

Future Gravity Missions

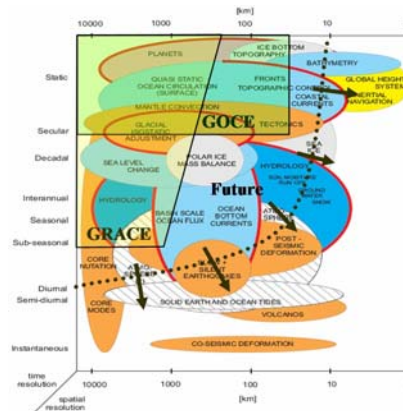
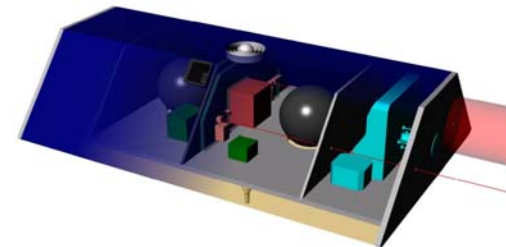
Outlook & Application

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agenda

- Introduction
- GRACE Continuation
- e.motion Earth Explorer 8
- ESA Studies



Introduction

- *ESTEC Workshop 2007*
- *Graz Workshop 2009*



Workshops on Satellite Gravimetry

The Future of Satellite Gravimetry. April 2007, ESTEC.

Main Recommendations:

1. A **GRACE follow-on mission** based on the **present configuration** is strongly supported, with emphasis on the **uninterrupted continuation of time series**. This should be short-term **priority one**.
2. The **medium term priority** should be focused on **higher precision and higher resolution in space and time**. This step requires:
 - reduction of the current level of aliasing,
 - the elimination of systematic distortions (non-isotropic sensitivity of a single pair low-low SST), and
 - the improvement of the separability of the observed geophysical signals.
3. The **long term strategy** should include the gravimetric use of advanced **clocks** (ground based and flying clocks), **micro-satellite systems**, and space-qualified **quantum gravity sensors**.

The Future of Satellite Gravimetry

Report from the

Workshop on The Future of Satellite Gravimetry

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

Radboud Koop and Reiner Rummel (Eds.)



Workshops on Satellite Gravimetry

Roadmap Towards Future Satellite Gravimetry Missions in Support of Monitoring Mass Redistribution, Global Change, and Natural Hazards. October 2009, TU Graz.



Towards a Roadmap for Future Satellite Gravity Missions
September 30 - October 2, 2009, Graz, Austria



GROUP ON
EARTH OBSERVATIONS

<http://www.iag-ggos.org/workshops/Graz>



Main Conclusion:

1. A multi-decade, continuous series of space-based observations of changes in the Earth's gravity field begun with the GRACE mission, and leading, before 2020, to satellite systems capable of global determination of changes in the Earth's gravity field from global down to regional spatial scales and on time scales of two weeks or shorter, as a contribution to an integrated, sustained operational observing system for mass redistribution, global change, and natural hazards, and in support of global water management, the understanding of climate variations, and the characterization and early detection of natural hazards.
2. The roadmap defines the following 4 activities:
 - Science development: User needs; Scientific challenges.
 - Technology development: Short, Medium & Long term.
 - Mission Implementation: International & Inter-agency coordination.
 - Processing, Modeling & Applications:



Workshops on Satellite Gravimetry

At both workshops representatives from science and industry who are involved in the GEOTECHNOLOGIEN “Future Gravity Missions” (GT-FGM) project actively participated. These are:

- Albert Einstein Institute, Hannover
- Deutsches GeoForschungsZentrum Potsdam
- EADS Astrium
- Kayser-Threde
- Leibnitz University Hannover
- Technical University Munich
- University Bonn
- University Stuttgart



GRACE Continuation

- ***Studies***
- ***Science***
- ***Programmatics***



GRACE Continuation – Study Objectives

Various **studies on GRACE Follow-on missions** conducted by GFZ/STI (GRAF, 3M4C, 3M4C-FPS) between 2008 and 2010.

GRAF: GRACE-Follow-on mission (2008/2009)

- Elaboration of the **importance for long-term mass motion monitoring** in science application fields.
- Compilation of **lessons learned from present GRACE** mission and elaboration of options for technical implementation based on today's space technology.
- Perform supporting **simulations and investigate possible gain** in accuracy and spatial/temporal resolution.

3M4C: Mass Motion Monitoring for Climate (2009)

- Refine mission, **detail Laser SST and breadboard requirements**.
- Analyse **S/C operation** option(s).
- Continuation of **simulation** studies.

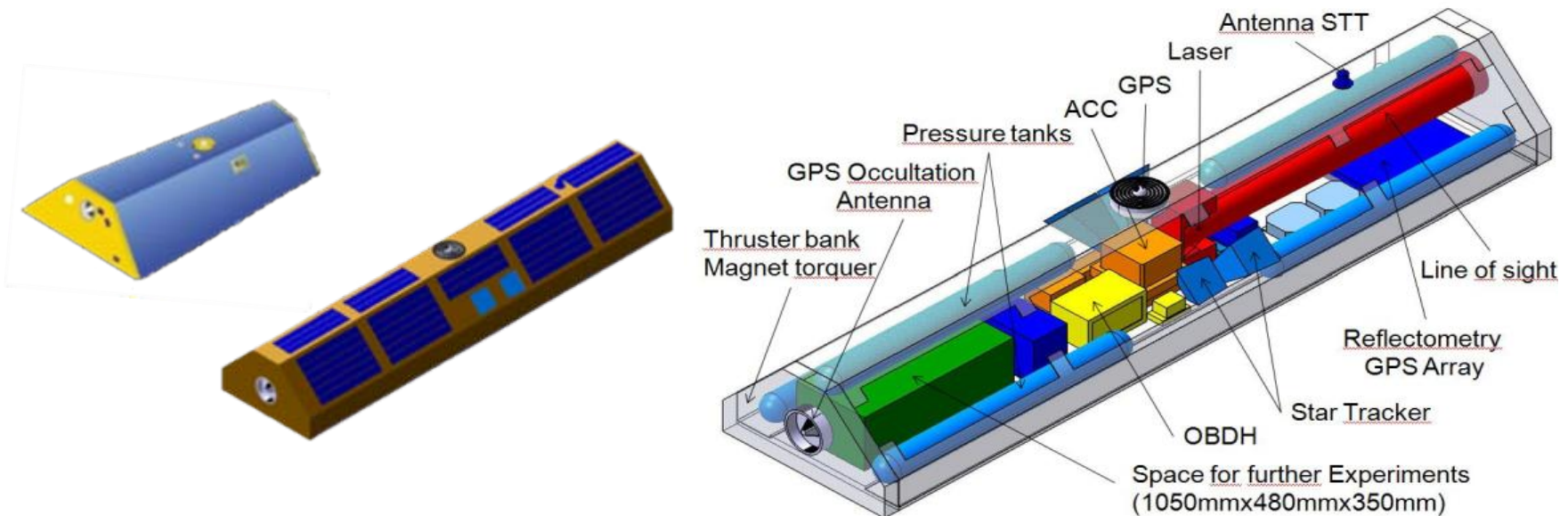
3M4C: Mass Motion Monitoring for Climate (2010)

