

# Realization of a satellite mission “GRACE-I” for parallel observation of changing global water resources and biodiversity

GRACE/GRACE-FO Science Team Meeting  
28.10.2020

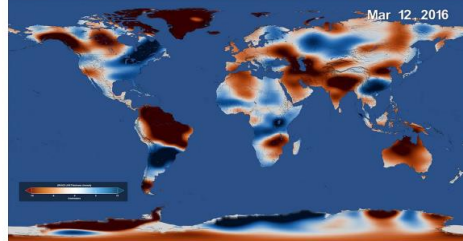
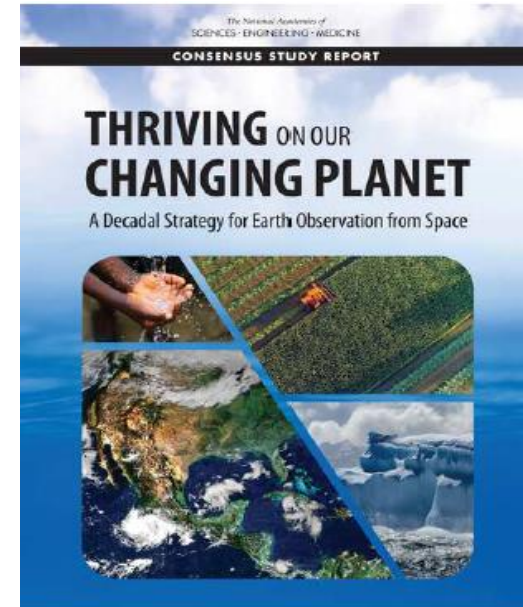
Frank Flechtner<sup>1</sup> and the GRACE-I Team<sup>2</sup>

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2: DLR RfM, DLR institutes Hannover and Bremen, Airbus D&S GmbH, Space Tech GmbH, MPG institutes Hannover and Konstanz

# Background

- GRACE-FO
  - has a **nominal mission lifetime** of 5 years (5/2023).
  - Fuel consumption, thruster activities or solar activity evolution **predict a lifetime at least of 2027/28**.
  - Unfortunately, **2 single point of failures** (GFO-2 IPU, GFO-1 accelerometer) could **end the mission any time**.
- 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 such as Mass Change Mission (MCM) NASA is seeking for international partnership.**
- **Continuation of the very successful technological and scientific GRACE and GRACE-FO partnership between the U.S. and Germany is in the involved partners' highest interest** (see White Paper 2019) and would be based on a strong heritage in the fields of satellite manufacturing, laser ranging interferometry or science data utilization.



Mar 12, 2016

**A next GRACE mission in the Quantum Era**

Why we need a future Mass Change Mission and why it shall be realized again predominantly in a U.S.-German partnership

Version 2, 22.01.2019

Reinhard Hüttl  
(Scientific Executive Director GFZ German Research Centre for Geosciences)

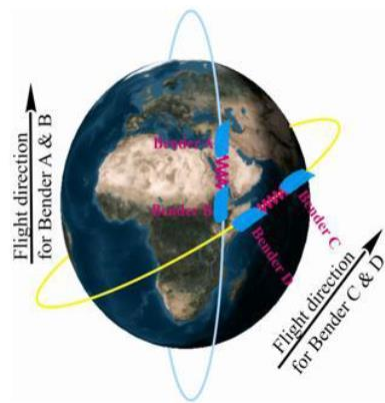
Pascale Ehrenfreund  
(Chair of the DLR Executive Board)

Karsten Danzmann  
(Director Albert-Einstein-Institut, AEI Hannover: Max-Planck-Institut für Gravitationsphysik und Institut für Gravitationsphysik der Leibniz Universität Hannover)

