Jet Propulsion Laboratory
California Institute of Technology

Interspacecraft Laser Interferometry on the Path to a Gravitational Wave Observatory in Space: the LISA and GRACE Follow-On Missions

IFCS 2016

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Jet Propulsion Laboratory, California Institute of Technology

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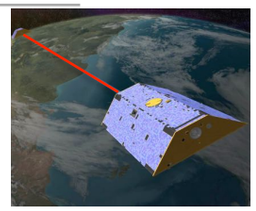
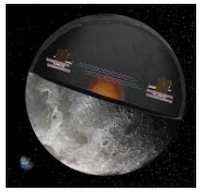
Interferometry in space

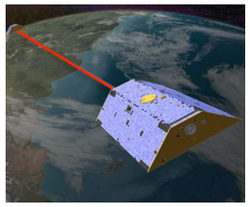
- GRACE [μm] (2002-present)



- GRAIL [μm] (2012)

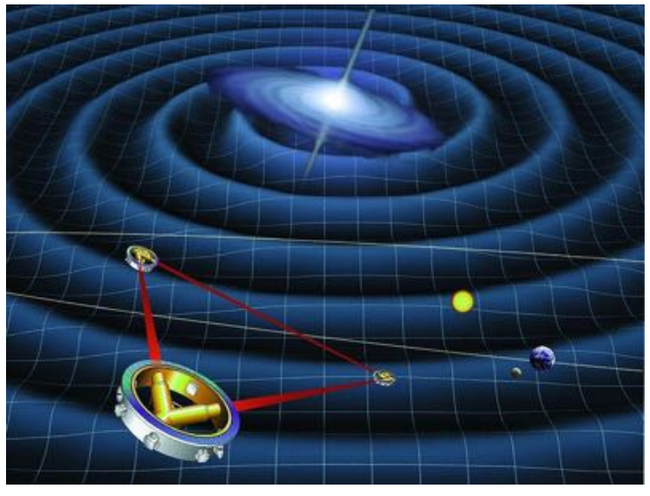


- GRACE [μm] Follow-on [nm] (2017)



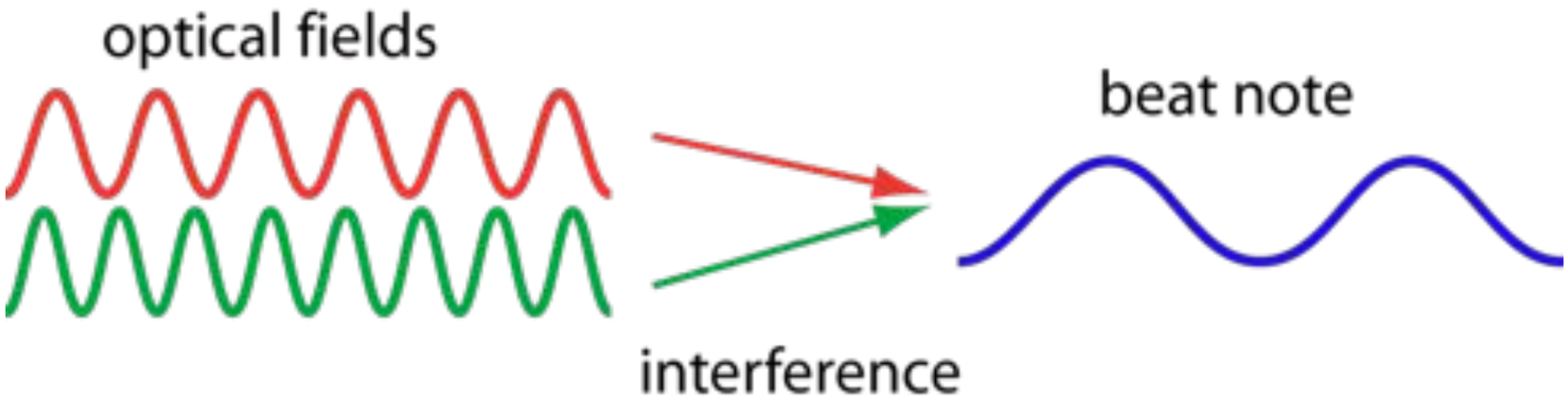
- GRACE 2 [nm] (2020s)
  - Earth Science Tier 3 Decadal

- LISA [pm] (2034, possibly earlier)
  - NASA 2010 Decadal
  - ESA Cosmic Visions L3



- Microwave
- Laser

Laser Heterodyne Interferometry



- One wavelength shift in one optical field produces a one wavelength shift in the beat note.
- No “lock” point. Full fringe readout with large dynamic range.
- LISA and GRACE Follow-on beat note ranges from 2 MHz -20 MHz due to Doppler shift from spacecraft motion.
- The science signal appears as a milliHertz phase modulation on a megahertz beat signal.

Outline of remainder of talk

- (GRACE and) GRACE Follow-on
- (LISA Pathfinder and) LISA
- Near future

GRACE Follow-on Laser Ranging Interferometer (LRI)

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The first interspacecraft laser interferometer

$$\frac{\Delta L}{L} = \frac{10nm}{200km} = 5 \times 10^{-14}$$

Concept for measuring Earth Gravity

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Milo Wolff, JGR 1969

- Satellite pair, low-earth orbit, 200 km separation
- Satellite-to-satellite tracking
- Laser phase metrology (!)
- Relative velocity ~ gravitational potential

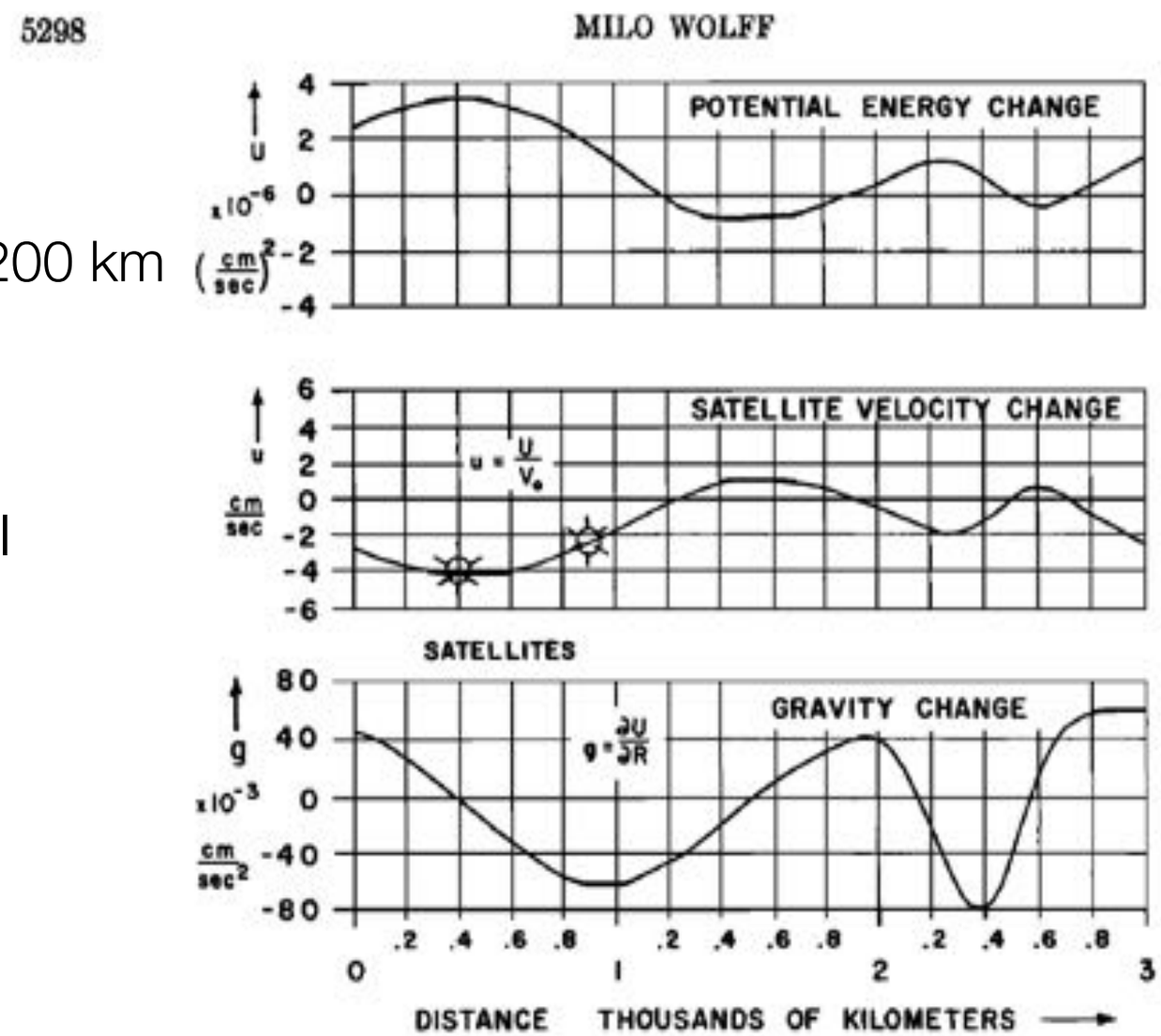

Fig. 1. Hypothetical changes in potential energy, velocity, and gravity for a low altitude circular-orbit satellite.

Gravity Recovery and Climate Experiment

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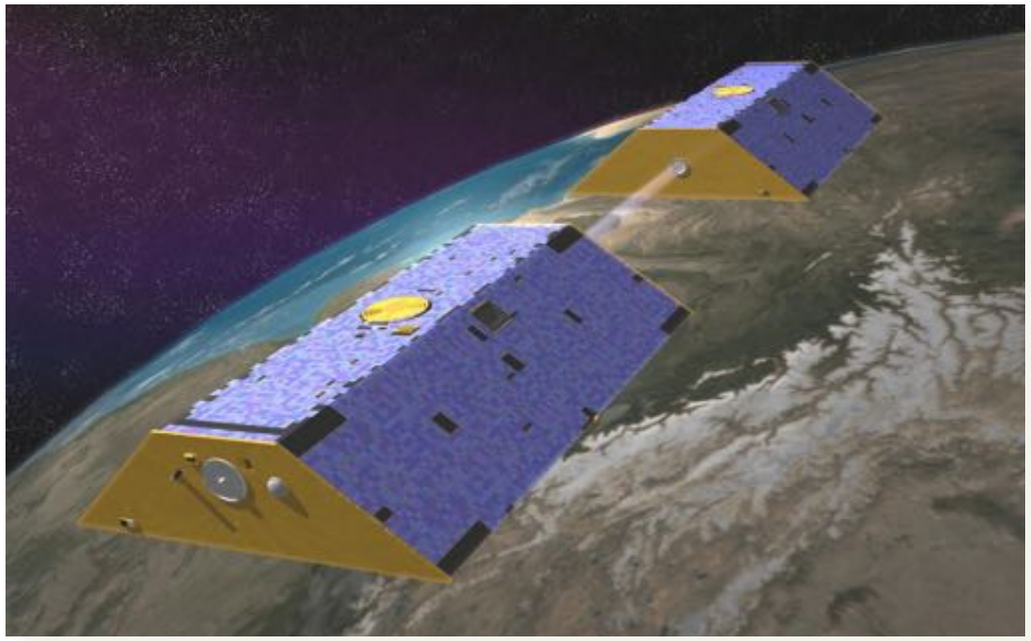
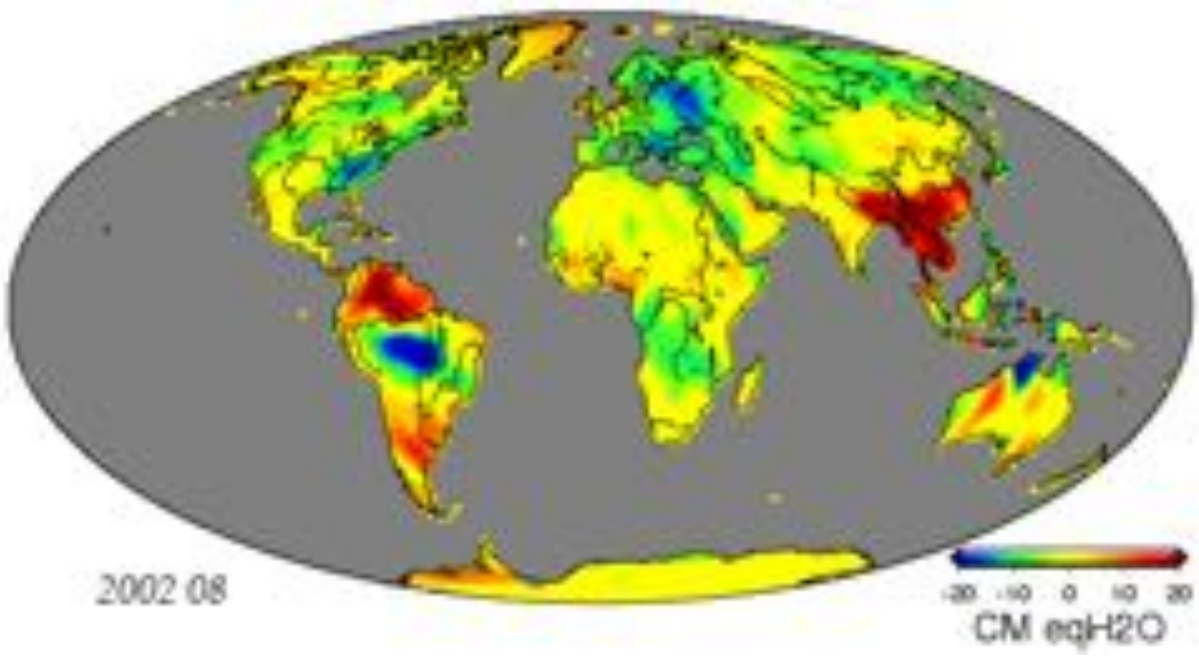
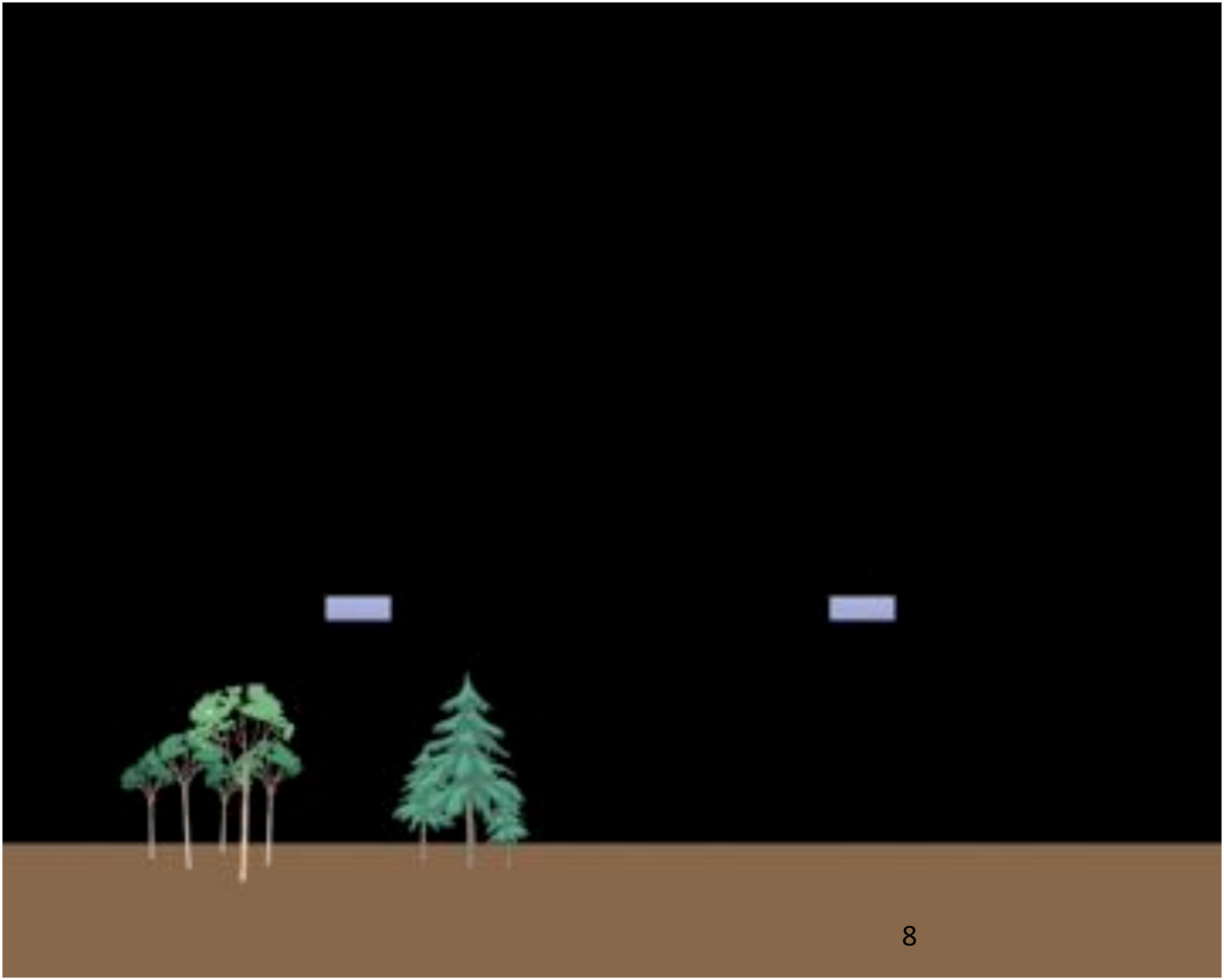
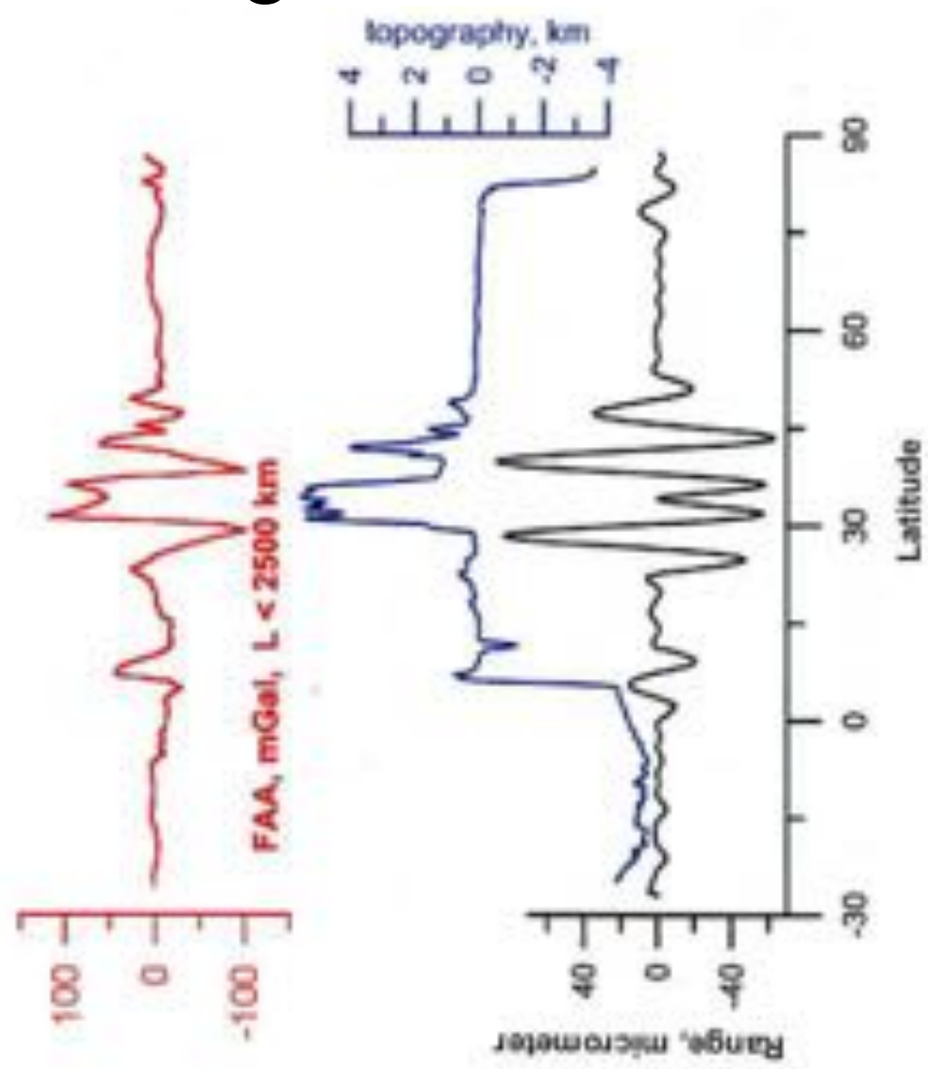
- NASA/German Research Centre for Geosciences (GFZ) partnership
- Operating since 2002
  - Two identical satellites orbit one behind the other, 200 km apart, 500 km high
  - Separation measurement of 2 spacecraft by dual microwave links (3 μm/√Hz over 200 km) (10^{-10} ms^{-2}/√Hz accelerometer)
  - Spacecraft separation + location (GPS) yield orbit
    - Orbit+separation defines gravity map
  - Gravity map evolution over months and years
    - Changes in rainfall
    - Water storage
    - Ice mass
    - Effects of climate change







