GRACE-I: A joint US-German mission for continued mass transport monitoring and enabling global biodiversity monitoring

GRACE/GRACE-FO Science Team Meeting
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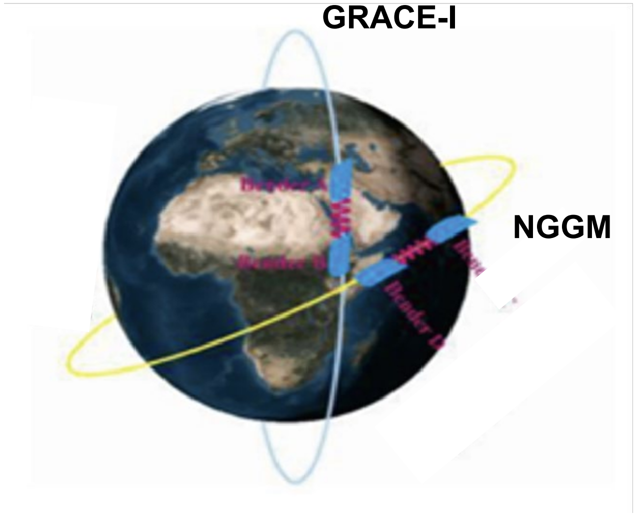
GRACE-I Background

- The NASA Earth Science Decadal Survey Report highlights **mass transport monitoring** as **one of five top priorities in EO for the next decade**.
- To realize a Mass Change Mission (MCM) **NASA seeks for international partnership**.
- **To continue the very successful technological and scientific** GRACE/ GRACE-FO **partnership** Germany proposes a **joint US-D GRACE-I (MC) mission** combining
  - a quickly realized single-pair **GRACE-FO successor** based on LRI SST with launch in 2027 into a polar orbit to guarantee **data continuity**, and
  - a (optional) **ICARUS payload** (International Cooperation for Animal Research Using Space) which would combine 2 NASA Designated Observables (Mass Change and Surface Biology and Geology).
- In parallel ESA is currently preparing a **NGGM*** mission in the Mission of Opportunity element of FutureEO.
  - GRACE-I would be the polar pair P1 if combined with an inclined NGGM P2 to build **MAGIC***
  - This hybrid Bender pair configuration launched in a staggered approach would **significantly increase spatial and temporal resolution** of mass transport products.



* NGGM = Next Generation Gravity Mission
MAGIC = Mass change And Geosciences International Constellation

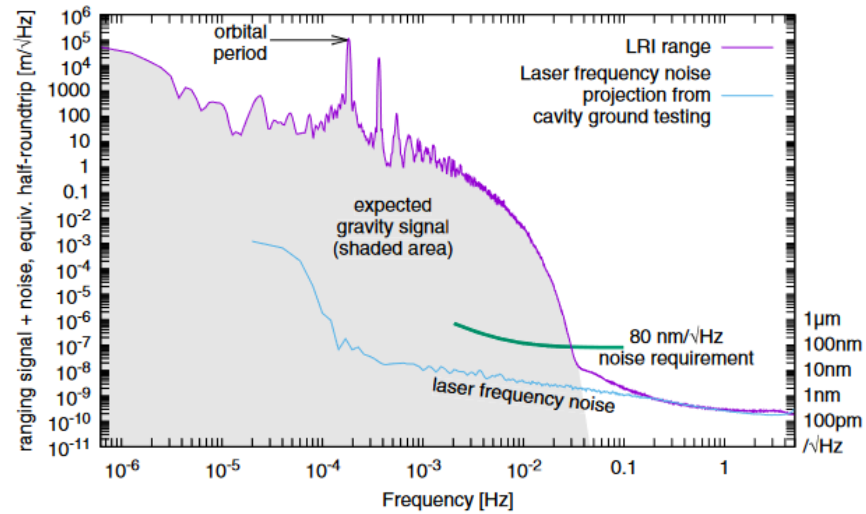
This talk: Status GRACE-I Phase A Study (Apr-Sep 2022)

