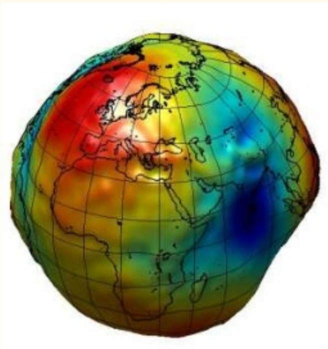
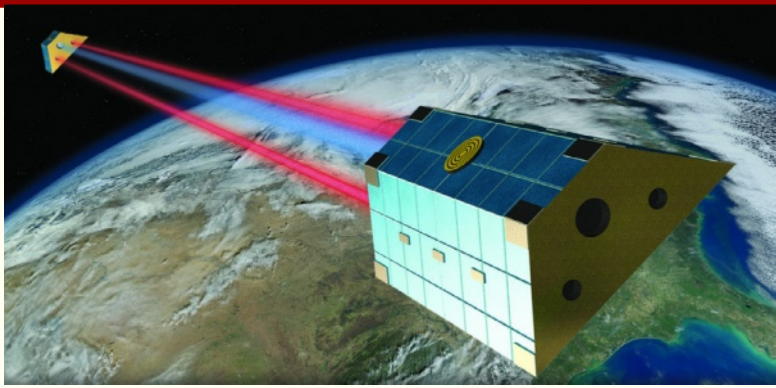


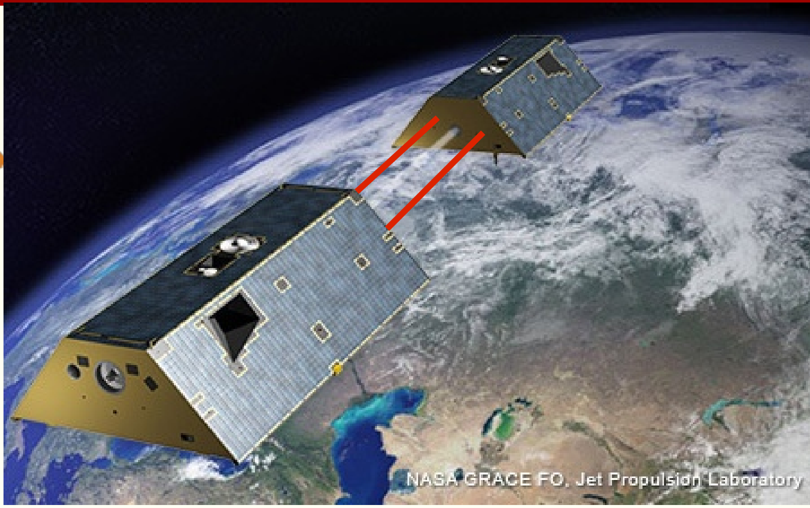


Laser Ranging Interferometer aboard **GRACE Follow-On**

Vitali Müller
AEI Hannover

GRACE Follow-On (GFO)

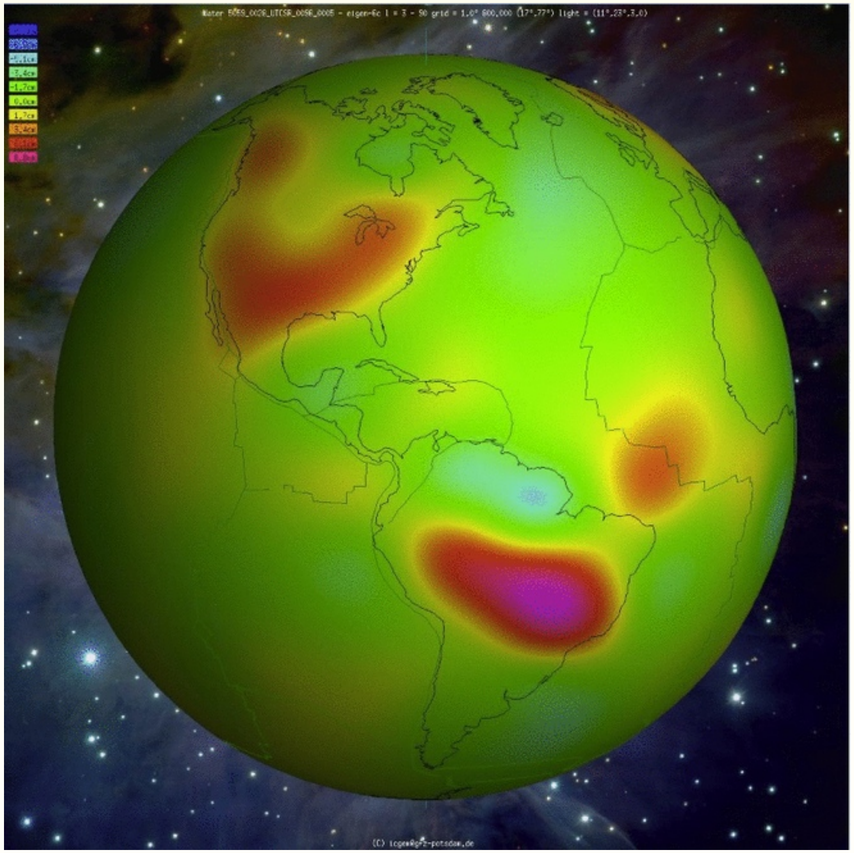
- Quick successor mission for GRACE by NASA & GFZ (Germany)



- Initially indented as copy of GRACE satellites with some improvements and evolved instruments
- Polar orbit with 220±50 km S/C separation at ~490 km height (as in GRACE)
- Mission Objectives:
  - 1st Continue series of high-resolution global gravity field maps

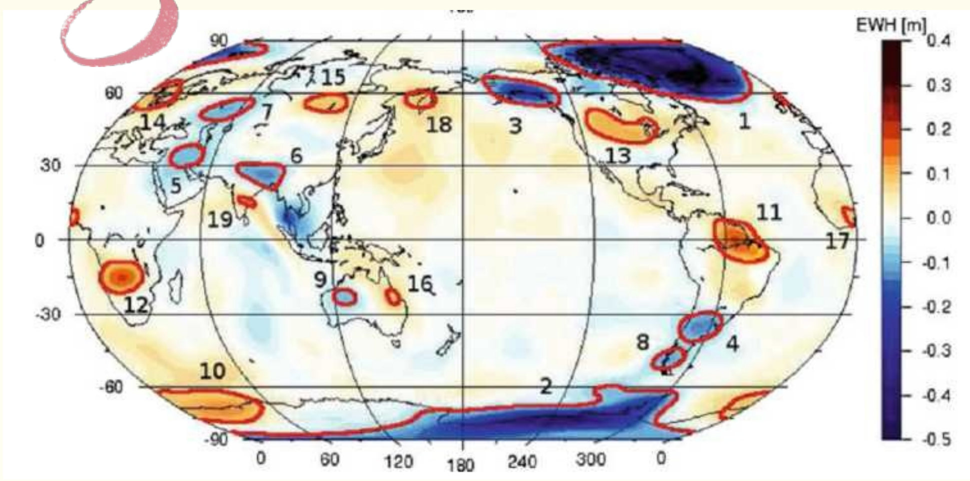
(image credit: Airbus DS GmbH, Mathias Pikelj)

GRACE Science Results

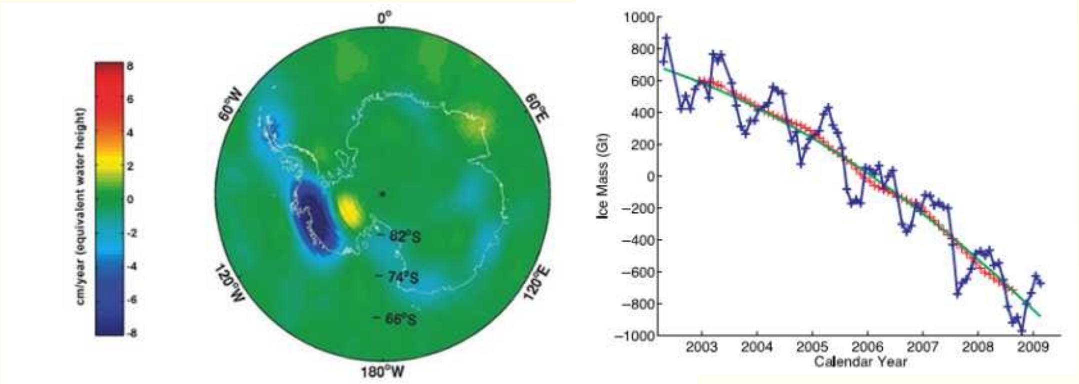


Typical monthly snapshots of the time-variable gravity field by GRACE

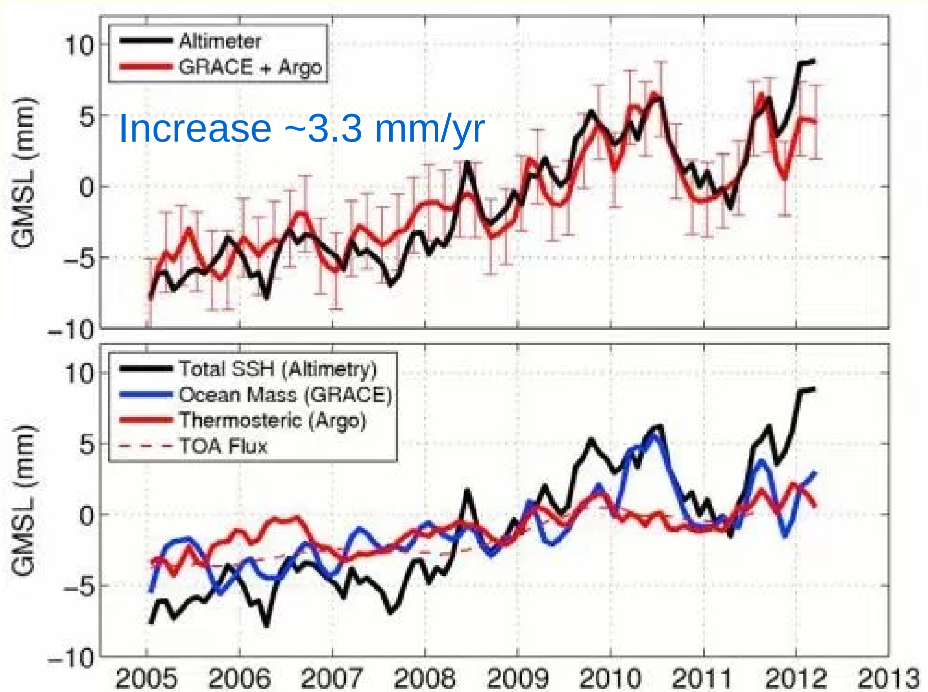
GRACE Science Results II



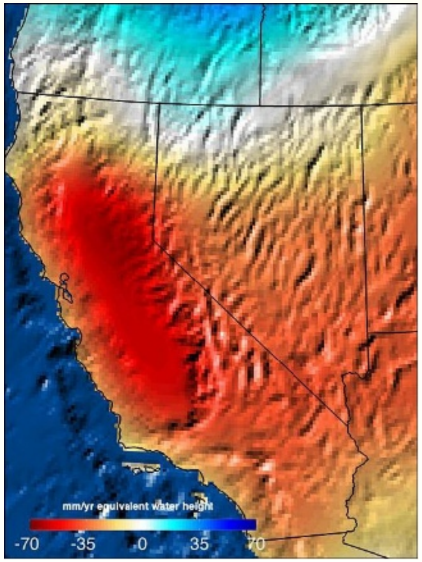
[O. Baur (2013): “Continental mass change from GRACE over 2002-2011 and its impact on sea level”]



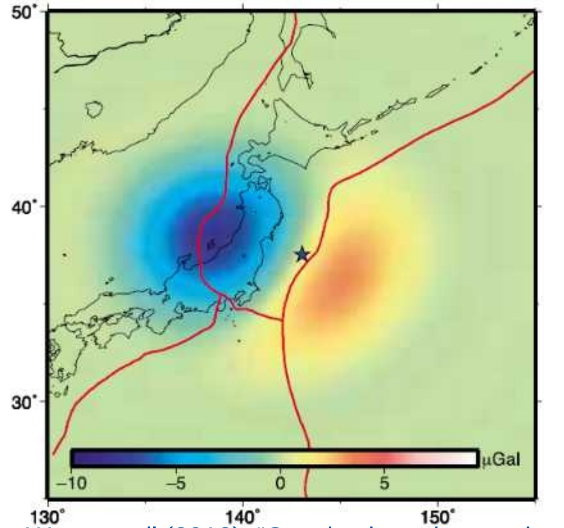
Velicogna, I. (2009), Increasing rates of ice mass loss from the Greenland and Antarctic ice sheets revealed by GRACE, Geophys. Res. Lett.,
http://www.jpl.nasa.gov/news/features.cfm?feature=2378



https://tamino.wordpress.com/2012/11/09/sea-level-and-la-nina/



https://directory.eoportal.org/web/eoportal/satellitemissions/content/-/article/grace

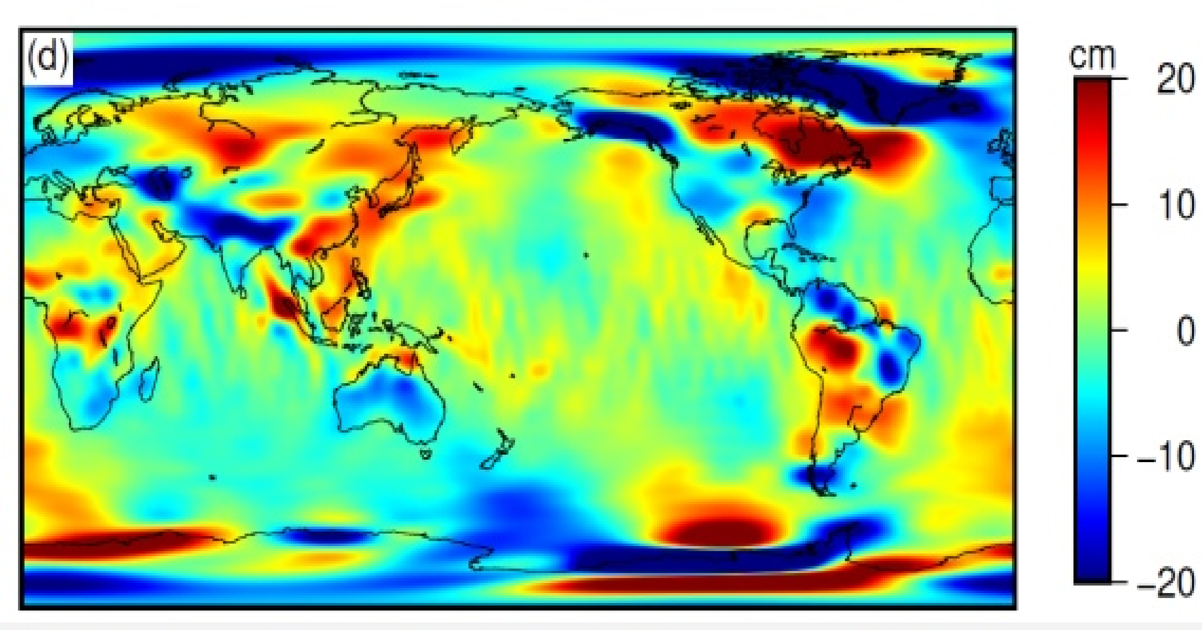


Wang et all (2012), “Coseismic and postseismic deformation of the 2011 Tohoku-Oki earthquake constrained by GRACE gravimetry”, Geophys. Res. Lett.

