NEROGRAV

New Refined Observations of Climate Change from Spaceborne Gravity Missions

International Spring School
Neustadt an der Weinstraße, Germany, March 10-14, 2025

Introduction

Frank Flechtner (TU Berlin & GFZ Helmholtz Centre for Geosciences)

TU berlin | Freie Universität Berlin | Technische Universität München | GFZ Helmholtz Centre for Geosciences | Universität Bonn | hcu HafenCity Universität Hamburg

Content

- General Information on the NEROGRAV Spring School
- The Research Group NEROGRAV
- Status GRACE-FO and future SST Missions (GRACE-C & NGGM/MAGIC)

Participants and Rooms

- Got 63 ECR applications till deadline
- After evaluation of CVs and motivation letters we selected 37 ECRs
- 18 female and 19 male (most from Europe, but also from US, China, Argentina …)
  - Please sign participation list

Spring School NEROGRAV, 10.-14.3.2025, Neustadt a.d. Weinstraße, Participation List

Name	First Name	Institute	Country	From – To	Signature
Flechtner	Frank	TU Berlin	Germany	10.-14.3.2025	

- Additionally, 22 participants of RU incl. 6 External Speakers
- Rooms are available from 13:00 on the day of arrival
  - Booked 59 Single and Double Rooms in Main Building and Villa (has bathrooms on floor)
  - All of you should have already been allocated a room
- You need to vacate them by 9:00 on the day of departure.
  - Luggage can stored in the meeting room (or in a separate room at the front desk)

Program

Time	Monday	Tuesday	Wednesday	Thursday	Friday
08:00-09:00		Breakfast	Breakfast	Breakfast	Breakfast
09:00-09:45		Background Model Ocean Tides (Mike Hart-Davis)	Stochastic Modeling of GRACE/GRACE-FO Data (Michael Murböck)	Practical 3: GRACE-FO Data Analysis: Global Analysis of EWH Grid Data	The future: Satellite Missions with Quantum Sensors (M. Weigelt)
09:45-10:30		Background Model AOD1B (Linus Shihora)	From Level-2 Spherical Harmonics to Level-3 Grid Data (Eva Börgens)		Feedback NEROGRAV School and Discussion (all)
10:30-11:00 (fix)		Coffee Break		Coffee Break	Coffee Break
11:00-12:15		Practical 1: GRACE-FO Data Analysis: Spherical Harmonic Analysis	Practical 2: GRACE-FO Data Analysis: Filtering/De-striping	Practical 4: GRACE-FO Data Analysis: Regional Analyses	
12:15-13:15 (fix)		Lunch	Lunch	Lunch	
13:15-14:00		13:30 Bus to Speyer 14:15 Museum of Technology Speyer 17:00 Bus to Neustadt	Mass Change of the Cryosphere (Ingo Sasgen)	Practicals: Feedback and Q/A	
14:00-14:45	The Research Group NEROGRAV and Status GRACE-FO and future SST Missions (Frank Flechtner)			Gravimetry Data for Monitoring the Global Water Cycle and Comparisons with Climate Models (Annette Eicker)	
14:45-15:30	Special Aspects of GRACE-FO Level-1 Instrument Data: (Vitali Müller)		Surface Loading in View of the Earth's deformability (Volker Klemann)		
15:30-16:00 (fix)	Coffee Break			Coffee Break	
16:00-17:30	From Level-1B Instrument Data to Level-2 Spherical Harmonics (Thomas Gruber)		Mass Change of the Oceans (Michael Schindelegger)	GRACE/GRACE-FO Data for Model Assimilation and Service Applications (Anne Springer)	
18:00-19:00 (fix)	Dinner	Dinner	Dinner	Dinner	
19:30-21:00	Ice Breaker		Wine Taste	SLR for Gravity Field Determination (45´, Bryant Loomis)	

Fixed times

Group Foto

online

Meeting Rooms & Spring School Material

- Meeting Room 1 (whole week)
- For Practicals we divide into two groups (We have additionally Meeting Room 8)
- Material: There are 2 folders available at https://www.asg.ed.tum.de/iapg/nerograv/spring-school/: Practicals and Lectures
  - Lectures shall be made available after spring school (need to have ok from all speakers)
  - Practicals will be published on the respective day; solutions thereafter

Today: Icebreaker 19:30-21:00 in "Pfalzkeller"

- Drinks of the icebreaker are not included, but can be taken from the bar on a self-service basis and must be paid in cash (Euros). There is a change box there and this is on a trust basis.

- Note, that there are also drinks vending machines in the building opposite the dining room and also a cafeteria with a self-service machine. Small change (Euros) is required for this.

Tomorrow 13:30-17:30 “Visit of Technik Museum Speyer”

- 12:15-13:15 Lunch
- 13:30: 2 Busses for transfer Neustadt – Speyer (ca 31 km / 30 min.)
- We get a Daily Pass incl. IMAX Cinema
- 14:30-16:00: 3 guided tours (2 English)
- 16:00-17:00: IMAX or own choice

Tuesday, 11.03.2025

10:00	Apollo 11
11:30	The Magic of Flight
13:00	Wunderwelt Südpazifik
14:30	Delfine
16:00	Wunderwelt Südpazifik
17:30	The Magic of Flight

Wunderwelt Südpazifik

45 Minuten

ohne Altersbeschränkung

- 17:00: Transfer back to Neustadt
- 18:00: Dinner

Technik Museum Sinsheim Speyer

Wednesday 19:30-21:00 “Wine Taste” in Pfalzkeller

- Winery Sommer will come to us
- 8 Wines + Chocolate & Cheese
- Non-alcoholic drinks also available (for those who have requested, see email Feb. 26)

Source: https://gokonfetti.com

Part 2: The Research Group NEROGRAV

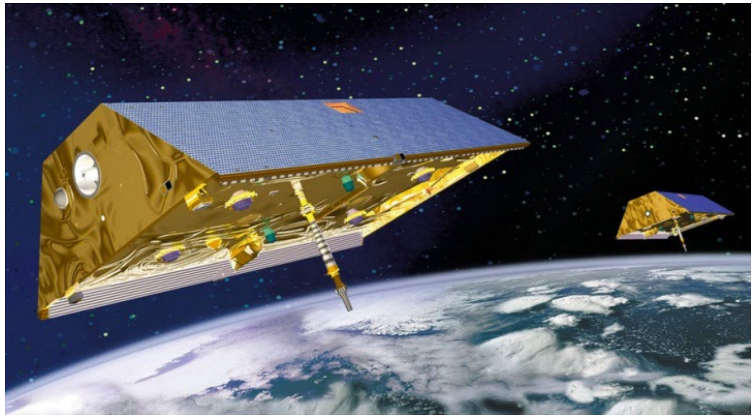
Why do we have this RG in Germany?

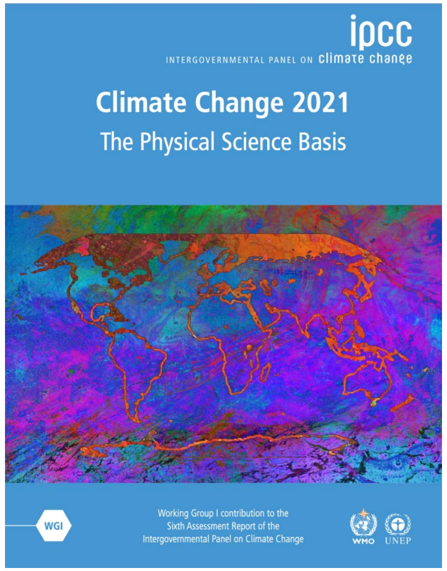
What are the main objectives?

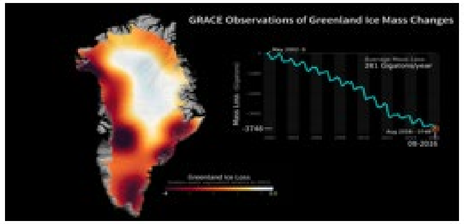
Background

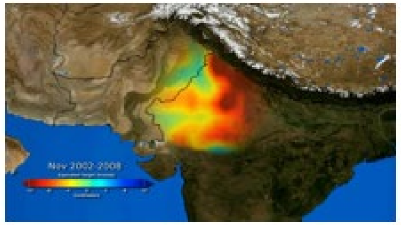
- Satellite gravimetry as demonstrated with the US-German GRACE & GRACE-FO missions is the only satellite remote sensing technology capable of directly quantifying mass redistribution in the Earth System.

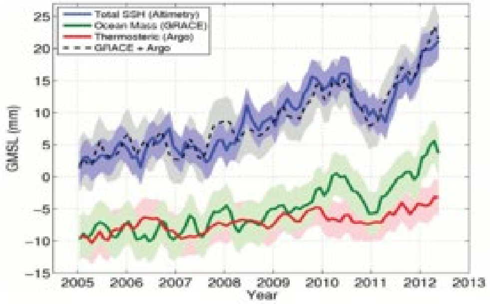
- GRACE & GRACE-FO data
  - revealed groundbreaking insights into a wide range of different geodynamic processes in hydrology, glaciology, oceanography or solid Earth sciences and
  - is an indispensable data set of IPCC reports
    - Terrestrial Water storage is an official GCOS Essential Climate Variable (ECV) since 2022
    - GRACE is the second most instrument after MODIS in the AR6

