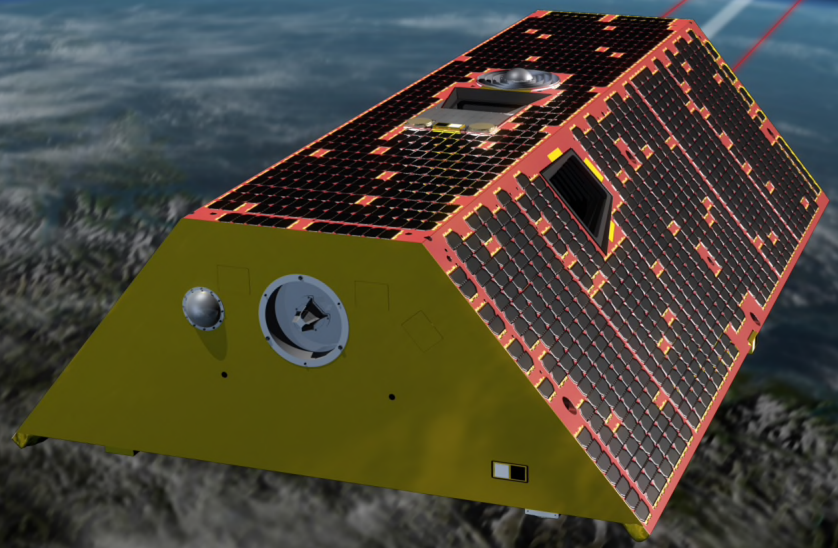
First Results from the GRACE Follow-On Laser Ranging Interferometer

Robert Spero, for the
US and German LRI collaboration

NASA/Jet Propulsion Laboratory,
California Institute of Technology

12'th LISA Symposium, July 13, 2018



GRACE-FO Partnership

LRI 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.

GRACE and GRACE Follow-On

- **Gravity Recovery and Climate Experiment GRACE (since 2002 to 2017):**
  - NASA/German Research Centre for Geosciences (GFZ) partnership
  - 220km separation measurement of 2 spacecraft by dual microwave links
  - Spacecraft separation + location (GPS) yield orbit

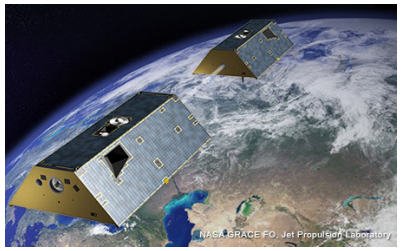
    Orbit determines gravity map
  - Gravity map evolution over months and years

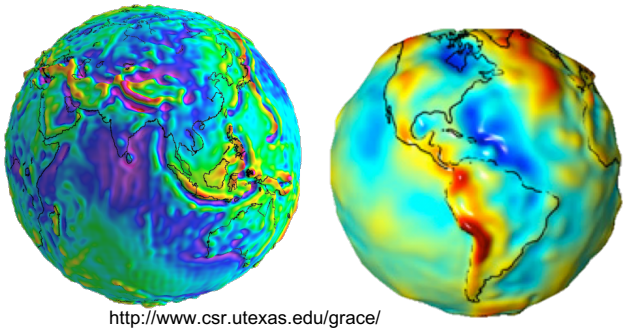
    Insight into earth systems & effects of climate change

    Really impressive science!

- **GRACE Follow-On (Launched May 22, 2018) will continue science**
  - Microwave Ranging Instrument (MWI) and Accelerometer similar to GRACE
  - ***Tech-Demo for All-Optical GRACE*** *: Laser Ranging Interferometer (LRI)*

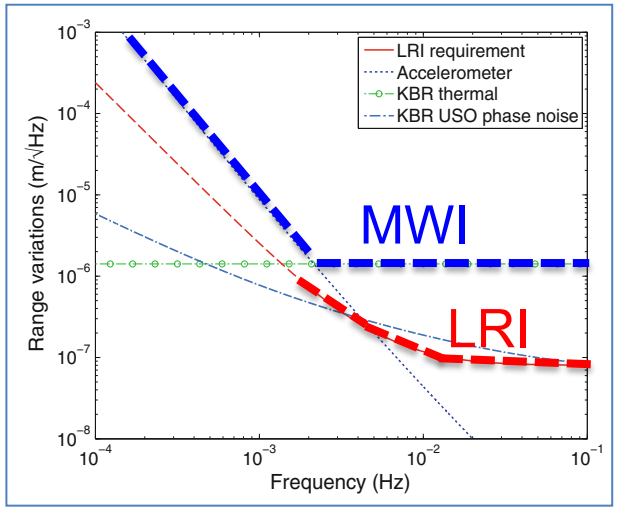
    First inter-spacecraft interferometer
  - ***Long running development Astrophysics (LISA) and Earth Science (GRACE 2) funnding***





http://www.csr.utexas.edu/grace/

GRACE Follow-On Instrument noise



B. Sheard et al, J Geod (2012)

The Laser Ranging Interferometer (LRI)

