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

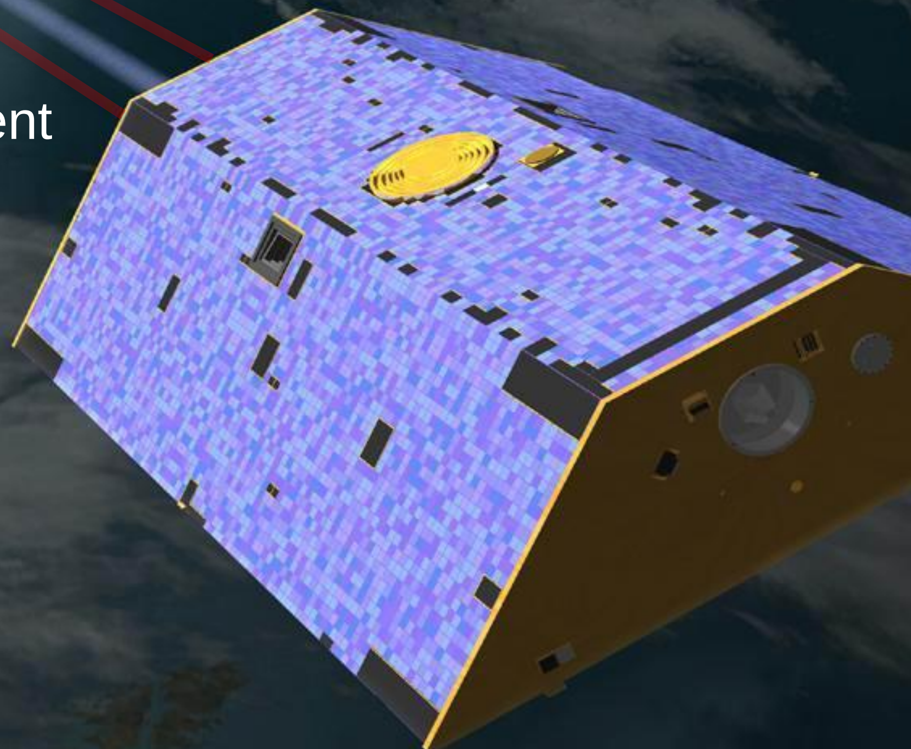
An inter-spacecraft laser interferometry technology demonstrator with similarities to LISA

Robert Spero for the LRI Team
NASA's Jet Propulsion Laboratory,
California Institute of Technology

GRACE-FO

LRI Management

LRI implementation



Amaldi 12, 13 July 2017

Gravity-Sensing: Precision Phase Measurement Instruments in Space

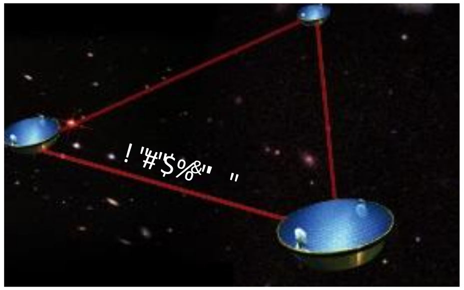
Microwave Instrument ~ Micrometer Precision

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

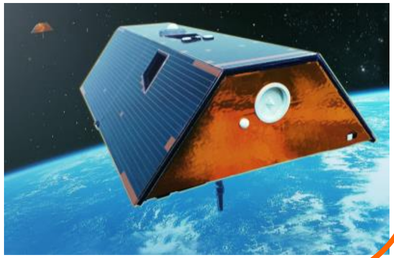
Gravity Recovery and Interior Laboratory (GRAIL),
Planetary science, microwave measurements (micrometers)
Sept 10, 2011 – Dec 17, 2012

Laser Instrument ~ Nanometer to Picometer Precision

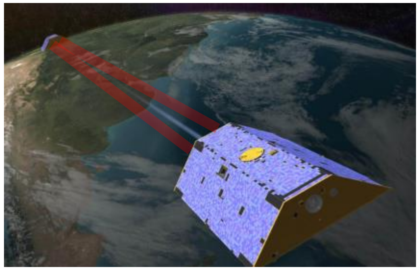
Laser Interferometer Space Antenna (LISA)
Astrophysics, (picometers)
-> ESA Cosmic Visions L3 (2034)



