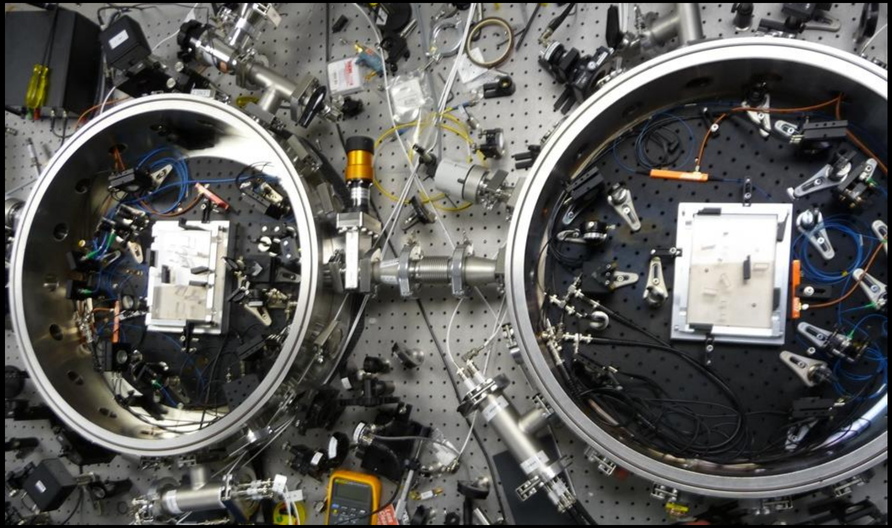
Phasemeter development for LISA at JPL

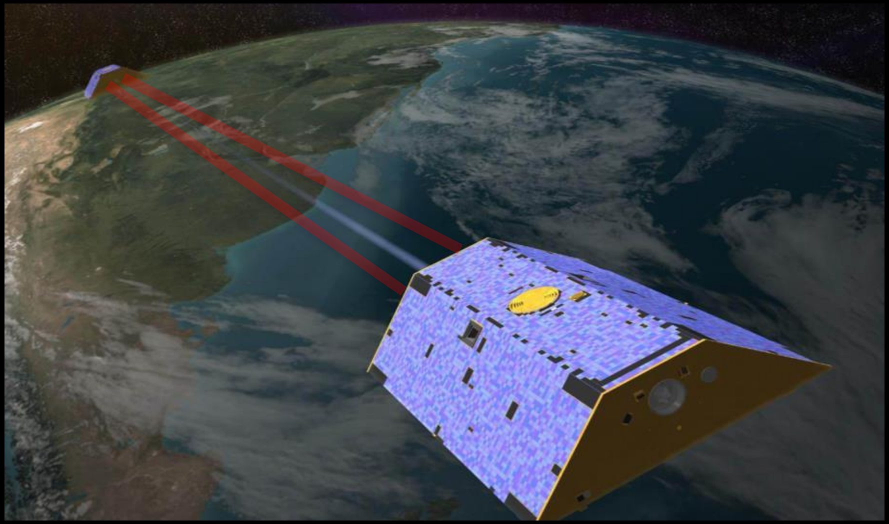
Jet Propulsion Laboratory
California Institute of Technology

Bill Klipstein, Kirk McKenzie
Brian Bachman, Jeff Dickson, Bob Spero, Brent Ware, Chris Woodruff

JPL LISA Interferometry Test bed
Built to prove the LISA Phasemeter



LISA (-lite) Phasemeter delivered as part of the
GRACE Follow-On Laser-Ranging Interferometer



Gravity-Sensing Instruments in Space

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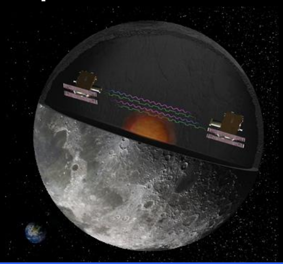
Microwave Instrument ~ Micrometer Precision

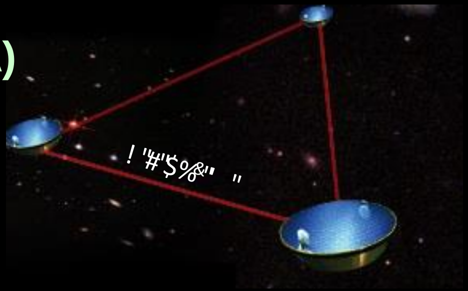
Gravity Recovery and Climate Experiment (GRACE),
Earth Science, microwave measurements (micrometers)
2002-present.



