

Flight Phasemeter on the Laser Ranging Interferometer on the GRACE Follow-On Mission

An inter-spacecraft laser interferometry technology demonstrator with similarities to LISA

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GRACE-FO



LRI Management

LRI implementation



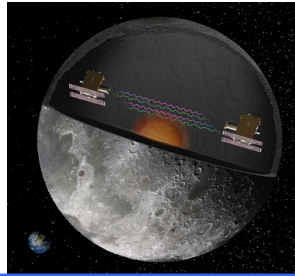
Amaldi 12, 13 July 2017

Gravity-Sensing: Precision Phase Measurement Instruments in Space

Microwave Instrument ~ Micrometer Precision



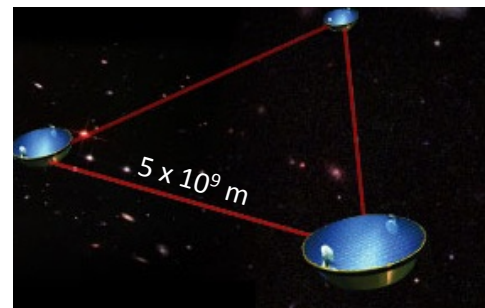
Gravity Recovery and Climate Experiment (GRACE),
Earth Science, microwave measurements (micrometers)
2002-present.



Gravity Recovery and Interior Laboratory (GRAIL),
Planetary science, microwave measurements (micrometers)
Sept 10, 2011 – Dec 17, 2012

Laser Instrument ~ Nanometer to Picometer Precision

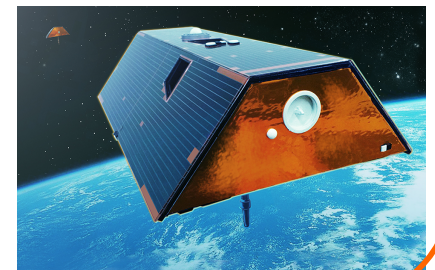
Laser Interferometer Space Antenna (LISA)
Astrophysics, (picometers)
-> ESA Cosmic Visions L3 (2034)



GRACE Follow-On

Earth Science,
Microwave (micrometers), Laser (nanometers)

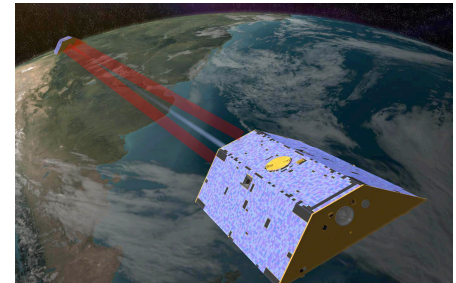
Laser Ranging Interferometer as Joint US-German instrument
2017 or early 2018 launch



The Laser Ranging Interferometer (LRI) on GRACE Follow-On

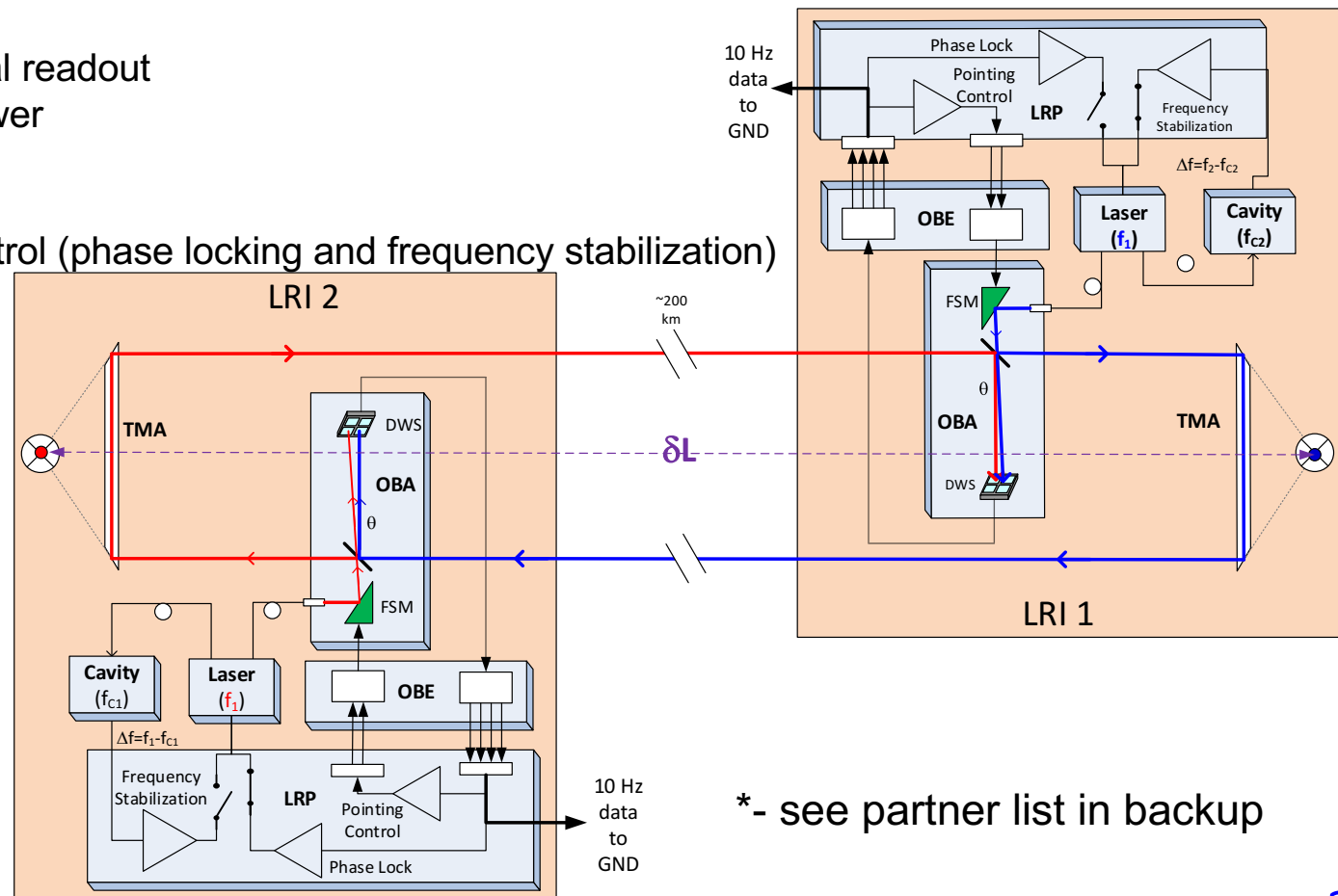
The LRI is a (highly successful) partnership between the US and Germany*