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

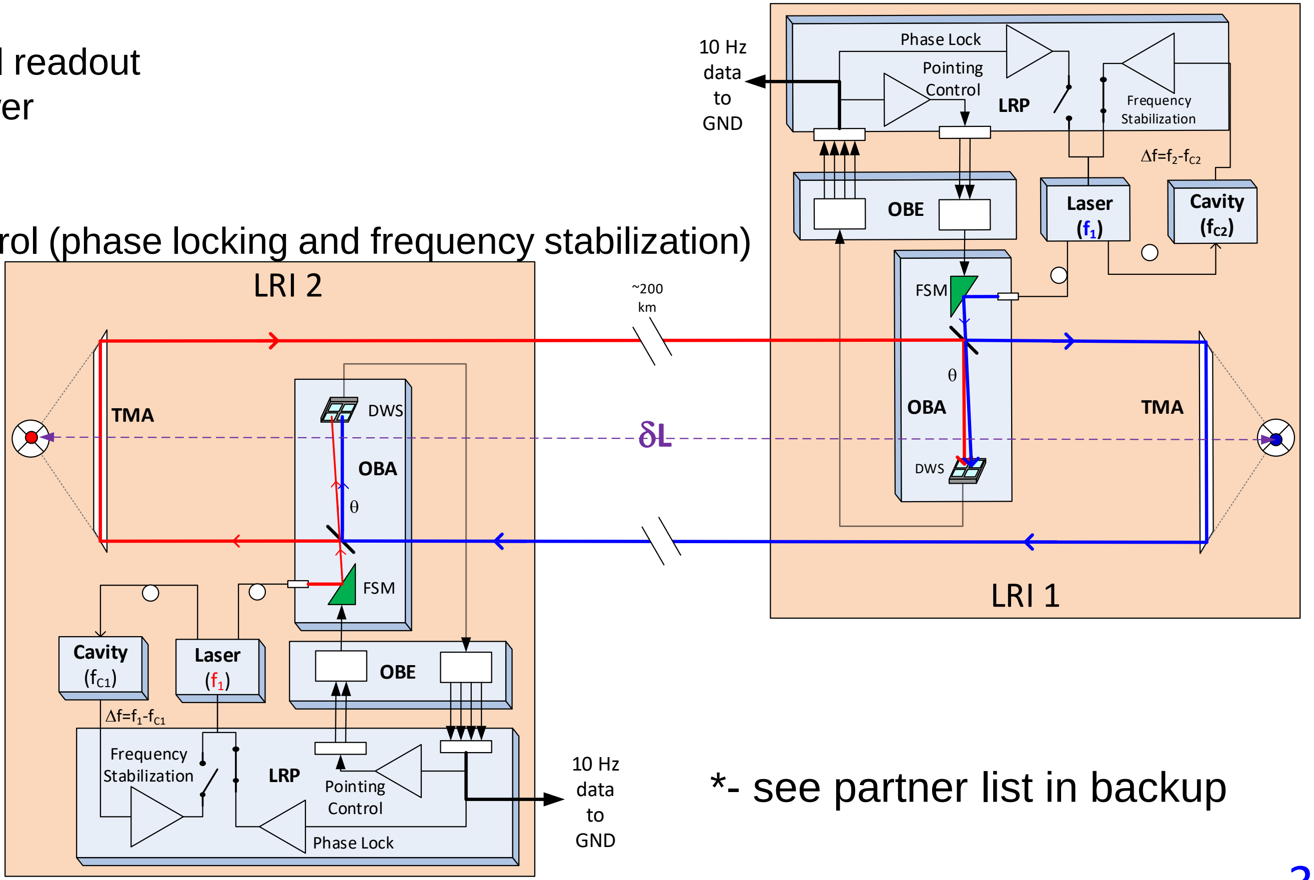


The LRI is a (highly successful) partnership between the US and Germany*

- **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

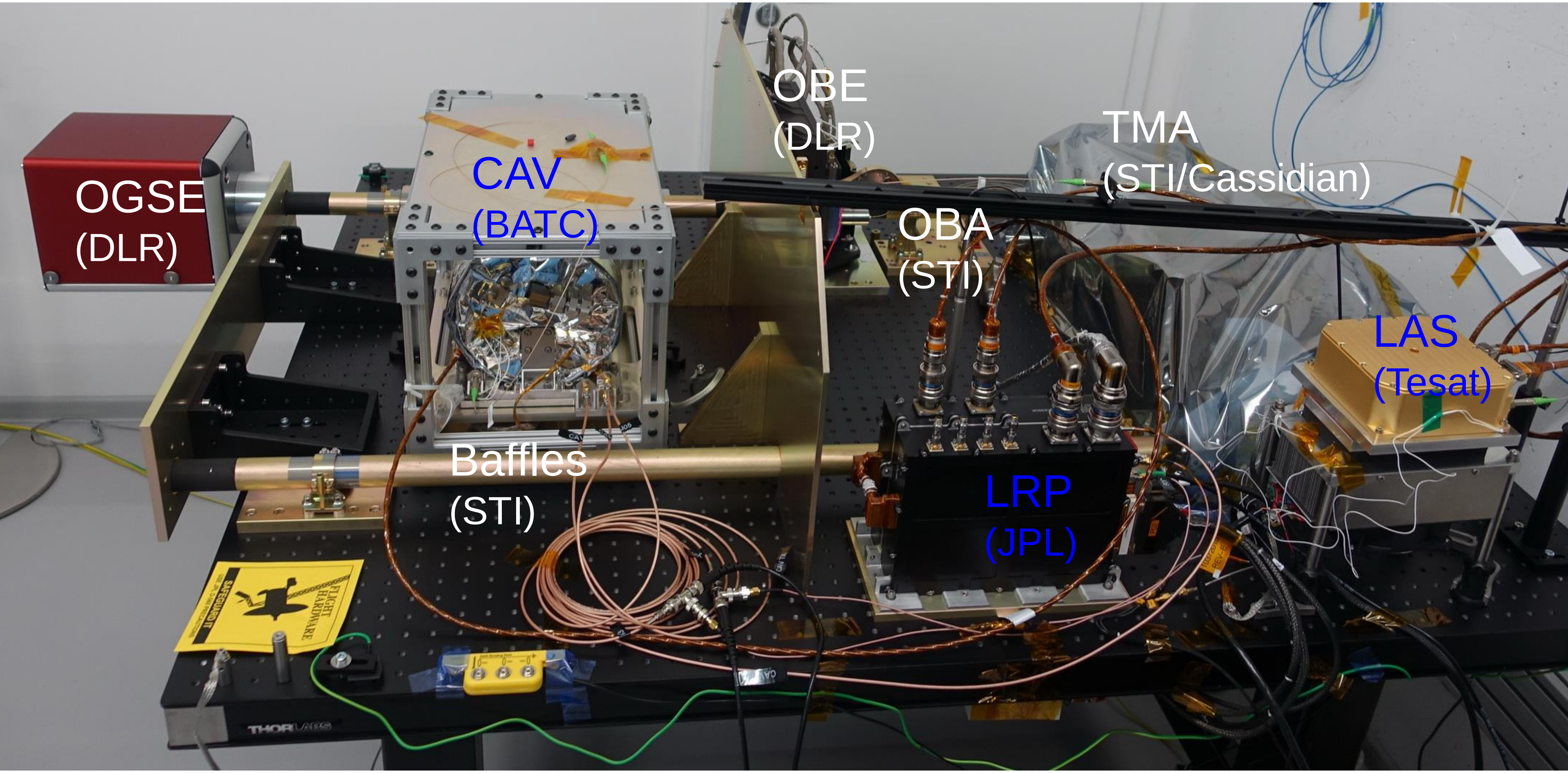
First interspacecraft laser interferometer (a different pathfinder for LISA)

- 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
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:

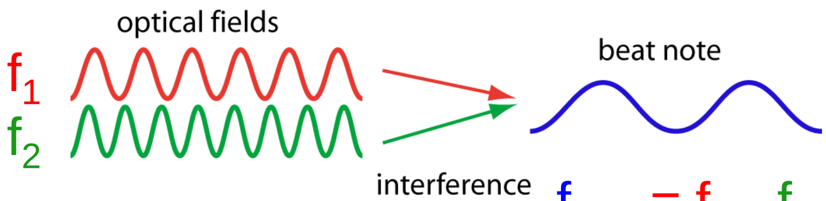
Doppler Shift and IF signal
Received optical power
Science Signal Frequency

Both LRI and LISA require:

- Low light power tracking
- Differential Wave Front sensing

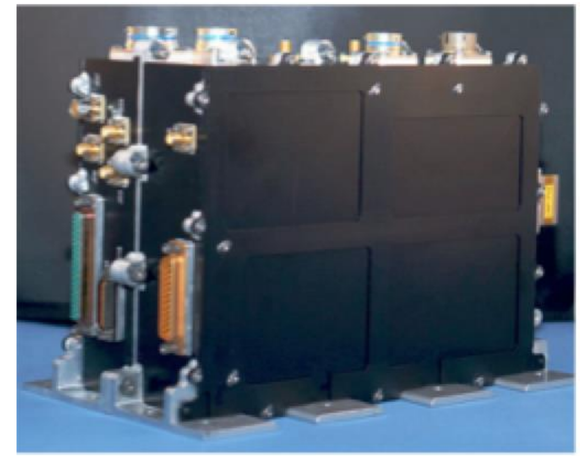
LRI provides a relevant technology demonstration for LISA and represents a valuable step towards LISA tech-development

LRI Flight Phasemeter aka Laser Ranging Processor (LRP)