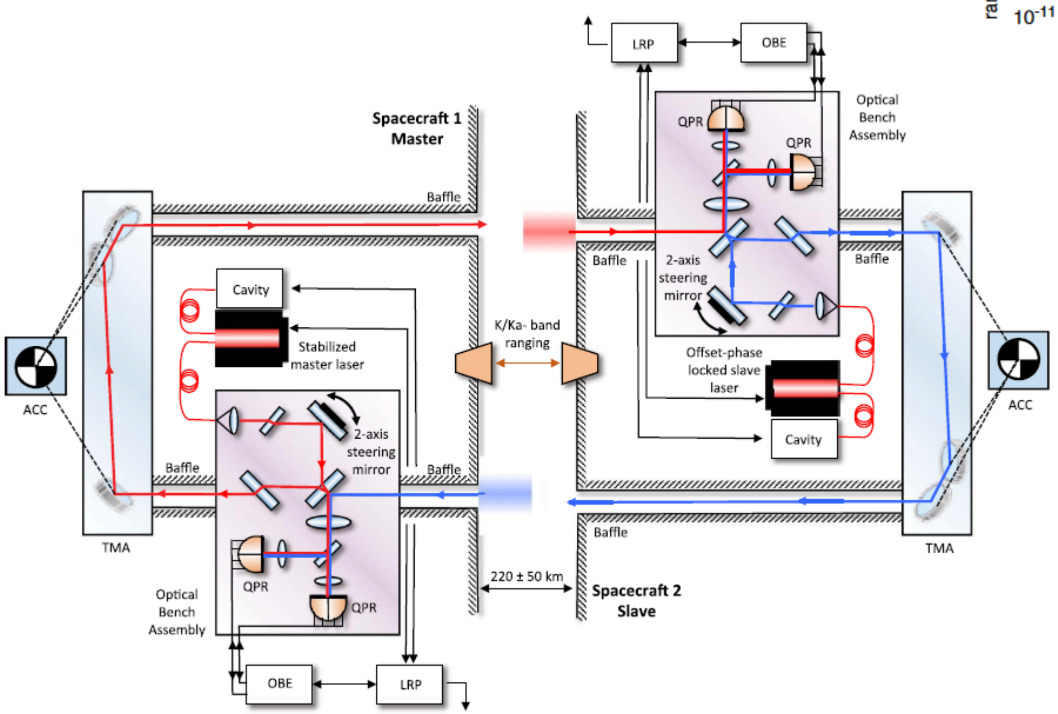
Detailed Mission Analysis (Funded by BMBF, Lead by GFZ, supported by DLR)

- **Objectives (Discussed in close collaboration with JPL (3 TIMs))**
  - Concretization of Phase 0 (Mar-Sep 2021) mission options and payload configurations (e.g., Electric Propulsion, ICARUS, QGG demo and accelerometers).
  - Perform weighting of system-level options
  - Derive a detailed design of required technical improvements wrt GRACE-FO
  - Derive a detailed schedule and cost estimation
- **Expected Outcome of Phase-A:**
  - Revised Phase 0 Customer Technical Requirement Specification (CTRS) and
  - A technically and scientifically feasible GRACE-I / MC mission scenario mutually agreed on between DLR/GFZ and NASA/JPL to be jointly realized within phase B/C/D
- **In view of MAGIC NASA/JPL and ESA have to agree in parallel on possible ESA contributions on GRACE-I**
  - Identify synergies, commonalities, schedule and other programmatic elements between P1 and P2 -> ESA participated in all TIMs to discuss technical and programmatic collaboration, e.g. to accommodate a Tech Demo microSTAR on GRACE-I
  - Finalize Constellation Requirements Document
- **Exemplarily details on GRACE-I mission elements shown next…**

Laser Ranging Interferometer (GRACE-FO)

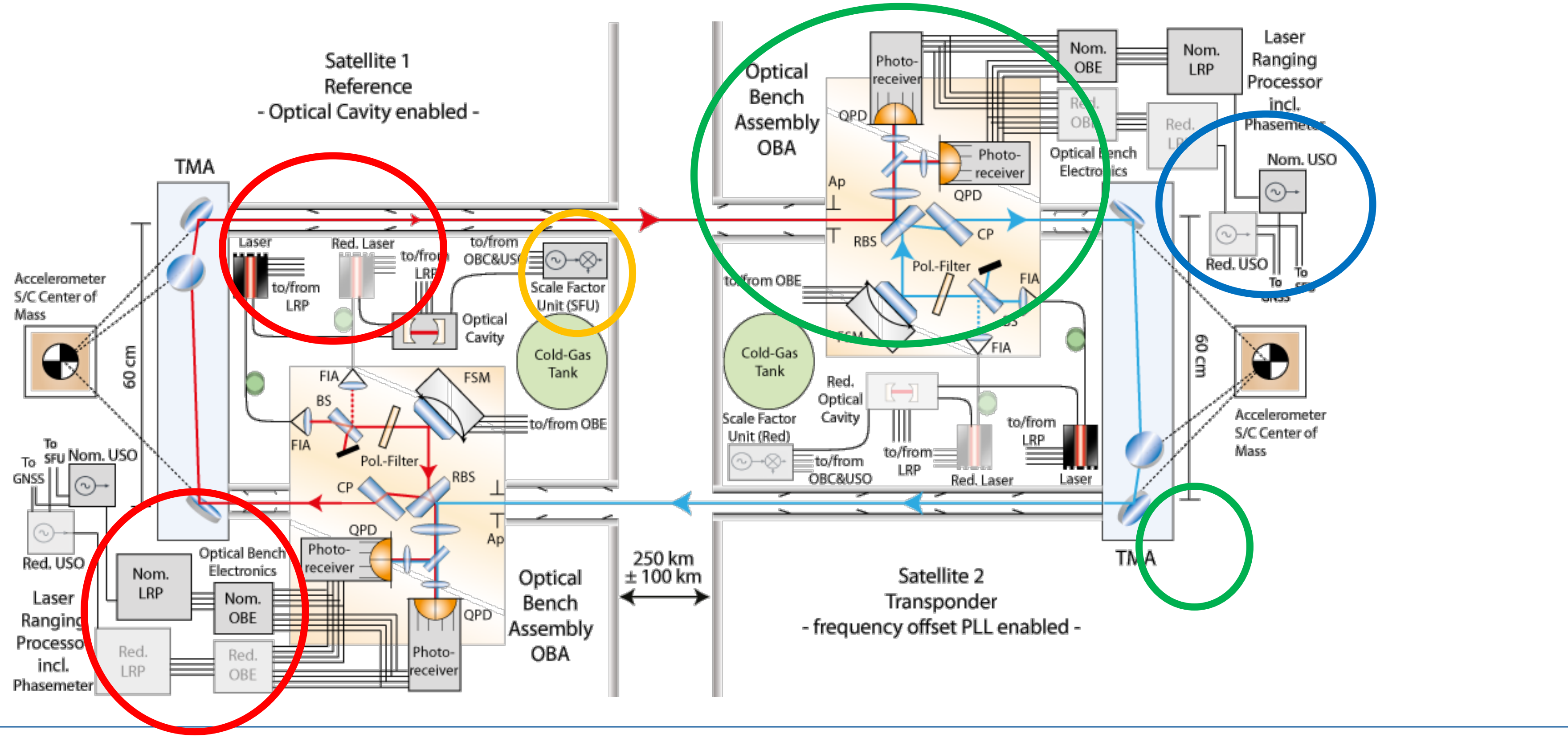
- LRI is flown as technology demonstrator
- Successful signal acquisition without a dedicated sensor
- Almost continuous and excellent data collection since launch
- Excellent ranging performance, especially at the higher end of the measurement band





