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European Gravity Service for Improved Emergency Management

WP2: E2E Simulator

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WP2: E2E Simulations (M06-M18)

Proposal: “In parallel we will update and use our E2E (end-to-end) data simulator for future space data to investigate, based on above harmonised processing standards and models, the gain for hydrological applications which can be achieved with GRACE-FO or Next Generation Gravity Missions.”

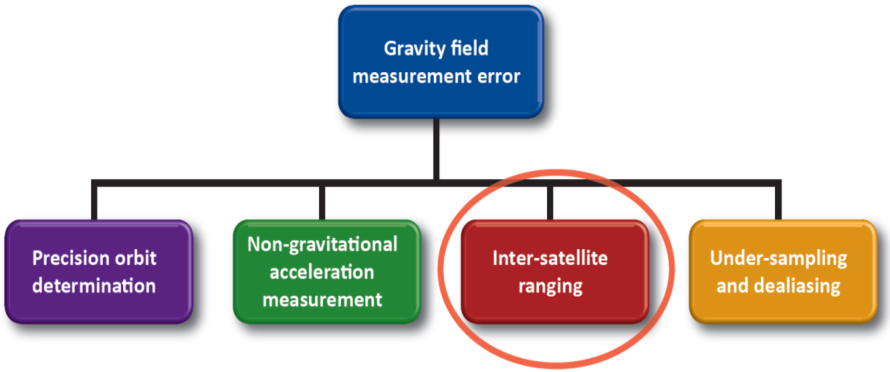
Today: “What can be expected from the GRACE-FO Laser Ranging Interferometer for Earth Science applications?”

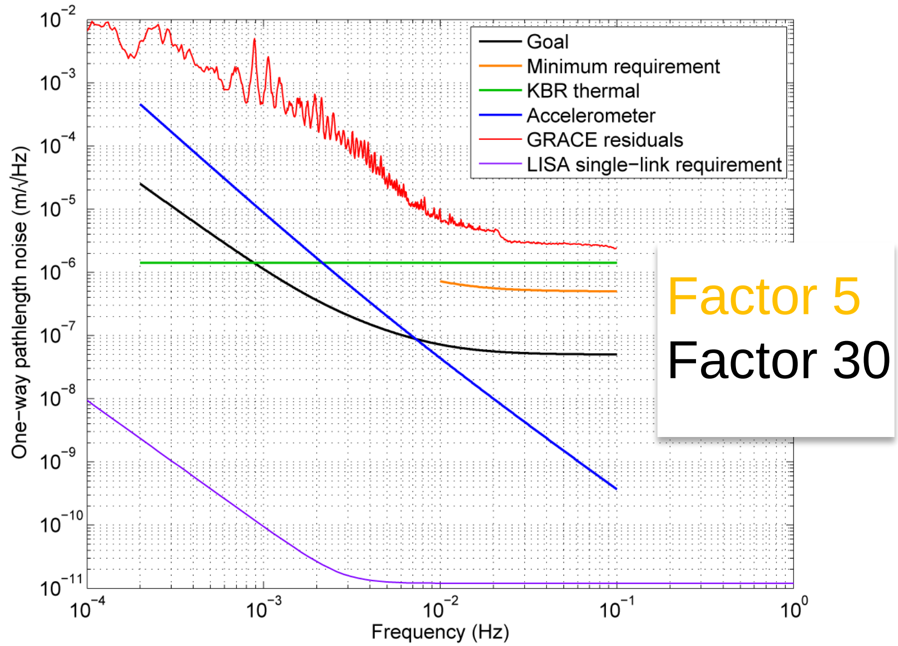
GRACE-FO Objectives

- The GRACE-FO mission's **primary objective** is to **continue the high-resolution monthly global models of Earth's gravity field** using evolved versions of the GRACE K/Ka-band microwave interferometer, GPS, star camera and accelerometer.

- **Secondary objectives** are
  - to **demonstrate** the effectiveness/technology of a **laser ranging interferometer (LRI)** in improving low-low SST measurement performance.
  - and to **continue** measurements of GRACE **radio occultations** for operational provision of e.g. vertical temperature / humidity profiles to weather services.

GRACE-FO LRI Top Level Requirements





- **LRI shall be operated in parallel to the MWI**

- **Minimum requirements ("mission success criteria")**
  - σSST(f) = 500nm/SQRT(Hz) * NSF(f) 10mHz < f < 100mHz
  - operation time = 1 year

- **Goal**
  - σSST(f) = 80nm/SQRT(Hz) * NSF(f) 0.2mHz < f < 100mHz
  - operation time = >> 1 year

Study Outline

We investigated the expected benefit of the LRI by

- full-scale simulation in terms of spherical harmonics
- over the nominal mission lifetime of five years
- using a realistic orbit scenario and
- error assumptions for orbit, instrument and background model errors.

Results are presented in the spectral and spatial domain (globally)

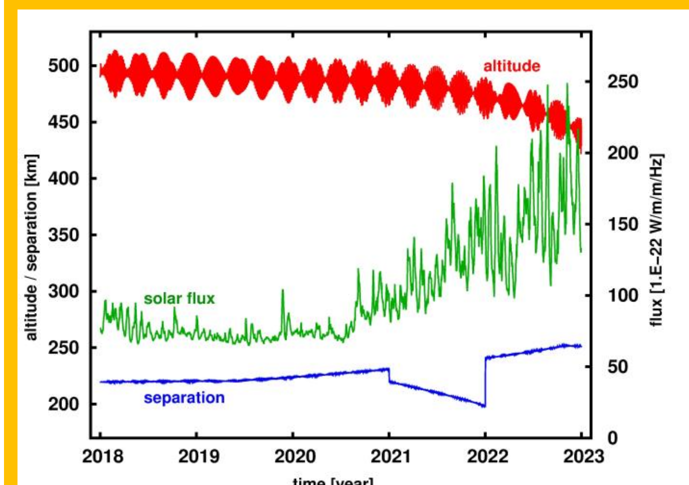
Also investigated how simulated seasonal / sub-seasonal (hydrology), secular (ice) and instantaneous (Earthquake) regional signals are recovered when using GRACE-FO MWI and LRI data

Show impact of LRI observations on a Next Generation Gravity Mission option like a two-pair Bender-type constellation

Approach (1)

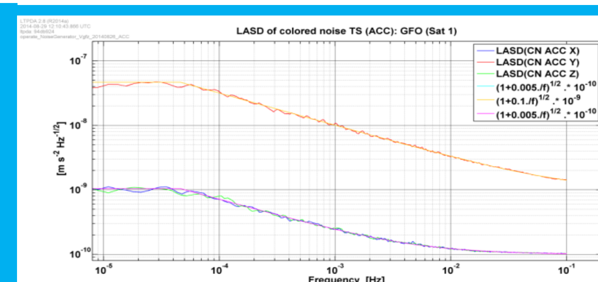
Step 1: Simulation Step (based on EPOS-OC Software)

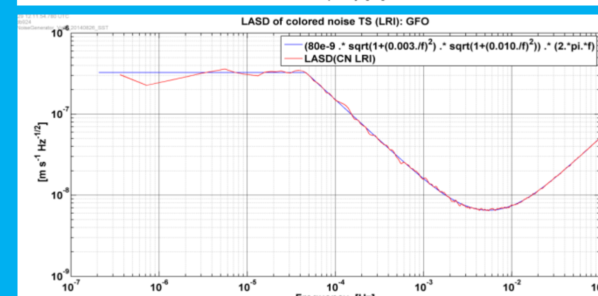
- Define initial orbit elements, mission life time, solar flux …
- Define a-priori („true world“) background models
  - static gravity field: EIGEN-GL04C (nmax=100)
  - ocean tides: EOT08a (8 main constituents)
  - non-tidal mass variations: ESA AOHIS model (see talk by Dobslaw et al.)
- Simulate daily geometric HL-SST (GPS) & LL-SST (MWI, LRI)
- Simulate daily non-gravitational forces (from air drag, solar radiation and albedo models) and transform to accelerometer data (ACC)
- Attitude: yaw steering



