European Initiatives and Studies on Mass Change Mission Architectures

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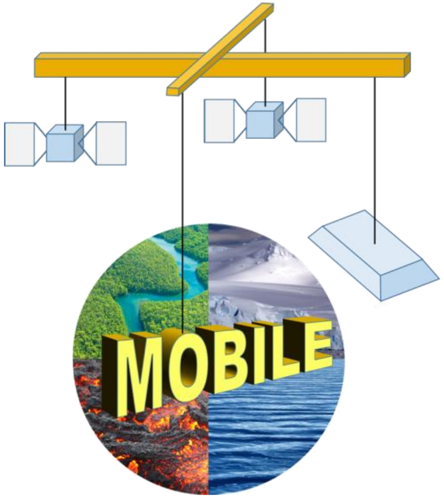
Earth Mass Transport Mission

Mass Variation Obs. Sys. high-low inter-Sat. Links

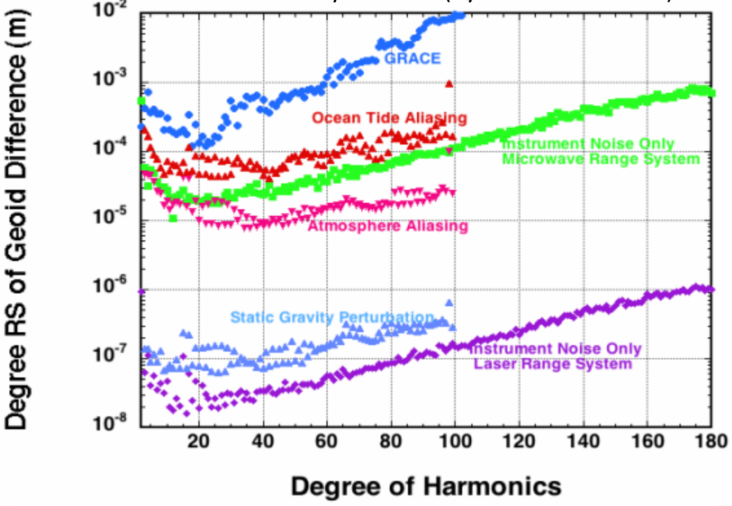


e.motion **e^2.motion** **e.motion^2**

2007 Workshop Recommendations

Workshop on The Future of Satellite Gravimetry, 12-13 April 2007, Noordwijk, The Netherlands

Error on Gravity Solution (by M. Watkins 2007)



Recommendations

- GRACE follow-on mission based on the present configuration and with emphasis on the uninterrupted continuation of time series of global gravity changes is strongly supported,
- Geophysical a-priori background models should be improved,
- Medium term priority should be focused on higher precision and higher resolution in space and time to be achieved by improved sensor systems, such as optical ranging systems, and configuration flights.

2009 Workshop Recommendations

Int. Workshop of the IGCP (International Geoscience Programme), "Towards a roadmap for future satellite gravity missions", 30 Sept. – 2 Oct. 2009, Graz, Austria

Declarations

- Long and uninterrupted series of satellite gravity missions with accuracies and resolutions at least as good as GRACE's.
- Provide the basis for a global service to inform decision makers in a timely manner about changes in the water cycle related to droughts, groundwater depletion, sea level changes, and other potential impacts of climate change.

Roadmap towards future satellite gravity missions

- Science requirements and Earth system modelling
- Increase performance: spatial & temporal resolution, accuracy
- Mission implementation: Virtual constellation, Inter-agency coordination
- Improve processing, geophysical modelling, applications & services

Guidelines towards Future Gravity Missions

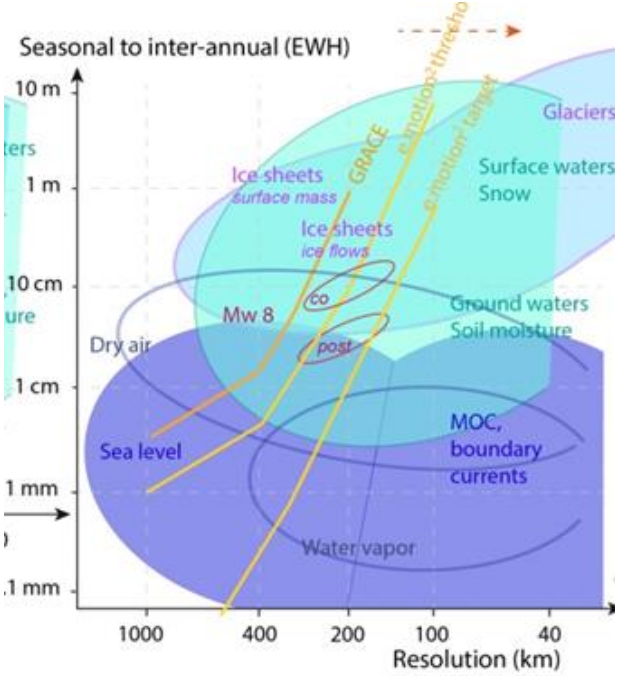
Science Requirements (IUGG study*) ➡ Next Talk by Roland Pail