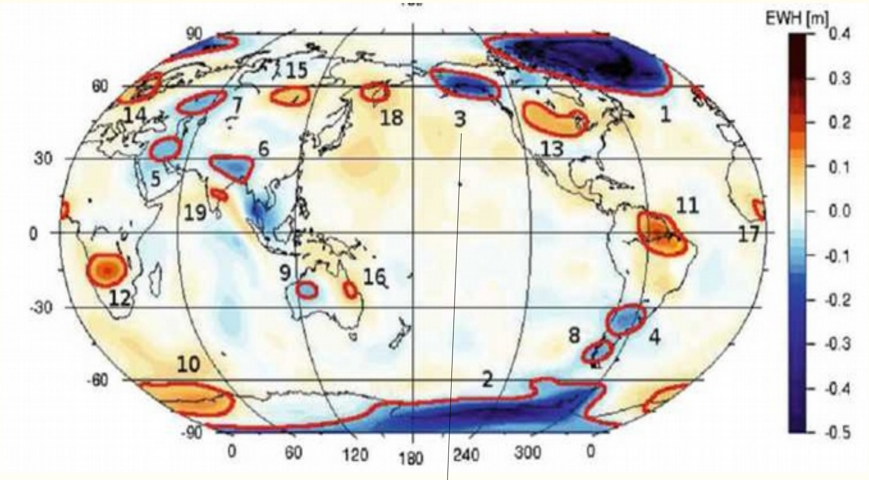
More than 1300 GRACE related publications

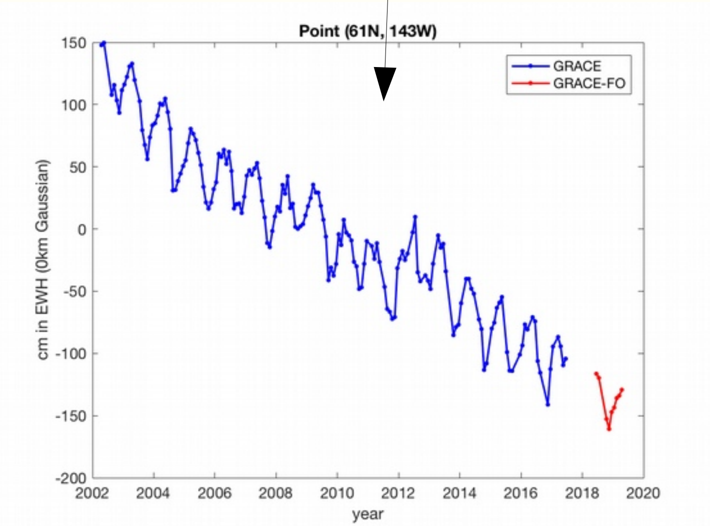
GFO Level 2 data

[O. Baur (2013): "Continental mass change from GRACE over 2002-2011 and its impact on sea level"]



Level-2 RL06 CSR data, 2019-Jan
Plot by Changqing Wang, IGG, Wuhan

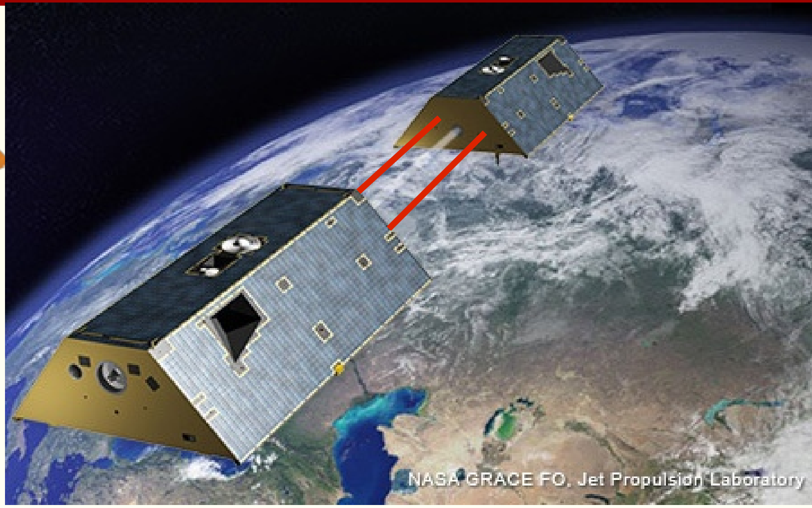




Level-2 RL06 CSR data
Plot by Jin Li, SHAO

GRACE Follow-On (GFO)

- Quick successor mission for GRACE by NASA & GFZ (Germany)



- Initially indented as copy of GRACE satellites with some improvements and evolved instruments
- Polar orbit with 220±50 km S/C separation at ~490 km height (as in GRACE)
- Mission Objectives:
  - 1st Continue series of high-resolution global gravity field maps
  - 2nd Proof feasibility and show performance of a Laser Ranging Instrument
- New laser ranging instrument as technical demonstrator next to the conventional microwave ranging instrument
  - AEI involved since 2010
  - Important for other missions such as LISA:
    - Gravitational Wave Observatories in Space

(image credit: Airbus DS GmbH, Mathias Pikelj)

GRACE Follow-On has the first inter-satellite laser ranging interferometer

GRACE Follow-On Launch

- Launched on 22 May 2018 from Vandenburg Airfoce Base, California
- SpaceX Falcon 9 launcher, ride-share with 5 Iridium NEXT satellites

- Nearly perfect orbit insertion of GRACAE FO satellites, saved satellite propellant during orbit adjustments

a few days later ...

MWI Ranging is working

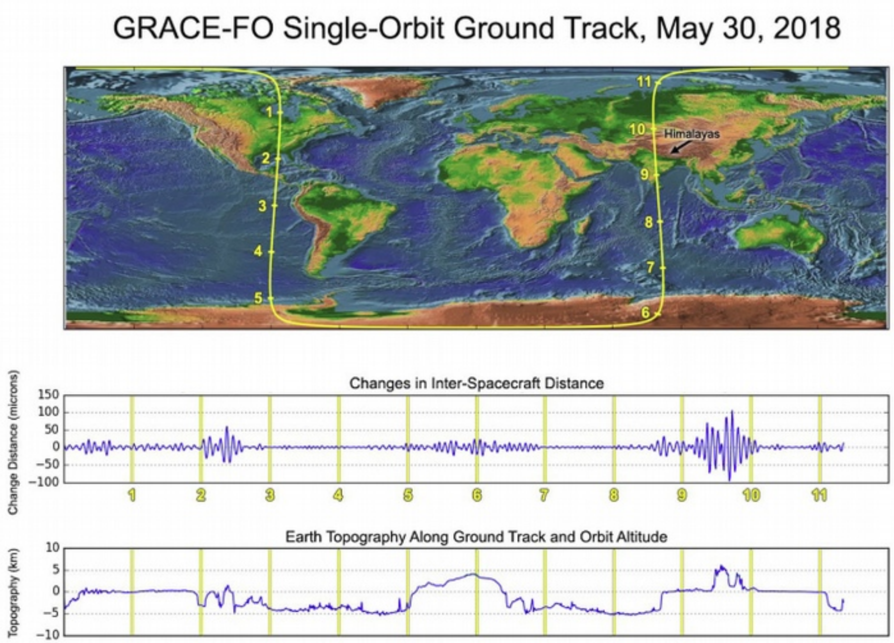
Jet Propulsion Laboratory
California Institute of Technology

GRACE-FO

Mission Science Data Gallery

NEWS | June 11, 2018

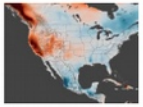
GRACE-FO Turns on ‘Range Finder,’ Sees Mountain Effects



Along the satellites' ground track (top), the inter-spacecraft distance between them changes as the mass distribution underneath (i.e., from mountains, etc.) varies. The small changes measured by the Microwave Ranging Instrument (middle) agree well with topographic features along the orbit (bottom). Credit: NASA/JPL-Caltech/GFZ

Featured Resources


Scale in the Sky

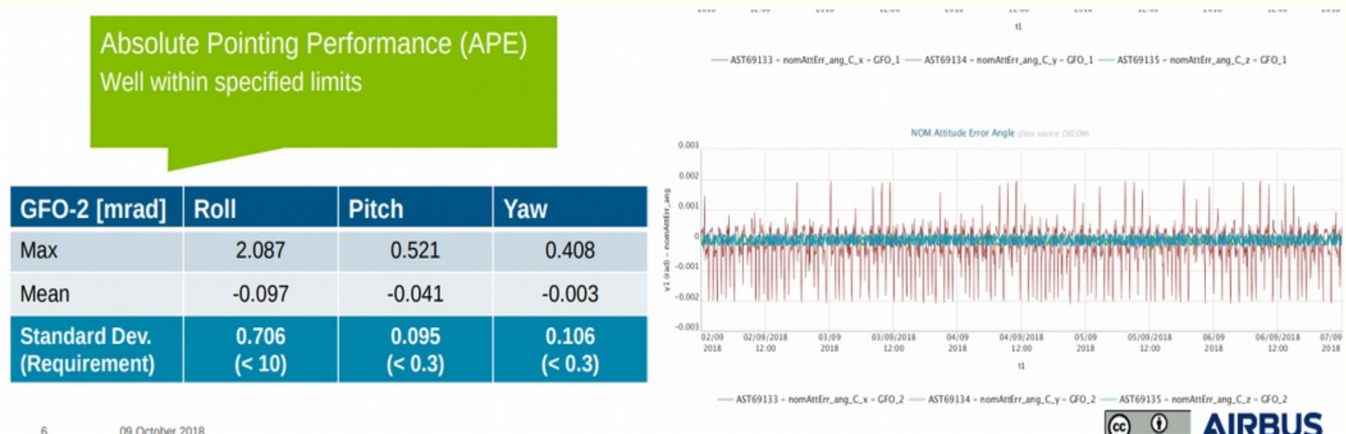

Global Terrestrial Water Storage Anomaly


GRACE-FO in Orbit (View 2)

› more resources

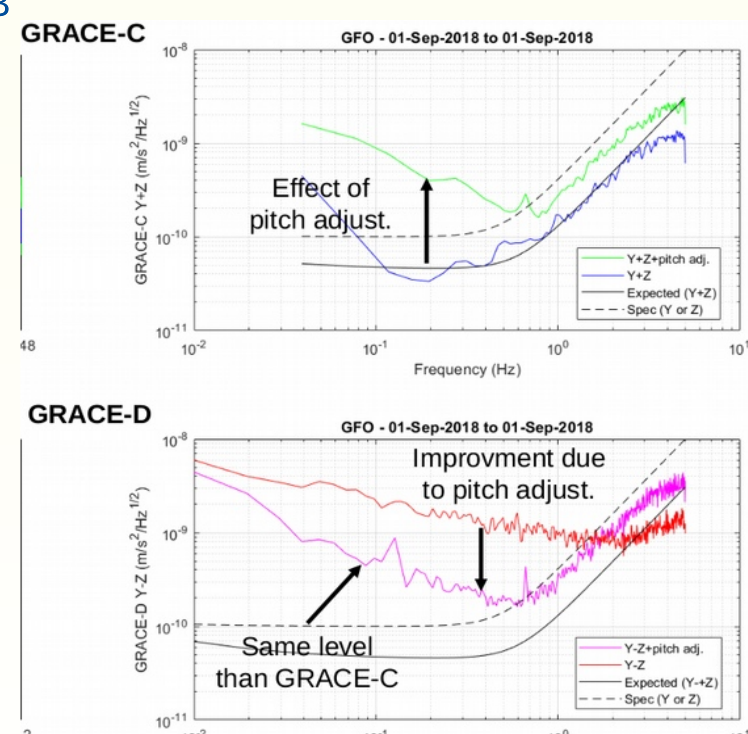
Current Status of GRACE FO

- Commissioning phase finished at end of January 2019; since then in science phase
  - Level1A,B and Level2 data products are publicly available by now
- The GRACE-FO satellite platforms perform excellent
  - Attitude Control, Thermal Environment, Propellant consumption, batteries
- One of the GRACE-FO satellites (called GRACE-D) shows a non-optimal behavior
  - July 2018: Instrument Processing Unit stopped working, switched to redundant IPU
  - Accelerometer (ACC) performance on GRACE-D degraded
  - Feb 2019: OBC issue with switch-over to command telemetry unit (CTU) B
- New challenges for data analysis due to ACC and new instruments
  - several monthly gravity field maps have been obtained (with KBR data)
  - Quality of maps similar to GRACE results



GFO-2 [mrad]	Roll	Pitch	Yaw
Max	2.087	0.521	0.408
Mean	-0.097	-0.041	-0.003
Standard Dev. (Requirement)	0.706 (< 10)	0.095 (< 0.3)	0.106 (< 0.3)

[GSTM2018: Nico Brandt, "Satellite Status", https://meetingorganizer.copernicus.org/gstm-2018/presentations]

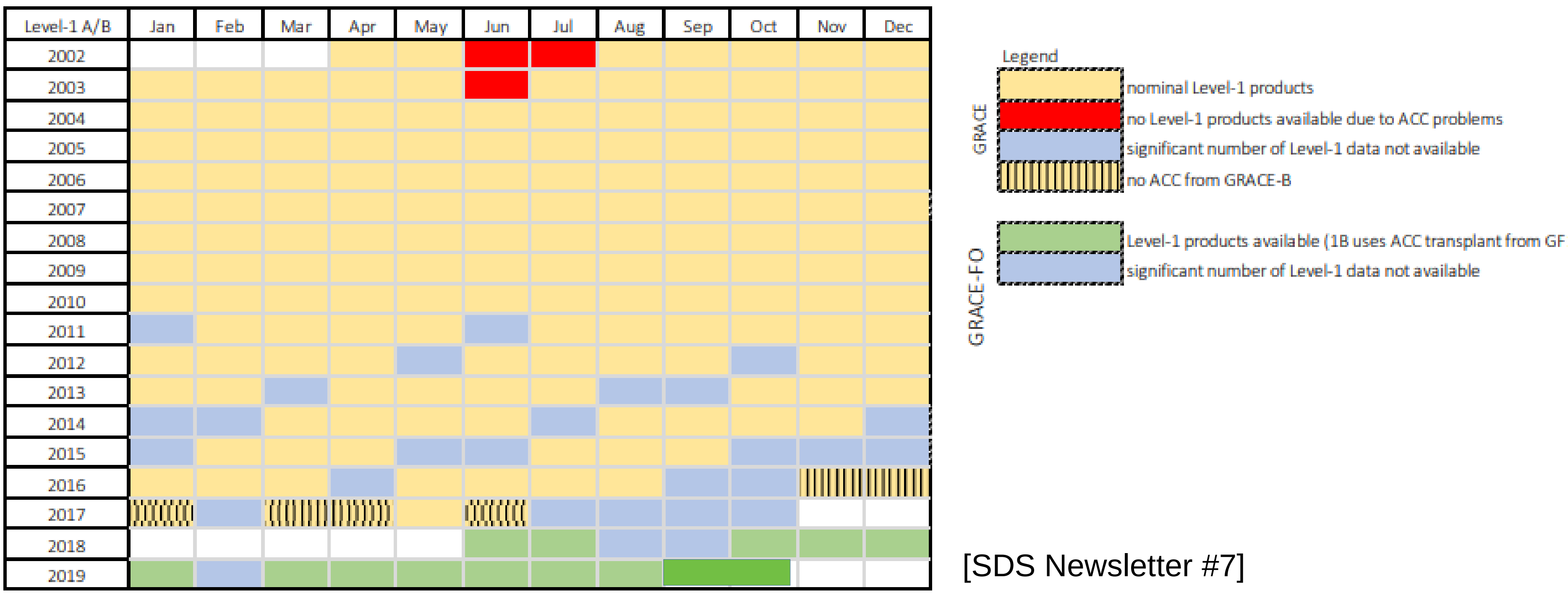


[GSTM2018: Bruno Christophe, "ACC Performance", https://meetingorganizer.copernicus.org/gstm-2018/presentations]

Collected Science Data

1.B – Level-1 GRACE-FO Data Availability

Table 1: Current version: Level-1 v04.