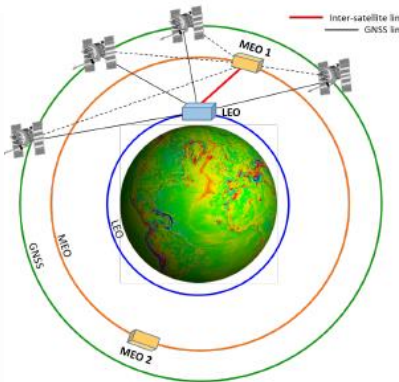
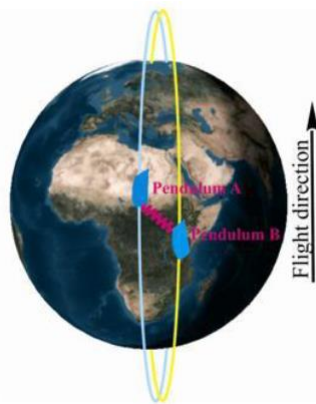
Martin Wikelski  
(Director of the Max-Planck-Institute for Ornithology, Radolfzell after May 2019: Max Planck Institute of Animal Behavior, Konstanz)

# User Priorities

- 1) Continuous mass transport data w/o any gap to secure already existing (pre)operational services. This would need a quick realization of another single pair mission with phase A starting in 2021 and launch end of 2026 to secure an overlap with GRACE-FO for cross-calibration.
- 2) Increased spatial and temporal resolution for improved mass transport products (expressed by threshold and target requirements, see Pail et al.). This would need more advanced mission architectures and instrumentation such as a double pair ("Bender"), a Pendulum constellation (with large tilt angle) or the MARVEL/MOBILE concept.



Elsaka et al. 2014



"Mobile"

Pail et al. 2019

Surv Geophys (2015) 36:743–772  
DOI 10.1007/s10712-015-9348-9



## Science and User Needs for Observing Global Mass Transport to Understand Global Change and to Benefit Society

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# Study Goals

- The goal of a study, jointly performed in summer 2020 between DLR space administration and institutes, industry and HGF and MPG scientists, was to **bundle up an attractive scientific and technological German package for further discussions with NASA** which
  - 1) compares the cost and benefit of technical modifications with respect to GRACE-FO
  - 2) is not only attractive for a future MCM but also for the Laser Interferometer Space Antenna (LISA) and
  - 3) strengthens at the same time Germany's role towards ESA's Next Generation Gravity Mission (NGGM) implementation.
- This joint US-D mission is intended to be a **single-pair GRACE-FO successor**
  - a) **securing** the user need for **continuity** (user priority #1) and
  - b) **may be realized in a double-pair constellation with GRACE-FO**, e.g. launched into an inclined orbit and thus realizing the **first Bender-type constellation fulfilling the user need for increased resolution** (priority #2)

Note: Decision on inclination must already be made @ System PDR (~2022) to fix ACC, solar cell arrangement or launcher related issues. Final trim of orbital parameters @ System CDR.

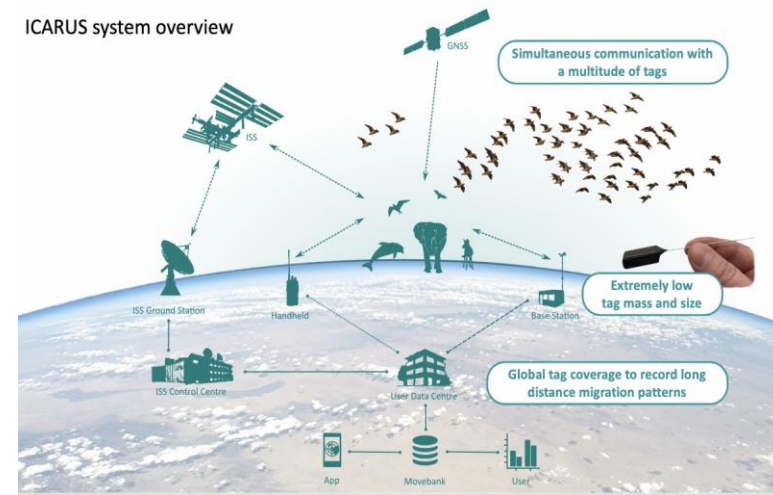
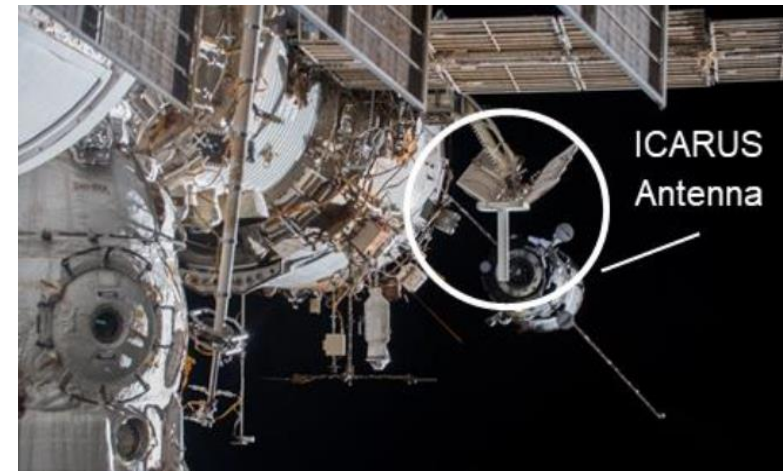
# Mission Options