Laser Ranging Interferometer (GRACE-I Architecture)

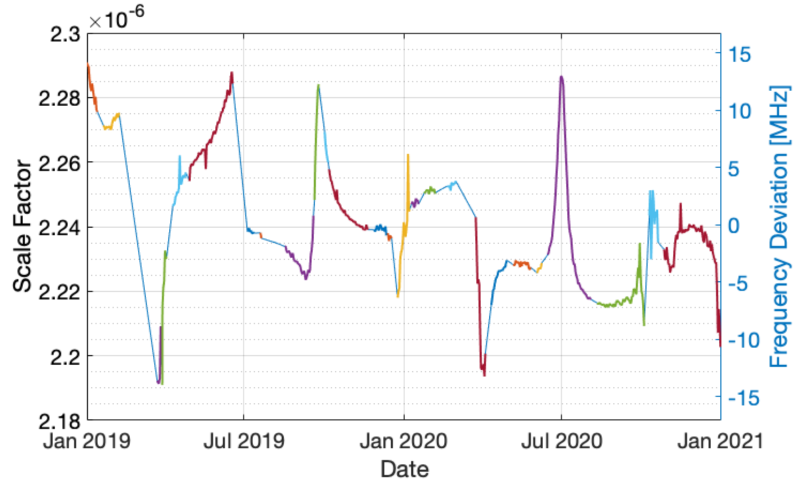
- Same responsibilities US (electronics, Laser) / D (optics)
- Still non-redundant optical paths (TMA & OBA)
- (Redundant) USO added
- Scale Factor Unit added (as no MWI available), provided by JPL/NASA
- Lessons learnt from GFO (e.g. reduce Laser sensitivity to thruster shocks (valve open/close))
- Added more redundancy (e.g. LRP, OB Electronics, Laser heads). Recent discussions at JPL/NASA suggest (cost constraints) LRI implementation w/o redundancy



New: LRI Scale Factor Unit

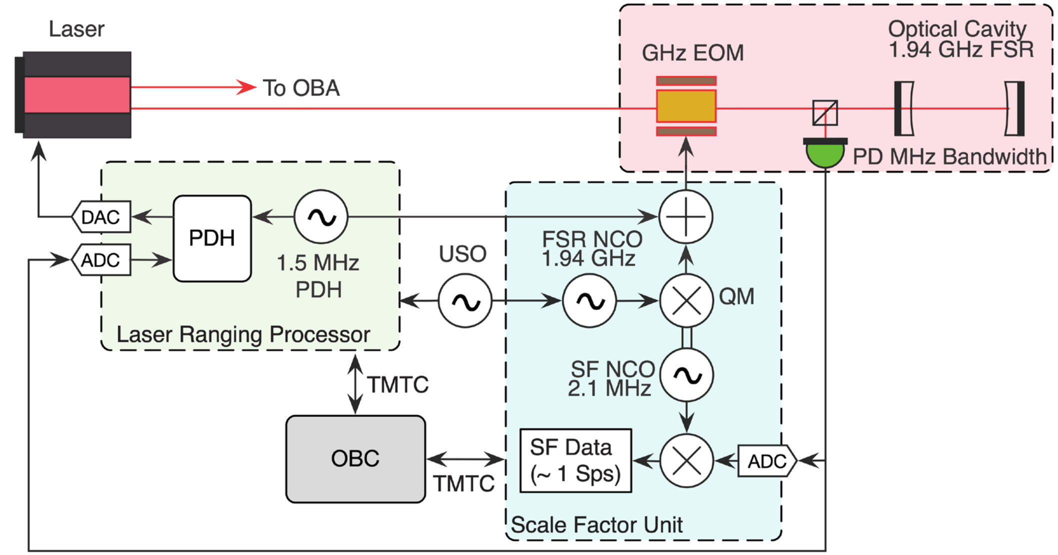
- Scale factor definition:
  - Correction applied to ground-measurement of laser wavelength when converting from optical phase [Cycles] to displacement [m]
  - Scale needs to be known to 1e-8 level
- Scale factor correction in GRACE-FO:
  - Inferred by comparing MWI and LRI range measurements
  - Peak-to-peak deviation is ~1e-7