Step 2: Noise (from IfE)

- Add realistic (colored) noise to all (SST, ACC) observations





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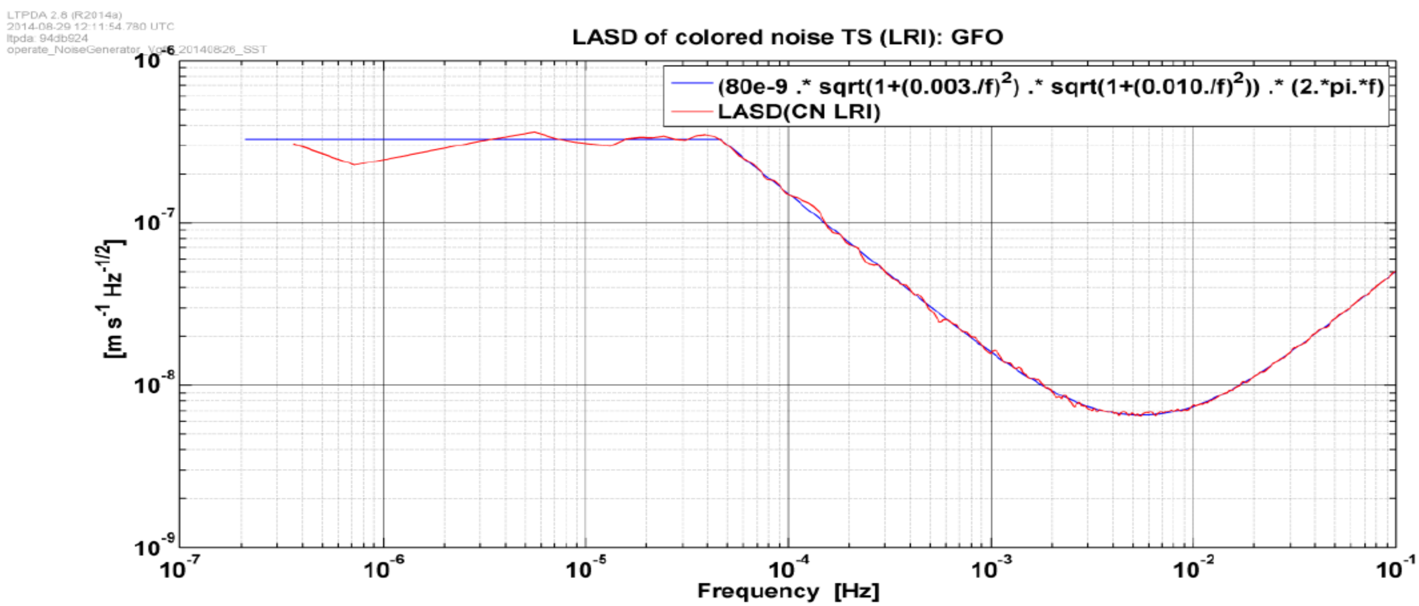
LRI Noise

The 5s SST noise values for MWI and LRI are modeled in terms of amplitude spectral density (ASD) as a square root of power spectrum density (PSD) with a distance (220km) dependent factor.

Values applied in our study are consistent with the expected performance of the GRACE-FO LRI (Sheard et al. 2012) and MWI (GFZ GRACE RL05 data) SST noise:

- LRI: 80 nm (range) resp. 9.9 nm/s (range-rate);
- MWI: 2.1 µm (range) resp. 0.24 µm/s (range-rate).



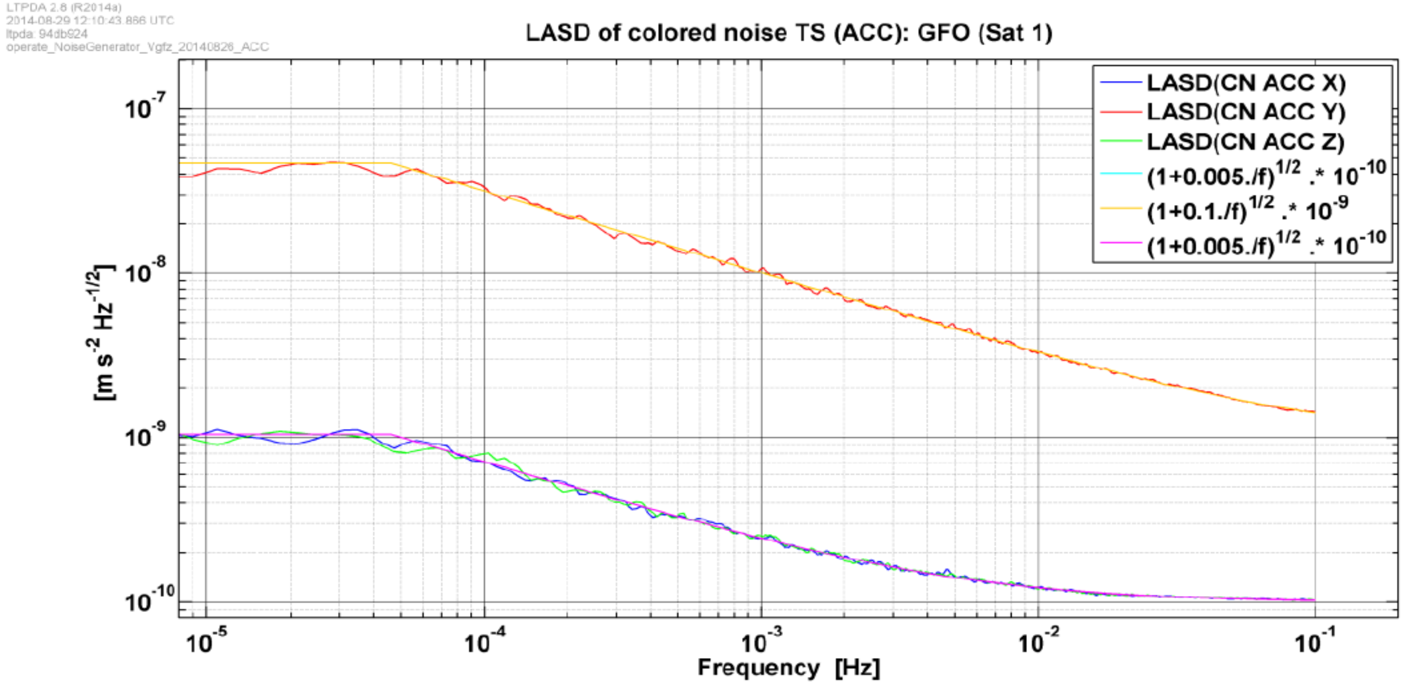
Note: below $5 \cdot 10^{-5}$ Hz a white noise behavior has been fixed in order to avoid long-term trend in noise time series

Note: No tone errors so far simulated

ACC Noise

The procedure to derive accelerometer noise time series using spectral density values for a frequency (f) band of 10^{-4} to 10^{-1} Hz of GRACE-like accelerometer errors:

- $(1 + 0.005/ f)^{1/2} \times 10^{-10}$ $m/s^2/Hz^{1/2}$ for transversal and radial direction
- $(1 + 0.100/ f)^{1/2} \times 10^{-9}$ $m/s^2/Hz^{1/2}$ for normal direction



Note: below 5 ·10^{-5} Hz a white noise behavior has been fixed in order to avoid long-term trend in noise time series

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Orbit Errors

- The high-low SST GPS phase and code observations, used to define a reference frame for LEO orbit integration have been simulated with white noise of 0.3 and 30 cm, respectively.
- The resulting global MWI range-rate residual root mean square (RMS) error (when down-weighting LL-SST) was typically simulated as 1.5 µm/s which is identical to GFZ GRACE RL05 real data analysis (e.g. for June 2014)

Approach (2)