- Three mission options have therefore been investigated:
  - 1) A reference design based on the GRACE-FO platform and technology with a redundant LRI as the main satellite-to-satellite tracking instrument
  - 2) Add-on of the ICARUS payload, and
  - 3) Implementation of further technology options such as
    - S/C and mission related enhancements, e.g. improved AOCS, drag compensation / drag free options or inclusion of Galileo tracking signals,
    - LRI related enhancements which are important for LISA and/or MCM such as enabling of absolute range measurements, data transfer between both satellites or a German developed phasemeter or cavity issues and
    - inclusion of technology demonstrators based on quantum technologies such as inertial sensors with cold atoms, monolithic accelerometers or the LISA-based gravity reference sensor (GRS).
- Nominal separation for all options was 220 km at an altitude of
  - a) 490 km with free-decay (Options 1a, 2a and 3a), or alternatively
  - b) 420 km maintained by electric propulsion (Options 1b, 2b and 3b).
- No simulations have been performed (subject for next study phase), but it is already known that flying lower will definitely improve the medium and small spatial scales of a single-pair mission on a polar orbit.



# Why ICARUS?

- Germany has recently pioneered a **novel ground-to-space IoT** (Internet of Things) **communication system ICARUS** (International Cooperation for Animal Research Using Space).
- ICARUS is currently **successfully operated as a technology demonstrator onboard the ISS** by transmitting various sensor data from on-animal 'wearable tags'. The data are collected into the Internet of Animals, which synthesizes the collective sensor information from thousands of animals around the globe already in real time.
- ICARUS on a future polar-orbiting GRACE-like "GRACE-ICARUS" (or short "**GRACE-I**") mission could provide **scientific extension of biodiversity monitoring, which is another designated observable in NASA's Decadal Survey** (Surface Biology and Geology).

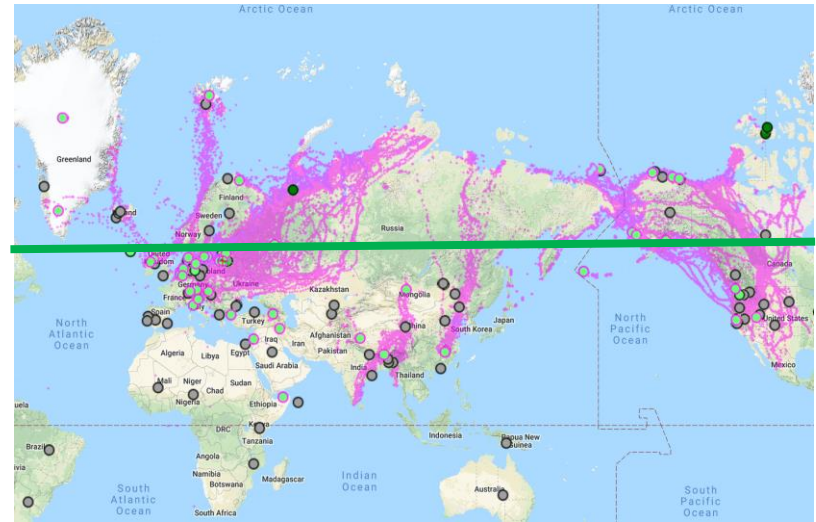


# Arguments for add-on Payload ICARUS

- GRACE-I enables an **operational ICARUS mission at relevant latitudes ( $i > 51^\circ$ )** and **further tag miniaturization** for a multitude of applications.
- **Unique cooperation** MPG-HGF and Germany-NASA/JPL possible
- May help to secure funding from German Federal Ministry for Economic Affairs and Energy (**BMWi**) **requiring technological advances** such as the LRI on GRACE-FO!