The LRI is a partnership between the US and Germany

US: Stabilized laser and Metrology

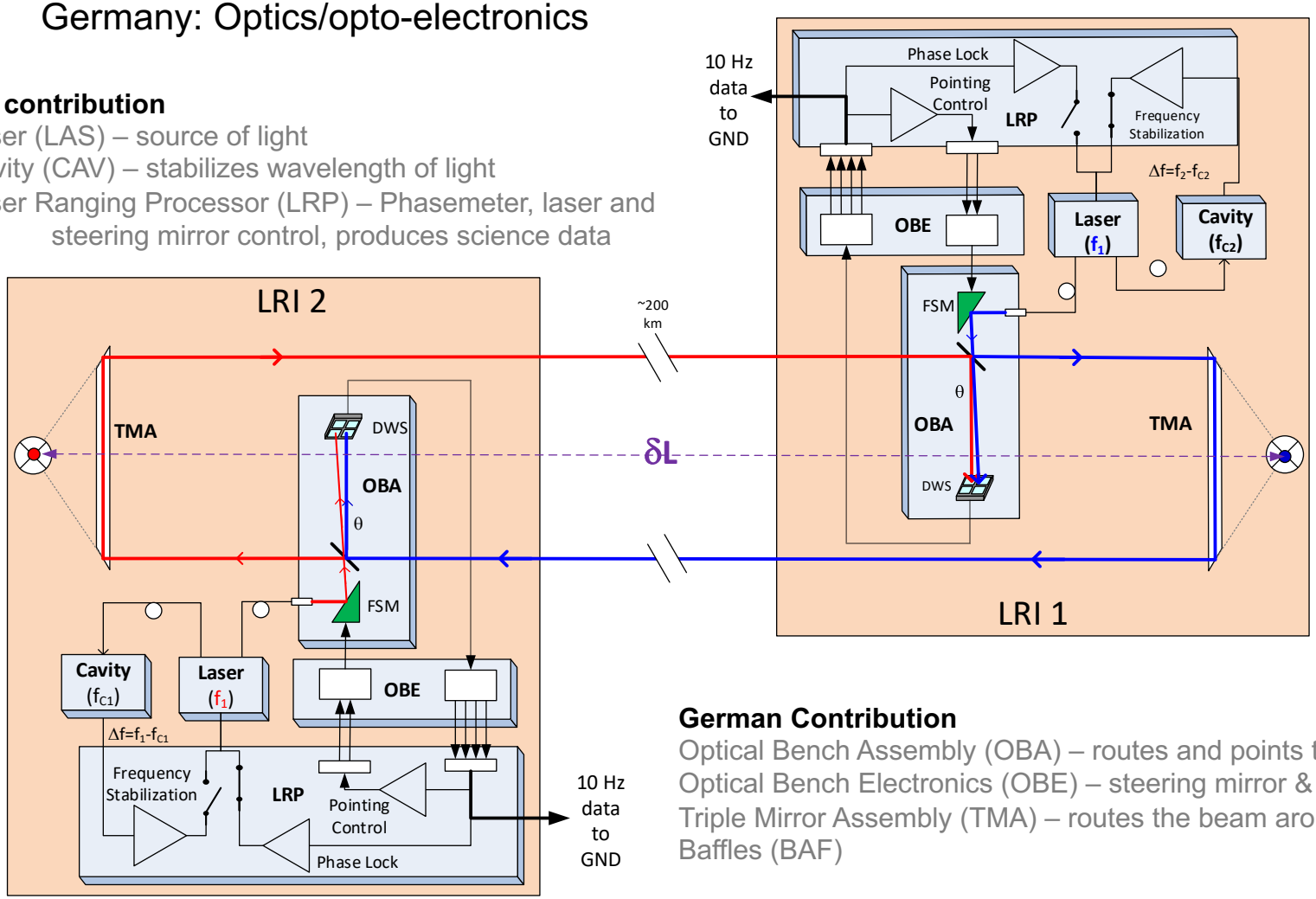
Germany: Optics/opto-electronics

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)

Comparison of the LRI and LISA

Parameter	LRI	LISA
Measurement Noise	80 nm/rtHz	20 pm/rtHz
Shot Noise	*0.01 nm/Hz$^{1/2}$*	*7 pm/Hz$^{1/2}$*
Photoreceiver Noise (but note carrier to noise density requirement)	*1 nm/Hz$^{1/2}$*	*3 pm/Hz$^{1/2}$*
Phasemeter Noise	*1 nm/Hz$^{1/2}$*	*1 pm/Hz$^{1/2}$*
Optical Pathlength Noise	*30 nm/Hz$^{1/2}$*	*3 pm/Hz$^{1/2}$*
Laser Frequency Noise	*35 nm/Hz$^{1/2}$*	*1 pm/Hz$^{1/2}$*
USO Noise	*1 nm/Hz$^{1/2}$*	*1 pm/Hz$^{1/2}$*
Satellite Separation	**170..270 km**	**5 million km**
Satellite Relative Velocity	**≤±3m/s**	**≤±15m/s**
Wavelength	**1.064×10^{-6}m**	**1.064×10^{-6}m**
Phase Precision	**10^{-3} cycles Hz$^{-1/2}$**	**1 microcycle Hz$^{-1/2}$**
Nominal Carrier-to-noise Density	**≥ 75 dB-Hz (single phasemeter channel)**	**≥ 75 dB-Hz (single phasemeter channel)**
IF Signal Frequency	**4–16 MHz**	**2–18 MHz**
IF Signal Dynamics (@ 1 Hz)		
Before Frequency Stabilization	*5000 Hz Hz$^{-1/2}$*	*5000 Hz Hz$^{-1/2}$*
After Frequency Stabilization	*30 Hz Hz$^{-1/2}$*	*300 Hz Hz$^{-1/2}$*
Science Bandwidth	2mHz – 100mHz	0.1 mHz – 1Hz
Rx Optical Power	**79–625 pW**	**80 pW**
Number of Phase Channels	**4**	**44+**
ADC Clocking Rate	**38.656 MHz**	**50 MhZ**
Time Coordination	**GPS (laser ranging code could be used)**	**Laser ranging code**
Laser Phase Locking	**Required**	**Required**
Pointing Information	**Wavefront sensing**	**Wavefront sensing**
Pointing Precision	*1 urad/Hz$^{-1/2}$*	*80 nrad/Hz$^{-1/2}$*

NASA Technology Development Roadmap for a Future Gravitational-Wave Mission

LRI design based on LISA technology and capabilities.

- **Designed by LISA scientists and technologists (NASA and Germany)**

- LRI top level precision relaxed
- Tighter laser stability requirement

Similar:

Doppler Shift and IF signal
Received optical power
Science Signal Frequency

Both LRI and LISA require:

- Low light power tracking
- Differential Wave Front sensing
- 5 degree of freedom acquisition

LRI is providing technology demonstration for LISA and represents a huge step towards LISA