GRACE signals



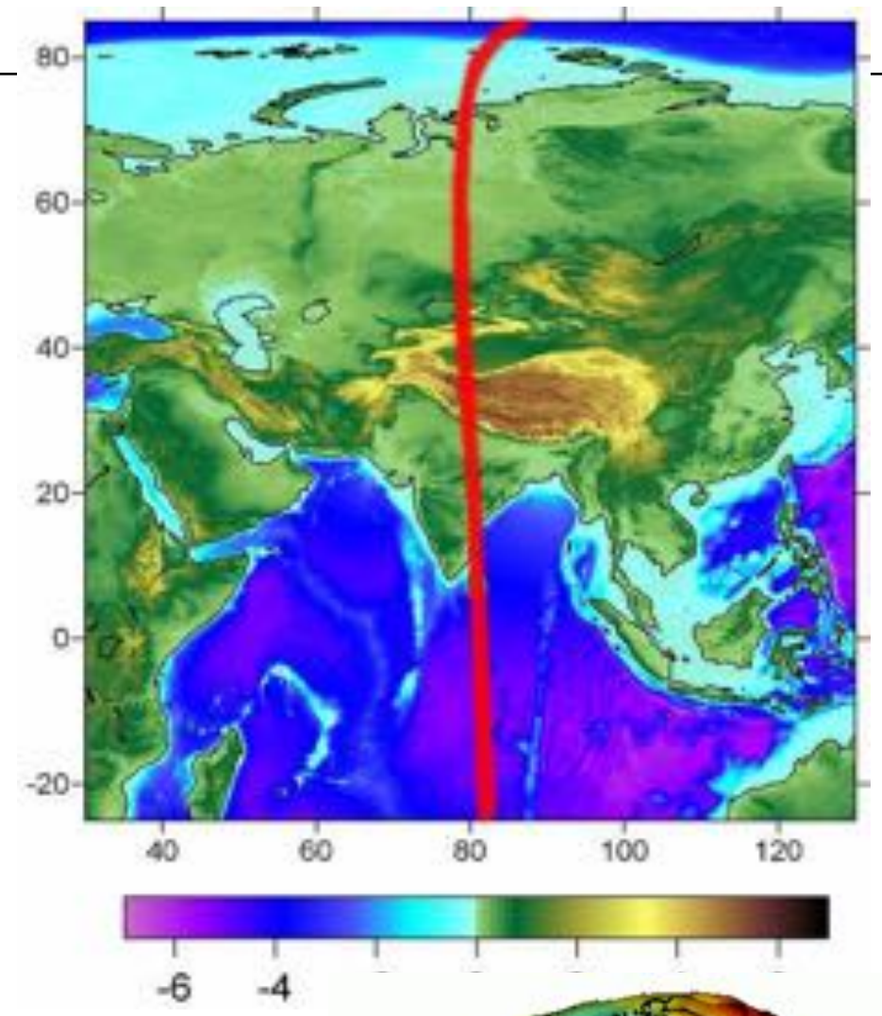
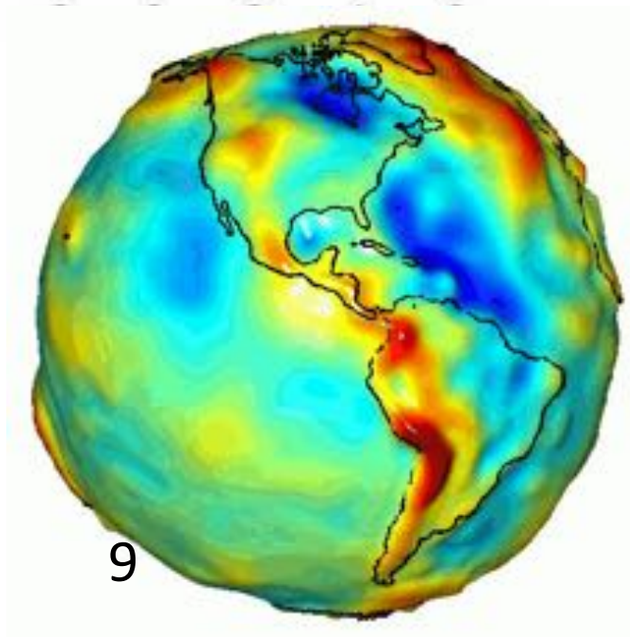


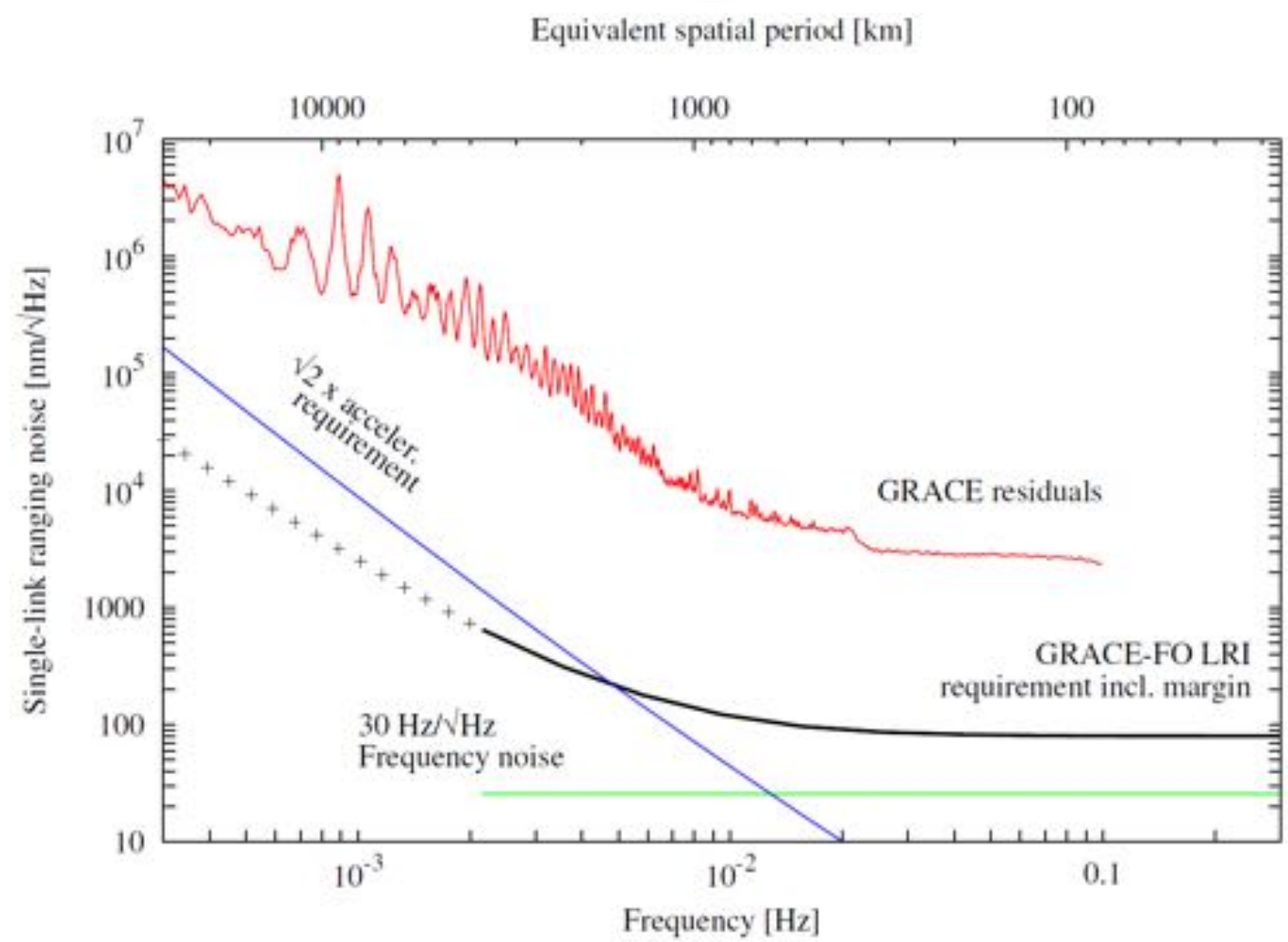
Image credit: AIUB CSR

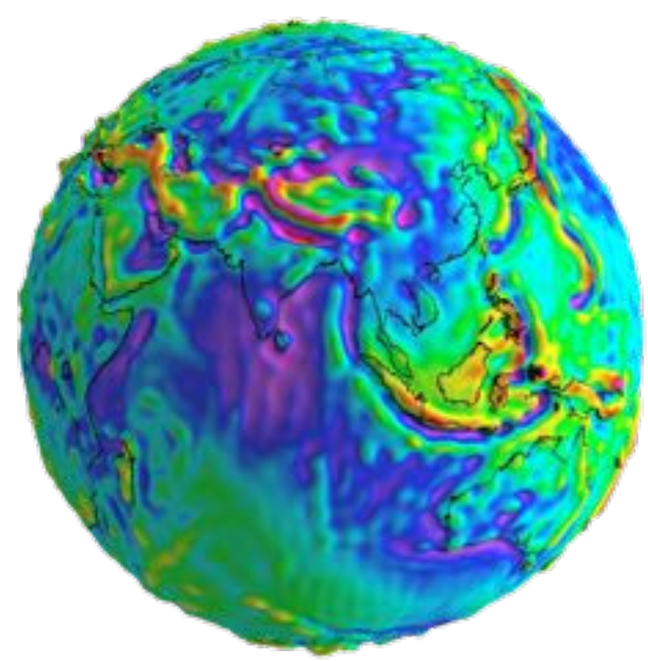
- Observe small changes in large signal
- Typical results are monthly solutions with 200km ground resolution and some ~mm equivalent water height noise level

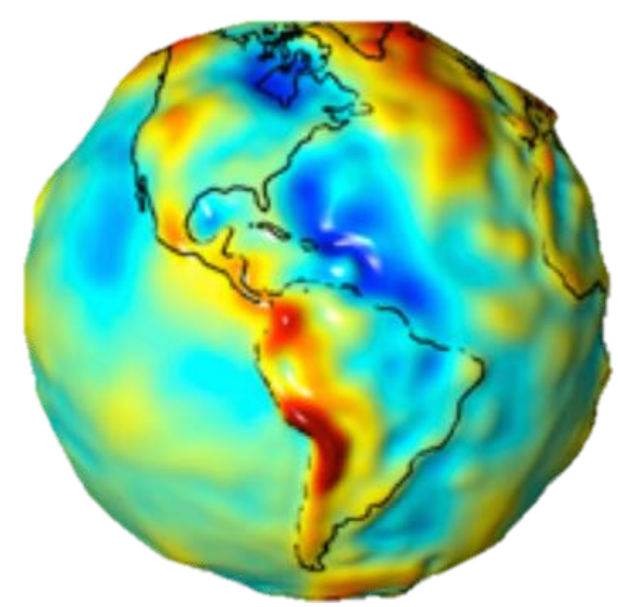


GRACE Follow-On

- Continue GRACE Science
- NASA/German Research Centre for Geosciences (GFZ) partnership
- Microwave Ranging Instrument (MWI) similar to GRACE
- Accelerometer from ONERA as on GRACE
- Launch: 2017
- 5 year mission
- Tech Demo: Laser Ranging Interferometer (LRI)
  - LRI goal is > 10 times better sensitivity than MWI
  - ~90 nm/√Hz vs ~3 μm/√Hz
  - λ_{LRI}= 1 μm vs λ_{MWI} ~ 1cm
  - LRI sensitivity limit: residual laser frequency noise

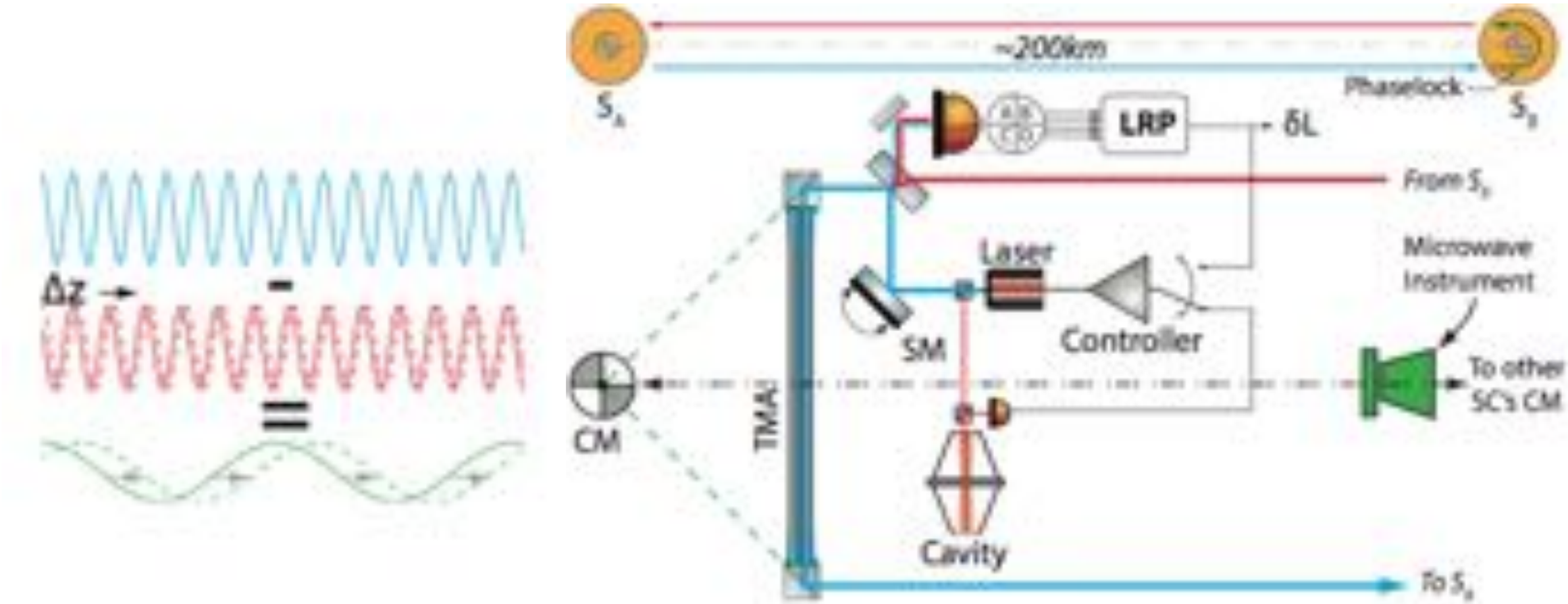






Adapted from Sheard et al, J Geod, (2012)

GRACE-FO LRI Measurement



- Interference between two single-frequency optical fields causes a ‘beat-note’ in the field power at their offset frequency.
- Active transponder: round trip measurement by phaselocking at ‘slave’ SC.
- Accelerometer at CM to subtract non-gravitational forces.
- Changes in the laser’s wavelength directly corrupt the measurement:
  - ***Laser Frequency noise is a limiting noise source for the GRACE-FO LRI.***
  - ***Laser stabilized to a ULE reference cavity.***

LRI components

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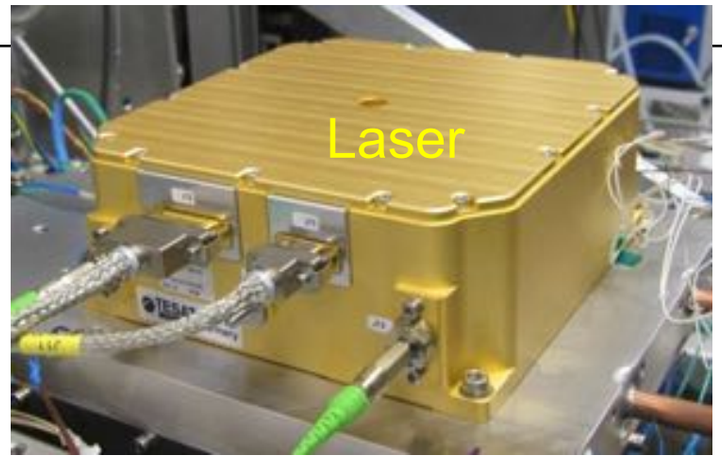