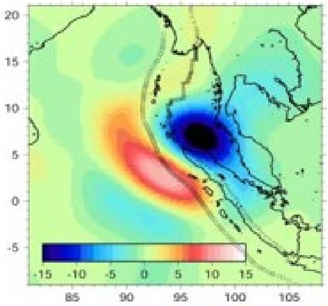


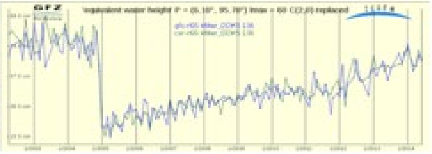




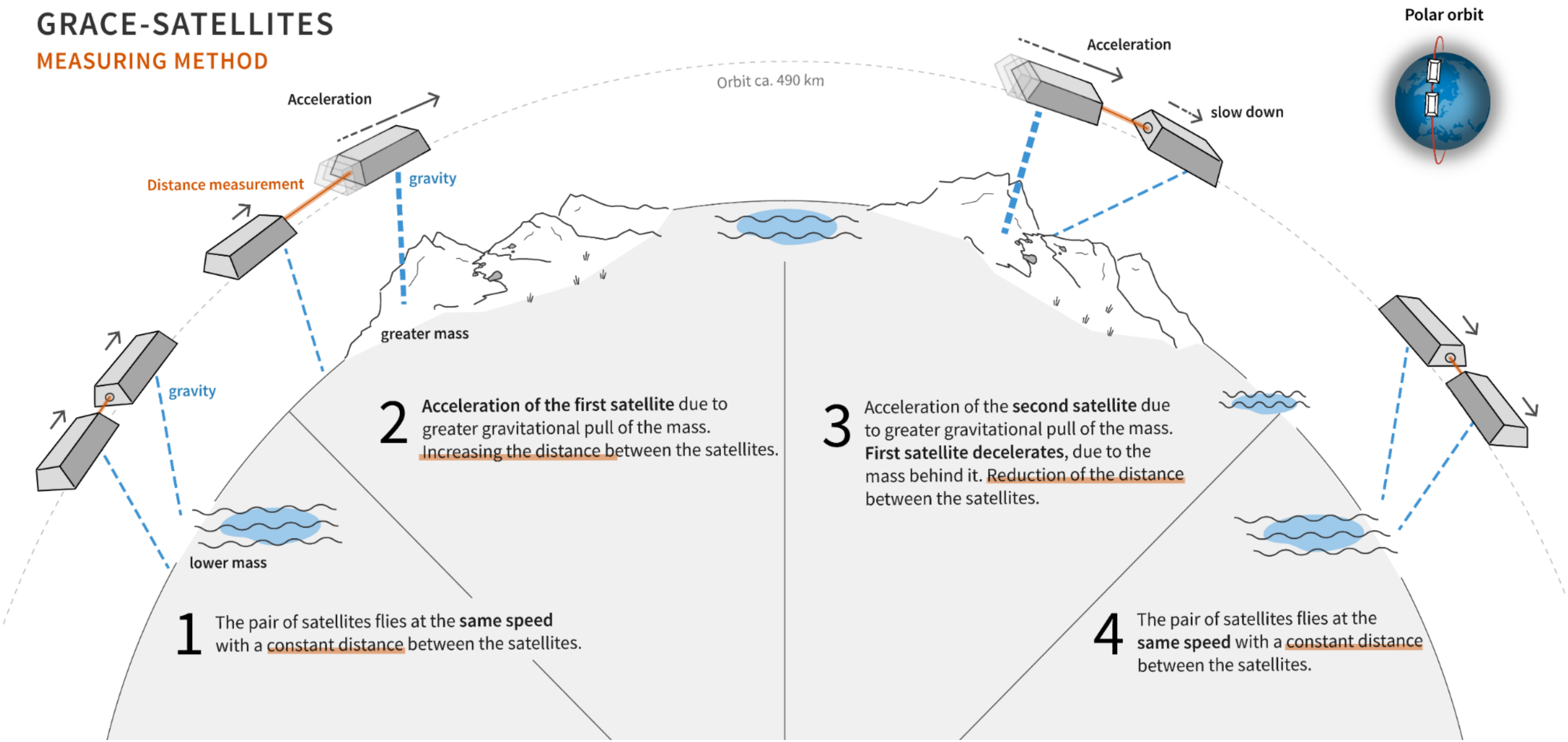




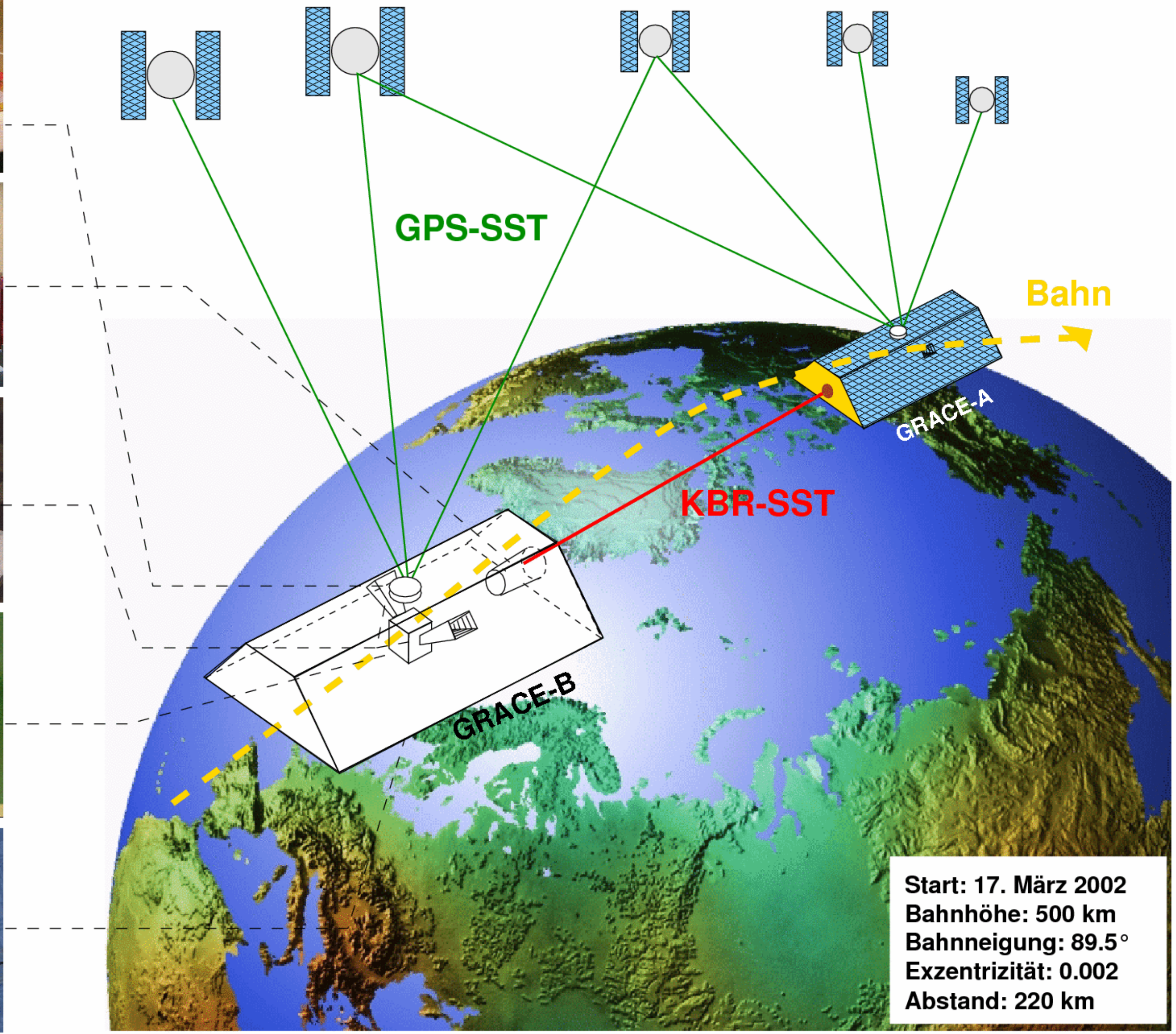




GRACE Measurement Principle

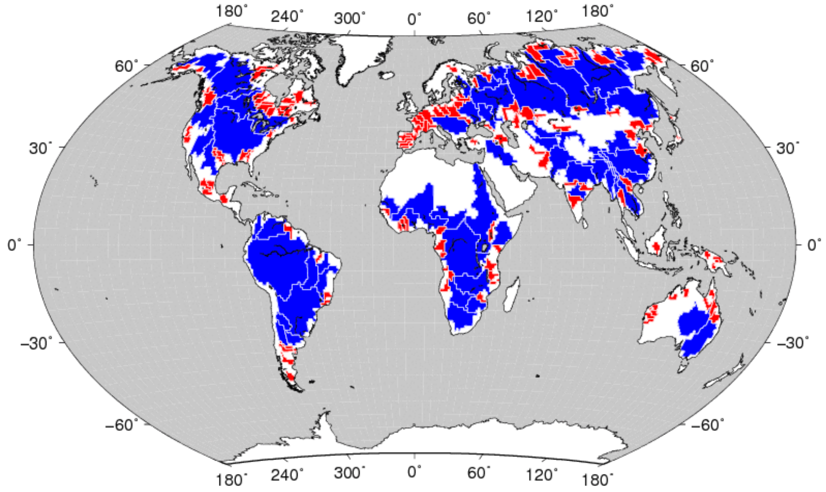


GRACE Instruments



Questions in Fall 2018: Improving Mass Transport from Space: Why? Why now?

- In 2014, a multi-disciplinary expert panel has consolidated under the auspices of the IUGG the science and user needs for future satellite gravimetry missions:
  - higher spatial resolution in order to allow for more regional applications,
  - better accuracy and
  - long and consistent time-series



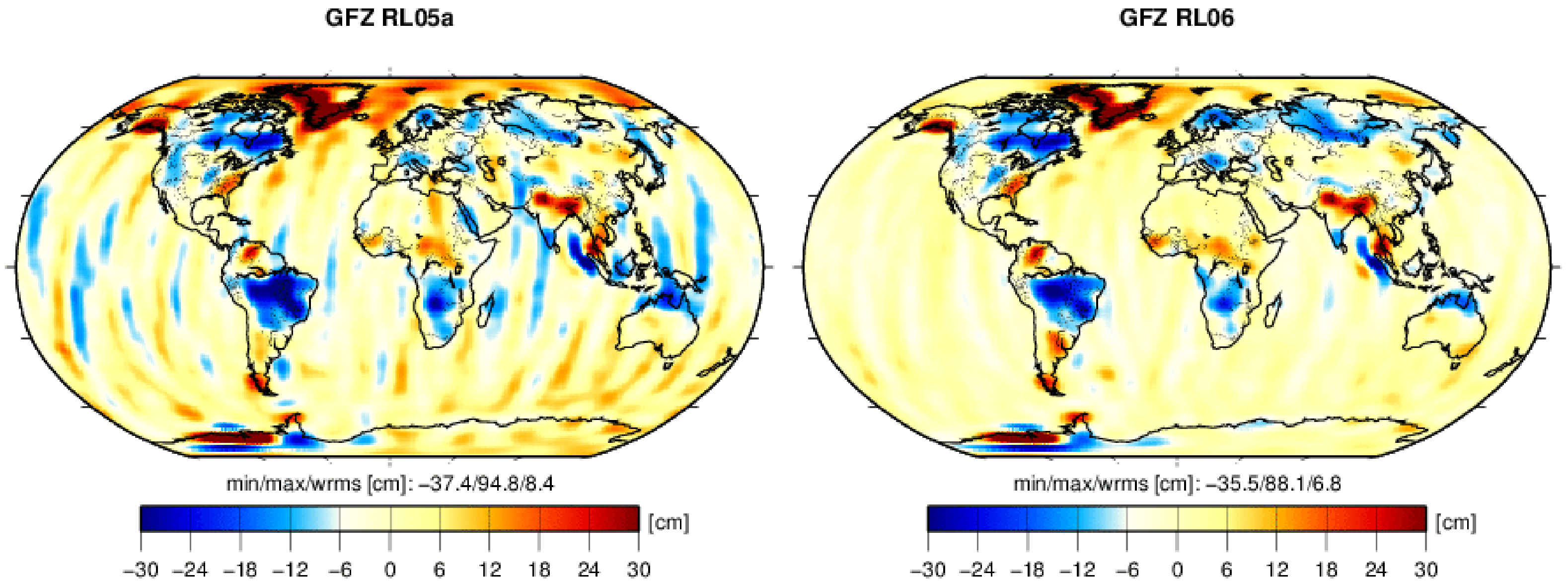
- On May 22, 2018, GRACE-FO was successfully launched carrying also a Laser Ranging Interferometer as a technology demonstrator for NGGMs.

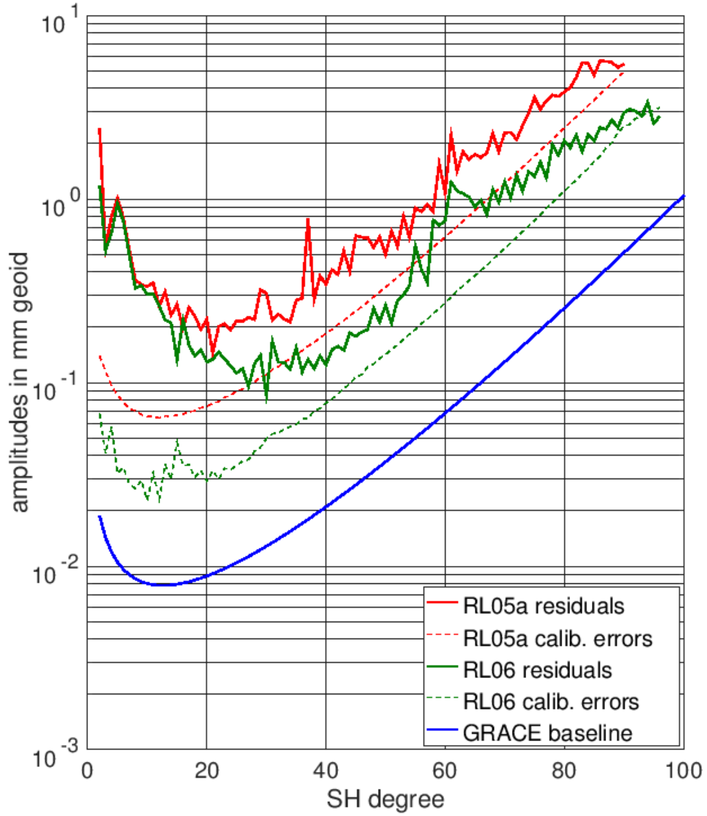
- NASA has selected early 2018 a Mass Change Mission (GRACE-2) within their Decadal Survey Program as one of the top five designated Observing System Priorities for NASA in the next decade.