LRI is demonstrating the first inter-spacecraft interferometer

GRACE Follow-On Spacecraft

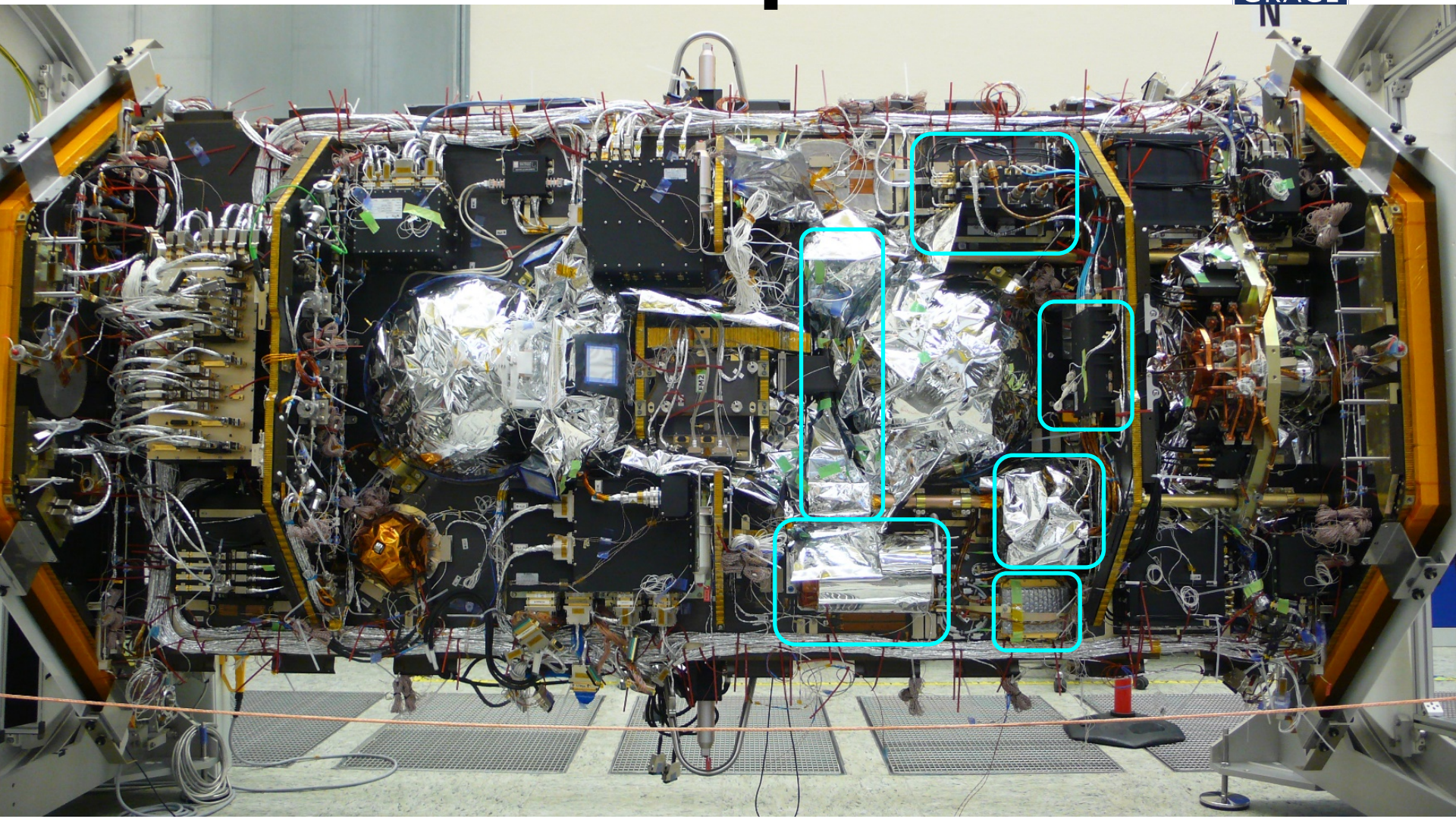
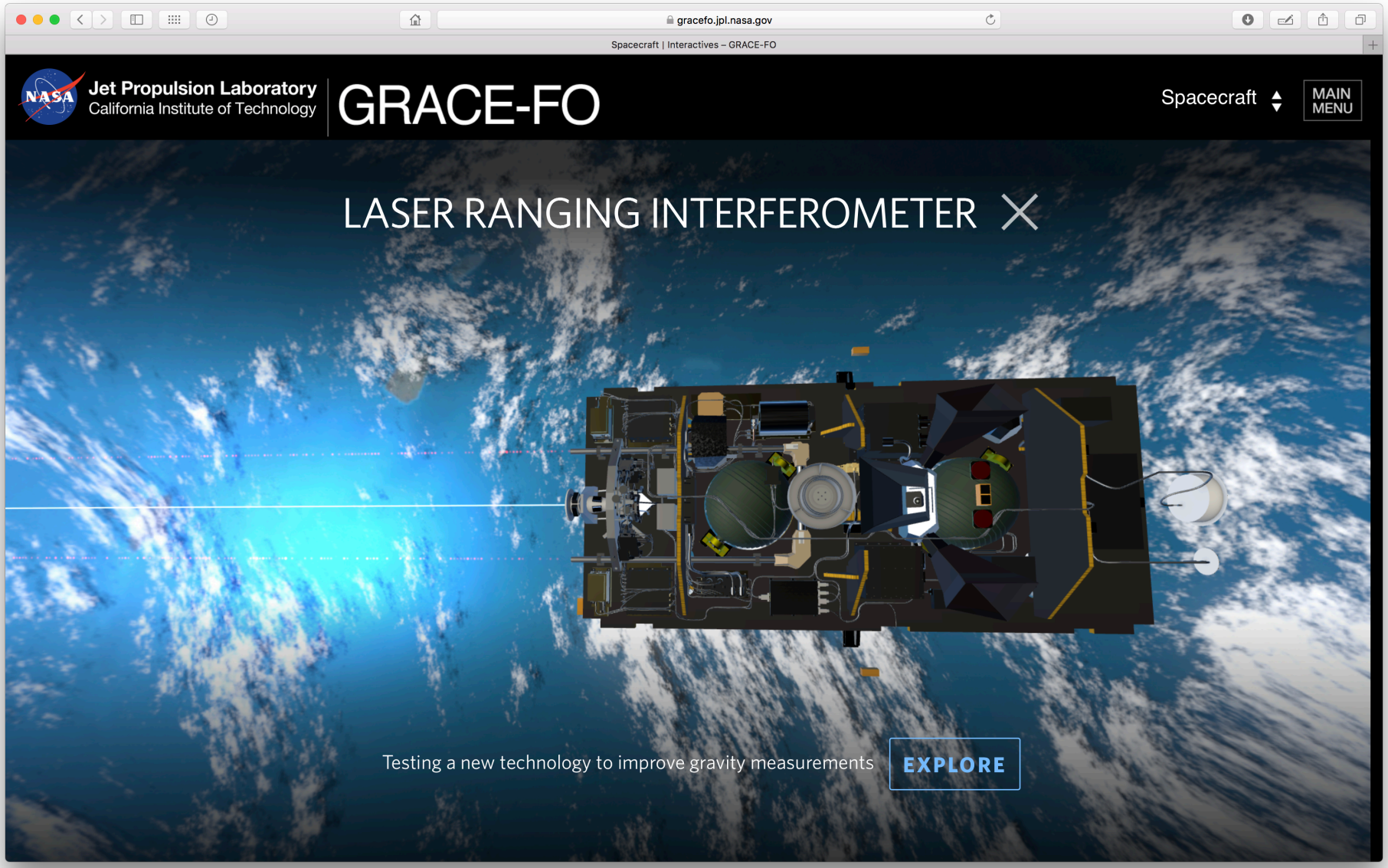
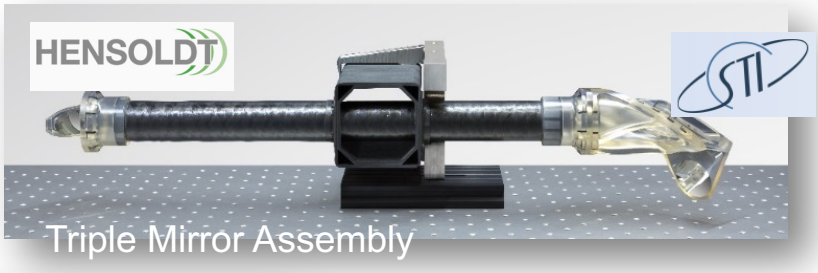


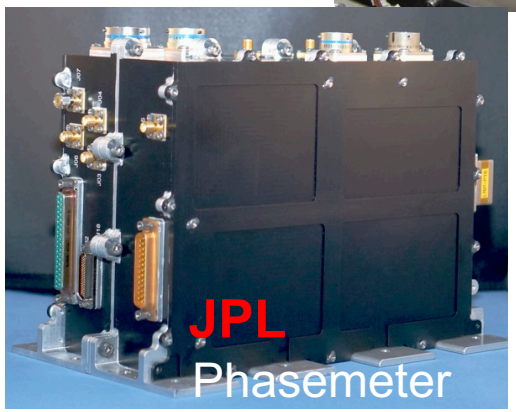
Image Courtesy of Airbus and JPL

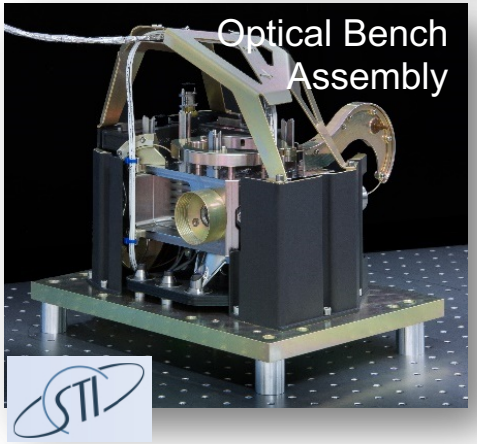
https://gracefo.jpl.nasa.gov/interactives/spacecraft/