Threshold

Spatial resolution	Equivalent Water Height		Geoid	
	Monthly field	Long-term trend	Monthly field	Long-term trend
400 km	5 mm	0.5 mm/yr	50 µm	5 µm/yr
200 km	10 cm	1 cm/yr	0.5 mm	0.05 mm/yr
150 km	50 cm	5 cm/yr	1 mm	0.1 mm/yr
100 km	5 m	0.5 m/yr	10 mm	1 mm/yr

Target

Spatial resolution	Equivalent Water Height		Geoid	
	Monthly field	Long-term trend	Monthly field	Long-term trend
400 km	0.5 mm	0.05 mm/yr	5 µm	0.5 µm/yr
200 km	1 cm	0.1 cm/yr	0.05 mm	5 µm/yr
150 km	5 cm	0.5 cm/yr	0.1 mm	0.01 mm/yr
100 km	0.5 m	0.05 m/yr	1 mm	0.1 mm/yr



Threshold requirements improved roughly by factor 5, Target by a factor of 50 with respect to GRACE.

* Pail, R.; Bingham, R.; Braitenberg, C.; Dobslaw, H.; Eicker, A.; Güntner, A.; Horwath, M.; Ivins, E.; Longuevergne, L.; Panet, I.; Wouters, B.: Science and User Needs for Observing Global Mass Transport to Understand Global Change and to Benefit Society; Surveys in Geophysics, Vol. 36, Nr. 6, pp 743-772, Springer Netherlands, ISSN 0169-3298, ISSN (Online) 1573-0956, DOI: 10.1007/s10712-015-9348-9, 2015

Guidelines towards Future Gravity Missions

Improved Spatial & Temporal Resolution

State-of-the-art

- GRACE monthly fields exhibit the well known stripes.
- Extensive filtering is required (reducing spatial resolution)

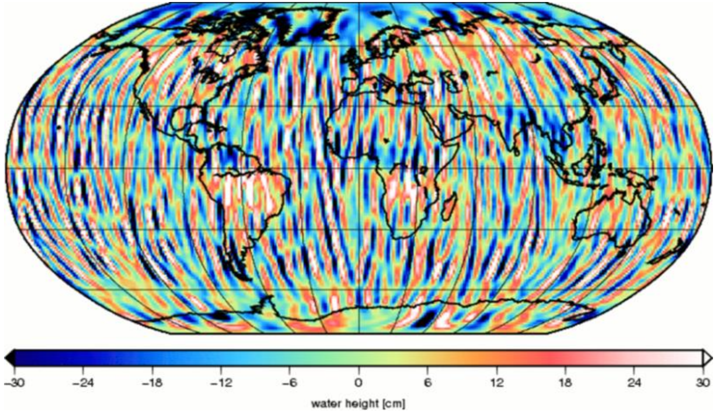
Reasons for this:

- 1-D observation system in flight direction – anisotropic error behaviour.
- Temporal aliasing of high frequency signals (< 1 month): Need to be reduced with external models (De-Aliasing); Model errors alias into monthly solutions.