GFO Scale Correction from MWI-to-LRI Comparison



- Scale Factor Unit (SFU) for GRACE-I/MCM LRI relates laser frequency to USO, providing a measurement of long-term laser frequency stability:
  - SFU is a separate unit to the Laser Ranging Processor (LRP)
  - Will be used to phase modulate the Laser at the Cavity Frequency System Reference (FSR)
  - Lab experiments (see paper) show performance ~3e-9 level over a month

Scale Factor Unit (SFU) Concept

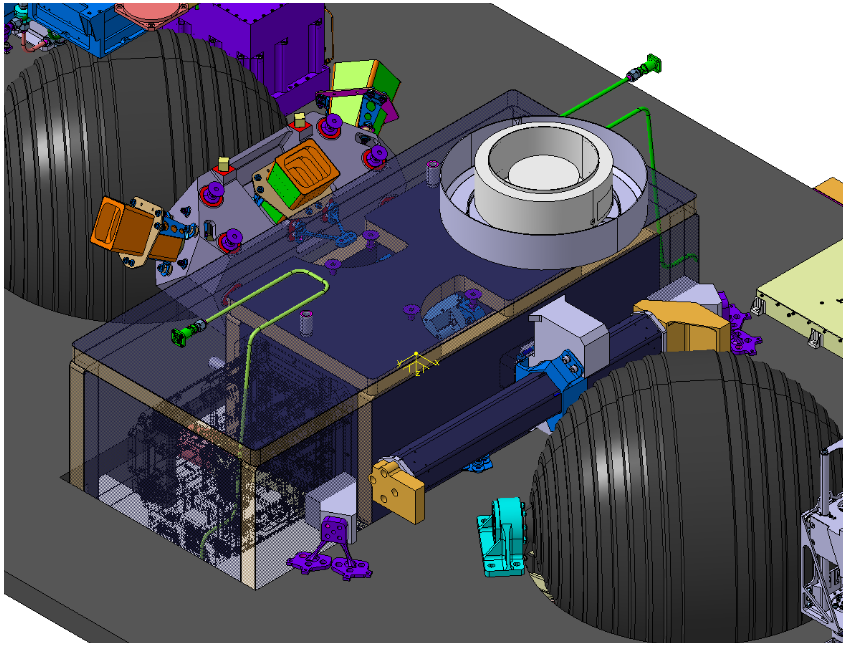


Paper: Emily Rose Rees, et al., Opt. Express **29**, 26014-26027 (2021)

GRACE-I Accelerometer (US Responsibility)

Trade from Phase 0 and Baseline in Phase-A:

- Accommodation of three GRACE-FO-type accelerometers in cross track direction with three individual ICUs
  - Provides redundancy for observing non-gravitational forces
- Accelerometer / Star Tracker Support Structure (ASTSS) comprised of:
  - Outer CFRP (Carbon Fiber Reinforced Plastic) Sandwich Main Support Structure with three isostatic mounts, and
  - Inner Accelerometer Support Structure
- Alignment concept adapted to take into account late ACC delivery/integration



Recent discussions at JPL/NASA suggest (cost constraints at NASA) to realize the instrument

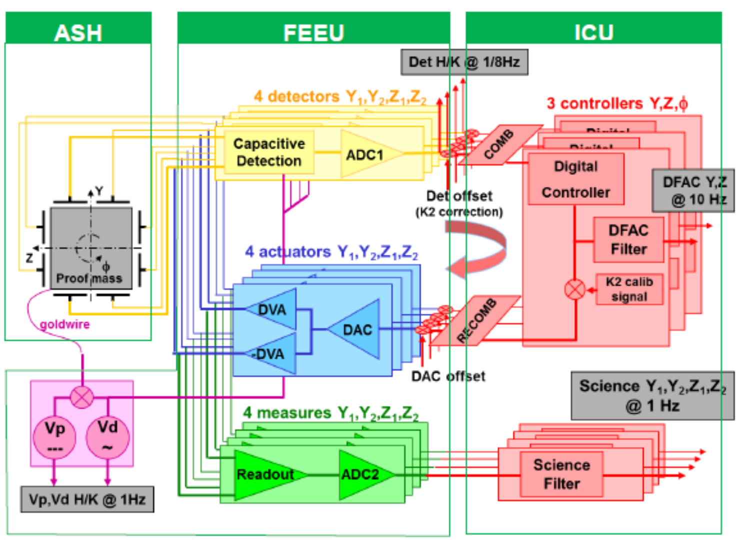
1) Without redundancies using one GRACE-FO spare ACC for each spacecraft (baseline), or
2) Alternatively, option 1) with additional ACCs yet to be build (potentially with ESA contributions of an adapted MicroSTAR family of accelerometers).