- Review and **refinement** of 3M4C identified **pointing concepts**.
- Derive the **technical requirements** for satellite interfaces of SST instrument and SST performance targets.
- Detailed **design of selected pointing concept**.

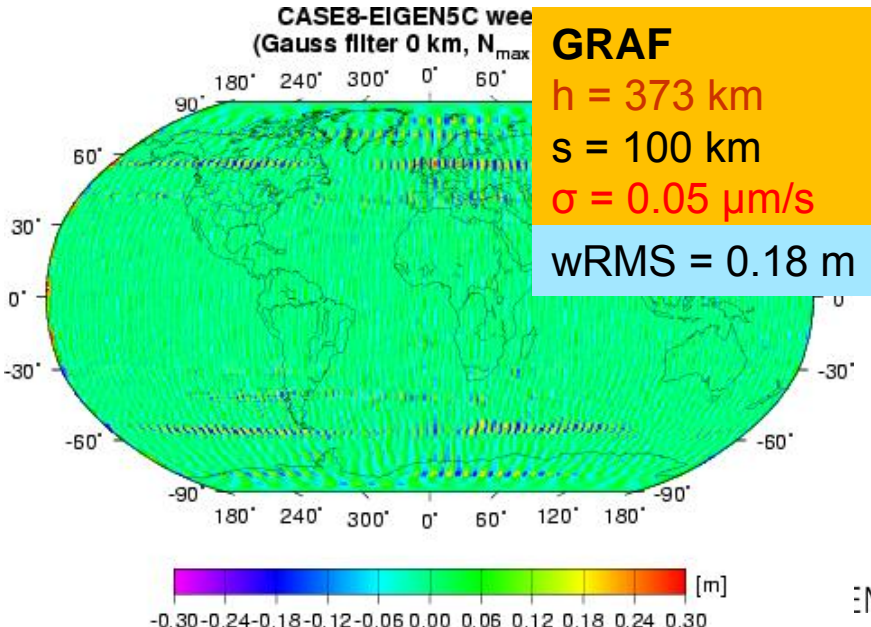
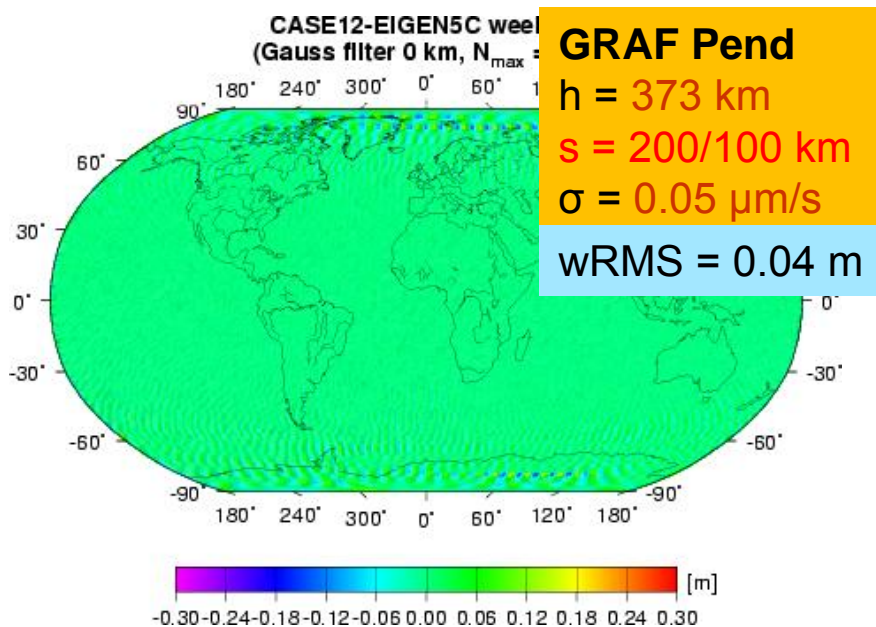
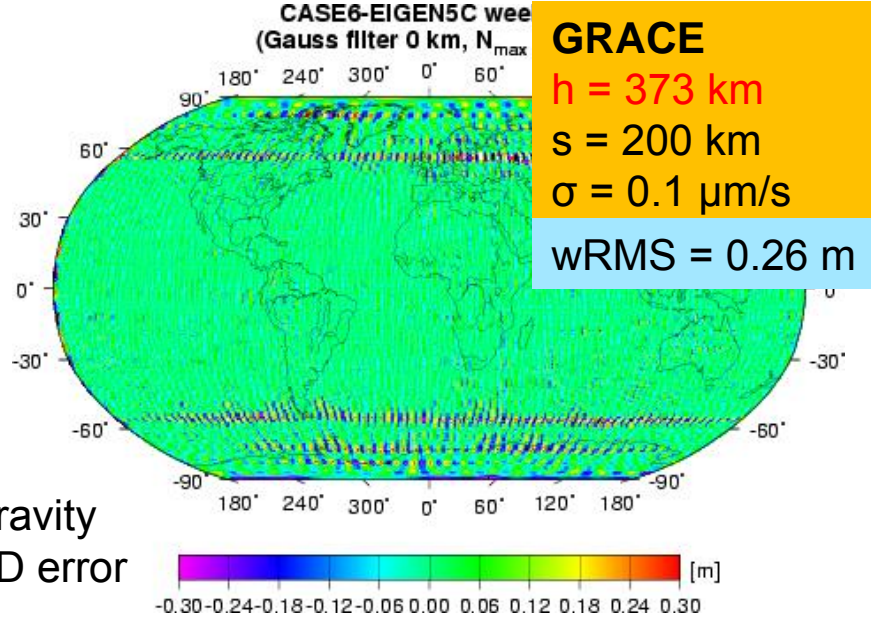
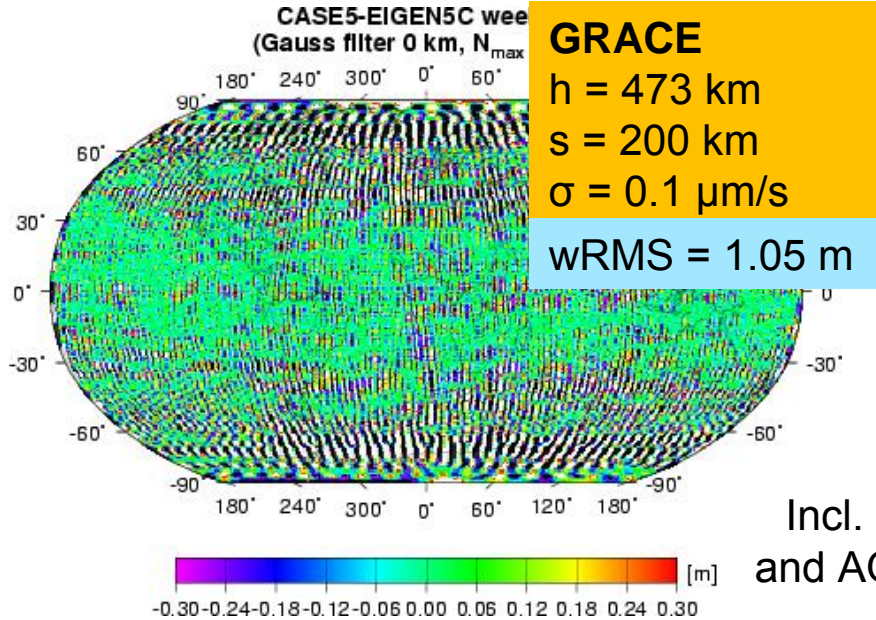