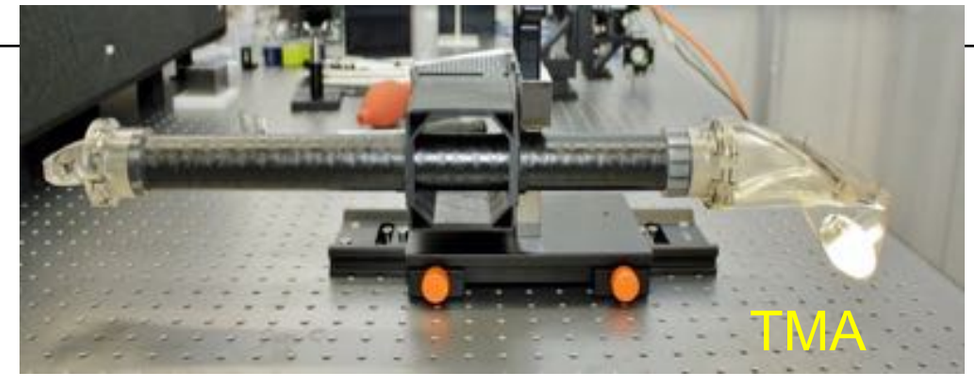

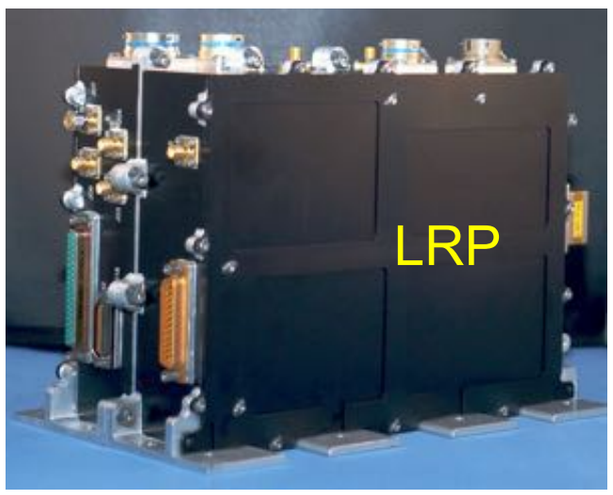

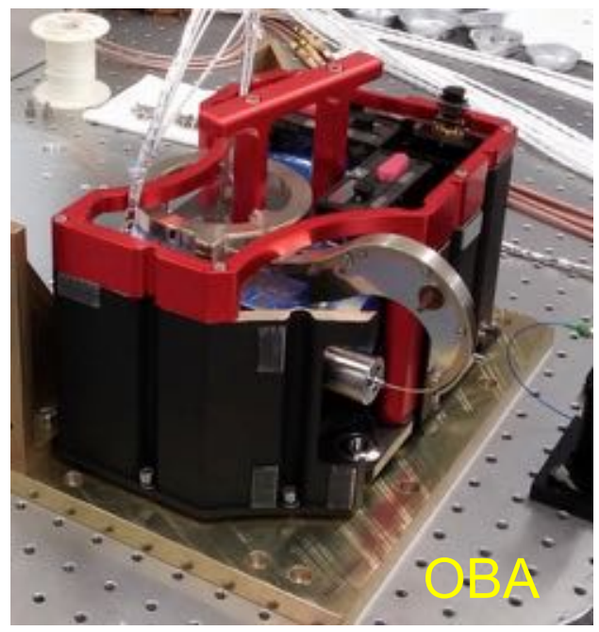

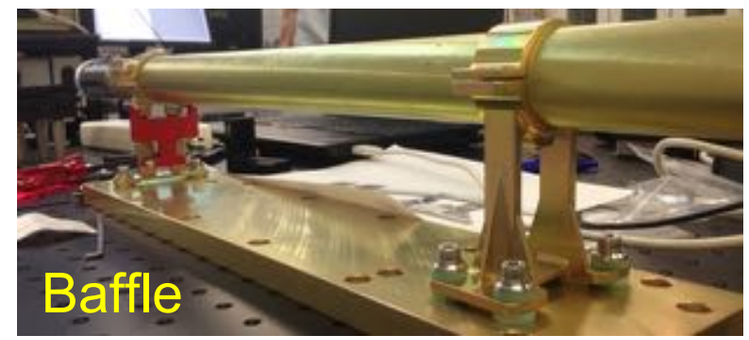

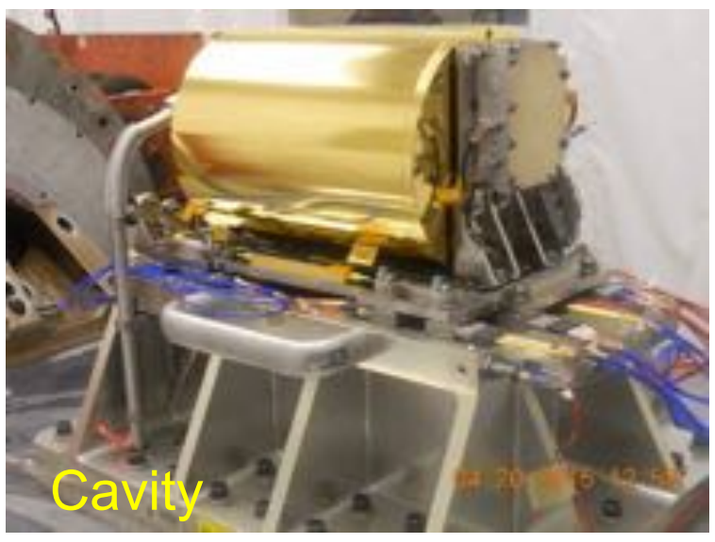

GRACE-FO LRI Block Diagram

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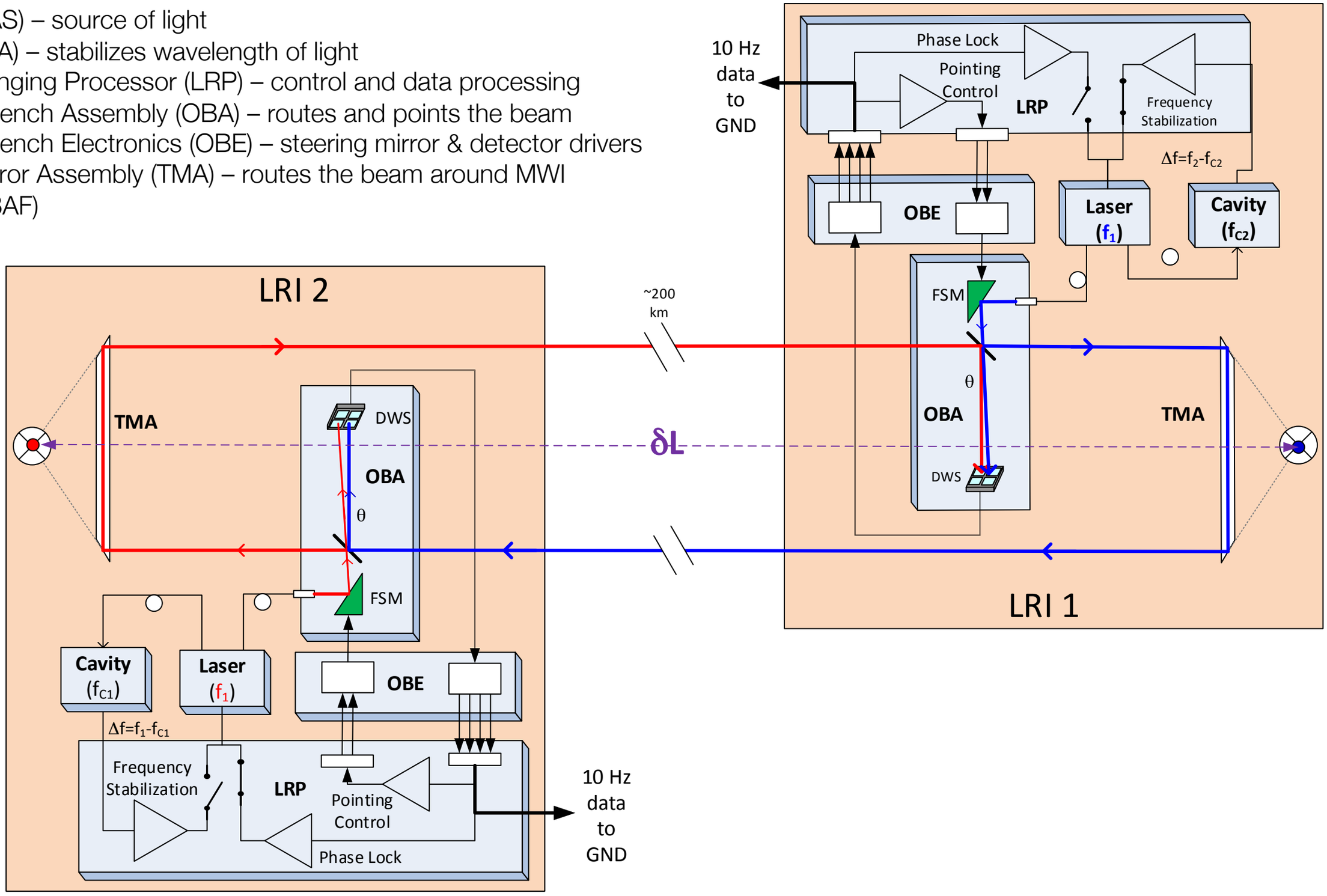
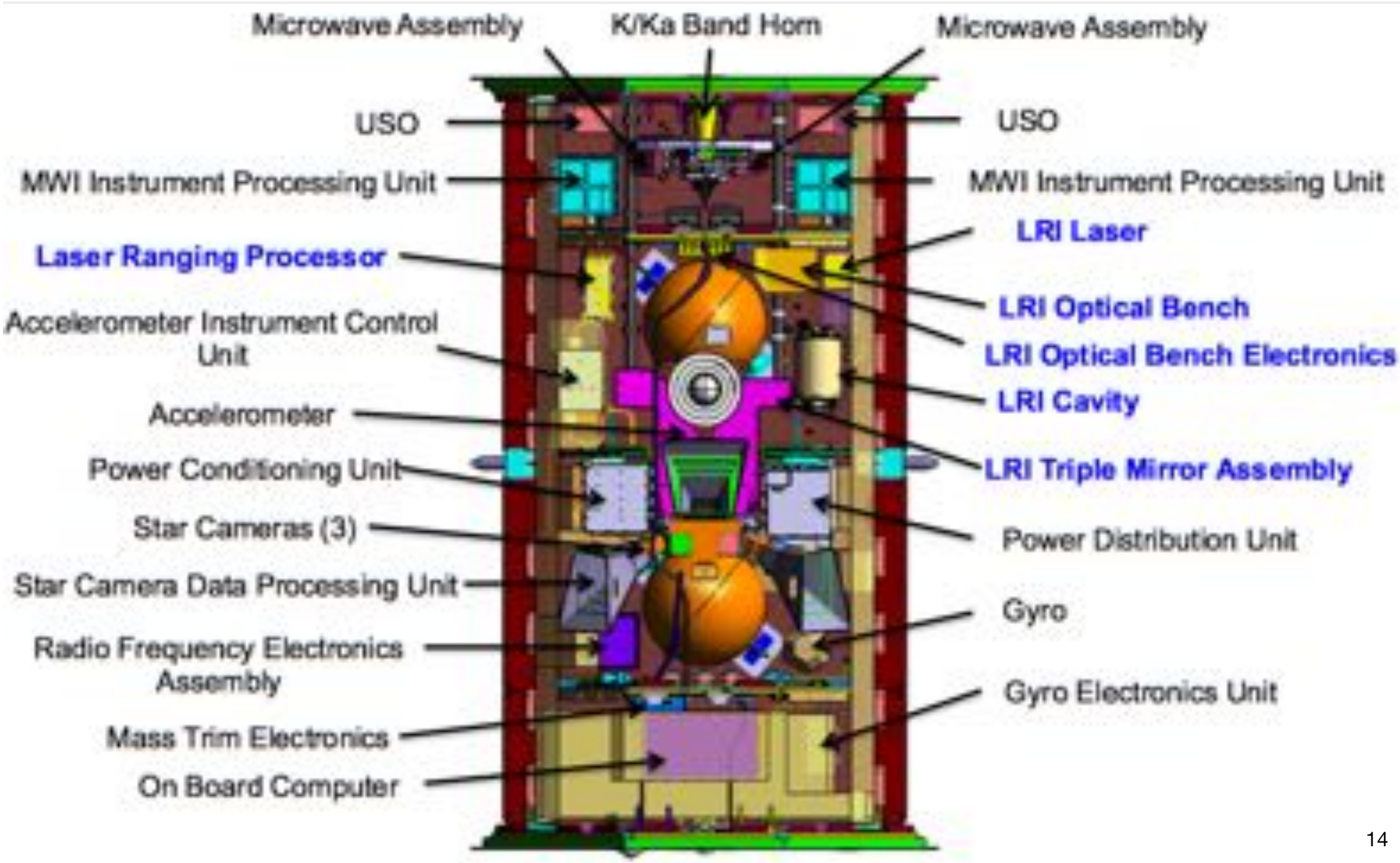
LRI Components

1. Laser (LAS) – source of light
2. Cavity (CA) – stabilizes wavelength of light
3. Laser Ranging Processor (LRP) – control and data processing
4. Optical Bench Assembly (OBA) – routes and points the beam
5. Optical Bench Electronics (OBE) – steering mirror & detector drivers
6. Triple Mirror Assembly (TMA) – routes the beam around MWI
7. Baffles (BAF)

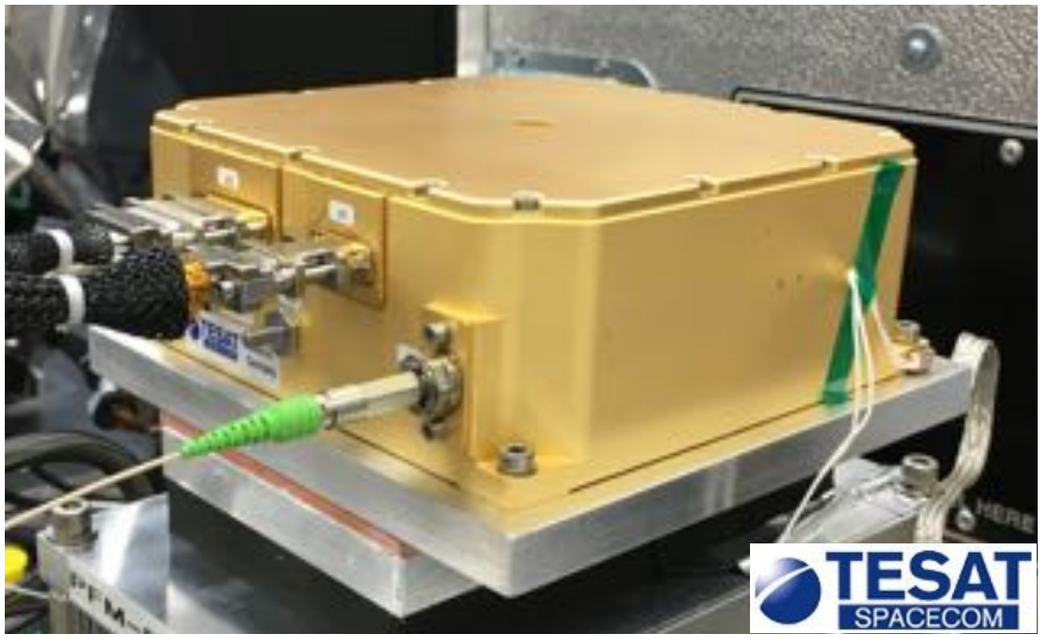


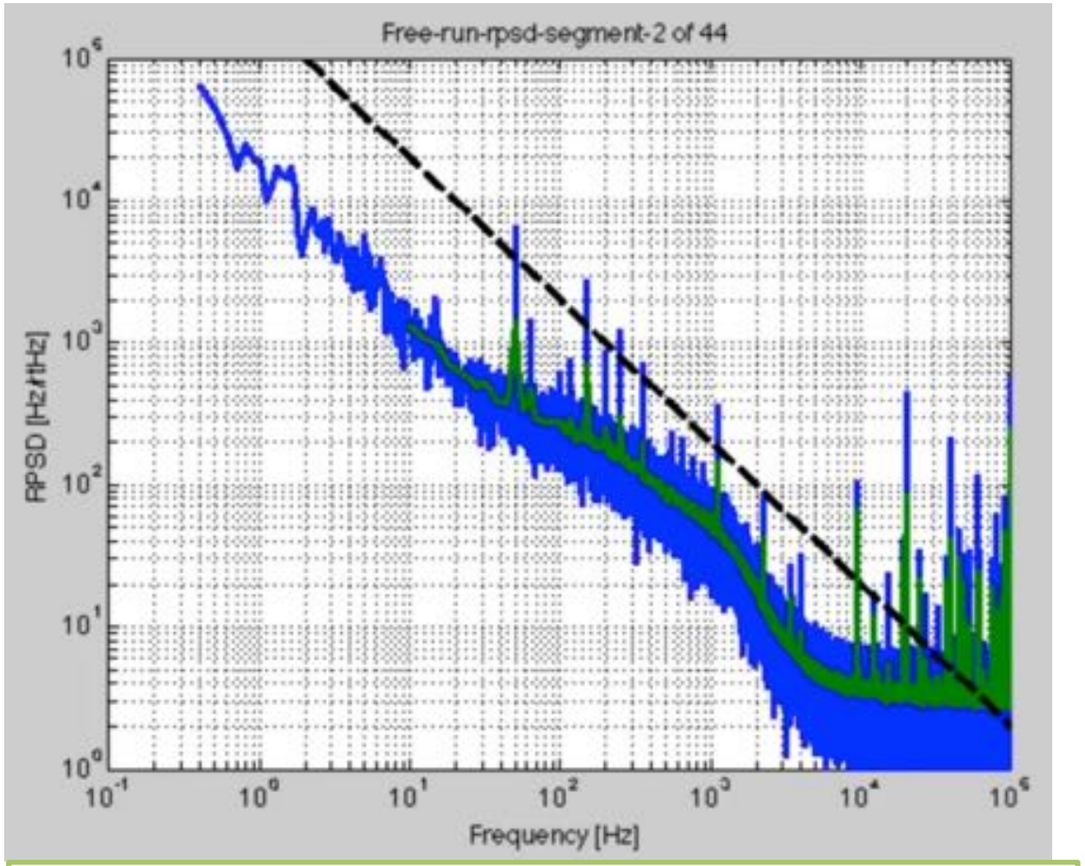
Spacecraft (1 of 2)



Laser

- Similar to Laser on LISA Pathfinder
- 1064 nm
- Nd:YAG Non-Planar Ring Oscillator (NPRO)
- 25 mW ± 20%
- Frequency noise requirement
  - < 200kHz/√Hz *1Hz/f
- 1 year minimum lifetime





Frequency noise requirement met.

Reference Cavity

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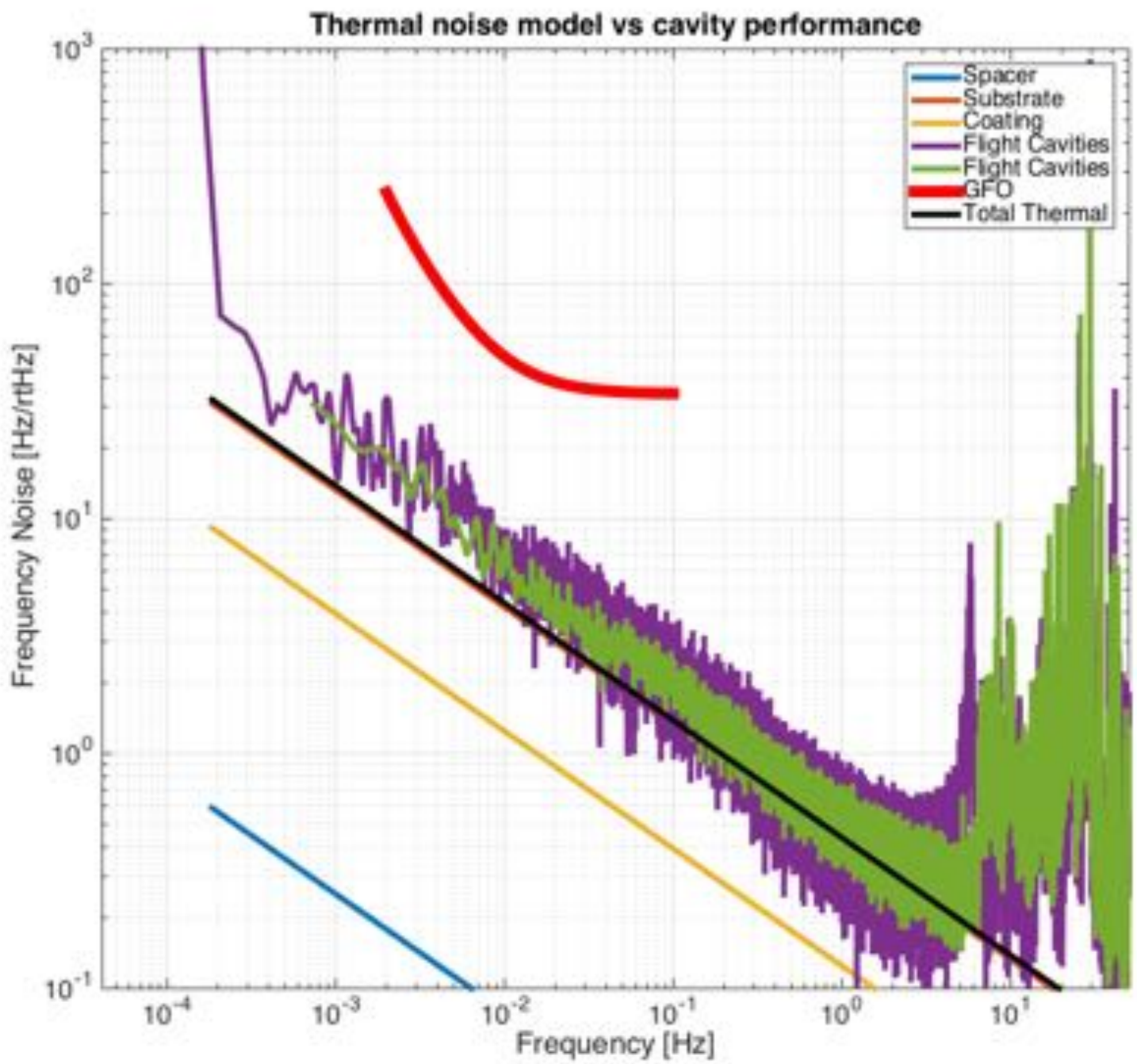
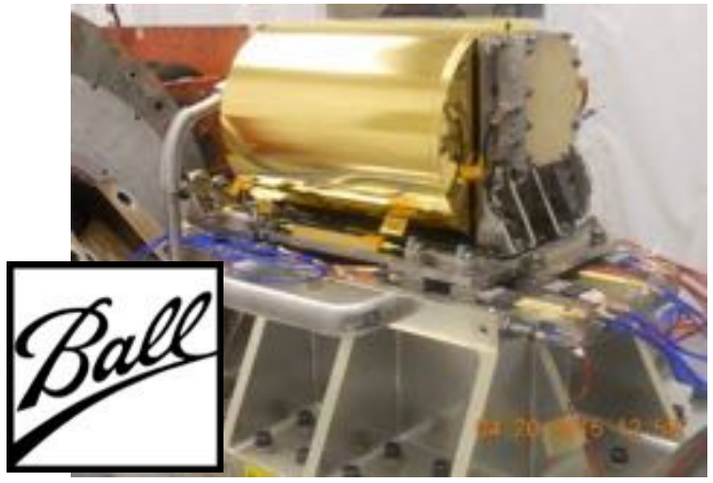
- PDH stabilization
- Near thermal limit





W. M. Folkner et al., *"Laser Frequency Stabilization for GRACE-2"*, Proc. ESTF 2011.

Laser Ranging Processor (LRP)

