Continuing mass change observations beyond GRACE-FO: update on the development of the NASA/DLR GRACE-Continuity Mission

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And many more, including JPL, GFZ, CSR, GSFC SDS teams, US/German LRI teams, and project engineering teams

October 10, 2024
GRACE/GRACE-FO Science Team Meeting
Potsdam, Germany

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[3] Germany Space Agency at DLR, Department Earth Observation, Germany

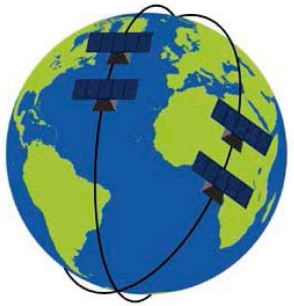
Dr. Peter L. Bender was an esteemed experimental physicist at the University of Colorado Boulder. He leaves behind a legacy marked by significant contributions to the field of astrophysics, precision measurements, and geodesy.

Pete was deeply involved in pioneering research that has shaped our understanding of the universe. He will leave a lasting impact in the field of geodesy for advancing the integration of advance metrology into GRACE(-FO) missions, and for evaluating different orbit configurations for multi-pair gravity missions.

Hopefully, we will realize the polar/inclined *Bender-Pair* orbit with GRACE-C (NASA/DLR) and NGGM (ESA) as the joint MAGIC concept.

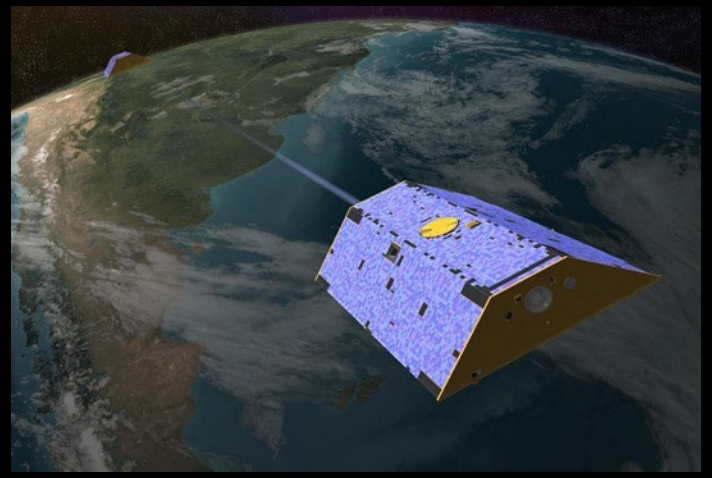
In Memoriam
Pete Bender

April 20, 2024, at the age of 93



GRACE, GRACE-FO, and GRACE-C

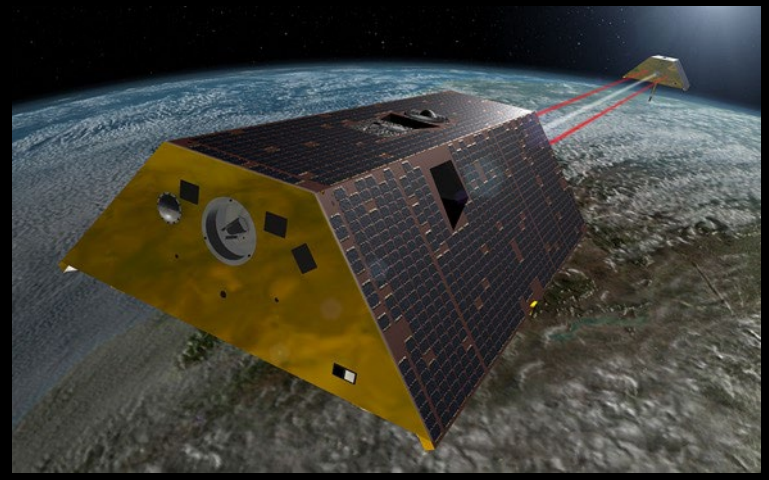
Tracking Earth's surface mass changes & water cycle