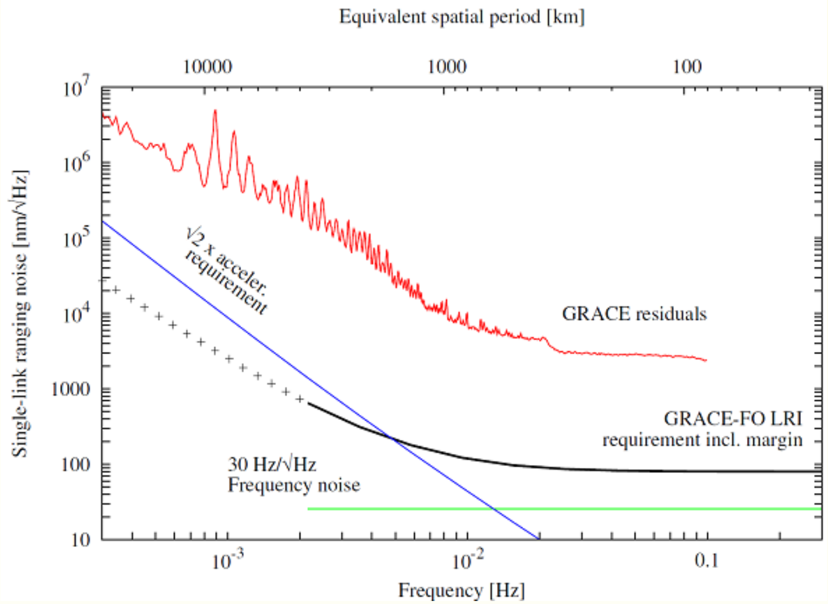


[SDS Newsletter #7]

14 months of Level 1 data recorded

GFO Laser Ranging Interferometer (LRI)

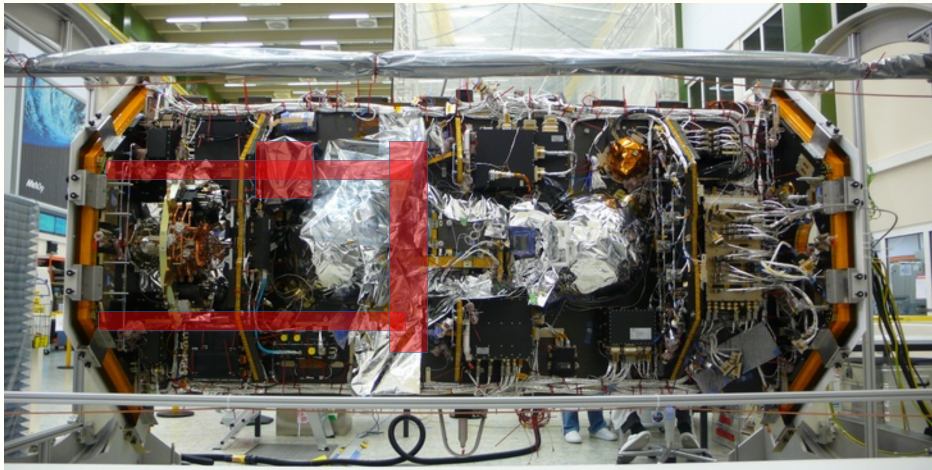
- Inter-satellite biased ranging with a noise req. of $\lesssim 80\mathrm{nm}/\sqrt{\mathrm{Hz}} \times \mathrm{NSF}(f)$



- Utilizes near-IR light
  282 THz ~ 1064 nm
- Heterodyne interferometry: 4...16 MHz
- Weak-light interference: worst case picoWatt level (~10^{-12} W)
- LRI offers yaw & pitch information w.r.t. line-of-sight

- Two independent measurements of biased range by LRI & MWI in parallel
  - LRI demonstrator less strict requirements on lifetime, reliability, redundancy

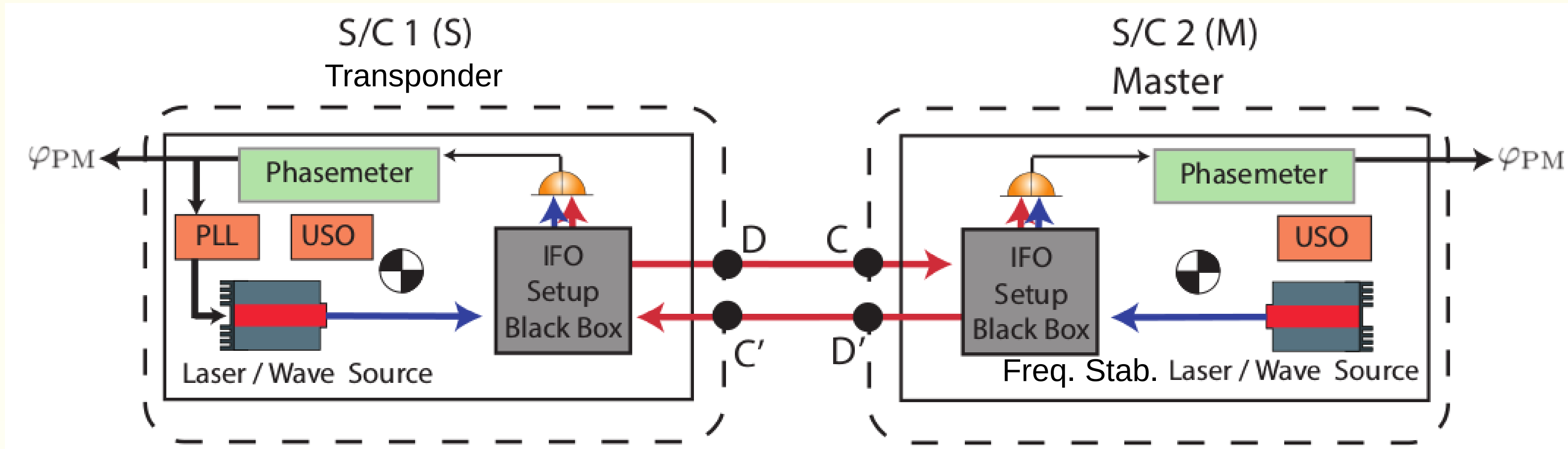
- Joint US & German project
  - 🇺🇸 : Laser Ranging Processor LRP (JPL), Laser (Tesat), Frequency Stabilization Reference (Cavity, Ball Aerospace)
  - 🇩🇪 : Optical Bench (STI), Photoreceiver (DLR) Triple Mirror & Beam Steering (STI/Airbus)



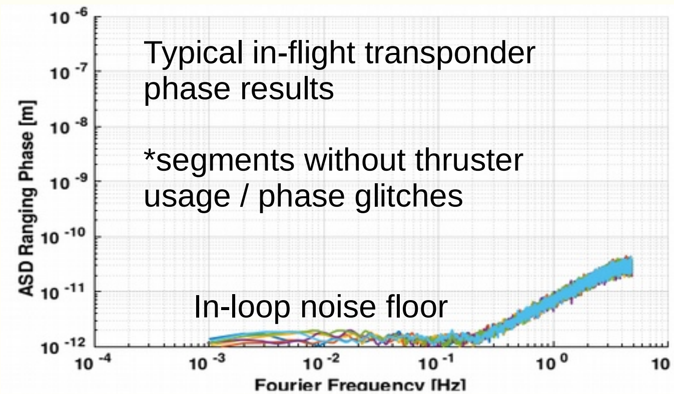
GRACE Follow-On S/C 2016, credit: Airbus & JPL

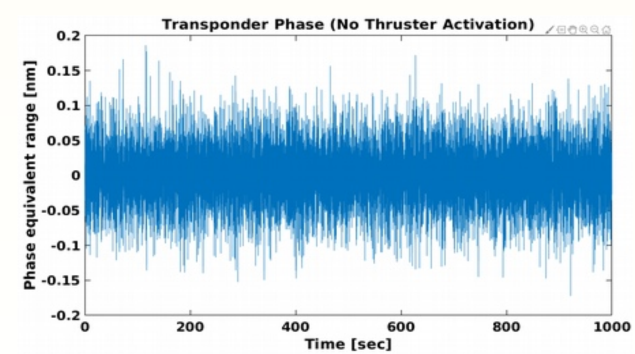
Gerhard Heinzel (AEI) is the PI on german side for the LRI

Functional Concept: Transponder

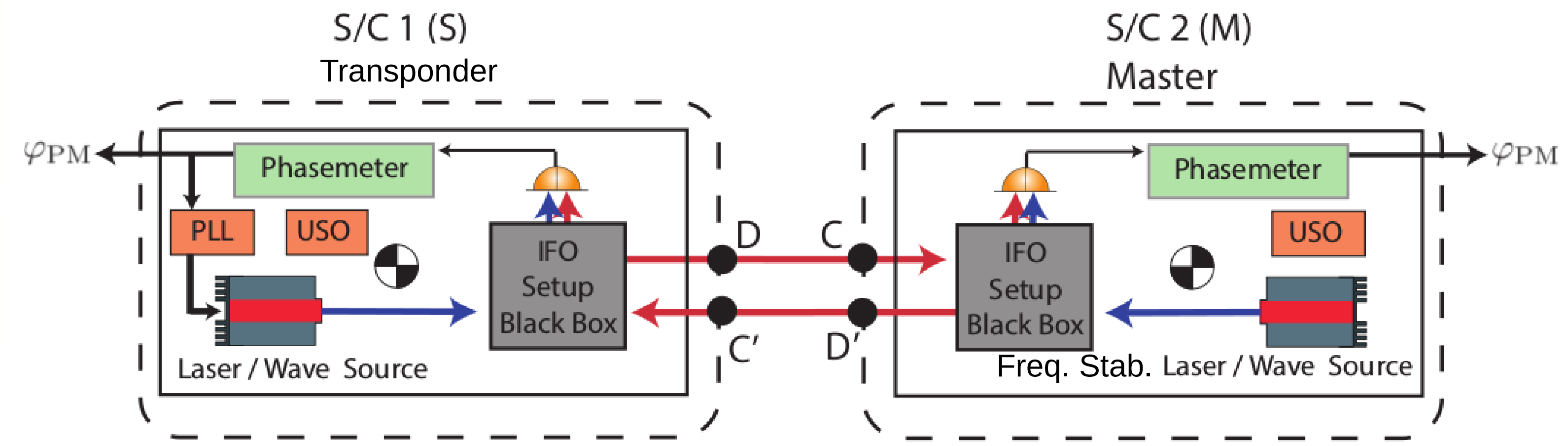


- Role of Master and Transponder interchangeable
  - Both S/C are almost identically equipped
- Transponder S/C
  - High-gain Phase-Locked Loop (PLL) with frequency-offset
    → zeros the measured phase*
    → implemented via frequency-lock (10 MHz)





Functional Concept: Transponder



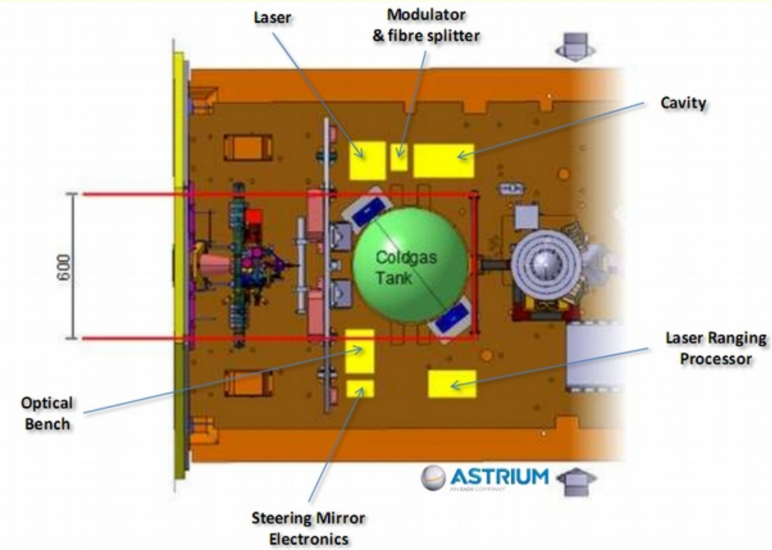
- Role of Master and Transponder interchangeable
  - Both S/C are almost identically equipped
- Transponder S/C
  - High-gain Phase-Locked Loop (PLL) with frequency-offset
    → zeros the measured phase*
    → implemented via frequency-lock (10 MHz)
- Master S/C
  - Active laser frequency stabilization
  - Measured Frequency
    ~ 2x Doppler + frequency offset
- (Laser) phase noise suppression in the optical domain (different for DOWR)
  - In principle, single data stream for ranging

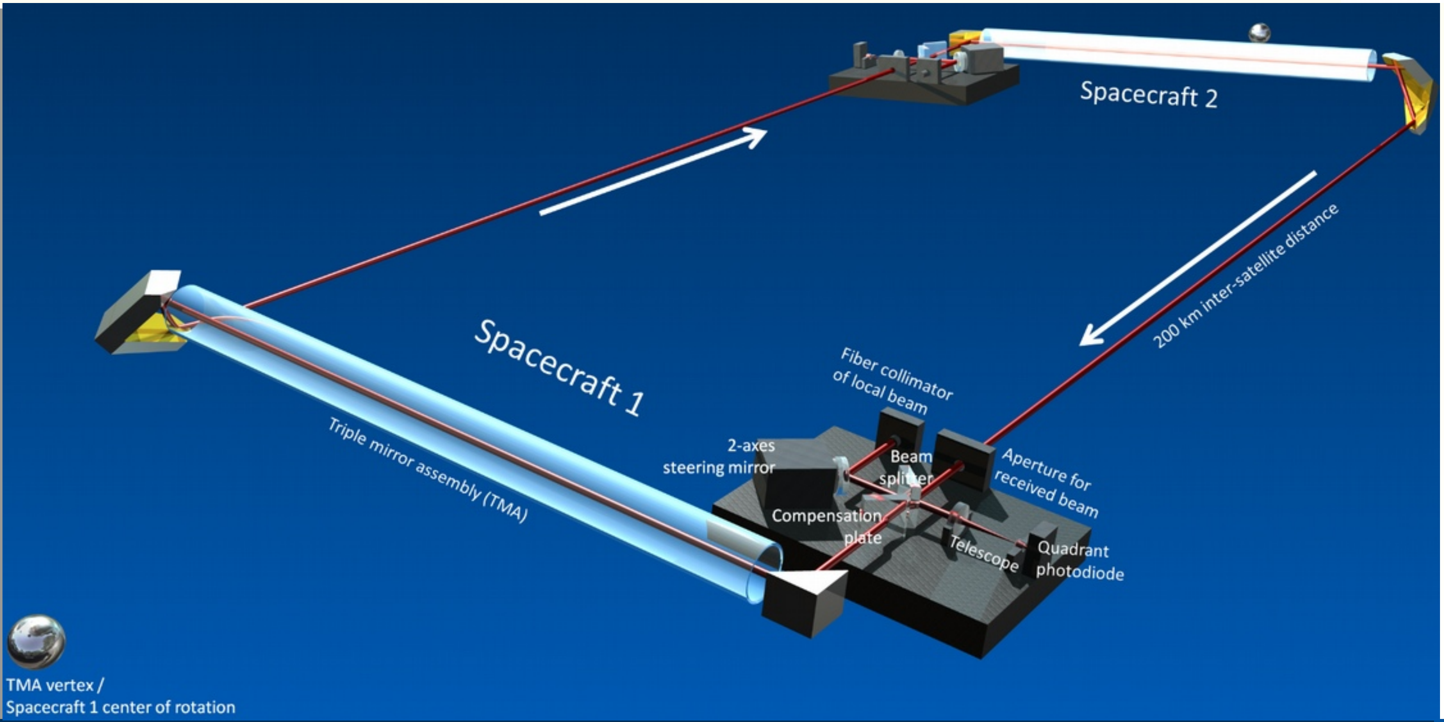
- **Dual One-Way Ranging (DOWR) used in microwave ranging**
  - Ranging signal (Doppler) distributed equally on both S/C
  - Combination of both phase measurements reduces laser/USO phase variations in post-processing
  - Requires: Frequency stabilized (laser/µwave) sources on both S/C & frequency offset
    - Advantage: In principle, √2 less frequency noise