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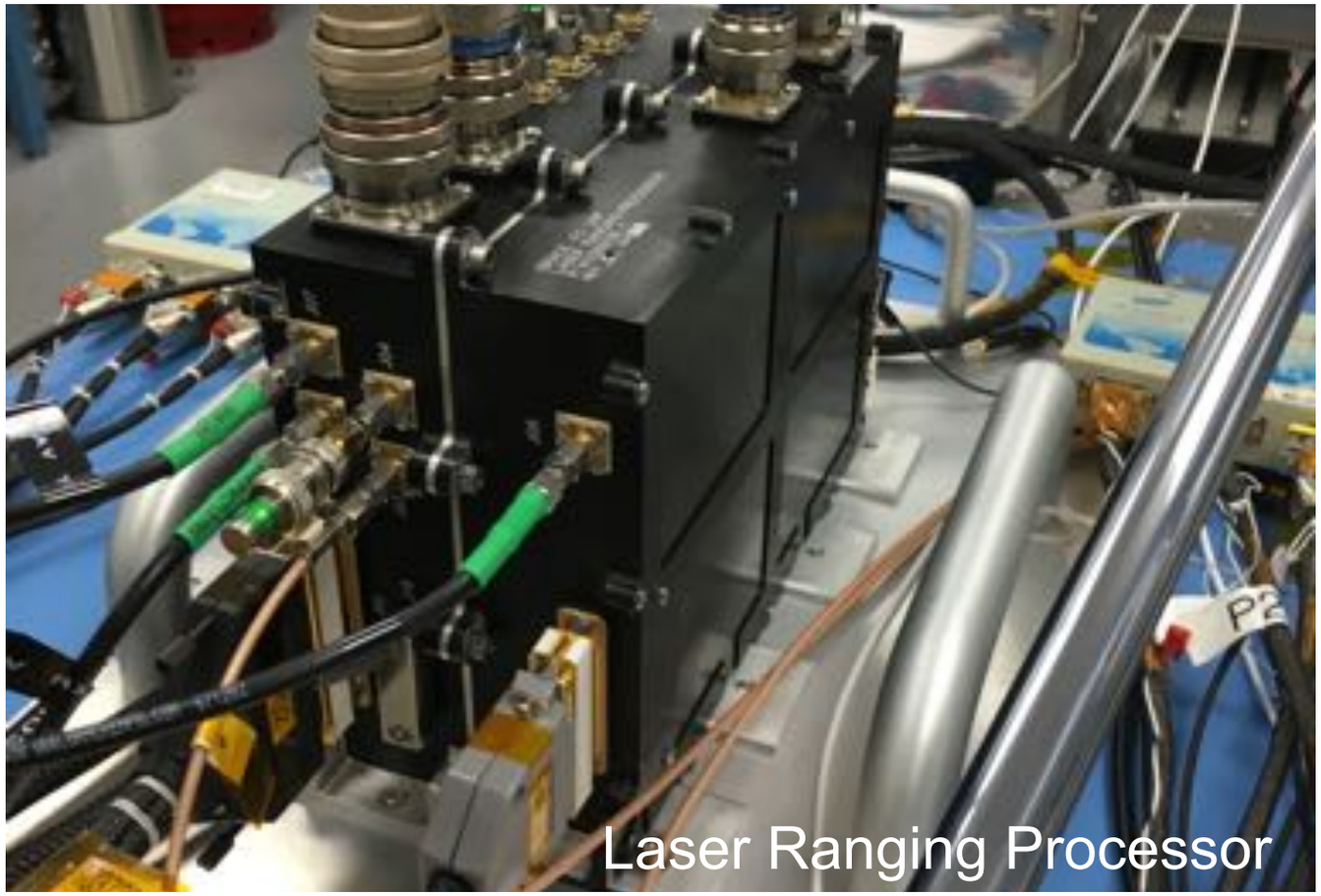
- Developed at JPL with heritage from LISA TRL 6 Phasemeter, Blackjack…
- Tasks:
  - Science phase measurement
    - cycle-slip-free phase measurement 1 pW shot noise
  - Stabilizes the master laser to the cavity
  - Offset phase locks the slave laser to the received laser light
    - μHz phase synchronization with the master laser
  - Optical link acquisition
    - receives data from QPD
    - controls FSM
  - Derives differential wavefront sensing signals for laser pointing
  - Communicates with the spacecraft
  - Collects telemetry for the LRI instrument



LRP control of Steering Mirror from Differential Wavefront Sensing

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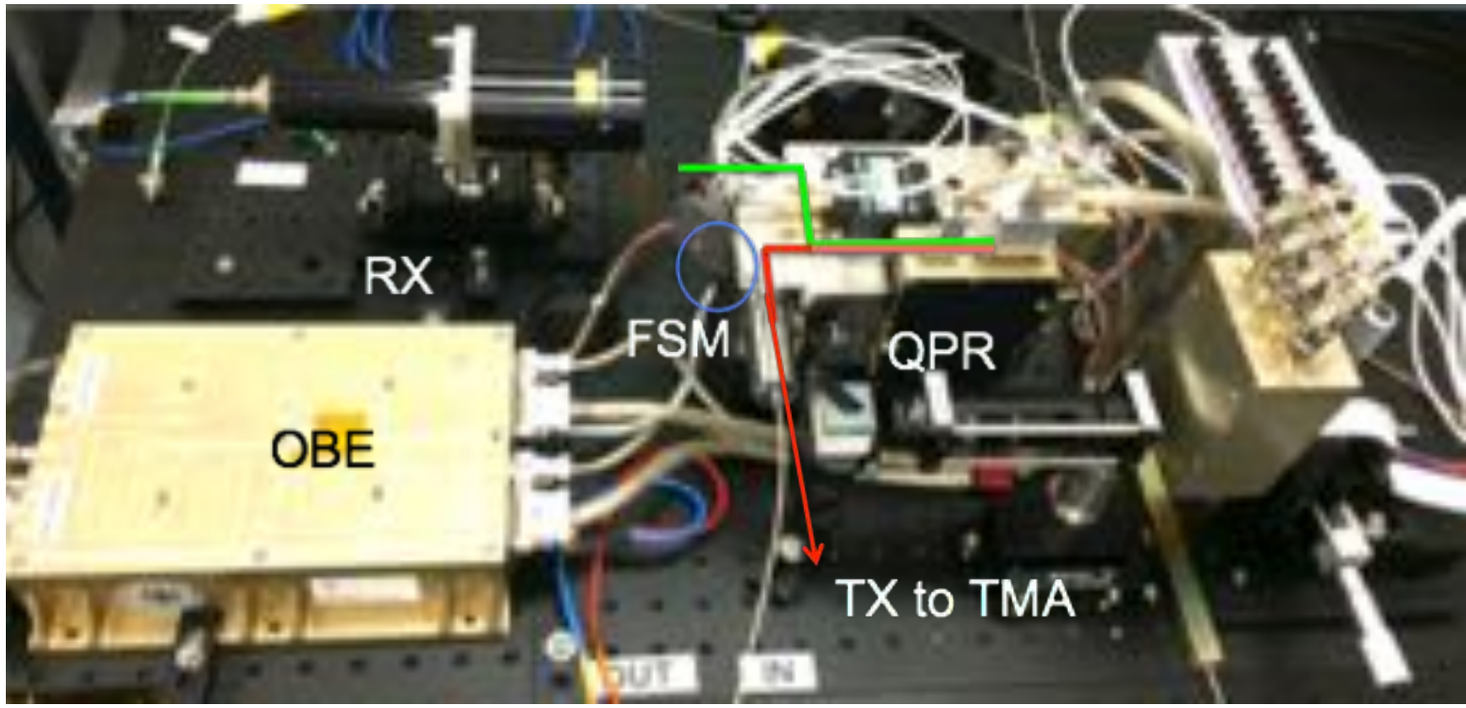
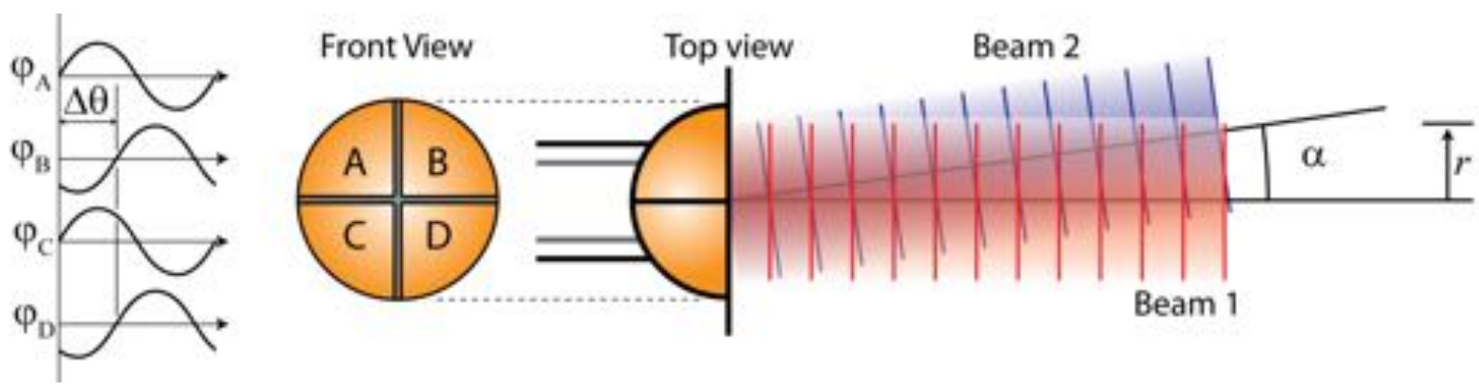
Two modes of control of fast steering mirror:

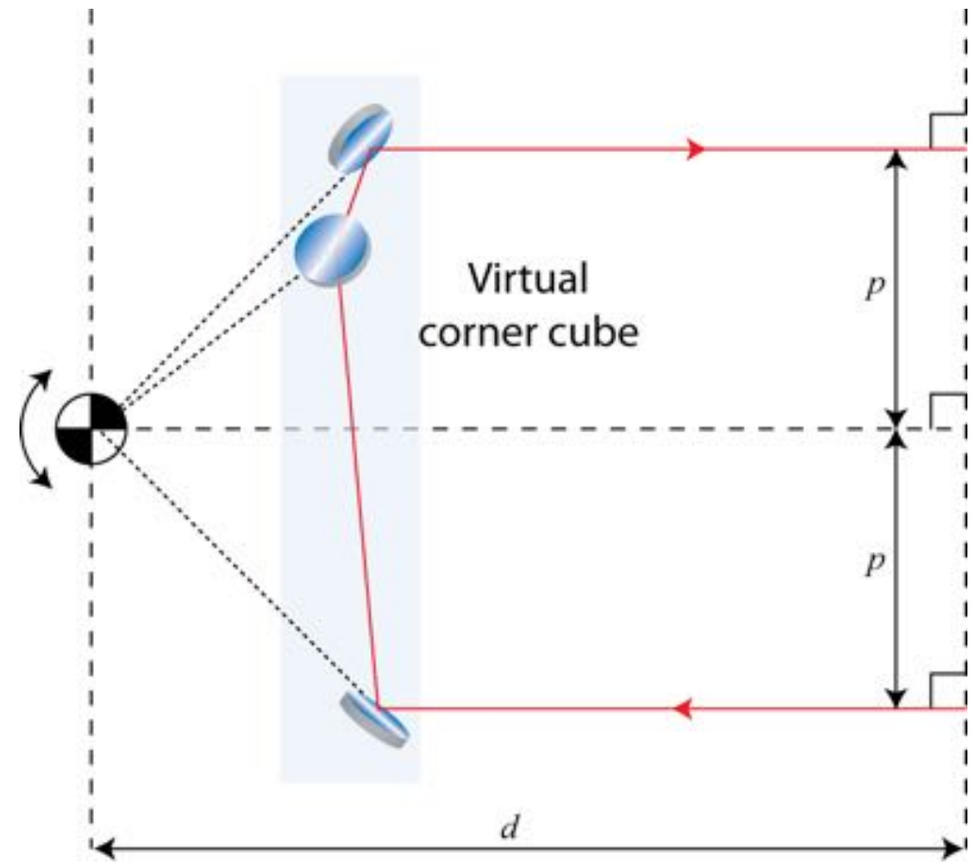
1. Open-loop acquisition scan to find heterodyne signal.
2. Continuous high-bandwidth active retroreflector" feedback using phase-sensitive Differential Wavefront Sensing (DWS)

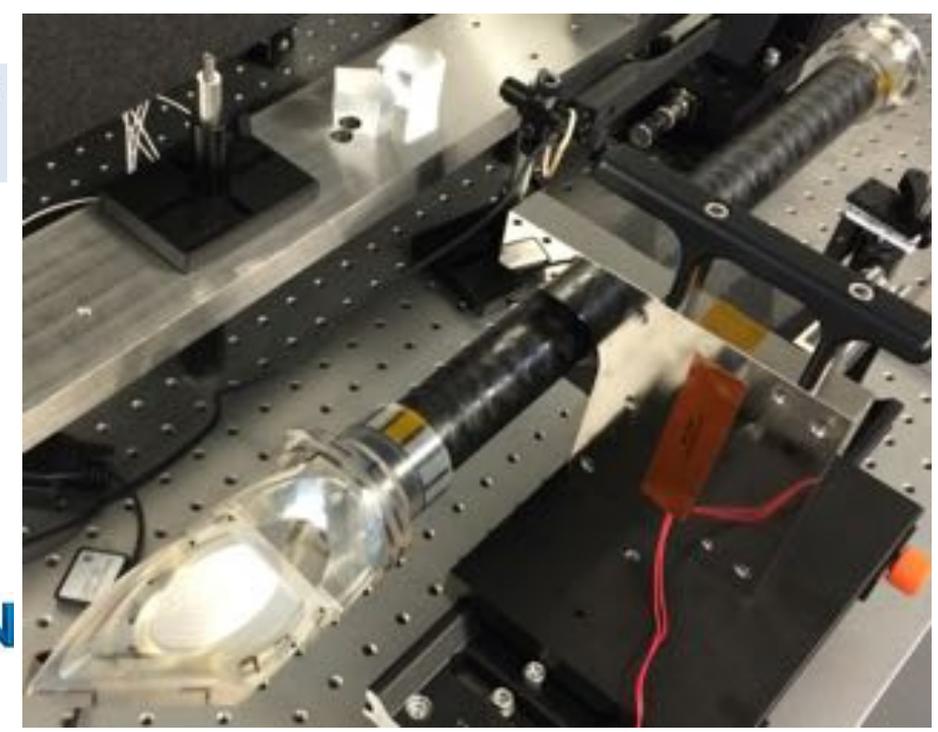




Triple mirror assembly

- Intersection point is virtual and can be arbitrarily placed, e.g. inside accelerometer housing
- Invariant parameters under rotation around intersection point
  - round-trip pathlength
  - propagation direction of reflected beam is always counter-propagating to incident
- Developed by STI and Cassidian
- TMA also prototyped by ANU
- Requirement on co-alignment is 40 microradians
- Path length stability 21nm/√Hz

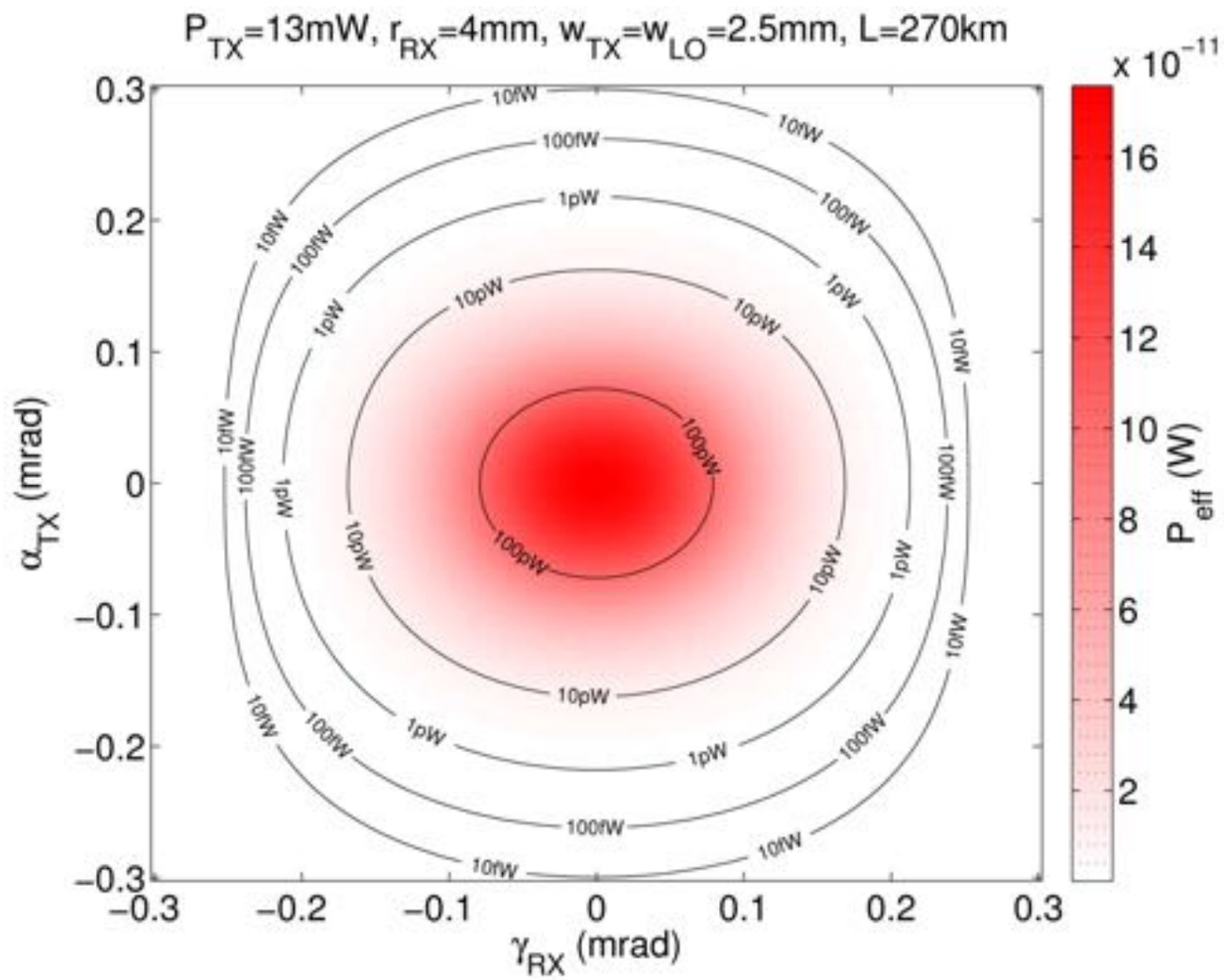




Beam divergence, transmit and receive

- Transmitted beam size is 140 microradians compared to initial uncertainty in alignment of 3 milliradians

- Receiver acceptane angle “heterodyne effiiency” is same as transmitted.



Acquisition Scans

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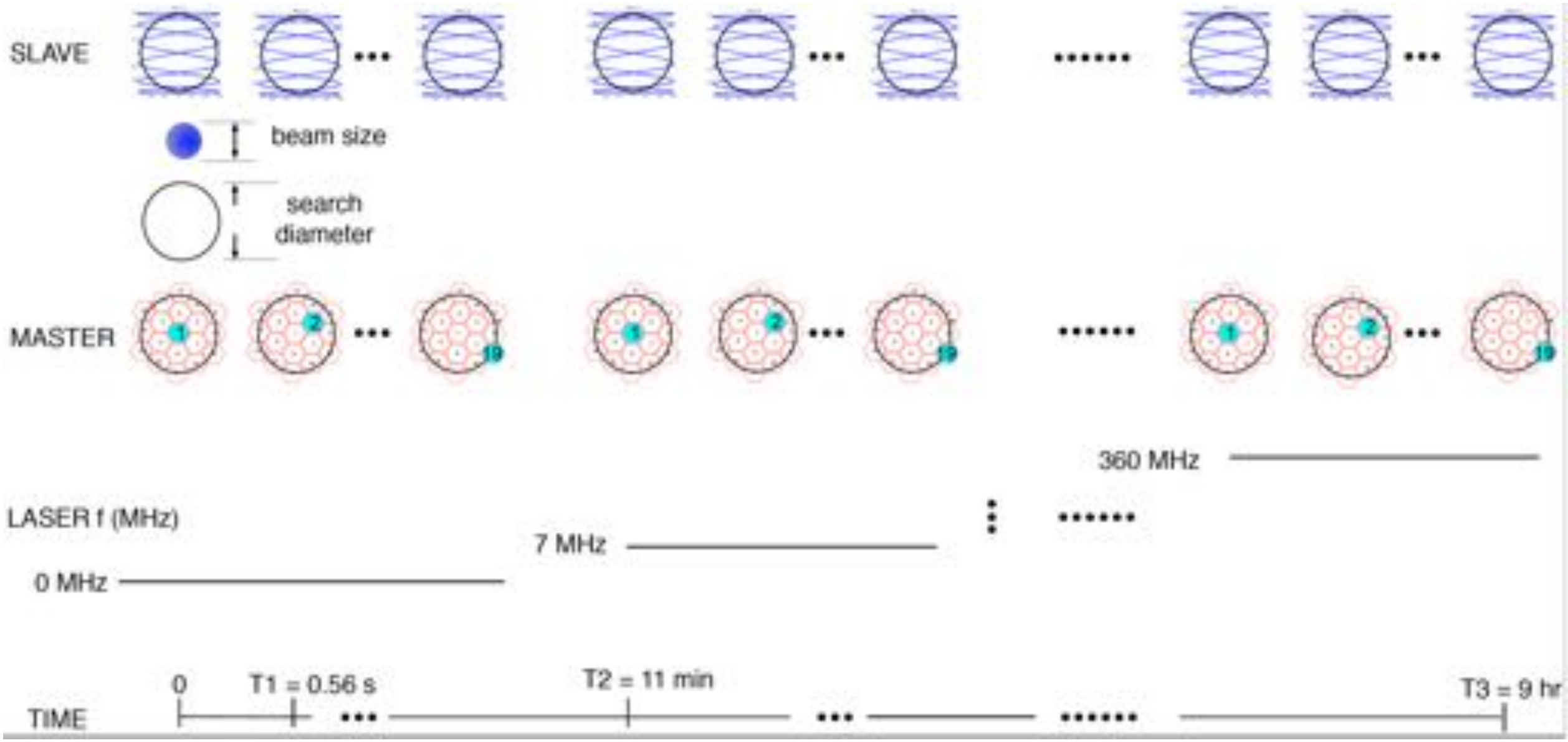