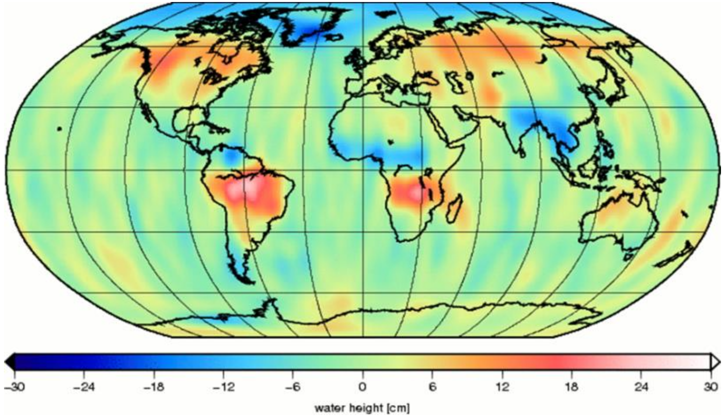
Requirements for future missions:

- **Multi-directional observations**
- **Significantly improved space-time sampling**

Monthly GRACE Field (original)



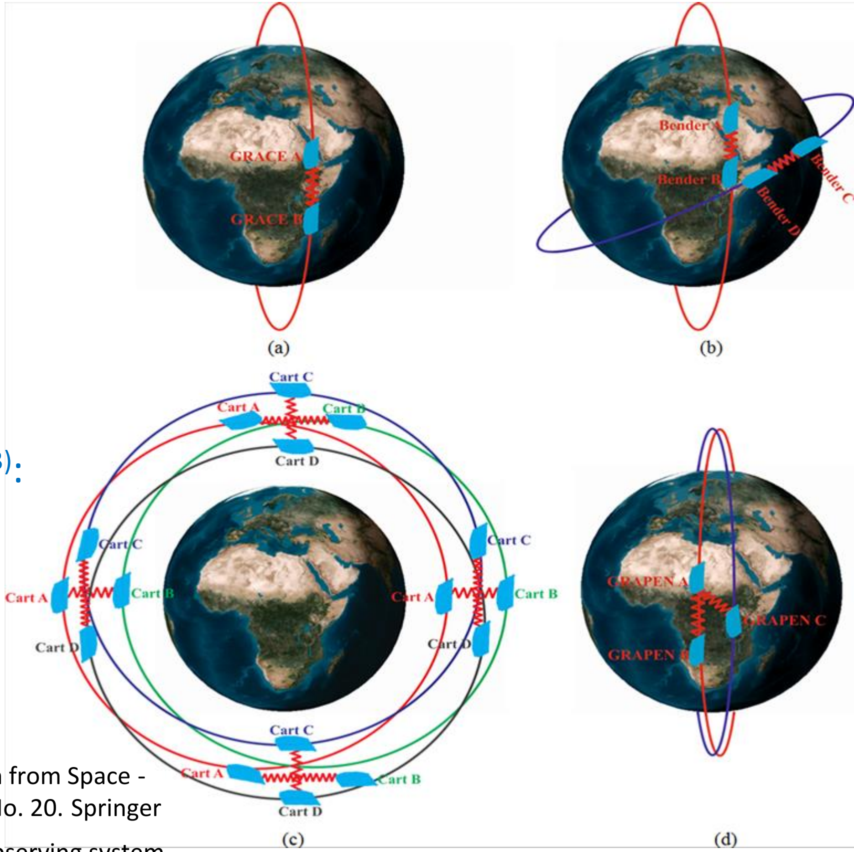
Monthly GRACE Field (500 km smoothing)



Guidelines towards Future Gravity Missions

Configuration Flights

- Virtual or dedicated constellations are able to improve spatial and temporal resolution (e.g. Bender pairs) [1)2)].
- Multi-directional observations support increase of spatial resolution.
- Multiple-pairs or configurations support increase of temporal resolution
- NASA/ESA Interagency Gravity Science Working Group [3)]: *"The full set of user requirements in terms of accuracy and spatial and temporal resolution can only be met by constellations of spaceborne future gravity missions."*



Figures by Elsaka, B. (2014) International Journal of Geosciences, 5, 267-273

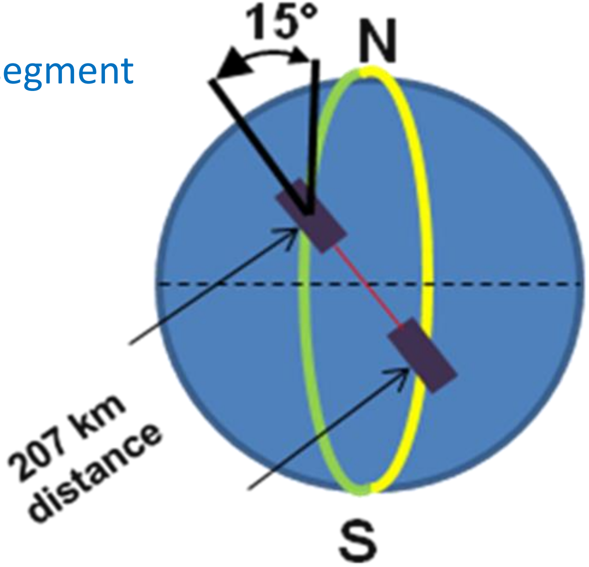
[1)] Wiese, D., W. Folkner, und R. Nerem. (2009) „Alternative mission architectures for a gravity recovery satellite mission". Journal of Geodesy 83, Nr. 6, 569–81.

