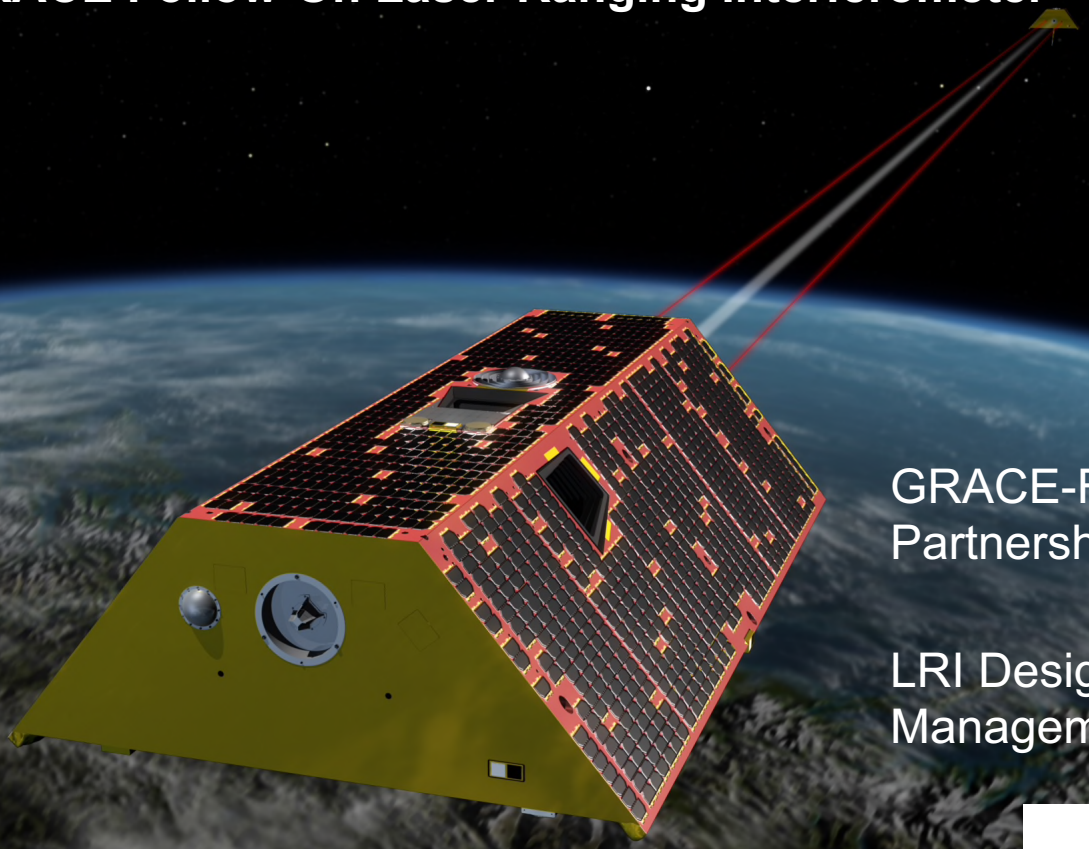
Data processing and calibration for the GRACE Follow-On Laser Ranging Interferometer

Brent Ware, for the
US and German LRI collaboration

NASA/Jet Propulsion Laboratory,
California Institute of Technology

GSTM-18 GFZ Potsdam 9 October 2018



GRACE-FO Partnership

LRI Design & Management

LRI implementation

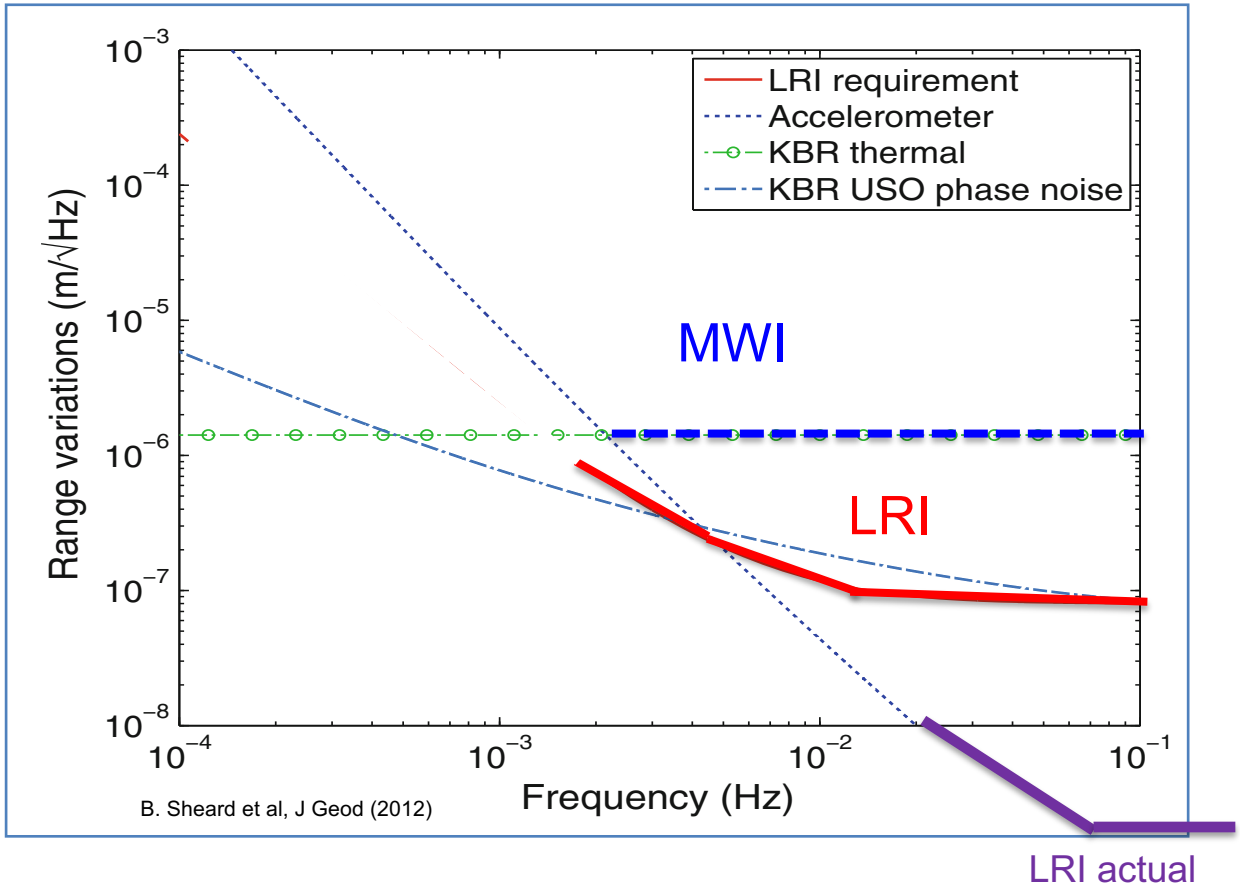
© 2018 California Institute of Technology.
Government sponsorship acknowledged.

Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

LRI data analysis and calibrations outline

- **Scale factor comparison and calibration**
- **MWI and LRI initial postfit residuals**
- **Phase jumps**
- **LRI continuous readout of line-of-sight angles**
- **Predicted sensitivity versus measured**

GRACE Follow-On Requirement Noise Levels



The Laser Ranging Interferometer (LRI)

The LRI is a partnership between the US and Germany

US: Stabilized laser and Metrology

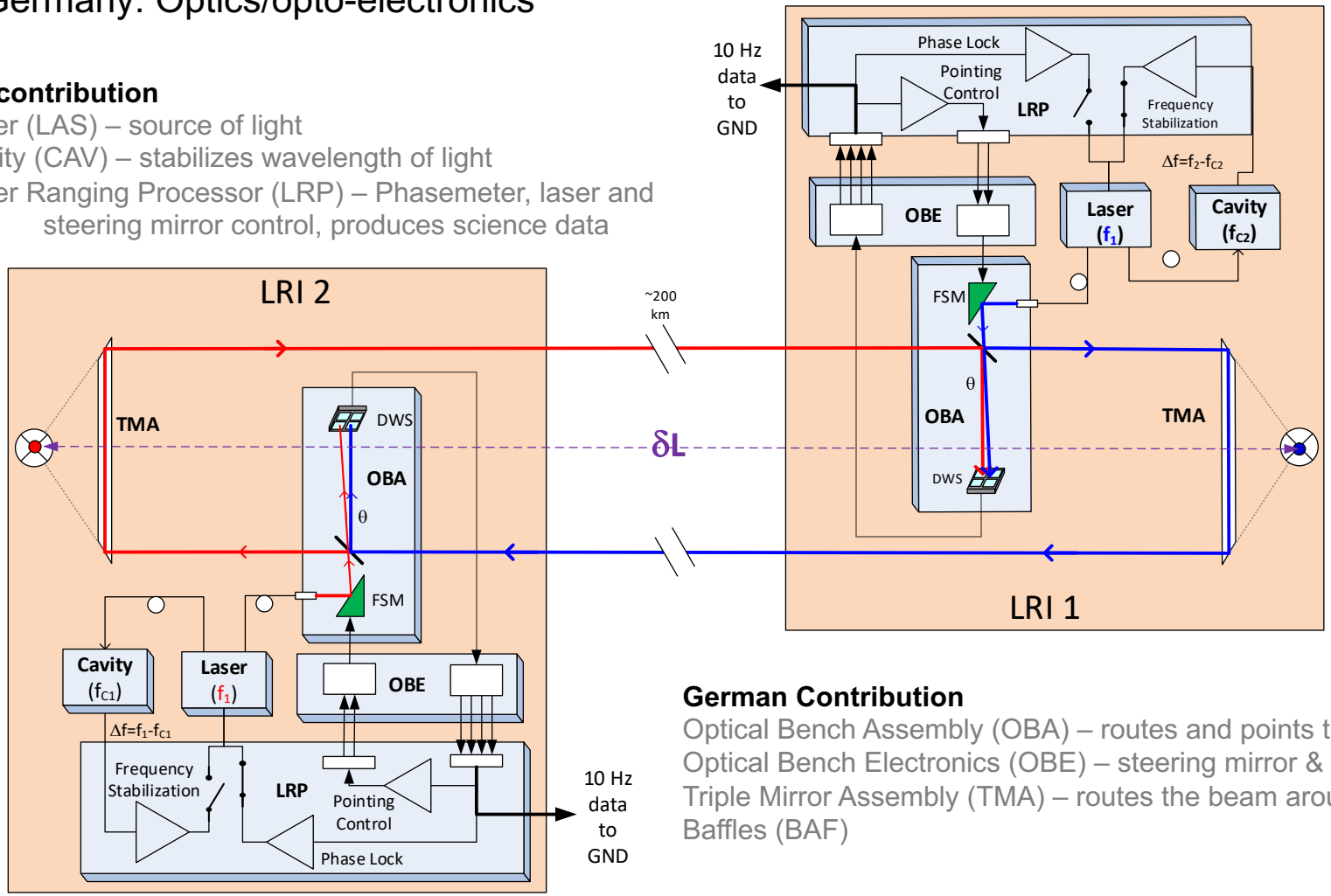
Germany: Optics/opto-electronics

US contribution

Laser (LAS) – source of light

Cavity (CAV) – stabilizes wavelength of light

Laser Ranging Processor (LRP) – Phasemeter, laser and steering mirror control, produces science data



