, computation of mass changes requires that the density of the material responsible for observed variations is known. In practice, this is not the case, which may cause large errors in the estimations.

Measuring the non-steric (mass-related) component of sea-level variations is of importance for better understanding of oceanographic processes, which, in particular, have a large impact onto the Earth climate. Again, satellite gravimetry is the only tool to monitor such variations directly. An alternative is to take the difference between total volume variations, which can be measured with altimetry, and steric (mostly, temperature-related) variations, which are measured in situ. The spatial coverage with in situ sensors is, however, limited (especially in the southern hemisphere). Furthermore, in situ sensors are typically located in first few hundreds of meters from the ocean surface.

9 Conclusions

Mission design is driven by well-defined scientific targets. A mixture of requirements of spatial resolution, temporal behaviour (both resolution and mission duration) and geoid/gravity precision can be accomplished by proper orbit design, choice of observation type and hardware performance.

In this document, we have thoroughly reviewed the science that has been revealed through TVG. We have additionally, quantified mass transport signals in terms of spatial and temporal scale, which could be analyzed with an NGGM having requirements surpassing what exists today.

In prioritizing the mass transport processes to be observed by an NGGM, it is important to take into account the following questions:

1. Is the signal of sufficient magnitude to be observed by satellite gravity?
2. Are there alternative more cost-effective techniques for observing the signal?
3. How important is an improved quantification of a particular mass transport process for managing our environment and enhancing our ability to derive sustainable benefit from it?

With regards to Question 1, this document has identified numerous signals that are sufficiently large to be observed using satellite gravity. An improvement in the temporal and spatial resolution and/or the accuracy of an NGGM with respect to present capabilities will increase significantly the number of mass transport signals, which can be studied. In addition, these improvements may reveal, signals and processes, which are as yet unknown.

With regards to Question 2, we note that, currently only remote sensing techniques can be typically considered as a fair alternative to satellite gravimetry. In-situ observations usually lack spatial coverage, so that the quality of derived models may show large spatial variations. However, remote sensing is only sensitive to surface or near-surface processes, while many of the mass transport processes discussed in this document may not have an expression at the surface. In addition, certain quantities such as mass balance of the ice sheets or groundwater depletion, which require observations of mass change, cannot be measured using remote sensing techniques.

Throughout this document, we have attempted to justify our desires for improved quantifications of the various mass transports in terms of their contribution to understanding the interaction of the various components of the Earth system. While not explicitly stated, an understanding of the cause-effect relationship between human activities and environmental change, when it exists, is sought. In addition, certain mass-transport processes, including earthquakes, volcanoes, and GIA, which are not the result of human activities, nonetheless can have a dramatic effect on mankind. Improving our understanding of these processes is also important for assessing the threat of natural hazards.

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11 Appendix

11.1 GGOS Workshop, Towards a Roadmap for Future Satellite Gravity Missions, Declaration

DECLARATION

Towards a Service for the Water Cycle

Noticing that

one billion people are currently without sufficient access to clean drinking water;

according to the 2nd UN Water Assessment Report, this deficit is a result of governance problems and poorly informed decision-making;

demand for water resources is rising due to increased water usage for potable consumption, energy production, irrigation for agriculture purposes, industrial and urban uses, while climate change is locally to regionally impacting water resources through increased frequencies and magnitudes of droughts and floods;

a better understanding of the water cycle on regional to global scales is critical for managing water resources in a sustainable manner;

and recognizing that

the GRACE satellite gravity mission has demonstrated the ability to measure mass redistribution in the water cycle, 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 measurement of net decreases in the masses of ice stored in Greenland, certain regions of Antarctica, and Alaskan glaciers over the same time period;

the Participants of the Workshop on a Roadmap for Future Satellite Gravity Missions declare that a long and uninterrupted series of satellite gravity missions with accuracies and resolutions at least as good as GRACE's is a crucial element of an observation system to adequately monitor the global water cycle and to improve our understanding of the processes and consequences of change;

such a series of satellite gravity missions would provide the basis for a global service to inform decision makers in a timely manner about ongoing and forecasted changes in the water cycle related to droughts, groundwater depletion, sea level changes, and other potential impacts of climate change.

Furthermore, the Participants of the Workshop have agreed on a roadmap towards future satellite gravity missions and, with this declaration, bring this roadmap to the attention of the GEO Plenary, the governments of the GEO Member Countries, and the Participating Organizations in GEO in an effort to initiate international action for the implementation of this roadmap, for the benefit of science and society in support of a sustainable and peaceful development. The participants declare their support for this action.

11.2 MTS Model Description

Here a description of the individual models that went into the mass-transport model used in the ESA MTS is presented.