[2)] Flechtner, Frank, Nico Sneeuw, und Wolf-Dieter Schuh (2014), Observation of the System Earth from Space - CHAMP, GRACE. Advanced Technologies in Earth Sciences, GEOTECHNOLOGIEN Science Report No. 20. Springer

[3)] NASA/ESA Interagency Gravity Science Working Group (IGSWG) (2016), Towards a sustained observing system for mass transport to understand global change and to benefit society, Final Report: Doc. TUD-IGSWG-2016-01

e.motion - EE8 Mission Proposal

- Proposal due 1.6.2010
- Proposers: J. Johannessen (lead), I. Panet and T. Gruber (coordination & proposal) & a large team from European science, technology & industry *
- Opportunity mission, budget limit: 100 M€ industrial cost for space segment



Mission Configuration

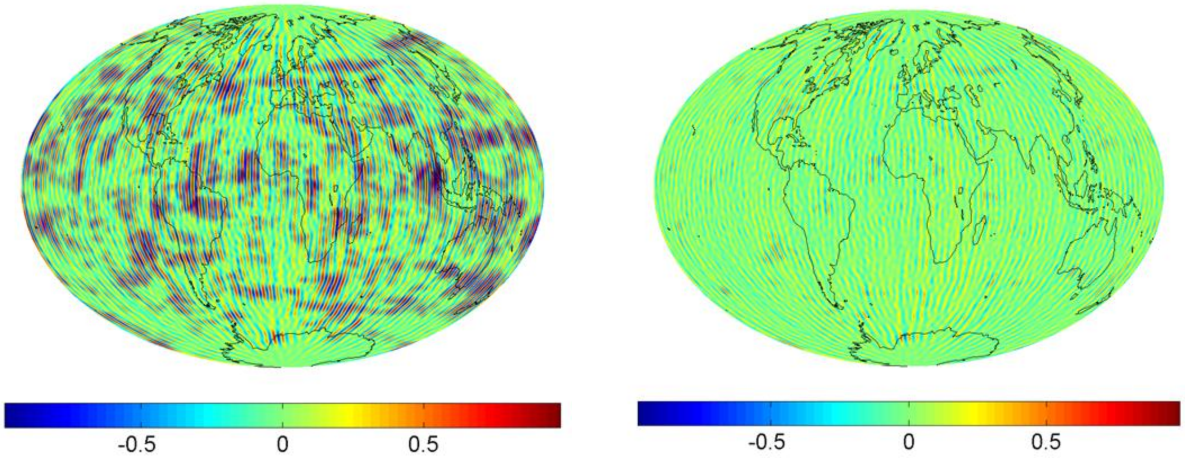
- Science requirements similar to threshold requirements
- Mission duration > 7 years
- Low-low SST concept in a near-polar pendulum configuration at 373 km height
- Instrumentation: LRI with some 10's of nm; ACC with 10^{-11} m/s^2 with 3 high sensitive axes; Drag reduction needed; GNSS, Star cameras …

* Panet, I., J. Flury, R. Biancale, Th. Gruber, J. Johannessen, M.R. van den Broeke, T. van Dam, u. a. „Earth System Mass Transport Mission (e.motion): A Concept for Future Earth Gravity Field Measurements from Space". Surveys in Geophysics online (2012). https://doi.org/10.1007/s10712-012-9209-8.

e.motion - EE8 Mission Proposal

Simulations

- Noise-free numerical simulation results - Impact of pendulum versus co-planar configuration
- Pendulum orbit improves homogeneity of gravity field solutions and reduction of stripes