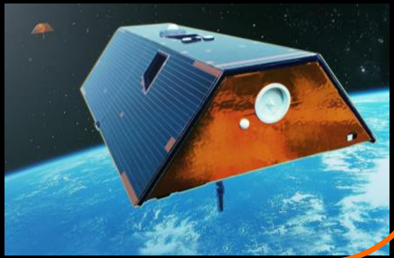
Gravity Recovery and Interior Laboratory (GRAIL),
Planetary science, microwave measurements (micrometers)
Sept 10, 2011 – Dec 17, 2012

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
Aug, 2017 launch



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

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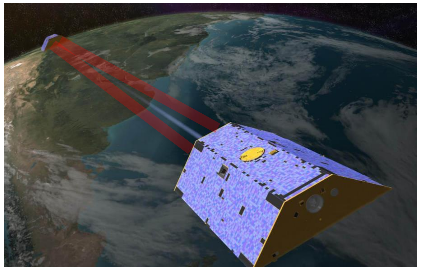
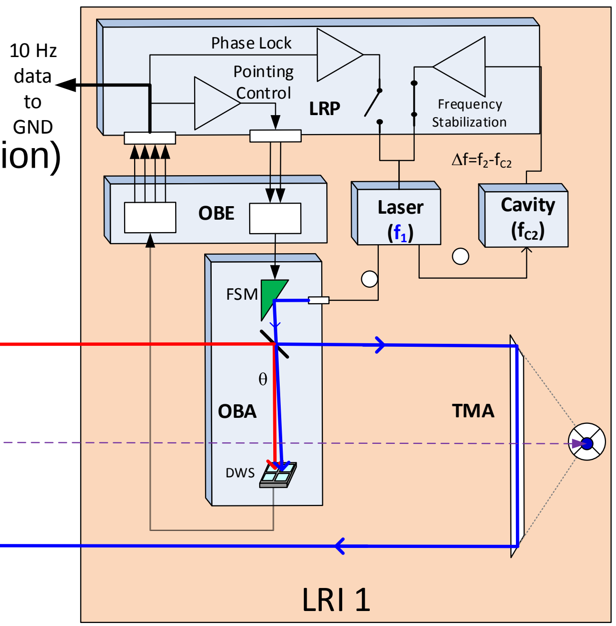
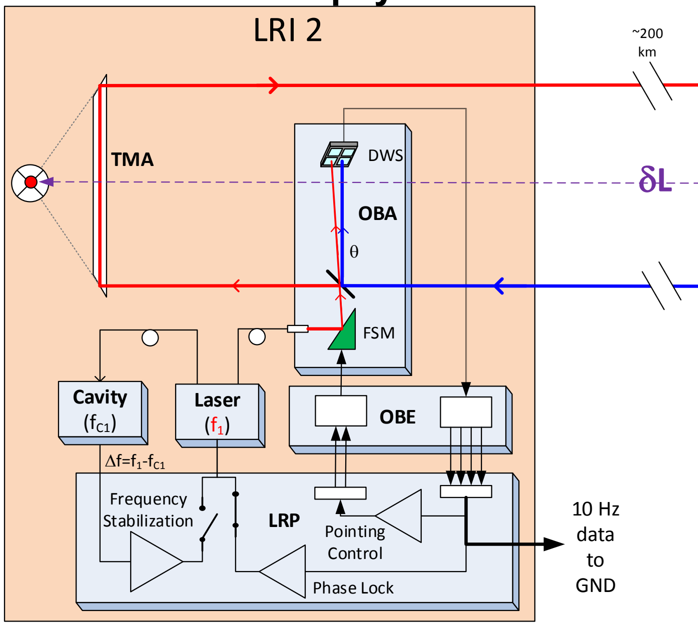
The LRI is a (highly successful) partnership between the US and Germany*



