The Laser Ranging Interferometer on GRACE Follow-On

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The geoid is a hypothetical construct that represents that surface on which all points have the same gravitational potential.

It represents what the Earth would look like if it were completely covered with water and in the complete absence of all non-gravitational forces.

The geoid is a function of the mass distribution. It changes when rocks move, when ice melts or water accumulates.
The GRACE Principle

- Pioneered by US-German GRACE mission 2002-2017
- μ-wave ranging with ≈ 2 µm/√Hz noise
- No absolute ranging (GPS positions are enough)
- Needs accelerometer to measure non-gravitational forces
Satellite gravity missions and laser interferometry

Variations due to water etc. are much smaller
Numerous disturbances such as ocean tides, solid earth tides, aliasing...
Optimal data processing is still under development after 15 years of operation
Final gravity field resolution: \( \approx 350 \text{ km spatial resolution for monthly global gravity fields, } \approx 200 \text{ km for static fields} \)
Some GRACE results

Image credits: GFZ, NASA, CSR
Changing water level

Annual geoid variations due to rainy/dry seasons

Image Credits: NASA/JPL
GRACE Follow-On

- GRACE mission ended 2017, long past its design life
- New mission to continue the same data stream
  - Same US-German collaboration
  - Near rebuild of GRACE using microwave ranging as primary instrument
  - New: laser interferometer as experimental demonstrator:
    first laser interferometer between satellites.
Transponder configuration

- Primary measurement: distance variations (nm) between spacecraft (200 km apart)
- Offset phase locked transponder
  - Different from KBR Dual one-way ranging
  - Similar to a LISA link in many aspects

$$|f_D| = \frac{|v_{rel}|}{\lambda}$$
Laser Ranging Interferometer

- Optical bench is rather simple
- Elegant and efficient beam steering that aligns both TX and RX with a single steering mirror that is outside of the sensitive path
- Send 90% of laser beam to other spacecraft via steering mirror and triple mirror; use 10% as local oscillator for beatnote detection on photodiode
LRI Laser ranging noise sources

- **Laser frequency noise (requirement 30 Hz/√Hz, like LISA)**
  - Reference cavity on one spacecraft, offset phase lock on second spacecraft

- **Pointing jitter**
  - Beam steering mechanism and special properties of triple mirror

- **Thermally driven effects**
  - Mitigate with appropriate material choice, thermal shielding and control

- **Readout noise (important for acquisition):**
  - USO noise
  - Shot noise
  - Laser power noise
  - Photodetector electronic noise
  - Parasitic signals (e.g. scattered light and electronic cross-talk)
  - ADC quantization noise
  - Spurious electronic phase shifts
Expected LRI gravity results

- Gravitational field is recovered by combining
  - *inter-satellite ranging data*
  - non-gravitational forces measured by accelerometers
  - precise satellite orbits
  - Background models, ...

- We only deal with the ranging instrument performance
- Pre-launch simulations predict an only modest improvement in the gravity fields
- LRI performance is designed to be well below other noise sources
- Has **huge margin** for coming improvements in background models, data processing etc.
- Will allow **cross-instrument diagnostics** between KBR and LRI
LRI performance requirement

- Noise budget designed to be not dominant at any frequency
- LRI is conceived as experimental demonstrator
  - Reduced requirements on lifetime and reliability
  - No redundancy
- Aim for reliable long-time operation nevertheless

LISA: 0.01 nm/√Hz
Laser ranging interferometer

- Measurement is directly the round-trip distance between TMA vertices, insensitive to paths on optical bench
- \( M = x_1 + x_2 + x_5 + x_3 + x_4 + x_5 = 2(d_1 + d_2 + x_5) = 2L \)
Laser frequency stabilisation

- Frequency noise coupling proportional to arm-length mismatch:
  \[ \delta x = \Delta L \frac{\delta \nu}{\nu} \]

- \( \Delta L = 200 \text{km}, \) Stabilisation is required,

- LISA tricks (armlocking, TDI) not applicable, since there is only one link (“arm”)

- Space qualified reference cavity developed by Ball Aerospace and tested at JPL

- Fulfills LISA requirements as well

Prototyping at AEI

- Optical Bench
- Triple mirror vertex
- Functionality
LRI Flight Components

- Laser Phasemeter
- Cavity
- OBA
- Triple Mirror Assembly
- Baffle
- Optical Bench Electronics

JPL

US

D
LRI testing: TVAC at IABG (2017)
LRI Link acquisition

• Large initial pointing uncertainty must be calibrated
• Later reacquisition has smaller range but must be autonomous
• Was considered critical and intensively studied by detailed simulations and experiments (AEI, JPL, ANU)