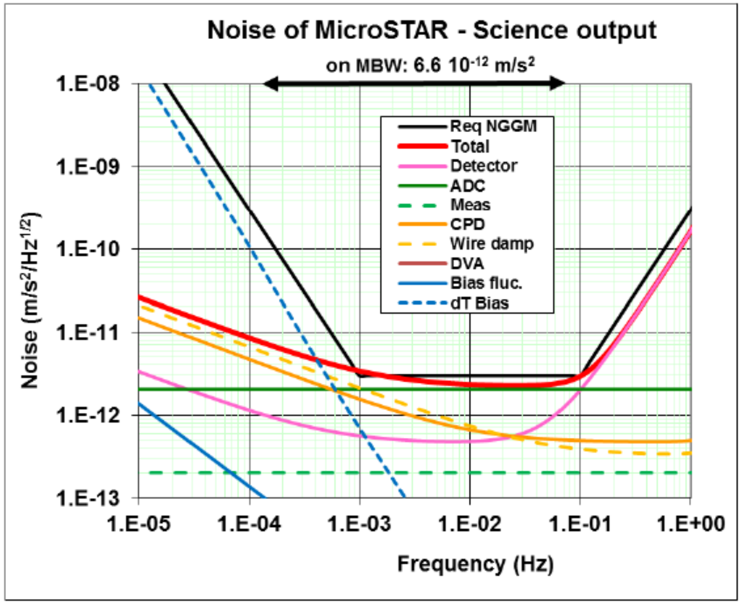
Adapted MicroSTAR Accelerometer Tech Demo

Further development of SuperSTAR (ca. 10 times increased performance), foreseen on P2

- Airbus has considered mechanical, thermal, EMC, interface, envelope, AOCS, performance issues and impact that such implementation would have on GRACE-I satellite level:
  - One MicroSTAR ACC Sensor Head (ASH) could be implemented either at a separate location in the fully packed bus, or
  - Two units could replace the 2 cross-track SuperStar-type ACCs (ASH volume still to be adapted to fit ACC housing structure).
  - Both option would also require adapted Front End Electronic Units (FEEU)
- ONERA, ESA and NASA/JPL are studying feasibility, decision in December