German Contribution

Optical Bench Assembly (OBA) – routes and points the beam

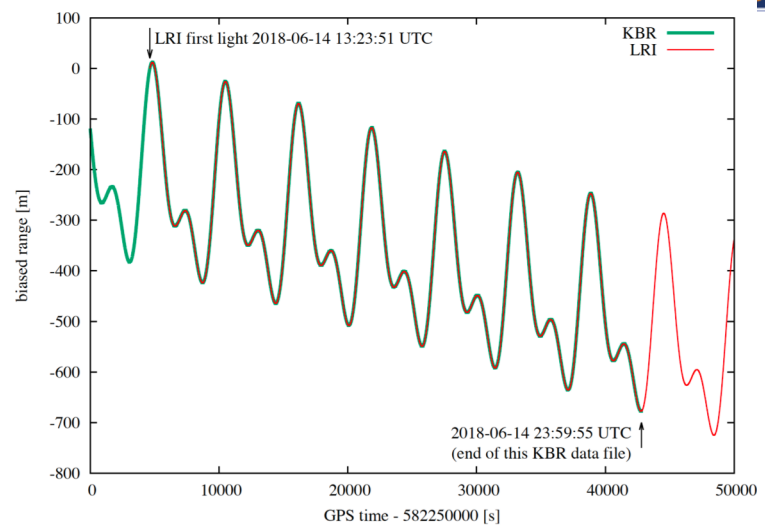
Optical Bench Electronics (OBE) – steering mirror & detector drivers

Triple Mirror Assembly (TMA) – routes the beam around MWI

Baffles (BAF)

Calibration – scale factor between MWI and LRI

- LRI and MWI are measuring the same signal

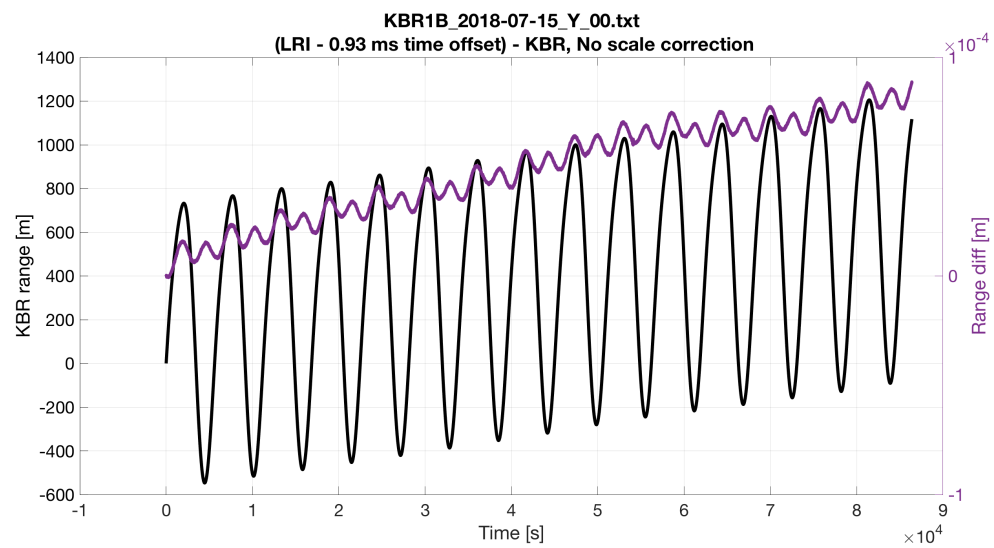


- Analyse the difference:
  - 1 part in 10^9 over a day

- Calibration between LRI and MWI
  - 80 µm/day drift → this is plausible with laser frequency change due to cavity temperature change of 13 mK/day