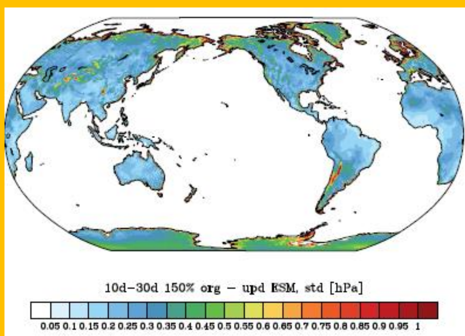
Step 3: Recovery

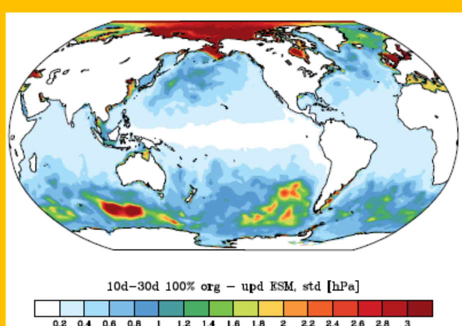
- Exchange „true world“ background models from step 1 by models which describe „best knowledge“ uncertainties

  static gravity field: EIGEN-GL04C -> EGM96 (nmax=100)

  ocean tides: EOT08a -> GOT4.7 (8 main constituents)

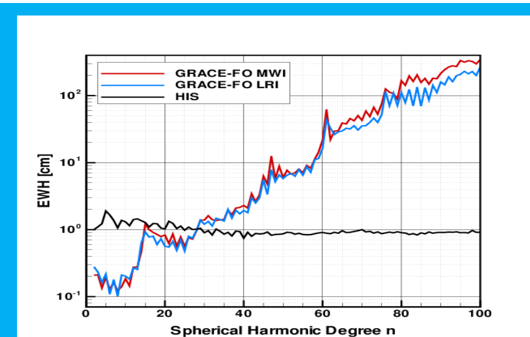
  non-tidal mass variations: ESA AOHIS model -> AO + AO errors
- Perform monthly gravity field determination using noisy observations from step 2
- Adjusted parameters: Initial states, ACC/KBR bias & scale (3h), GPS ambig.

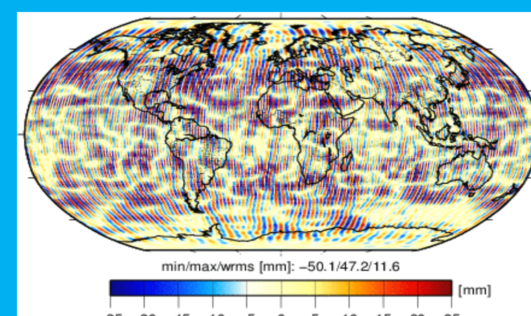




Step 4 (Analysis)

- Compare 60 „recovered“ and „true world“ monthly models in spectral and spatial domain for LRI or MWI case
- Perform regional analysis for typical earth science applications





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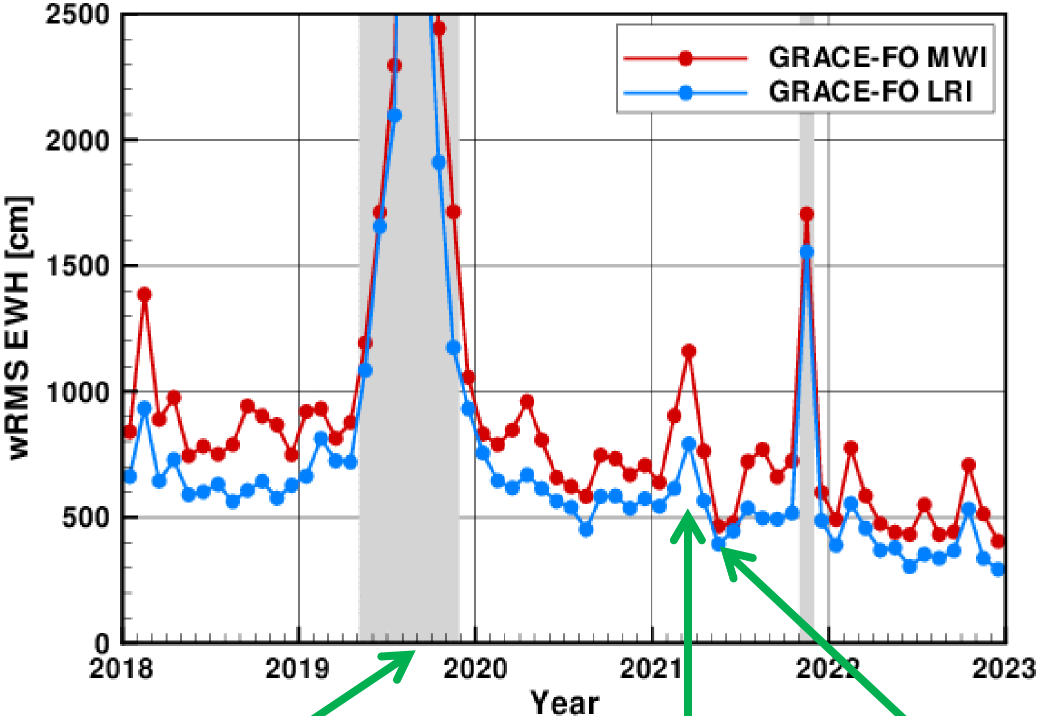
Unfiltered wRMS

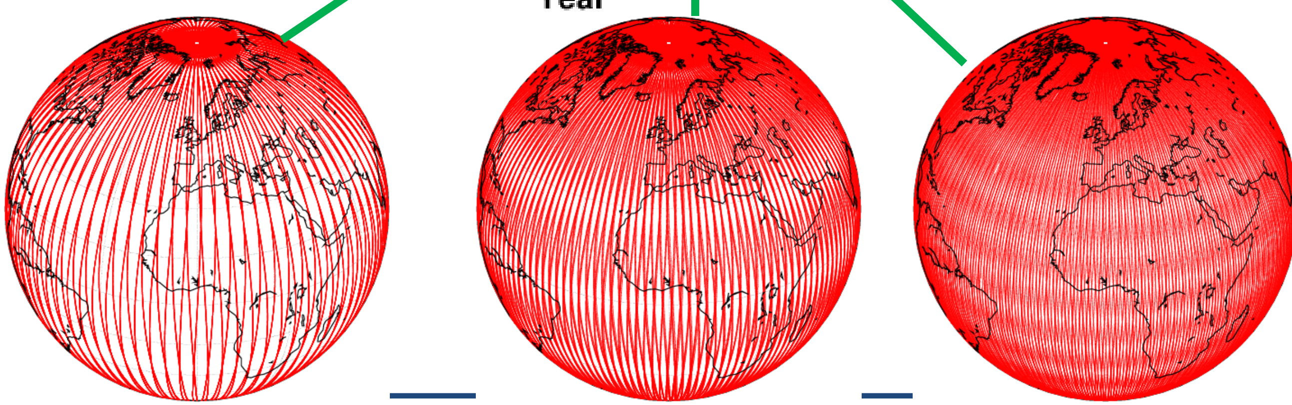


Mean wRMS [EWH] over 5 years (w/o grey periods):

MWI:	737 cm
LRI:	565 cm
Gain in gravity model:	23 %

Gain obtained from a factor 30 improved SST!