GRAF/3M4C – Study Results

- Launch around 2015
- Minimum GRACE modification mission: **Microwave SST link.**
- GRACE based mission “GRACE+” with additional **experimental laser interferometer SST link.**
- Selection of **suitable laser pointing concept** required.
- Laser SST and accelerometer near CoG, small error budget.
- Cold gas for minimum 5 years mission(100kg instead of 20kg)
- 4 instead of 2 star sensor heads



GRAF/3M4C - Science



GRACE Continuation - Programmatic

- Science applications urgently ask for **GRACE continuation** in order to enable **monitoring of trends and seasonal mass variations** in system Earth.
- NASA wants to realize **GRACE-C with strong participation of Germany** (had extremely good technological/science cooperation with GRACE)
- GFZ has submitted a **pre-proposal to BMBF's FONA program** in May 2010 for German contributions Laser Ranging Instrument (LRI), Launcher and Science **incl. support letters** from NASA, DLR Agency, AWI, DFD SPP and Geotechnologien).
- Had very successful Technical Interface Meetings at JPL (June), STI/Astrium (July). Next scheduled at GFZ (November 10).
- **Overall preparations extremely good**, waiting for confirmation of funding in the US and Germany (several positive indications, but no written commitment).
- STI and AEI in contact (GT-FGM project) to **develop laser interferometer breadboard** and to reach TRL 7 (demonstrator laser - with components from JPL ~2014) and TRL8 (operational laser ~2015).
- Laser interferometer demonstrator could pave the way for an **operational laser interferometer SST mission** in timeframe 2018+ (e.motion).



e.motion EE8 Proposal

- *Science Requirements*
- *Mission Assumptions*
- *Technology*



e.motion – Science Requirements

Research objectives concerning three fields:

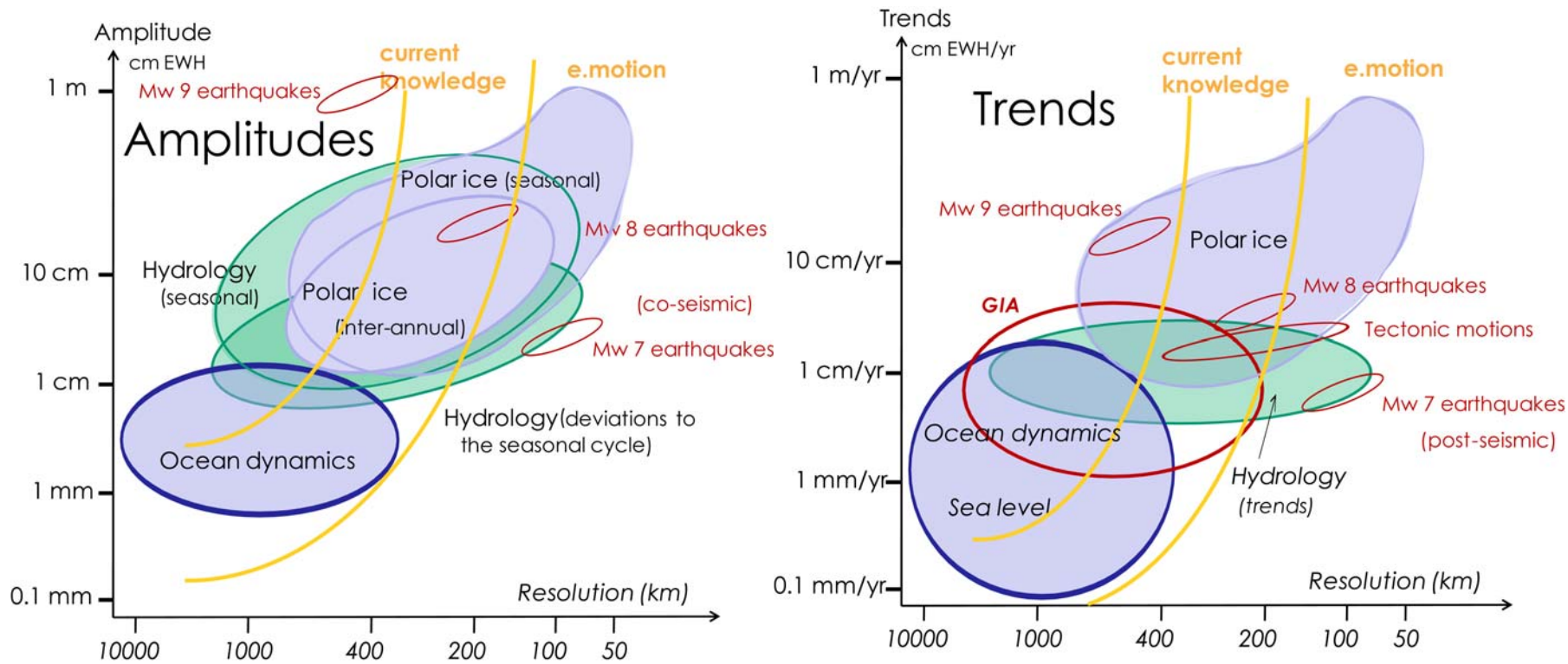
- Mass **variations in the global water cycle**,
- Mass **variations within the solid Earth**, and
- Precise gravity **reference** for geodesy and Earth observation

Specifically, the science requirements for e.motion are:

- To recover temporal gravity and mass variations in the Earth system with a **spatial resolution of 200 km** or better, with **global coverage**;
- To recover small amplitude mass variations with **10 times increased sensitivity** compared to current knowledge;
- To resolve mass variations at **seasonal to decadal time scales**, by extending the existing record of satellite data by a time series of 7 years or more with enhanced quality, with a **temporal resolution of 1 month** or better.



e.motion – Science Requirements

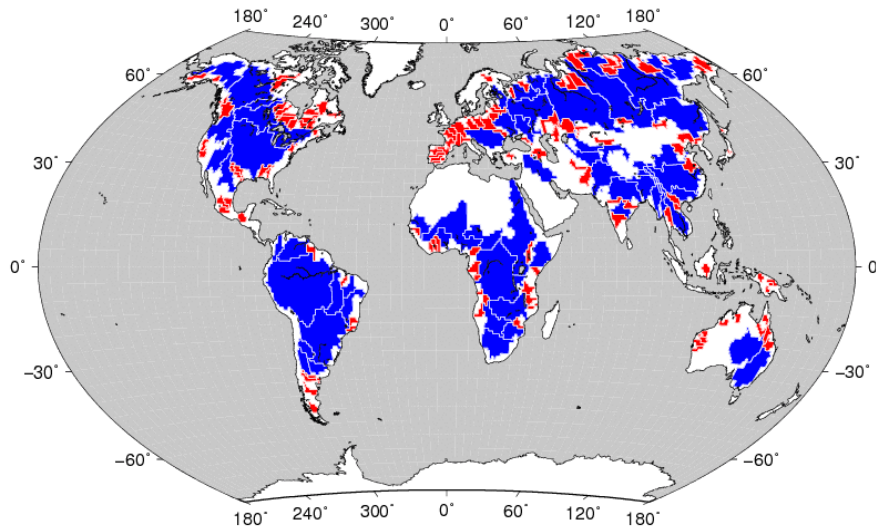


Signal amplitudes of mass variations in EWH as a function of spatial resolution, together with present-day and e.motion performance and resolution. Solid Earth mass variations are converted to EWH. Contributions from seasonal to interannual variations (left panel), and contributions from long-term trends (right panel).



e.motion – Science Requirements

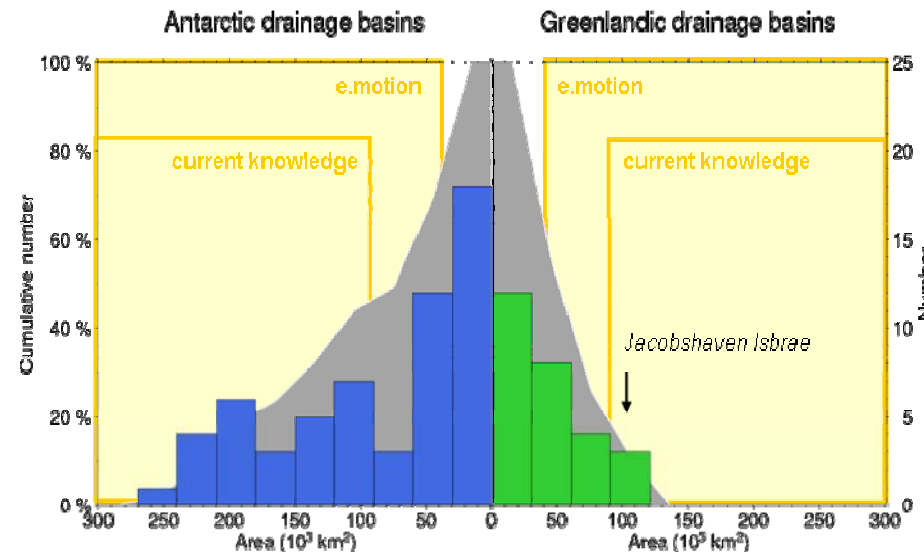
Hydrology



River drainage basins with a size between 40000 km² and 200000 km² (red) which will be resolved by e.motion, as well as basins larger than 200000 km² (blue) which corresponds to the present day resolution.