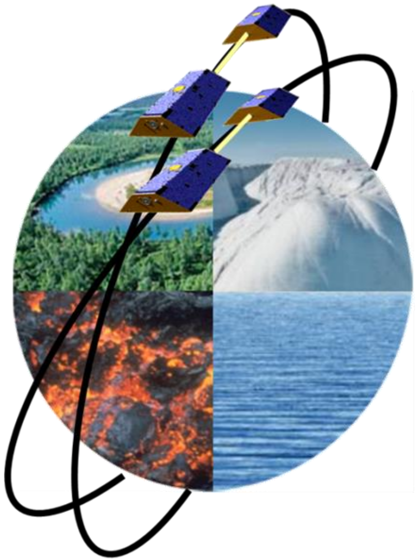
Recovery errors for conventional satellite pair in polar orbit (left) and pendulum configuration (right). The figures show dimensionless residuals obtained from a noise free simulation, scaled to the maximum residuals of the left figure (±1 mean maximum/minimum difference).

Proposal Evaluation

- Strong science; Insufficient technological maturity; Unrealistic budget estimation
- Not recommended to be chosen for a phase A study.

e^2.motion – EE9 Preparatory DLR Study

- Preparatory study for EE9 call funded by DLR (July 2014)
- Study lead: T. Gruber, M. Murböck (TUM); Contributors: Team from German science, technology & industry *
- Study included science requirements, orbit configuration, instrument and attitude control systems and simulations



Mission Configuration

- Science requirements equal to threshold requirements
- Monthly down to weekly and shorter temporal resolution
- Mission duration up to 10 years
- Double low-low SST pair (Bender) at 420 km height, 1 polar pair, 1 inclined pair (70 deg.)
- Instrumentation: LRI with 25 nm; ACC with $4x10^{-11}$ m/s^2; Drag reduction foreseen; GNSS, Star cameras …

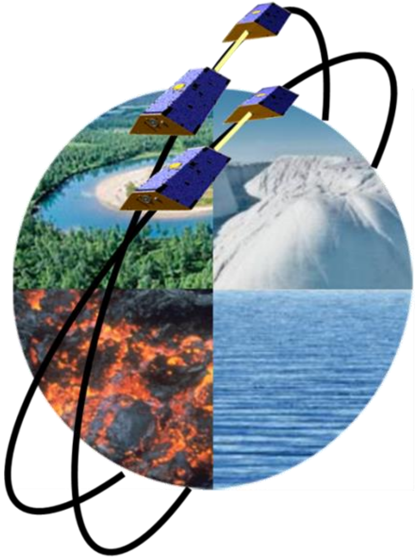
* NGGM-D Team (Ed.), e^2.motion - Earth System Mass Transport Mission (Square)- Concept for a Next Generation Gravity Field Mission -Final Report of Project "Satellite Gravimetry of the Next Generation (NGGM-D)“, München 2014, ISBN 978-3-7696-8597-8; https://dgk.badw.de/fileadmin/user_upload/Files/DGK/docs/b-318.pdf

e.motion² – EE9 Mission Proposal

- Proposal due 24.6.2016 (revised call: due date 15.6.2017)
- Proposers: T. Gruber & I. Panet (lead), & a large team from European science, technology & industry partners
- Opportunity mission, budget limit: 120 M€ industrial cost for space segment (revised call 150 M€)

Mission Configuration

- Science requirements address target requirements (as a minimum threshold requirements)
- Monthly down to daily temporal resolution (observe high-frequency mass variations instead of de-aliasing)
- Mission duration 5 years (minimum) 10 years (extended)
- Double low-low SST pair (Bender) with 2 options
- Instrumentation: LRI with 25 nm; ACC with 4×10^{-11} m/s^2; Drag reduction foreseen; GNSS, Star cameras …