MicroSTAR electronics schematics

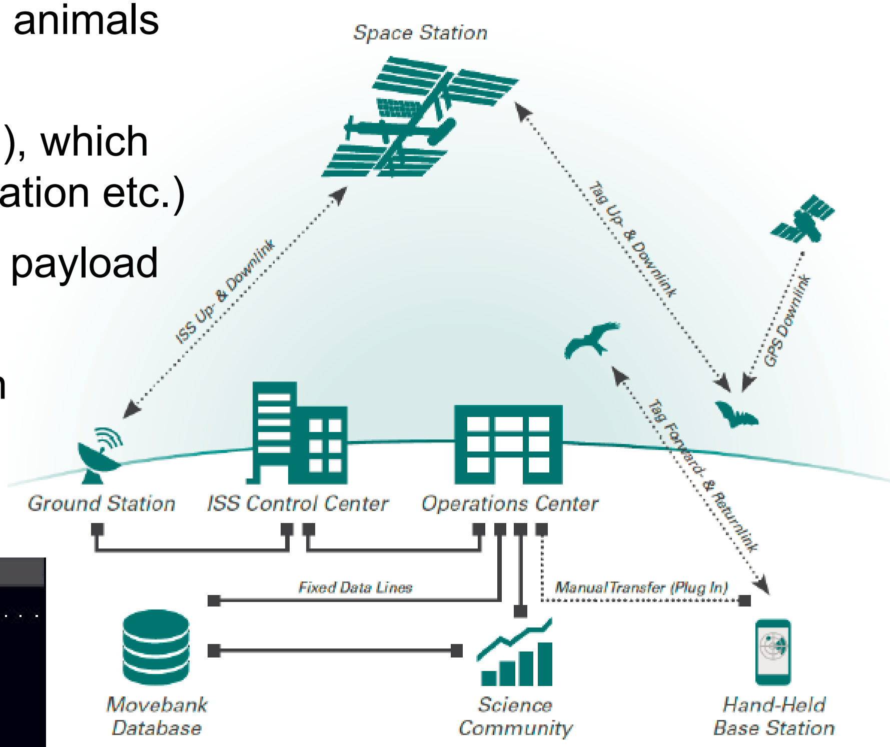


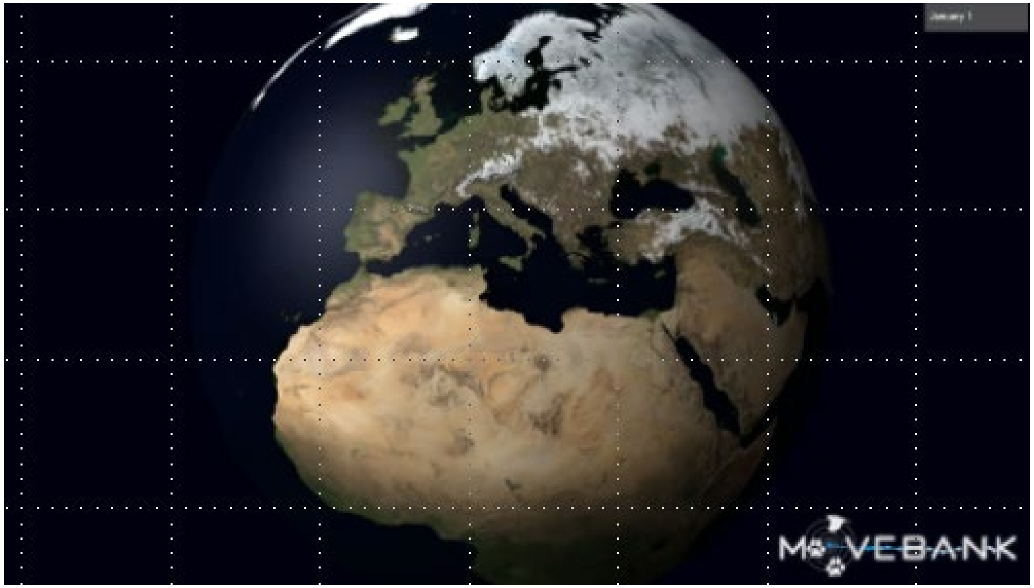


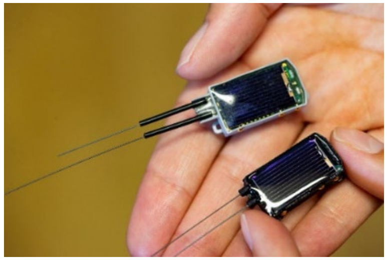
Christophe et al., ONERA accelerometers for future gravity missions, online poster, EGU2020

ICARUS on ISS

- Demonstrator mission for a system to track small animals (or any other objects) from space
- Animals/objects are equipped with small tags (5g), which log position and other data (temperature, acceleration etc.)
- Whenever in view, tags transmit logged data to a payload installed on Russian segment on ISS
- Data are communicated to ISS Control Center on ground, archived and distributed via MPG hosted Movebank archive







ICARUS = International Cooperation for Animal Research Using Space

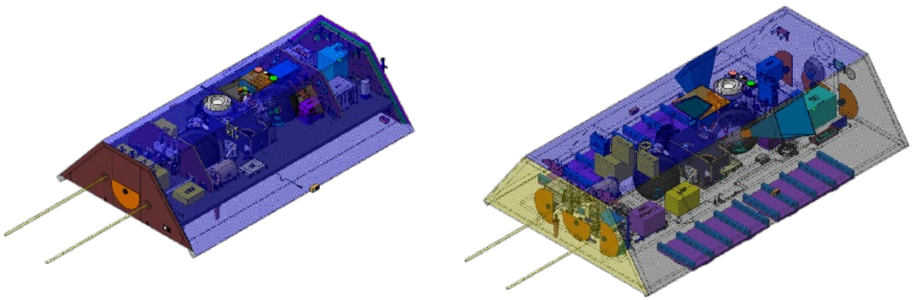
ICARUS on GRACE-I

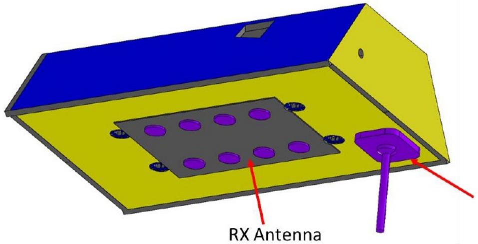
- **Objective for adding ICARUS to GRACE concept:** First time parallel operational monitoring of the global water cycle and animal tracks leading the way to simultaneous monitoring of linked variables (TWS, biodiversity) in the Earth System.

- Implementation will affect satellite size, mass and power consumption (paid by D)

- No disturbance of gravity mission shall be guaranteed by:
  - No moving parts
  - ICARUS H/W on both S/C always in same operational modus -> minimize thermal imbalance

- Still under discussion: deployable or body mounted TX antenna (affects launch configuration and drag coefficient)