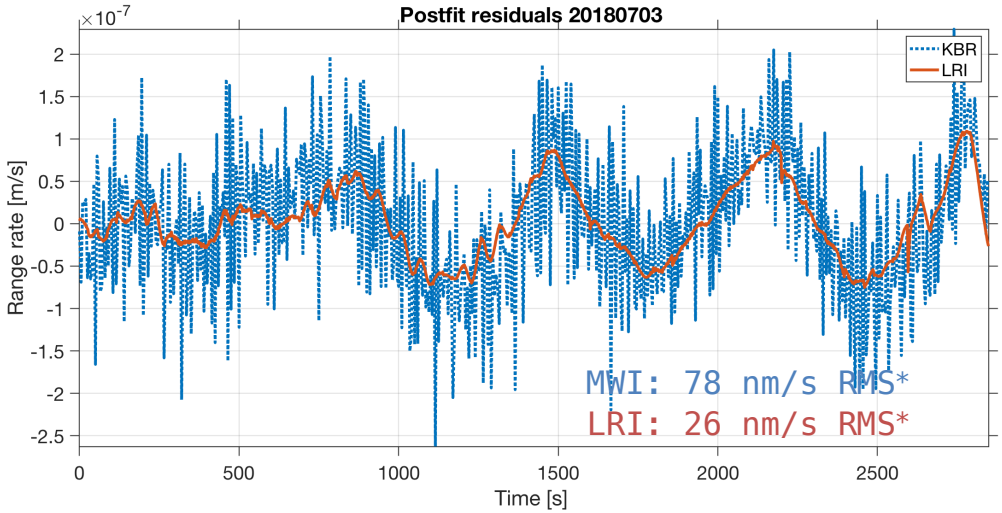
- Analysis ongoing

- Good agreement between the instruments



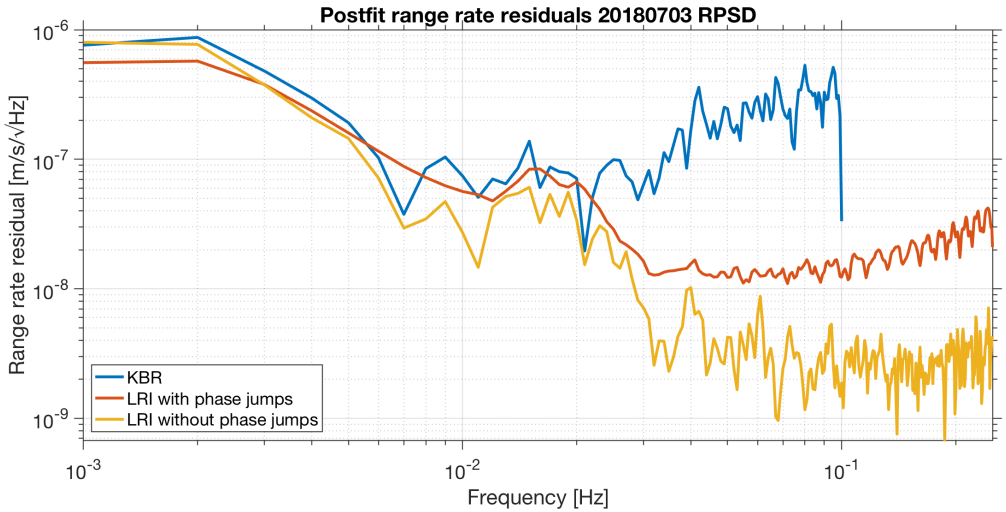
LRI and KBR postfits first results (with phase jumps)

- Postfit residual
  - After incorporating measurement into gravity field estimation: postfit residual = measurement – gravity field estimation.



- LRI signal is clean at high frequencies
  - LRI – 1.0 nm/s over 5s (estimate of the instrument noise only)

- At lower frequencies – still some signal
  - Both track identically
    - see scale factor

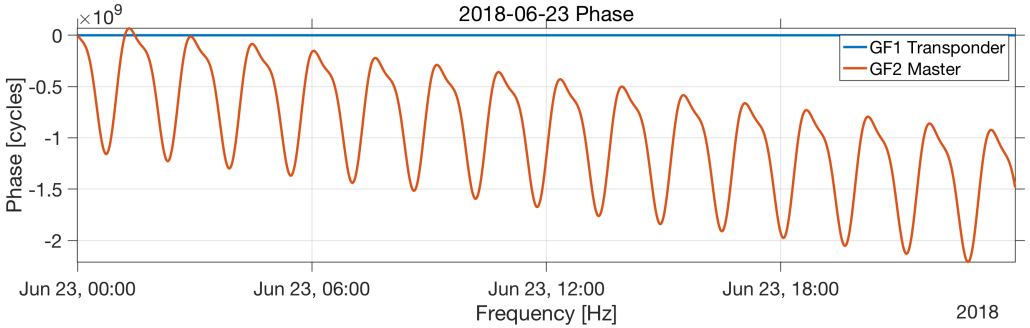


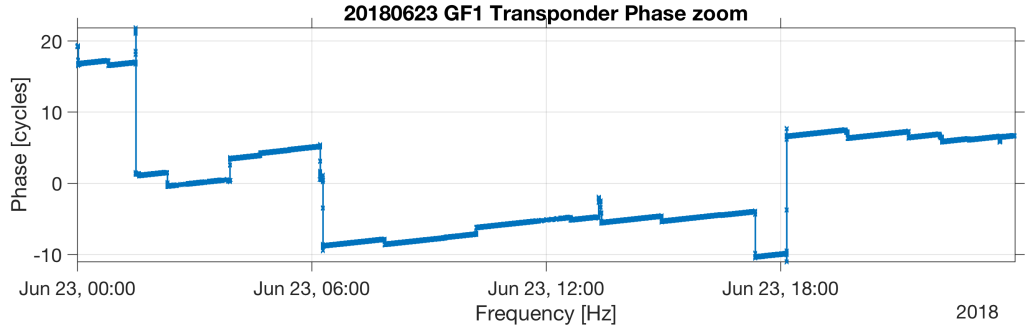
- **LRI provides better measurements above 20 mHz**

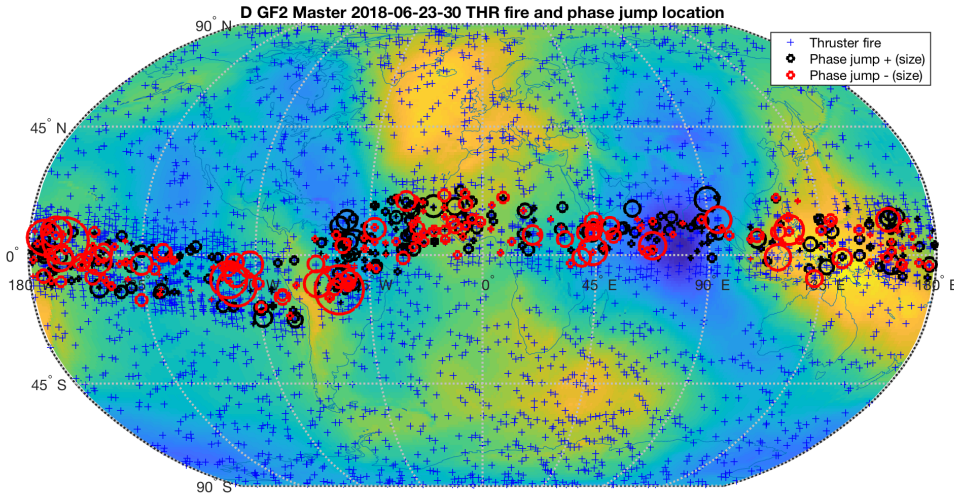
*Data from Dah-Ning Yuan, JPL

Phase jumps in inter-spacecraft science data

- Infrequent unexpected changes in phase
- Don't yet understand the cause; but can remove them perfectly
  - **Science not affected!**
- Coincident with thruster fires on master (currently GF2)
  - **Not cycle slips** – phasemeter tracks the phase jumps
  - Almost entirely coincident with roll thrusters on master (currently GF2)
  - Not every roll thruster fire causes a phase jump (1/3)
  - Every roll thruster fire is the same, but not every phase jump is the same
- **Phase jumps DO NOT impact science!**