$f_{beat} = f_1 - f_2$

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



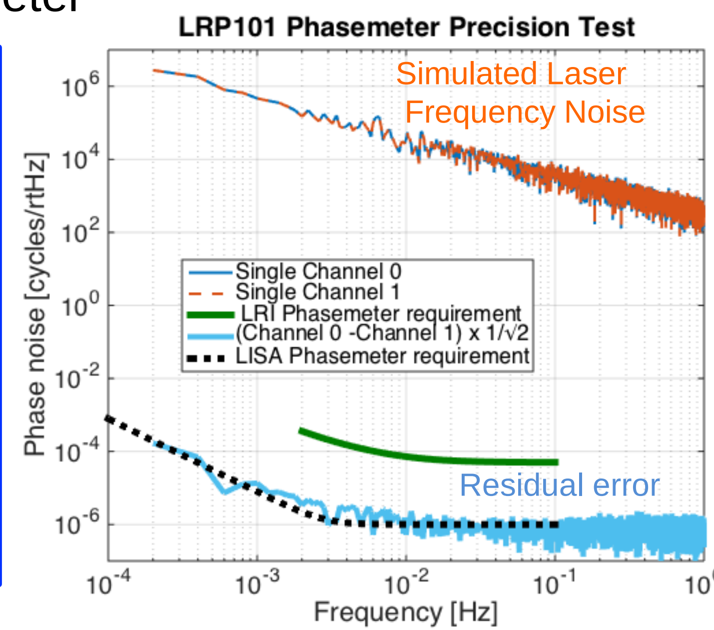
LRI Flight model Phasemeter

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



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

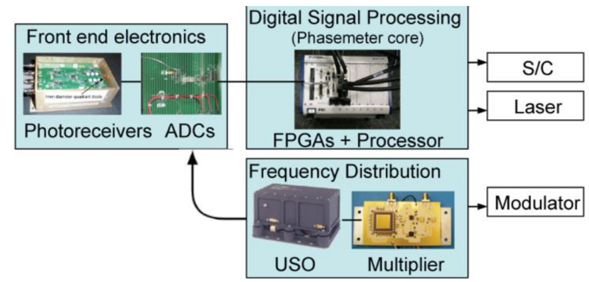
- *All* above functions have been demonstrated at TRL 4/5 or above for LISA required levels.
- Blue functions have been demonstrated at TRL 9 (FLIGHT) for LRI (some performance requirements not tested to LISA levels – e.g. phase locking – due to relaxed requirements for LRI)

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.



Upgrading to TRL5 with GFO HW

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

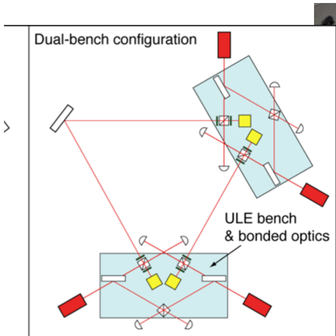
Experimental Demonstration of Time-Delay Interferometry for the Laser Interferometer Space Antenna

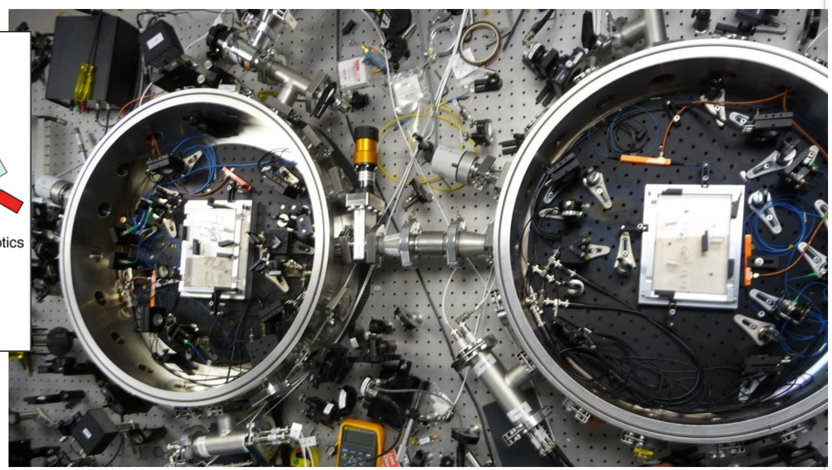
Glenn de Vine,* Brent Ware, Kirk McKenzie, Robert E. Spero, William M. Klipstein, and Daniel A. Shaddock†

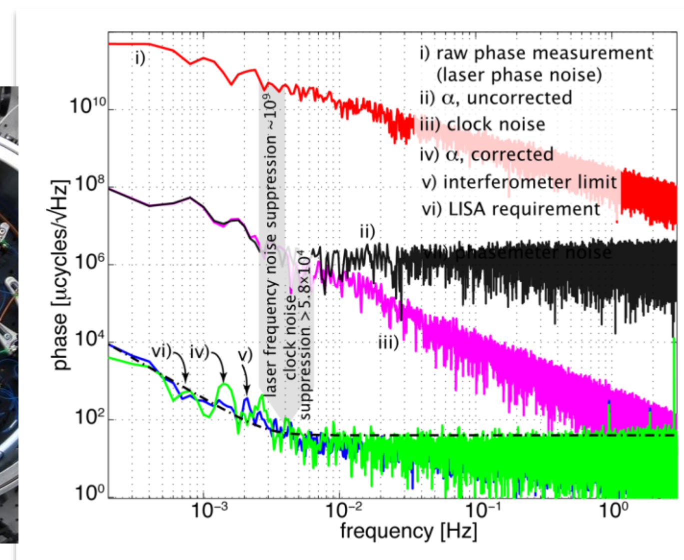
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA

(Received 1 April 2010; published 27 May 2010)

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



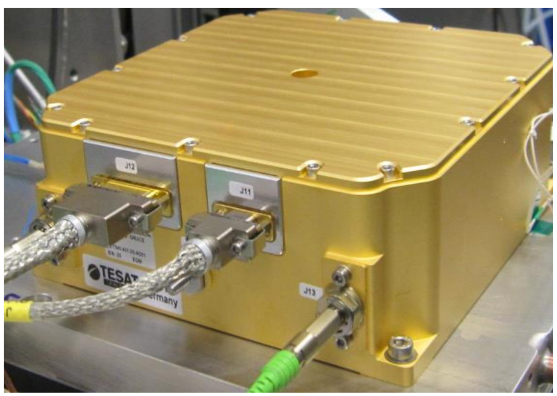




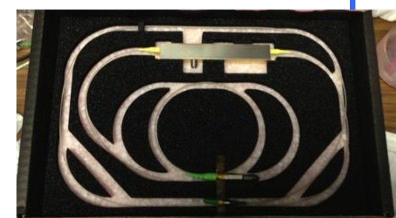
[1] NASA's LISA Technology Development Plan V 1.0 (2005)

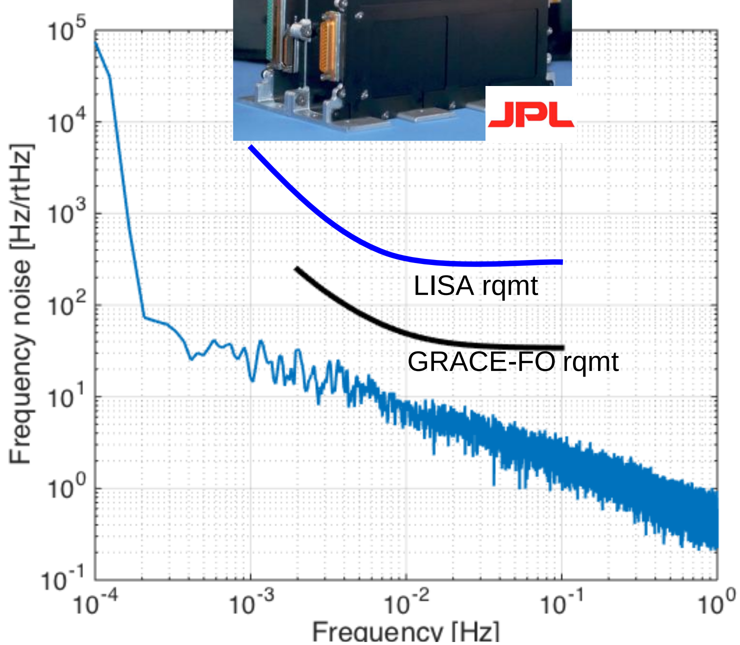
Laser Frequency Stabilization Using Flight Phasemeter with flight Cavity and flight Laser (LRI-U)

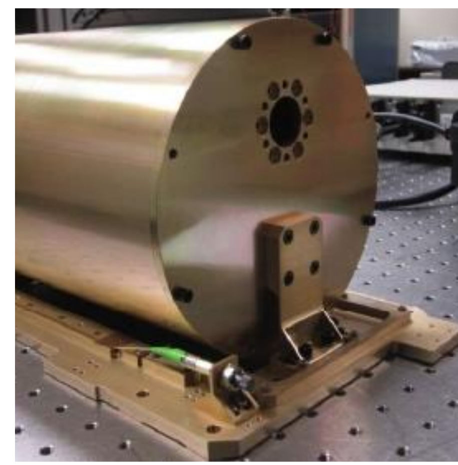
- Similar to Laser on LISA Pathfinder
  - Wavelength: 1064 nm
  - Nd:YAG Non-Planar Ring Oscillator
- Laser output power: 25 mW +/- 20%