Filtering still necessary



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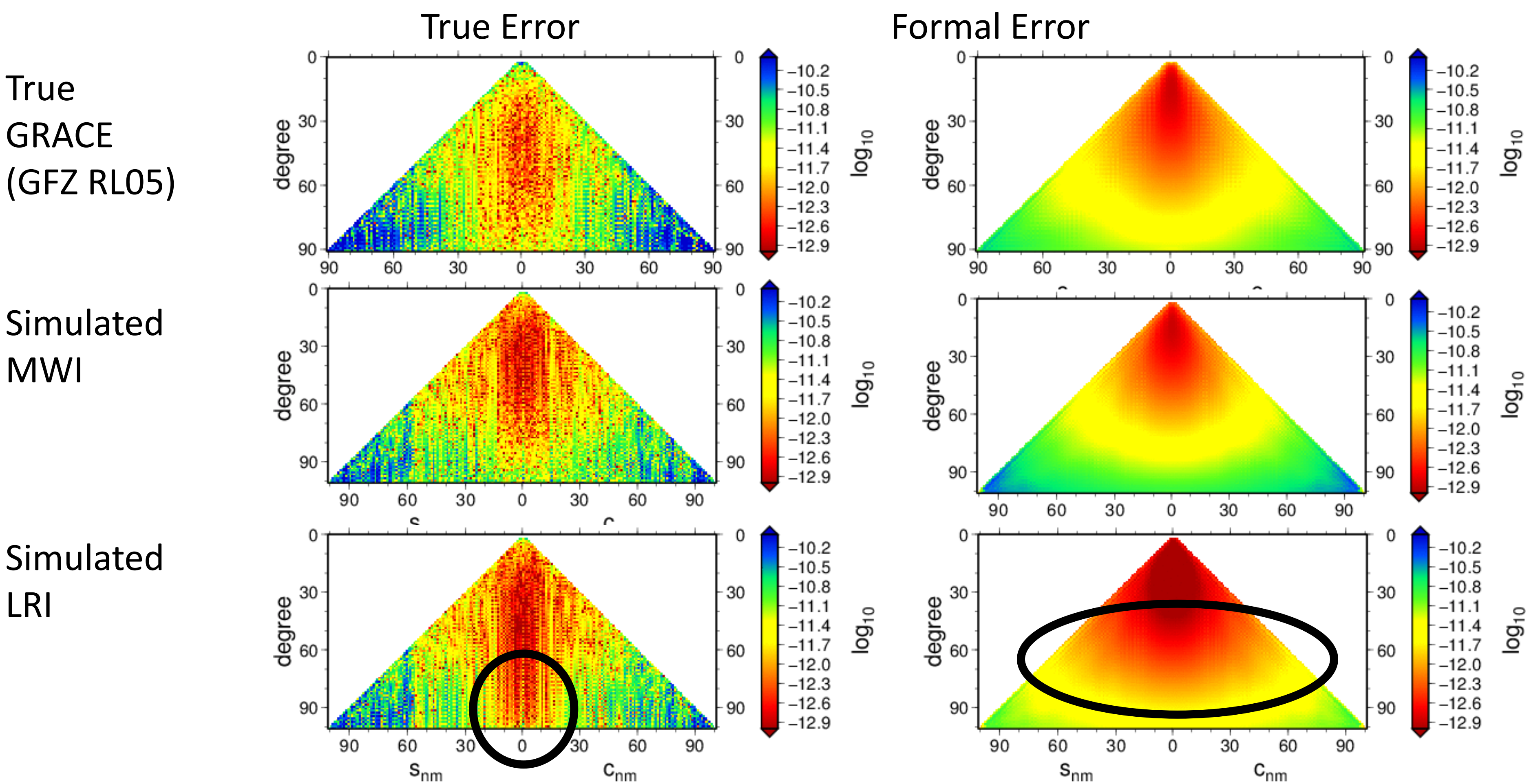
Filtered Results

Filter	MWI mean wRMS [cm]	LRI mean wRMS [cm]	mean wRMS reduction [%]
Unfiltered	736.64	564.56	22.9
Destriping & Gauss 530 km	0.70	0.69	1.2
Destriping & Gauss 340 km	0.94	0.91	3.1
Destriping & Gauss 240 km	3.01	2.64	12.6
Destriping & Gauss 220 km	4.64	3.96	15.1
Destriping & Gauss 160 km	17.59	13.67	23.6
Gauss 530 km	1.13	1.15	-1.5
Gauss 340 km	2.95	2.79	4.7
Gauss 240 km	16.23	13.65	15.1
Gauss 220 km	26.31	21.67	16.8
Gauss 160 km	110.62	87.23	20.4
Anisotropic DDK1 (530 km)	0.70	0.68	1.7
Anisotropic DDK2 (340 km)	1.20	1.19	1.0
Anisotropic DDK3 (240 km)	2.29	2.25	1.7
Anisotropic DDK4 (220 km)	2.73	2.66	2.6
Anisotropic DDK5 (160 km)	4.25	3.97	6.5

True and Formal Errors (May 2021)



- middle vs. top: Simulations realistic, but slightly too optimistic
- middle vs. bottom: Improvements in the near zonals and smaller formal errors by LRI