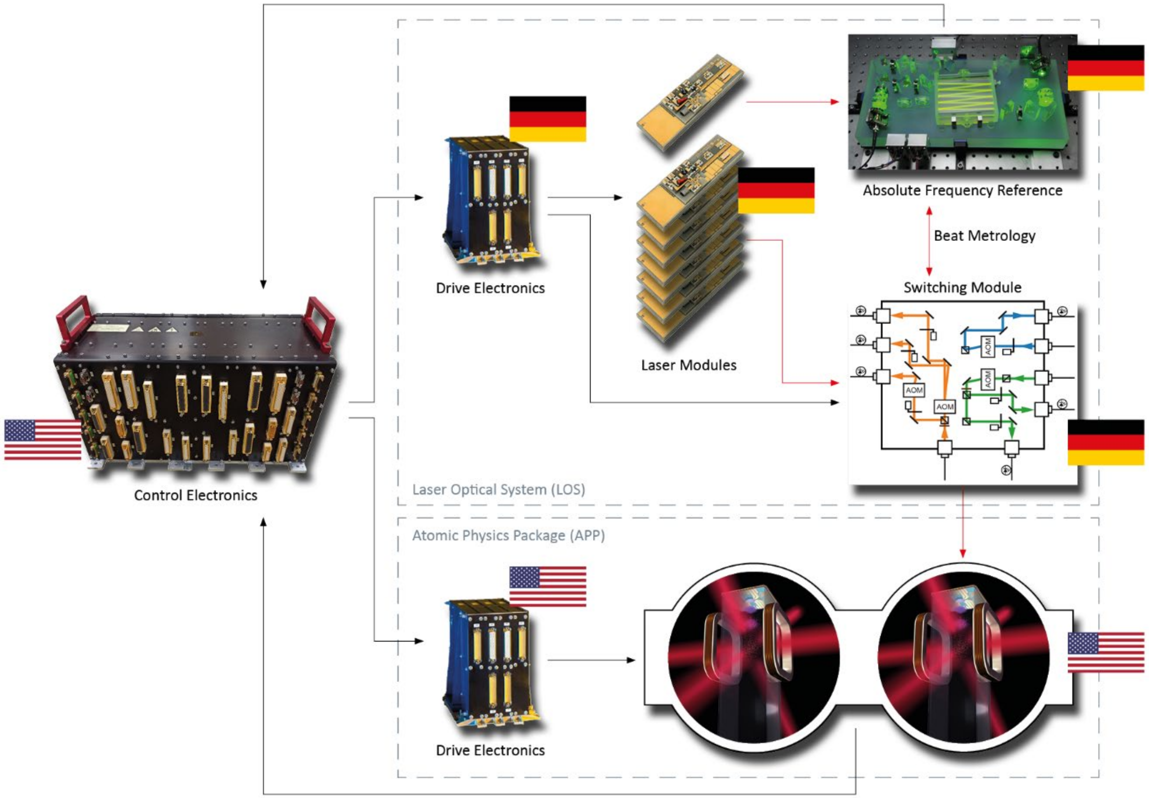
	Option 1 (Grace-FO heritage)	Option 3 Add ICARUS instrument
Instruments	Redundant LRI 3 ACC (SuperSTAR) GNSS Receiver no additional payloads	Redundant LRI 3 ACC (SuperSTAR) GNSS Receiver ICARUS
Power	Power Capability 349W	Power Capability 539W
Structure	LxWxH: 3.1 x 1.9 x 0.8 m Mass: ~630kg	LxWxH: 3.7 x 2.4 x 0.9 m Mass: ~830kg

Quantum Gravity Gradiometer (Phase 0 Option)

- QGG Tech Demo on GRACE-I would be the first QGG in space (similar to LRI idea on GRACE-FO)

- Responsibilities shared between Germany and US:
  - DE: Laser Optical System
  - US: Atomics Physical Package & Control Electronics

- Phase A TIM-4 decision: As there is no confirmed funding for a QGG on the US side **no QGG will be realized on GRACE-I**.

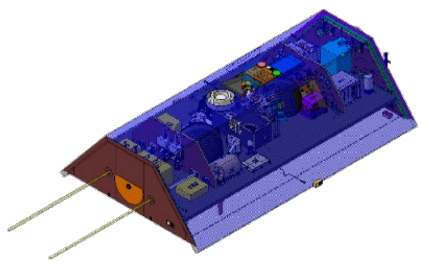


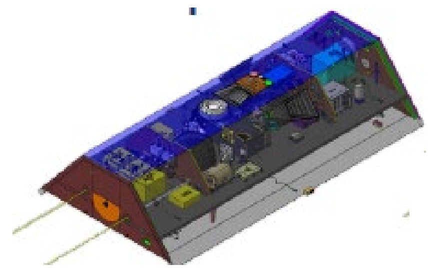
- But: The US (NASA/JPL) and German (Airbus/DLR) sides have set up a **QGG working group** with the objective to develop near and long-term science and technology roadmaps for QGG technology demonstration