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

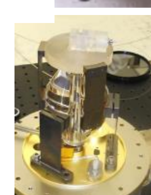






TESAT SPACECOM

- Flight phasemeter controlling flight laser to flight cavity, x2



Ball

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

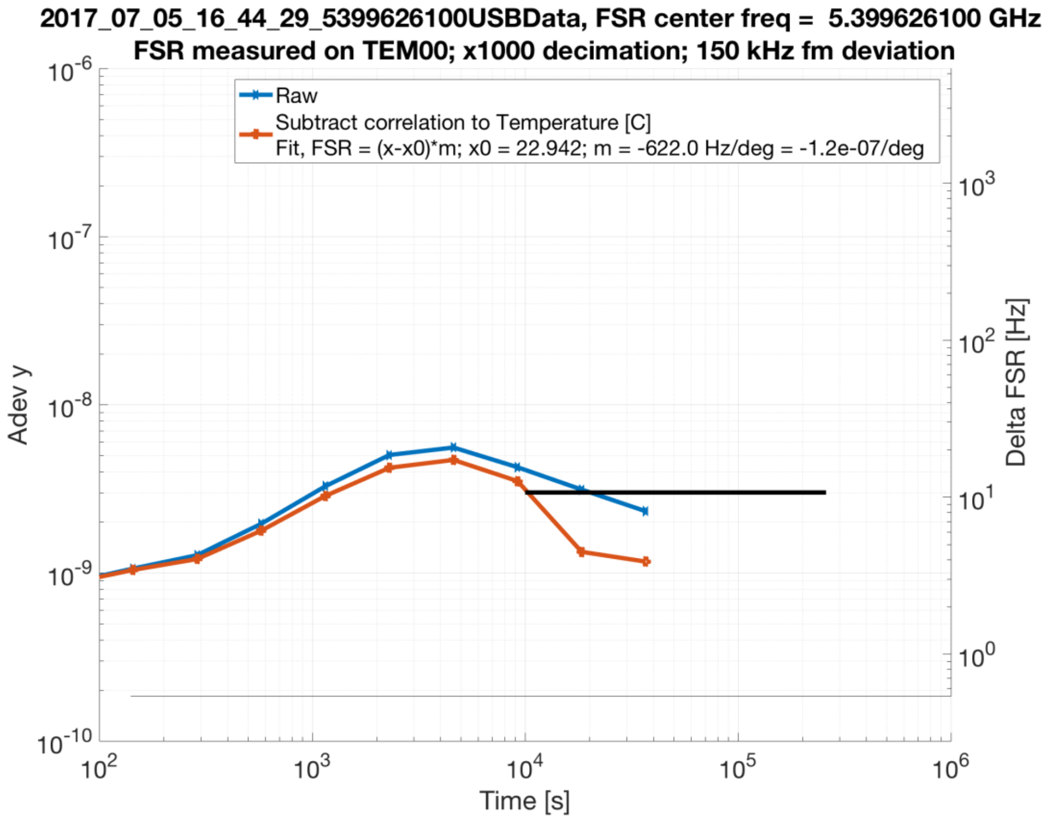
- Instrument design and many technology elements from LISA development

- 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)

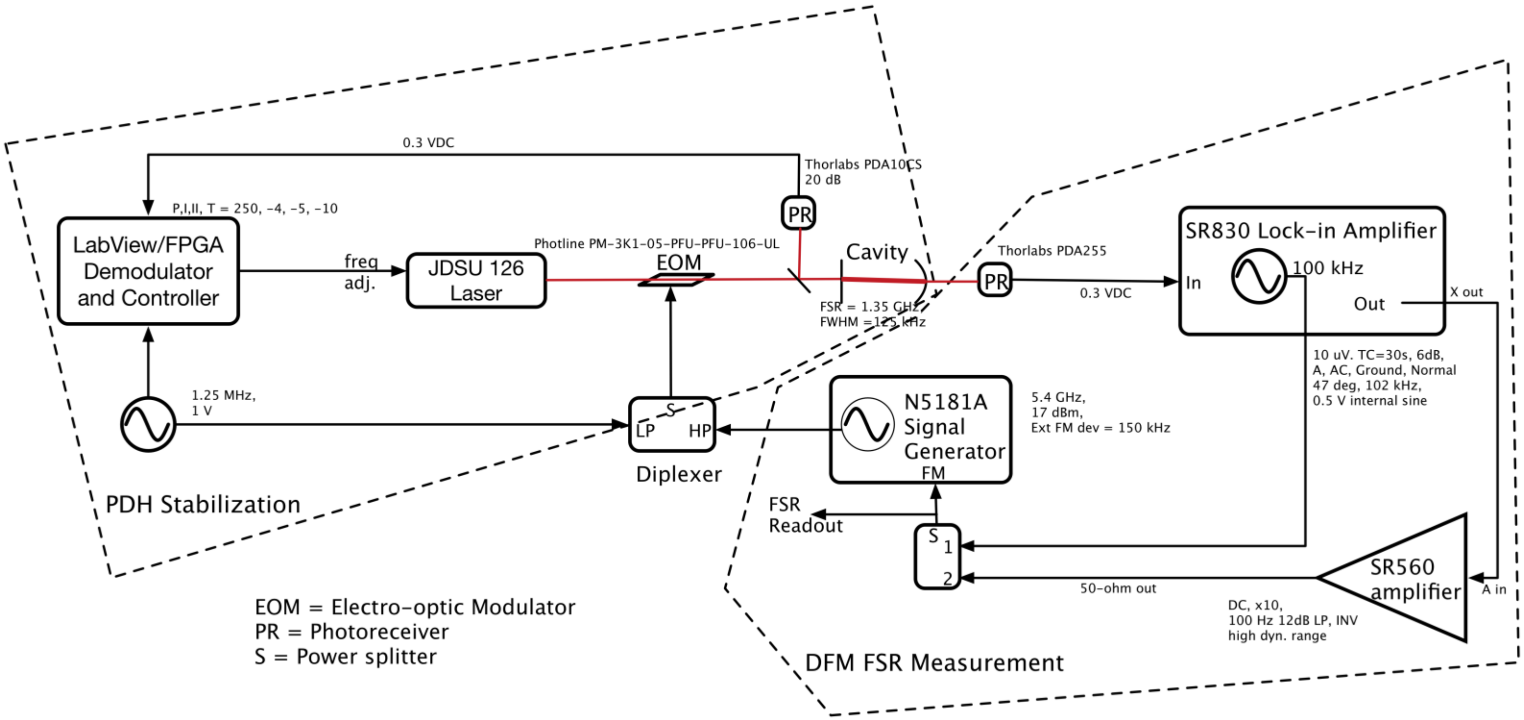
- The LRI provides viable platform to test key LISA technologies in-flight (NASA-APRA grant, PI K. McKenzie)
  - Time-Delay Interferometry (see S. Francis, et al., “Tone-assisted time delay interferometry on GRACE Follow-On,” Phys. Rev. D 92, 012005 (2015)
  - Arm locking (see J. Thorpe and K McKenzie, “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