2002 - 2017

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

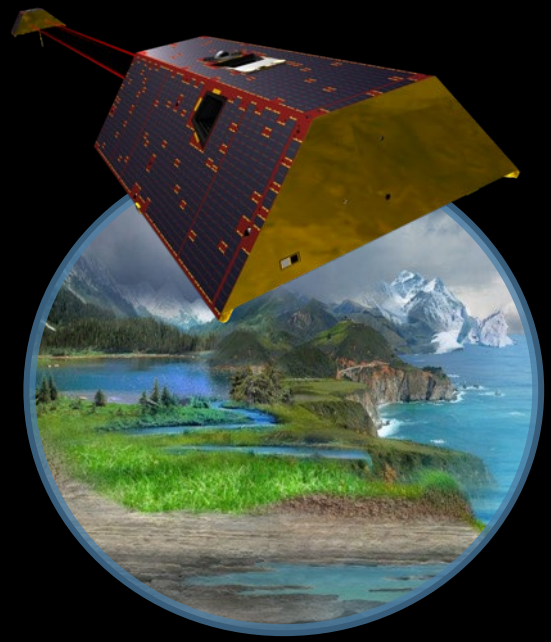
GRACE



2018 - present

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

GRACE-FO



2028 (scheduled)

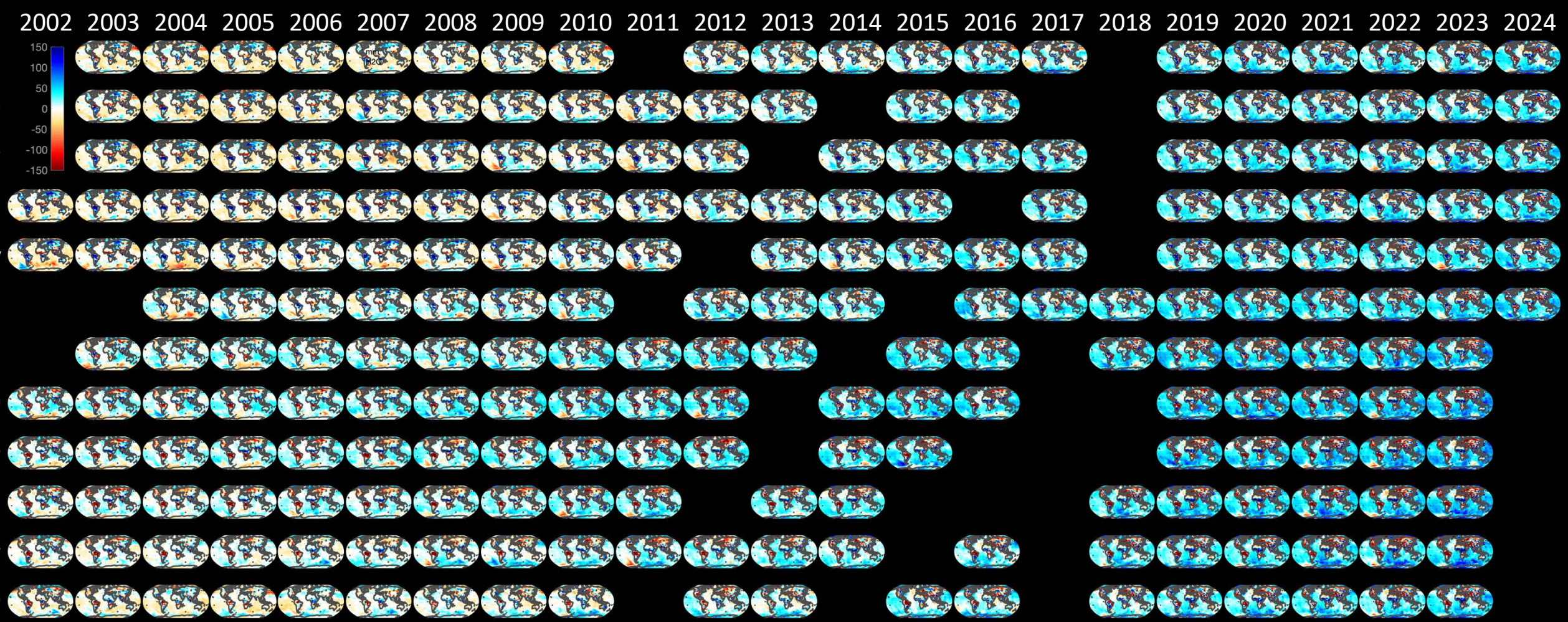
GRACE-Continuity will maintain and expand the foundational mass change measurements of Earth's changing water cycle.