State of the Art Fall 2018: GRACE RL06 Reprocessing

- The Science Data System had (ca. 2015/2016) reprocessed the complete GRACE time series based on reprocessed instrument data, updated background models, updated parametrizations and standards. RL06 is the baseline for GRACE-FO processing.

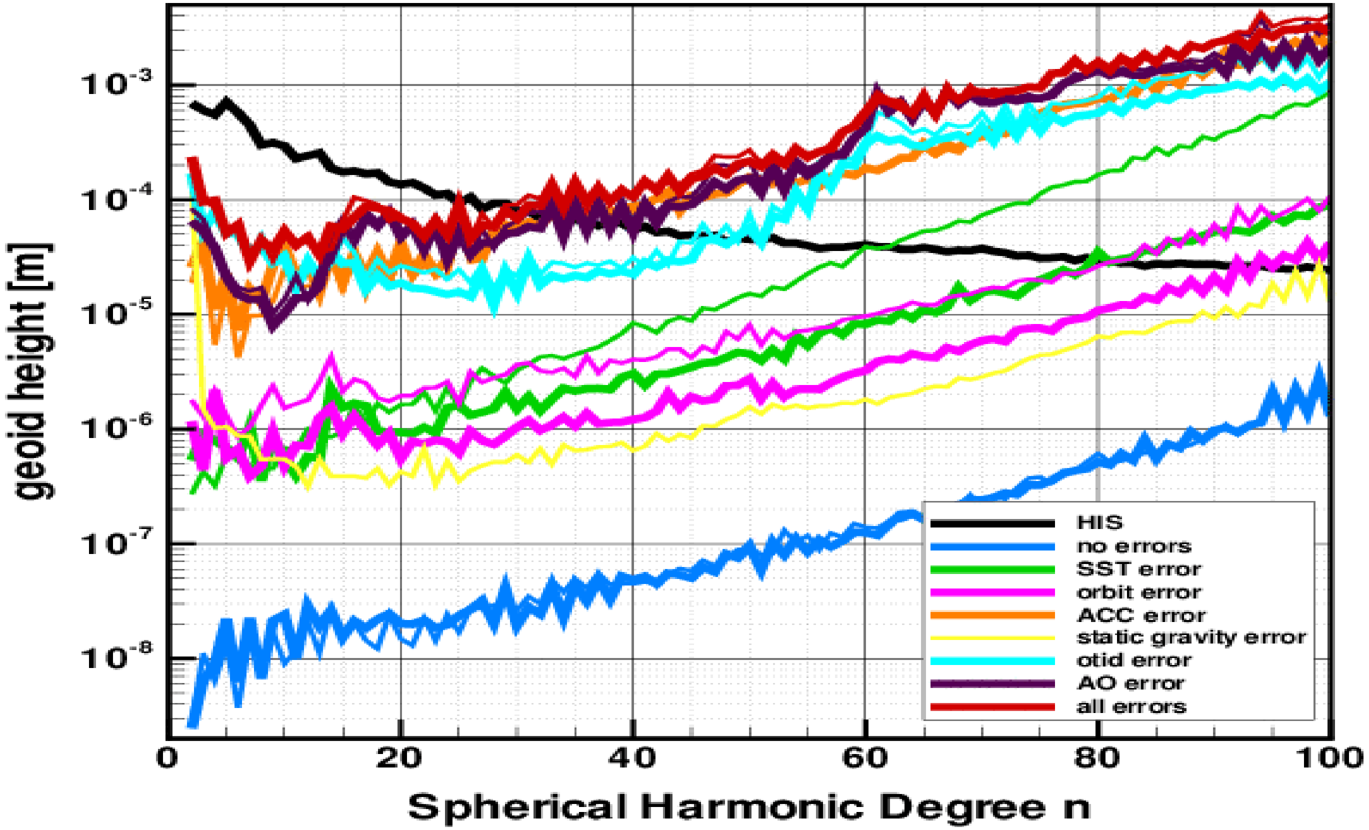
- RL06 is another improvement wrt RL05 (example August 2003), but has still many disadvantages, e.g.
  - a-posterior Level-2 filtering necessary
  - unrealistic spatial signals
  - a-posterior error calibration necessary
  - pre-launch baseline not reached





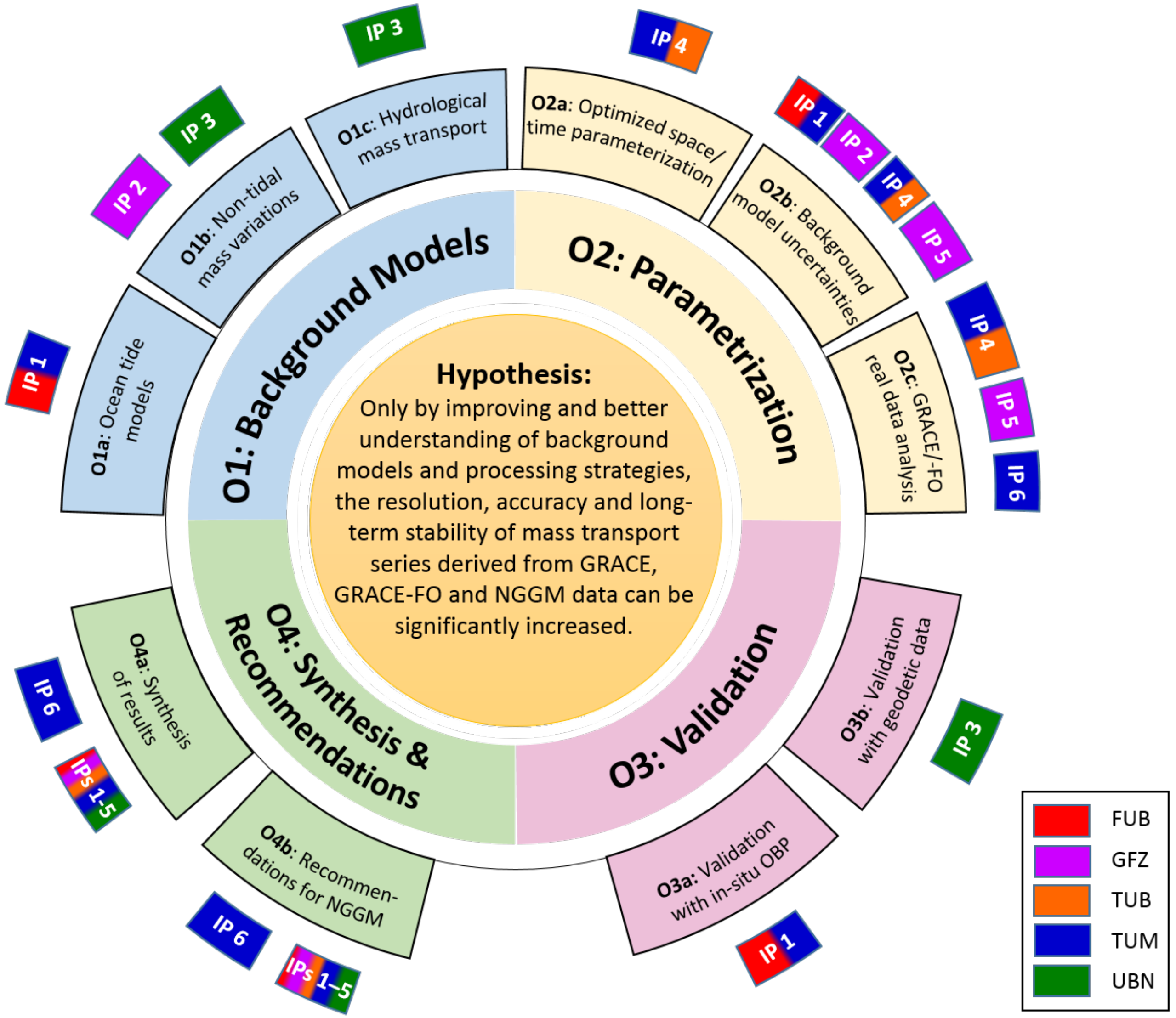
Main Reasons for Reduced Quality of Mass Transport Series

- Errors in the background models to correct **short-term tidal** and **non-tidal mass** variations
- Errors to correct **non-gravitational forces**
- Insufficient stochastic modelling of instrument data and background models



Flechtner et al. (2016), Surveys in Geophysics

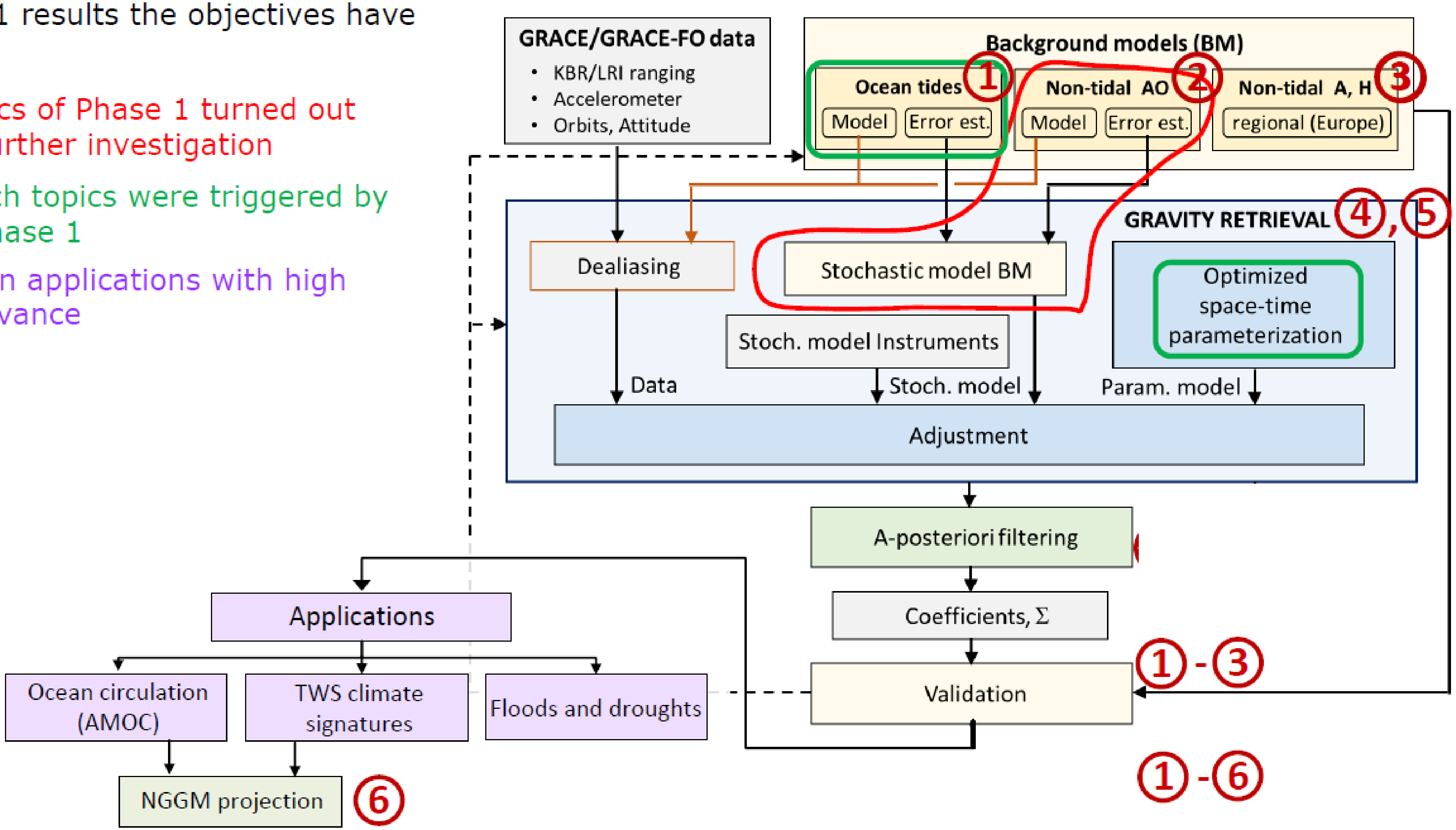
Central Hypothesis and Objectives of RU NEROGRAV Phase 1 (2019-2022)