MWI similar to LRI: Heterodyne interferometry with phase tracking

LRI Optical Layout: Off-Axis

- Racetrack configuration with corner-cube retro-reflector (Triple Mirror Assembly, TMA)
  - 60 cm lateral separation, space constraints due to KBR & cold gas tanks
  - TMA vertex ("phase center") separated from physical structure
    → LRI measures effectively between vertices
    → co-located with CoM/ACC,
    → lever arm for rotation coupling only ~100 µm





<u>Optical Bench</u>

- Quadrant Photodiodes
  → measure interfered light
- 2-axes steering mirror (SM)
  → automatic beam alignment
  → acquisition
- 2-lens beam compressor
  → image aperture & SM onto PD, resize beam
  → suppress beam walk & diffraction rings

Automatic beam alignment turned out to be a very interesting feature

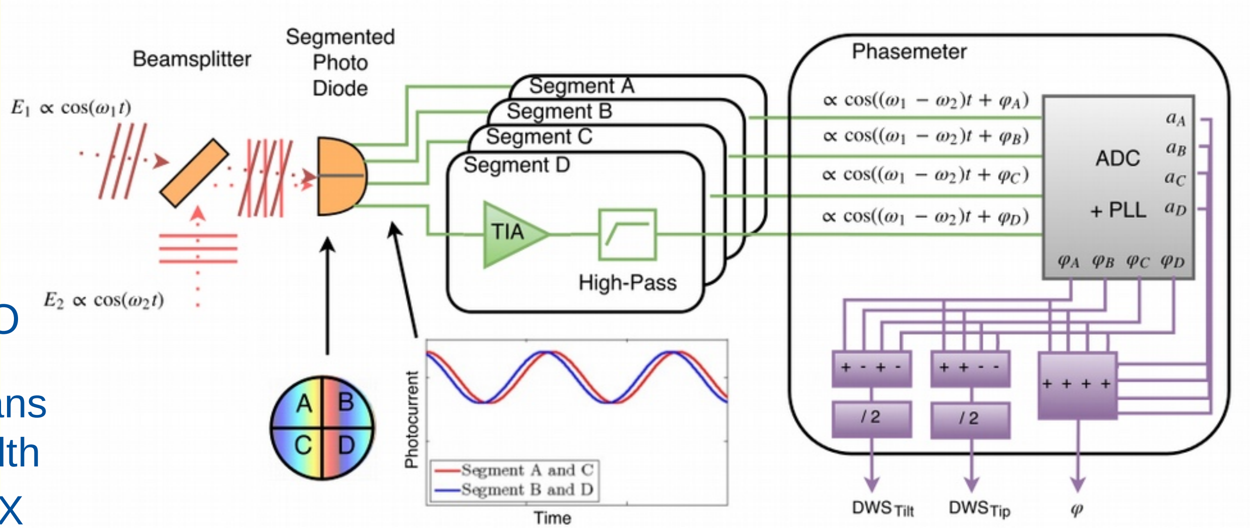
LRI Automatic Beam Alignment and TX Pointing

Quadrant photodiodes and multi-channel phasemeter enable to form

- Average phase of segments ~ ranging
- Differential phase of segments (DWS) ~ relative beam tilt & tip between RX & LO

LRI utilizes a control loop to zero DWS by means of a steering mirror with high gain and bandwidth

- Optimal wavefront overlap between LO & RX
- Maximizes SNR for phase readout
- Higher common-mode error rejection

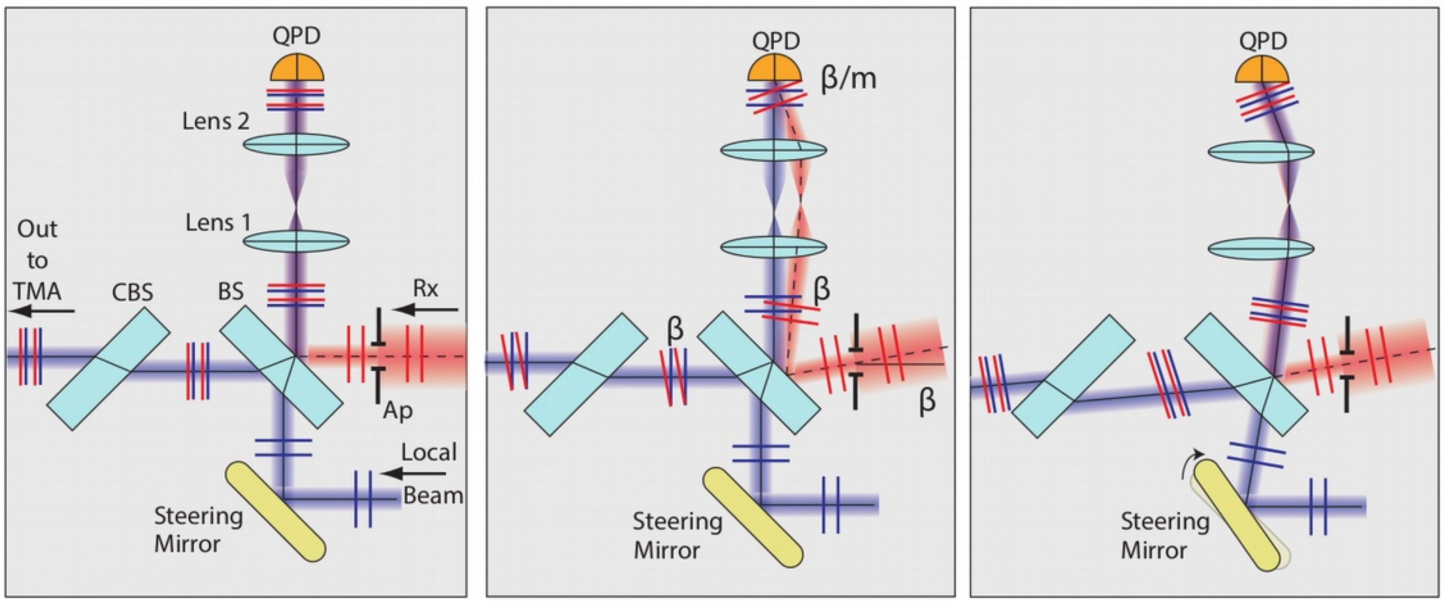


Beam tilt & tip caused by **local** S/C yaw & pitch misalignment

- DWS zeroed
- Dedicated steering mirror angle sensing

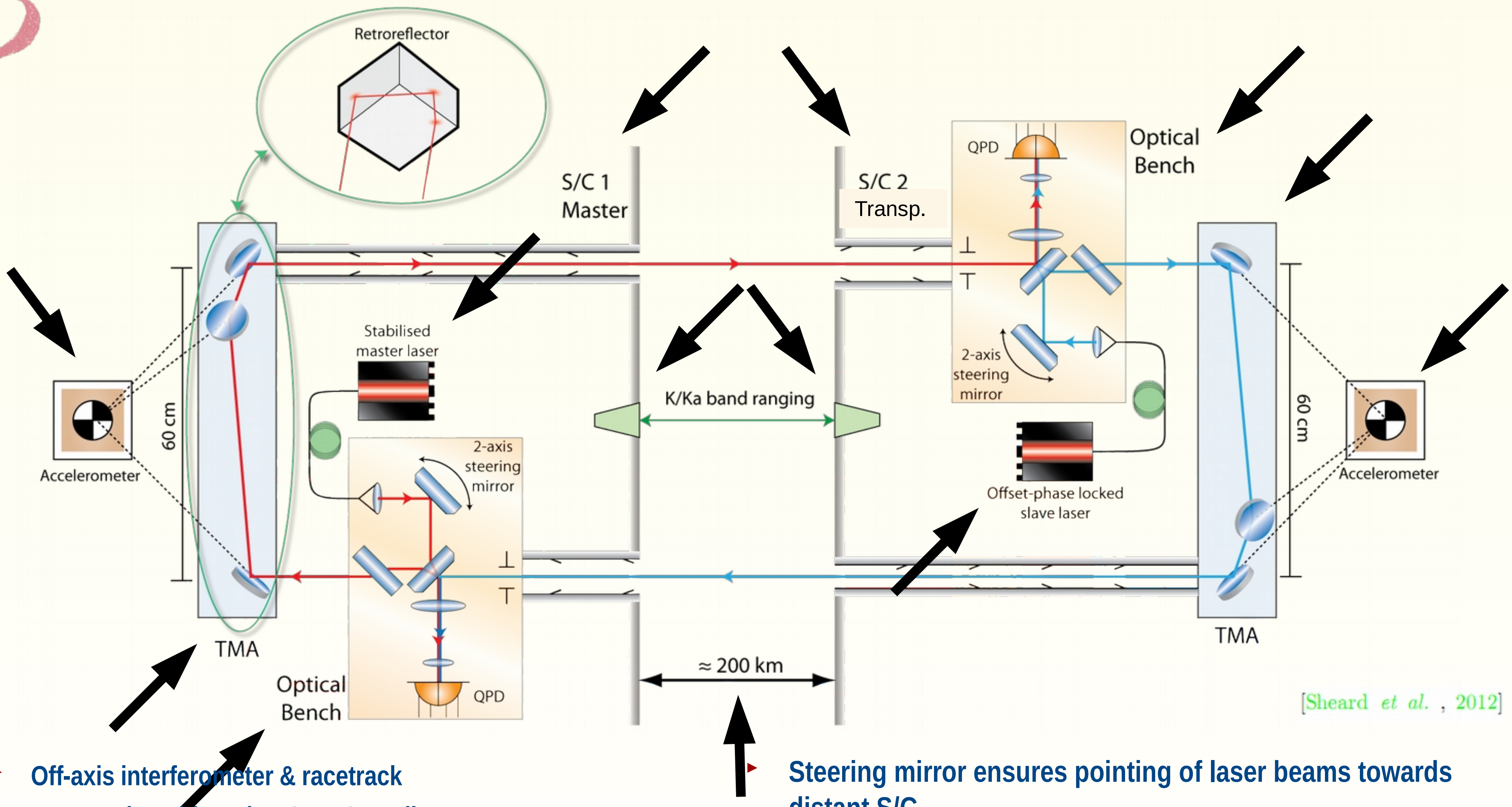
Closed Loop Operation

- OB in&out waves parallel
- OB enhances light power, no light deflection
- TMA retro-reflection sends beam to distant S/C
- **Optimal TX beam pointing**



Allows: S/C pointing error > LRI beam pointing requirement

GFO LRI Overview



- Off-axis interferometer & racetrack
- Racetrack pathlength ~ CoM-CoM distance
- Heterodyne interferometry with master and transponder principle
  - Transponder S/C acts as “active retro-reflector” due to phase lock / Transponder
  - Offset of 10 MHz causes beatnote on both PDs

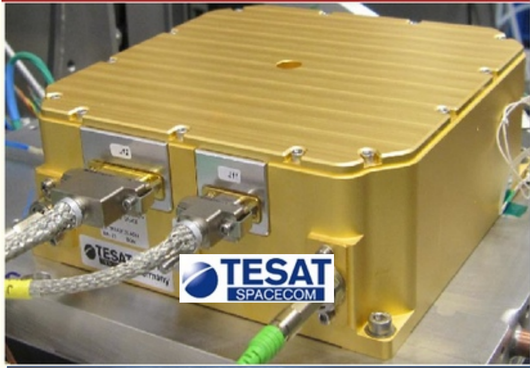
- Steering mirror ensures pointing of laser beams towards distant S/C
- Differential Wavefront Sensing & FSM provides precise attitude information w.r.t. line of sight

Main optical components of LRI ...

LRI US Sub-Systems

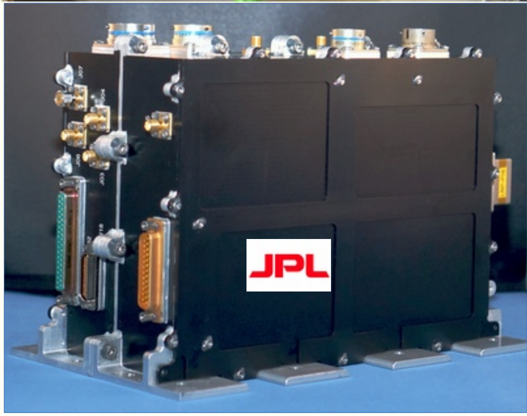
Laser Source

- Nd:YAG NPRO with 1064 nm
- Optical Power to Optical Bench: ~25 mW



Phasemeter: Laser Ranging Processor (LRP)

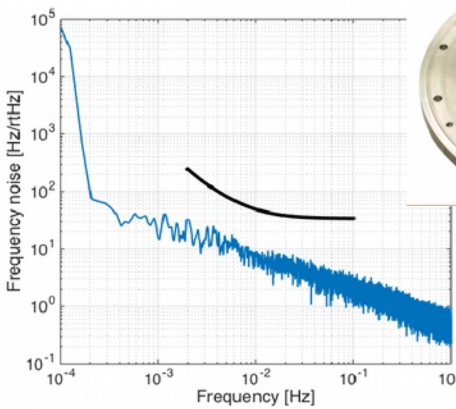
- Four Channels (RF in)
  → Phase readout
- Clock Input for USO
- Control of
  → Laser
  → Frequency Stabilization (Master S/C)
  → Phase-Lock-Loop (Slave S/C)
  → OB Electronics
- Laser Link Acquisition Algorithm

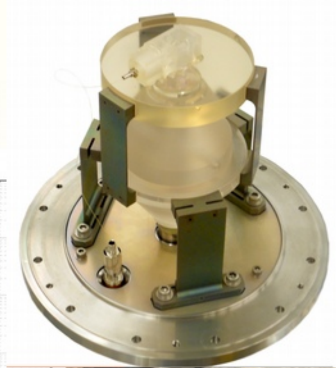


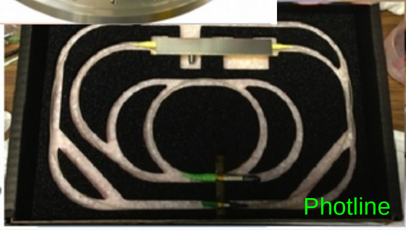
Frequency Stabilization/Reference

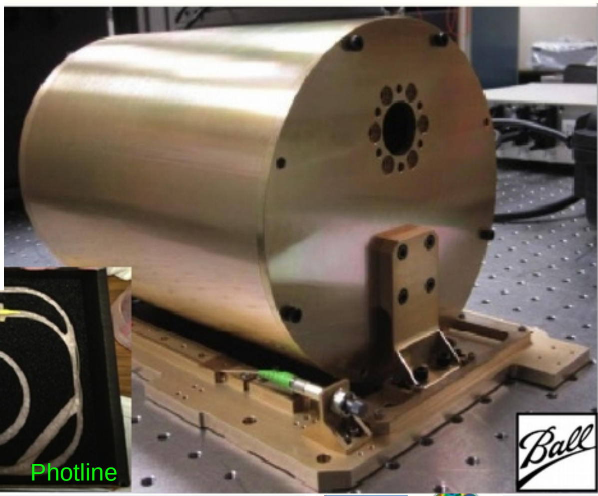
- Cavity with
  77.5 mm ULE spacer
- Pound-Drever-Hall technique
  with electro-optic modulator
- Lock laser to cavity resonance
- Noise requirement:

$$30\text{Hz}/\sqrt{\text{Hz}} \times \text{NSF}(f) \simeq 25\text{nm}/\sqrt{\text{Hz}} \times \text{NSF}(f)$$