GRACE-Continuity

Trillions of observations over two decades keep an eye on the ever-evolving planet.

Unique monthly Earth system Mass Change Observations

GRACE and GRACE-FO: 22+ Years of Scientific Discoveries and Important Applications for Everyday Life



Unique monthly Earth system Mass Change Observations

GRACE and GRACE-FO: 22+ Years of Scientific Discoveries and Important Applications for Everyday Life

Continued Mass Change Observations are Foundational

Table 3.5;
2017 Decadal Survey

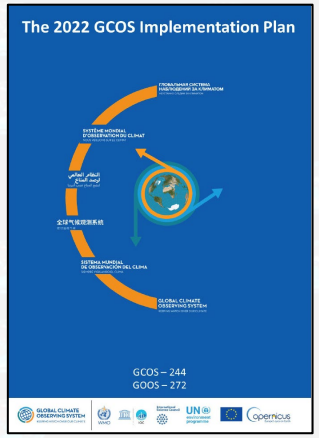
Ensures continuity *of*

- *measurements of groundwater and water storage mass change,*
- *land ice contributions to sea-level rise,*
- *ocean mass change,*
- *ocean heat content (when combined with altimetry),*
- *glacial isostatic adjustment, and*
- *earthquake mass movement.*

Also ***important for operational applications****, including*

- *drought assessment and forecasting,*
- *hazard response, and*
- *planning water use for agriculture and consumption."*

Terrestrial Water Storage *(TWS) declared as* ***Essential Climate Variable*** *(ECV) in 2020 by the Global Climate Observing System (GCOS) Steering Committee.*



"Urgent actions are needed to ***ensure continuity*** *gravimetry missions"*

2022 GCOS Implementation Plan

Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

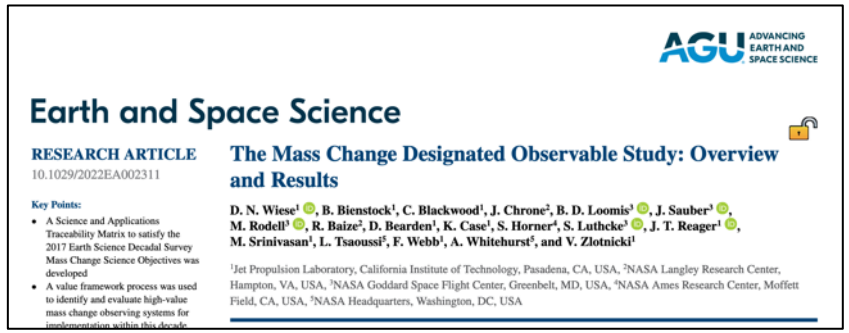
2010 2011 2012 2013 2014 2015 2024

GRACE-C Timeline

2018 2019 2020 2021 2022 2023 2024 Today 2025

2017: Decadal Survey recommends Mass Change as a Designated Observable to continue observations from GRACE-FO

2018-2021: Mass Change Study Team studied approaches to obtaining measurements called for in DS and recommended small subset of architectures for further study