- **Joint:** Instrument Management shared between JPL and AEI
- **US (NASA/JPL):** Phasemeter, Laser, and Optical Cavity,
- **Germany (GFZ/AEI, STI, DLR):** Optical Bench, Photodetectors, Triple Mirror Assembly, Baffles



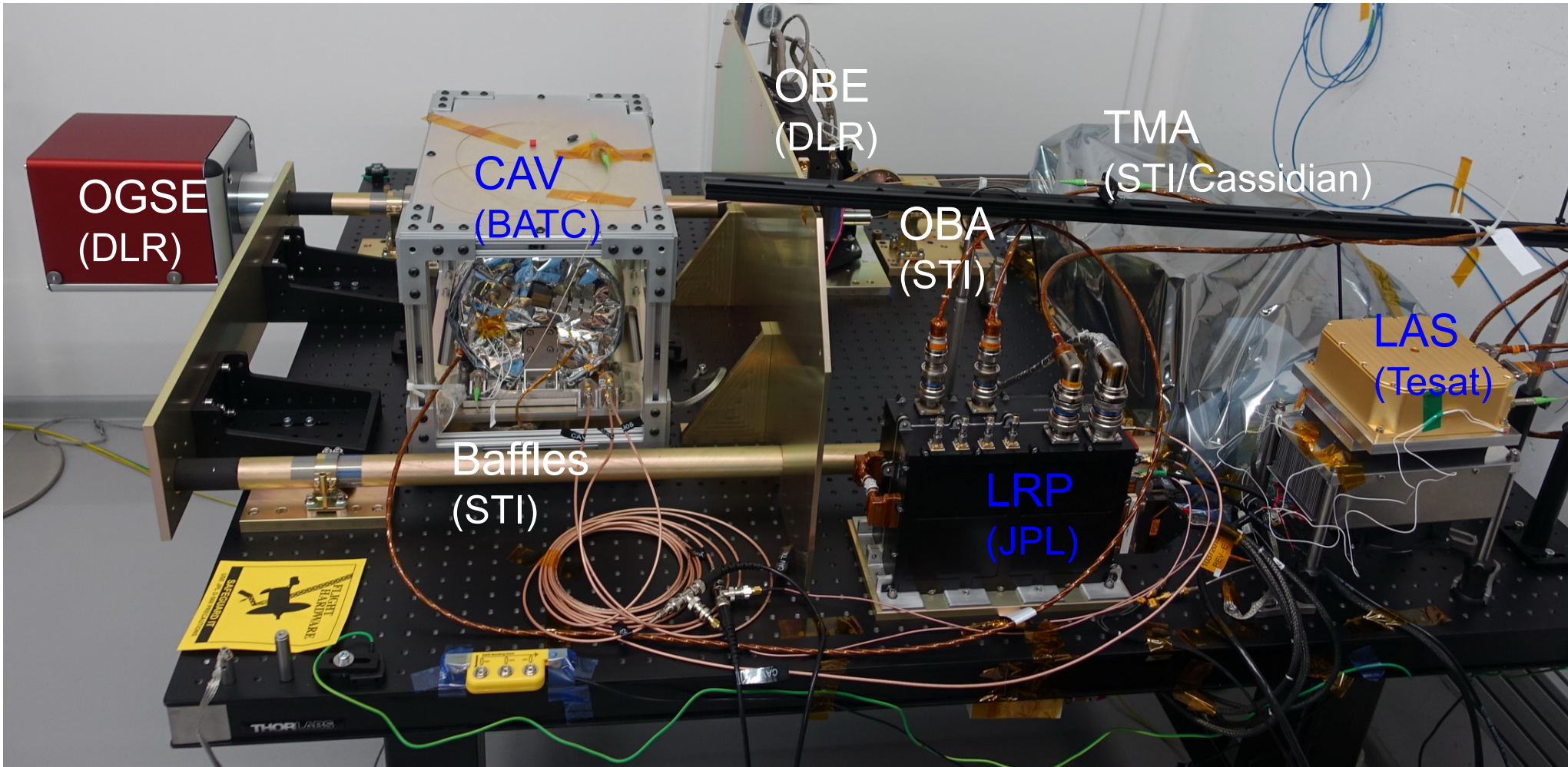
First interspacecraft laser interferometer (a different pathfinder for LISA)

- LRI Phasemeter was design based on LISA technology and capabilities
- LISA/LRI have similar
 - Phase tracking/signal readout
 - Received optical power
 - Lasers
 - Photodetectors
 - Laser frequency control (phase locking and frequency stabilization)