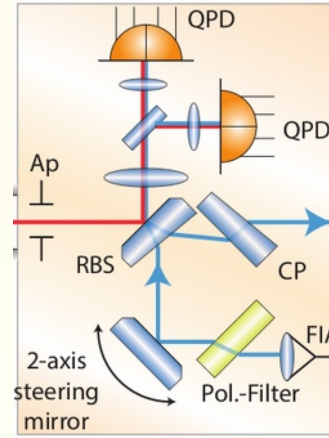


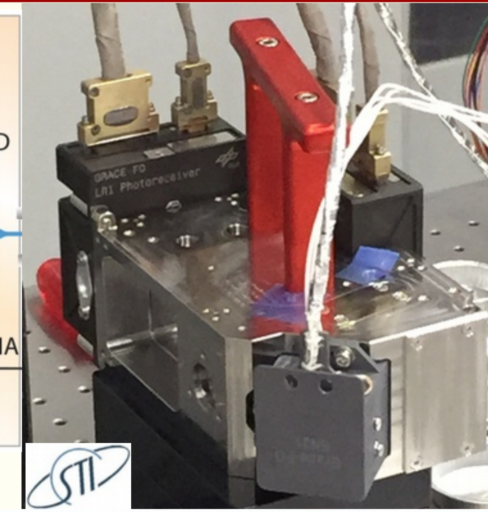


LRI German Sub-Systems

Optical Bench (OB)

- Titanium structure
- Beam compressor / imaging system
- Two hot redundant quadrant photodiodes (QPDs)
- Fiber Injector Assembly (FIA): Beam launcher
- Fast steering mirror, a few mrad range
- Recombination Beamsplitter (RBS)
- Compensation Plate (CP)





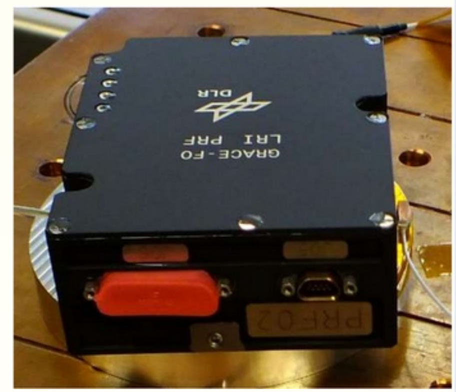
OB Electronics

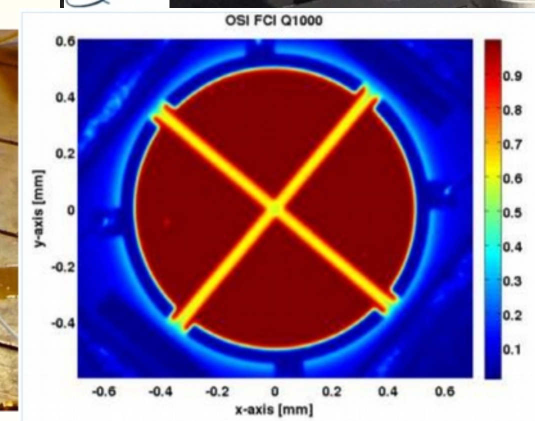
- DC & AC splitting
- Variable AC gain stages
- Summation of QPDs, Redundancy Switching

Photoreceiver

- InGaAs QPDs with 1 mm diameter
- Bandwidth: 4...16 MHz
- Equivalent Input Current Noise Req.:

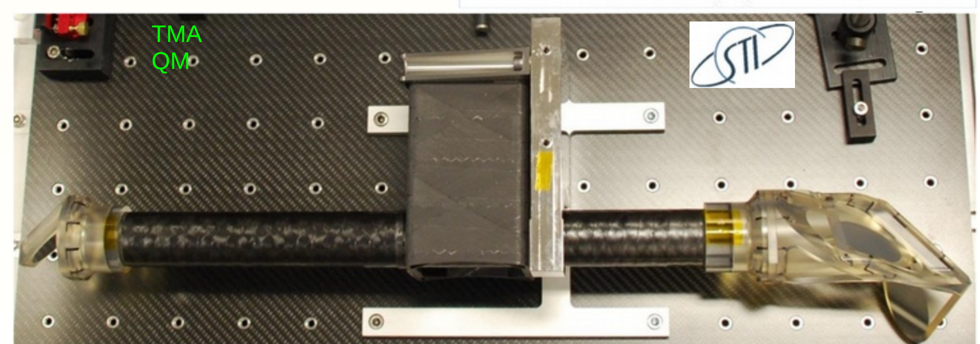
$$\lesssim 5\ \mathrm{pA}/\sqrt{\mathrm{Hz}} \times \mathrm{NSF}(f)$$





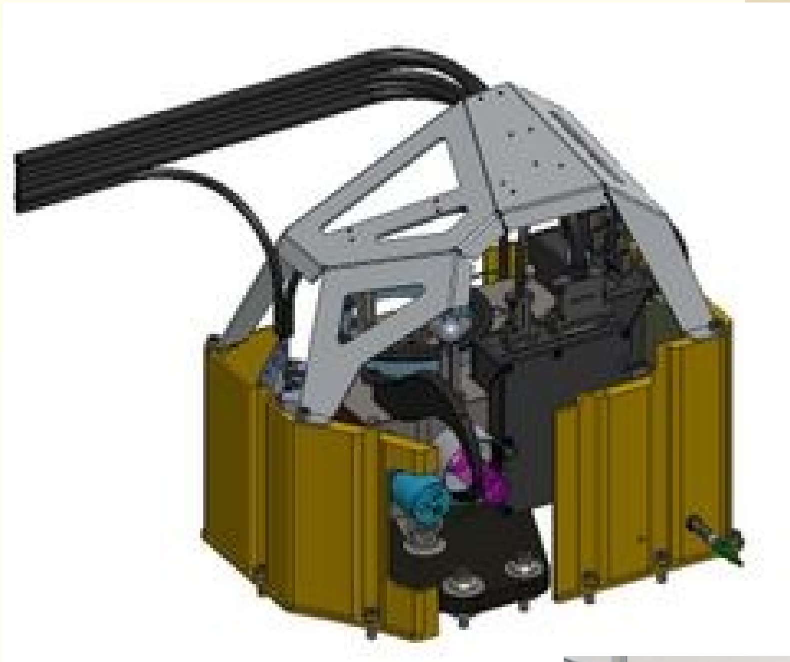
Triple Mirror Assembly (TMA)

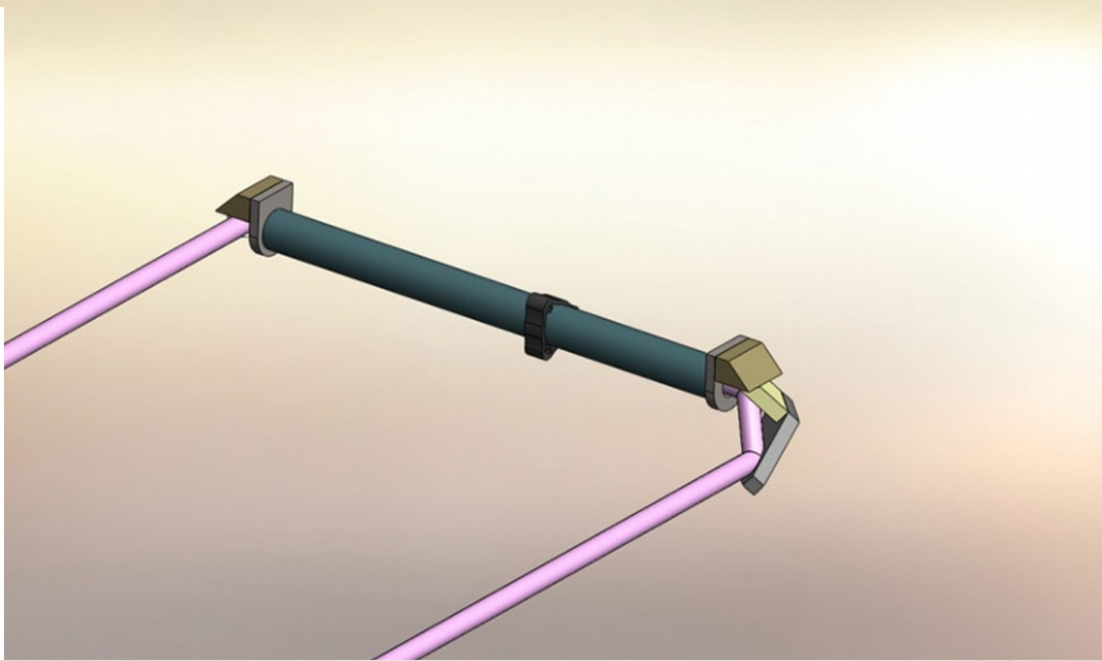
- 60 cm lateral displacement between in & outgoing beam
- Co-Alignment requirement: 50 µrad
- lightweight CFRP structure



… and baffles / light path closure

Flight Hardware





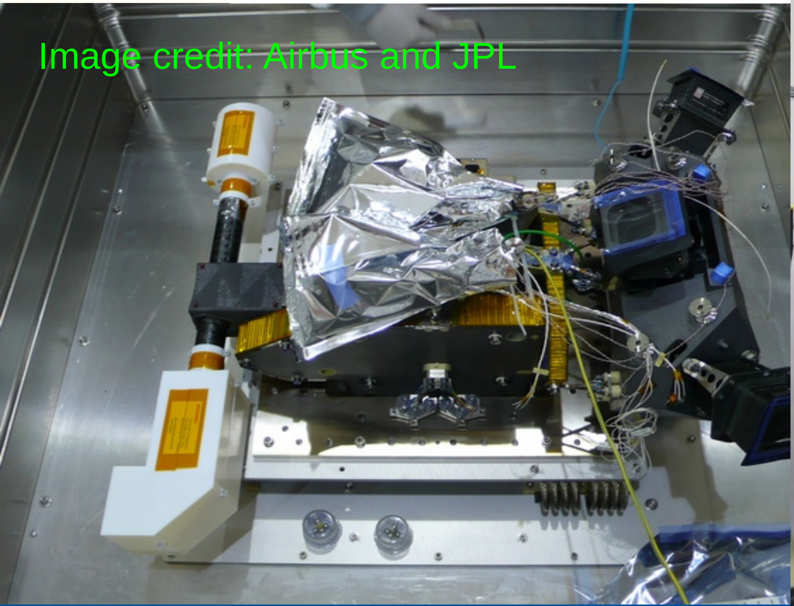
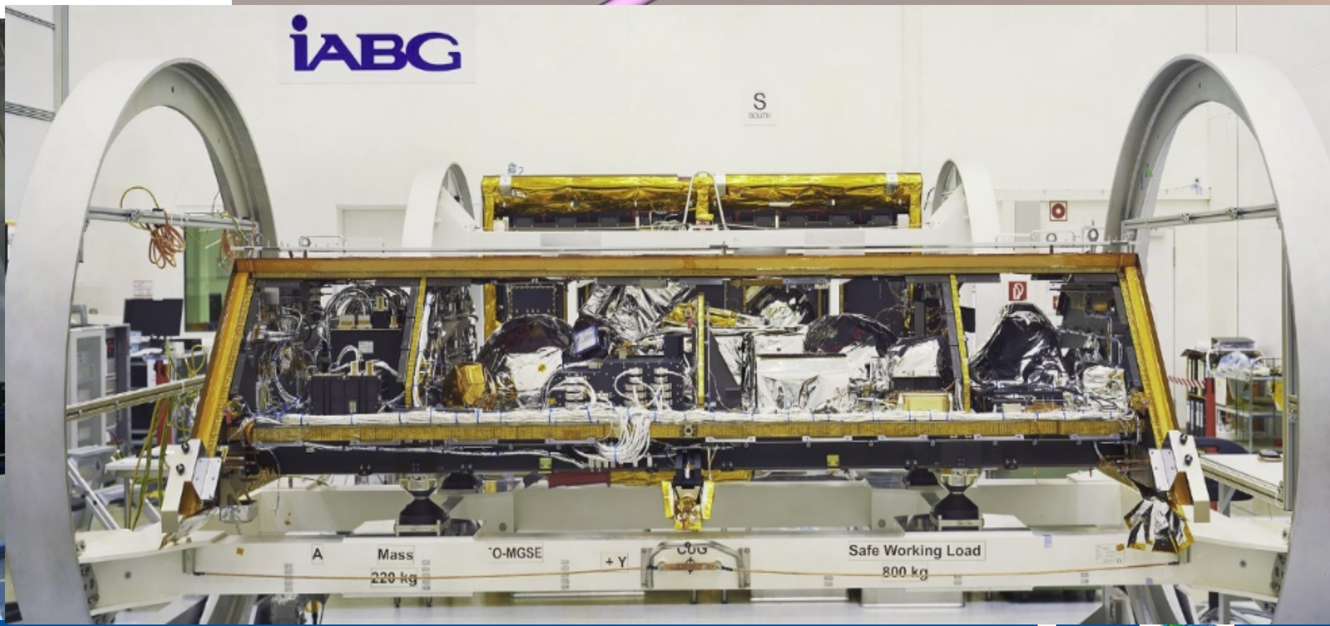
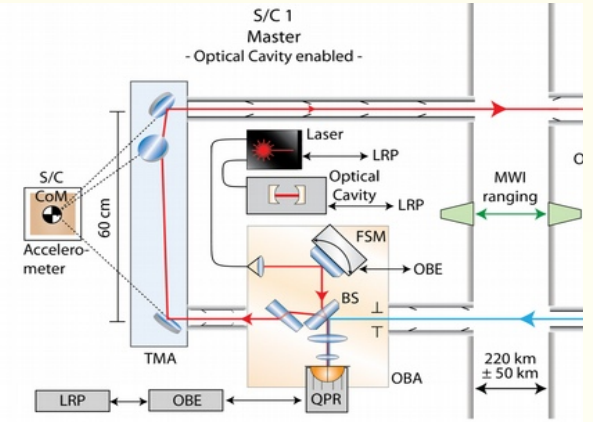