AGU ADVANCING EARTH AND SPACE SCIENCE

Earth and Space Science

RESEARCH ARTICLE
10.1029/2022EA002311

The Mass Change Designated Observable Study: Overview and Results

Key Points:
- A Science and Applications Traceability Matrix to satisfy the 2017 Earth Science Decadal Survey Mass Change Science Objectives was developed
- A value framework process was used to identify and evaluate high-value mass change observing systems for implementation within this decade

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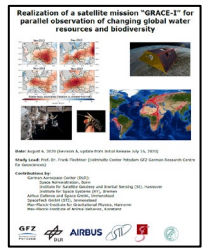


2020: Germany suggests a US-German combined mass change and biodiversity GRACE-I mission

2022: GRACE-I Phase-A study @Airbus (led by GFZ, funded by BMBF)

Pre-Phase A | Phase A | Phase B | Phase C

Mission Concept Review *Successfully Passed*

System Requirements Review *Successfully Passed*

Mission Definition Review *Successfully Passed*

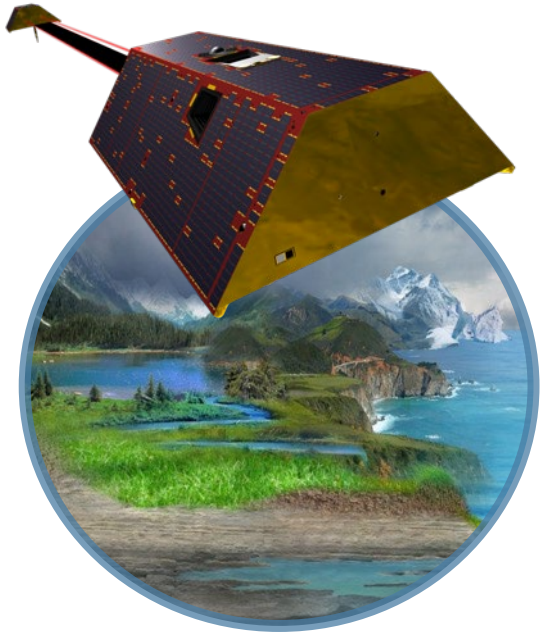
Preliminary Design Review *Successfully Passed*

Critical Design Review *Planned Spring 2025*

GRACE-Continuity (GRACE-C) became mission name in Fall 2023
(Note: previous names included Mass Change (MC), and GRACE-I)

GRACE-C Baseline Concept

Phase A/B activities matured the mission concept for GRACE-C



Project / Program Details

- Partnership between NASA & DLR
- Two identical Spacecraft separated by 100-300 km
- Launch Date: December 2028
- Orbit: 500 km altitude, 89º Inclination
- Launch Vehicle: Space-X Falcon 9
- Spacecraft Bus: Airbus; GRACE-FO Heritage
- Redundancy: Dual-string laser ranging interferometer; Spacecraft redundant accelerometers

Measurement System

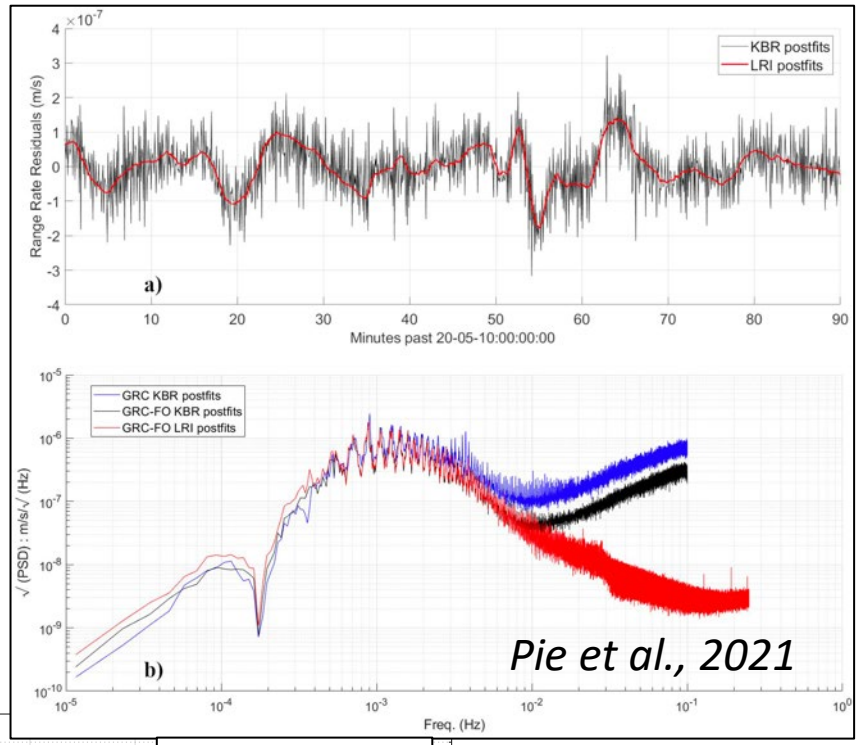
- Satellite to Satellite Tracking: Laser Ranging Interferometer (no MWI anymore)
- Accelerometer
- GNSS Receiver
- Star Camera attitude determination
- LRR (independent orbit control)