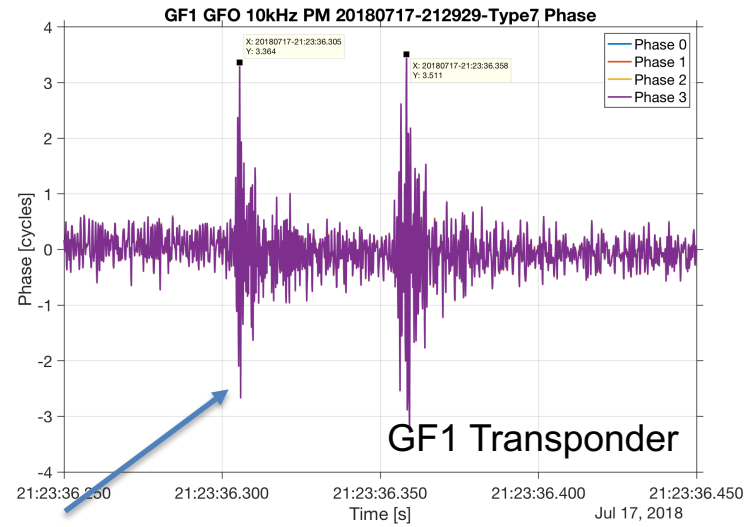




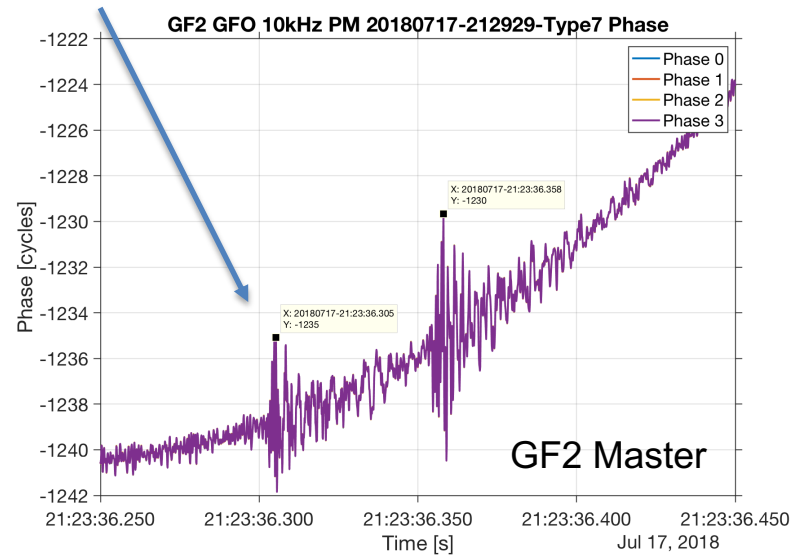


Investigation: Simultaneous high-rate data during roll thruster fire

- 10 kHz data taken on both spacecraft during roll thruster fires
- Pulses correspond to thruster on/off
- LRI sees every thruster fire in the high-rate data, but only roll thrusters on master cause phase jumps in low-rate science data.
- Roll thruster response in high-rate data is an order of magnitude larger than other types of thruster (yaw, pitch, orbit)

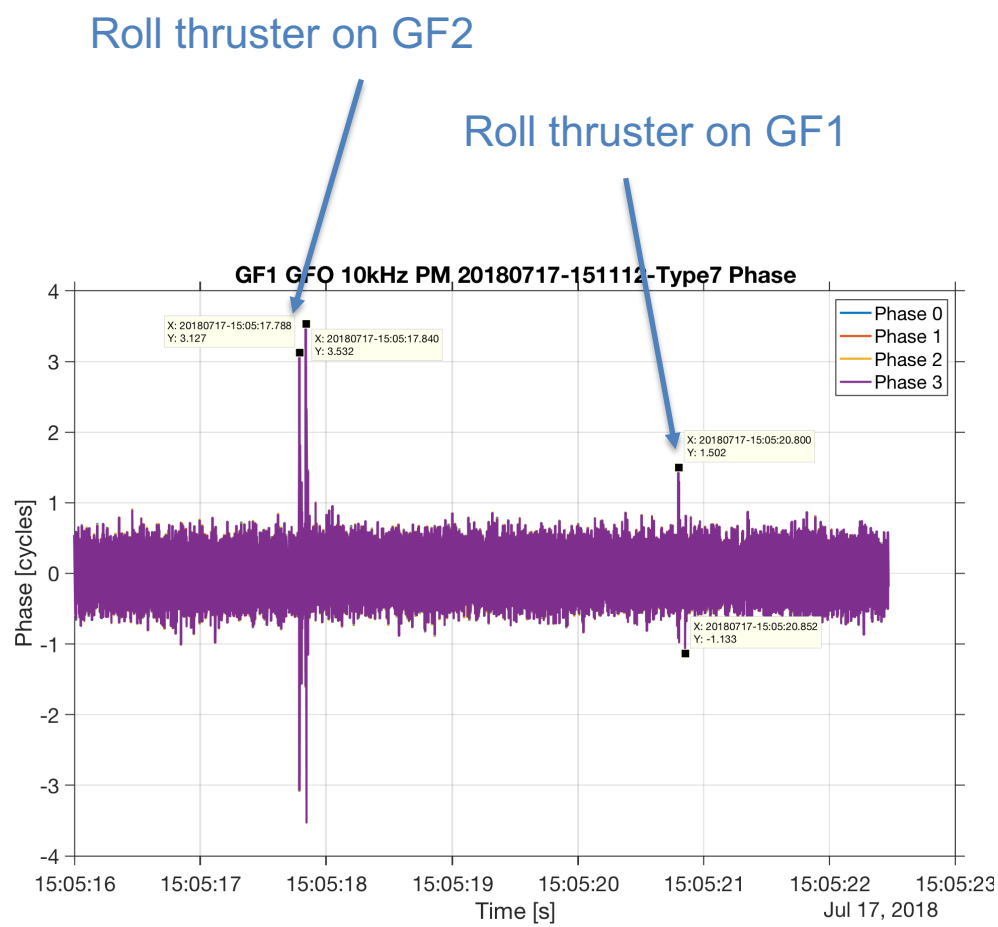


GF2 roll thruster fire



Thruster signal on both SC

- First set of pulses is GF1 transponder tracking GF2 response to GF2 master roll thruster firing
- Second set is GF1 responding to its own roll thrusters
- Both LRIs have the same response to thruster fires