*- see partner list in backup

LRI Flight Hardware just prior to spacecraft integration



German
US

LRI 1 at STI

Immenstaad am
Bodensee

Comparison of the LRI and LISA

Parameter	LRI	LISA
Measurement Noise	80 nm/rtHz	20 pm/rtHz ²
<i>Shot Noise</i>	0.01 nm/Hz ^{1/2}	7 pm/Hz ^{1/2}
<i>Photoreceiver Noise (but note carrier to noise density requirement)</i>	1 nm/Hz ^{1/2}	3 pm/Hz ^{1/2}
<i>Phasemeter Noise</i>	1 nm/Hz ^{1/2}	1 pm/Hz ^{1/2}
<i>Optical Pathlength Noise</i>	30 nm/Hz ^{1/2}	3 pm/Hz ^{1/2}
<i>Laser Frequency Noise</i>	35 nm/Hz ^{1/2}	1 pm/Hz ^{1/2}
<i>USO Noise</i>	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)		
<i>Before Frequency Stabilization</i>	5000 Hz Hz ^{-1/2}	5000 Hz Hz ^{-1/2}
<i>After Frequency Stabilization</i>	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
<i>Pointing Precision</i>	1 urad/Hz ^{-1/2}	80 nrad/Hz ^{-1/2}

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:

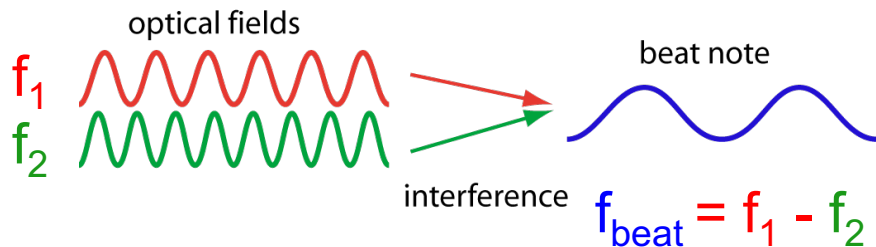
Doppler Shift and IF signal
Received optical power
Science Signal Frequency

Both LRI and LISA require:

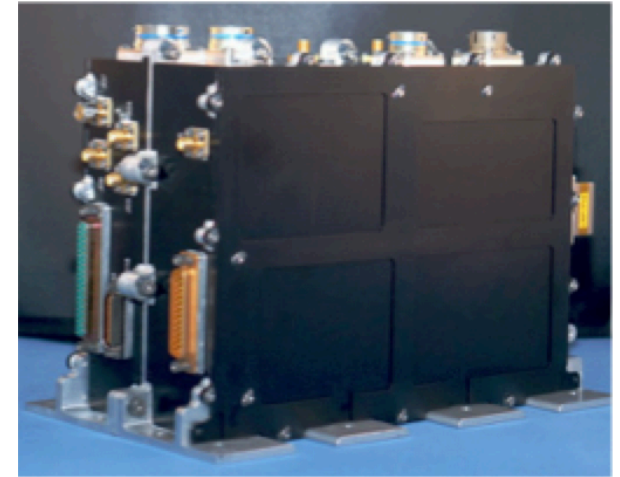
- Low light power tracking
- Differential Wave Front sensing

LRI provides a relevant technology demonstration for LISA and represents a valuable step towards LISA tech-development

LRI Flight 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

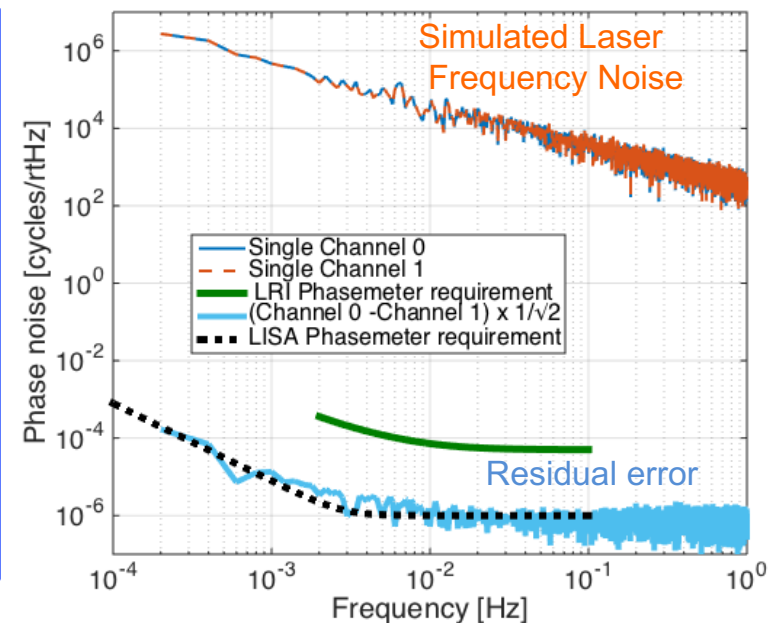
LRP developed at JPL, based on the LISA Phasemeter

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 \sim LISA performance

LRP101 Phasemeter Precision Test



All functions of the Phasemeter at TRL 4 or Flight

- The phasemeter core functionality:
 - Produces science data (interferometer readout)
 - Offset phase locks the slave laser to the received laser light
 - Stabilizes the master laser to the frequency reference (cavity)
 - Derives differential wavefront sensing signals for laser pointing
 - Measures “clock sidebands” for USO noise cancellation
 - Measures inter-spacecraft separation to 1m absolute accuracy to facilitate Time Delay Interferometry
- All above functions have been demonstrated at TRL 4/5 or above for LISA required levels.
- Blue functions have been demonstrated at TRL 9 (FLIGHT) for LRI (some performance requirements not tested to LISA levels – e.g. phase locking – due to relaxed requirements for LRI)

Note: This presentation covers the US Phasemeter efforts. See Backup for references. For updates on parallel AEI efforts see LISA-Metrology System FinalReport (2016) <http://hdl.handle.net/11858/00-001M-0000-0023-E266-6>

Time Delay Interferometry with the LISA Phasemeter (LRP in progress)

JPL LISA interferometer testbed built to demonstrate the phasemeter and measurement system performance to TRL 4.