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Gerhard Reile

LRI
Dennis Weise
Reinhold Flatscher
Simon Doerr

GFO LRI Summary

- GFO LRI is the first inter-satellite laser interferometric ranging instrument:
  - US-German collaboration (+AUS), like GRACE, launch 2017,
  - Technology demonstrator based on technology developed for LISA interferometry
  - Expected to produce better data than microwave link
  - Demonstrates many LISA interferometry technologies
    - Phasemeter/Phaselocker
    - NPRO laser
    - DWS
    - Acquisition
    - pW operation
    - Laser frequency noise suppression
    - Potential to do more
      … Time Delay Interferometry and Arm-locking
      (NASA has funded an investigation of this: LISA Experience from GRACE Follow-On Optical Package (LEGOP))
- LTP measurements are underway, demonstrating:
  - micronewton thrusters
  - optical bench
  - GRS
  - drag-free
  - metrology
- GFO LRI will also demonstrate much of the technology needed for GRACE II

A future GRACE II mission: what is needed

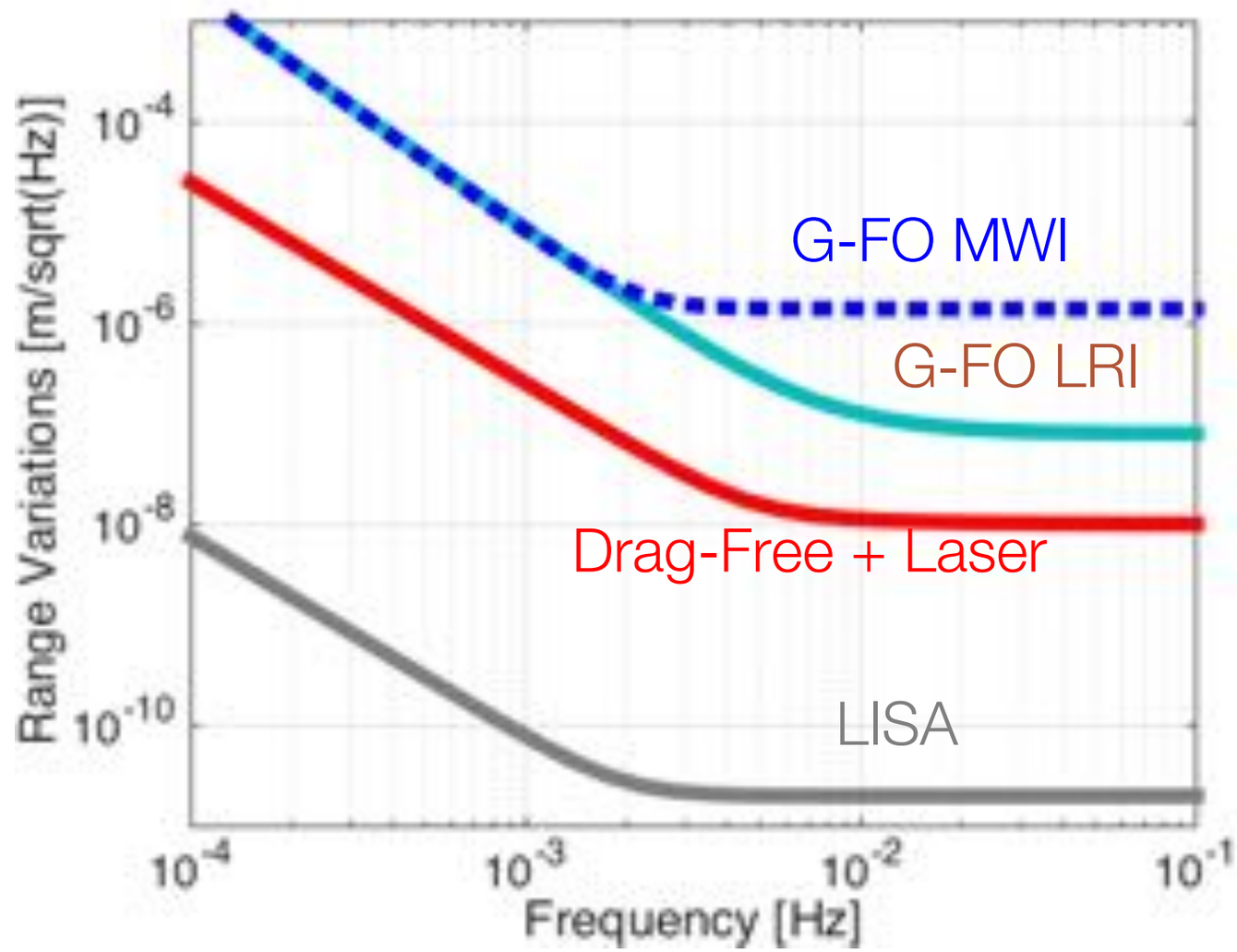
1) Better Instrument Noise

Inter-spacecraft range

- K-Ka band (~1um/rtHz)
- Laser (~10nm/rtHz)

Accelerometer

- GRACE Type (~1 x10^{-10}ms^{-2}/rtHz)
- Drag-Free (GOCE ~10^{-12}ms^{-2}/rtHz)
  (LISA Pathfinder ~10^{-14}ms^{-2}/rtHz)



Laser Interferometer Space Antenna Space Antenna (LISA)

$$\frac{\Delta L}{L} = \frac{10\,pm}{5Mkm} = 2 \times 10^{-21}$$

LISA

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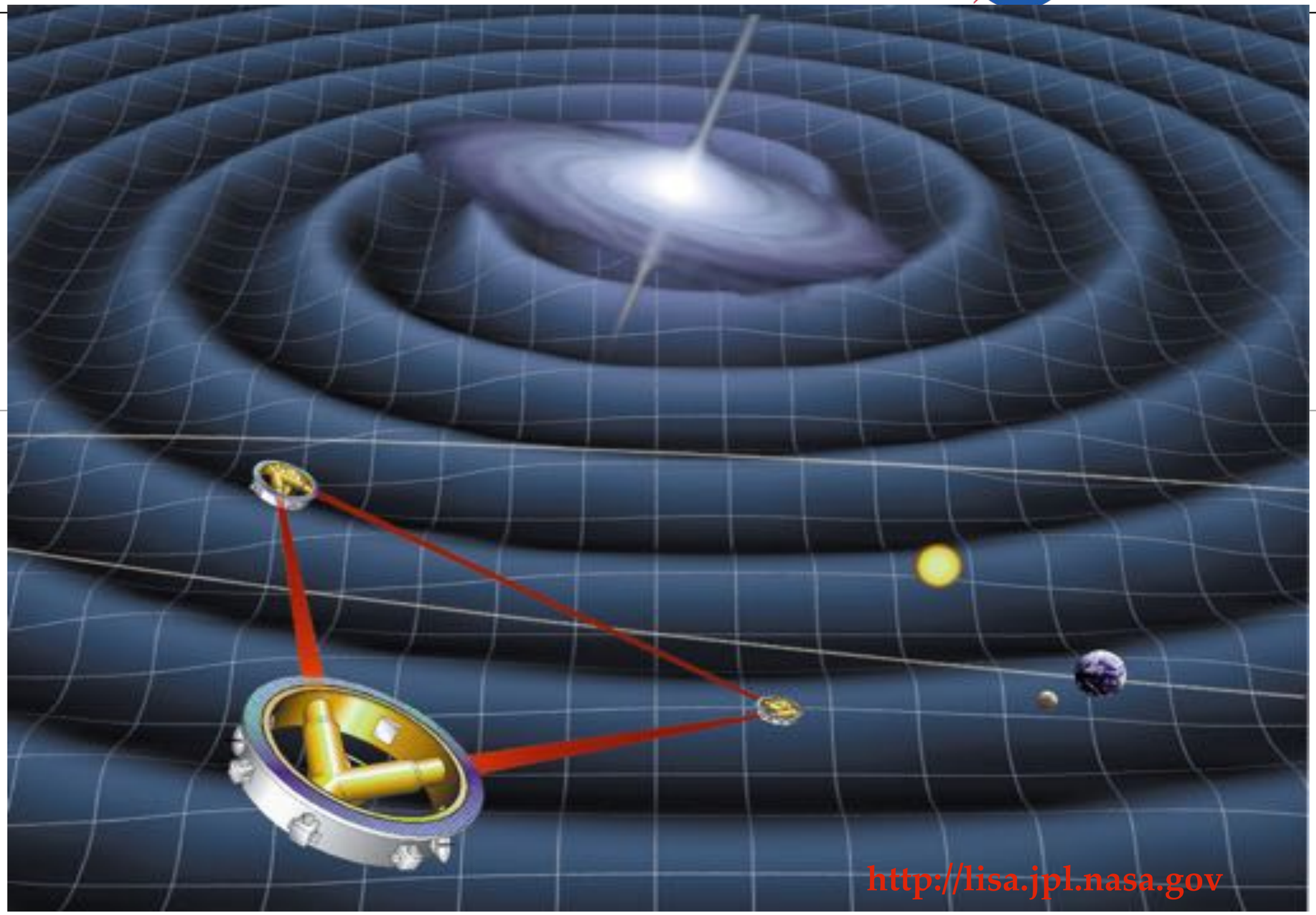

Nothing is too wonderful to be true if it be consistent with the laws of nature

-- Faraday

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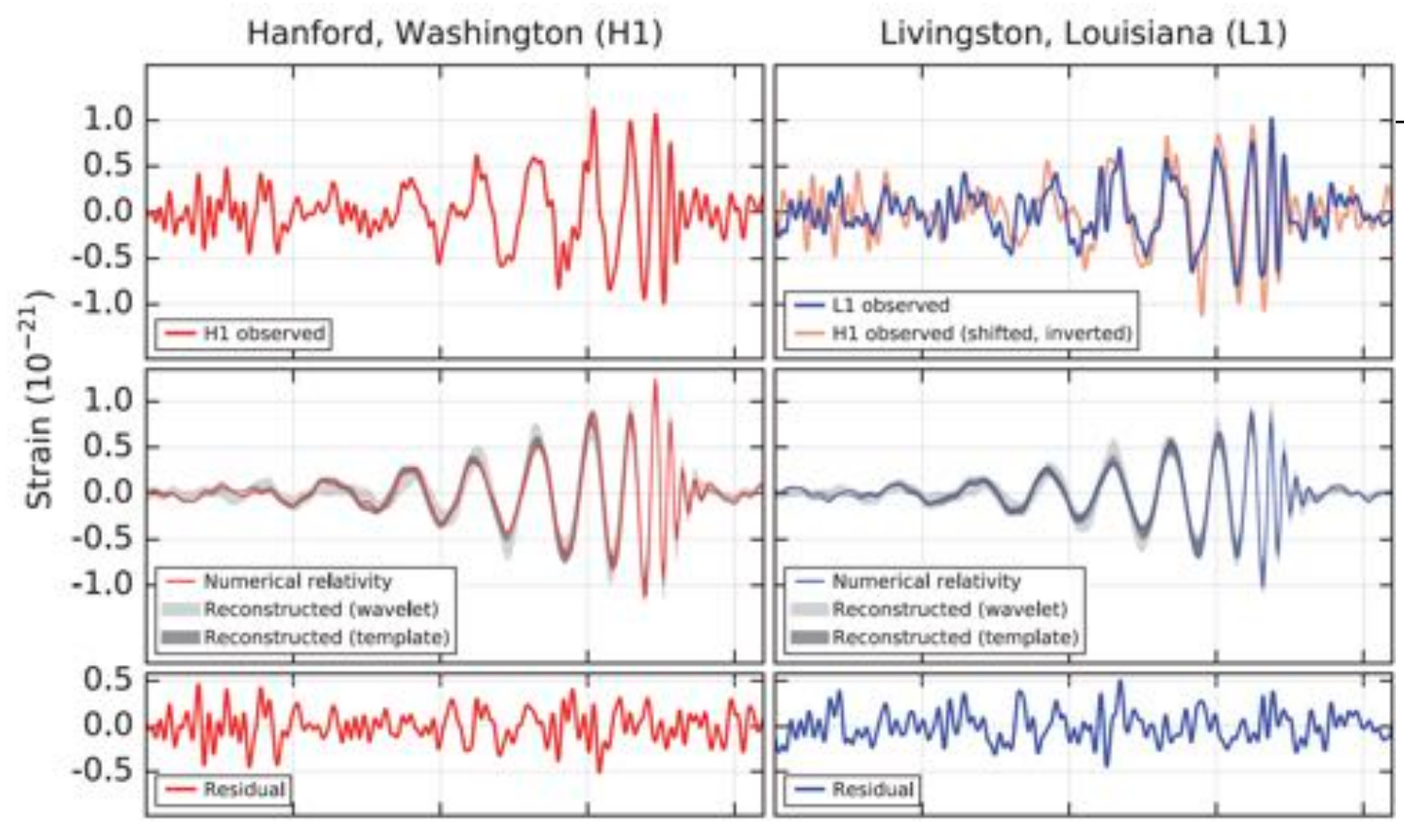
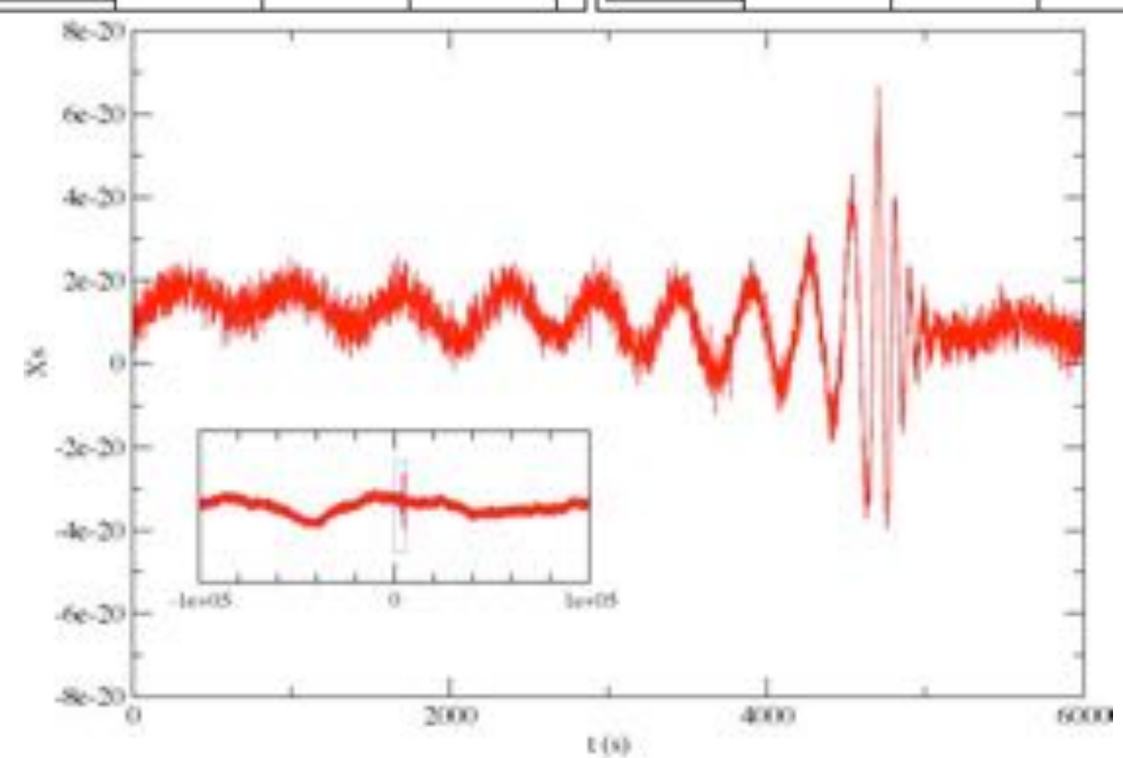
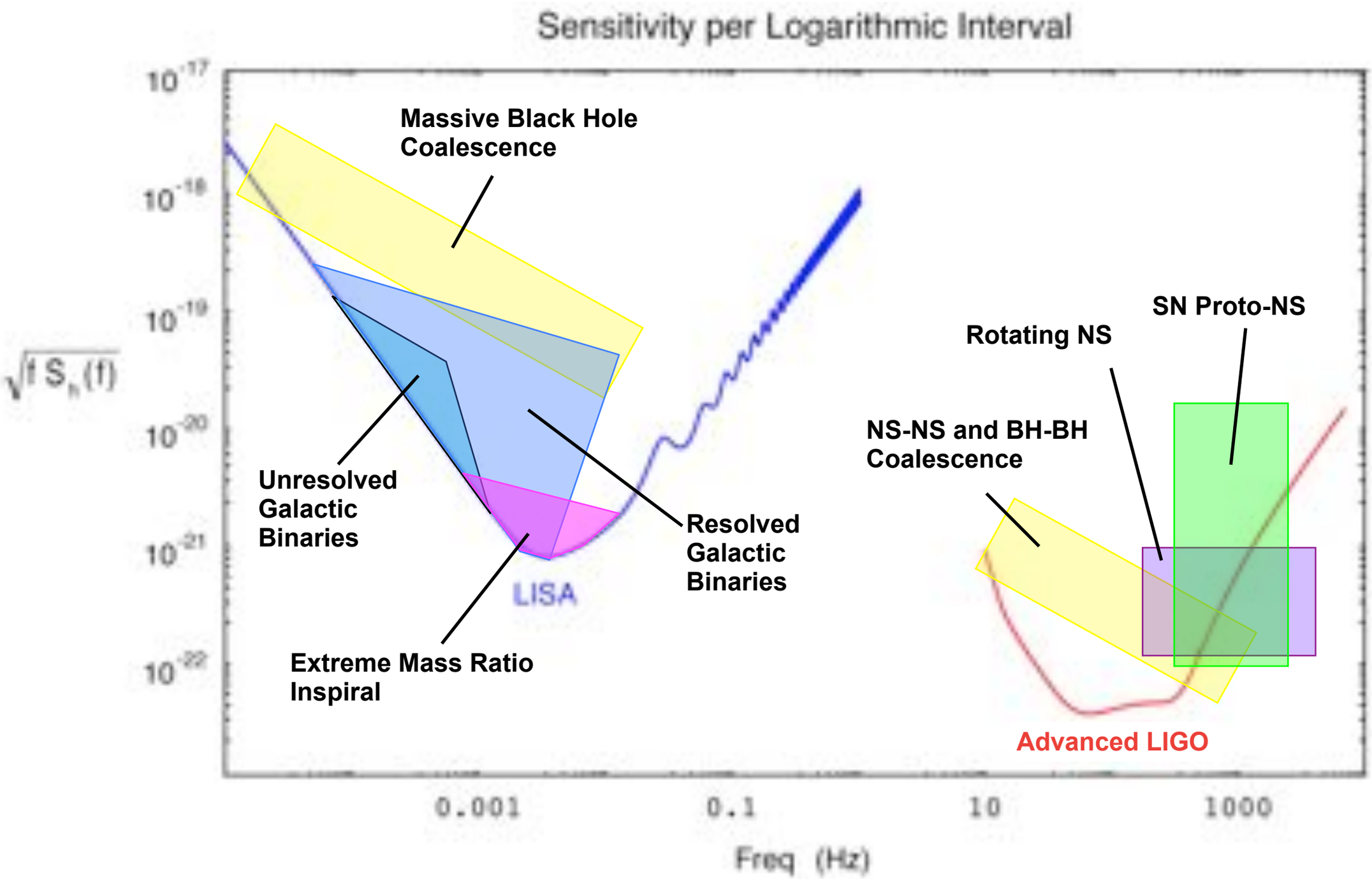
LIGO, 2015:
30 solar-mass BH binary

z = 0.1



LISA, 2030's:
10^6 solar-mass BH binary,
z = 15




Sensitivity per Logarithmic Interval
Massive Black Hole Coalescence
Unresolved Galactic Binaries
Resolved Galactic Binaries
LISA
Extreme Mass Ratio Inspiral
Rotating NS
SN Proto-NS
NS-NS and BH-BH Coalescence
Advanced LIGO
$\sqrt{f\,S_h(f)}$
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
0.001
0.1
10
1000
Freq (Hz)