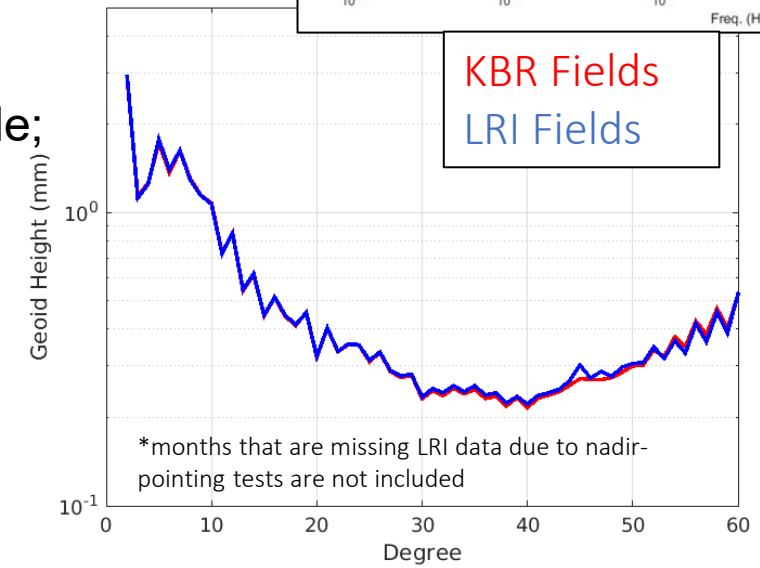
Mission Science

- GRACE-C will provide continuity of the monthly Earth system mass change data record, which is foundational to the program as recommended in the Decadal Survey
- GRACE-C will produce observations consistent with the GRACE and GRACE-FO science record, documented in the baseline MCDO study Science and Applications Traceability Matrix
- One of 5 Core Focus Areas addressed by 4 missions for NASA's Earth System Observatory