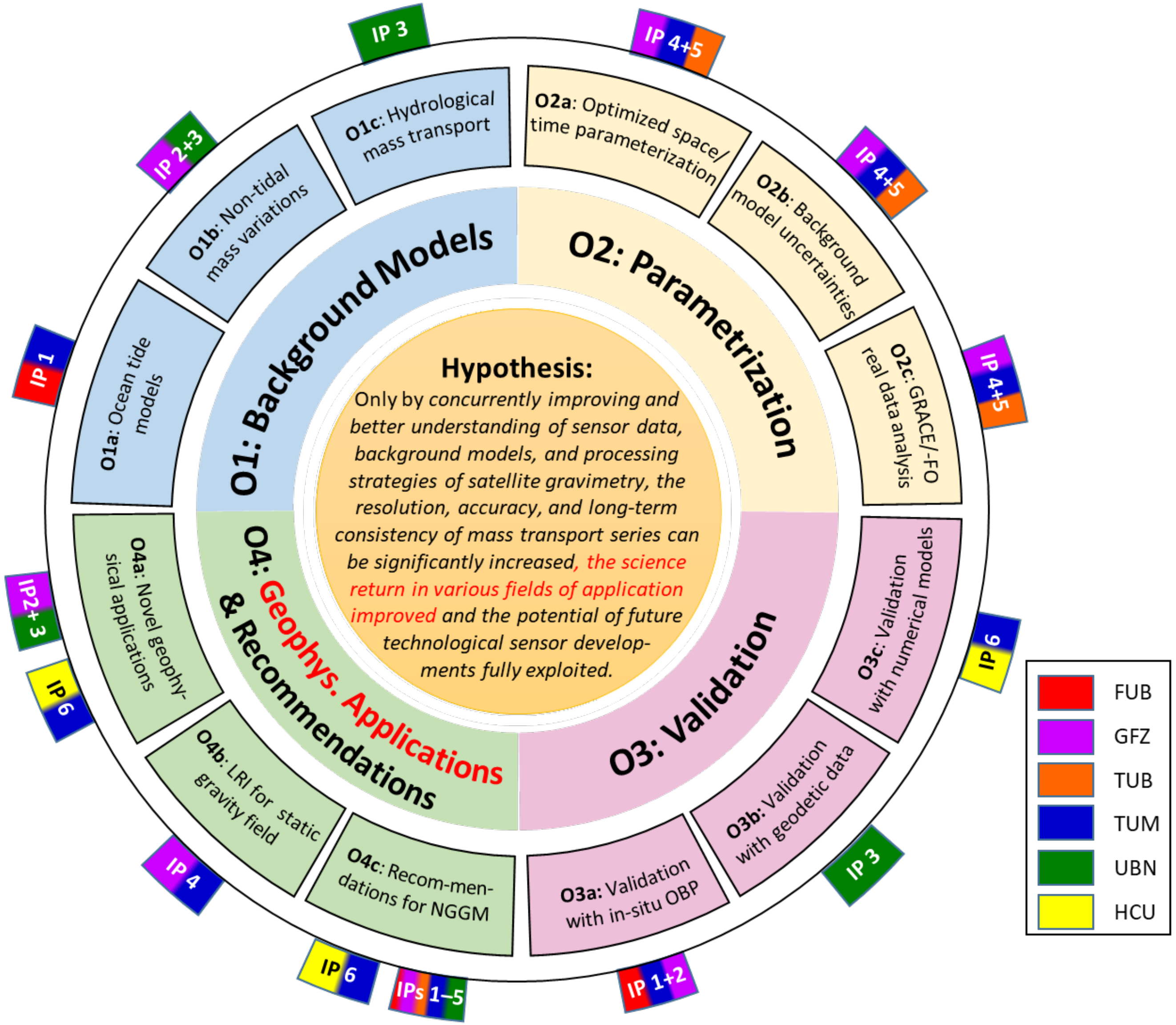
Central Hypothesis and Objectives of RU NEROGRAV Phase 2 (2023-2025)

Based on Phase 1 results the objectives have been adapted:

- Several topics of Phase 1 turned out to require further investigation
- New research topics were triggered by results of Phase 1
- New focus on applications with high societal relevance



Central Hypothesis and Objectives of RU NEROGRAV Phase 2 (2023-2025)



Individual Projects Covering the Objectives of Phase 1 and/or 2

IP 1: Improved Tidal Dynamics and Uncertainty Estimation for Satellite Gravimetry (TIDUS-1 & -2; FU Berlin, DGFI - TU Munich)

IP 2: Next Generation Non-tidal Atmospheric and Oceanic De-aliasing Models (NAODEMO; GFZ)

IP 3: High-Resolution Atmospheric-hydrological Background Modelling for GRACE/G[illegible]CE-FO – regional refinement and validation (HIRABAM-1 & -2; University Bonn)

IP 4: Optimized Space-Time Parameterization for GRACE and GRACE-[illegible]nalysis (OSTPAGA; TU Munich, TU Berlin)

IP 5: Improved Stochastic Modeling in GRACE/GRACE-[illegible]ta processing (ISTORE; PI: GFZ)

IP 6: Post-process Techniques, Impact on NG[illegible]commendations (POTINAR; TU Munich)

IP 2 (Phase-2): Atlantic Meridional [illegible]ng Circulation: Inferences from Satellite Gravimetry and Numerical Ocean Models (AM[illegible]FZ, University Bonn)

IP 4 (Phase-2): Nea[illegible]e, Long-term, LRI and SLR combination aspects (NELOS; GFZ, TU Munich)

IP 5 (Phase-2): Opt[illegible]ized Space-Time Parameterization for GRACE and GRACE-FO data Analysis (OSTPAGA-2; TU Munich, TU Berlin)

IP 6 (Phase-2): Climate Signals from GRACE/GRACE-FO and Next Generation Gravity Missions (CLISGY; HCU Hamburg, TU Munich)

Many of these topics will be covered this week!

Example: Results from NEROGRAV planned to be used for GFZ RL07

- Stochastic modeling of GRACE(-FO) key instruments (**OSTPAG**, **ISTORE-2**)
  - ✓ Noise models for ACC & KBR/LRI ☐ Murböck et al. (2023), https://doi.org/10.5880/nerograv.2023.001

- Stochastic modeling of GPS observations (**ISTORE-2**)

- Stochastic modeling of ocean tide background model (**TIDUS**, **TIDUS-2**, **ISTORE**)
  - ✓ OT VCM ☐ Sulzbach et al. (2023), https://doi.org/10.5880/nerograv.2023.003

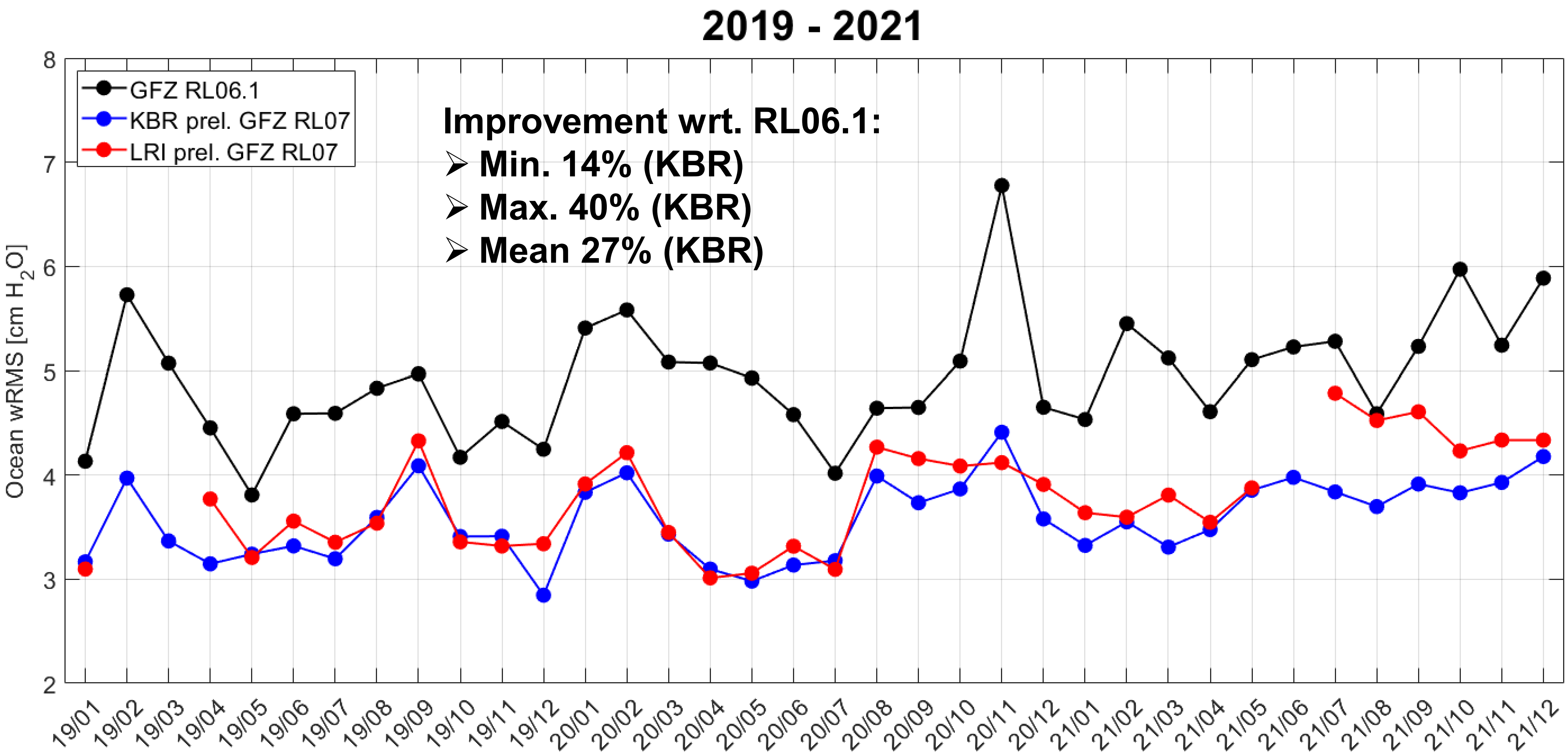
- Updated AOD model incl. stochastic modeling (**NAODEMO**, **ISTORE**)
  - ✓ AOD1B RL07 ☐ Shihora et al. (2022), https://doi.org/10.5880/GFZ.1.3.2022.003
  - ✓ AOD VCM ☐ Shihora et al. (2023), https://doi.org/10.5880/nerograv.2023.004
  - ✓ Test of non-stationary AOD VCM (**ISTORE-2**)