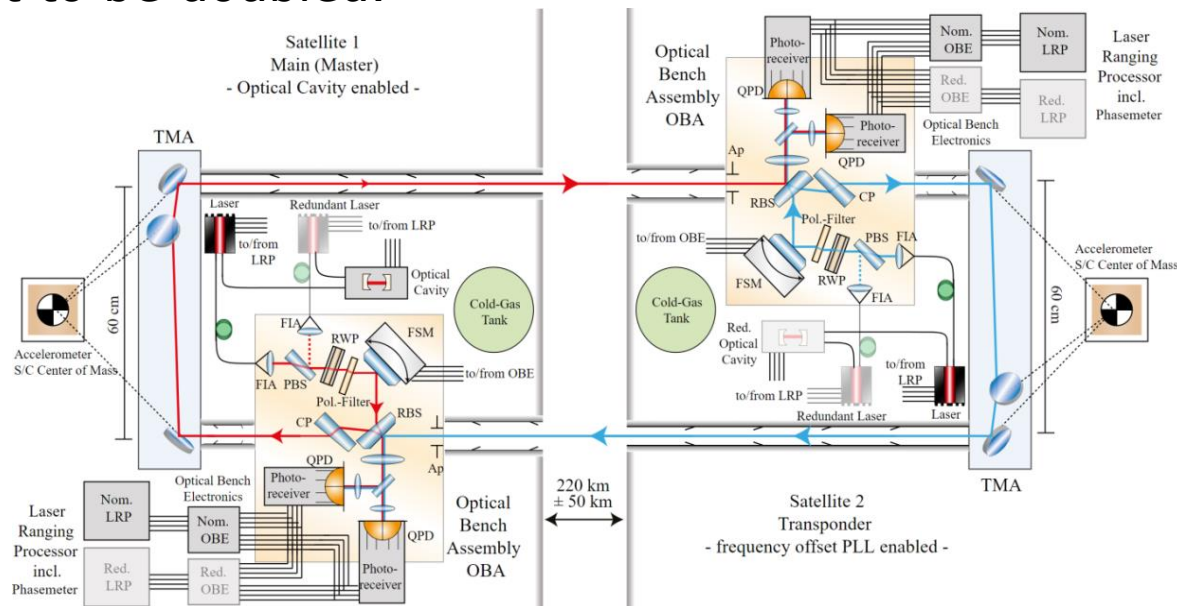
Example of current tags



Global movements of geese. Several species travel from the high arctic into subtropical regions and thus span almost the entire range of climate zones.

# Major Findings of GRACE-I study (1)

- The realization of a **GRACE-I baseline mission** orbiting at 490 km (Option 1a) based on GRACE-FO heritage (e.g. accelerometry or AOCS) and a redundant LRI as the main satellite-to-satellite tracking (SST) instrument, is technically possible.
- The **redundant LRI** would comprise cold redundant components for the laser head, the laser ranging processor including the optical bench electronics as well as for some other critical components such as the laser fibers. The optics of the triple mirror assembly and the optical bench need not to be doubled.