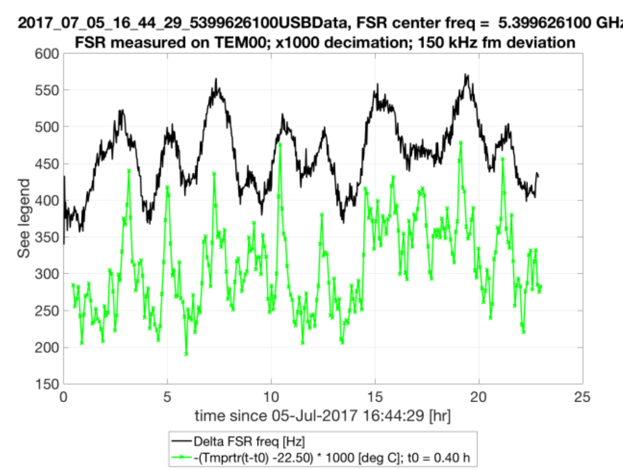
Post-script on calibration (2 of 3)



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

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

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

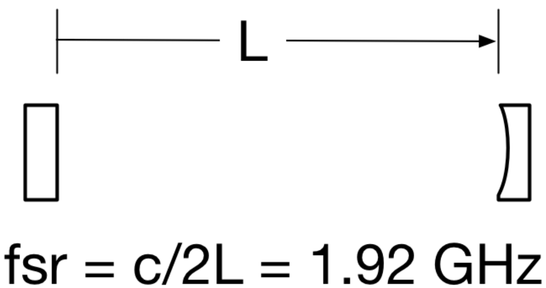


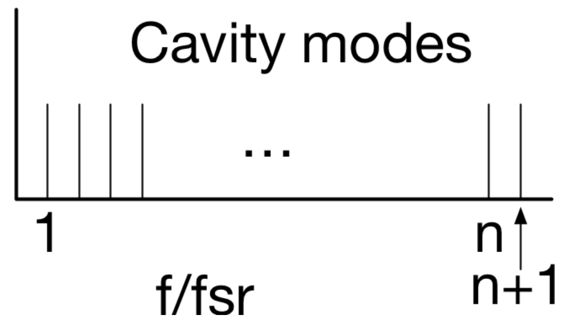
Post-script on calibration (3 of 3)

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.