e.motion^2 – EE9 Mission Proposal

Mission Configuration

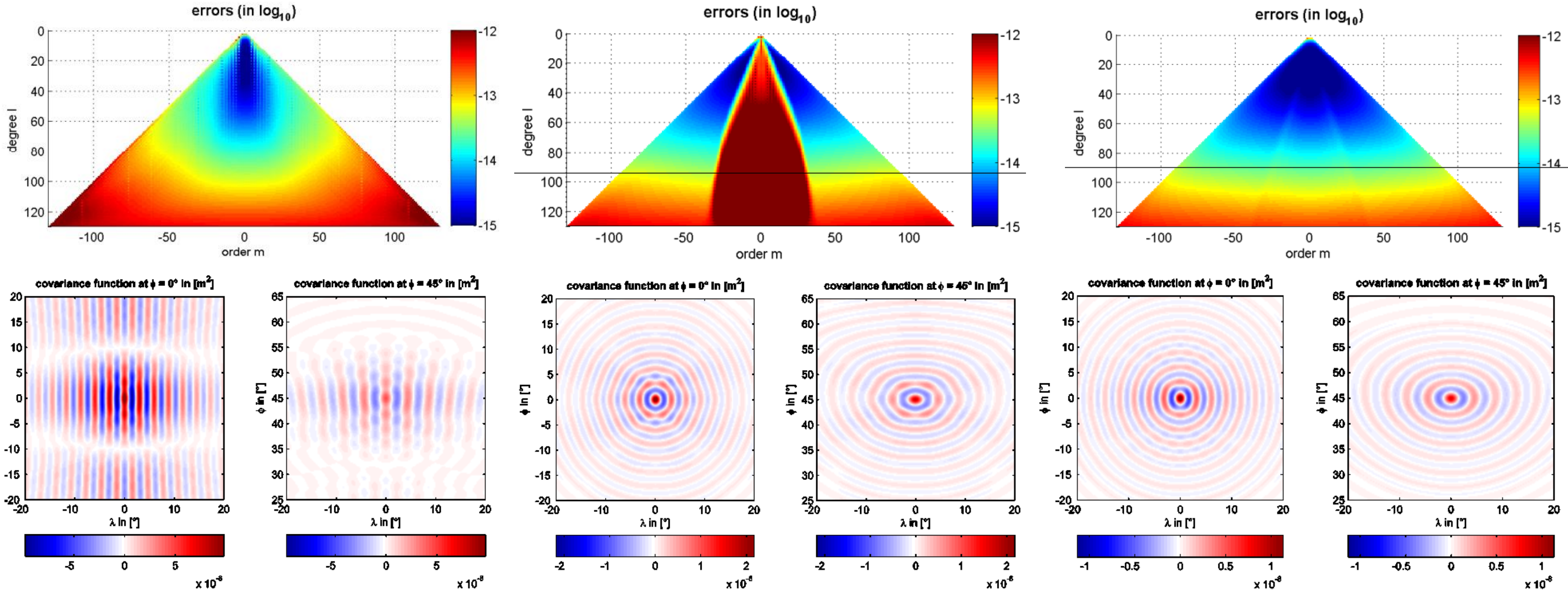
	e.motion^2 (Option 1)	e.motion^2 (Option 2)	GRACE-FO	GRACE-II (Option 1)	GRACE-II (Option 2)
Observation Concept	SST-ll with LRI, ACC for non-gravitational forces				
Inclination	70^0	115^0	near-polar	near-polar	near-polar
Orbit Height	~420 km	~342 km	~480 km at launch	~420 km	~362 km
Repeat Cycle	Yes (31d)	Yes (29d)	no	Yes (31d)	Yes (11d)
Nominal Lifetime	2023-2028	2023-2028	2018-2023	2025-2030	2025-2030
Extended Lifetime	2023-2033	2023-2033	2018-2028	2025-2035	2025-2035

Constellation Scenario	Inclined pair	Polar pair	Overlap Period Nominal	Overlap Period Extended	Science Objective
E1-GFO	e.motion^2 Option 1	GRACE-FO	2023 - 2023	2023 - 2028	2 times threshold
E1-GRII1	e.motion^2 Option 1	GRACE-II Option 1	2025 - 2028	2025 - 2033	threshold
E2-GRII2	e.motion^2 Option 2	GRACE-II Option 2	2025 - 2028	2025 - 2033	target

e.motion^2 – EE9 Mission Proposal

Simulation Results

Formal error triangle plots (top) and spatial covariance functions (bottom) for scenario E2GRII2



polar pair

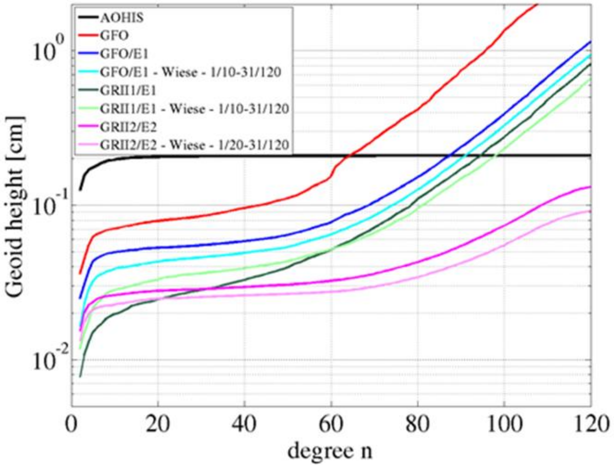
inclined pair (70^0)