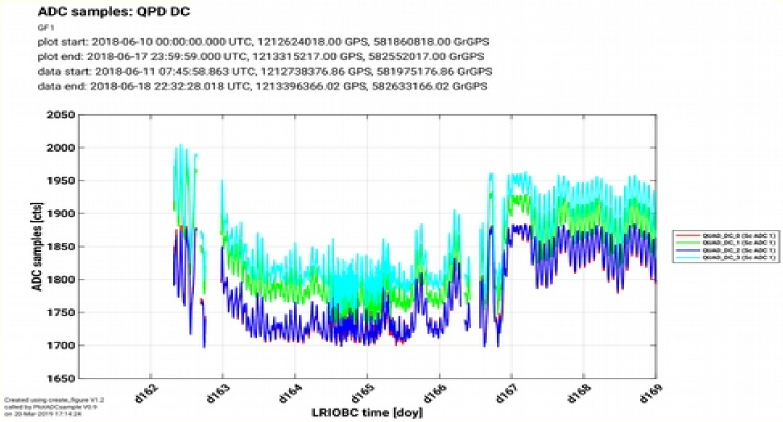
Image credit: Airbus and JPL



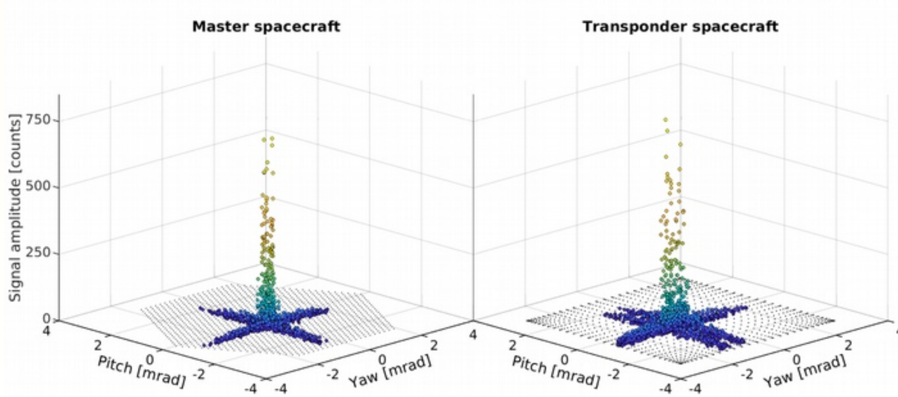
Instrument Comissioning

- 11th and 12th June 2018: Power-on and checkout of individual LRI components on GF-1 and GF2
  - All subsystems behave nominally
  - Photodiode QPR DC values are as expected
    - Laser generates approx. 25 mW of laser light
    - Laser beams well aligned within interferometer
    - Drifts and 1/rev oscillation mainly due to temperature
    - Gaps in the plot due to diagnostic scans





- 13th June 2018: Initial laser-link acquisition scans started
  - Complex 5 degree of freedom search
    - Yaw and pitch angles per S/C, actuation via fast steering mirror on optical bench
    - Laser frequency difference between both S/C
    - All 5 need to be within a narrow range at the same time to obtain an interferometric signal
    - No real-time comm between S/C



Many flashes seen on both S/C during the 8.5 hour scans

Why Acquisition Scan

- LRI field-of-view is approx. 120 µrad
  - Hitting a coin in 100 m distance in order to be able to measure

- Autonomous transition into science mode

- Steering Mirror Control Loop becomes operational

- Quick Re-Acqiusition scan

- Variations in satellite pointing of up to 300 µrad w.r.t. the line of sight due to attitude control accuracy
  - Size of tea cup in 100 m distance

Lost Lock

- Science Mode
- Steering mirror can compensate for satellite pointing variations of up to several 1000 µrad

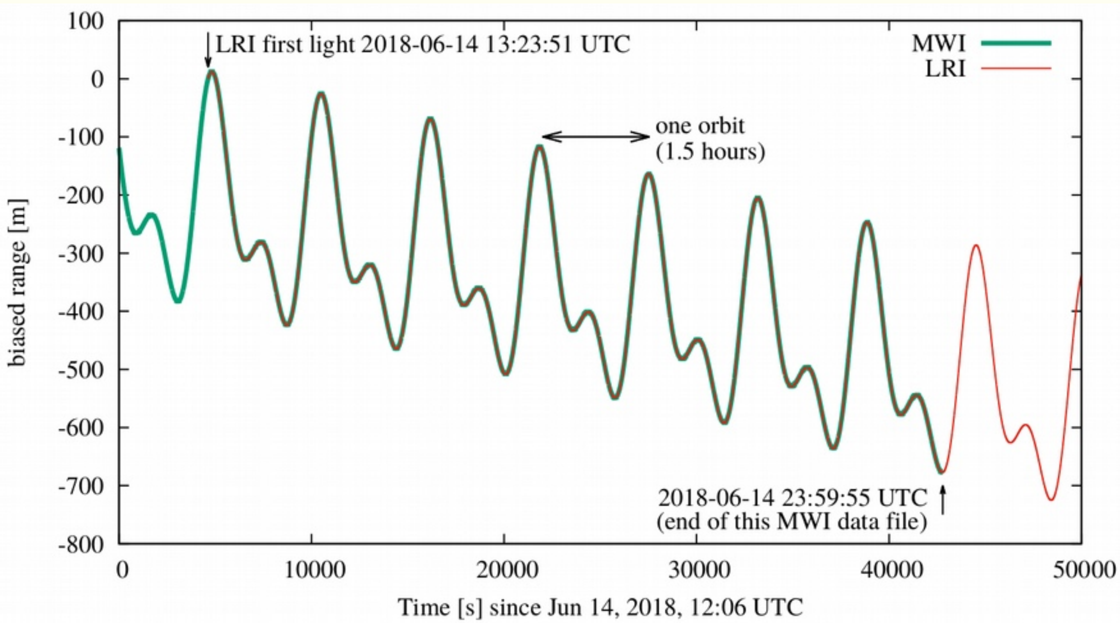
- Initial acquisition search
  - 5 degree of freedom
- Result:
  Frequency offset & 4 angular offsets

- Unknown angular offsets in the alignment of the laser beams after the launch of up to several 1000 µrad

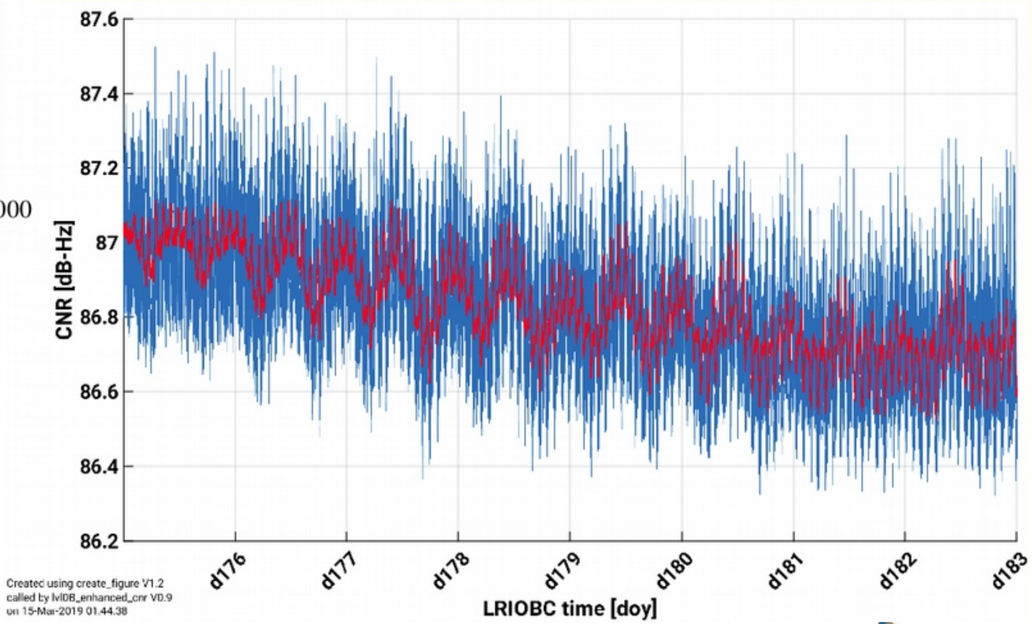
Non-trivial procedure

Transition to Science Mode operation

- Calibration parameters, e.g. angular offsets, from initial acquisition scan uploaded to S/C on 14th June 2018
  - Command to enter re-acquisiton mode
  - Next ground-station contact: LRI transitioned autonomously into science mode



- LRI measures indeed inter-satellite distance variations



- Signal strength (Carrier-To-Noise Ratio, CNR) > 85 dB-Hz for both S/C
  - ample of margin to requirement 70 dB-Hz
  - close to the expected maximum
  - Optimal alignment of laser beams, low losses

Signals look fine at first glance …

GFO LRI: First Himalaya Plots


ALBERT EINSTEIN INSTITUTE HANNOVER
Max Planck Institute for Gravitational Physics and
Leibniz Universität Hannover

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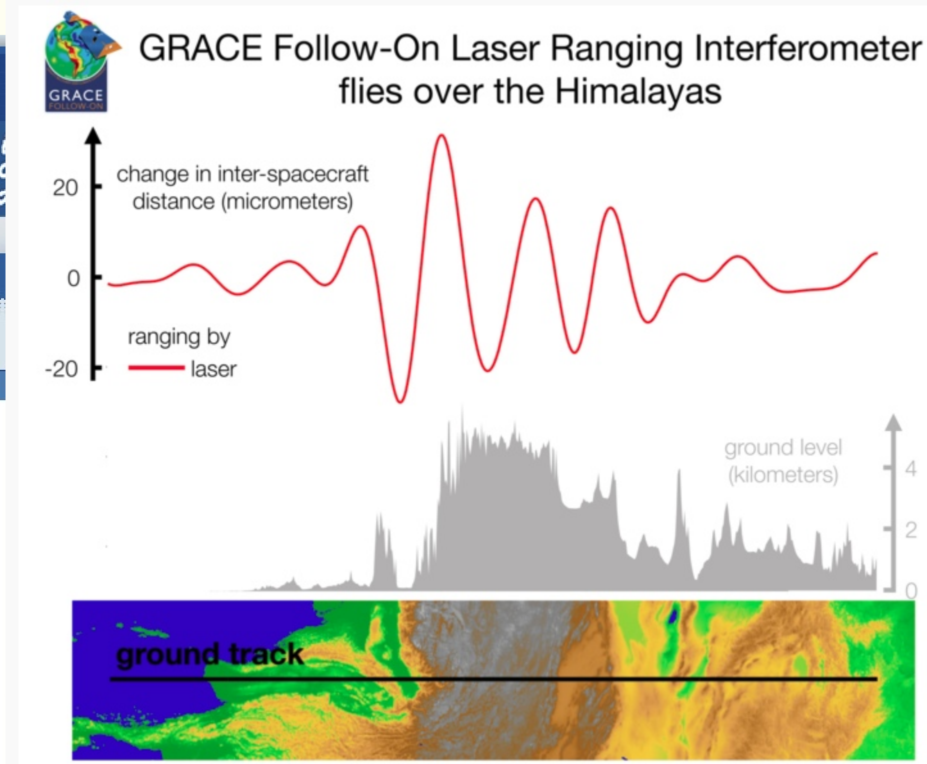
Laser Interferometry in Space

First light for GRACE Follow-On Laser Interferometer

For the first time, laser interferometry between two satellites in space measures their 220-kilometer distance to nanometer precision

July 02, 2018

The laser ranging interferometer (LRI), a novel instrument onboard the GRACE Follow-On satellite mission, had its "first light" on 14th June 2018. An international team of researchers from the German Max Planck Institute for Gravitational Physics (Albert Einstein Institute, AEI) in Hannover, the Leibniz Universität Hannover, and the NASA Jet Propulsion Laboratory switched on their instrument and achieved success on first try. Since then, the LRI has been taking scientific measurements in parallel to the main microwave ranging instrument. Initial results agree well, and the research team is optimistic that the LRI's improved precision will assist in tracking indicators of climate change by observing Earth's gravity field and its variations. GRACE Follow-On is a joint project of NASA with German partners, which are led by the GFZ German Research Centre for Geosciences. The success is also an important milestone on the path towards LISA, the planned gravitational-wave observatory in space.



Top: Ranging data taken by the GRACE Follow-On Laser Ranging Interferometer as it flew over the Himalayas. Middle and bottom: The topography beneath the satellite tandem.

graphic: B. Knispel/G.Heinzel/Max Planck Institute for Gravitational Physics; GRACE FO data: NASA, GFZ, JPL; map data: SRTM

Press release

First publication on in-orbit performance

PHYSICAL REVIEW LETTERS **123,** 031101 (2019)

Editors' Suggestion | Featured in Physics

In-Orbit Performance of the GRACE Follow-on Laser Ranging Interferometer

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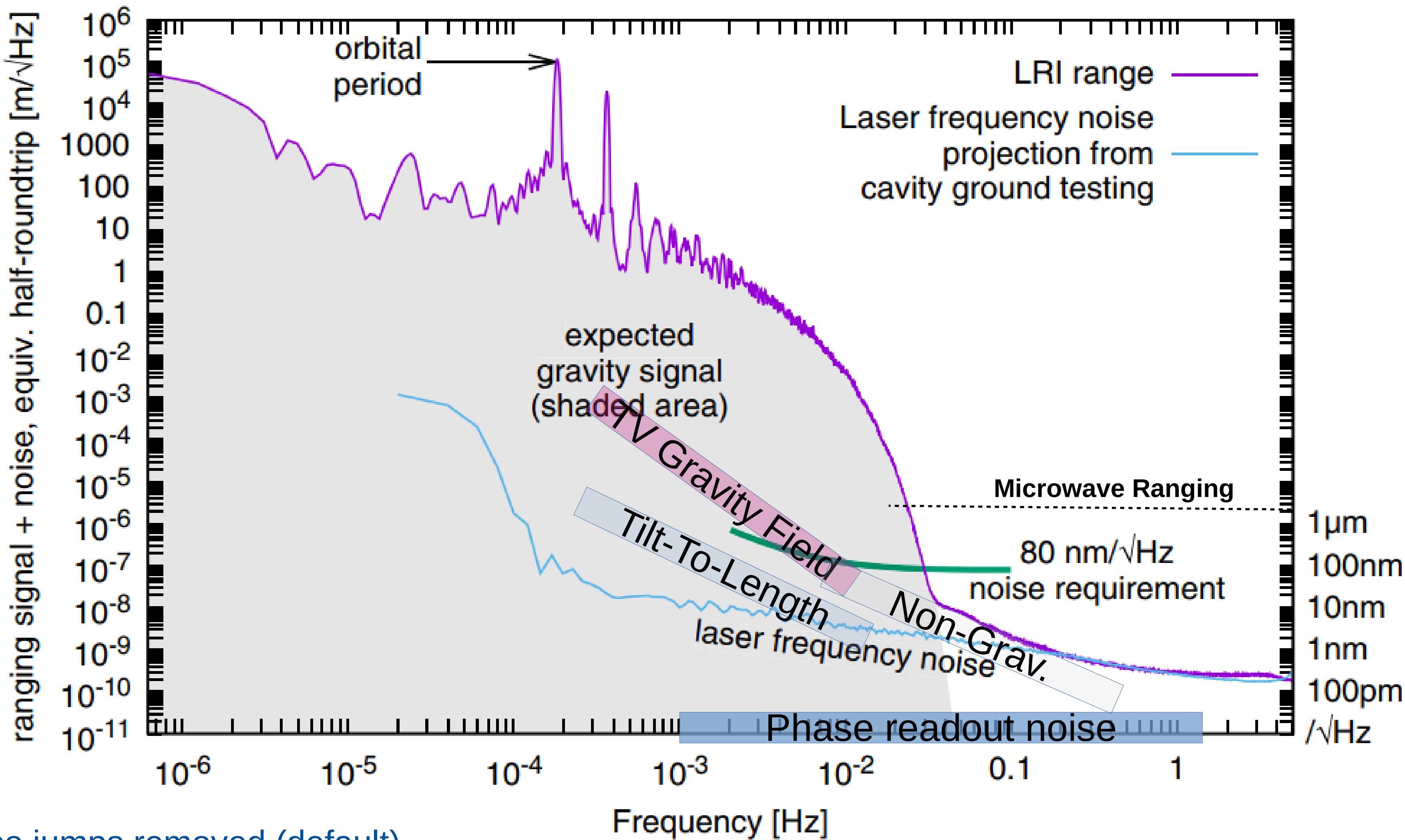
The Laser Ranging Interferometer (LRI) instrument on the Gravity Recovery and Climate Experiment (GRACE) Follow-On mission has provided the first laser interferometric range measurements between remote spacecraft, separated by approximately 220 km. Autonomous controls that lock the laser frequency to a cavity reference and establish the 5 degrees of freedom two-way laser link between remote spacecraft succeeded on the first attempt. Active beam pointing based on differential wave front sensing compensates spacecraft attitude fluctuations. The LRI has operated continuously without breaks in phase tracking for more than 50 days, and has shown biased range measurements similar to the primary ranging instrument based on microwaves, but with much less noise at a level of 1 nm/$\sqrt{\mathrm{Hz}}$ at Fourier frequencies above 100 mHz.