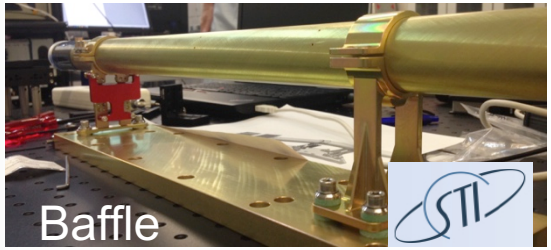


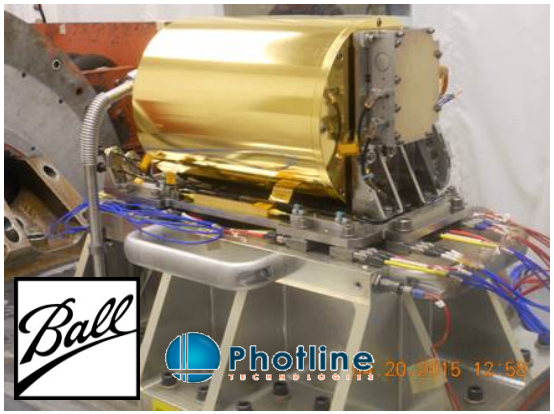
LRI Flight Components











Cables not shown (complete):
LRP-CAV: power, coax (x2)
LRP-LAS: power, cmd/tel
LRP-USO: coax (x2)
OBE-LRP: coax (x4), cmd/tel
OBE-OBA: Tel, power

Optical Bench Electronics

SpaceX @SpaceX · 8h
Successful deployment of GRACE-FO satellites.
39 518 3.9K

SpaceX @SpaceX · 8h
Second stage engine cutoff confirmed.
21 185 2.1K

SpaceX @SpaceX · 8h
Fairing has deployed.
48 260 2.7K

SpaceX @SpaceX · 8h
Main engine cutoff and stage separation confirmed. Second stage engine burn underway.
20 219 2.3K

SpaceX @SpaceX · 8h
Liftoff!
114 1.1K 8.7K

SpaceX @SpaceX · 8h
T-60 seconds until launch → spacex.com/webcast
24 331 1.7K

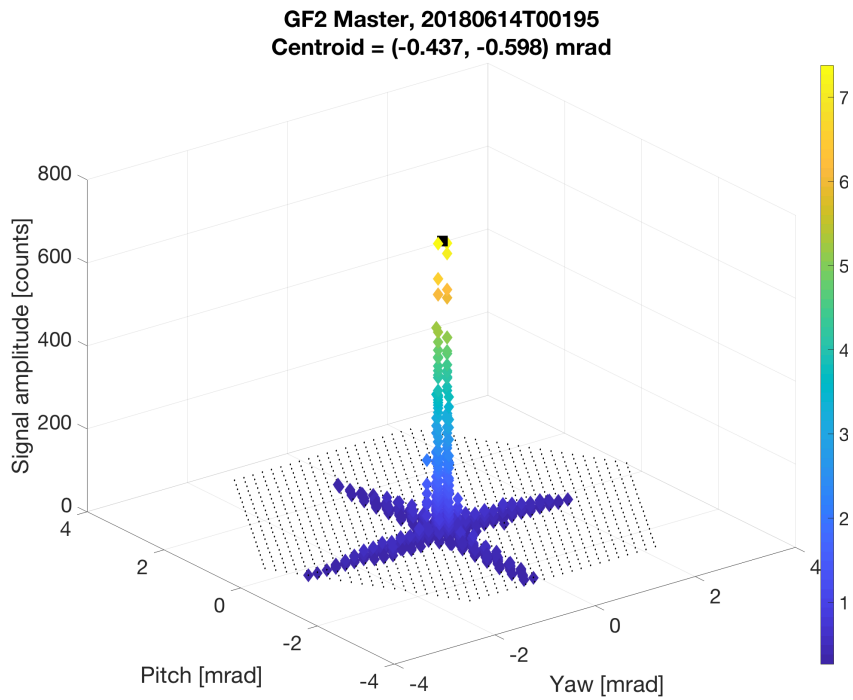
LRI Turn on and start of commissioning

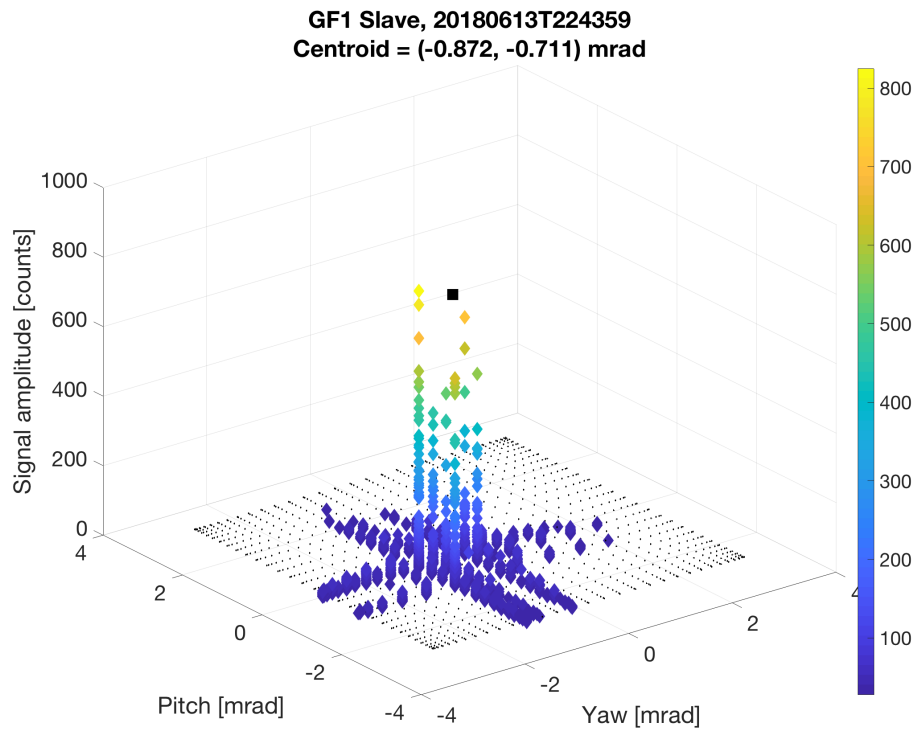
- LRI Powered on June 11th (spacecraft 1) and June 12th (spacecraft 2)
- Single spacecraft Checkout overnight showed the Laser, Cavity, Optical Bench, and Control electronics all checked out well
  - The phasemeter and Triple Mirror Assembly could not be checked until the link was formed
- The Open Loop Search Scan ran on June 13th
  - Nine hour spatial scan
  - Looking for a heterodyne beatnote (unlike LISA acquisition which has a dedicated CCD sensor)
  - **Inter-spacecraft signal detected with high SNR!**
  - > this gives: where to point the steering mirrors and laser frequency settings
- Upload of new parameters on June 14th

Inter-spacecraft laser interferometer link acquired autonomously on the very first acquisition attempt