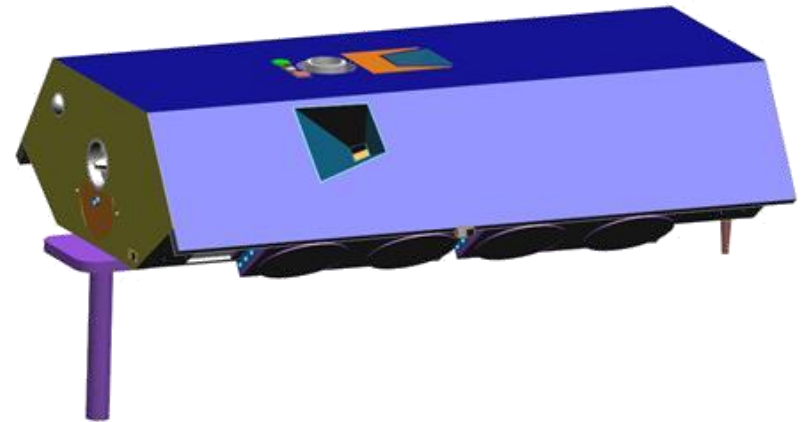
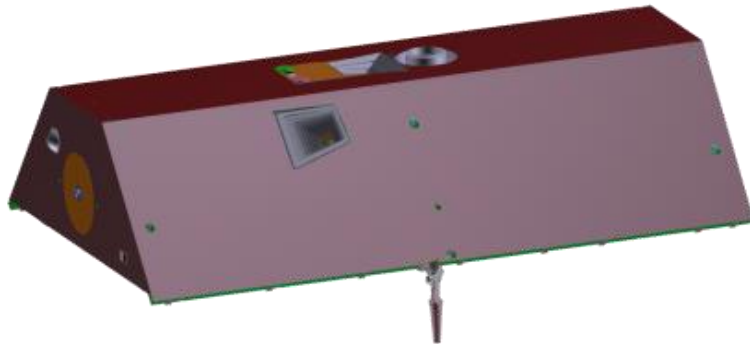


# Major Findings of GRACE-I study (2)

- Flying at a lower **altitude of 420 km** (to increase the sensitivity for monitoring variations in the gravity field) **needs implementation of an electric propulsion system** (Option 1b).
- A **combined cold gas / electric propulsion system** is suggested where the heritage **GRACE-FO cold-gas system** is extended by **advanced cusped field thrusters with high throttle range** which guarantees a very high operational flexibility.
- **Using Krypton instead of GN2** the heritage propellant tanks will provide plenty of margins and could even be reduced in size.

# Major Findings of GRACE-I study (3)

- **Add-on of the ICARUS payload** is possible for both orbital altitudes (Options 2a and 2b). As the power demand will increase by about 110W an approximately 20% larger solar array is required which will elongate the spacecraft body by about 70 cm, but secures similar ballistic coefficient (ICARUS antenna design still offers potential for further optimization).



# Major Findings of GRACE-I study (4)

- Other **orbit options** have been reviewed within Option 3:
  - Flying on e.g. a **pendulum orbit with large tilt angle** (which would increase the sensitivity to East-West gravity variations) will need further investigations as resulting relative velocities of the two spacecraft will be likely too high for LRI operation.
  - For **lower altitudes than 420 km** (to further increase the sensitivity for gravity changes) the increased magnitude of the non-gravitational forces maybe too large for the accelerometer and **an even more sophisticated AOCS may be necessary**.
  - **Increasing the separation of the spacecraft** from 220 to e.g. 300 or 400 km (which would decrease the effect of accelerometer errors) **would on the other side increase the pointing requirements between both satellites** which might counteract the positive effect of the large distance.

All three would need to be further investigated in a follow-up study.

# Major Findings of GRACE-I study (5)

- Further **LRI-related enhancements**, which may not only improve GRACE-I but also advance the technology and provide **valuable demonstrations for LISA**, include the
  - implementation of **absolute ranging capability**,
  - **data transfer or clock synchronization between both satellites**,
  - add-on of a **dedicated acquisition sensor** to speed up the process of initial acquisition,
  - **substitution of the baseline Fabry-Perot cavity** by an iodine laser frequency reference to increase the accuracy of the frequency to get a much stable conversion factor from optical phase to distance, or
  - use of an **alternative phasemeter or cavity manufactured in Germany or Europe**

**are all feasible** and should be further investigated in a follow-up study.

# Major Findings of GRACE-I study (6)

- **ONERA's SuperStar accelerometers** used on GRACE and GRACE-FO are also foreseen to be **used in the GRACE-I baseline mission design**.
- Alternatively, a **downscaled and significantly modified version of the Gravitational Reference Sensor (GRS) developed in the LISA mission context could be a viable option**.
  - The modifications are required due to the **fundamentally different environment** in the low Earth orbit of GRACE-I compared to the quiet deep space orbit of LISA-like missions.
  - **Some of the techniques used in the GRS could potentially enhance also accelerometry in GRACE-like missions**, which is currently subject of research and needs further investigations in a next study phase.