- Currently working to test the LRP (LRI phasemeter) on the JPL LISA Interferometry testbed.

PRL 104, 211103 (2010)

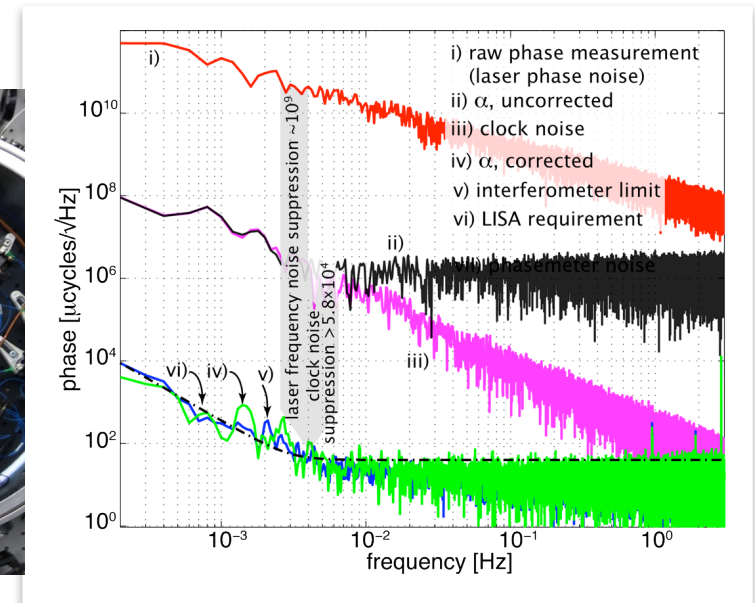
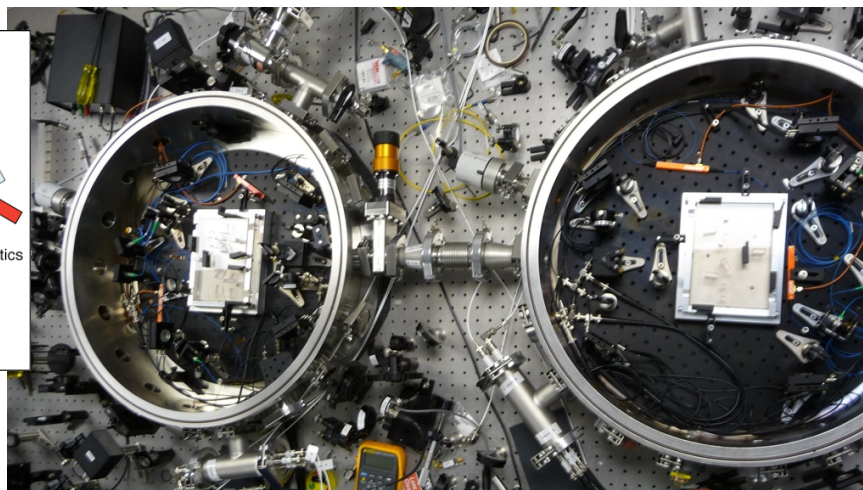
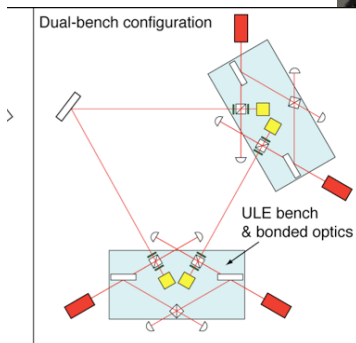
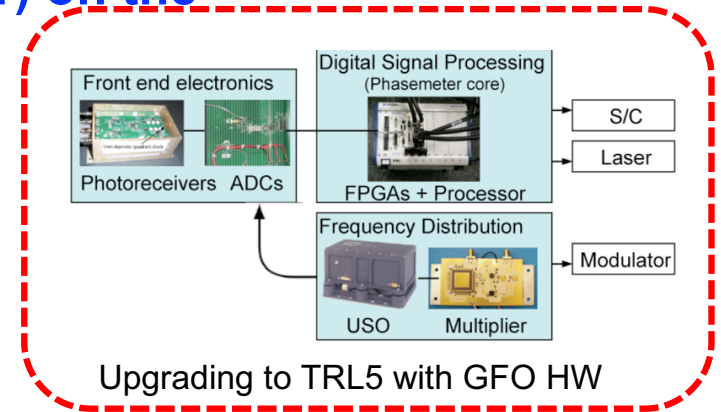
PHYSICAL REVIEW LETTERS

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)

- Retired the highest LISA phase measurement risk¹
- Frequency noise removal to interferometer displacement limit
- Clock Tone Transfer via GHz phase modulation
- Interpolation of data streams onto common time-base