- Optimal weighting (**ISTORE-2**)

Projects within NEROGRAV 1st phase, Projects within NEROGRAV 2nd phase

Long, reprocessed time series will be provided to Application Projects IP2 and IP6 in fall 2025

Preliminary GFZ RL07p Results

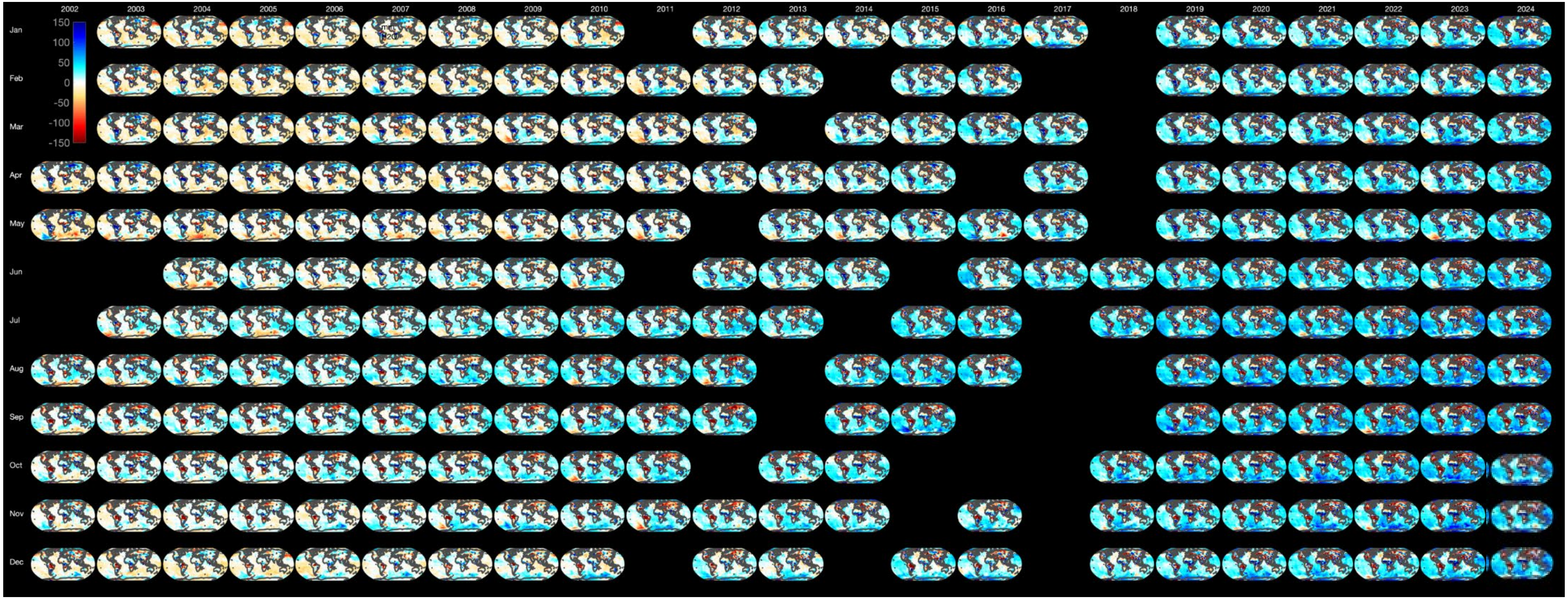


Ocean wRMS values relative to COST-G climatology, 300 km Gaussian smoothing

Part 3: Status of GRACE-FO and Future SST Missions

GRACE/GRACE-FO Available L2 Products

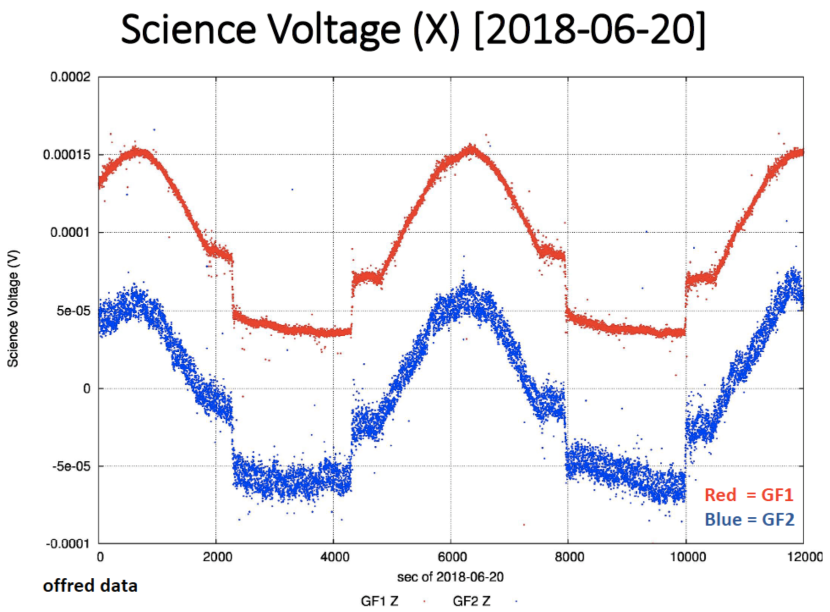
- Since 10/2018: Uninterrupted science data collection & processing
- 2002 – 2024: Consistent climate data record & impactful results



Plot: Felix Landerer (JPL)

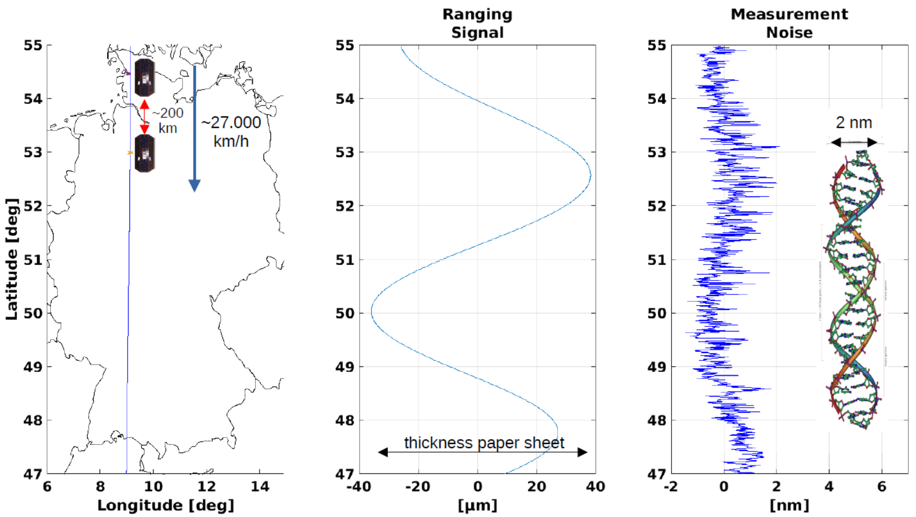
GRACE-FO Performance & Mission Lifetime Issues: ACC, IPU & LRI

- Both accelerometers (**ACC**) measuring real accelerations:
  - GF1 ACC is operating as expected and exceeding specifications
  - GF2 ACC appears to be under-performing relative to GF1
  - ONERA has investigated possible causes for anomalous observations (i.e., on roll thrust), SDS and ONERA have worked on calibration strategies: Resulted in transplanted solutions as already applied at the end of the GRACE mission



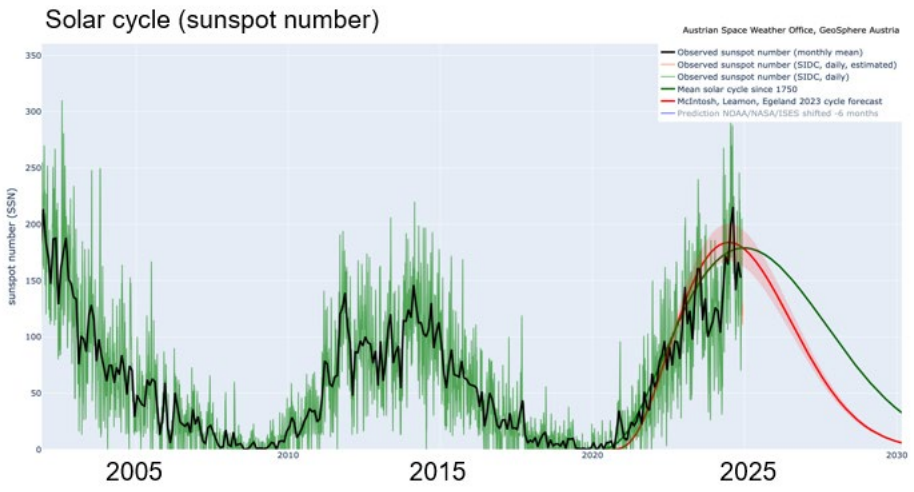
- On July 19, 2018, the Instrument Processing Unit (**IPU**) on GF2 has failed. Was successfully switched to redundant side and nominal science data collection was enabled in October.

- The Laser Ranging Interferometer (**LRI**) is performing better than specified before launch



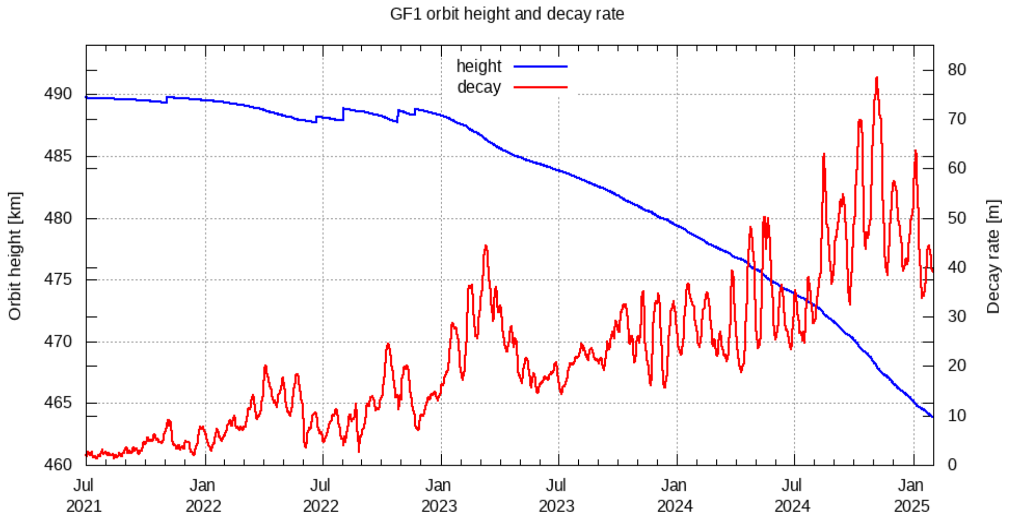
GRACE-FO Mission Lifetime Issue: Orbit Height and Decay Rate (4.2.2025)

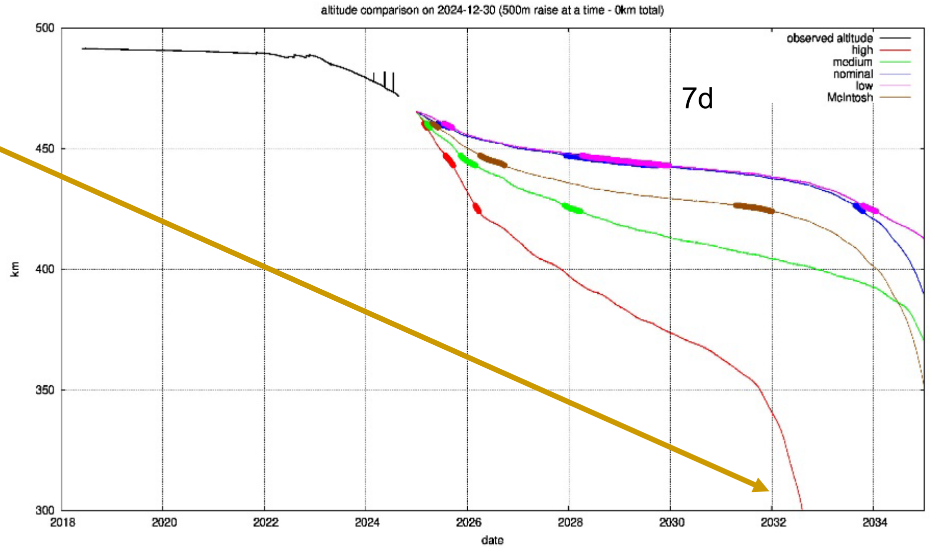
- Orbital Height: 463.0 km (491.5 km after launch)
- Average Decay Rate (2024): 38 m/d
- Upcoming (May) resonance altitudes of 7d (460-459 km)



https://helioforecast.space/solarcycle

In the most pessimistic solar activity case, **assuming very high activity**, the altitude of 300 km will be reached not before end of 2031.