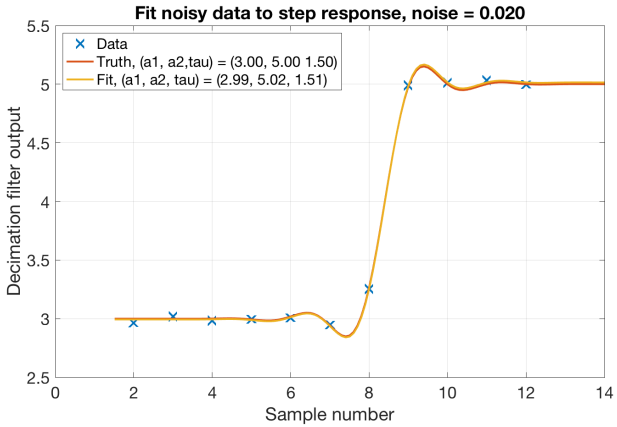


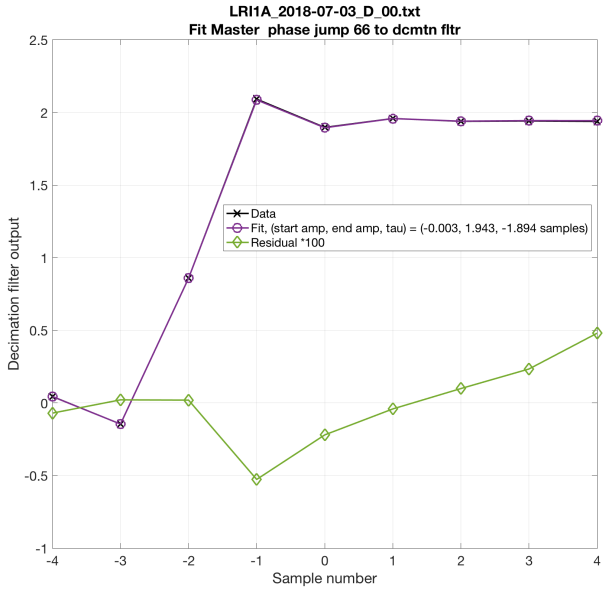
Phase jumps can be removed perfectly

- Phase jumps are a step impulse in phase
  - We know the decimation filter response
  - We don't know the amplitude and time

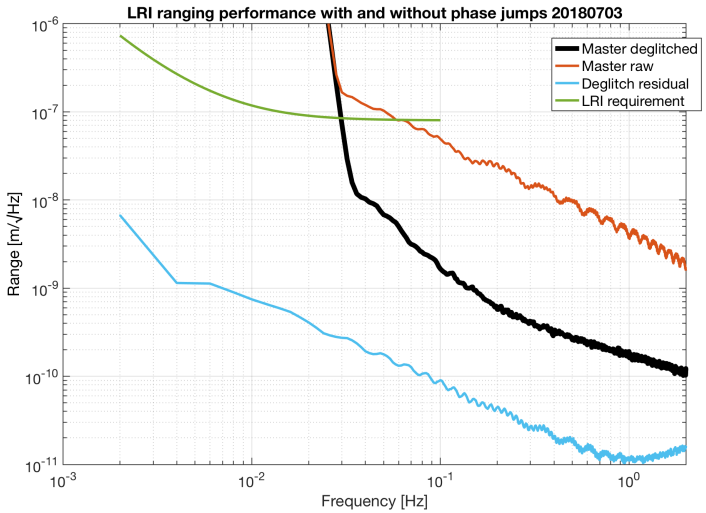
- Phase discontinuities can be removed by two methods.
  1. Find phase jump (aka glitch) in master phase and remove time and amplitude best fit template of it from master phase
  2. Subtract master phase - transponder phase (same processing as MWI)

- **We have two independent methods of removing phase jumps.**
- **Both work *very* well.**