Open Loop Scan results

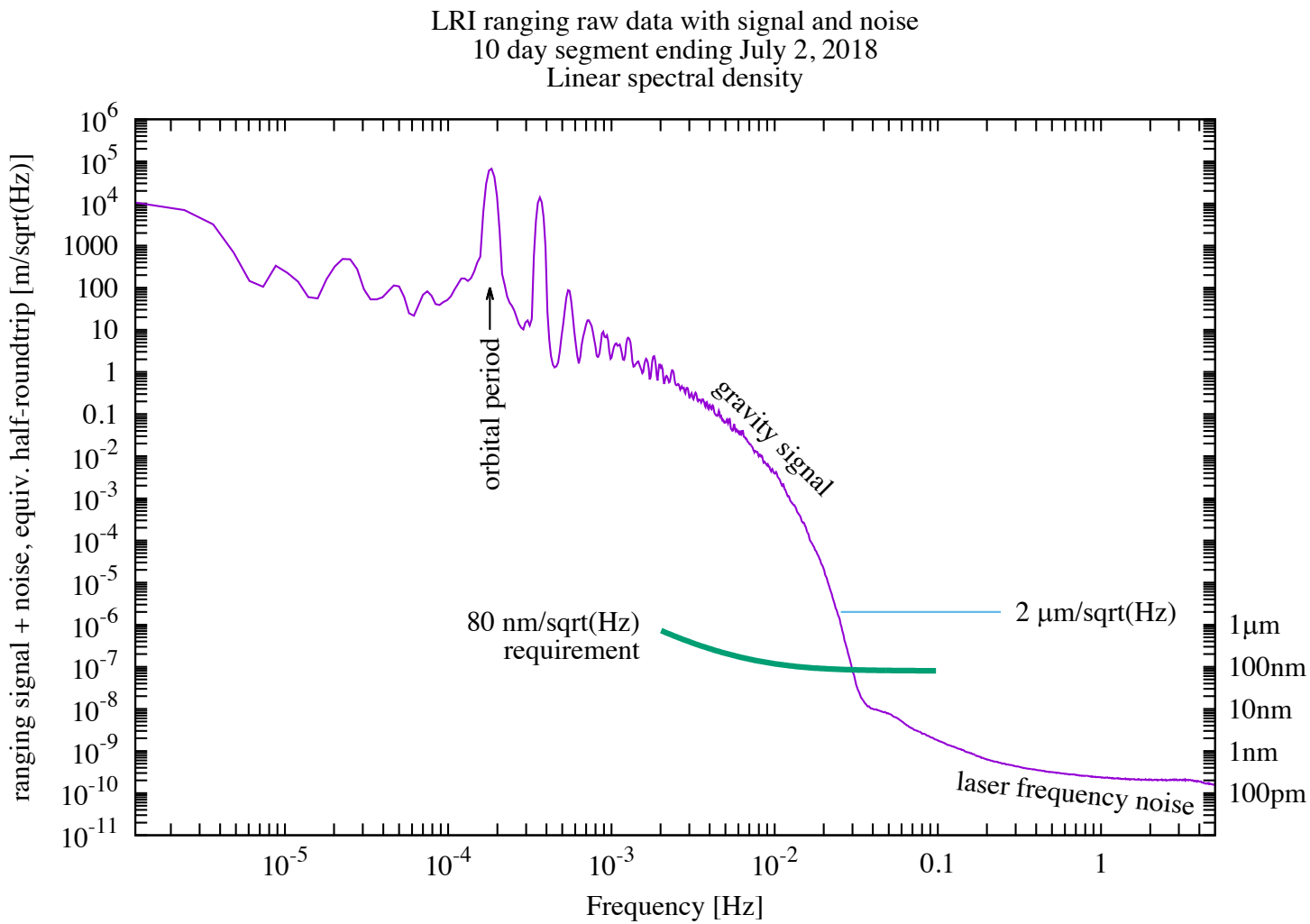
- Heterodyne flash detection scheme
- 8-hour duration open-loop scan of 4 spatial degrees of freedom + frequency. Downlink showed abundant flashes with high SNR.
- Measured offsets uplinked and interferometer link acquired autonomously within minutes.





Noise success: Interferometer performance exceeds requirements above gravity signal band

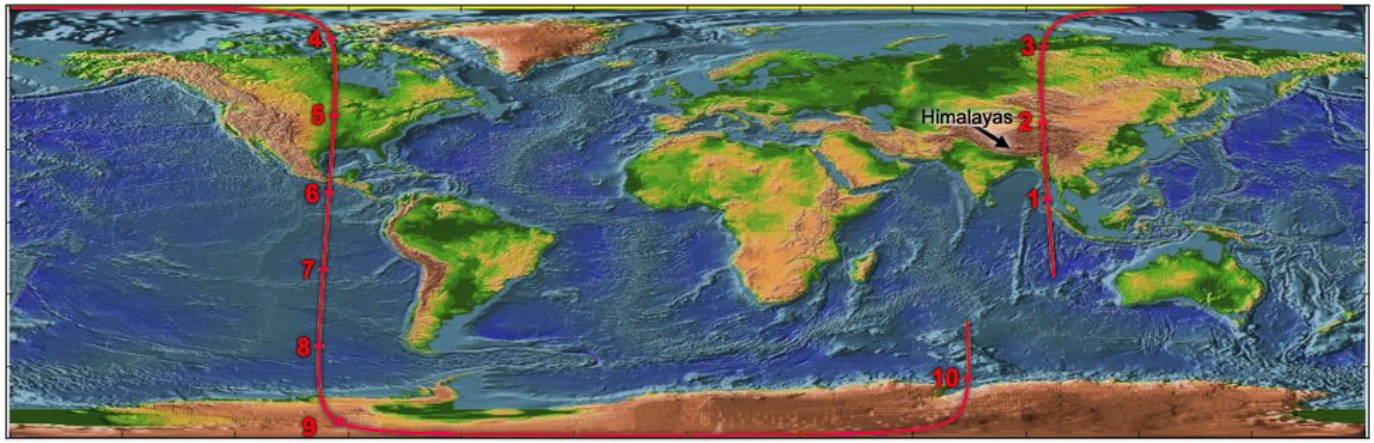
- Preliminary Result
- LRI has been tracking for almost 1 month
- No unexpected dropouts from continuous interferometry since.