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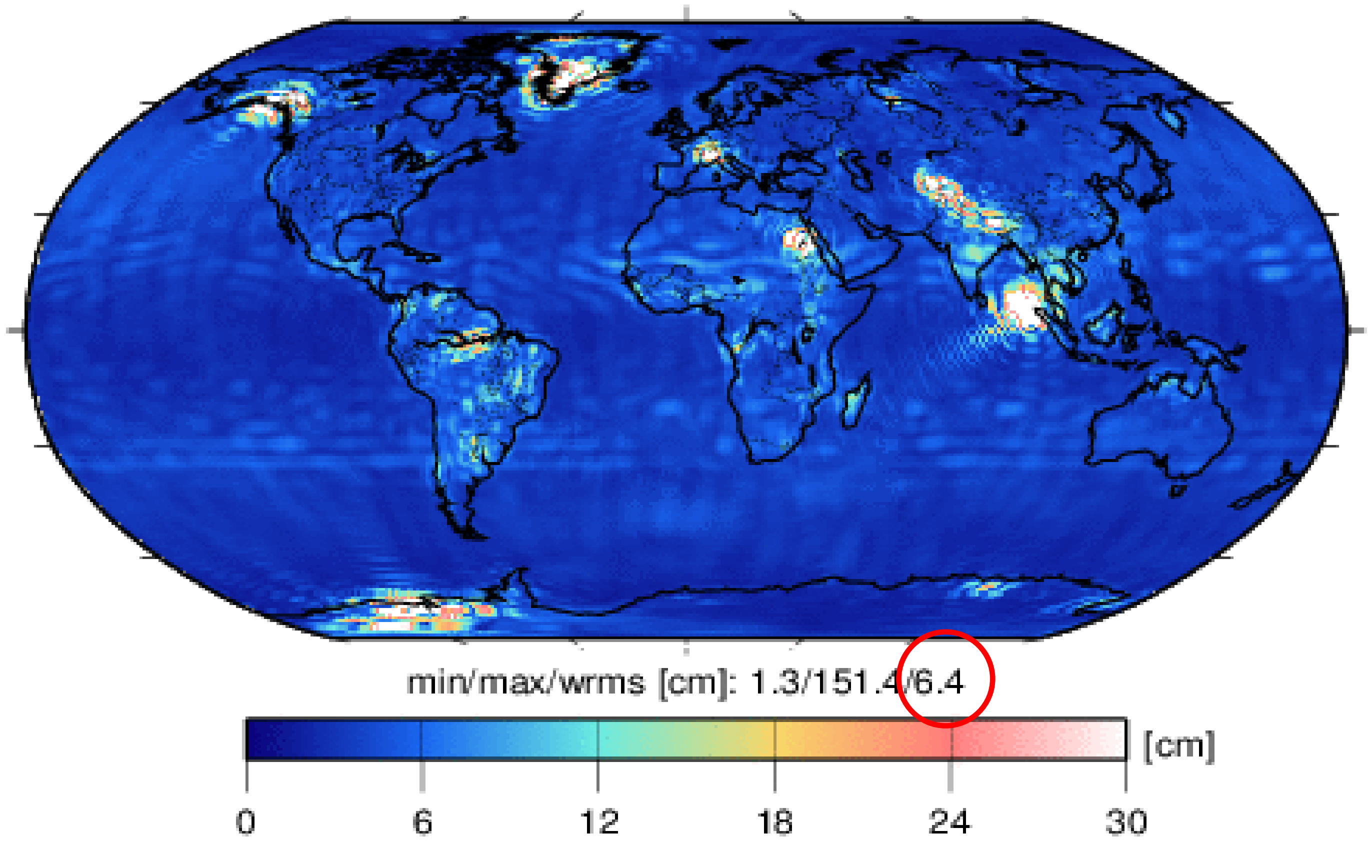
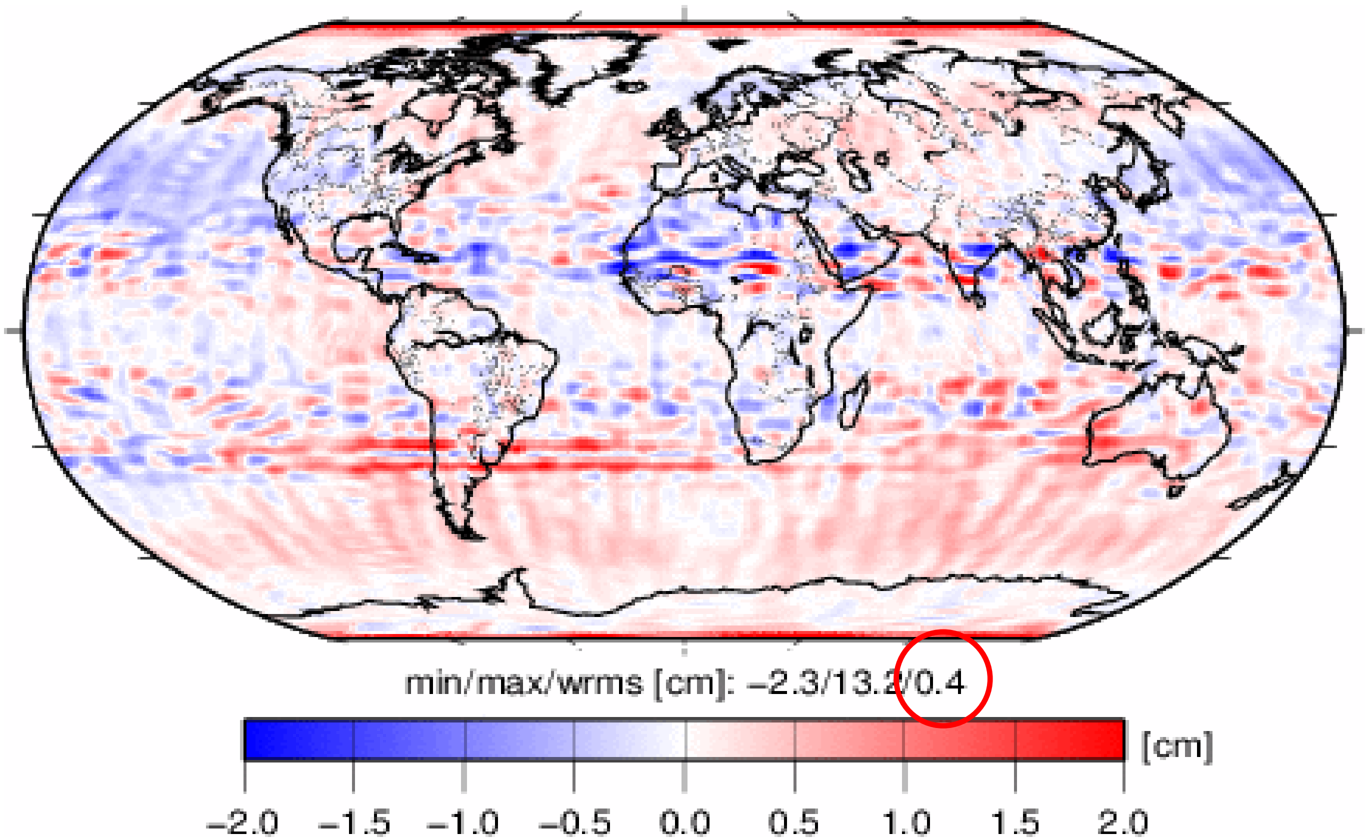
Global RMS Variability

- 5 years RMS variability of the difference between simulated ("true") and DDK4 filtered recovered gravity fields based on LRI data for 1°regular grids in EWH.
- Note: MWI looks very similar



Global RMS Variability

Difference between the RMS variability for MWI and LRI is shown in the right figure (red means LRI is closer to truth, blue means MWI is closer to truth).



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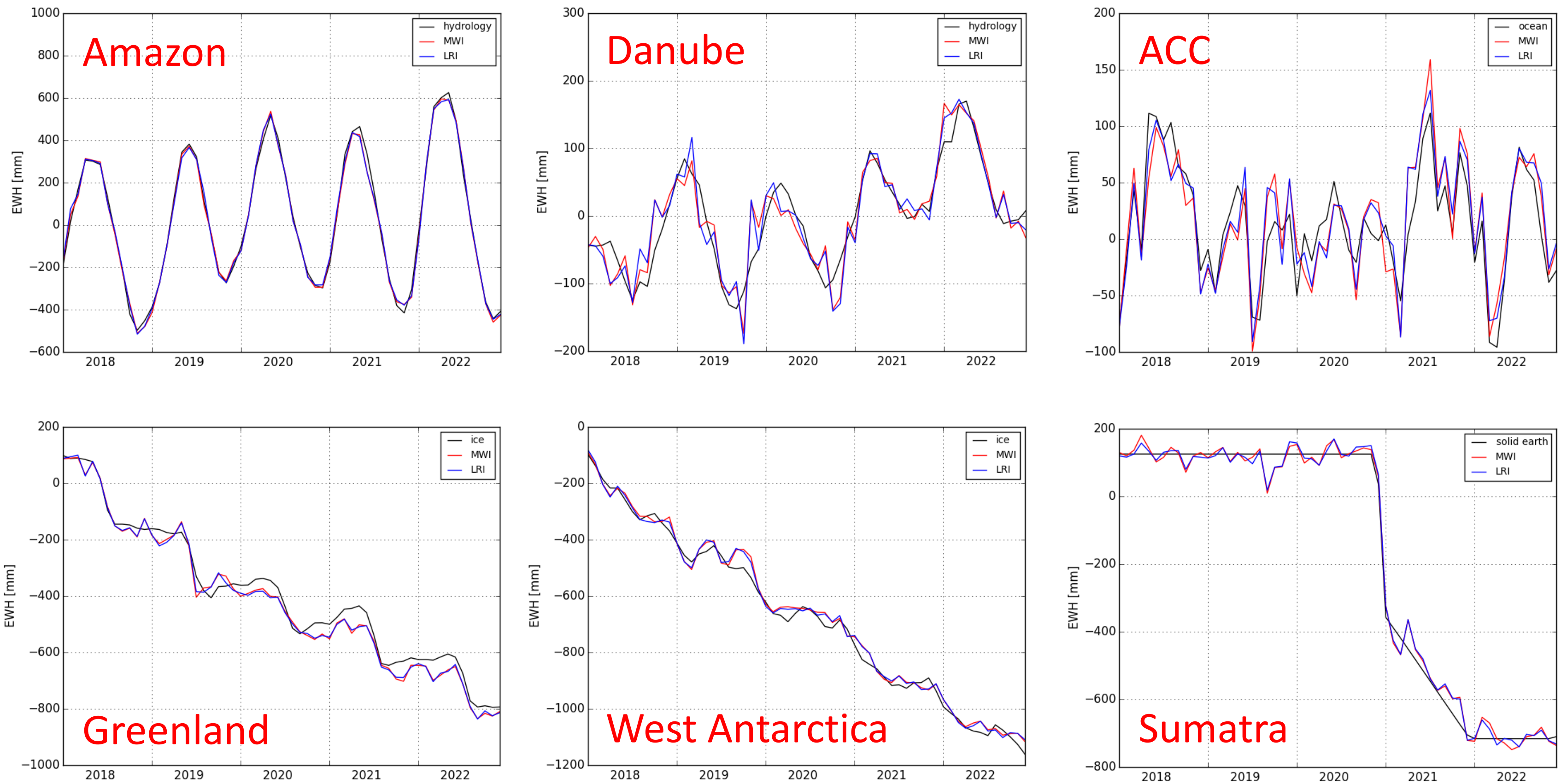
Regional RMS Variability

Time series for DDK4 filtered 2ºx2º grid boxes in EWH [mm] using MWI (red) or LRI (blue) data. The black line depicts the corresponding component H, I, O or S of the AOHIS model.