LIGO -> LISA

Jet Propulsion Laboratory
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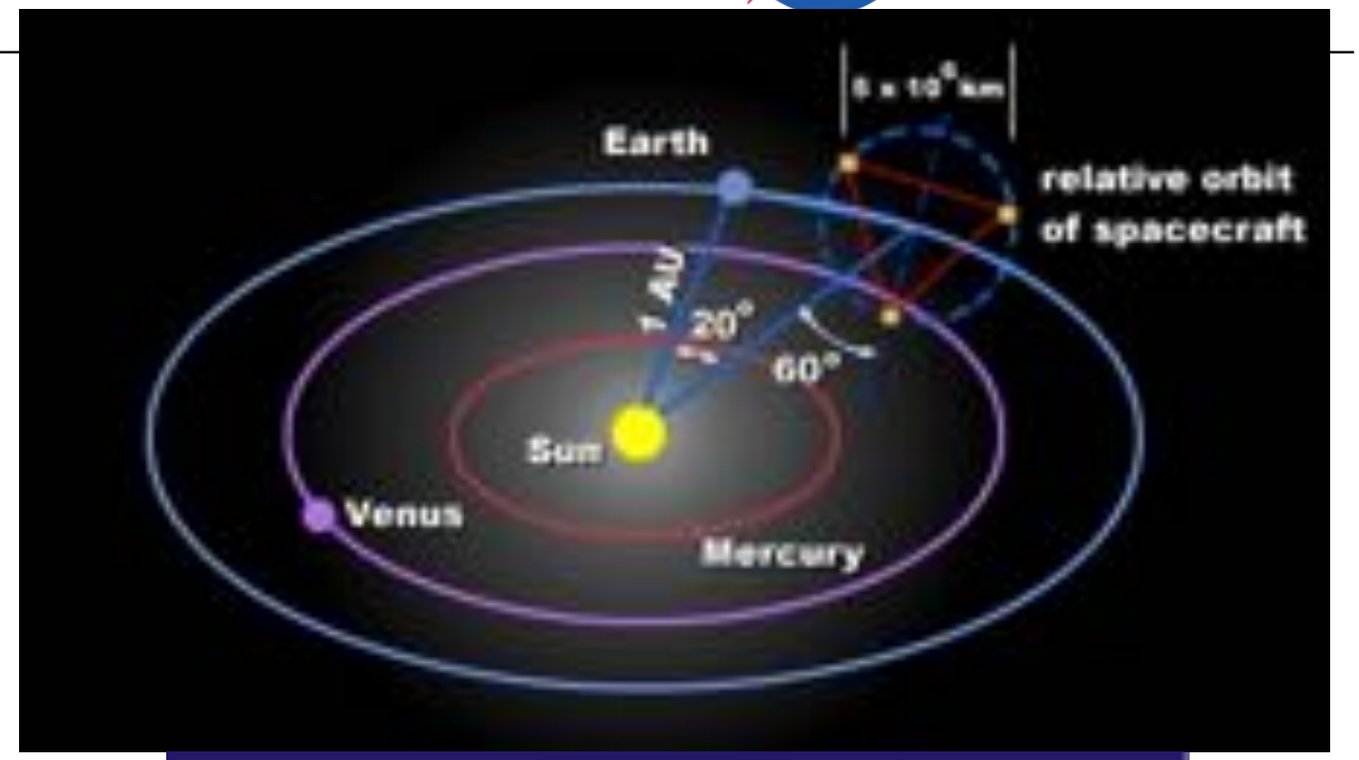
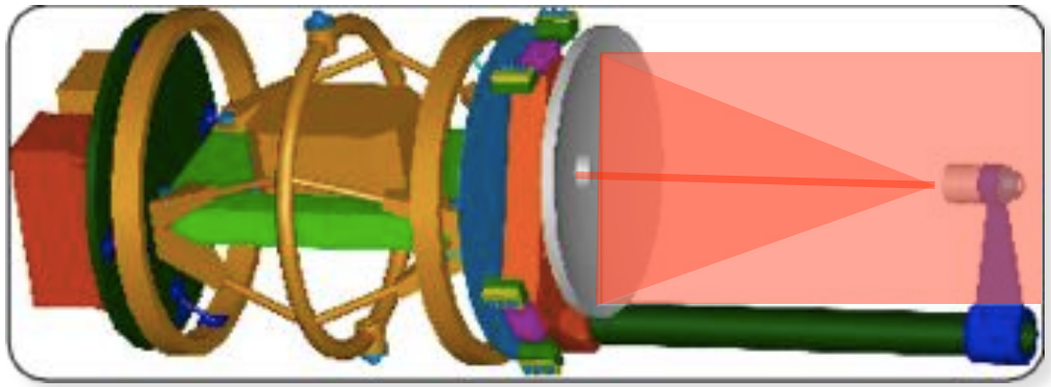


- Lower frequency, corresponds to larger masses, stronger signals
- Sensor noise
  - increase length of arms by 10^6
  - laser power is limited
  - 10^{-11} m/$\sqrt{\text{Hz}}$ @ 1 mHz
- Displacement noise
  - acceleration noise
- Gravitational noise (!)
  - unresolvable galactic binaries

Inter-spacecraft Interferometry

- 30 cm telescope



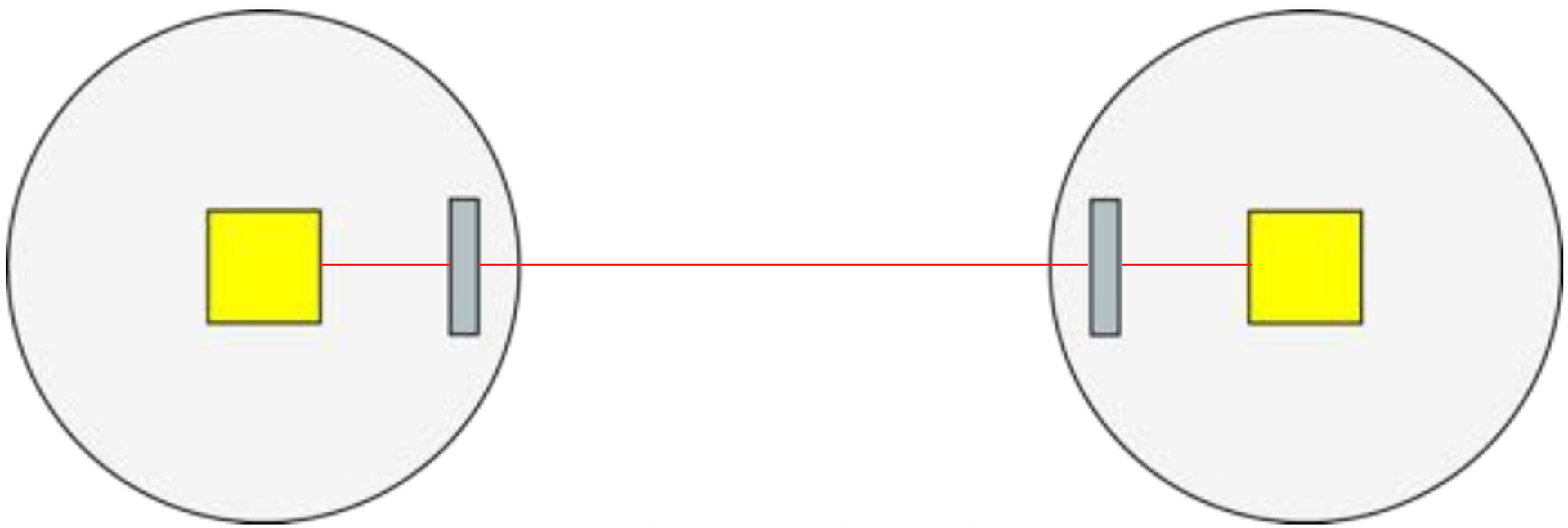
- ~1 Watt transmitted.
- ~10^{-10} Watts received.
  - shot noise of received power is dominant noise source at high frequencies ~10 pm/√Hz.
- Pointing fluctuations must be kept to below ~10 nrad/√Hz
- Arm length changes by ±1.5% over a year.

GRACE-FO interferometer and LISA

	LISA	LRI on GFO
Inter-satellite distance	5 million km	170...270 km
Orbit	Heliocentric (1 a.u.)	Low Earth Orbit (400…500 km)
Orbit environment	No atmospheric drag, stable thermal environment	Atmospheric drag, large thermal disturbances
Attitude and Orbit Control System	Drag-free using µN thrusters	Attitude control with magnetic torquers and cold gas thrusters
Measurement band	**100 µHz – 1 Hz**	**200 µHz –100 mHz**
Measurement noise	12 pm/√Hz (× freq. dep.)	80 nm/√Hz (× freq. dep.)
Telescope aperture diameter	38 cm	≈1 cm
Transmit beam waist radius	17 cm	≈2 mm
Transmit power	1 W	≈20 mW
Effective received power (at photodetector)	**≈100 pW**	**≈100pW**
Maximum relative L.O.S. velocity	±15 m/s	≤ ±4 m/s
Initial acquisition	**4+1 d.o.f, no communication**	**4+1 d.o.f, no communication**

LISA Interferometry

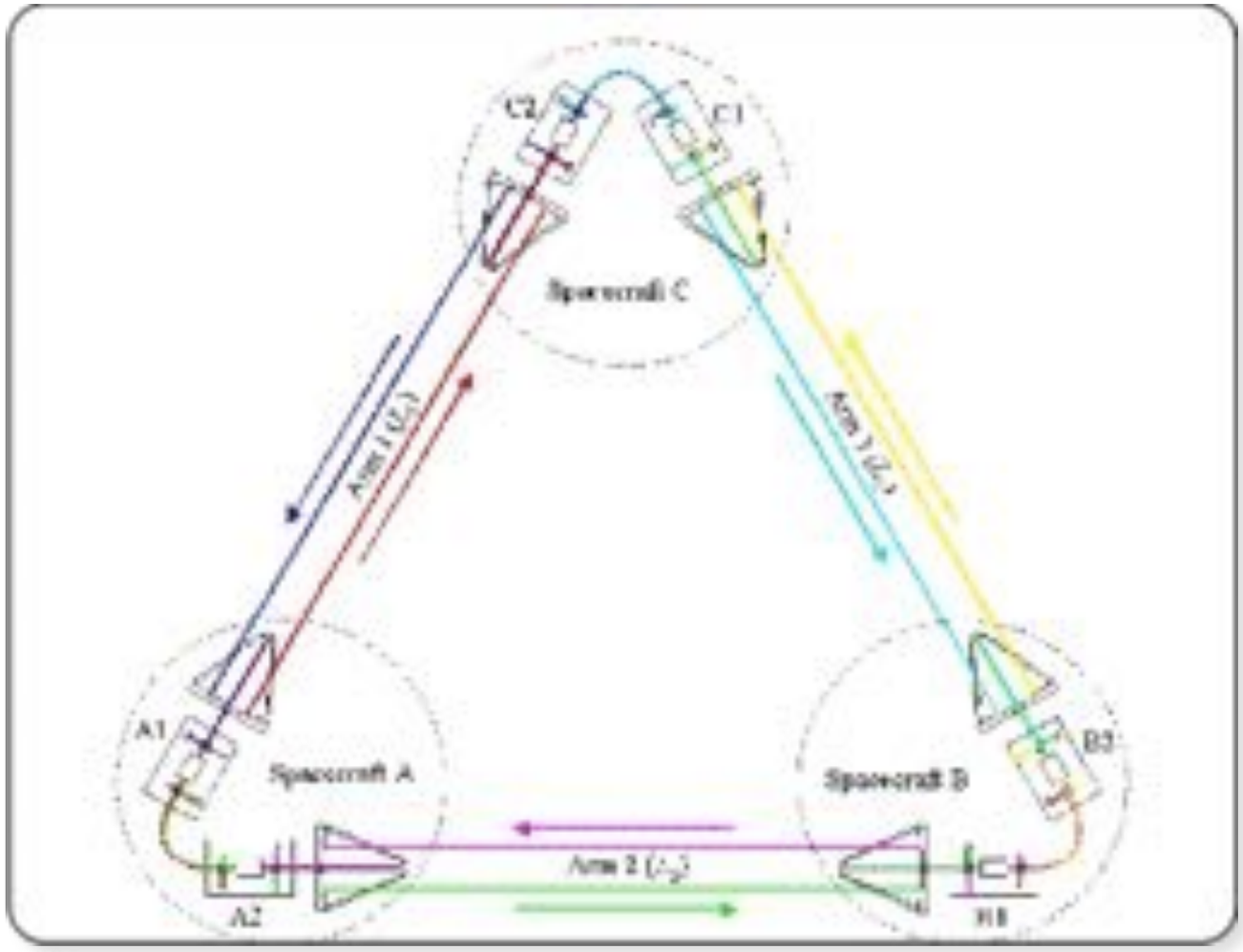
1. Local interferometry
(Proof Mass to Optical Bench)



2. Inter-Spacecraft interferometry
(Optical Bench to Optical Bench)

LISA

- 2 proof masses per spacecraft
  - one for each sensitive direction
  - drag-free
- 2 lasers per s/c
- 6 one-way measurements
- local phase measurements
- all measurements sent to ground
  - combined in post-processing

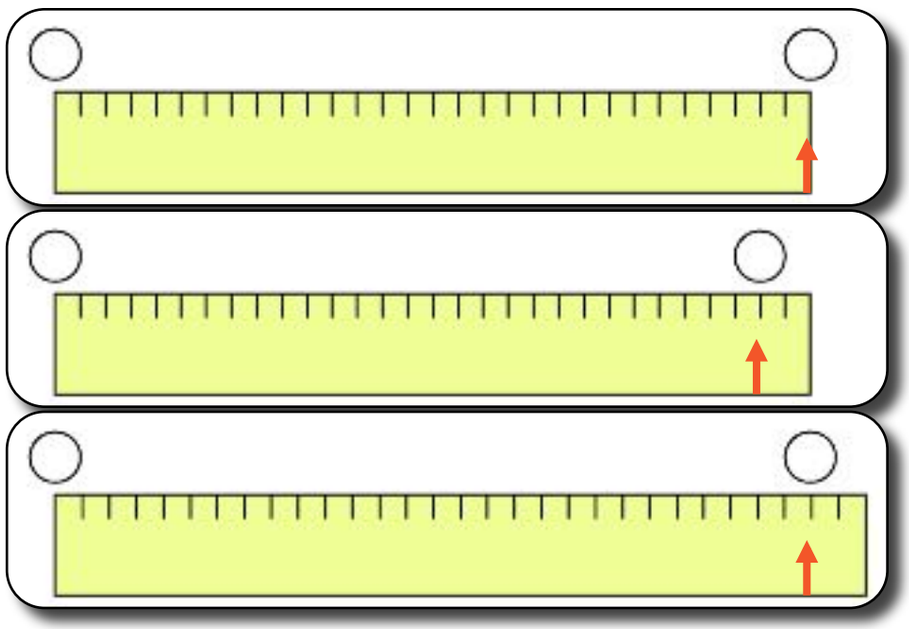


Laser Frequency Noise

Spacecraft separation measured by laser “ruler”.

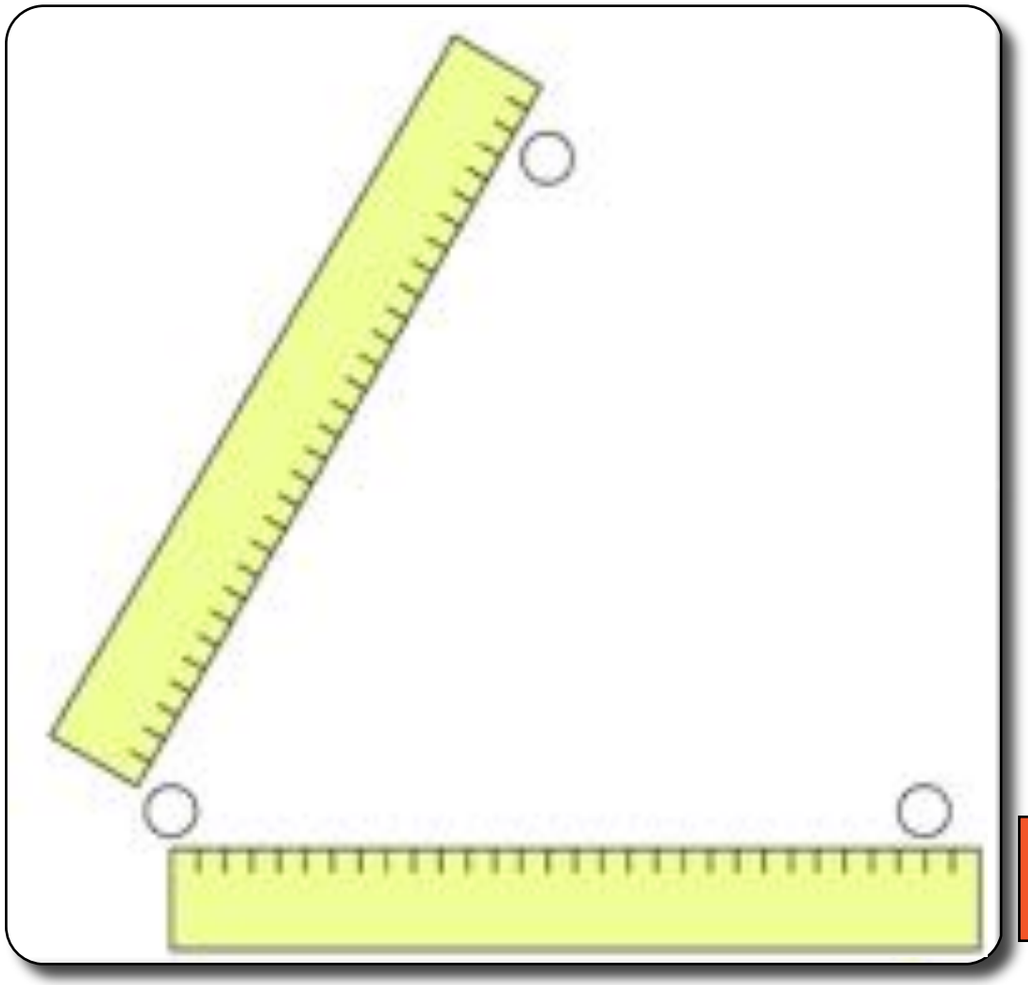
Laser’s wavelength is analogous to ruler’s tick marks

Changes in spacecraft separation are indistinguishable from changes in wavelength.



$$\frac{\delta L}{L} = \frac{\delta \nu}{\nu}$$

(singel-arm interferometer)



Difference between two equal length arms is immune to (common) ruler length changes.

$$\frac{\delta L}{\Delta L} = \frac{\delta \nu}{\nu}$$

(Michelson interferometer)

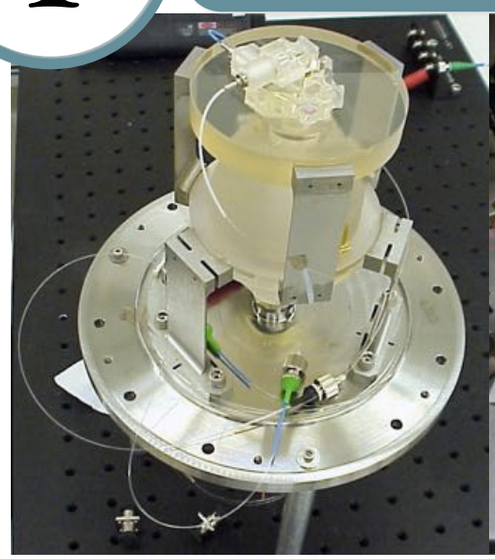
In LISA $\Delta L \approx 50{,}000\ \mathrm{km}$

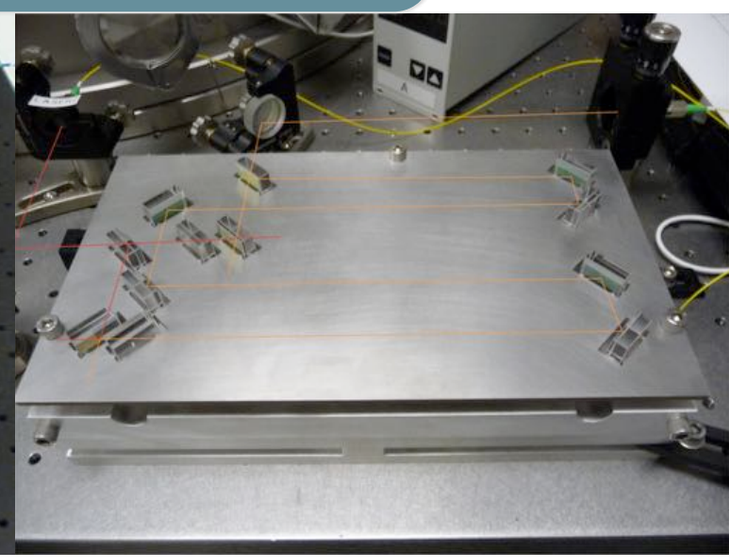
$1\ \mathrm{pm}/\sqrt{\mathrm{Hz}} \Rightarrow \delta\nu/\nu < 10^{-20}/\sqrt{\mathrm{Hz}}$

Best laser: $\delta\nu/\nu \sim 10^{-8}/\sqrt{\mathrm{Hz}}$ (@ 3 mHz)