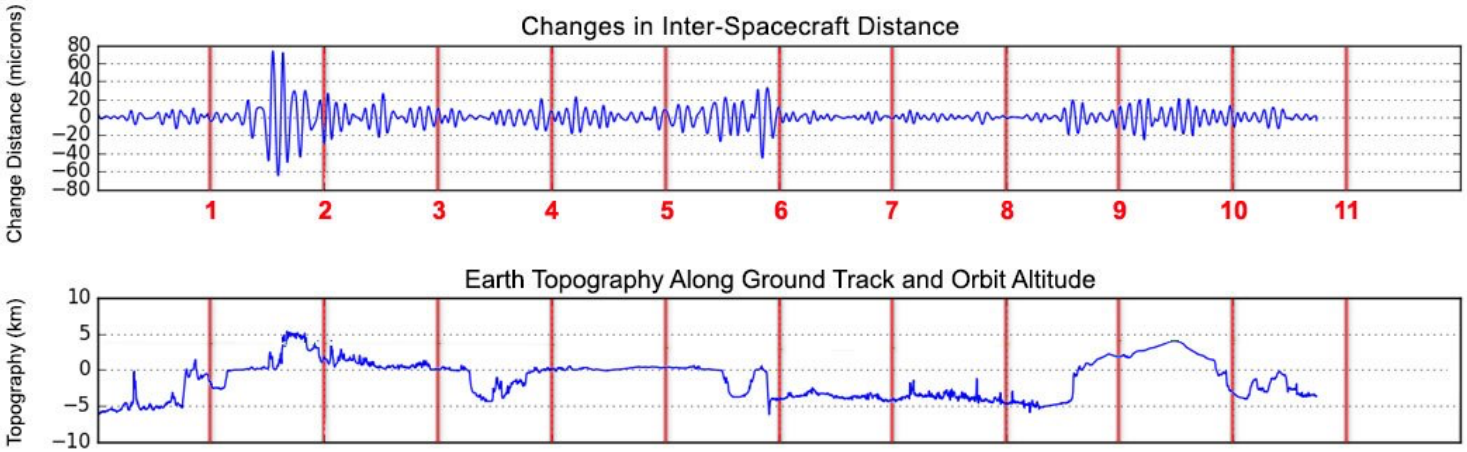


Signal success: Gravity measured

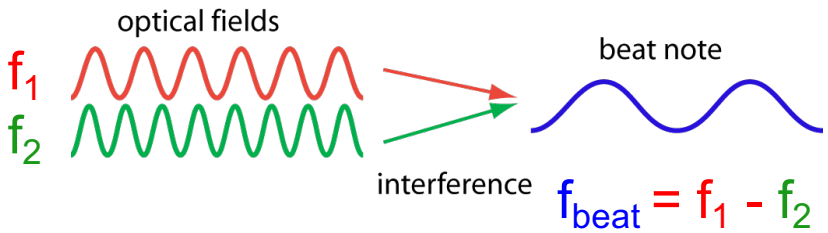
Filtered interferometer signal correlates with topography.

GRACE-FO Single-Orbit Ground Track, June 14, 2018

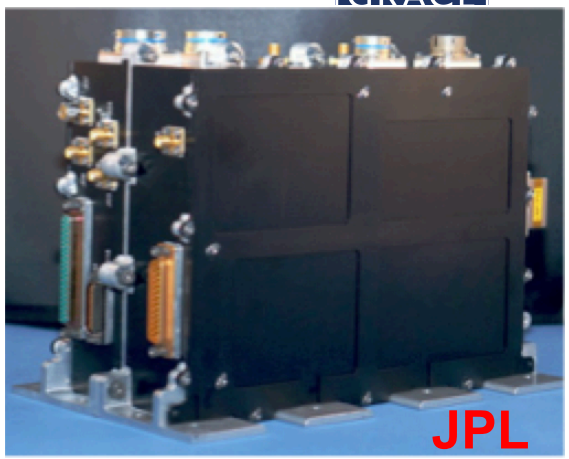




LRI Phasemeter aka
Laser Ranging Processor (LRP)



The phasemeter measures the science signal as a mHz phase modulation on a MHz beat signal.



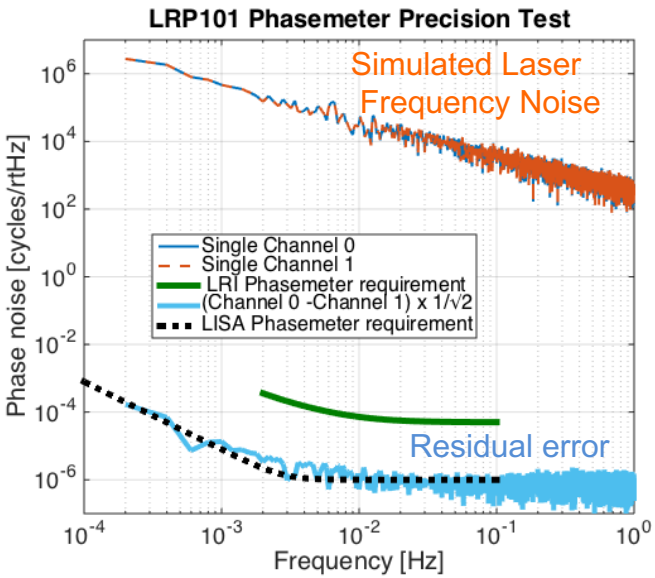
LRI Flight model Phasemeter

LRP developed at JPL, based on the LISA Phasemeter

The LRP implements the LISA phase tracking and frequency control algorithms, including:

- Phase tracking
- Differential wavefront sensing (and control)
- Laser Phase Locking
- Laser frequency stabilization

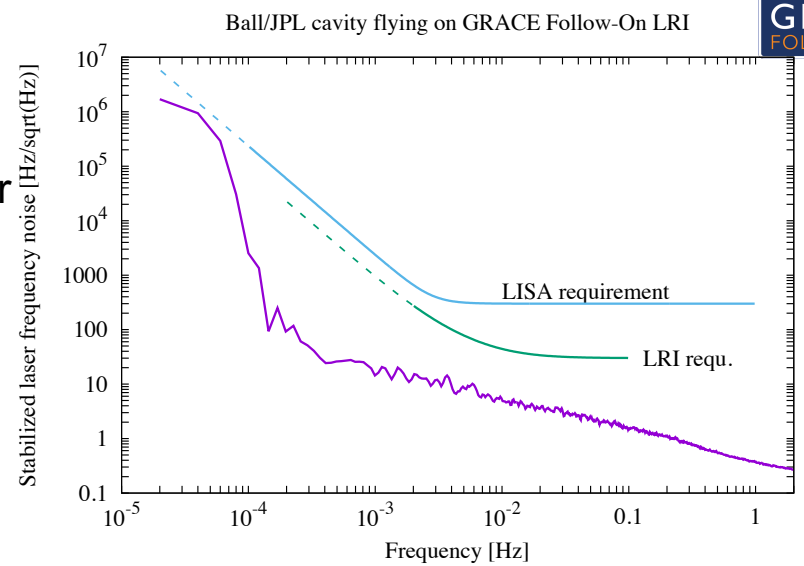
- Has only 4 input channels (vs 34 for LISA)
- Relaxed precision requirement, but ~ LISA performance

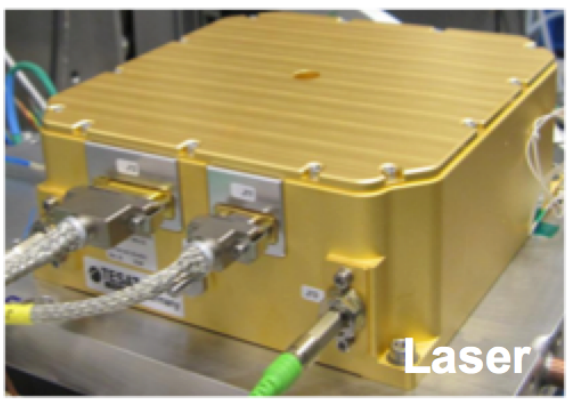


LRI Laser Frequency Stabilization: Flight Phasemeter, Flight Cavity, and Flight Laser