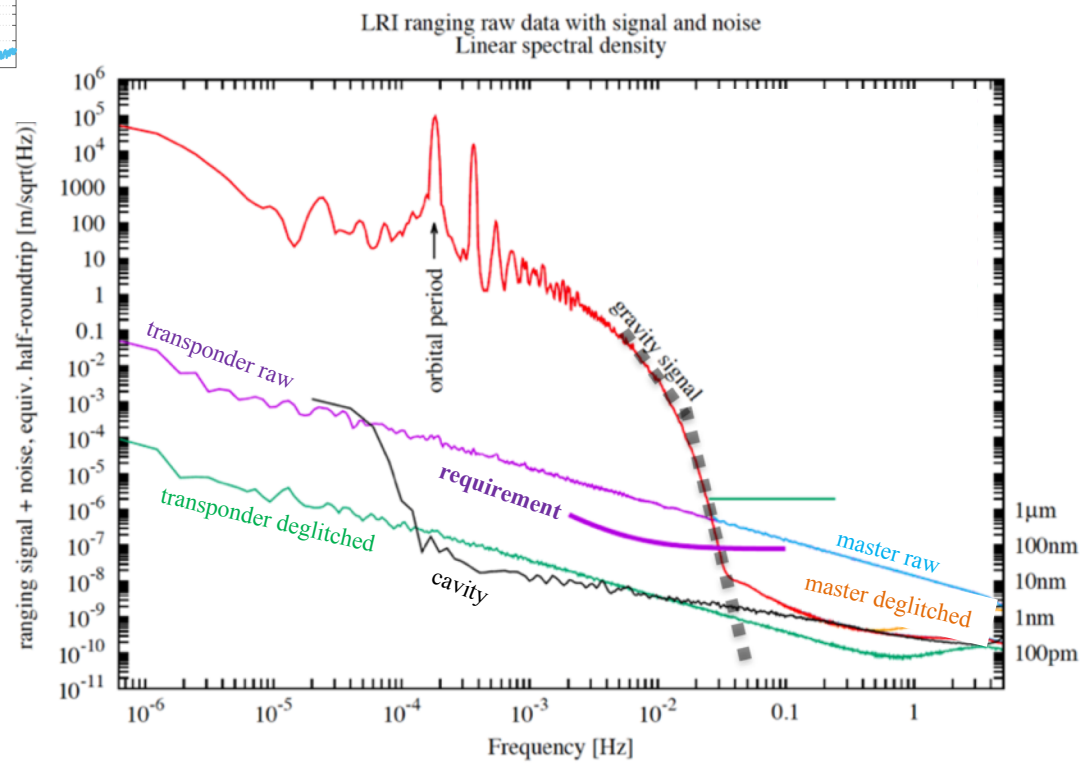


Phase jumps can be removed perfectly



Method 1

Method 2



- Science data more than meets requirements!

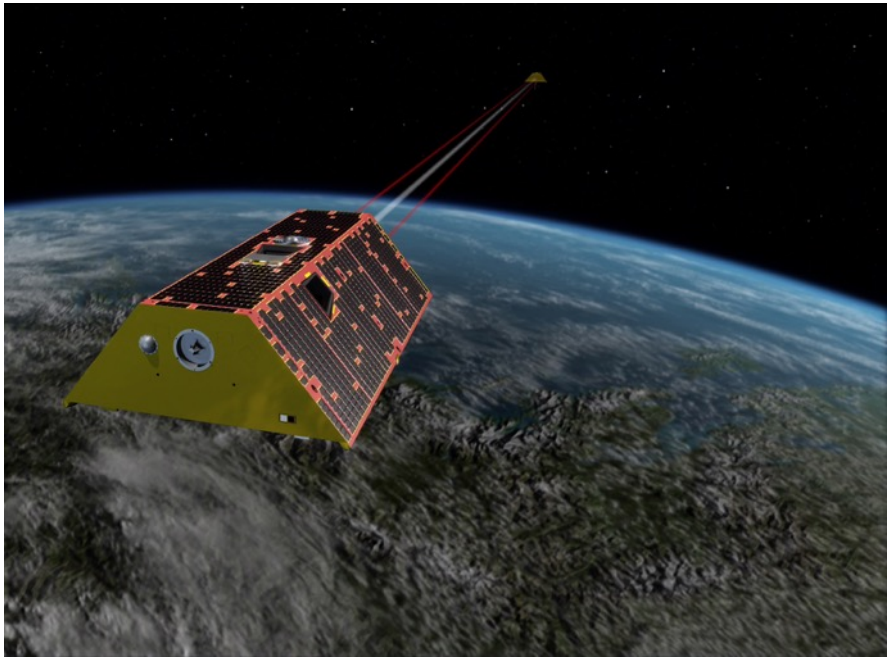
LRI Steering mirror measures Line-of-Sight to distant spacecraft

- Science data system uses spacecraft on-board sensors (IMU, SCA) to remove tilt-to-length coupling in data analysis.

- LRI fast steering mirror (FSM) directly measures the change in line of sight to the other spacecraft with high precision and accuracy

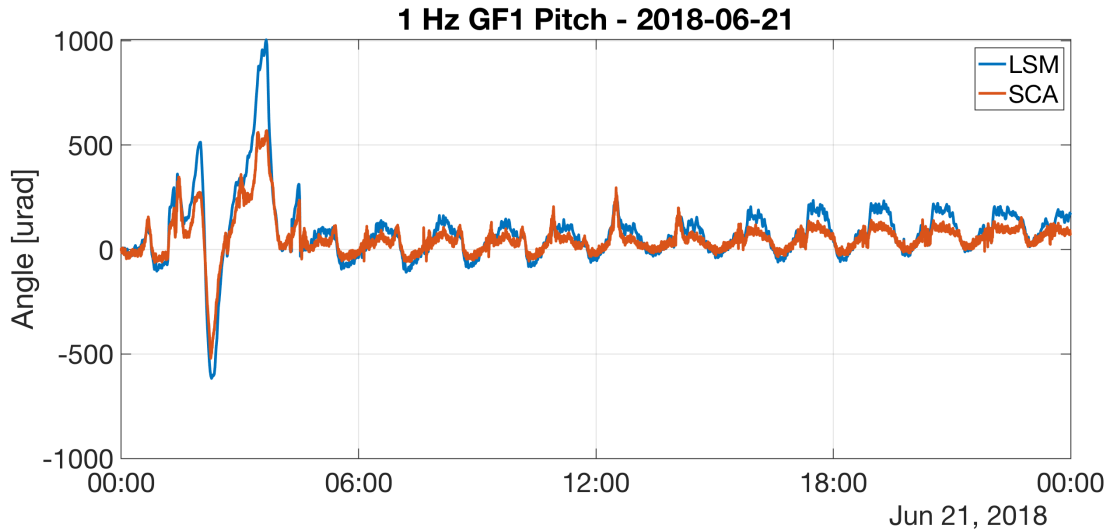
- FSM pointing is updated at LRI data rate (10Hz)