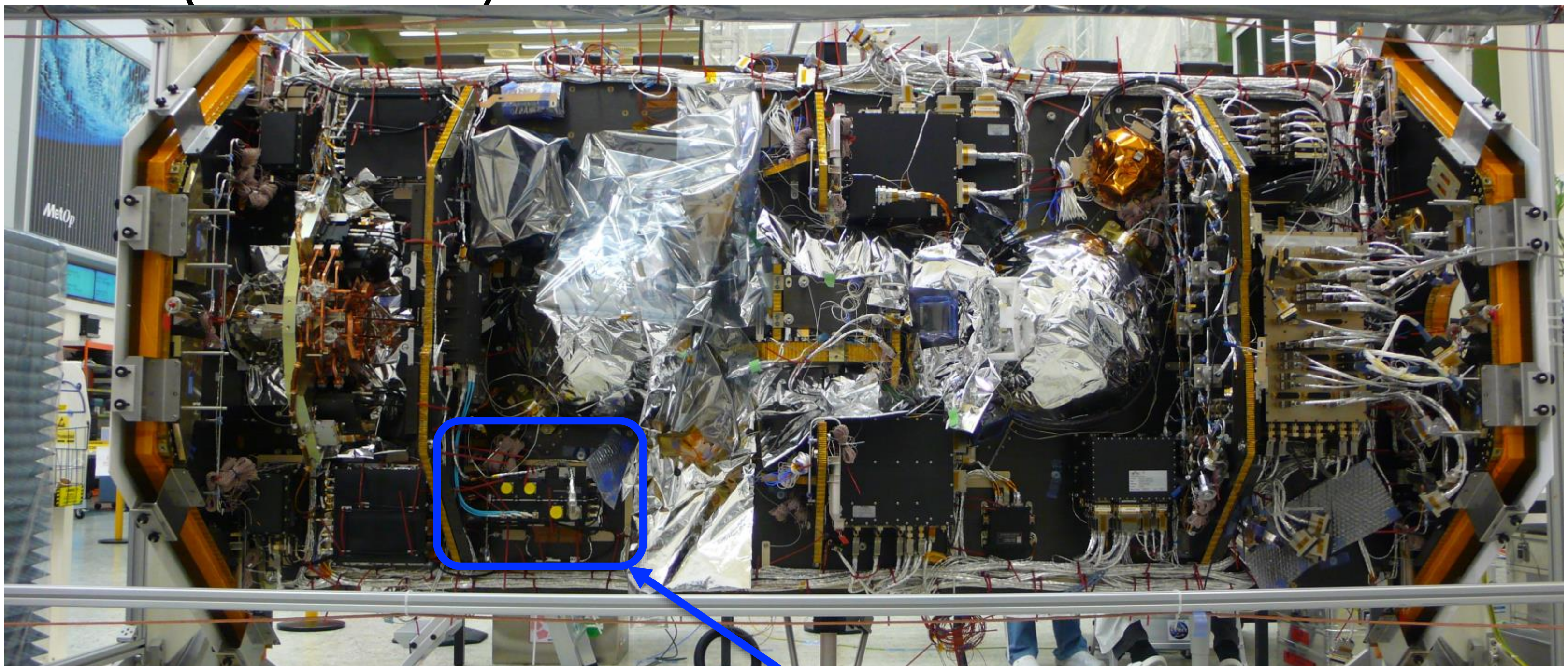
ρ measured in units of cavity length L by (slowly) slewing lock point to adjacent mode and tracking accumulated round-trip phase at master spacecraft while slave spacecraft remains phase-locked.





Testable on LRI with software upload only!

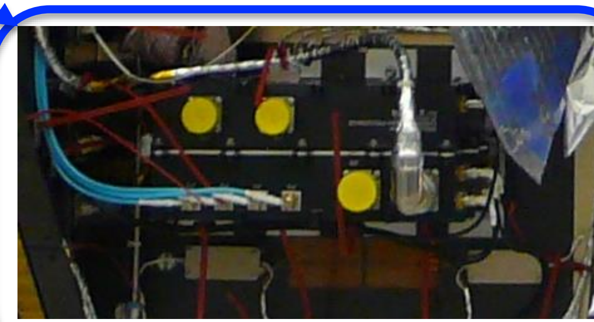
Phasemeter on the GRACE-FO Spacecraft (Airbus DS)



*Photos courtesy of Airbus and JPL

LRI fully mounted on FM1
During functional testing

LRP



GFO LRI Team

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

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

ANU
Daniel Shaddock
Roland
Fleddermann
Robert Ward
Danielle Wuchenich

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

Cassidian - TMA
Georg Luichtel
Roswitha Keppeler
Malte Schwarzer
Martin Hinz
Marcus Zimmermann
Gerhard Dersch
Gerhard Reile

DLR - QPR
Andreas Eckardt
Thomas Mangoldt
Bernd Zender
Burkhardt Guenther
Thomas Lieder
Josep Sanjuan
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 Interferometry[1] (1999)
- Post-processing interpolation TDI[2] – TDI made practical on a spacecraft (2003)
- Development of Arm locking[3,4] - Use LISA arms as frequency reference
- Velocity-correcting Time Delay Interferometry[5] (2004)
- Demonstration of clock noise suppression[6]
- LISA Phasemeter TRL 4 Technical Report[13]
- First experimental demonstration of TDI[7] (2008)
- Invention of picometer phasemeter (US 7,511,469)
- Optical ranging to absolute accuracy to 0.2m rms[8]
- Optical Communications on the laser link (20 kbps)[8]

GRACE Follow-On LRI[9] (2012)

- Design of LISA TDI experiment for GRACE Follow-On LRI[10]
- Design of LISA Arm Locking experiment for GRACE Follow-On LRI[11]
- Developed Flight Cavity [12]

1 J. W. Armstrong, F. B. Estabrook, and M. Tinto, ApJ 527 814 (1999)
2 D. A. Shaddock, B. Ware, RE Spero, M Valisineri PRD (2004)
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4 K. McKenzie, R. E. Spero, and D. A. Shaddock, Phys. Rev. D 80 102003 (2009)
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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).
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