# Major Findings of GRACE-I study (7)

- **Necessary additional resources** (volume, power, mass, data handling) **are available** as no KBR will be needed. Can be used for a subset of Option 3 **technology demonstrator payloads**, depending on the finally chosen configuration without or with ICARUS, e.g.
  - The technological maturity of **optomechanical inertial sensors** makes them an attractive option for GRACE-I where they would be very useful as **diagnostic tools to analyze events that cannot be resolved by the main accelerometer** due to its limited bandwidth. This includes e.g. micro-shocks that are introduced by thruster firings as observed on GRACE-FO.
  - In contrast electrostatic or capacitive accelerometers are prone to temperature-driven bias drifts. These can be mitigated by using a **hybrid accelerometer scheme** in which a classical accelerometer is paired with a cold-atom interferometer. However, **substantial work is required to miniaturize the current generation of cold-atom sensors** and to make them sensitive enough for an application in a mission like GRACE-I. Therefore, this promising technology **cannot be implemented on GRACE-I** yet, but will hopefully be usable for future missions.

# Major Findings of GRACE-I study (8)

- Even with the ICARUS payload GRACE-I is compatible with a **launch either on a European VEGA-C or a U.S. Falcon-9 launcher**. Both would offer additional space for co-passengers to reduce launch costs.
- **Fuel budget** analysis has shown that **GRACE-I can be operated in all options longer than 10 years**, even though we would propose to set a shorter mission lifetime requirement to save testing cost.

# Next Steps: GRACE-I Phase-0 Study

- A 10 months phase 0 study will be performed from late 2020 until summer 2021 by German industry under contract of DLR.
- Major goals: Analyse feasibility and scientific benefit of single-pair GRACE-I concept
  - Satellites
  - Payloads (gravity incl. LRI enhancements or tech demonstrators; addons)
  - Orbit / gravity simulations:
    - polar pair (altitude (490 vs. 420 km); separation (100,200,300 km) vs.
    - more advanced pair (inclination  $70^\circ$  ) or Pendulum (TBD)
- Coordination with JPL via TIMs incl. layout of simulations (background model and instrument error models, orbit variants etc.) in JPL's 3<sup>rd</sup> phase of their Mass Change Study.
- This period will also be used to have detailed discussions with German Ministries BMBF and BMWi as well as HGF and MPG to secure necessary funding for German provided GRACE-I mission elements.

# Next Steps: Combination with ESA's NGGM

- Significant improvement in accuracy and resolution of future mass transport models fulfilling the target and threshold science user requirements **can only be reached by a double pair constellation.**
- A first realization could be (depending on status of GRACE-FO and decisions @ GRACE-I System PDR) a **GFO/GRACE-I combination in 2027.**
- NASA and ESA are already in close discussions for a double-pair realization and ESA is currently preparing for a NGGM in the Mission of Opportunity element of FutureEO. **DLR, GFZ are supporting NGGM and are in contact with ESA and NASA for a harmonized approach.**
- An advanced NGGM single-pair (low polar orbit ~350km, improved accelerometry and AOCS, etc.) could substitute GRACE-FO in 2028/29 and be combined with GRACE-I to aim for **another (or first) Bender constellation.**
- A 2nd advanced NGGM (if funding exists), successively launched after NGGM-1 into a 70° orbit, could **extend the period of Bender constellations and further improve MC products.**

20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38
GRACE-FO operation																		
							GRACE-I @ 70°											
									NGGM @ 90°									
							Bender-1		Bender-2									
											NGGM-2 @ 70° (?)							
											Bender-3							