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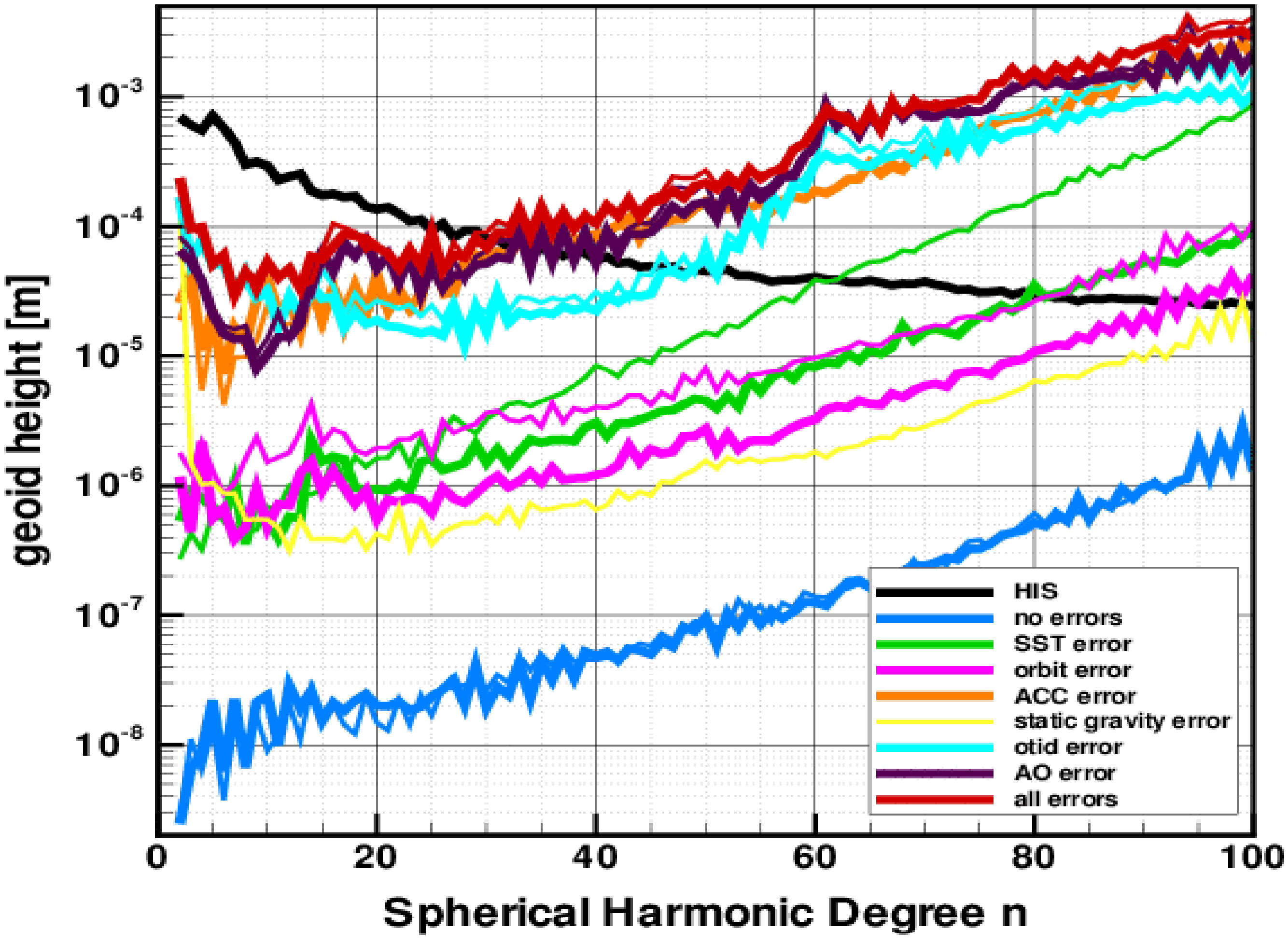
Regional RMS Variability

RMS between recovered and simulated AOHIS signals [mm EWH] for various 2ºx2º grid boxes after DDK4 filtering as well as corresponding LRI gain [%] in terms of RMS reduction. Additionally, the DDK4 filtered "real data errors" [mm] derived from CSR and GFZ GRACE RL05 Level-2 data and the corresponding factor w.r.t. the simulated MWI RMS values are shown.

	MWI RMS [mm]	LRI RMS [mm]	LRI Gain [%]	RL05 CSR-GFZ RMS [mm]	Factor RL05 / MWI
Sumatra	33,58	31,52	6,5	30,57	0,91
Bellingshausen	26,44	22,93	15,3	21,83	0,83
Amazon	23,95	25,49	-6,0	42,88	1,79
Danube	31,78	32,17	-1,2	27,93	0,88
West Antarctica	25,60	25,18	1,7	23,70	0,93
Greenland	29,94	28,50	5,1	21,12	0,71
Sahara	37,13	39,65	-6,3	32,30	0,87

- Average factor (w/o Amazon basin) = 0,86.
- Reason: too optimistic or neglected simulated errors (e.g. MWI phase center variations or not-investigated leakage effects).

Individual Effects May 2021



ACC, AOHIS & OT Errors

MWI Noise

LRI Noise

20000 km 333 km 200 km

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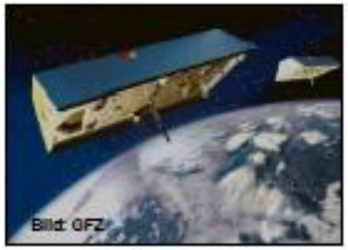
GRACE-FO Full-scale Simulation Results

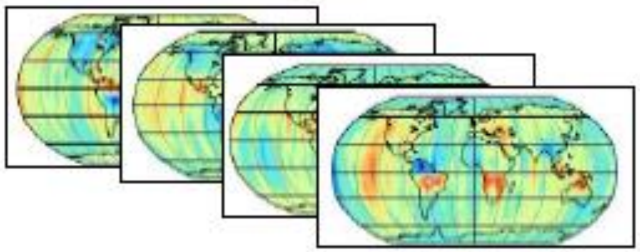
- LRI will improve the MWI based GRACE-FO gravity models **only moderate**
- LRI is a **technology demonstrator** which will be used for Next generation Gravity Missions to improve spatial resolution and accuracy of monthly models (see next)

GRACE/GRACE-FO: From Mission to Science



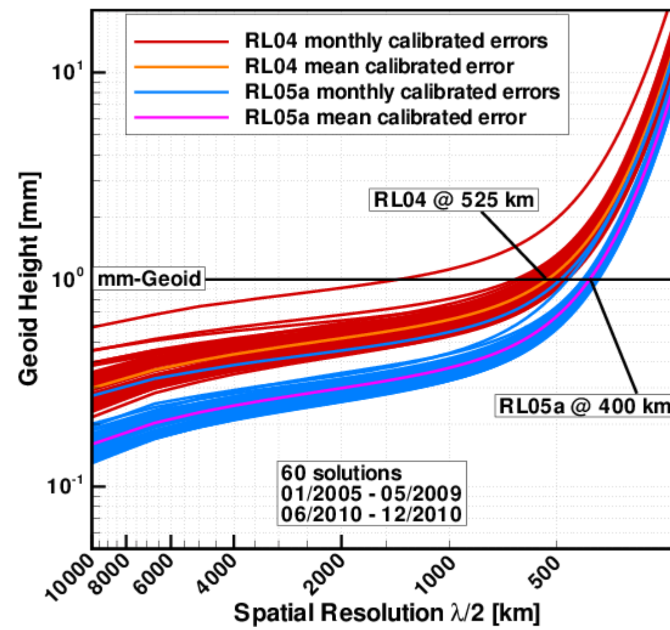
E = Experiment

# satellites:	2
orbit height:	500 km
SST accuracy:	1 µm/s
ACC accuracy:	1e-10 m/s²



temporal res.:	1 month
spatial res.:	300-400 km
accuracy (geoid height):	
1mm @ 400 km	

Hydrology	Ocean	Cryosphere	Solid Earth	Geodesy
Ground water	basin scale mass change	Ice mass balance	upper mantle density	Leveling by GPS
Soil moisture/ snow	sea-level change	Polar ice and glaciers	Seismic hazards	Unified height system
	bottom barotropic currents	- Large ice-stream dynamics -Accumulation variability	Ocean Lithosphere Asthenosphere	Inertial navigation system
			Volcanoes	Satellite orbits
			Plate tectonics	
			Core motions	
			...	