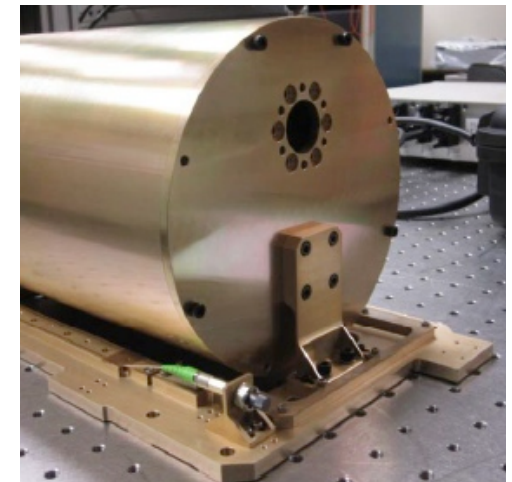
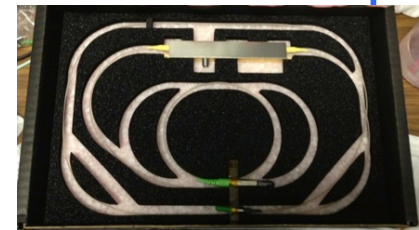
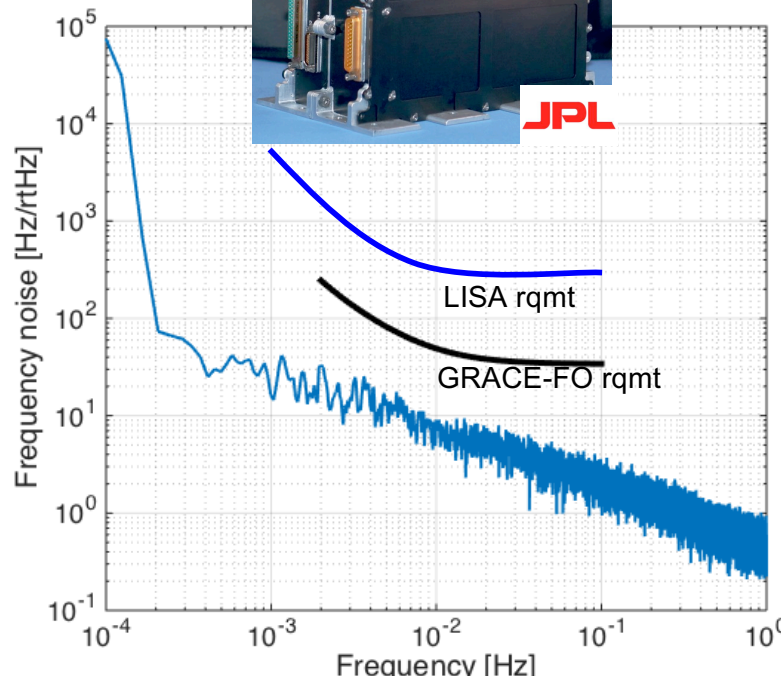
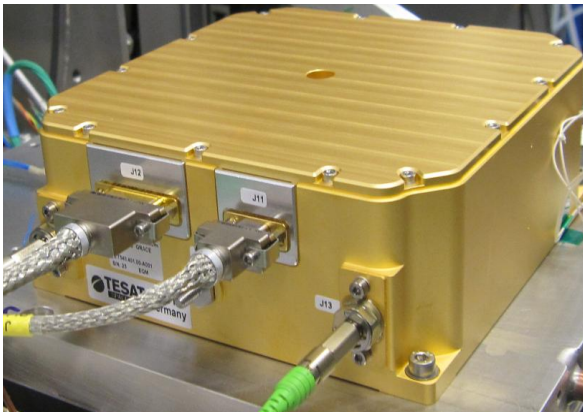


¹ NASA's LISA Technology Development Plan V 1.0 (2005)

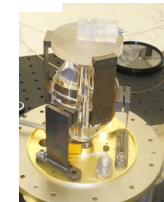
Laser Frequency Stabilization Using Flight Phasemeter with flight Cavity and flight Laser (LRI-U)

- Similar to Laser on LISA Pathfinder
 - Wavelength: 1064 nm
 - Nd:YAG Non-Planar Ring Oscillator
- Laser output power: 25 mW +/- 20%

- LRP implements laser frequency control (locks laser to cavity resonance)
 - Near mirror thermal noise stability