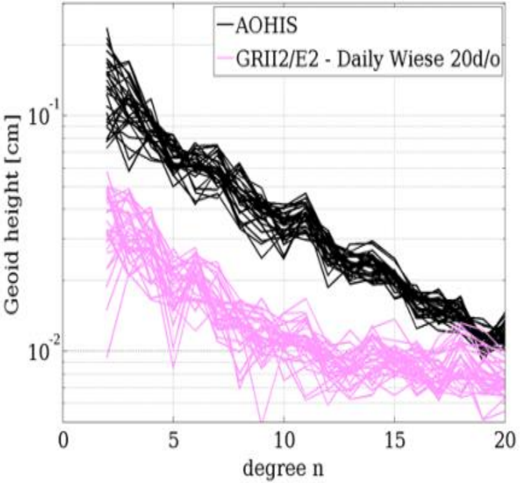
polar & inclined pair

e.motion² – EE9 Mission Proposal

Simulation Results

Cumulative geoid height differences of true minus recovered signal in [cm] of mass transport model





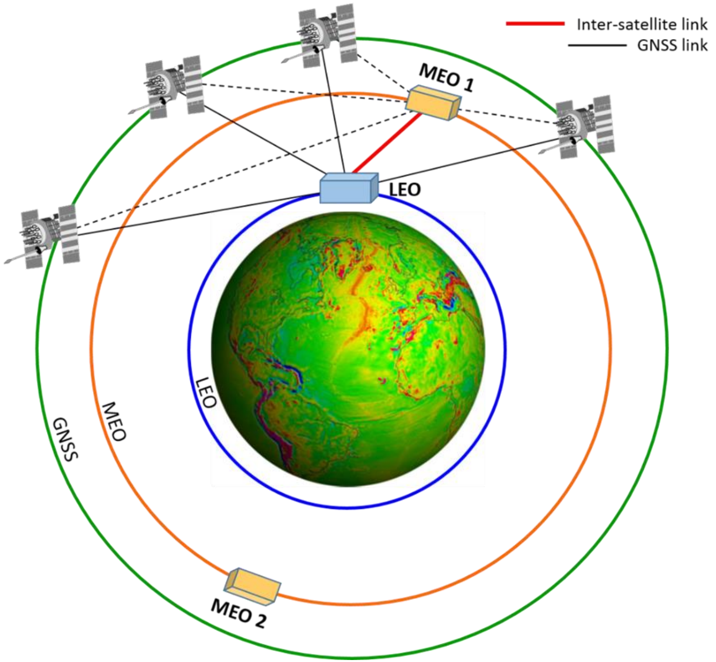
Square root of daily degree variances of coefficient differences of true AOHIS minus recovered signal in terms of geoid heights in [cm]

Proposal Evaluation

- The e.motion² mission qualifies as an Earth Explorer. The dual pair constellation provides a unique capability and new science opportunities whilst sustaining present day results from GRACE at a lower spatial and temporal resolution. The e.motion² mission could prepare as precursor the way for a sustained operational constellation concept.
- Not recommended to be chosen for a phase A study for programmatic reasons (budget)
- No resubmission of proposal for revised call for programmatic reasons (budget, 2nd pair)

MOBILE – EE10 Mission Idea

- Proposal for mission idea due 2.3.2018
- Core mission, budget limit: 225 M€ industrial cost for space segment



Boundary Conditions for this Call

- Vega-C launch configuration (baseline), 2027/28
- In-line with key elements of ESA Earth Observation Science Strategy
- High degree of innovation
- SRL 5 to be achieved at the end of Phase A (end 2020), TRL 5 to be achieved at the end of phase B1 (mid 2022)