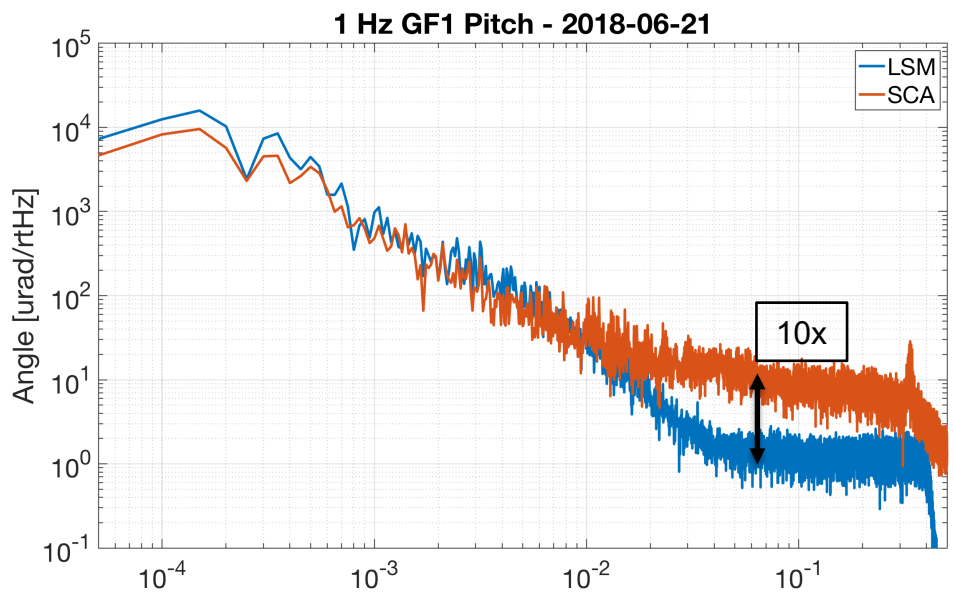
- LRI points to the other spacecraft with < 1 μrad resolution rms (over 10 seconds);
  - at 200 km separation this corresponds to less than < 20 cm error over 10 s



LRI improves pointing information

- Differential wavefront sensing and high-gain control gives continuous monitor of line of sight.
- LRI steering mirrors point to other spacecraft with 2 μrad/√Hz precision
- LRI steering mirror is ~10x quieter than Star Camera



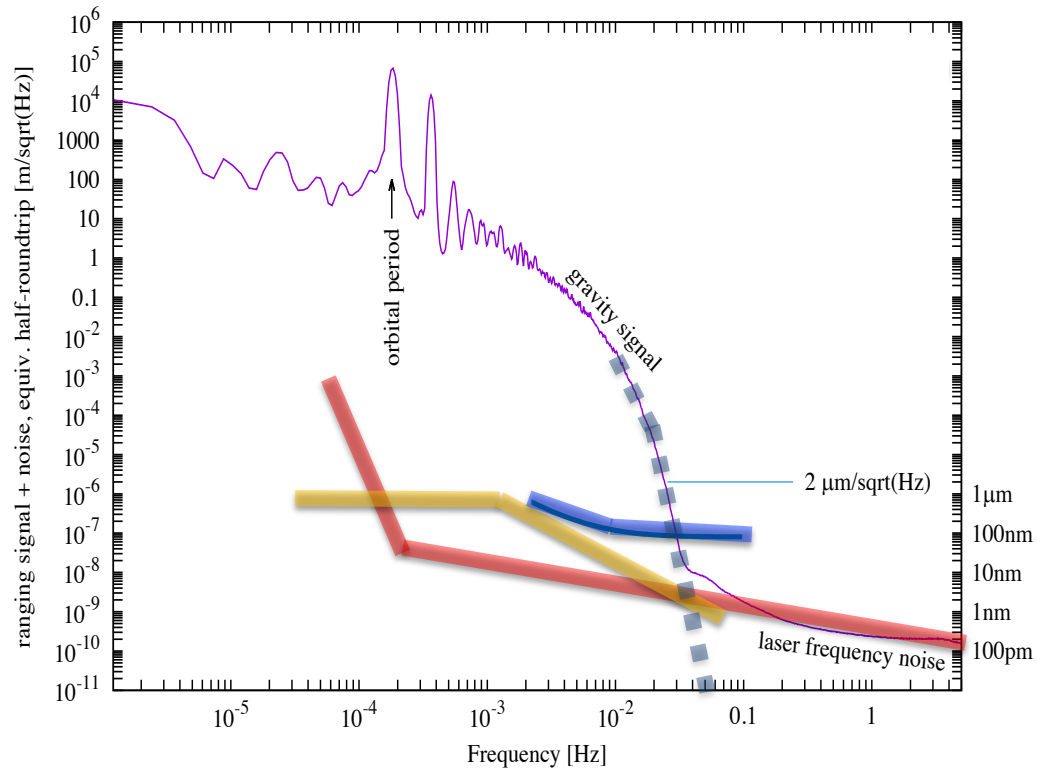


Preliminary evaluation of ground projections of on-orbit performance

Compare **L3 LRI range displacement requirement** with projected performance

- Projection of ground test measurement of **laser frequency noise** matches at high frequency (only fit parameter is spacecraft separation)

- Preliminary projection of spacecraft **attitude to length** coupling using *requirement level coupling factors* is below LRI requirement
  - *Final planned to be measured explicitly via spacecraft maneuvers*
  - Spacecraft attitude control system working really well.



Observed LRI performance agrees well with predicted performance

Summary and status

- GRACE Follow-On Laser Ranging Interferometer, the first inter-spacecraft laser interferometer, has successfully returned science data when operating since first power-on in June 2018.

- Performance in orbit as measured matches expected values from ground testing
- Preliminary analysis indicates better than requirements

- LRI Steering mirror telemetry can be used to improve gravity solutions for both instruments

- Phase jumps due to thruster firing were unexpected, but **can be perfectly removed: DO NOT impact Science**
  - Can be removed from each data stream individually, or subtracted after interpolation
  - Cause is under investigation

- Incorporating LRI into L1A/B data stream ongoing
  - L1B data will have phase jumps removed

- Calibration is in progress
  - Working on understanding scale factor variations from MWI, and sensititivity to scale factor error

- October 2018:
  - In-orbit commissioning is ongoing
  - LRI have interesting data analysis to understand our system in flight
  - Looking forward to getting back in science mode!

GFO LRI Team

Jet Propulsion Laboratory
California Institute of Technology

AEI

Helmholtz Centre
POTSDAM

Adlershof
Bremen
GSOC