3 (maybe 2) steps to reduce frequency noise

1 Pre-Stabilization

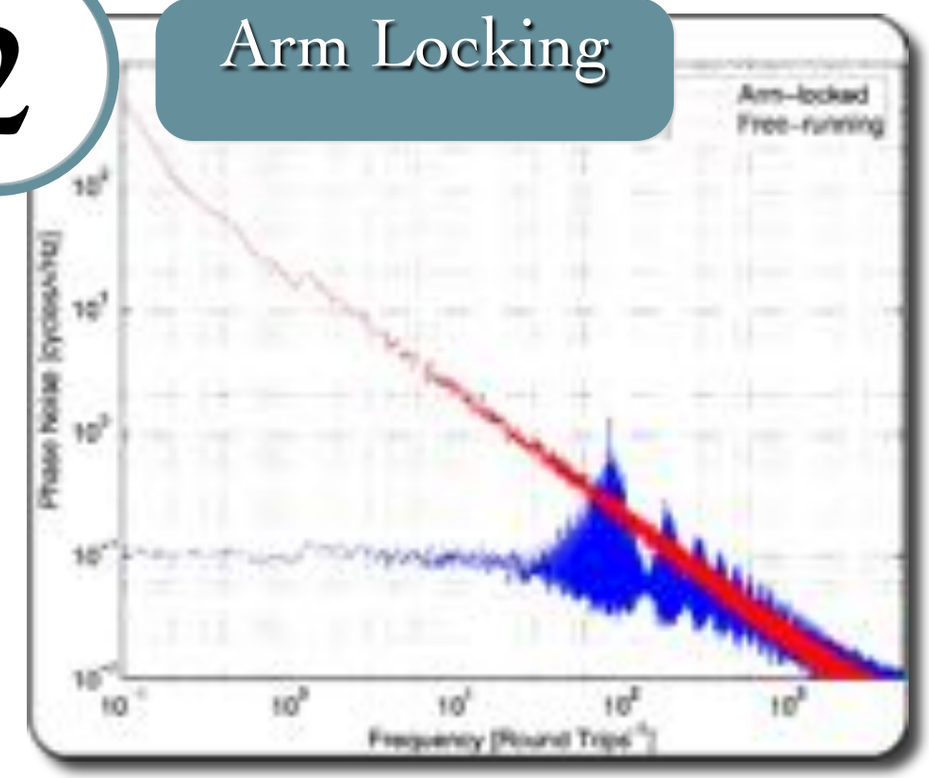




LISA lab

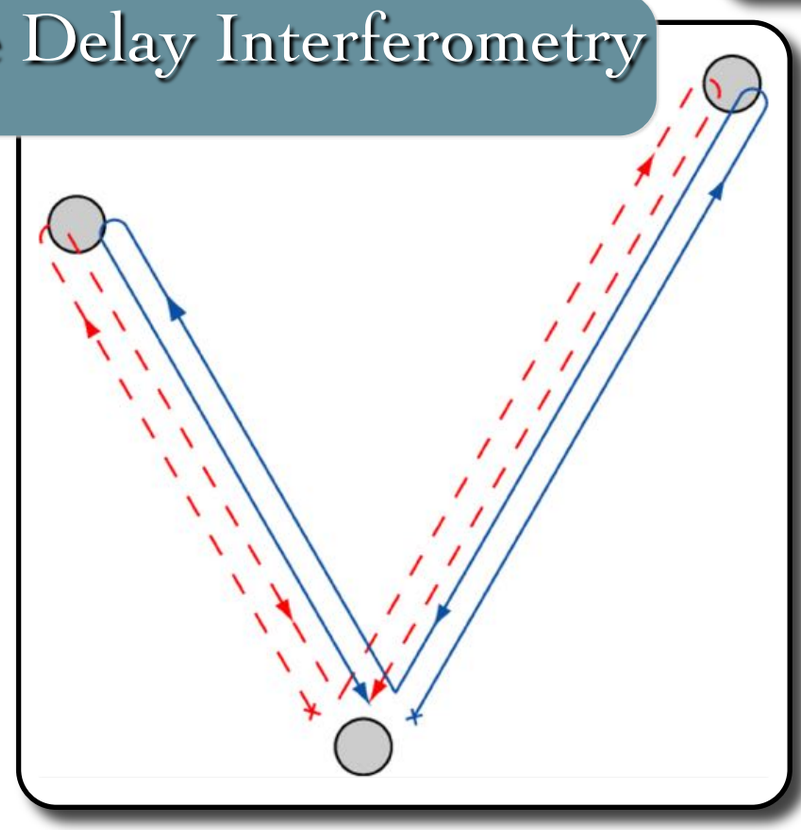
IIP07 Folkner

2 Arm Locking



K. McKenzie, R. Spero, and D. Shaddock, Phys. Rev. D **80** (2009)

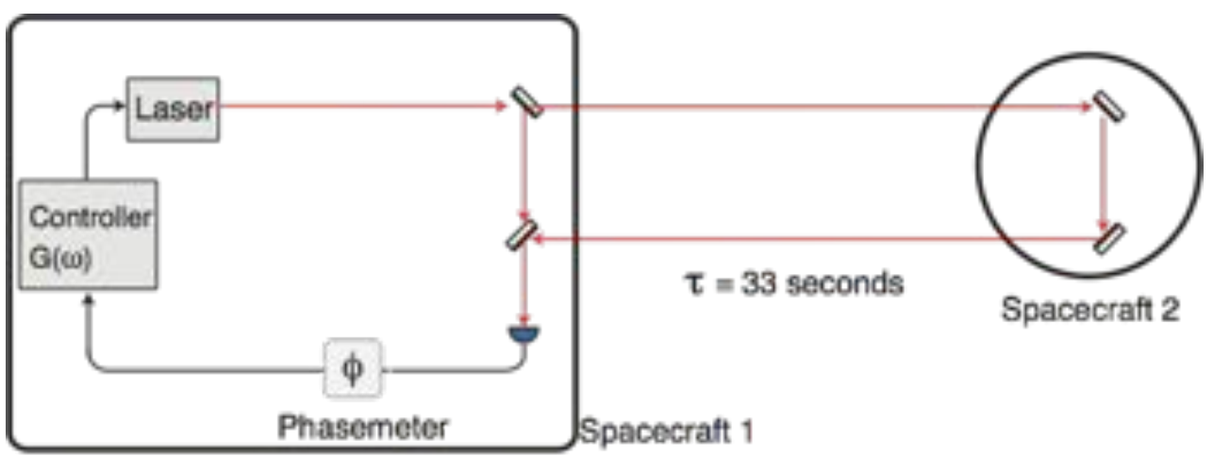
3 Time Delay Interferometry



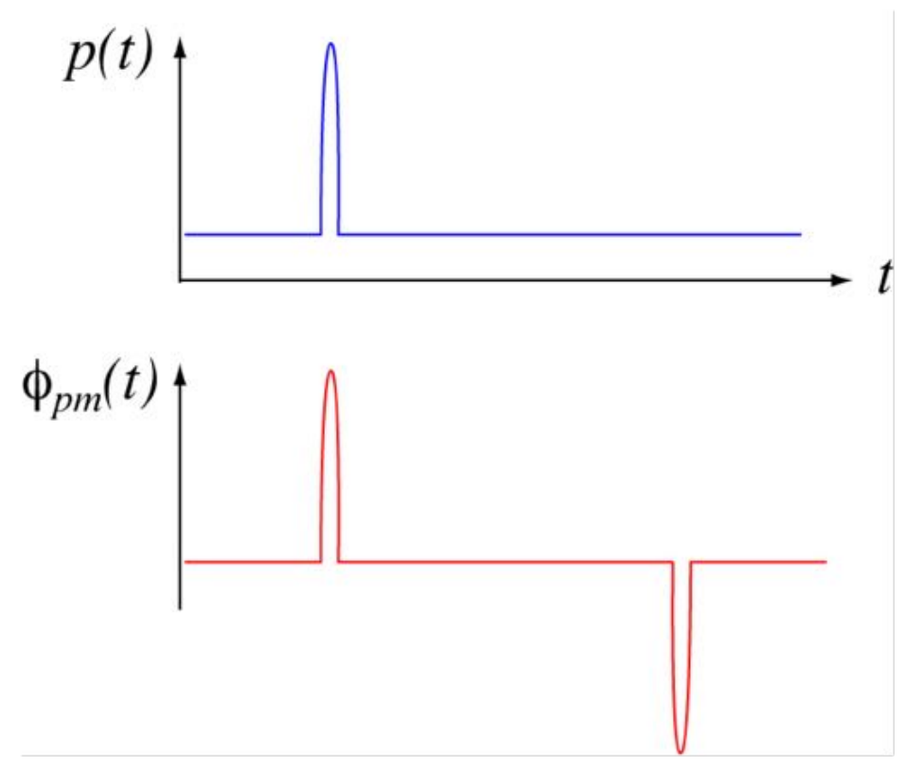
J. W. Armstrong, F. B. Estabrook and M. Tinto
ApJ **524** 814 (1999)

Arm locking concept

- LISA arm is the best frequency reference.
- High bandwidth feedback possible despite 33 s delay.



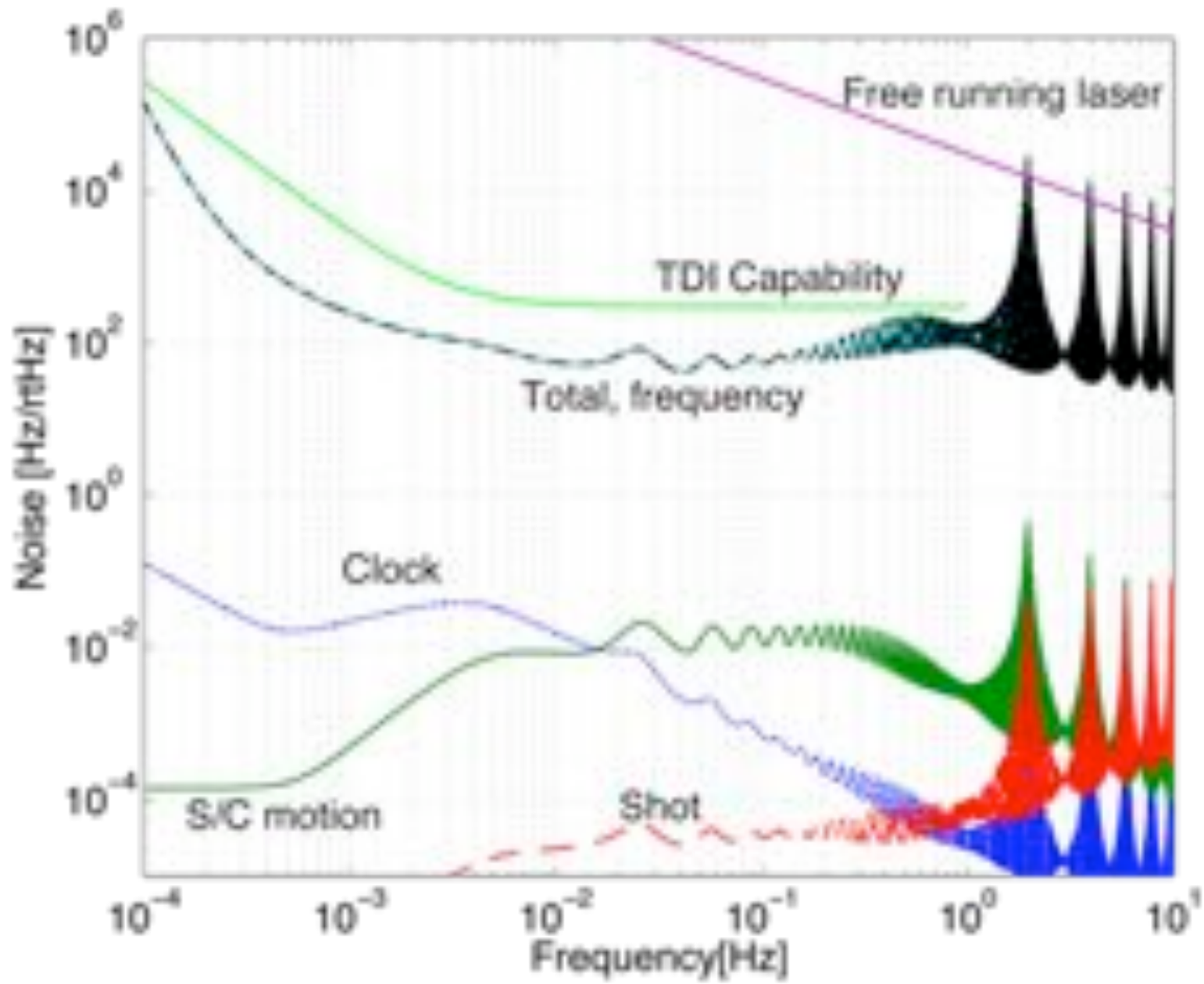
Simple model of a LISA arm



Impulse Responses

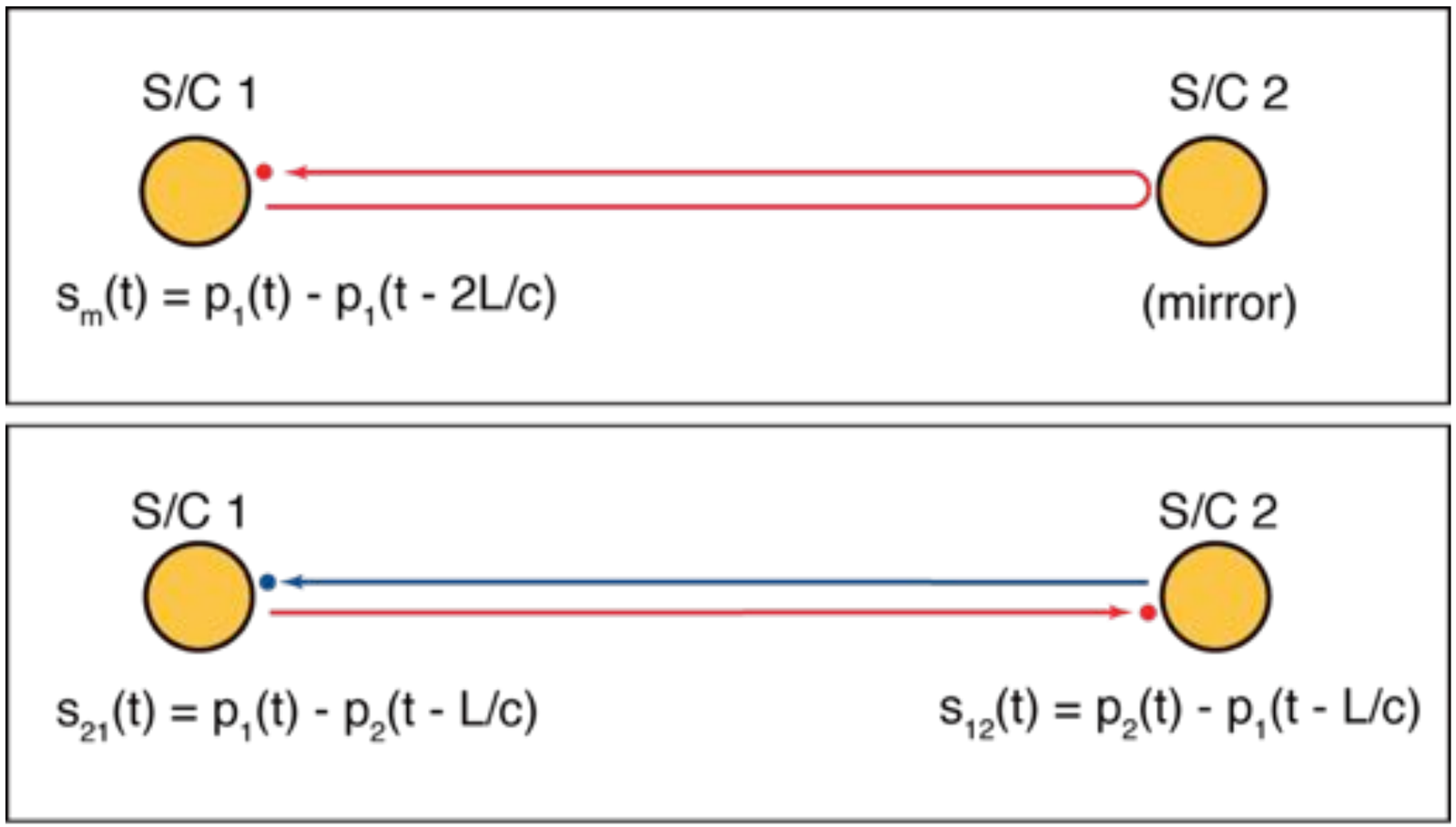
Arm locking performance

By using both LISA arms, laser can be stabilized to required level without explicit prestabilization.



Modified Dual Arm Locking, *McKenzie, Spero, Shaddock, PRD 80,102003 (2009)*

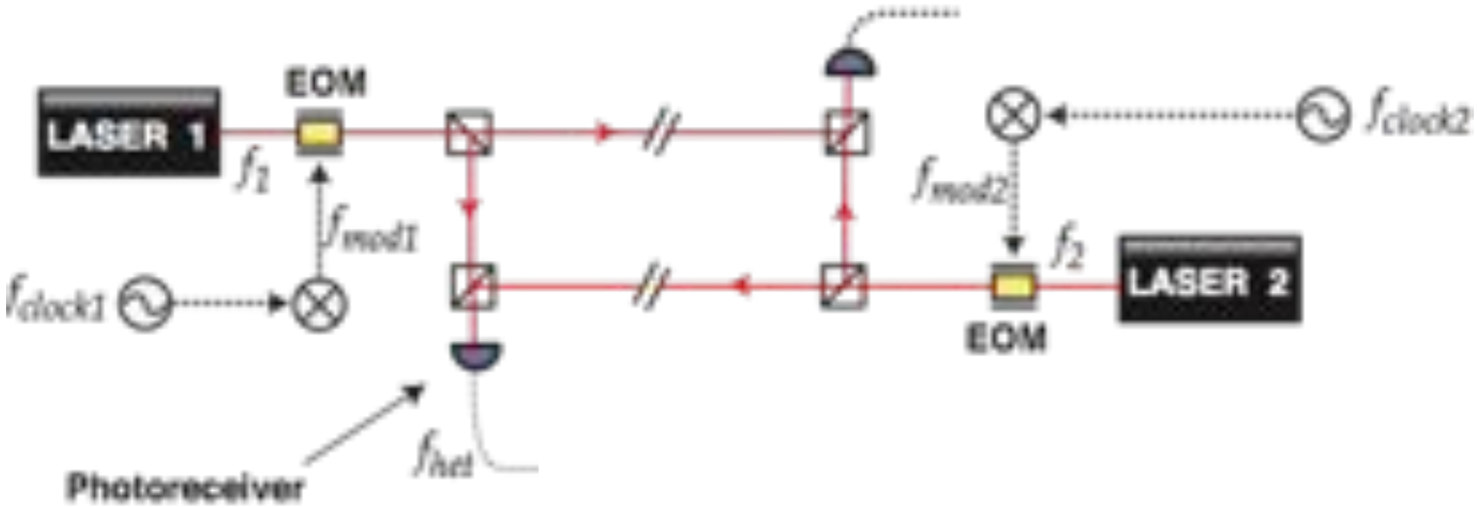
Time-Delay Interferometry (TDI) in Essence



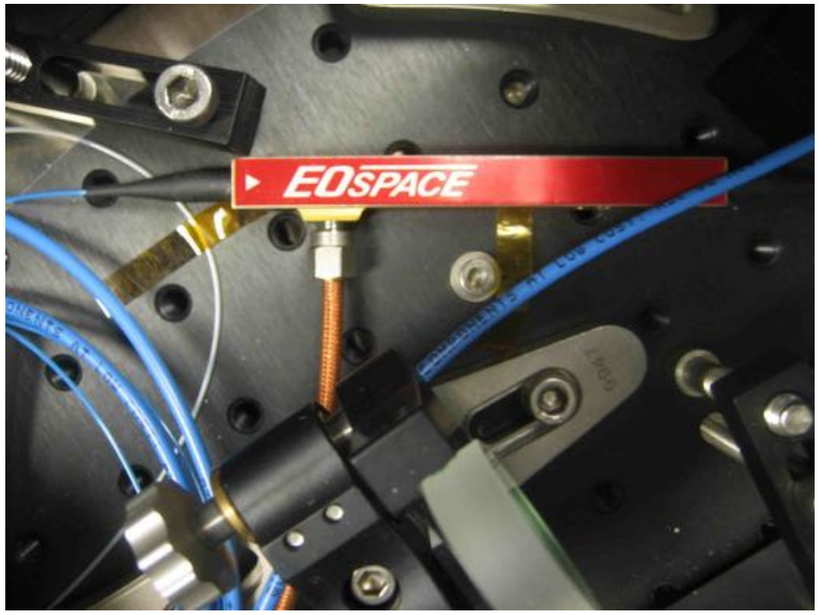
- Measurement is (prompt)–(delayed)
- s(t) phase of interference p(t) laser phase
- Measurements combined using knowledge of delays

$$s_m(t) = s_{21}(t) + s_{12}(t - L/c)$$

Phase Measurements → USO Noise Correction → Interpolation →



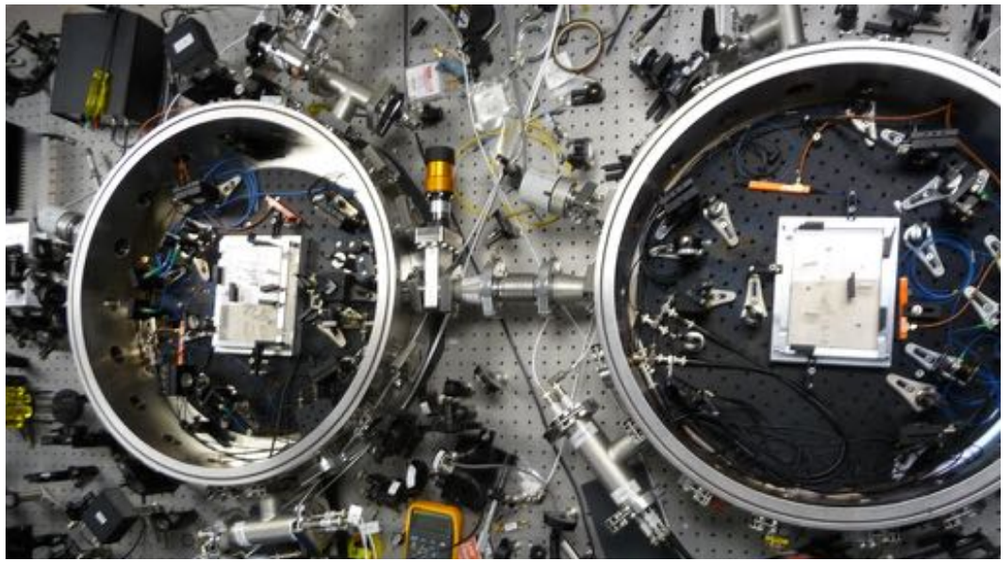
- Clock frequency multiplied to 6 GHz for high SNR of phase fluctuations
- Transmitted to distant spacecraft as sideband on science signal
- Detected sideband/sideband beat signal ~ 2 MHz
- Clock tone separated from science signal within phasemeter, separately recorded