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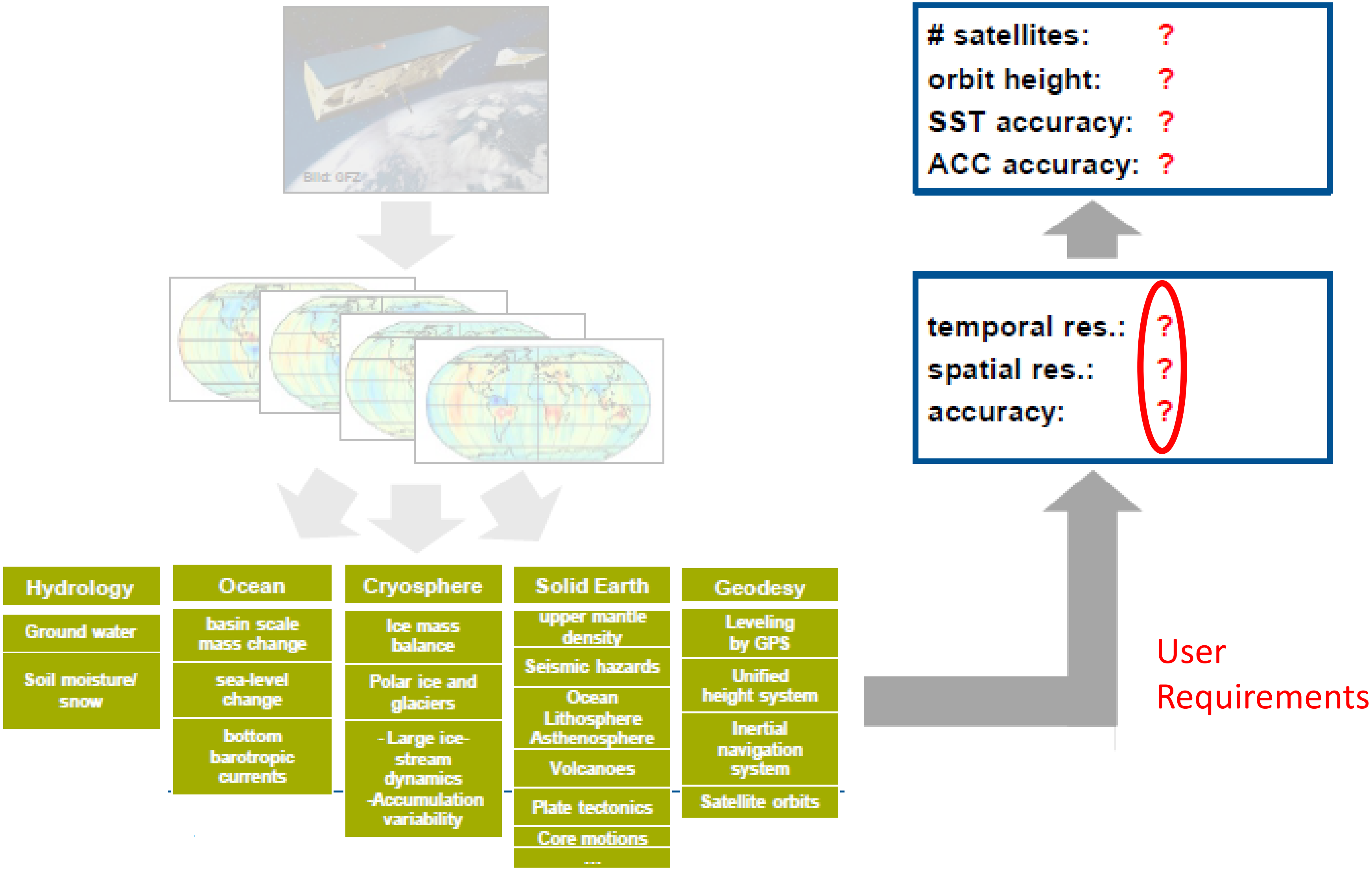
Next Generation Gravity Mission: From Science to Mission



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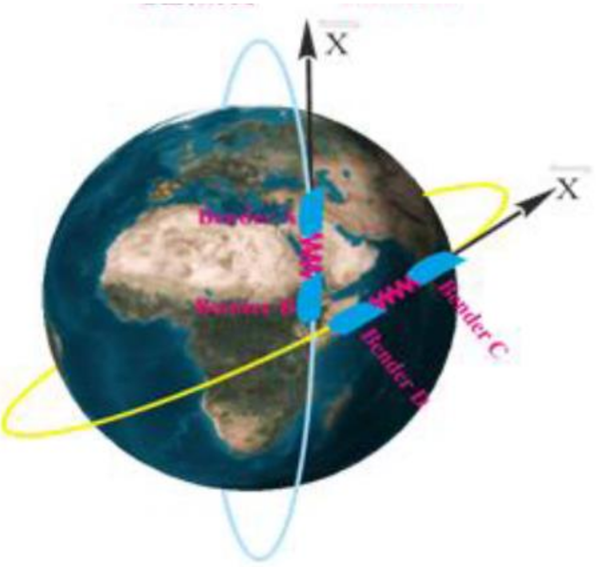
Example: NGGM-D

Study funded by DLR, final presentation July 2014. Lead TU Munich with partners from science (GFZ, AEI, UBonn et al.) and industry (Airbus, STI)