GNSS Receiver

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

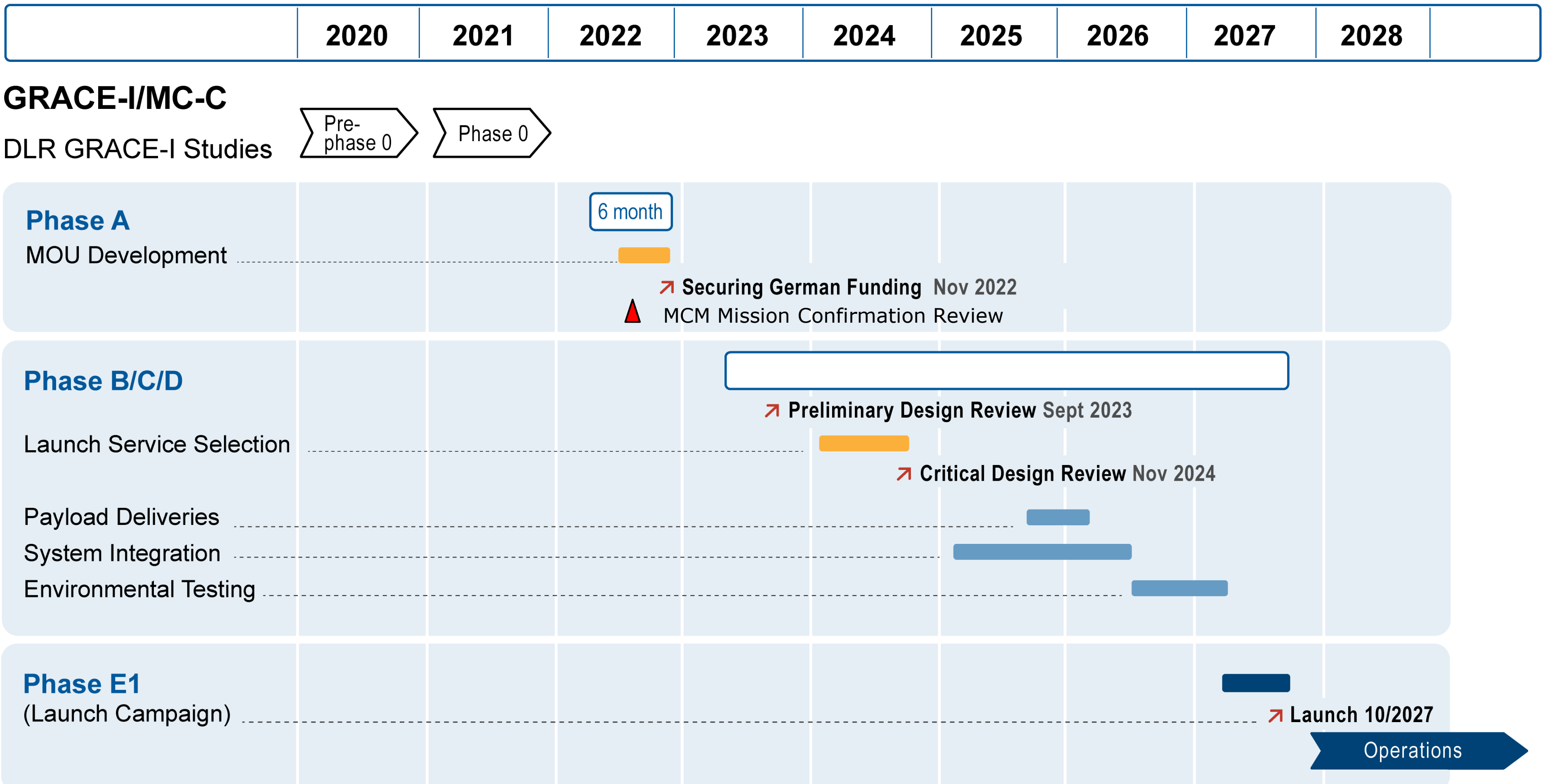
- **Optional:** add RO capability by adding e.g. (non-redundant) GRAS-2 instrument from RUAG
  - Implementation will affect (like ICARUS) satellite size, mass and power consumption due to additional RO electronics





	Option 1 (Grace-FO heritage)	Option 1b Add Radio Occultation
Instruments	Redundant LRI 3 ACC (SuperSTAR) GNSS Receiver no additional payloads	Redundant LRI 3 ACC (SuperSTAR) GNSS Receiver RO Instrument
Power	Power Capability 349W	Power Capability 386W
Structure	LxWxH: 3.1 x 1.9 x 0.8 m Mass: ~630kg	LxWxH: 3.4 x 1.9 x 0.8 m Mass: ~700kg

GRACE-I Schedule



Summary

- GRACE-I (MC) mission shall be realized jointly between Germany and JPL/NASA to guarantee mass transport data continuity based on LRI SST data

- Phase-A has been performed in close cooperation with JPL suggesting
  - Launch in fall 2027 (Space-X Falcon-9, backup ESA VEGA-C) into a 500 km orbit, lifetime 5 years, consumables for 7 years (till 2034)
  - Redundancy concept for LRI and ACC
  - German contributions similar to GRACE-FO: optical components LRI, launcher, mission operations, SDS contribution; satellites shall be build again by Airbus (subcontract from JPL)
  - Optional ICARUS payload would realize first time operational biodiversity monitoring in parallel to variations in the global water cycle (funding for payload and bus adaption by D)

- GRACE-I could be P1 of a staggered MAGIC Bender P1/P2 constellation (overlap ca. 3 years)

- Phase-A goal to derive a baseline mission concept to be developed in Phase B/C/D not yet completely reached. Further discussions still needed to fix
  - ACC concept (spare GFO ACCs, add on of ESA provided adapted MicroSTAR ACC),
  - Redundancy concept of LRI and ACC
  - Additional payloads (ICARUS and/or additional RO GNSS receiver)

- To be decided till December (as all affect bus design, cost and probably mission lifetime)

- German funding shall be secured till November 2022 (ongoing activities with German politics)

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