LRI Provides Improved Ranging Precision

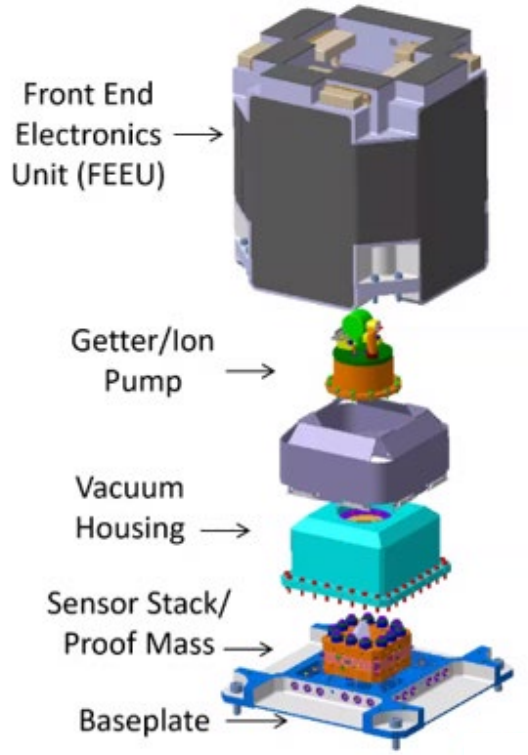
- Flight Proven on **GRACE-FO** (see various orals and posters in A.1)
  - Consistent gravity fields derived from MWI and LRI data (Pie et al., 2021)
  - LRI ranging precision relative to MWI better by ~x100
  - Worked flawlessly on GRACE-FO: only 5 unplanned reboots in 5 years
- LRI on **GRACE-C** (see A.3 talk V. Müller & poster R. Sudha)
  - Same contributions as on GRACE-FO:
    - US (electronics, Laser) / Germany (optics)
  - Scale Factor Unit (SFU) is new since no MWI available; scale needs to be known to ~25 ppb
  - Redundancy added; concept based on reliability assessment
    - Constellation redundant: Cavity and SFU
    - Redundant: LAS, LRP, OBE, OSC
    - Non-redundant: TMA, OBA optical path, FSM