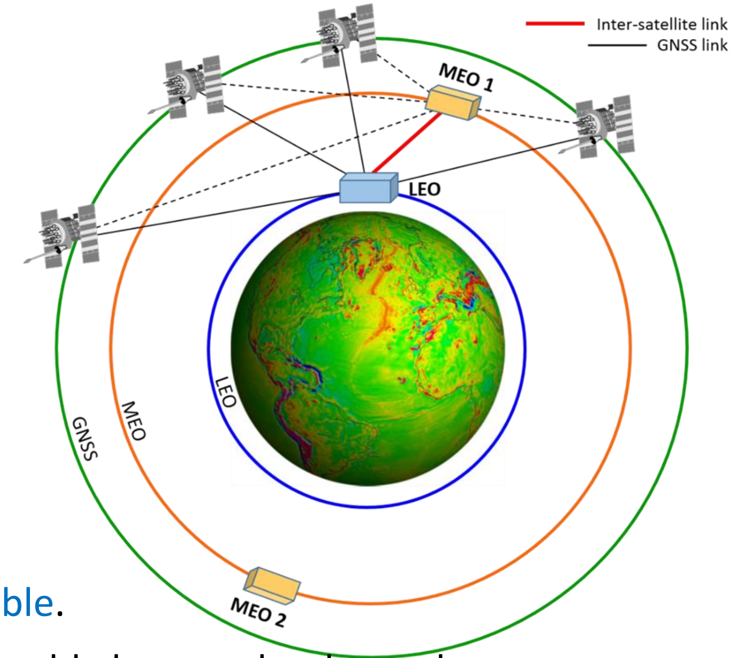
Why a new Concept?

- Is one SST pair with LRI technology innovative enough and/or is a pendulum mission an option?
- Is a 2nd pair affordable? Is somebody else providing the 1st pair?
- Alternative configurations with smaller/cheaper satellites, scalable and sustainable?

MOBILE – EE10 Mission Idea

Mission Design

- High-low inter-sat. ranging between Mean-Earth Orbiters (MEO) and Low-Earth Orbiter (LEO) with µm accuracy.
- Minimum configuration: 2 MEOs (~10,000 km) and 1 LEO (~350-400 km), in polar orbits to maintain stable configuration (no relative drift of orbit planes).
- Main instrument: LRI placed at the LEO. MEOs: passive reflectors (or transponders).
- All satellites are equipped with accelerometers.



Proposal Evaluation

- The scientific requirements are well justified and fully traceable.
- MOBILE is innovative and will contribute to development of stable laser technology, phase measurement interferometric technologies and high performance inertial sensors.
- Although of high scientific merit, the mission is to be studied in Phase-0 due to technical and programmatic risks not recommended

Future Mission Concepts: Potential for Improvements

1. New/improved measurement technologies

- Improved Inter-satellite ranging: KBR vs. LRI
- Improved technologies of accelerometry/gradiometry
- High-prec... ...tical
- Improved thruster te...

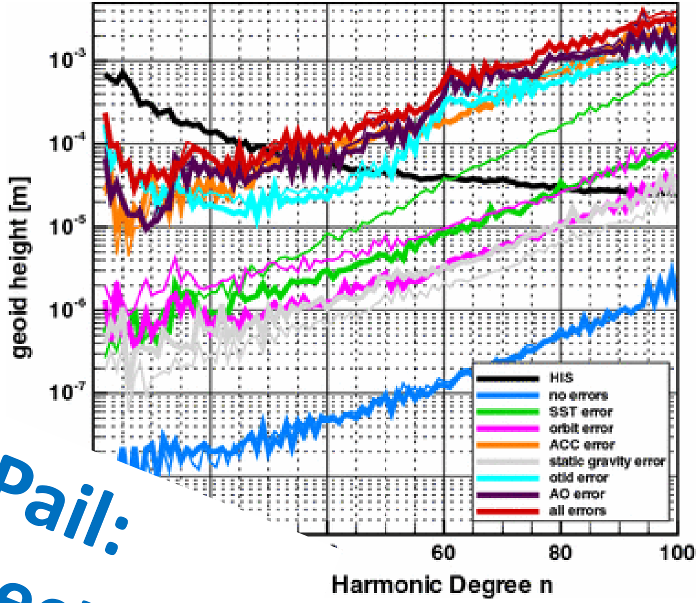
2. Satellite formations

- Improved spatial and temporal re... formation flights in a certain constellatio...

3. Processing & combination with complementary geophysica...

- by means of improved spatial-temporal parameterization
- Improved separation of signals due to complementary information
- Integrate models of the complex system Earth

See Talk by Roland Pail: Future NGGM Architectures



Flechtner et al, 2016