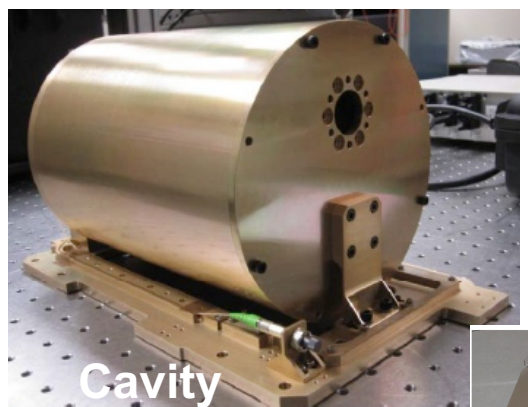
- Similar to Laser on LISA Pathfinder:
  - Wavelength: 1064 nm
  - Nd:YAG Non-Planar Ring Oscillator
- Laser output power: 25 mW

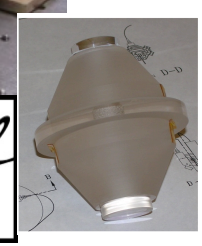
- NASA Earth Science developed Cavity
  - IIP: Ball Aerospace/JPL
- LRP implements laser frequency control (locks laser to cavity resonance)
  - Near mirror thermal noise stability





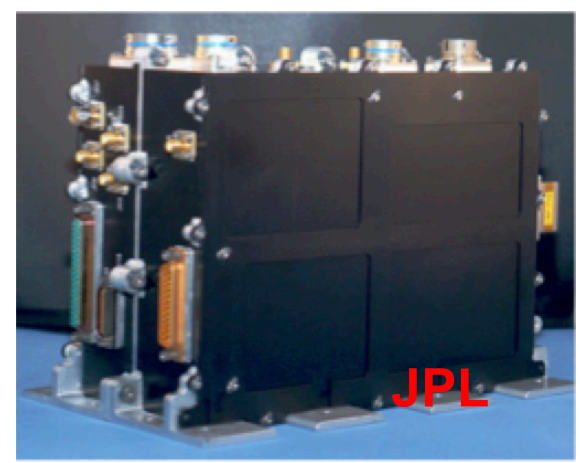
TESAT SPACECOM





Ball

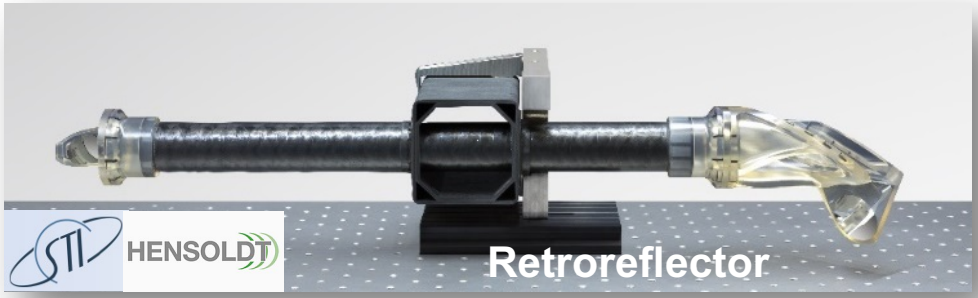
Flight phasemeter controlling flight laser to flight cavity, x2

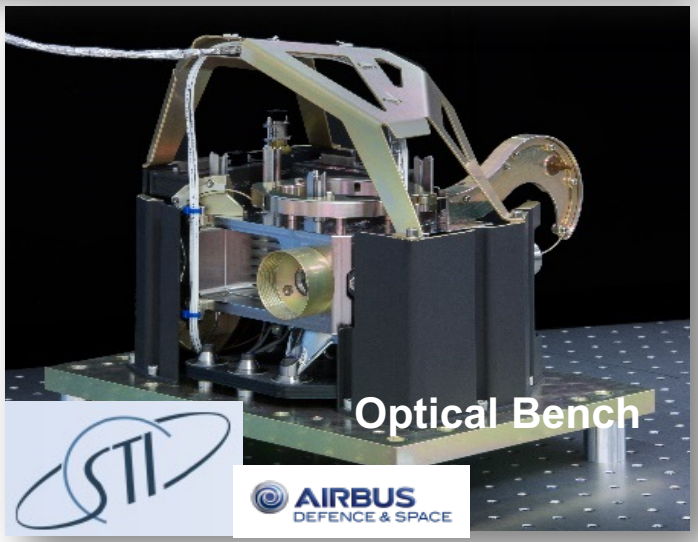


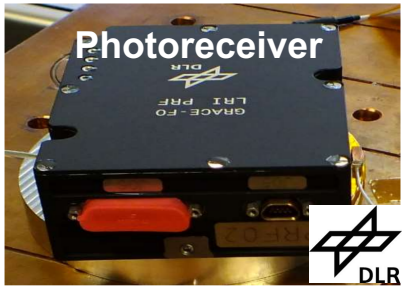
LRI : Beam Manipulation and heterodyne signal detection
Flight Optical Bench, Flight Retroreflector and Baffles

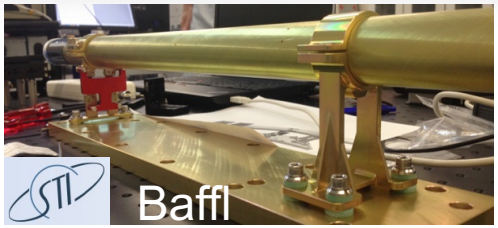
- <u>Triple Mirror Assembly (TMA)</u>
  - 60 cm lateral displacement between in & outgoing beam
  - lightweight CFRP structure + Zerodur mirrors

- Optical Bench Sub-System (OBS)
  - Titanium structure
  - Beam compressor / imaging system
  - Two hot redundant quadrant photoreceivers
    - InGaAs QPDs with 1 mm diameter
    - Bandwidth: 4...16 MHz
- External frontend electronics