Accelerometers are Built and Flight Proven

- ONERA built two flight spare units for GRACE-FO (SM1/SM2) that will be used on GRACE-C
- Fault tree analysis done on GRACE-FO pointed to workmanship issue that caused the underperformance of the GFO-2 accelerometer
- An Inheritance Review for SM1/SM2 was conducted and passed on Feb. 8, 2023. During the Review ONERA presented results of a Pre-Phase A deep dive into all functional and performance test data
  - SM1 & SM2 show no anomaly; in-family with GFO-1 ACC!



Summary

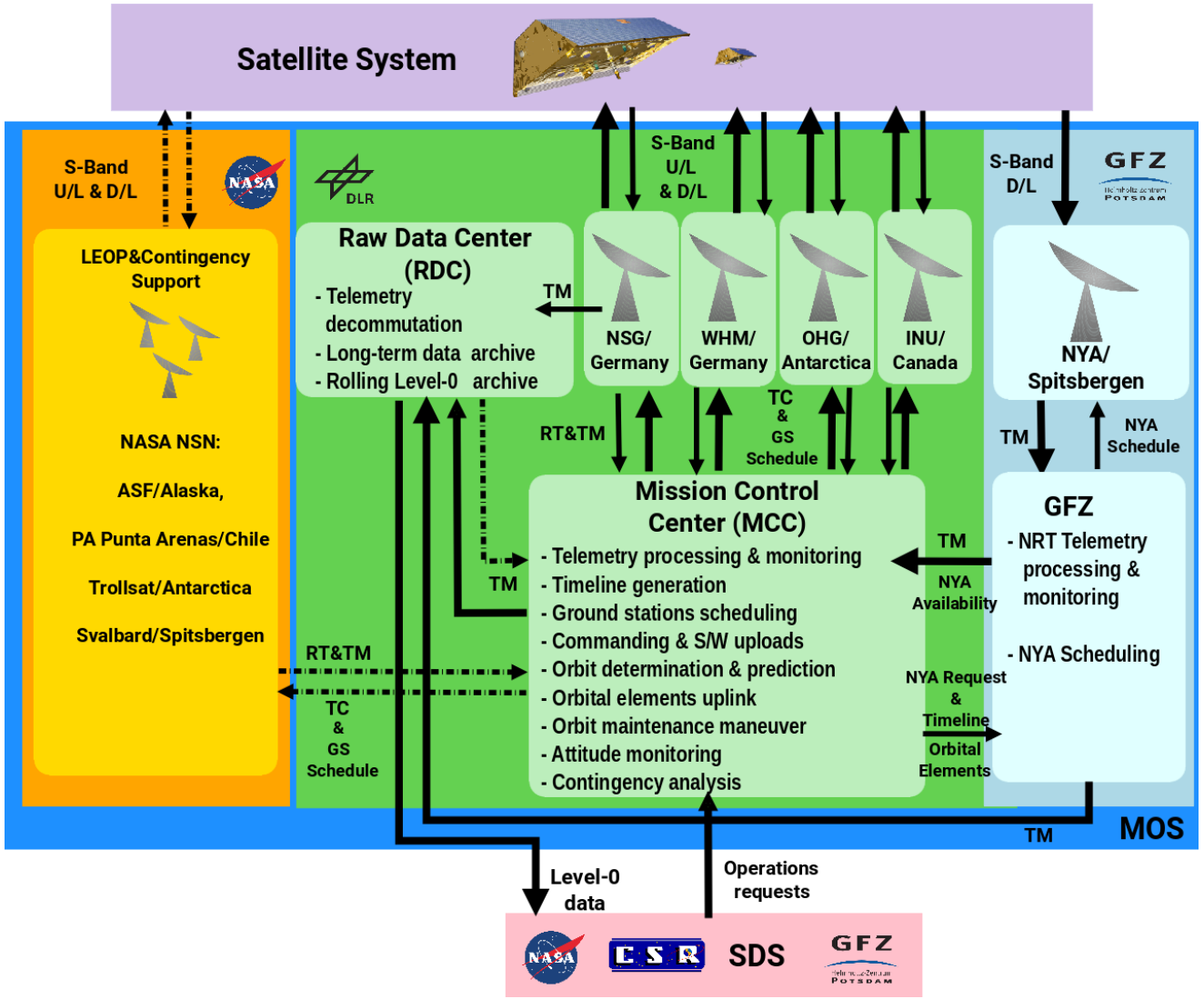
- The units have been recertified for flight (delivery review held in June 2024) by repeating functional and performance tests
- ACC H/W is flight-proven, built, and will be delivered to spacecraft in mid-2026 for integration