Source: Oki, T. & Sud, Y.1998, Earth Interactions; Rodell, M. and Famiglietti, J., 1999, Wat. Res. Research.

Continental Ice



Distribution of areas of continental hydrology drainage basins. Lines indicate recovery improvement of e.motion with regard to current knowledge. Grey area indicates the cumulative number of basins. Source: Oki & Sud,1998, Earth Interactions.



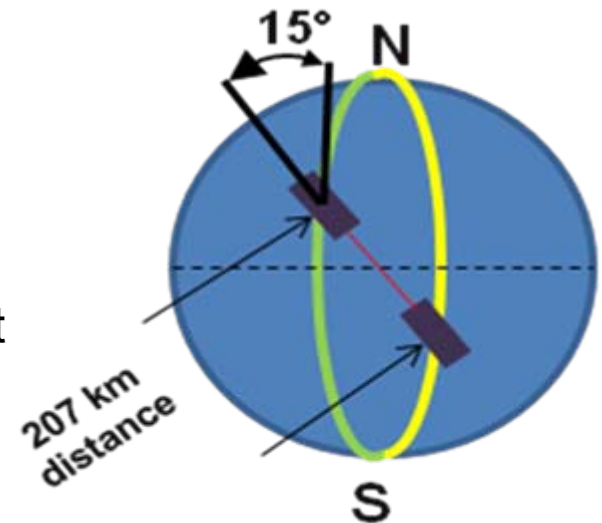
e.motion – Mission Assumptions

Selected Orbit Configuration:

- Near **polar** orbit; Mission duration **> 7 years**
- Nominal orbit height of **373km** (a slightly higher orbit as fallback option).
- Repeat **period of 28.92 days**, equatorial inter-track distance ca. 44 km.
- Sub-cycle of approximately **10 days** can be implemented.

SST-II Configuration:

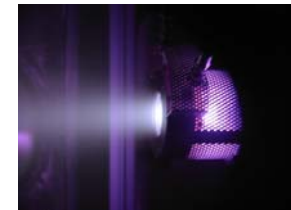
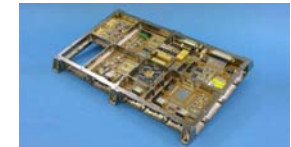
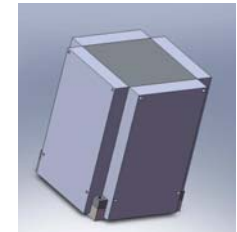
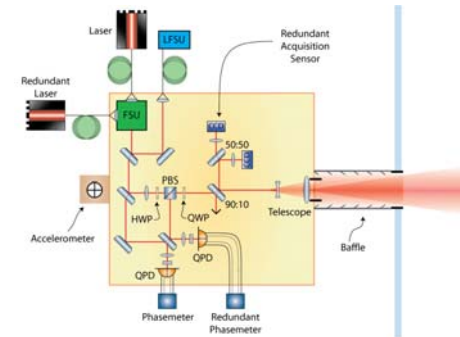
- For polar or near-polar orbits (both satellites in the **same orbital plane**) observations are mostly taken in **North-South** (or vice-versa) **direction**. This results in reduced cross-track resolution and North-South stripes.
- Therefore for e.motion a **pendulum orbit** is foreseen. Orbital planes of lead and trail satellites are rotated relatively to each other (change of right ascension of ascending node). Observations with a maximum tilt of about 15° at the equator are taken, leading to **multi-directional observations**.



e.motion – Mission Assumptions

Key Elements:

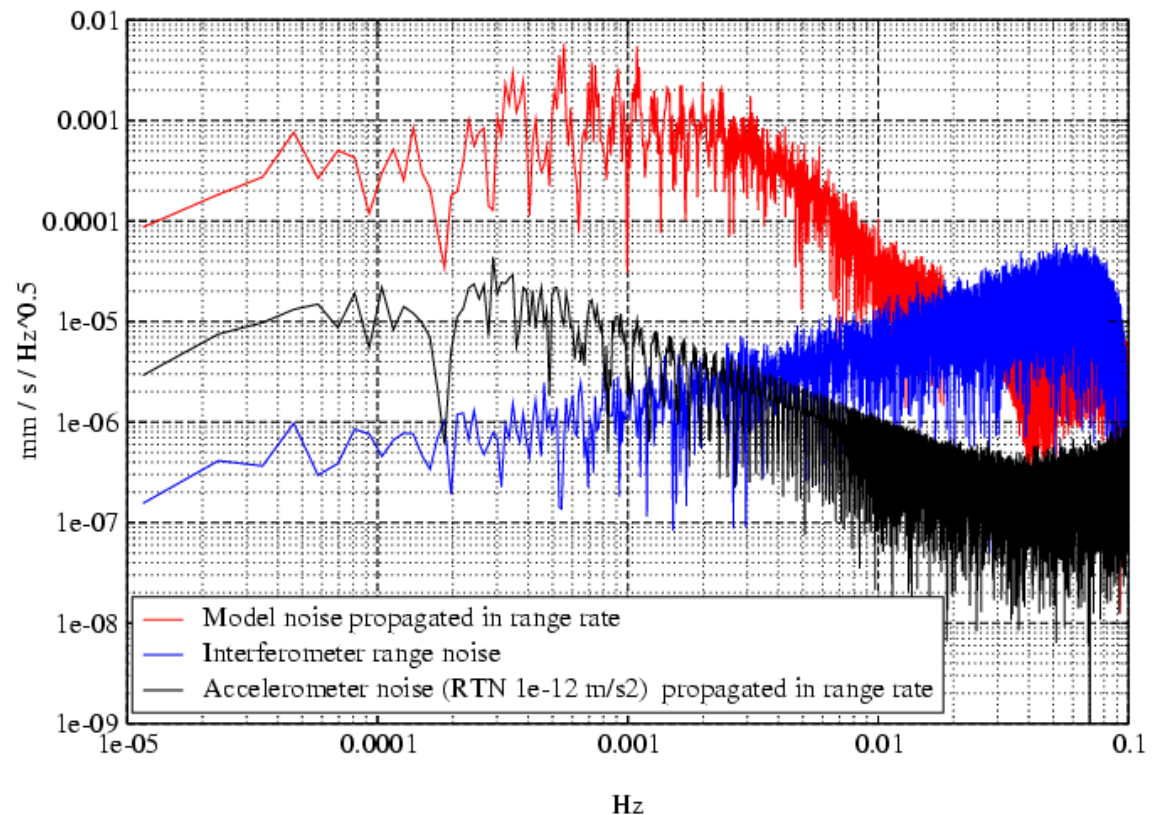
- The **inter-satellite ranges and range-rates** have to be observed with very high accuracy. For e.motion it is foreseen to use a **laser interferometer** system with a wavelength of $1\ \mu\text{m}$ in order to observe ranges with an **accuracy level of some 10's of nanometer**.
- Accelerations originated from **non-gravitational forces** have to be observed within a dedicated measurement range with a high-sensitive accelerometer. We seek for a resolution on the level of 10^{-11} to $10^{-12}\ \text{m/s}^2$ with **drag compensation** and **3 high sensitive axes**.
- The **geo-location of the satellite** has to be observed by a GNSS space receiver delivering ultimate accuracy.
- In order to implement an efficient pendulum orbit, **both satellites have to be oriented with high accuracy** against each other enabling high precision inter-satellite measurements. For this purpose also the **attitude** of the satellites has to be observed / reconstructed with **very high accuracy**.