- Flight phasemeter controlling flight laser to flight cavity, x2

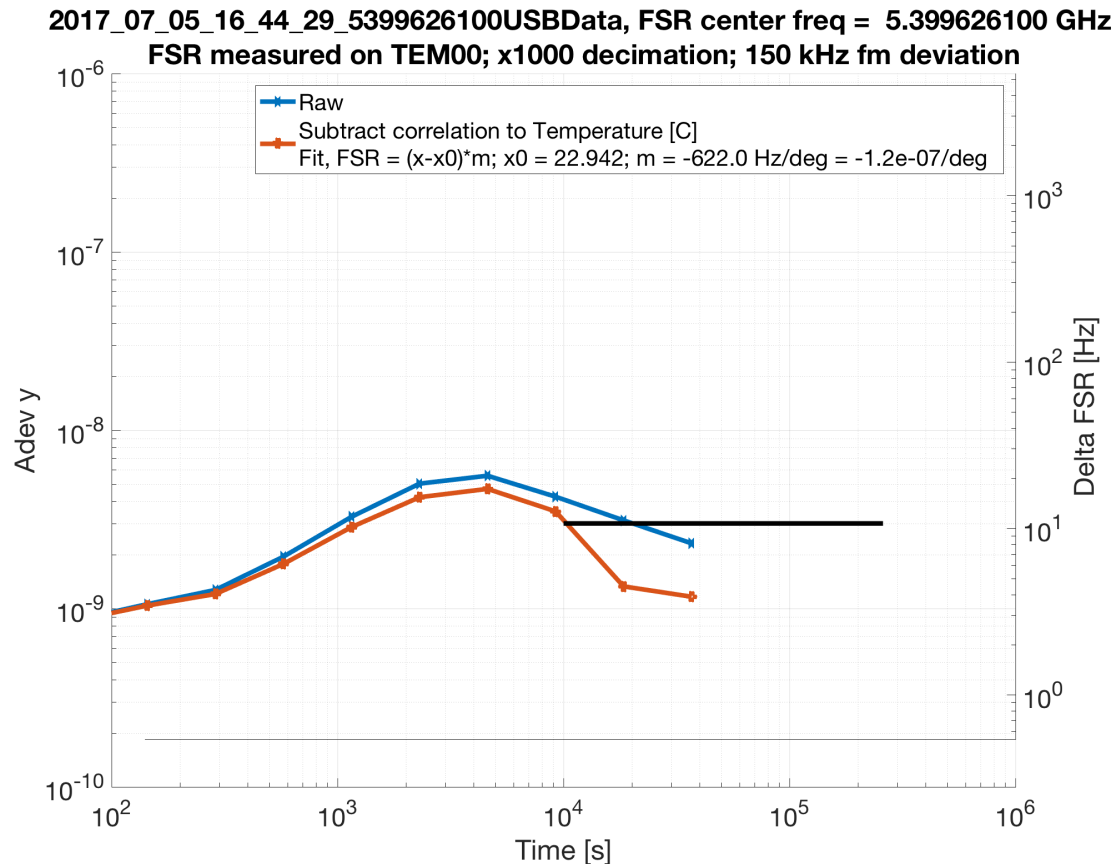


Summary

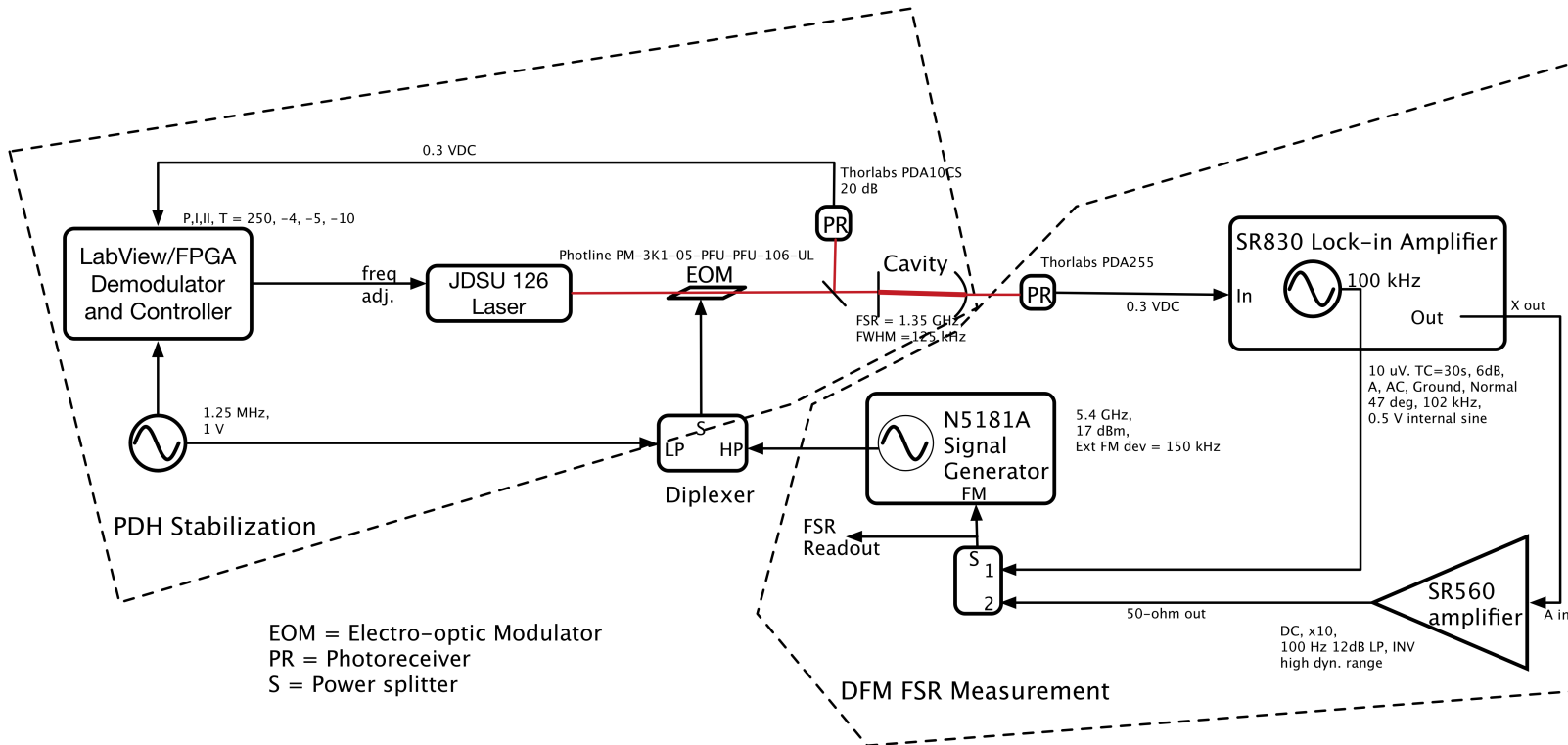
- GRACE Follow-On to launch in late 2017 or early 2018, with the first inter-spacecraft interferometer onboard, the Laser Ranging Interferometer (LRI)
- The LRI is a US-German partnership.
 - US: Phasemeter, Cavity, Laser, GSE
 - Germany: Photoreceivers, Optical Bench, Triple Mirror Assembly, Baffles, OGSE
- 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
(for US: advanced phasemeter and Optical Cavity)
- The LRI provides viable platform to test key LISA technologies in-flight (NASA-APRA grant, PI K. McKenzie)
 - Time-Delay Interferometry (see S. Francis, et al., “Tone-assisted time delay interferometry on GRACE Follow-On,” Phys. Rev. D 92, 012005 (2015))
 - Arm locking (see J. Thorpe and K McKenzie, “Arm locking with the GRACE follow-on laser ranging interferometer,” Phys. Rev. D **93**, 042003 (2016))