- US (NASA/JPL): Phasemeter, Laser, and Optical Cavity,
  Germany (AEI, DLR, STI: Optical Bench, Photodetectors, Triple Mirror Assembly, Baffles
- 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)

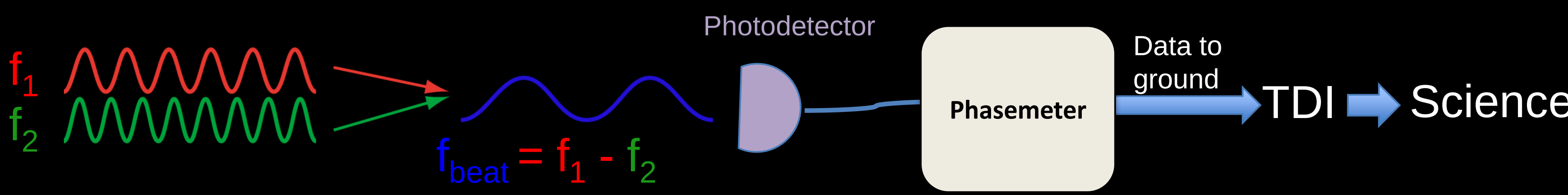
The Phasemeter has natural interfaces to Partner's payload elements





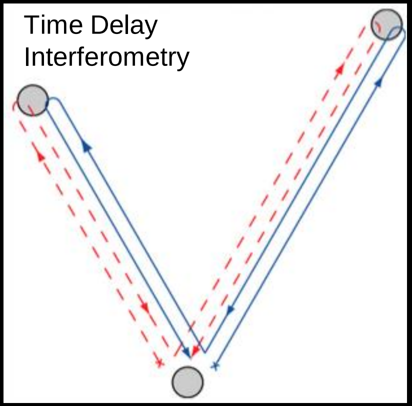
*- see partner list on last slide

Basics of LISA Interferometry



- LISA optical beat note ranges from 2 MHz - 20 MHz due to Doppler shift from spacecraft velocity.
- One wavelength shift in one optical field produces a one cycle shift in the beat note.
- The phasemeter measures the science signal as a milliHertz phase modulation on a megahertz beat signal.

- LISA has uneven arm lengths – *Time Delay Interferometry (TDI)* needed to synthesis a equal arm length interferometer
  - Phasemeter tracks “noisy” beatnotes and sends data to ground.
  - Algorithm of delayed phasemeter signal enables cancellation of laser frequency noise (common to both interferometer arms) leaving gravitational wave signal (differential signal).



All functions of the Phasemeter at TRL 4 or Flight

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- 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)