DOI: 10.1103/PhysRevLett.123.031101

LRI works like a charme

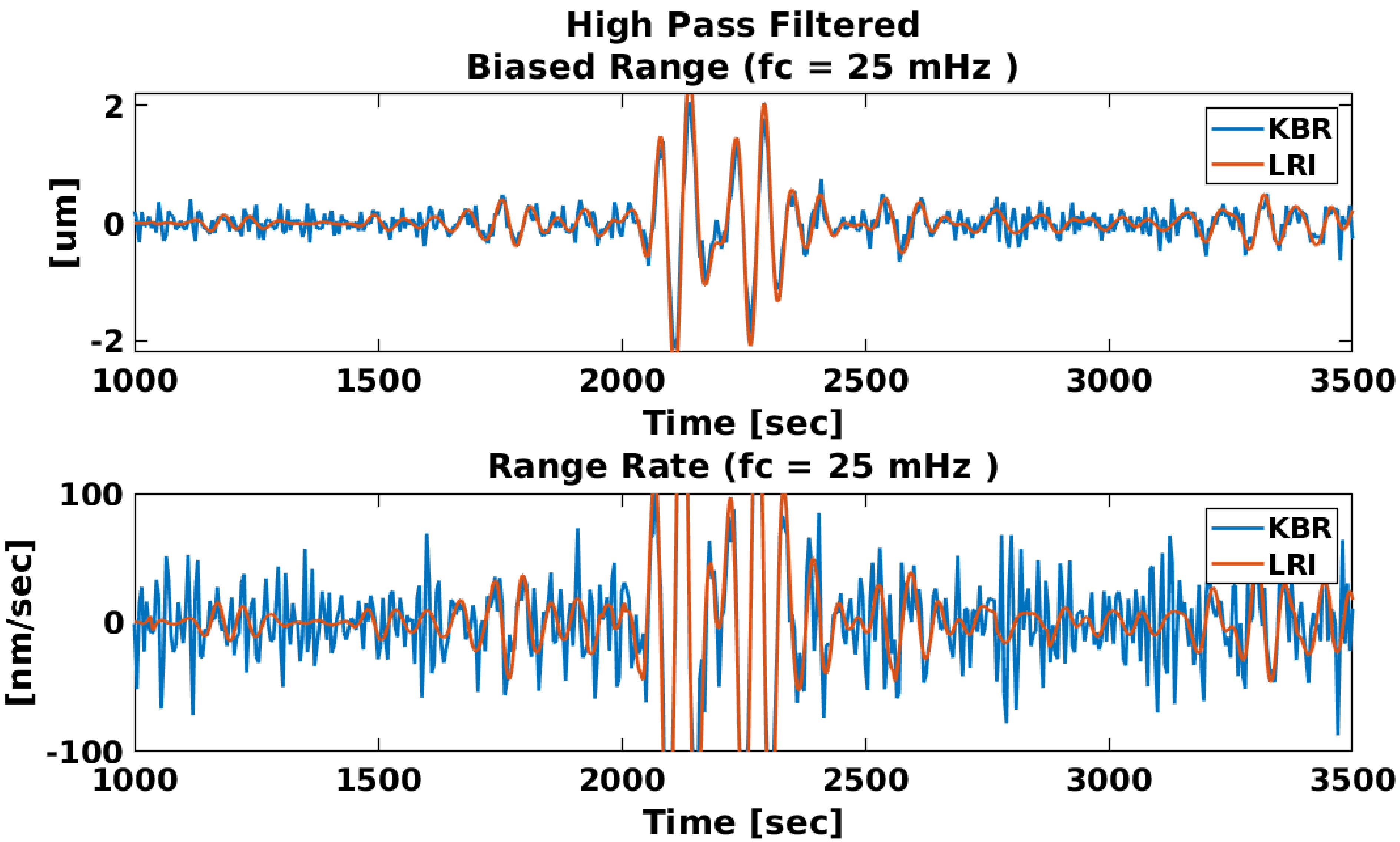
LRI Signal and Noise



- Phase jumps removed (default)
- Laser Frequency Noise limits LRI at high frequencies
- Instrument noise at low frequencies (< 35 mHz) difficult to evaluate
- Noise as low as 200 pm/√Hz at high frequencies > 1 Hz

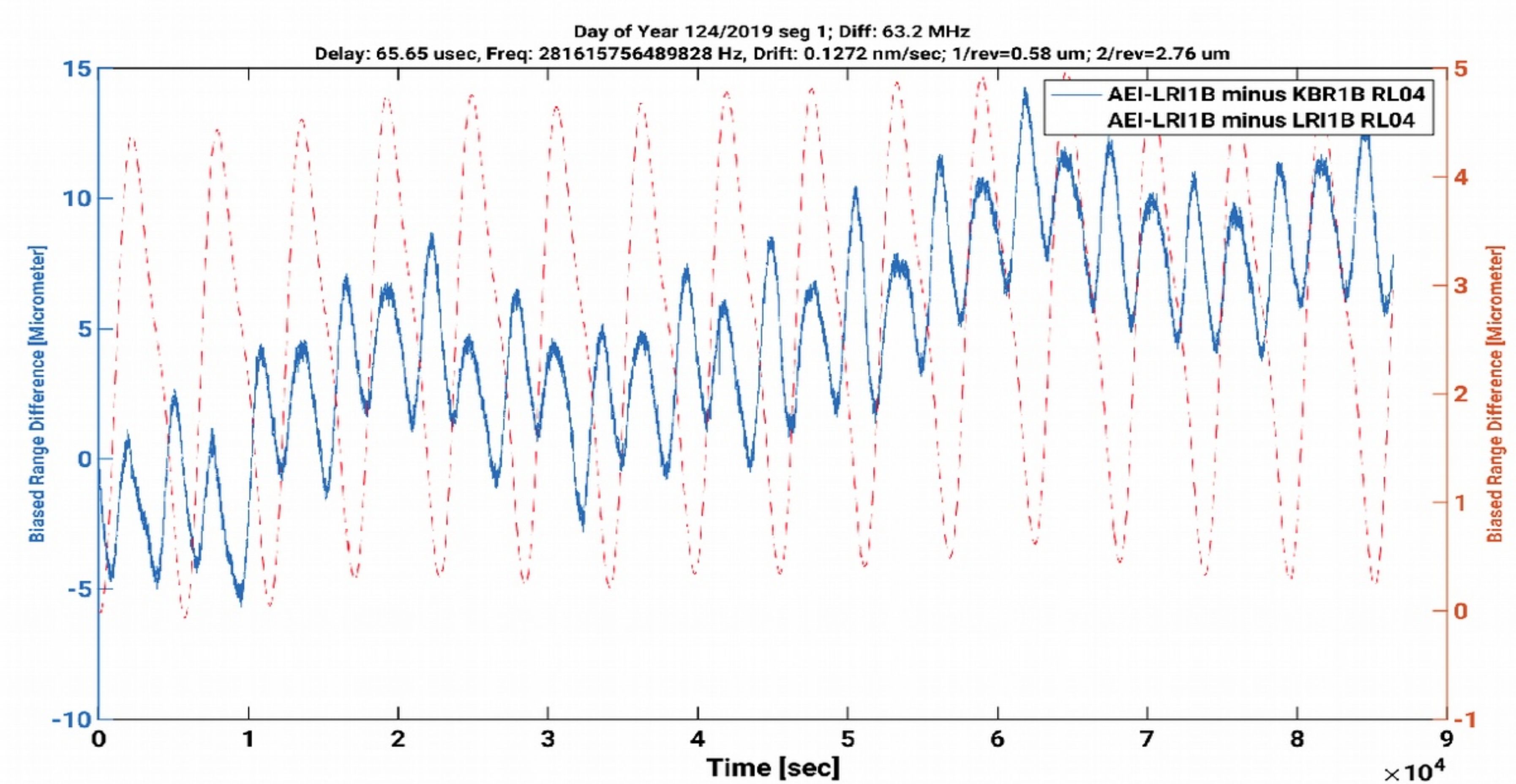
LRI resolves within 1 second distance changes of the size of a single Helium atom

LRI Signal and Noise – Time Domain



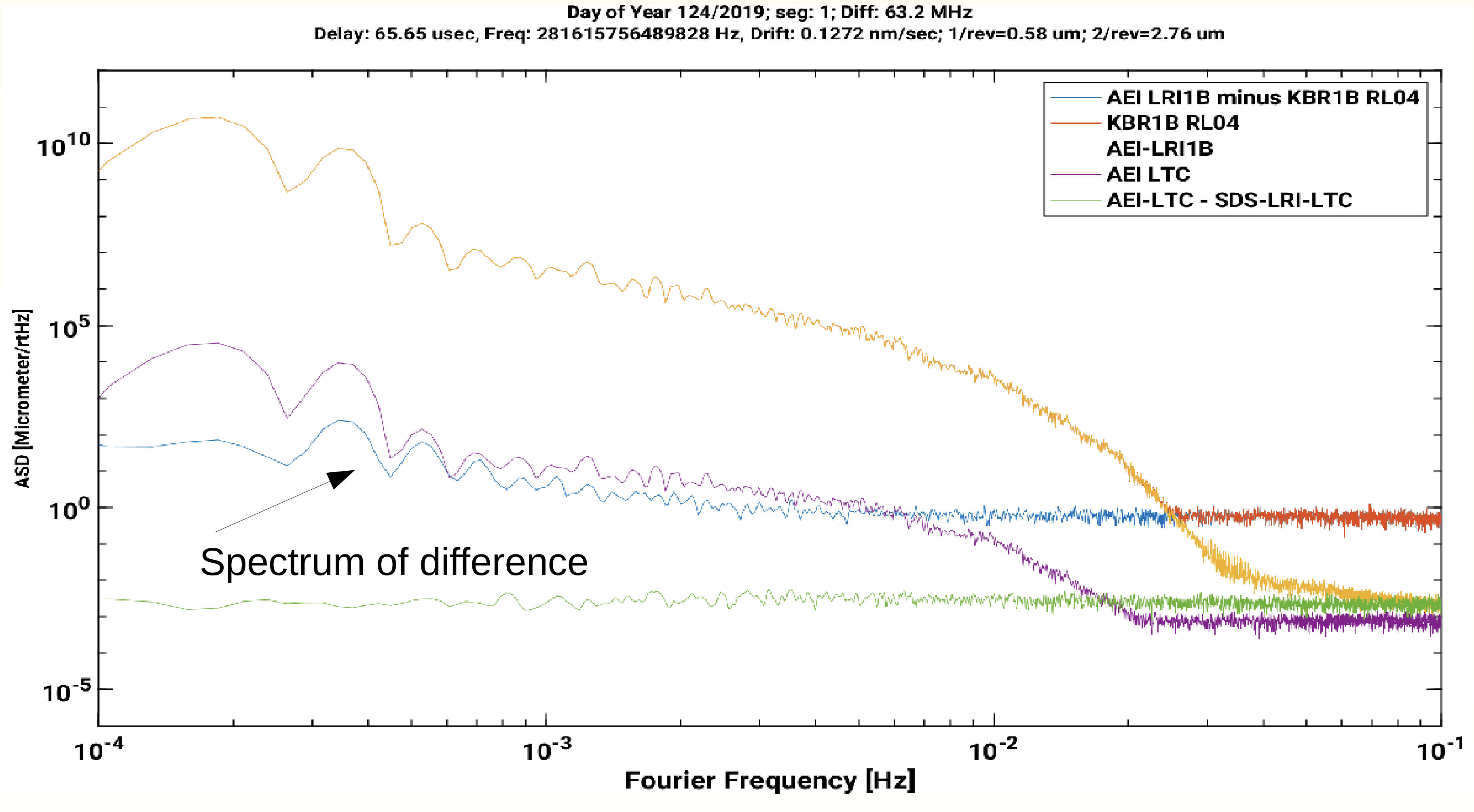
Which parts are noise and which parts are signal?

Difference between LRI and KBR



- Oscillations at once and twice the orbital frequency with a few micrometer amplitude
  - Likely tone errors within the K/Ka band ranging system
- Drift of 0.1 nanometer/second not understood yet
  - Might originate from KBR or LRI