Initial baseline scenario

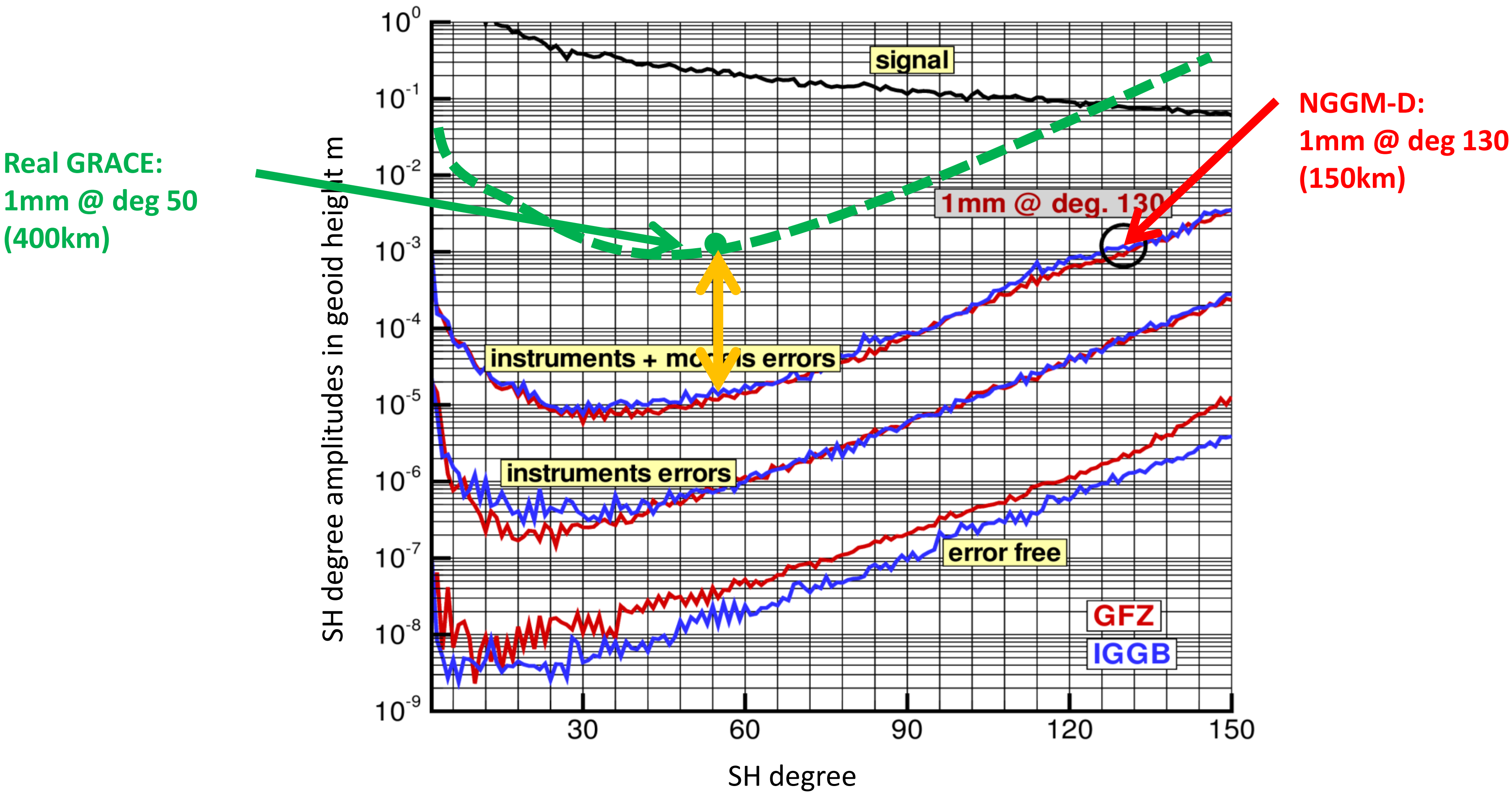
- Double pair constellation ("Bender")
- Near polar orbit & inclined orbit @ h=420km (2nd pair @ 70°)
- Satellite distance: 100 km
- Maximum spherical harmonic degree: 150 (133 km)
- Monthly period
- **SST noise**: 10^{-8} m (MBW) (**25 nm** vs 2000 nm (80 times better than GRACE MWI))
- ACC noise: 10^{-11} m/s^2 (MBW) (10 times better than GRACE)

Requirements for monthly geoid error (w/o postprocessing)

- 1mm geoid (1 cm EWH) @ 200km (minimum) (10 * better than GRACE)
- 1mm geoid (1 cm EWH) @ 150km (optimum)

NGGM-D Full-scale Simulations (similar error models)

- Consistent independent GFZ and IGG Bonn solutions



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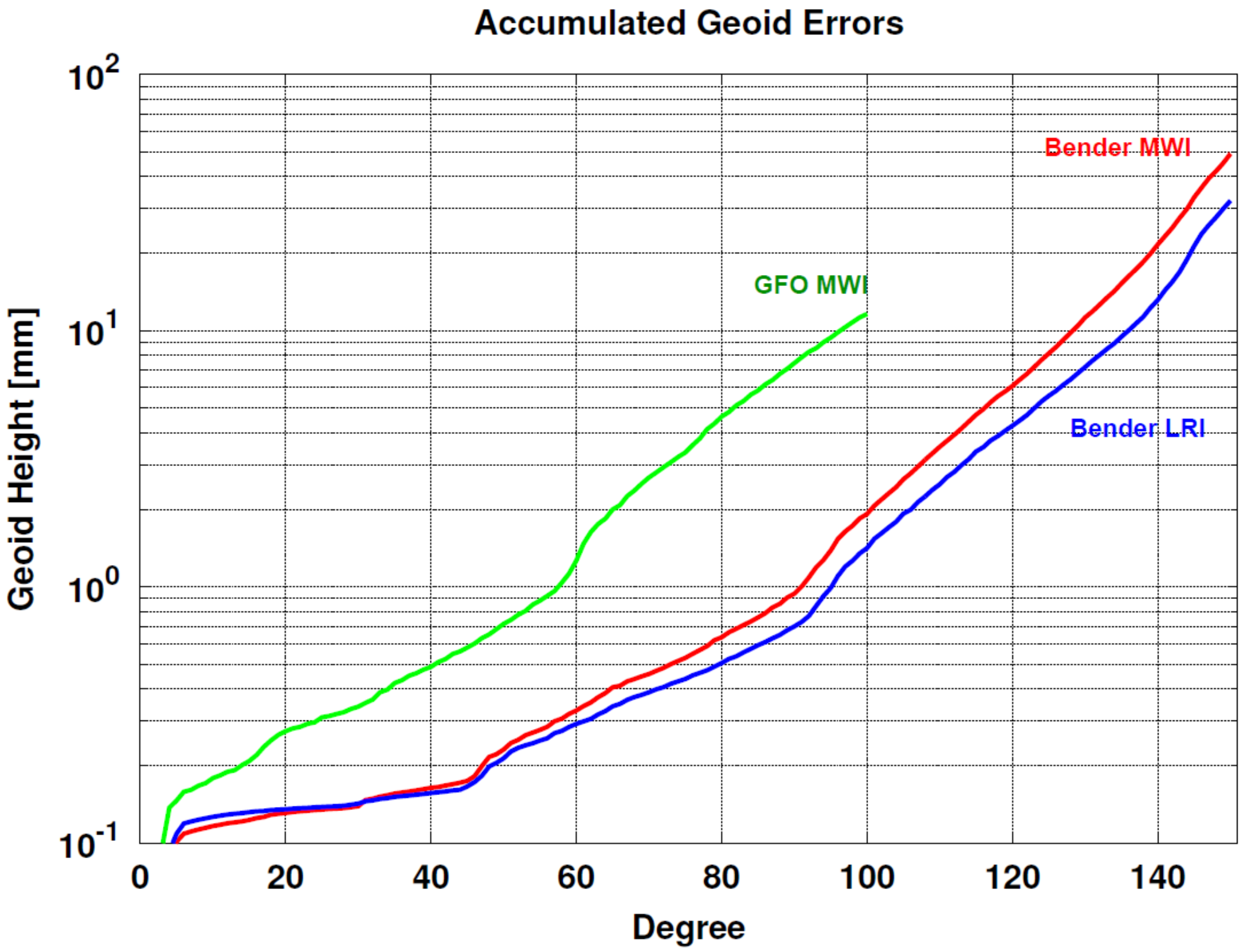
Summary

- A realistic (proven by various comparisons with real GRACE data) full-scale simulation has been performed to show possible relative gain by LRI
- The answer to "What can be expected from the GRACE-FO Laser Ranging Interferometer for Earth Science applications?" is that the LRI will only slightly improve results and the main objective is to continue the GRACE time series. Paper has been submitted to Survey in Geophysics.
- LRI is a technology demonstrator for Next Generation Gravity Missions
- NGGM will be driven „From Science to Mission“ to answer societal questions related with water management, early warning and risk management, climate change or implementation of services and will require 10 to 100 times better gravity models
- NGGM-D mission simulations using LRI data showed that this is doable
- Outlook:
  - GRACE-FO: Include attitude errors (main impact on MWI) and add tone errors
  - NGGM-D: Perform Bender-like simulations also with MWI (instead of LRI)

Backup

NGGM-D Simulation Preliminary Results (with updated AOHIS)



Factor 7 in Precision

GRACE-FO (MWI)
@ 200km: 10,5 mm

NGGM (MWI)
@ 200km: 2,0 mm

NGGM (LRI)
@ 200km: 1,5 mm

GRACE-FO (MWI)
1mm @ 350km

NGGM-D (MWI)
1mm @ 220km

NGGM-D (LRI)
1mm @ 210km

40% Gain in Spatial Resolution

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