11.2.1 Hydrology

Terrestrial water storage was modelled with the global hydrological model PCR-GLOBWB [*Van Beek*, 2007]. PCR-GLOBWB was forced with precipitation and evaporation from the ERA40 reanalysis data set (1995-1999) and the ECMWF operational archive (2000-2006). Total terrestrial water storage variations (in meters of water) were calculated for all land masses, except Greenland and Antarctica that were part of the ice-modelling, and were obtained by adding water in interception storage, snow pack, surface water, the two soil reservoirs and the groundwater reservoir. River discharge to the oceans was used as a boundary condition by the ocean model. Simulations resulted in unrealistic trends in terrestrial water storage due to a build-up of water in inland (closed) water bodies such as Lake Titikaka and the Caspian Sea. This was caused by an under-estimation of the local open-water evaporation from the meteorological forcing. Also, a slight jump in storage was observed from 1999 to 2000 due to a change in forcing data.

11.2.2 Atmosphere

There are only a few global atmospheric models, which provide the required information for modelling the atmospheric mass variations and specifically providing also the required input parameters for driving the other geophysical models. All geophysical models in the study were to be based on the same atmospheric model in order to guarantee a minimum level of consistency within the global water cycle. Thus, the ECMWF model was selected as source of information for all atmospheric parameters.

For estimating the atmospheric mass variations, two ECMWF model versions were applied. For the period from 1.1.1995 until 31.12.1999 data from the ERA40 reanalysis were used. For the period from 1.1.2000 until 31.12.2006 we applied data from the ECMWF operational analysis. For the operational analysis several model changes occurred during the analysis period. For the time period in which the reanalysis data were used, the data were based on a fixed model configuration. It turns out that changes in the applied topography causes major variations in the surface pressure distribution. For the data from the operational analysis, 5 jumps have been identified. They occurred on 4.4.1995, 1.4.1998, 12.10.1999, 20.11.2000 and on 1.2.2006. Most of the significant model changes happened before 2000. For this reason, the re-analysis data was applied for this time period. Because atmospheric parameters are used to drive all the other geophysical models (except for the solid-Earth), any jump in the atmosphere could potentially induce unrealistic jumps in our estimates of the total water cycle.

11.2.3 Oceans

For modelling the oceanic mass variations, the OMCT (Ocean Model for Circulation and Tides) was used.

At the transition from ERA-40 atmospheric forcing data to operational analysis data, there is a change in the mean ocean mass fields. In order to remove this discontinuity in the ocean mass field, a separate mean field for the ERA-40 period has been calculated by minimising the differences between mass anomalies from simulations forced by ERA-40 and the operational analysis for overlapping years 2000 and 2001. This mean field has been subtracted from all ERA-40 forced data.

Temporal variability of the simulated bottom pressure anomalies has been analyzed. Patterns and amplitudes for both analysis periods are comparable. In contrast, trends in ocean bottom pressure vary between both simulation periods.

Atmospheric freshwater fluxes exhibit large uncertainties resulting in unrealistic total ocean mass variations. An additional correction was applied based on the condition that net-fluxes from the atmosphere into the ocean must be zero within each year. Thus total ocean mass variations by atmospheric fluxes are only taken into account on seasonal and sub-seasonal time-scales.

11.2.4 Ice

For the ice sheets, a time series of surface mass fluxes was determined for the period 1995-2005 using ERA-40 up to 2001 and the ERA operational analysis beyond. The data were produced on a 5 km polar stereographic grid with a 6 hourly time step for Greenland and a daily time step for Antarctica, as we assume no diurnal bias for Antarctica. The surface mass balance (SMB), comprising accumulation-ablation was calculated using a regional climate model for Antarctica [*Van de Berg et al.*, 2006] and a simpler downscaling of the ECMWF data combined with an SMB model for Greenland [*Bougamont et al.*, 2005]. Superimposed on the SMB were secular trends in ice dynamics (i.e. solid ice fluxes into the ocean), reflecting changes that are known to be taking place from a range of satellite observations. The magnitude of these changes is representative of real world signals but was also designed to capture a range of mass change and spatial scales.

The spatial pattern and magnitude of the trends are comparable with recent observations of regional mass loss. In addition to the spatially distributed mass changes we also calculated the flux of ice at the margins entering the ocean grid cells. This was done with the aid of the OMCT ocean/land mask. For Antarctica the fluxes were calculated annually as there is no seasonal or daily variation in this flux so that the daily value was 1/365 of the annual value. For Greenland the margin fluxes were calculated on a daily time step due to the seasonality of surface runoff. Both Greenland and Antarctica were excluded from the hydrology model.

Non-ice sheet, continental ice regions (i.e. mountain glaciers) were treated separately, within the hydrological model. Four mountain glacier regions were identified and assumed to be losing 1% of their mass per year. This rate and the volumes are representative values based on recent observational data, although for Alaska the real mass loss rate in the last decade has been estimated to be nearer 12%. This is, however, exceptional and related to the high proportion of tidewater-terminating glaciers in this area.

11.2.5 Tides

Ocean tides may be modelled on either a global or regional basis. Recent global tide models include FES2004 [*Lyard, et al*., 2006], GOT00.2 [*Ray*, 1999], TPXO6.2 [*Egbert and Erofeeva*, 2002], CSR4 [*Eanes*, 1994] and NAO.99b [*Matsumoto, et al*., 2000]. FES2004 is on a 1/8th degree grid, TPXO6.2 on a 1/4 degree grid and the remainder on 1/2 degree grids. In contrast, regional models may have resolutions up to 5 km, such as the regional Arctic model AOTIM5 [*Padman and Erofeeva*, 2004]. These models each assimilate much of the available tidal data archive from tide gauges, bottom pressure records and satellite altimetry.