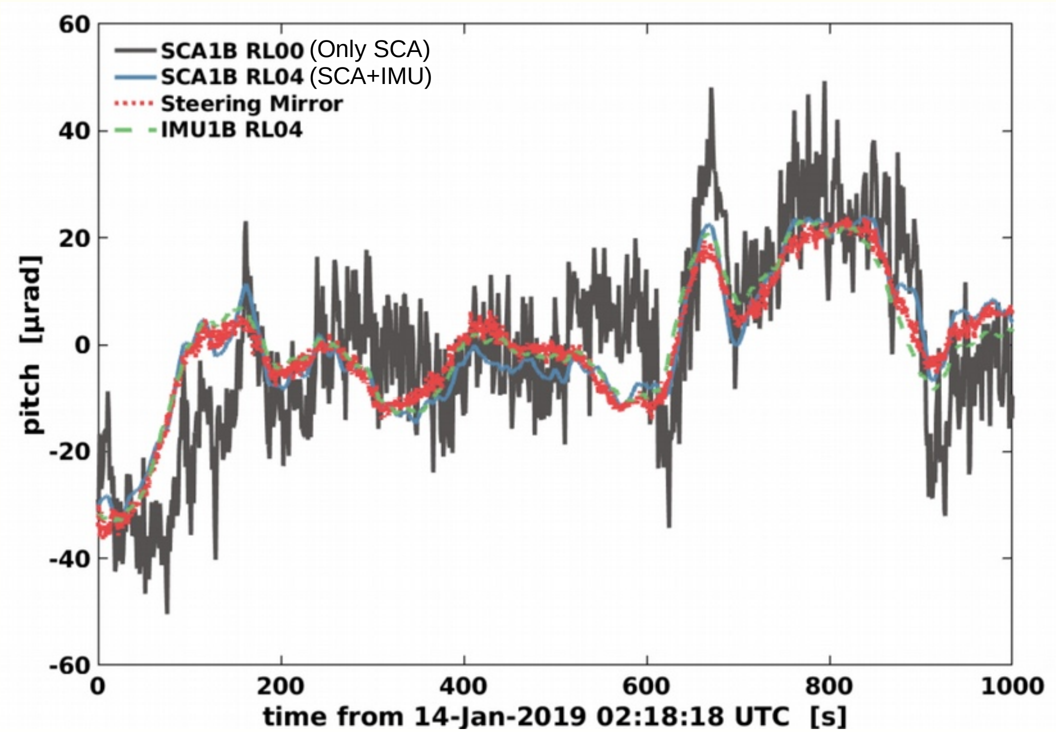
Difference between LRI and KBR

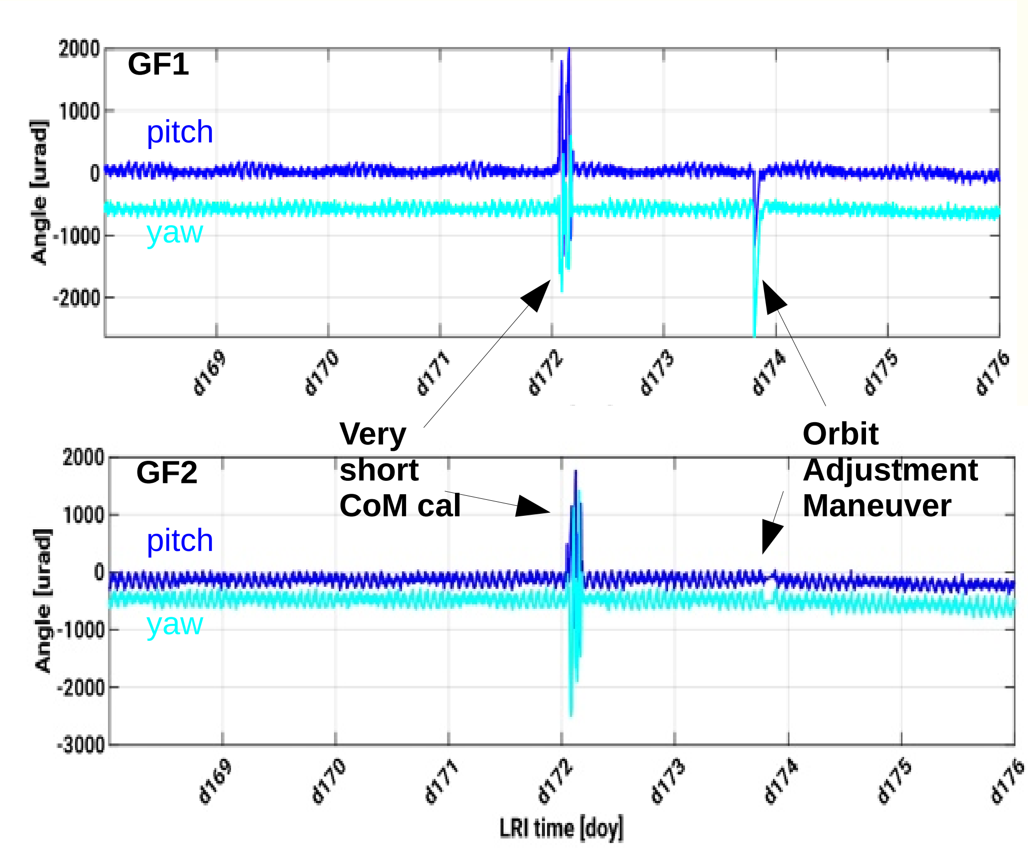


Difference is dominated by the KBR noise

LRI Steering Mirror

- Steering mirror & Differential Wavefront Sensing provide yaw and pitch angles with respect to the line of sight
  - Steering mirror angles consistent with other instruments, reflect actual attitude variations of the S/C



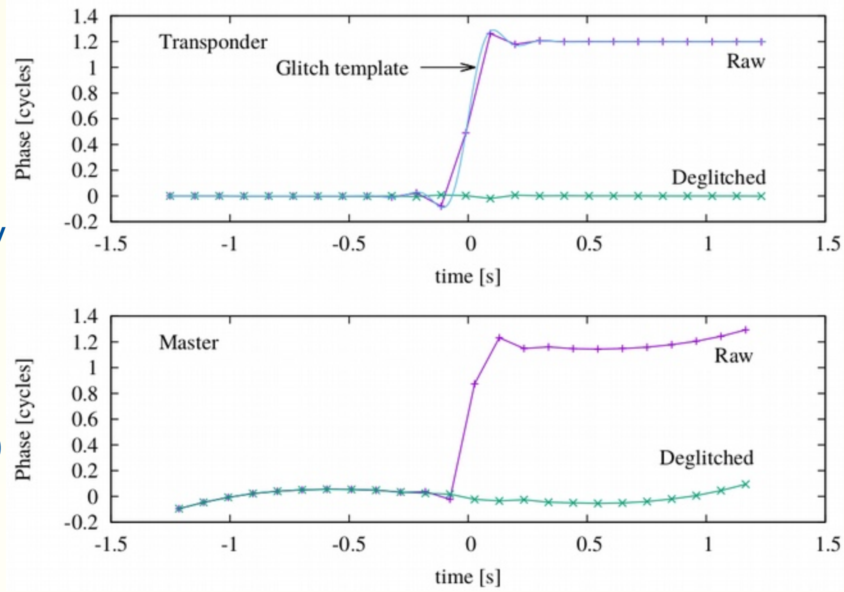


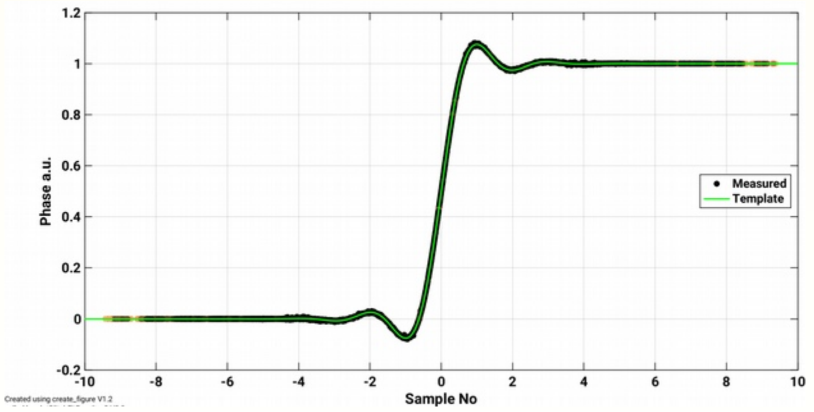
SM angles ideal to characterize tilt-to-length coupling, because they are w.r.t. LOS

Data Analyses Aspects: Phase Jumps

- LRI has in general very good data quality with very few unintended interruptions
  - continuous ranging data stretch with over 1650 orbital revolutions (~108 days)

- Raw LRI ranging data exhibits some jumps, called phase jumps or glitches
  - Coincident with attitude thruster usage, mainly on master S/C and mainly roll thruster
  - Coupling of vibrations into the NPRO laser, which produce frequency variations faster than the bandwidth of
    - the cavity PDH lock
    - the frequency lock on transponder side
  - Variations always within bandwidth of phase measurement (tracking)
    - Propagate from master to transponder
    - Measured with same amplitude on both sides
  - Glitch with normalized-amplitude = a few discretely-sampled points of the decimation filter response
  - Glitches removed to a large extent from the official Level1B level product
    - official RL04 data processing not optimal
  - Optimal method
    - Determine glitch parameters on transponder
    - remove glitch from master and transponder
    - Subtract deglitched transponder from deglitched master (removes non-modeled glitch features)

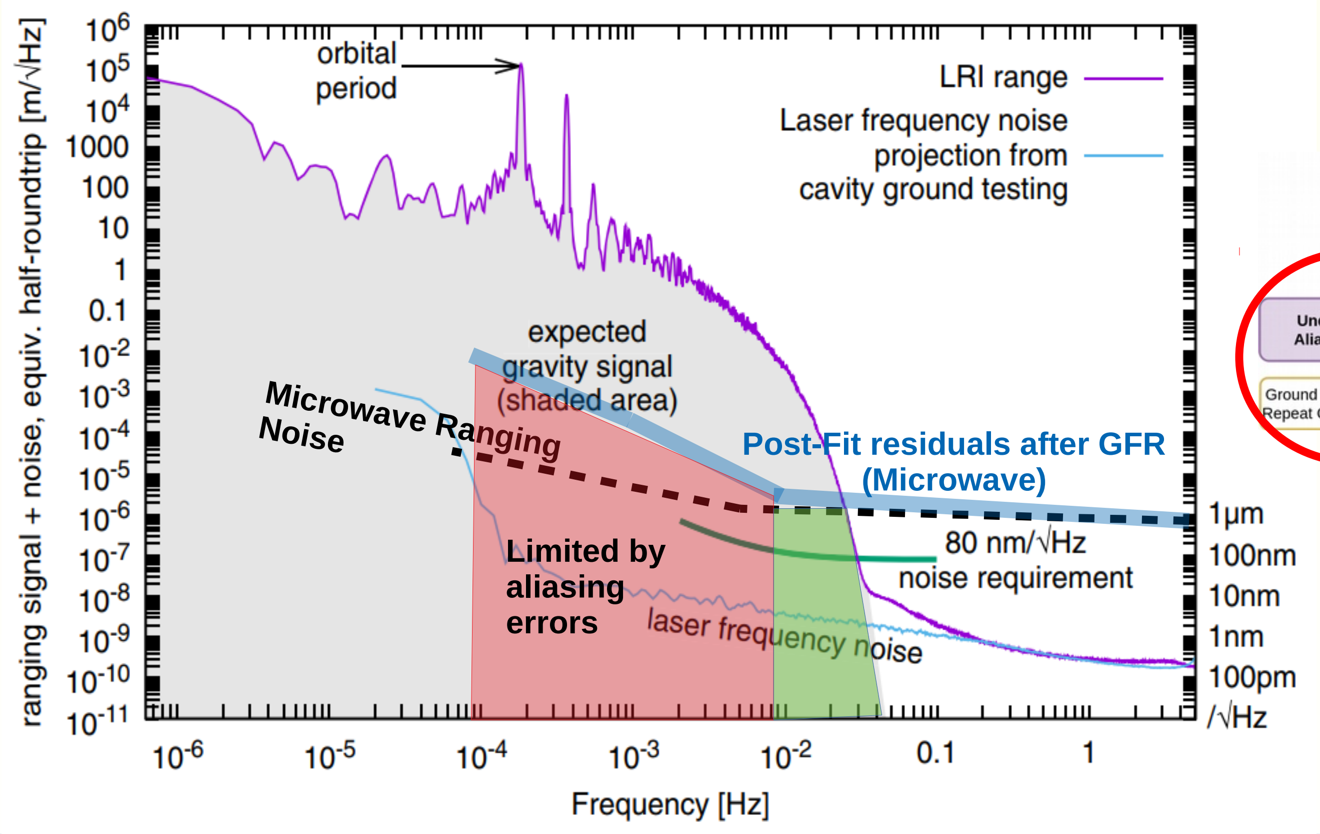


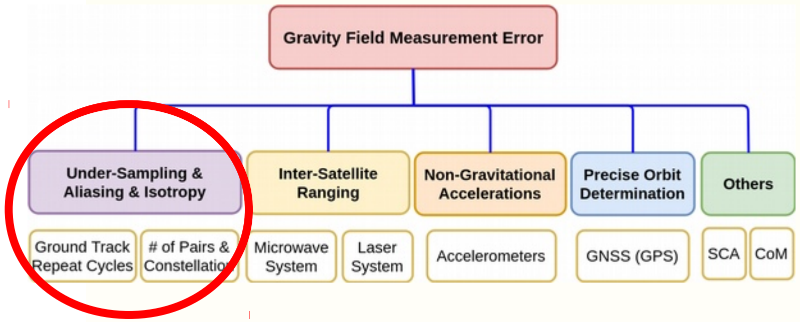


These are not (integer-valued) cycle slips

Does the LRI improve gravity field maps?

- Pre-launch simulations indicate only minor improvement for gravity field maps using LRI data (1%..20%)
  - Flechtner et al.: “What can be expected from the GRACE-FO Laser Ranging Interferometer for Earth Science Applications?”, Surv Geophys, DOI 10.1007/s10712-015-9338-y
- Current preliminary results: KBR and LRI gravity fields very similar; Work in progress
- My expectation
  - Low frequencies dominated by aliasing errors: need more satellite pairs & improved background models
  - Band between 10 … 40 mHz could contain new “science”, 100 … 350 km spatial resolution (half wavelength): TV gravity too weak, maybe improvement in static (“averaged”) gravity field maps from GRACE





Comparison of GFO LRI and LISA

	LISA	LISA Pathfinder	GRACE F.O.
# of Spacecraft	3	1	2
Avg. ρ	$\approx$ 2.5 Mkm	38 cm	200 km
Max. $\dot{\rho}$	5 m/s	$\approx$ 0	5 m/s
Max. Doppler Shift	5 MHz	$\approx$ 0	5 MHz
Max. ρ_{mod}	10000 km	$\approx$ 0	4 km
Modulation Period	1 year		93 min
Max. $\ddot{\rho}$	1 µm/s^2	$\approx$ 0	6 mm/s^2
Max. Doppler Rate	1 Hz/s	$\approx$ 0	6 kHz/s
Max. $v_{12,\perp}$	200 m/s	$\approx$ 0	250 m/s
Point Ahead Angle	1.4 µrad	$\approx$ 0	1.6 µrad
Beam Div. θ_{TX}	$\approx$ 2 µrad	n.a.	$\approx$ 140 µrad
Environm. Condition	Deep-Space	Deep-Space, LP	LEO
Concept	Transponder	Several MZ IFOs	Transponder
Readout Scheme	Heterodyne	Heterodyne	Heterodyne
Phase Retrieval	DPLL	SBDFT	DPLL
Beatnote Frequency	4..20 MHz	1.0 kHz	4...20 MHz
Laser Wavelength	1064 nm	1064 nm	1064 nm
Science Meas. Band	0.1 mHz..0.1 Hz	1 mHz..0.1 Hz	0.1 mHz..0.1 Hz
Ranging Sensitivity†	$\approx$ 10 pm/$\sqrt{\text{Hz}}$ $\hat{=}$9 µcycl./$\sqrt{\text{Hz}}$	$\lesssim$ 10 pm/$\sqrt{\text{Hz}}$ $\hat{=}$9 µcycl./$\sqrt{\text{Hz}}$	80 nm/$\sqrt{\text{Hz}}$ $\hat{=}$75 mcycl./$\sqrt{\text{Hz}}$
On-Orbit Ranging Sensitiv.		35 fm/$\sqrt{\text{Hz}}$	
LFN Reduction	Transponder TDI	‡ Equal-Arm IFO	Transponder
Time Reference	USO per S/C + CTT	USO Single Common	USO per S/C GNSS avail.
Ranging Ref. Point(s)	Test-Mass	Test-Mass	Virtual at CoM
Absol. Laser Ranging	Yes, $\approx$ 1 m accuracy	Not Req.	Not Req. (GNSS avail.)
(Optical) Data Transm.	Yes	Not Req.	Not Req.

Summary

- GRACE FO is collecting data, gravity field maps (level-2) are available
- The Laser Ranging Instrument is healthy and recording biased range data with a noise level as low as 200 pm/rtHz.
  - The LRI provides attitude information in yaw and pitch
  - The Level1A data contains jumps in the phase, which can and should be removed in post-processing.
    - Level1B data products are deglitched
- GFO LRI is the first inter-satellite laser interferometer
  - Milestone towards gravitational-wave measurements in space (LISA mission)
- So far, we have not observed a degradation of the LRI
  - LRI should deliver low-noise data for many more years
  - This data may be of special value in future, when Earth background models improve (Aliasing errors reduce)

Thank you for your attention!