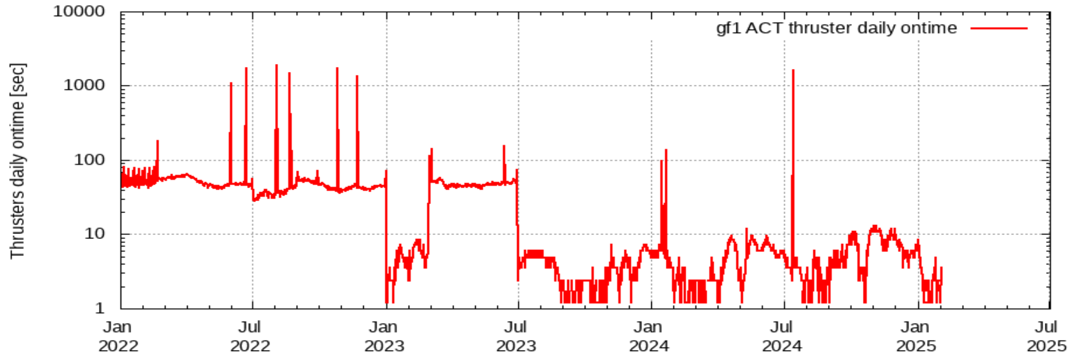


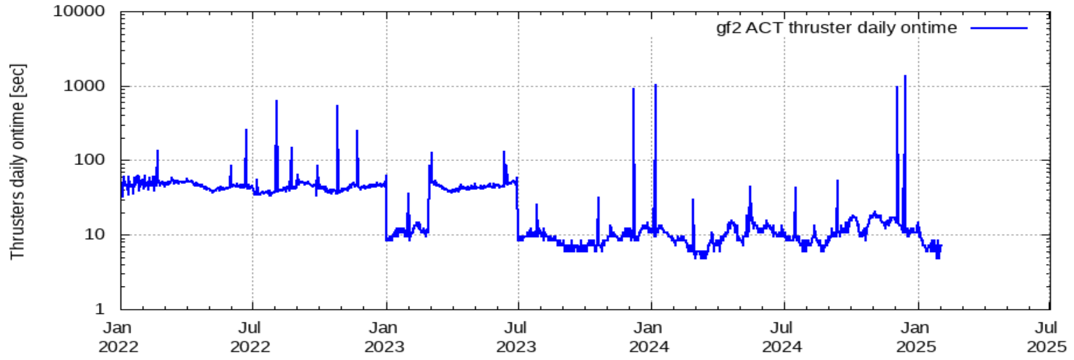
* Numbers from K. Snopek (orbits used for SLR predictions), consistent with GSOC numbers

Source: Himanshu Save (CSR)

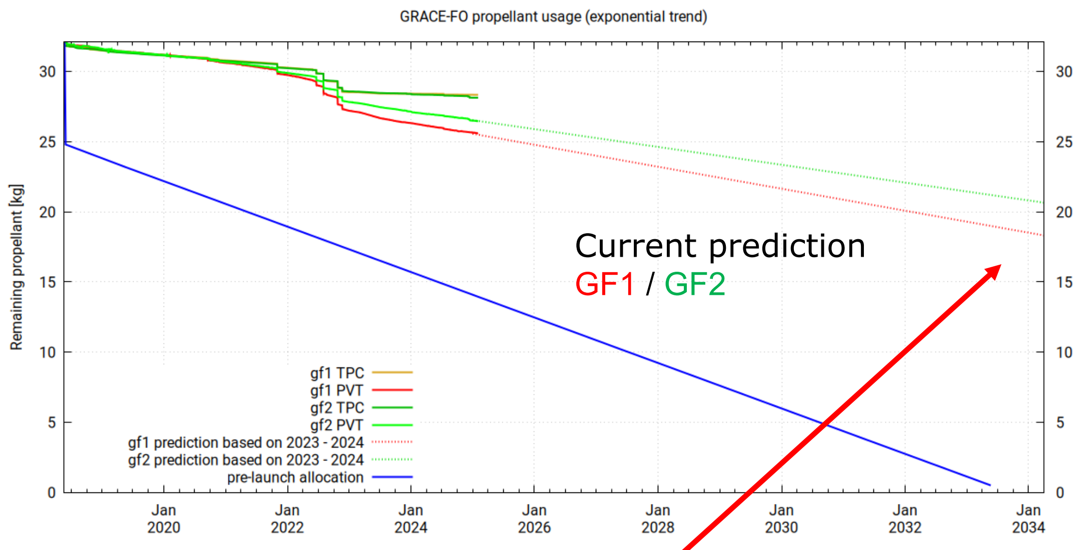
Mission Lifetime Issue: Fuel Consumption

- To reduce leak, satellites are operated in nadir pointing aka “wide dead-band” (WDB) mode (Jan/Feb-2023 and since Jul-2023). No LRI data!
  - Results in reduced thruster activity (ca. 5 -20%) and stabilized leak rate!





Both figures: K. Snopek (GFZ)

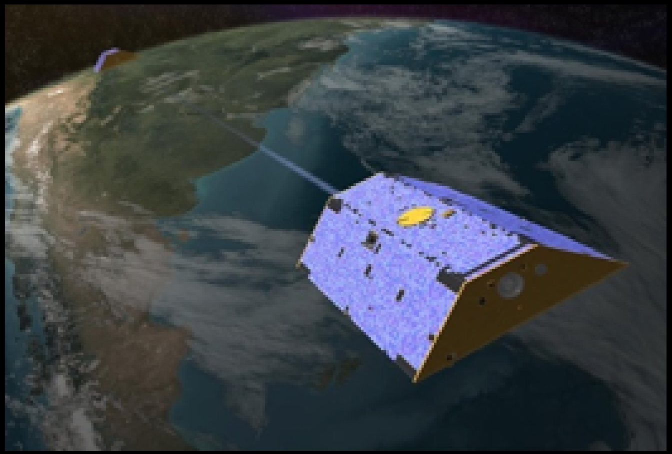


If we continue to fly in WDB mode, the gas usage or leak rate is not a lifetime issue anymore.

Mission lifetime will be a combination of fuel consumption and orbit decay!

Funding of GRACE-FO Mission Operations is an issue! GSOC proposal till end of 2029 exists.

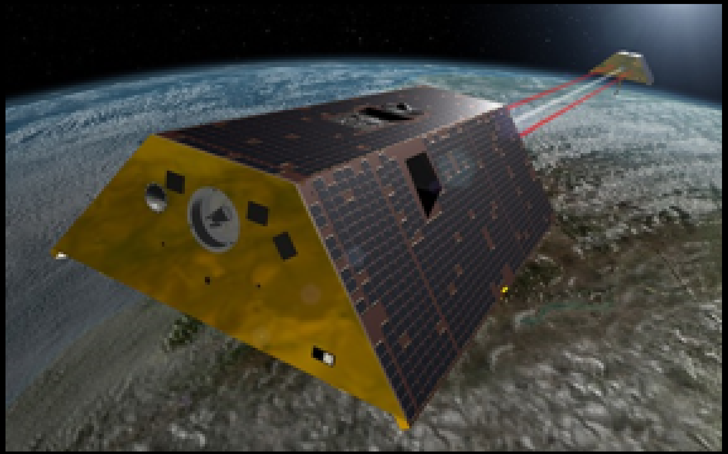
From GRACE to GRACE-C: Successful US-German Partnership



2002 - 2017

GRACE was the first mission to measure month-to-month gravity changes.

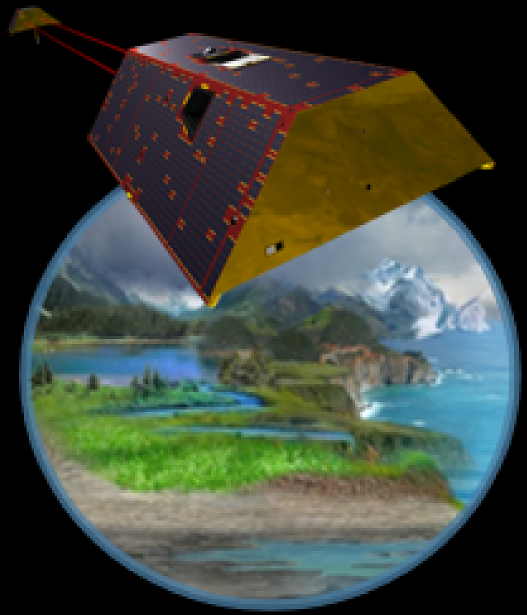
GRACE



2018 - present

GRACE-FO continues the observations, while also demonstrating new laser ranging interferometry (LRI).

GRACE-FO



2028 (scheduled)

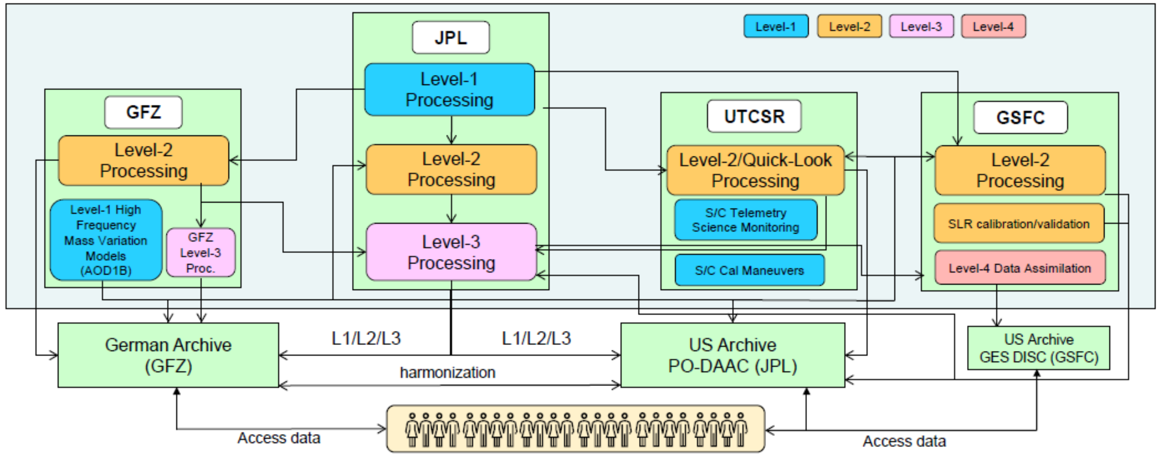
GRACE-Continuity will maintain and expand the foundational mass change measurements of Earth's changing water cycle.