Modified on GRACE-C: GNSS Receiver and Thrusters

- **GNSS Baseline (POD, Time Tagging):** PODRIX GNSS receiver from *Beyond Gravity* (replaces JPL furnished GPS within MWI)
  - Block redundant
  - Triple frequency (L1, L2, L5) (GPS/Galileo)
  - Already flown on Airbus projects Sentinel-2 and Sentinel-6

- **Thrusters**
  - 7 mN low shock thrusters from Advanced Space Technologies (AST) will replace 10 mN thrusters used on GRACE-FO
    - Factor ~10x reduced shock spectrum/pulse relative to GRACE-FO thrusters
    - Will result in quieter platform for science measurements

Mission Operations is High Heritage



Derived architecture from GRACE-FO

Primary data downlink frequently at GFZ´s SRS Ny-Ålesund (NYA)

Uplink and downlink via Weilheim (WHM, Germany), Neustrelitz (NST, Germany), O'Higgins (OHG, Antarctica) and Inuvik (INU, Canada)

NSN stations for LEOP, contingency support and software uploads

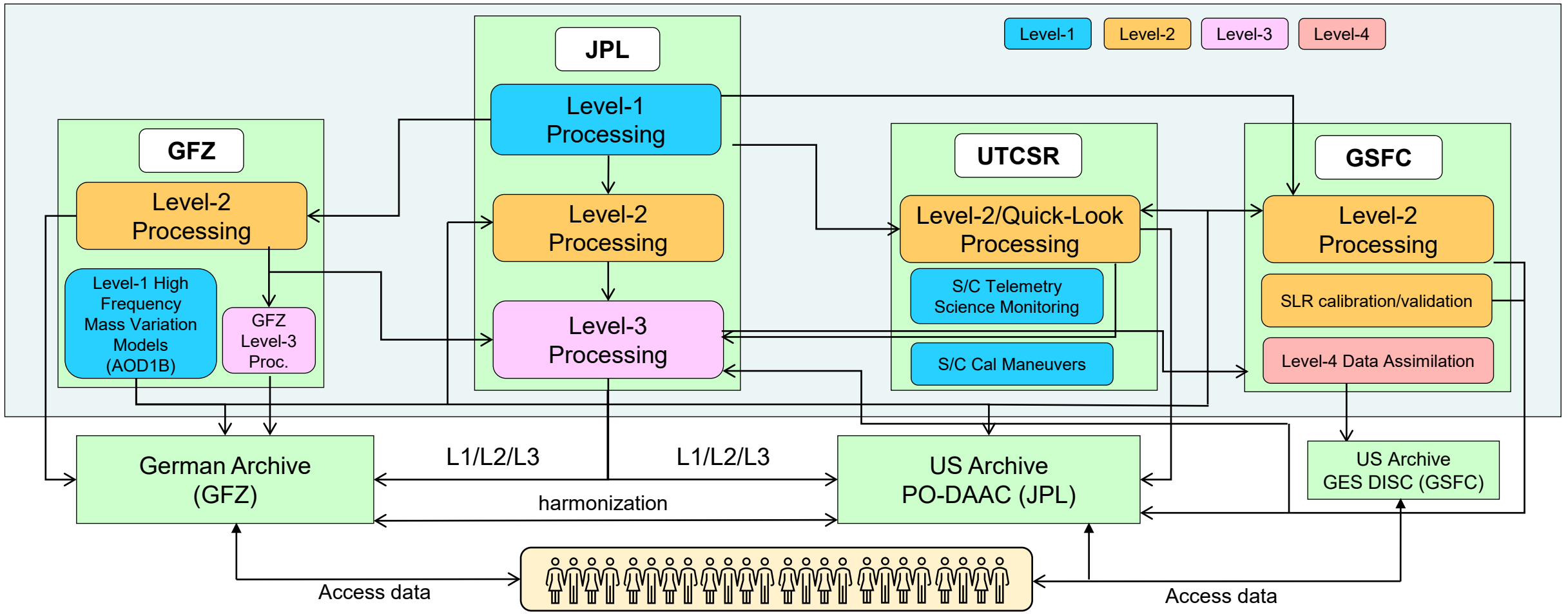
Mission Control Center (MCC) at DLR/GSOC, Oberpfaffenhofen, Germany

Raw Data Center (RDC) is pickup point for Science Data System (SDS) at DLR/DFD, Neustrelitz, Germany.

MOS Funding and Responsibility after Commissioning Phase from/at GFZ (similar GFO)

Science Data Systems is High Heritage

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



Overlap with GRACE-FO Drives FY28 Launch

- Desired to have a minimum 6 months of overlap with GRACE-FO for Cal/Val
- GRACE-FO project continues monitoring health and end of mission date (see MOS presentation in the SDS session on Tuesday)
  - Single string on accelerometer and IPU (GNSS receiver and MWI tracking)
  - Since July 2023, GRACE-FO completed operating in wide-pointing mode to reduce thruster leaks and minimize propellant loss
    - Wide-pointing mode is successful – leak rate has decreased
    - GRACE-FO will remain in wide pointing mode in the near-term (LRI tracking prohibited)
  - Operational decisions being made to simultaneously maximize quality of science data products and to extend mission lifetime

Overlap between GRACE-FO and GRACE-C is currently likely based on fuel budget, and overall system health

Summary

- GRACE-C will provide continuity of the mass change climate data record & important Earth science applications
  - Overlap with GRACE-FO is likely based on fuel budget and overall system health
- Quality of science data expected to be consistent with GRACE / GRACE-FO
  - Novel Level-3 and Level-4 data types will be produced, including low-latency data for applications (i.e., flood potential forecasting & monitoring)
- GRACE-C is a mature concept based on flight proven designs with high heritage
- GRACE-C is extending the successful partnership between the US and Germany, minimizing technical and cost risks
- Next milestone: Project Critical Design Review (CDR) in Spring 2025
- Launch is scheduled for December 2028