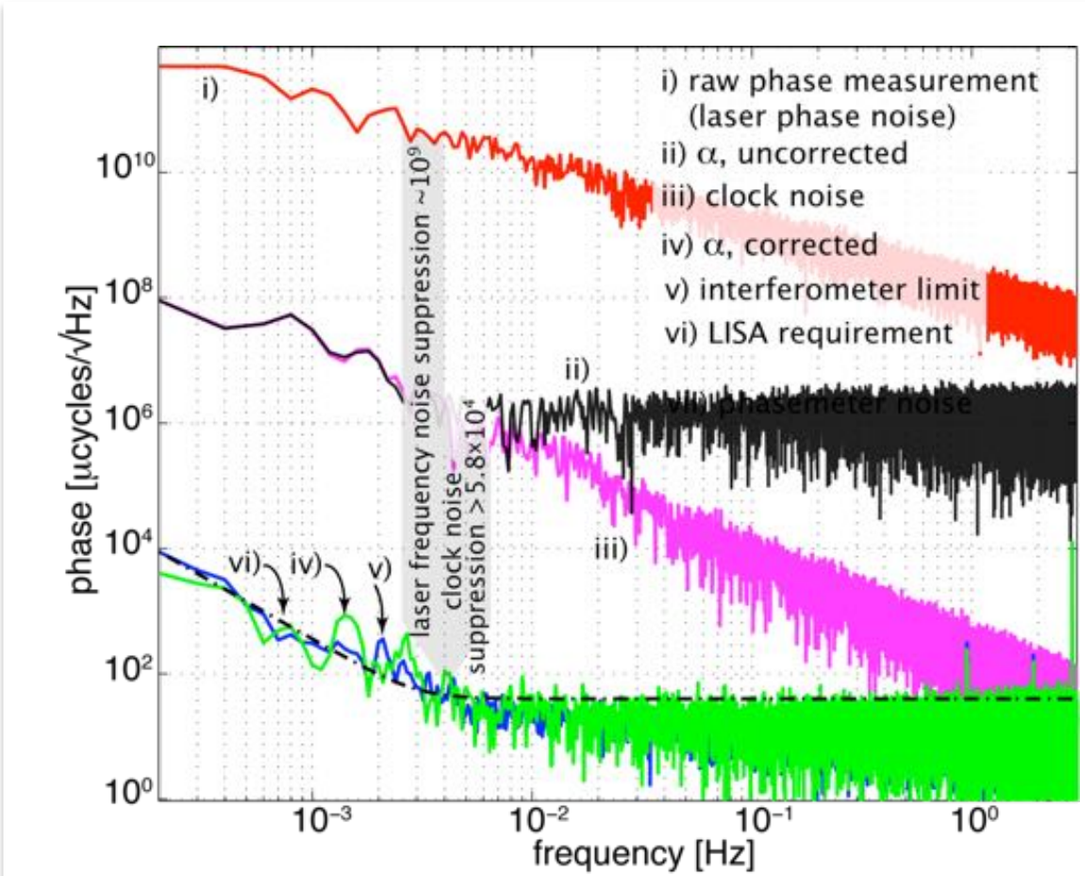


LISA Time Delay Interferometry at JPL

Jet Propulsion Laboratory
California Institute of Technology

- The LISA TDI scheme has been demonstrated at JPL in a Sagnac Interferometer
- Frequency noise removal to interferometer displacement limit
  - Clock noise removal
  - Clock Tone Transfer via GHz phase modulation
  - Interpolation of data streams onto common time-base
- Also, on the JPL TDI testbed
  - Optical ranging PRN to 0.2m rms
  - Optical Communications 20 kbps





A. Sutton, K. McKenzie, B. Ware, and D. A. Shaddock OE (2010)
G. de Vine, B. Ware, K. McKenzie, R.E. Spero, W. M. Klipstein and D. A. Shaddock PRL (2010)

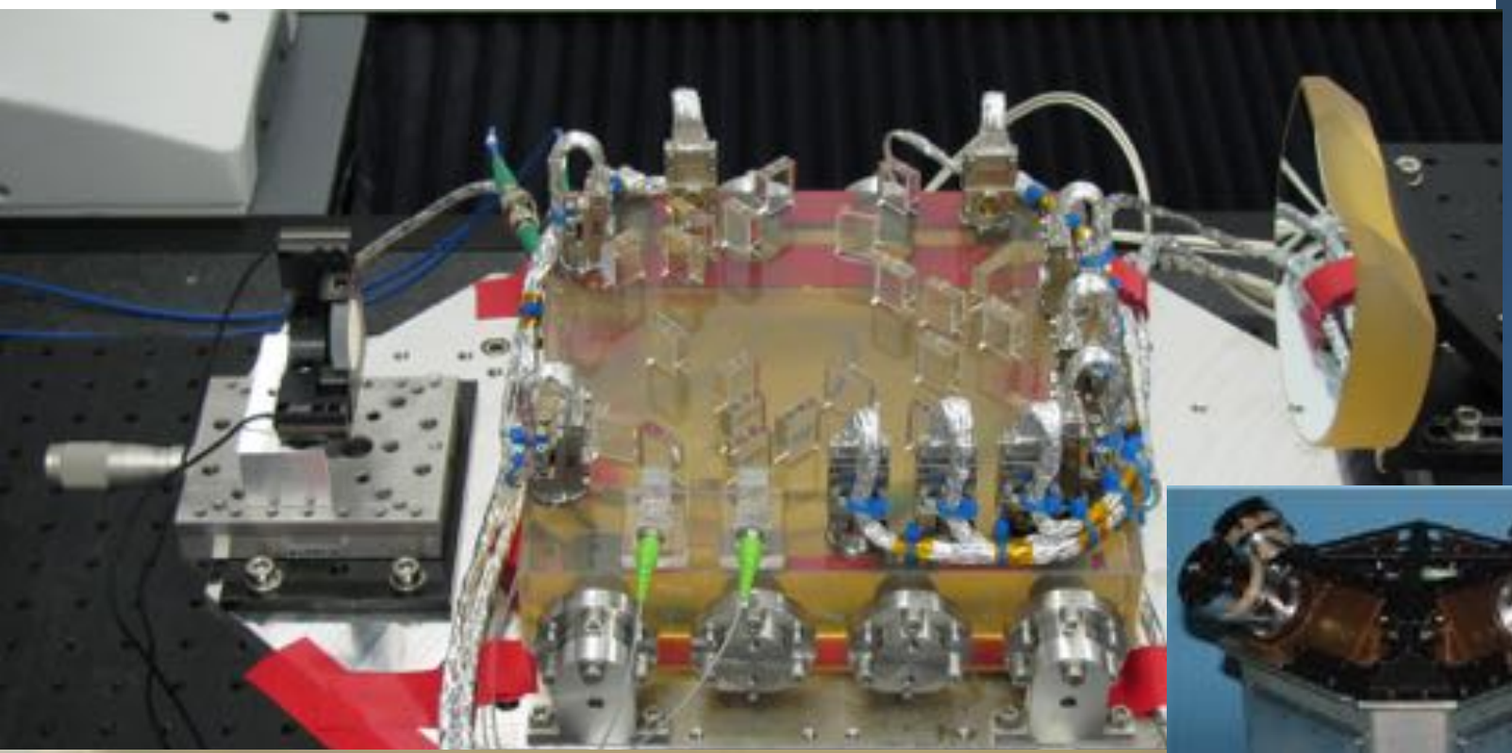
Elements of LISA

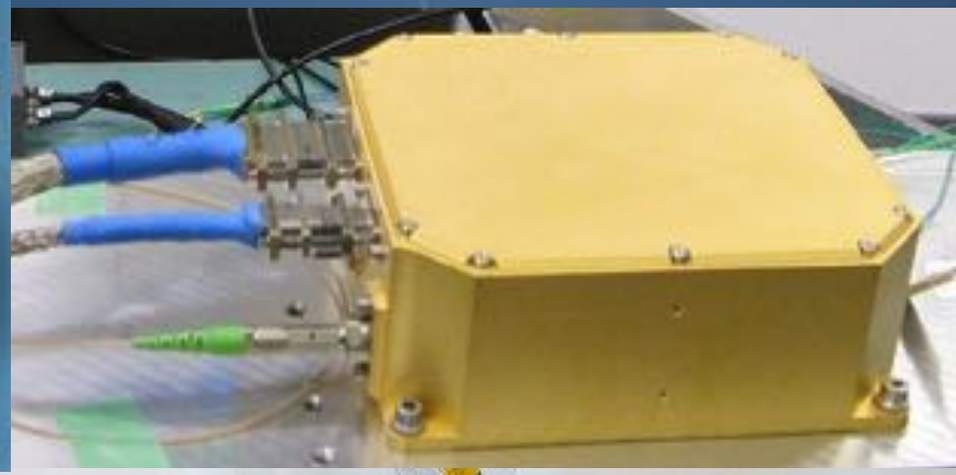
Jet Propulsion Laboratory
California Institute of Technology

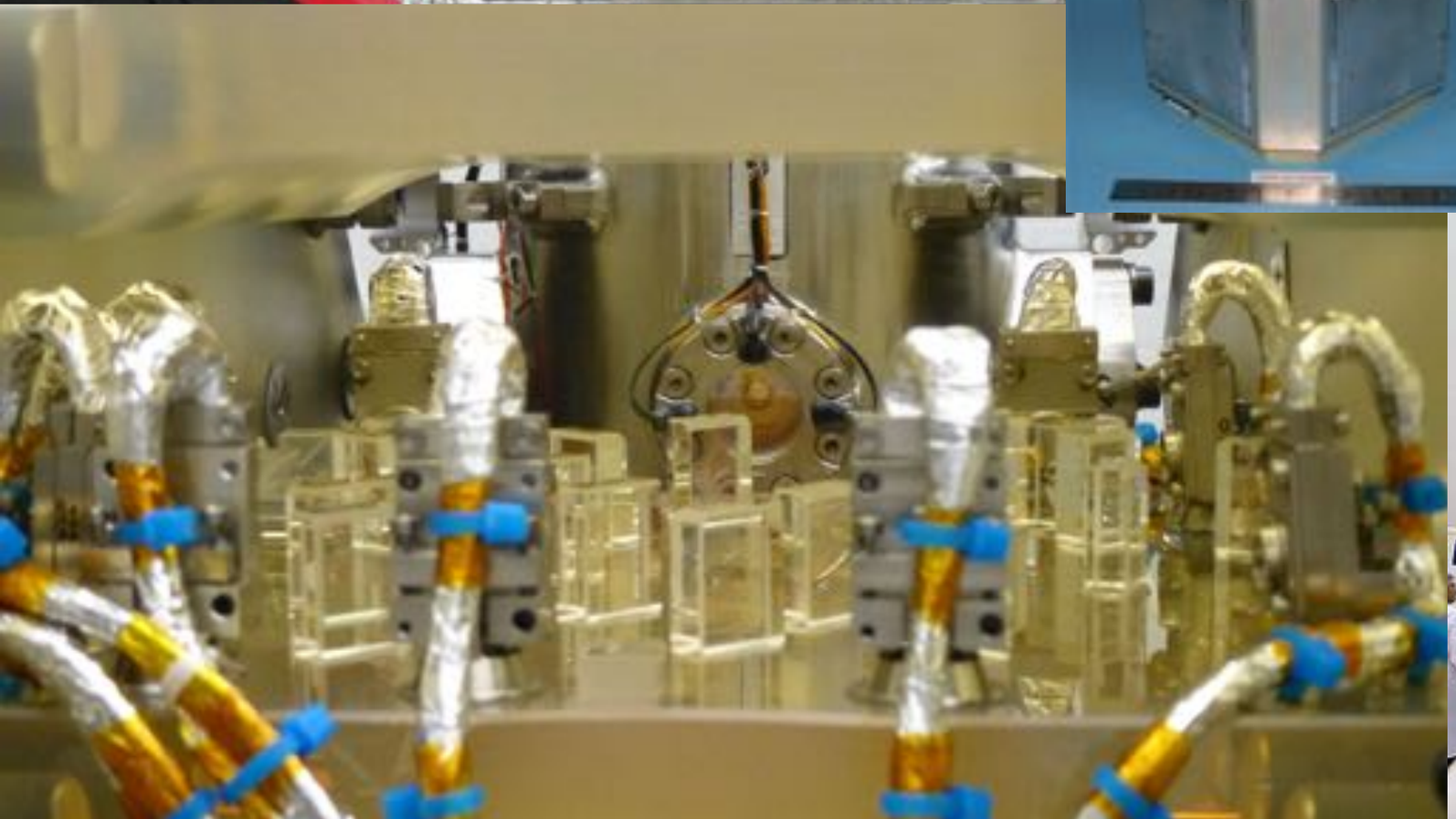
- Optical
  - Telescope
  - Point ahead actuator
  - Optical tracking/in-field guiding (arm breathing)
  - Metrology
  - Fiber noise
  - Bench*
  - Differential wave front sensing (DWS)
  - Fast steering mirror (FSM)
  - Acquisition*
  - Alignment
  - Baffles
  - Quad photodiodes (QPD)
  - Contamination
- Laser frequency noise suppression
  - Laser + laser amplifier*
  - Cavity pre-stabilization
  - Arm locking
  - TDI
- Thermal control*
- Structural/mechanical stiffness*
- Phase measurement
  - Clock noise suppression
  - Inter-spacecraft comms
  - Signal reconstruction
  - Phasemeter
  - Phaselocker
  - Multiple tones
- Laser Ranging Processor (LRP)
  - acquisition controller
  - FFT streaming
  - Data acquisition
  - State machine
  - Science measurement
  - Laser control
- GRS
  - Launch lock
  - Vacuum
  - Charge control
  - Drag-free control
  - Micro-newton thrusters

LISA Pathfinder
GFO
Testbed
*Work to go

LISA Pathfinder







LISA Pathfinder

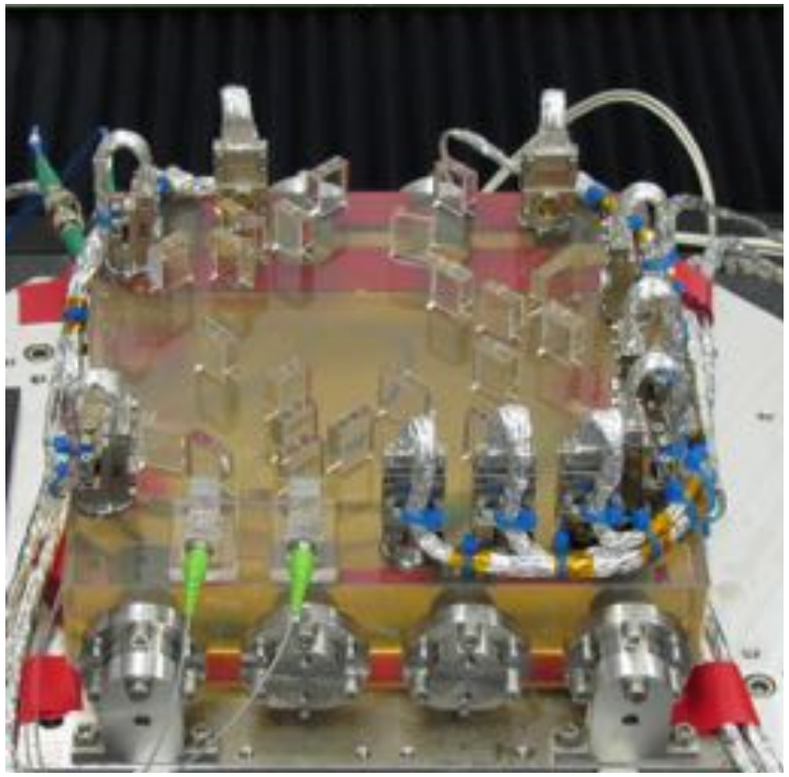
Jet Propulsion Laboratory
California Institute of Technology

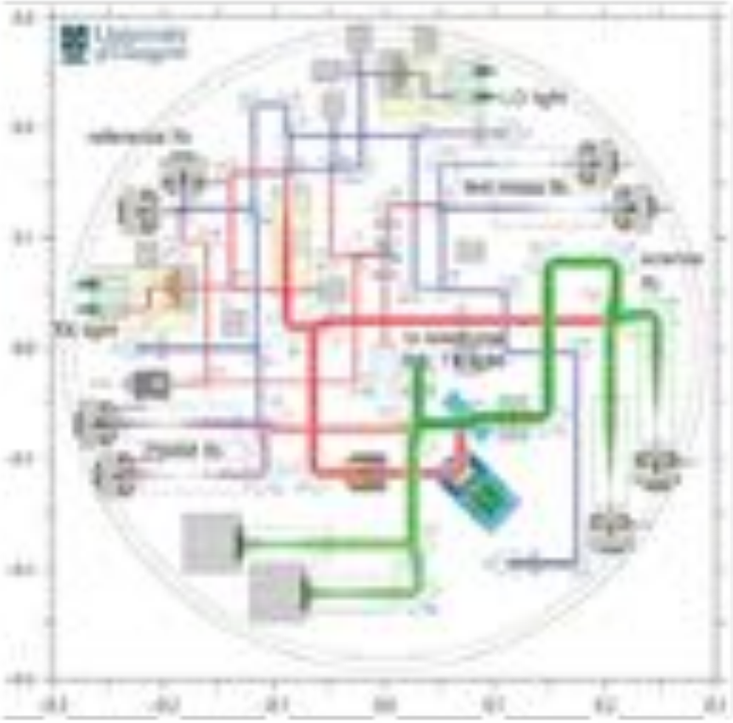
- Launched December 3, 2015
- Is retiring largest risk: GRS (accelerometer) sensitivity
- “Met preflight requirements”
- Paper release/announcement planned for late this month

Jet Propulsion Laboratory
California Institute of Technology

LISA To Do

- Optical bench is larger and more complicated than LPF
- 1 W laser vs 25 mW GFO
- 30-40 cm telescope vs 1 mm GFO
- Point ahead actuator
- Telescope with In-field guiding
- Thruster lifetime





Status

- LISA Pathfinder — Measurements underway
- LRI delivery to Airbus for ATLO — Underway
- GFO launch — 2017
- LISA/eLISA launch — ~ 2030

Next steps before LISA

Drag-free Accelerometers: Proven

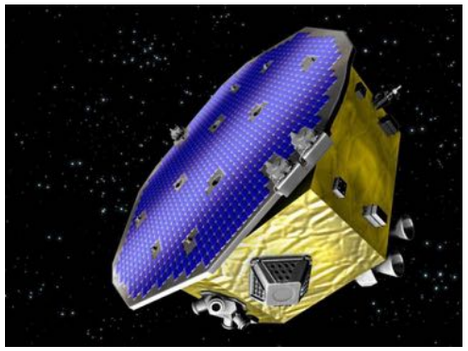
- **GOCE (2009-2013)**
  (~10^{-12} $ms^{-2}/\sqrt{Hz}$)

- **LISA Pathfinder/ST7 (Underway)**
  (~10^{-14} $ms^{-2}/\sqrt{Hz}$)

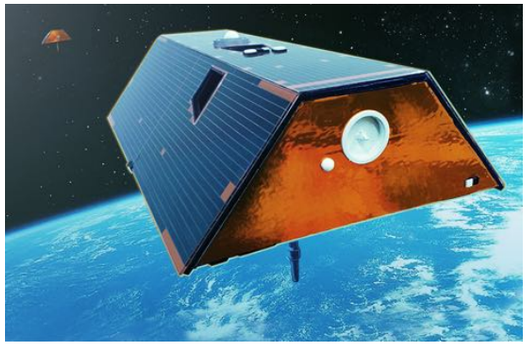
Inter-Spacecraft Laser Interferometry

- **GRACE Follow-On (2017)**
  - **(< 90 nm/$\sqrt{Hz}$)**

GOCE (ESA)



LISA Pathfinder/ST7 (ESA/NASA)



GRACE-FO (GFZ/NASA)

These technologies set the stage for the next generation of inter-spacecraft interferometers for geodesy (GRACE II) and towards gravitational wave detection (LISA).