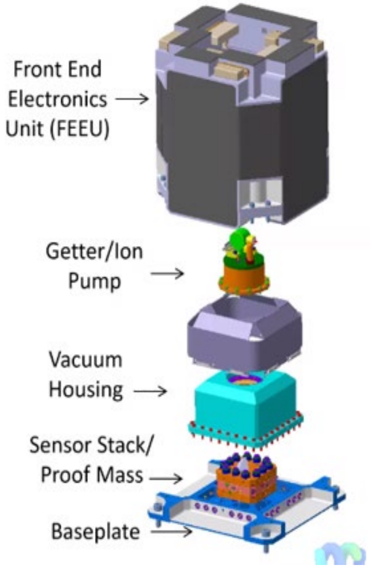
GRACE-Continuity

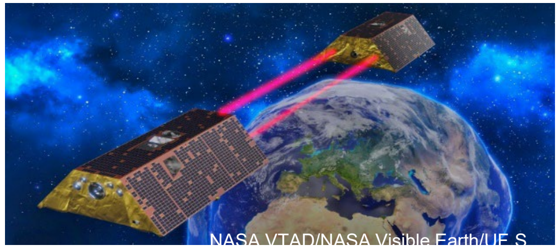
GRACE-C (Continuation): Some Facts

- US-German partnership (NASA-DLR)
- Significant contributions by GFZ and MPG/AEI
- SST: (largely redundant) LRI plus new Scale Factor Unit (no MWI available)
- ACC: Spare units from GRACE-FO
- POD: Podrix GNSS receiver
- SDS CDR (12.2.2025)
- Project CDR (6.-8.5.2025)
- Launch: December 2028
- MOS: Mission operations again @ DLR/GSOC. GFZ: MOS funding after launch, primary download station (Ny Alesund), Mission Operations Manager
- One year overlap with GRACE-FO planned
- GFO & GRACE-C Status will be presented at EGU

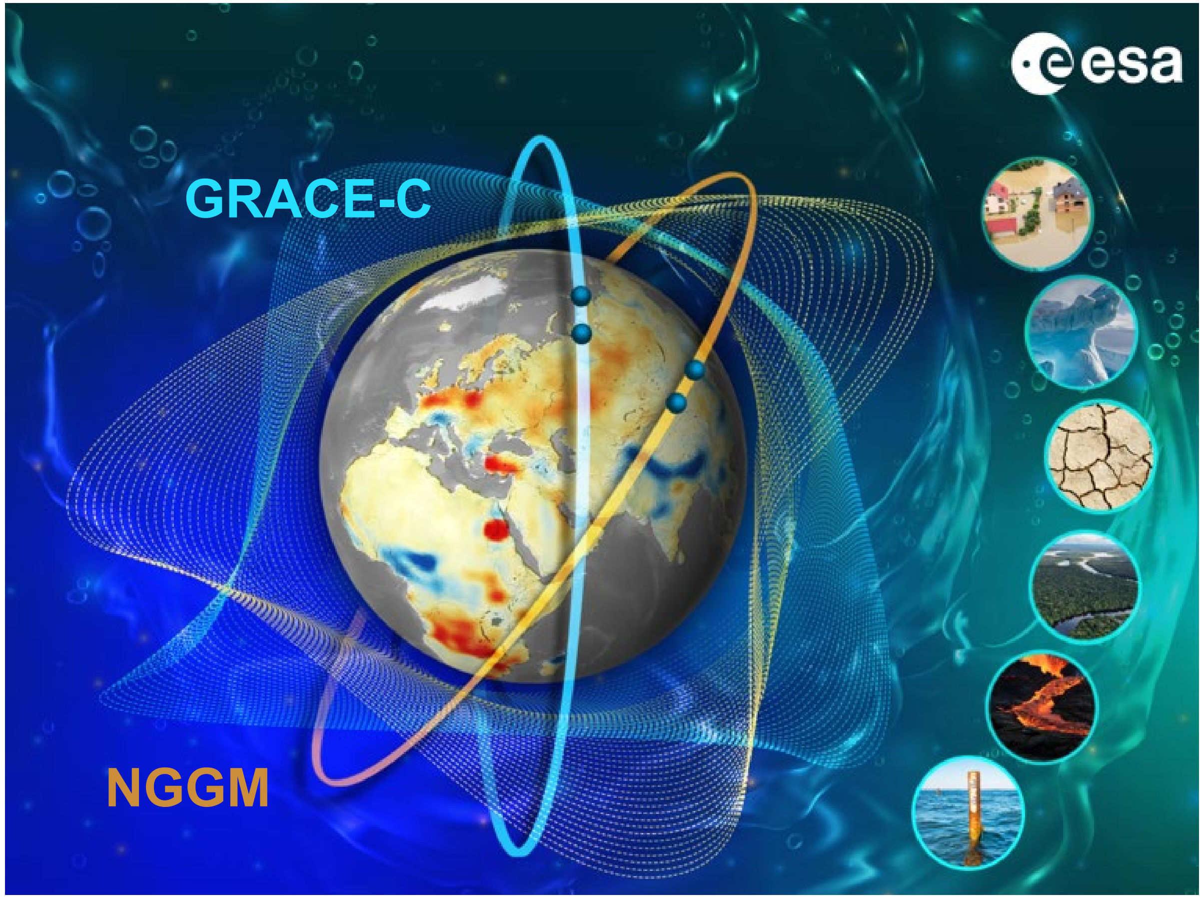
Currently operational on GRACE-FO: GRACE-C has no structural changes in terms of data flow/responsibilities from GRACE-FO







Mass-Change and Geosciences International Constellation (MAGIC)*

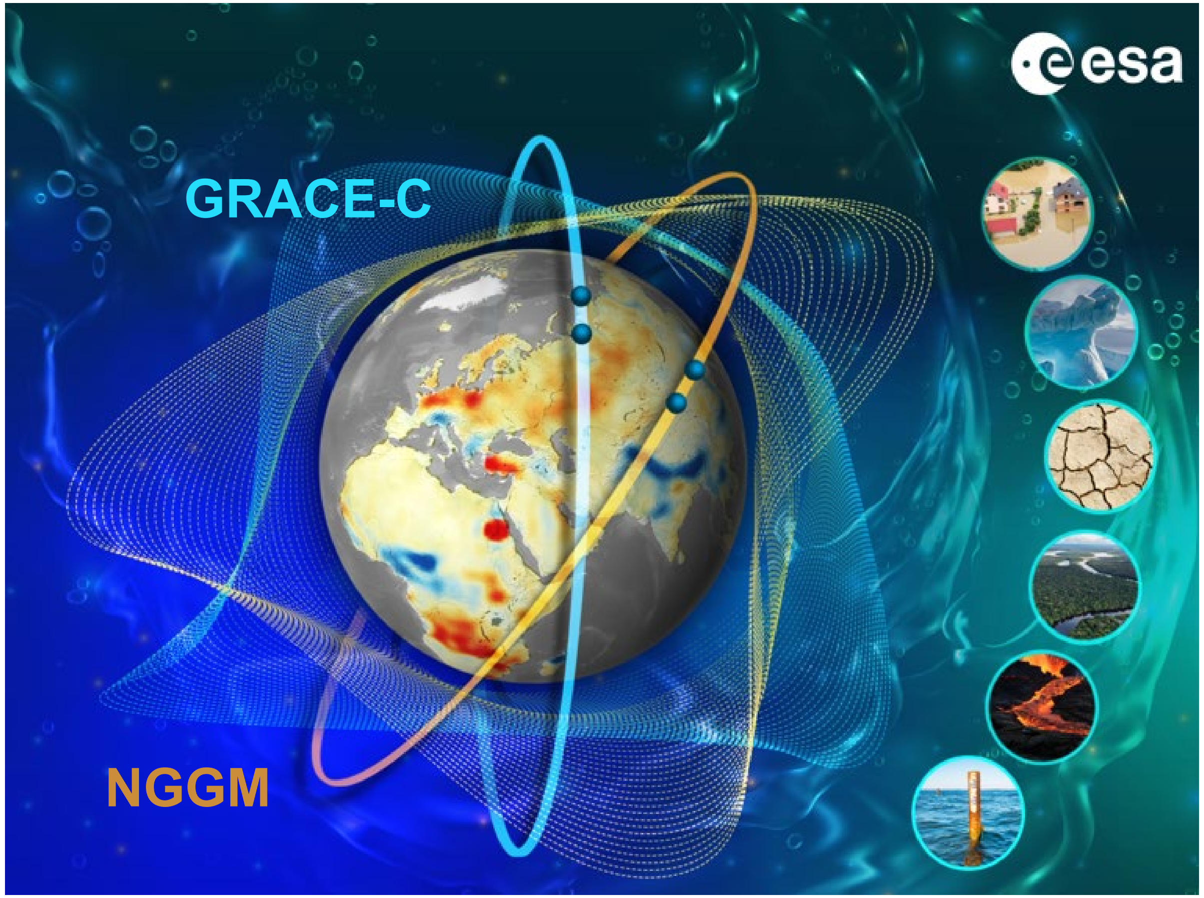


- The addition of an ESA provided inclined pair (Next Generation Gravity Mission) in 2032 shall lead to reduction of temporal aliasing effects and consequently of reliance on de-aliasing models and post-processing.
- The main novelty the MAGIC constellation is the delivery of mass-change products at
  - higher spatial resolution,
  - temporal (i.e. sub-weekly) resolution,
  - shorter latency and
  - higher accuracy

  than provided by a GRACE-like missions alone.
- This will pave the way to new science applications and operational services.

* Daras et al. (2023): Mass-change And Geosciences International Constellation (MAGIC) expected impact on science and applications, Geophys. J. Int. (2023) 00, 1–21, https://doi.org/10.1093/gji/ggad472

Mass-Change and Geosciences International Constellation (MAGIC)



- NGGM/MAGIC concept was/is investigated in two parallel industrial Phase A & B studies complemented by a science support study[1] (Phase A) and a NGGM and MAGIC End-to-End Mission Performance Evaluation study (ongoing).
- NGGM launch in 2032 with 4 years of combined NGGM and GRACE-C operations
- Most important modifications of NGGM wrt GRACE-C will be
  - Lower (397 km) and inclined (70 deg.) orbit
  - 5d repeat, drag free orbit
  - MicroSTAR ACC

1: https://www.asg.ed.tum.de/en/iapg/magic

Mass-Change and Geosciences International Constellation (MAGIC)

- Simulations studies (TUM/GFZ) with realistic assumptions for instrument noise and background models have shown that the double-pair configuration (“Bender”) will significantly enlarge the number of observable mass-change phenomena by resolving smaller spatial scales with an uncertainty that satisfies evolved user requirements expressed by international bodies such as IUGG.