Post-script on calibration (1 of 3)

- Lisa's signal is strain, $h = \Delta\rho/\rho$. GRACE's signal is gradient, same as strain.
- Calibration of $\Delta\rho$ is achieved by phase-to-length conversion, i.e. laser wavelength λ .
- Experiment underway to measure λ to precision of $1 \cdot 10^{-8}$, suited for GRACE or LISA cavity stabilization.
 - Measures reference cavity frequency by adding modulation sidebands at multiple of FSR
 - Minimal hardware impact



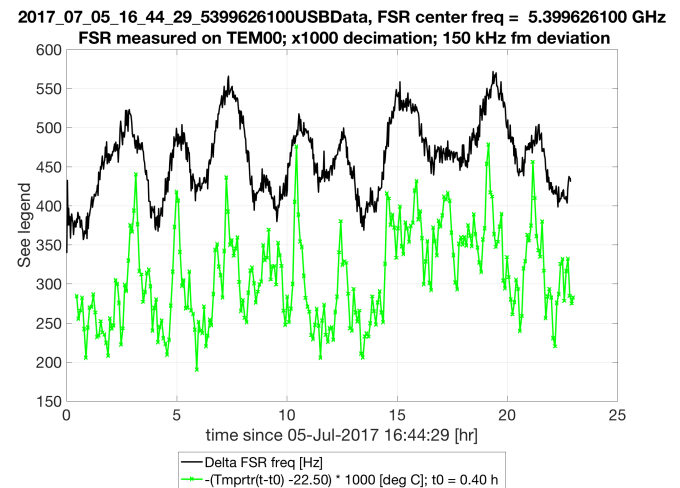
Post-script on calibration (2 of 3)



Frequency correlated to temperature at level of $\sim 1 \cdot 10^{-7} / \text{K}$.
 Candidate sources:

- Cavity alignment coupling to frequency
- Signal generator (easily correctable)
- Thermal expansion of cavity spacer (expect $3 \cdot 10^{-8} / \text{K}$)

Even without further improvement, likely adequate for GRACE 2. Easily adequate for LISA.

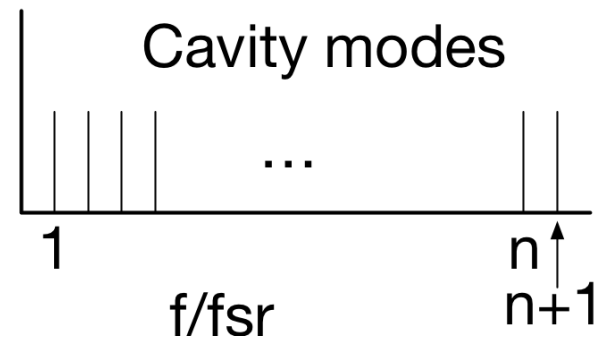
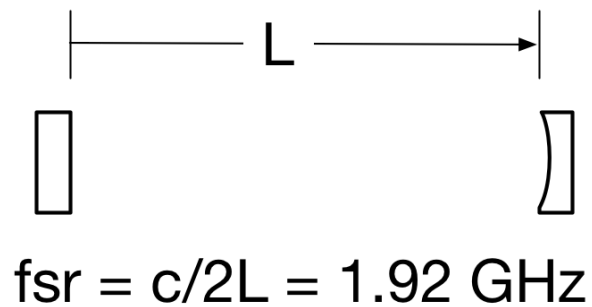


Post-script on calibration (3 of 3)

Big idea: Wavelength-independent strain measurement achievable by measuring both $\Delta\rho$ and ρ with respect to reference cavity.