e.motion – Mission Assumptions

Closed-Loop (Numerical) Simulation:

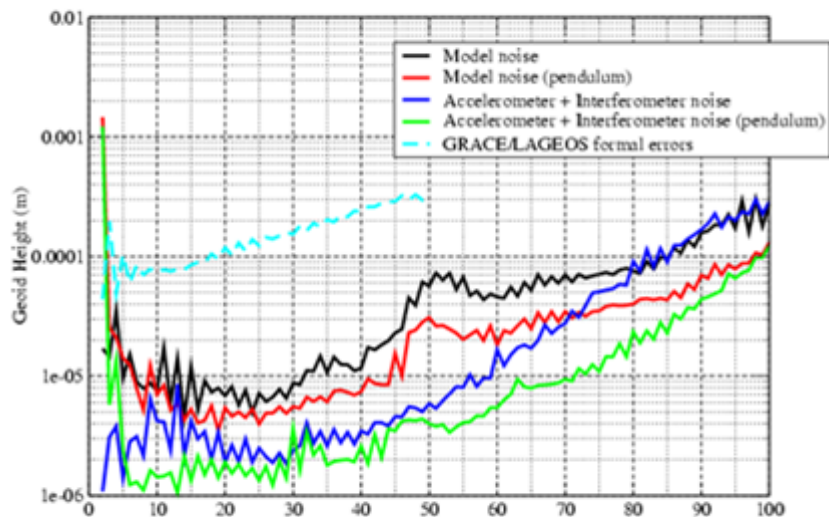
- Instrument noise:
 - Laser interferometer coloured noise $50 \text{ nm}/\sqrt{\text{Hz}}$ (white noise level),
 - Accelerometer coloured noise of $1 \cdot 10^{-12} \text{ m/s}^2/\sqrt{\text{Hz}}$ (white noise level).
- Background model noise:
 - Differences between nominal and reference models and scaling factor applied (0.1).



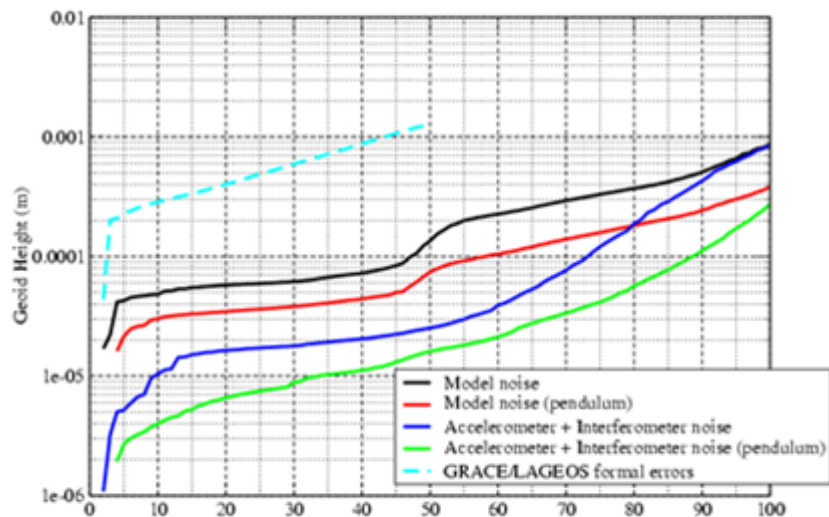
e.motion – Mission Assumptions

Closed-Loop (Numerical) Simulation:

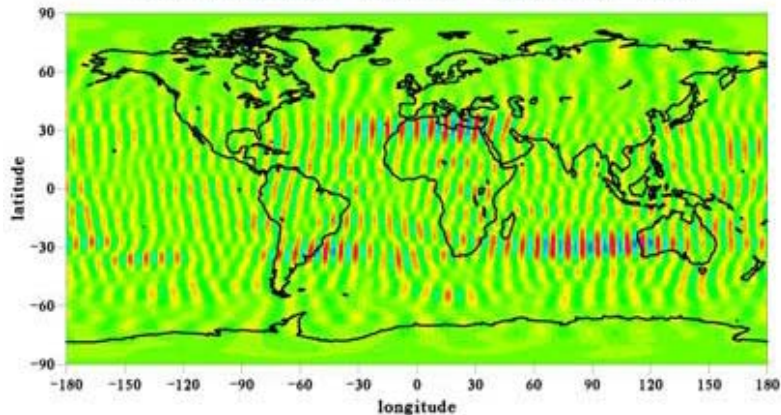
Spectra of gravity field errors per wavelength in terms of geoid height