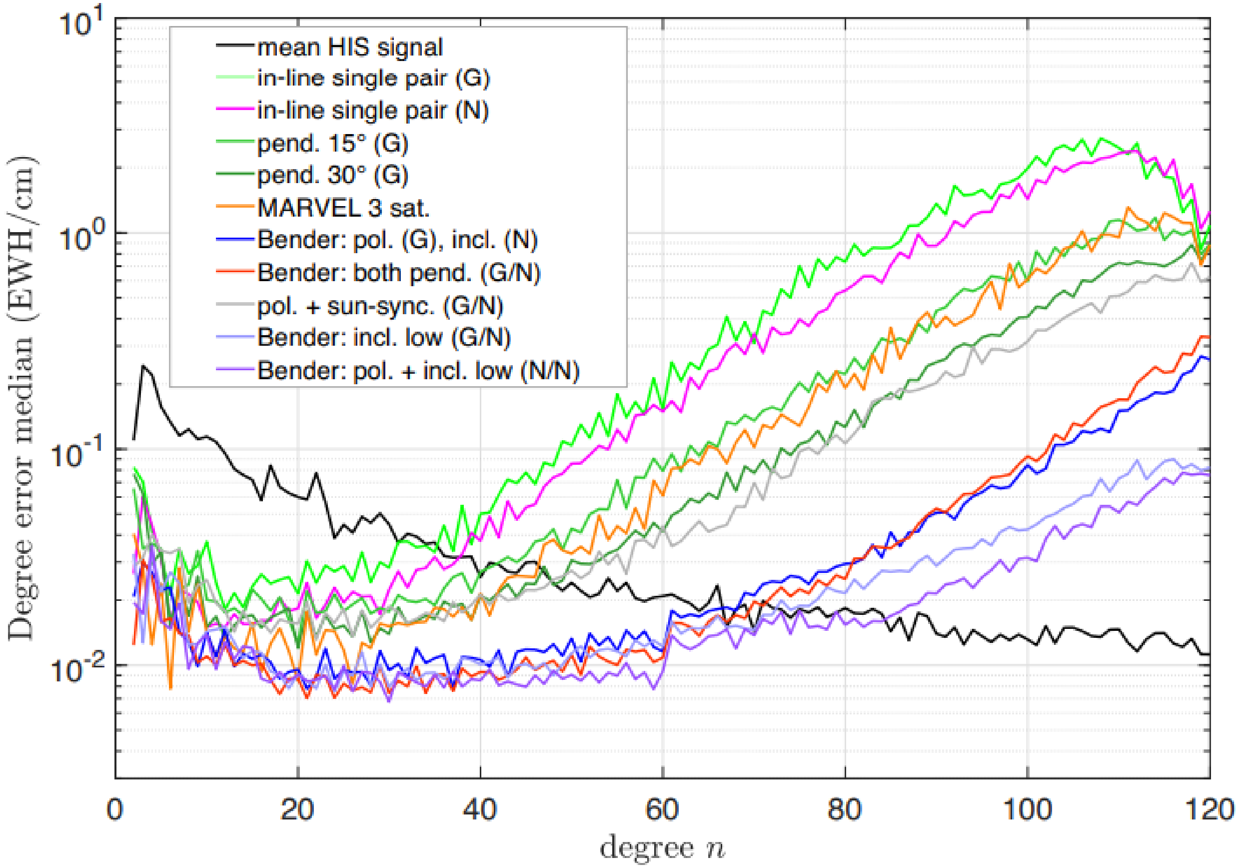


Figure 1. Degree error amplitudes of 31-d full-noise solutions from various mission constellations. ‘G’ means ‘SuperStar’ (GRACE-type) and *N* ‘MicroStar’ (NGGM/MAGIC-type) ACC performance. The numbers ‘15°’ and ‘30°’ refer to the opening angle of the pendulum formation.

Mass-Change and Geosciences International Constellation (MAGIC)

The required uncertainty levels of dedicated thematic fields met by MAGIC unfiltered Level-2 products will

- benefit hydrological applications by recovering more than 90 per cent of the major river basins worldwide at 260 km spatial resolution,
- cryosphere applications by enabling mass change signal separation in the interior of Greenland from those in the coastal zones and by resolving small-scale mass variability in challenging regions such as the Antarctic Peninsula,

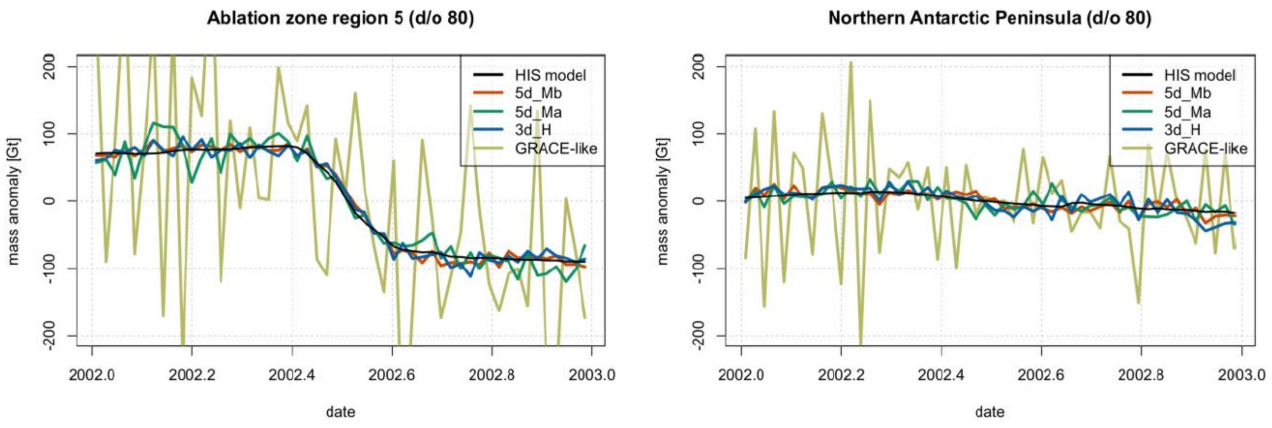


Figure 11. Mass variations in the low-elevation zone of GrIS basin 5 (left) and Northern Antarctic Peninsula (basins 24 and 25; right) simulated by the HIS model and retrieved from the four mission configurations simulations using the method of Wouters *et al.* (2008).

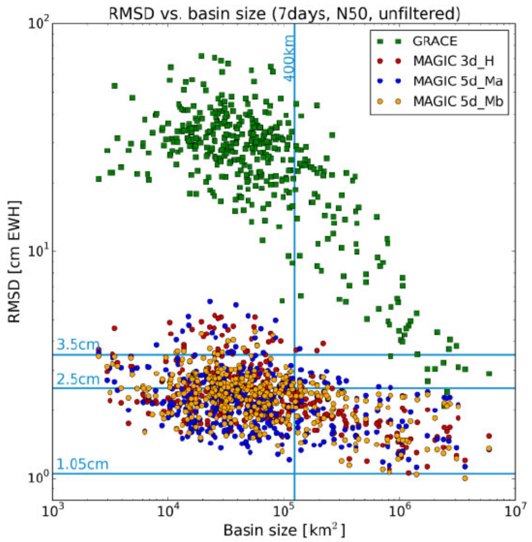


Figure 8. Top: scatter plot of RMSD of basin averages of water storage variations for 405 GRDC river basins truncated at *N* = 50 plotted against basin size. Blue horizontal lines indicate different uncertainty thresholds of 1.05 cm (i.e. the MRD threshold requirement), 2.5 and 3.5 cm EWH. The vertical blue line represents the area of a spherical cap with 400 km diameter.

Mass-Change and Geosciences International Constellation (MAGIC)

The required uncertainty levels of dedicated thematic fields met by MAGIC unfiltered Level-2 products will

- oceanography applications by monitoring meridional over turning circulation changes on timescales of years and decades,
- climate applications by detecting amplitude and phase changes of Terrestrial Water Storage after 30 yr in 64 and 56 per cent of the global land areas and
- solid Earth applications by lowering the Earthquake detection threshold from magnitude 8.8 to magnitude 7.4 with spatial resolution increased to 333 km.

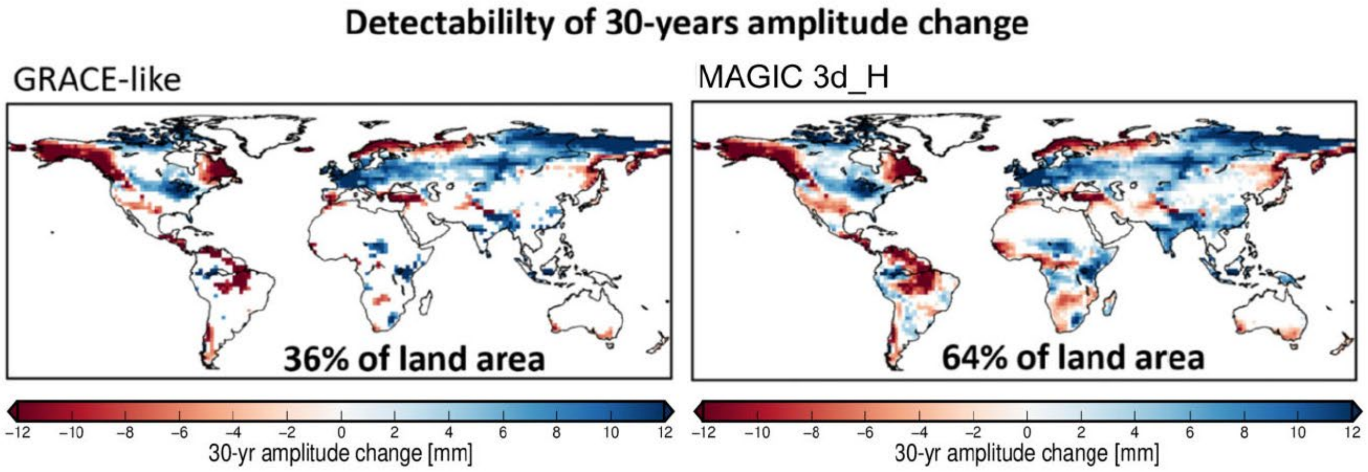


Figure 16. Top: standard deviation of GRACE-like (left) and MAGIC (right) TWS amplitude change of annual cycle over 30 yr. Bottom: detectability of amplitude change: coloured pixels denote where projected amplitude change exceeds the magnitude of the accuracy.

Program

Time	Monday	Tuesday	Wednesday	Thursday	Friday
08:00-09:00		Breakfast	Breakfast	Breakfast	Breakfast
09:00-09:45		Background Model Ocean Tides (Mike Hart-Davis)	Stochastic Modeling of GRACE/GRACE-FO Data (Michael Murböck)	Practical 3: GRACE-FO Data Analysis: Global Analysis of EWH Grid Data	The future: Satellite Missions with Quantum Sensors (M. Weigelt)
09:45-10:30		Background Model AOD1B (Linus Shihora)	From Level-2 Spherical Harmonics to Level-3 Grid Data (Eva Börgens)		Feedback NEROGRAV School and Discussion (all)
10:30-11:00 (fix)		Coffee Break		Coffee Break	Coffee Break
11:00-12:15		Practical 1: GRACE-FO Data Analysis: Spherical Harmonic Analysis	Practical 2: GRACE-FO Data Analysis: Filtering/De-striping	Practical 4: GRACE-FO Data Analysis: Regional Analyses	
12:15-13:15 (fix)		Lunch	Lunch	Lunch	
13:15-14:00		13:30 Bus to Speyer 14:15 Museum of Technology Speyer 17:00 Bus to Neustadt	Mass Change of the Cryosphere (Ingo Sasgen)	Practicals: Feedback and Q/A	
14:00-14:45	The Research Group NEROGRAV and Status GRACE-FO and future SST Missions (Frank Flechtner)			Gravimetry Data for Monitoring the Global Water Cycle and Comparisons with Climate Models (Annette Eicker)	
14:45-15:30	Special Aspects of GRACE-FO Level-1 Instrument Data: (Vitali Müller)		Surface Loading in View of the Earth's deformability (Volker Klemann)		
15:30-16:00 (fix)	Coffee Break			Coffee Break	
16:00-17:30	From Level-1B Instrument Data to Level-2 Spherical Harmonics (Thomas Gruber)		Mass Change of the Oceans (Michael Schindelegger)	GRACE/GRACE-FO Data for Model Assimilation and Service Applications (Anne Springer)	
18:00-19:00 (fix)	Dinner	Dinner	Dinner	Dinner	
19:30-21:00	Ice Breaker		Wine Taste	SLR for Gravity Field Determination (45´, Bryant Loomis)	

Group Foto