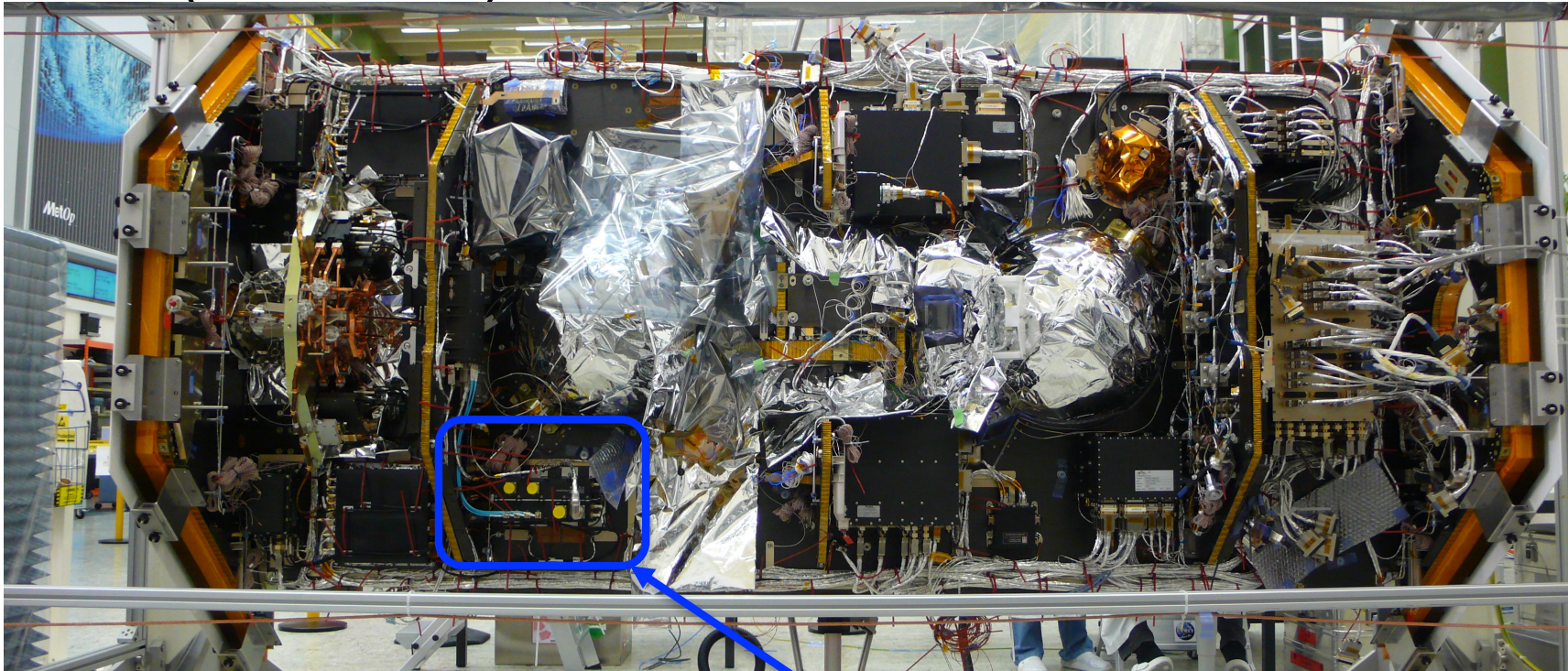
$\Delta\rho$ measured as usual, with respect to laser frequency stabilized to cavity.

ρ measured in units of cavity length L by (slowly) slewing lock point to adjacent mode and tracking accumulated round-trip phase at master spacecraft while slave spacecraft remains phase-locked.



Testable on LRI with software upload only!

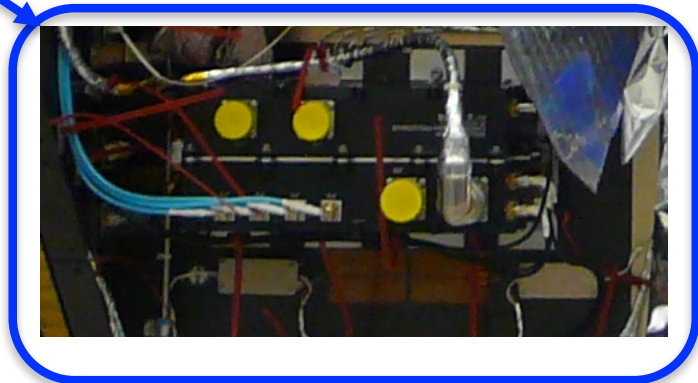
Phasemeter on the GRACE-FO Spacecraft (Airbus DS)



LRI fully mounted on FM1
During functional testing

*Photos courtesy of Airbus and JPL

LRP



GFO LRI Team



JPL

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 Martin Gohlke
 Claus Braxmaier



Apcon - OBE

Anton Lebeda
 Arnold Lebeda



LRI

Dennis Weise
 Reinhold Flatscher
 Simon Doerr

JPL LISA Interferometry References

JPL LISA interferometry contributions since 1996:

- Time Delay Interferometry¹ (1999)
- Post-processing interpolation TDI² – TDI made practical on a spacecraft (2003)
- Development of Arm locking^{3,4} - Use LISA arms as frequency reference
- Velocity-correcting Time Delay Interferometry⁵ (2004)
- Demonstration of clock noise suppression⁶
- LISA Phasemeter TRL 4 Technical Report¹³
- First experimental demonstration of TDI⁷ (2008)
- Invention of picometer phasemeter (US 7,511,469)
- Optical ranging to absolute accuracy to 0.2m rms⁸
- Optical Communications on the laser link (20 kbps)⁸

GRACE Follow-On LRI⁹ (2012)

- Design of LISA TDI experiment for GRACE Follow-On LRI¹⁰
- Design of LISA Arm Locking experiment for GRACE Follow-On LRI¹¹
- Developed Flight Cavity¹²

1 J. W. Armstrong, F. B. Estabrook, and M. Tinto, ApJ 527 814 (1999)

2 D. A. Shaddock, B. Ware, R. E. Spero, M. Valisineri PRD (2004)

3 B. S. Sheard, M. B. Gray, D. E. McClelland, and D. A. Shaddock, Phys. Lett. A 320, 9 (2003).

4 K. McKenzie, R. E. Spero, and D. A. Shaddock, Phys. Rev. D 80 102003 (2009)

5 D.A. Shaddock et al PRD (2003)

6 W. Klipstein et al., AIP Conf. Ser. No. 873 (2006)

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

8 A. Sutton, K. McKenzie, B. Ware, and D. A. Shaddock OE (2010)

9 B. Sheard, G. Heinzel et al *Journal of Geodesy* . doi:10.1007/s00190-012-0566-3. (2012)

10 S. P. Francis, D. A. Shaddock, A. J. Sutton, et al Phys. Rev. D 92, 012005 (2015)

11 J. I. Thorpe, K. McKenzie accepted PRD 2016

12 W. M. Folkner, G. deVine, W. M. Klipstein, et al Earth Science Tech. Forum, (2010).

13. D.S. Shaddock, B. Ware, R. Spero. W. Klipstein, LIMAS2007-002, LISA Project document (2007, updated 2009)