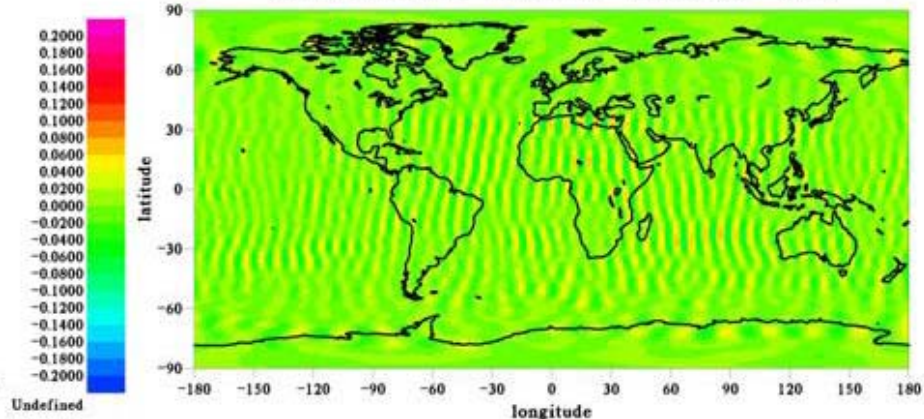
Spectra of cumulated gravity field errors in terms of geoid height



degree 02 to 060
(unit : m)
(mean: 0.0000 / st.dev: 0.0439 / min: -0.2029 / max: 0.2052)



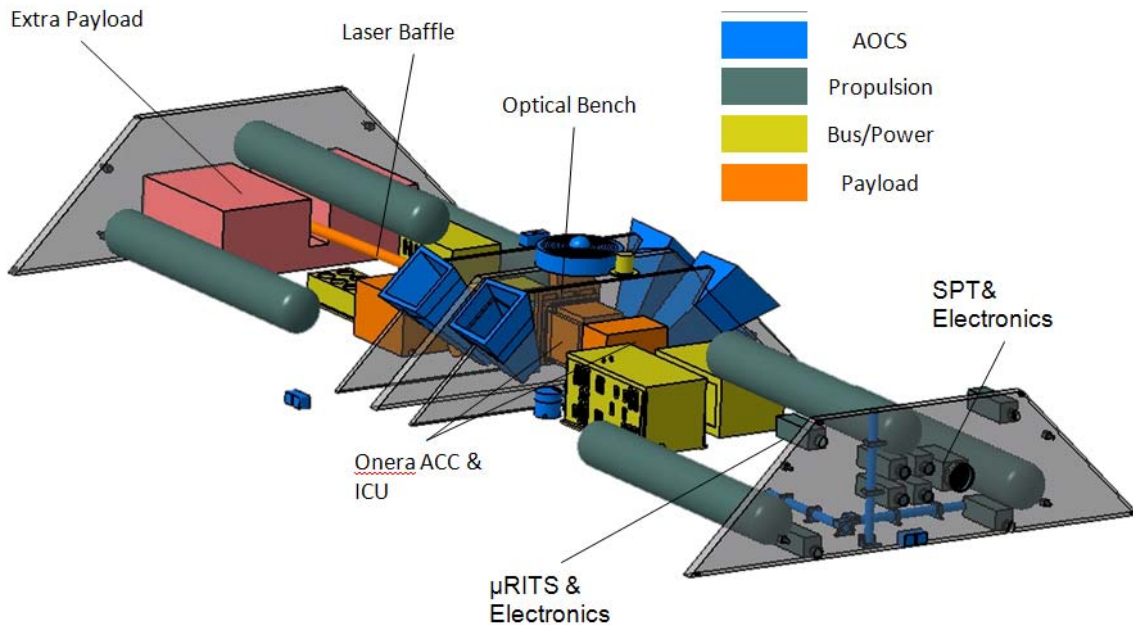
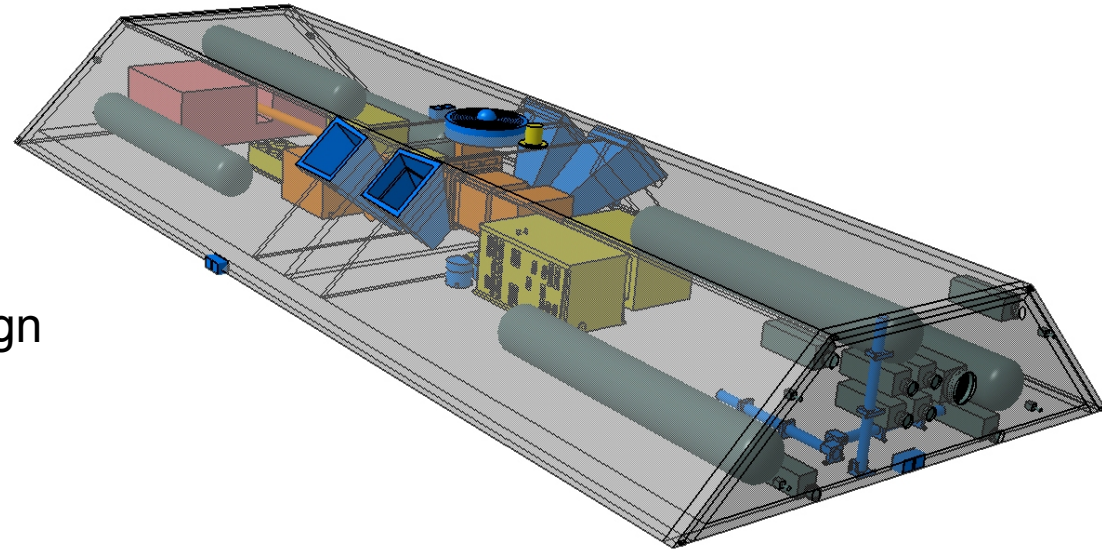
degree 02 to 060
(unit : m)
(mean: 0.0000 / st.dev: 0.0193 / min: -0.0813 / max: 0.0856)



e.motion – Technology

Space Segment:

Satellite Accomodation & Design



e.motion & GT-FGM

Significant elements of the science and technology proposal for e.motion was written by team members of the GT Future Gravity Mission project. In particular the following institutions contributed:

- Albert Einstein Institute, Hannover
- Deutsches GeoForschungsZentrum Potsdam
- EADS Astrium
- Leibnitz University Hannover
- SpaceTech GmbH Immenstaad (Lead Technology Proposal)
- Technical University Munich (Proposal Coordination)
- University Bonn
- University Stuttgart



ESA Studies

- *„Next Generation Gravity Field Mission“
led by Thales-Alenia*
- *„Next Generation Gravity Field Mission“
led by Astrium*



NGGM ESA Study

Study Objectives:

- Main objective: Establish a **mission architecture concept** aimed at the optimal recovery of the Earth variable gravity field. The mission shall be based on a **SST observation technique** and shall include the analysis of a variable number of pairs of satellites with different orbits and inclinations.
- Critical **review of requirements for the mission** to provide several sets of mission requirements of increasing level of complication in terms of space and time resolutions.
- The identification and **preliminary definition of system architecture concepts** fulfilling different sets of requirements of increasing level of ambition.
- The set-up of a modular and flexible **mission performance simulation tool** using the variable Earth gravity model and including models for the satellite and the instruments.
- Preliminary **design of the selected mission** and perform an **error analysis** and error allocation for the chosen alternative.
- The identification of **critical technologies** and the definition of technology **development roadmaps**.



NGGM ESA Study – Thales Alenia

Science Requirements:

	Description	Spatial resolution	Temporal resolution	Signal magnitude (geoid heights)
1	Melting of ice sheets (with separation of GIA)	100 – 1000 km	Seasonal – secular	0.01 mm/year (secular)
2	Non-steric comp. of sea-level var. at seasonal and shorter time scales	Global to basin level	Interannual – secular	0.1 mm/year (secular)
3	Ground water (soil moisture and snow) at higher spatial scales	10 – 200 km	Hourly – seasonal – secular	1 cm (seasonal)
4	Post-seismic deformation	10 – 200 km	Subseasonal	1 mm (subseasonal)

	Wave-length	10000 km	1000 km	200 km	100 km	10 km
	SH degree	2	20	100	200	2000
CGE (cum. Geoid error)	10 mm	Ground Water				
	1 mm	Non-steric sea-level		Seismic		
	0.1 mm	Ice sheets				

SH degree	150	200	250
CGE [mm]	0.1	1	10
CGE requirements			



NGGM ESA Study – Thales Alenia

Sensor Requirements:

Altitude [km]	k	SST:	ACC:	CGE [mm]		
		s_k	a_k	SH degree		
		$\left[\frac{m}{\sqrt{Hz}} \right]$	$\left[\frac{m}{s^2 \sqrt{Hz}} \right]$	150	200	250
300	3	8e-9	7e-12	0.09	0.62	4.31
350	8	3e-9	2e-12	0.09	0.86	9.09
400	15	5e-10	4e-13	0.05	0.64	9.32
450	20	9e-11	8e-14	0.02	0.49	10.15

Reference noise model for d = 75 km

Mission Architecture:

Basic Candidate Architectures under investigation:

- **Colinear tandem** in polar or SSO (sun-synchronous) orbit.
- **Pendulum tandem** in polar or SSO orbit.
- **Cartwheel tandem** in SSO orbit.
- Two colinear tandems (polar + 63°, polar + SSO) or
- Two pendulum tandems (both polar, polar + SSO)
- Two Cartwheel tandems (both SSO)



NGGM ESA Study – Astrium

Science Requirements:

- From Solid Earth (GIA, co/postseismic deformation)
~ 0.04-0.1mm/a@200km
- From Hydrology (groundwater, soil moisture, precipitation/evapotranspiration)
~ 0.1mm@150-200km, temp. resolution up to 10d
- From Cryosphere (drainage basins, snow accumulation)
~ 0.02-0.04mm/a@150-200km and long temp. coverage,
0.1mm@150km, temp. resolution up to 10d (snow)
- From Oceans (global sea level, basin mass change, barotropic currents)
~ 0.03mm/a@200km, 0.1mm@100-1000km.

Mission Architecture:

- SST **laser interferometer** is considered
- long-term mission (**10yr lifetime**)
- consider **drag compensation**
- investigate various concepts, including **pearl-string** (GRACE) and **pendulum**
- consider **simultaneous measurements** (> 1 satellite pair)



NGGM ESA Study & GT-FGM

Several team members of the GT Future Gravity Mission project are involved in the ESA NGGM studies. In particular these are:

- Deutsches GeoForschungsZentrum Potsdam
- EADS Astrium
- Technical University Munich
- University Bonn
- University Stuttgart



Conclusions



Conclusions

- Several Activities towards future Gravity Field Missions are ongoing.
- GRACE **continuation** is under definition/negotiation by the US-German GRACE consortium with a target **launch date** as early as possible (e.g. **2015**).
- e.motion proposal for ESA's **Earth Explorer 8 mission** submitted. SST **laser interferometer polar pendulum mission** with launch in **2018**. Goal **1 mm geoid** (10 cm EWH) for **200 km** resolution. Decision for phase A in November 2010.
- Two **ESA studies** running in parallel until end of 2010. SST **laser interferometer pendulum mission** is considered. Goal **1 mm geoid** (20 cm EWH) for **100 km** resolution. Studies target for a mission proposal for **Earth Explorer 9**.
- New **observation techniques** are investigated **for a long term strategy** of observing the gravity field from space.
- Intermediate results of GT-FGM project directly flow into current and future mission design studies. Strong **visibility of German project partners in international activities**.