In the MTS, tide models were regarded in a forward sense and hence, in order to describe the real world as accurately as possible, we tried to identify the most accurate ocean tide model(s). As an aside, mass changes at various tidal frequencies are known to alias into GRACE time series at periods of up to several years with admittances believed to be close to 100% [e.g. *Moore and King*, 2008]. Here, ocean tide modelling errors are characterised spatially through differencing a suitably identified “next best” model from the “best” model.

We note that FES2004 has been selected by the GRACE Analysis Teams for the Release-04 GRACE solutions. This model was selected in the MTS as the true model in the gravity field retrieval simulations. The TPX06.2 model was selected as the reference model in order to simulate ocean tide model errors.

11.2.6 Solid-Earth

Within the MTS, a distinction was made between solid-Earth contributions to the static and temporal gravity field. The solid-Earth static part was assumed to be part of the selected static background model, i.e. GGM01S [*Tapley et al*., 2003]. The solid-earth temporal part was explicitly added as part of the time-varying gravity field and consisted of gravity field changes due to post-glacial rebound and the co- and post-seismic parts of the December 2004 Sumatra-Andaman earthquake. All gravity field retrieval experiments focused on observing temporal gravity field changes and thus no attention has been paid to the observability of solid-Earth processes that lead to gravity field changes that can be considered static over time spans that can be covered by satellite missions (or even beyond). An open question is if signatures in the static gravity field that are caused by such solid-Earth can be identified and separated from other contributions.

11.2.7 Known Limitations of the Source Model

- An unrealistic positive trend is visible in the hydrology data.
- There is visible a significant jump in hydrology and ocean in early 2006. The reason is not fully understood, but one could speculate that it is caused by the jump in the atmosphere pressure field on 1.2.2006. The jump in the ocean also could be caused by unrealistic fluxes from the continent to the ocean (i.e. from the hydrology model to the ocean model).
- The Greenland ice mass fields exhibit an increase of ice mass for the analysis period. This is not well understood, because from the ice model one would expect an opposite trend. A more thorough investigation of the Greenland data would be required in order to identify the reason.
- Trends of atmosphere and ocean (except jump in 2006) show some realistic features.
- Trends in ice mass change in Antarctica are also unrealistic. They are much smaller than those observed with GRACE.
- The solid-Earth mean pressure values are in accordance with the applied models for GIA and the Sumatra earthquake.
- The water cycle is not closed by far due to the unrealistic features mentioned above. One could speculate if, in case one could identify the problematic areas, the total trend in the water cycle becomes zero. Probably, this would not happen. As one can expect, for a consistent modelling of the water cycle the contributing geophysical models have to be linked together closely. In this study it was tried to link the models by using the same atmospheric model for driving them and by modelling mass fluxes between ice, hydrology and ocean, respectively.
- For the purpose of the MTS (identifying potential satellite measurement systems and scenarios for observing mass transport from space) we felt that the trends did not play a crucial role. The change in total mass of the water cycle is reflected by the change of zero degree gravity potential-coefficient of the combined mass fields, when not taking into account the solid-Earth contributions. By not regarding this coefficient in the simulation approaches, one could force the water cycle to be closed artificially.

Any gravity field recoveries and subsequent conclusions drawn using this data set must be interpreted in terms of these limitations. While we have attempted to model mass transport within the Earth system as realistically as possible, the issues outlined above indicate that there are some problems in our source models.

Abbreviations and Acronyms

AOHIS	Atmosphere+Ocean+Hydrology+Ice+Solid-Earth
AOTIM	Arctic Ocean Tidal Inverse Model
CSR	Center for Space Research
DEOS	Department of Earth Observation and Space Systems
ECMWF	European Centre for Medium-Range Weather Forecasts
ERA	ECMWF ReAnalysis
ESA	European Space Agency
FES	Finite Element Solution
GGM	GRACE Gravity Model
GIA	Glacial Isostatic Adjustment
GIS	Institute of Geodesy, Universität Stuttgart
GLOBWB	GLOBal Water Balance model
GOCE	ESA's Gravity field and steady-state Ocean Circulation Explorer
GRACE	Gravity Recovery and Climate experiment
IAPG	Institut für Astronomische und Physikalische Geodäsie, TU München
IPCC	Intergovernmental Panel on Climate Change
ll-SST	low-low Satellite-to-Satellite Tracking
MTS	Mass Transport Study
NAO	National Astronomical Observatory
NGGM	Next Generation Gravity Mission
OMCT	Ocean Model for Circulation and Tides
PCR-GLOBWB	PCRaster-based GLOBal Water Balance model
RMS	Root Mean Square
SLR	Satellite Laser Ranging
SMB	Surface Mass Balance
SST	Satellite-to-Satellite Tracking
TPX	TOPEX (Ocean Topography Experiment)
TVG	Time Variable Gravity
ULUX	University of Luxembourg