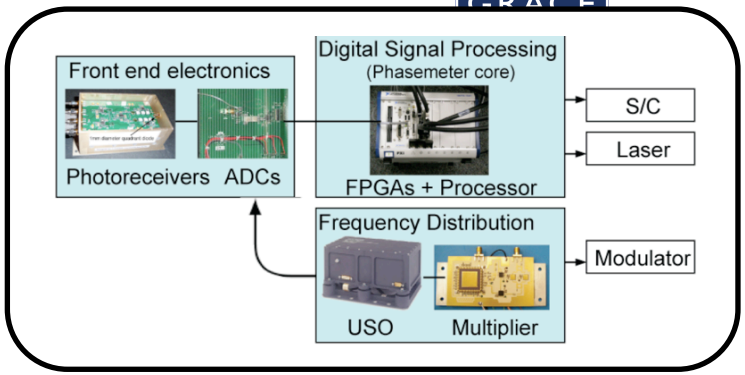


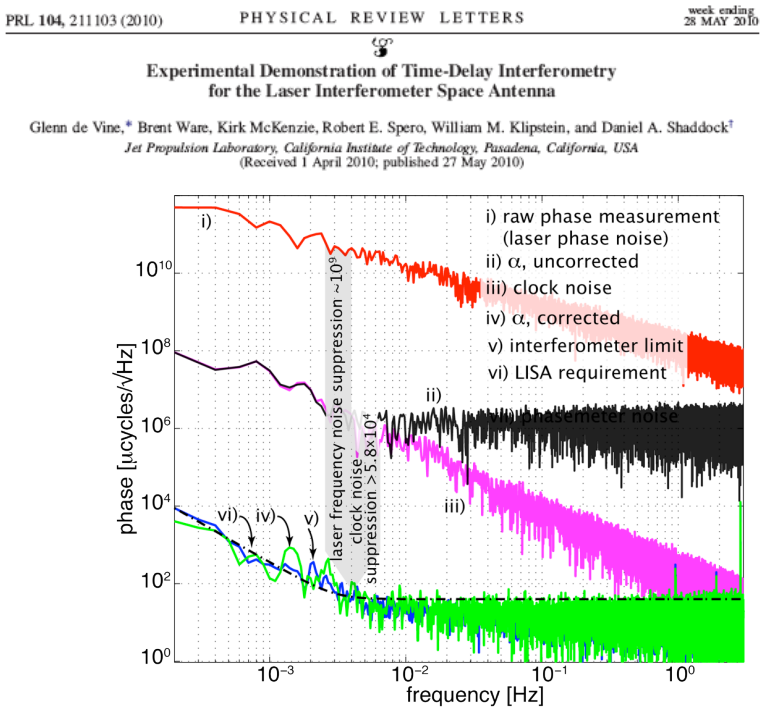
Time Delay Interferometry with the LISA Phasemeter

JPL LISA interferometer testbed used to demonstrate phase measurement system components and system performance to TRL 4

- Retired the highest LISA phase measurement risk[1]
- Frequency noise removal to interferometer displacement limit
- Clock Tone Transfer via GHz phase modulation
- Interpolation of data streams onto common time-base

Currently, testing the LRP (LRI phasemeter) on the JPL LISA Interferometry testbed.




PRL 104, 211103 (2010) PHYSICAL REVIEW LETTERS week ending 28 MAY 2010

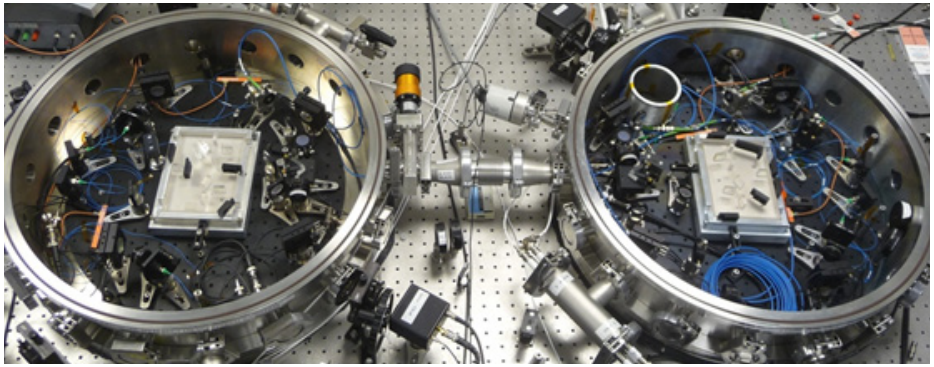
Experimental Demonstration of Time-Delay Interferometry for the Laser Interferometer Space Antenna

Glenn de Vine,* Brent Ware, Kirk McKenzie, Robert E. Spero, William M. Klipstein, and Daniel A. Shaddock†

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA

(Received 1 April 2010; published 27 May 2010)

JPL LISA Interferometry testbed



[1] NASA's LISA Technology Development Plan V 1.0 (2005)

Summary

- GRACE Follow-On Laser Ranging Interferometer (LRI), the first inter-spacecraft laser interferometer has been successfully operating since powering up in June, 2018.

- The LRI is a US-German partnership.
  - US: Phasemeter, laser and cavity
  - Germany: Optics/opto-electronics

- Instrument design and many technology elements from LISA development

- The LRI mission parameters have many similarities to LISA
  - Makes the LRI a relevant technology demonstrator for LISA
  - Increases maturity of key LISA technologies
    (US: advanced phasemeter and Optical Cavity)

GFO LRI Team UPDATE

JPL
Bill Klipstein
Bob Spero
Brent Ware
Serge Dubovitsky
Alex Abramovici
Greg Rosalia
Marty Scarbrough
Christian Liebe
Tony Sherrill
Glenn de Vine
Kirk McKenzie
Andrew Sutton
Jeff Dickson
Brian Bachman
Alex Murray
Chris Woodruff
Yutao He
Ken Clark
David Barr
Mark Katsumura
Kameron Larsen
Jehhal Liu
Max Bize
Mike Burke
Joseph Trinh
Doug Wang
Josh Ravich
Omid Ghassemi
Greg Taylor
Don Nguyen
Tony Grata
Rick Paynter
Valereen Essandoh
Bill Folkner
Rabi Wang
Daniel Shaddock
Peter Halverson

Tesat
Daniel Troendle
Steve Windisch
Juergen Schaeufler
Felix Kern
Steffi Gross
Iris Rock
Reinhard Baehring
Mustafa Cilo
Simon Braeuchle
Bjoern Siebertz
Rudolf Bauer
Hanno Scheife
Claus Seibert
Christoph Seiter

Photline
Philippe LeRoux
Houda Brahimi
Pascal Blind
Vincent Buin
Fatima Oruci
Jerome Hennemann

Ball
Michelle Stephens
Bob Pierce
Bengie Amparan
Gretchen Reavis
Mike Sileo
Dave Bender
Mike Comstock
Tracy Copp
Amanda Curry
Mike Davis
Larry Derouin
Michael Hoppes
Jim Howell
Carl Hunsaker
Ken Jackson
Paul Kaptchen
Jim Leitch
Aaron Mann
Mark Neitenbach
Tammy Osborne
Mike Taylor

ANU
Daniel Shaddock
Roland Fleddermann
Robert Ward
Danielle Wuchenich

AEI
Gerhard Heinzel
Ben Sheard
Christoph Mahrdt
Vitali Müller
Daniel Schütze
Gunnar Stede
Alexander Görth
Germán Fernández Barranco

STI
Frank Gilles
Kolja Nicklaus
Kai Voss
Rudolf Faimann
Manfred von Hoegen
Melanie Grossnick
Mark Herding
Timo Liebherr
Anne Feiri
Marina Dehne
Vadim Pflug
Christian Dahl
Katrin Dahl
Andreas Baatzsch

Hensoldt - TMA
Georg Luichtel
Roswitha Keppeler
Malte Schwarzer
Martin Hinz
Marcus Zimmermann
Torston Gross
Gerhard Dersch
Gerhard Reile

DLR - QPR
Andreas Eckardt
Thomas Mangoldt
Bernd Zender
Burkhardt Guenther
Thomas Lieder
Josep Sanjuan
Martin Gohlke
Klaus Abich
Claus Braxmaier

Apcon - OBE
Anton Lebeda
Arnold Lebeda

LRI & Integration
Dennis Weise
Reinhold Flatscher
Simon Doerr
Peter Gath
Nico Brandt
Dirk Gottschlag
Boris Messerschmidt
Denis Fischer
Martin Diener
Johan Blomqvist
Manfred Amann
Hauke Thamm
Klaus-Dieter Mau
HAAS, Klaus