“Phasemeter” Naming of parts

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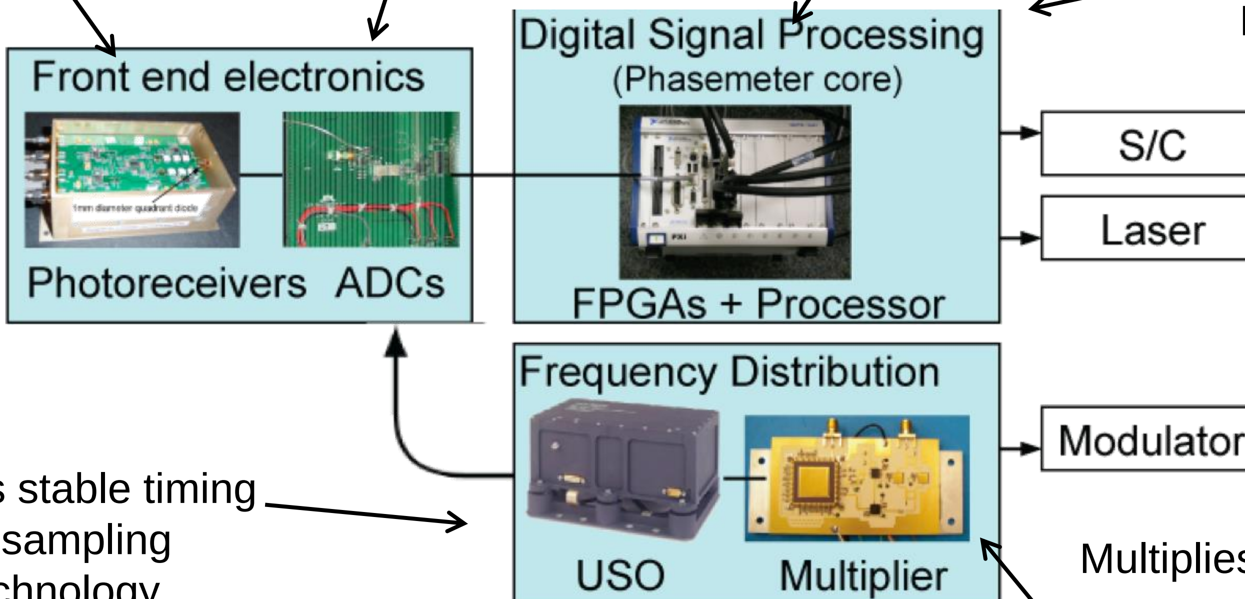
Quadrant photoreceiver converts laser beat note into electrical signal
TRL: 4/5 (LISA)
FLIGHT (LRI)

Amplifies and digitizes analog signal
TRL: 4 (LISA)
FLIGHT (LRI)

HEART OF THE PHASEMETER:
Digital phasemeter measures phase, controls laser frequency, and generates timing/ranging signals: approaching TRL 5/6
FLIGHT (LRI)

Processor back-end: TRL 4 (LISA)
FLIGHT (LRI)



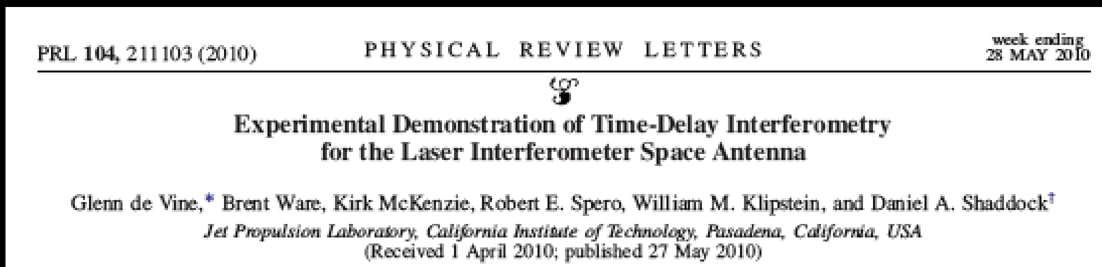
Provides stable timing for ADC sampling
Not a technology development required
FLIGHT (GRAIL)

Multiplies USO signal to programmable value to drive laser phase modulator:
FLIGHT (GRAIL heritage)

Performance in LISA interferometer testbed demonstrates system at TRL 4

Time Delay Interferometry with the LISA Phasemeter

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

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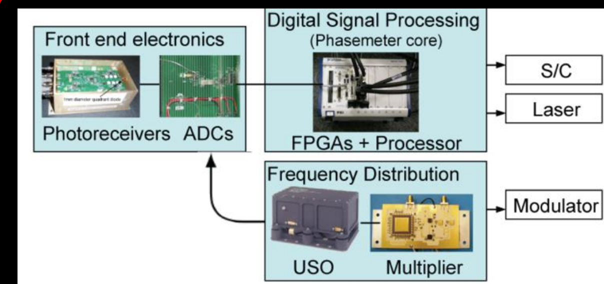
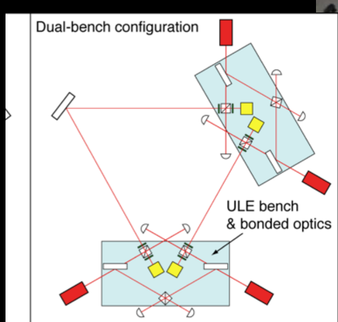
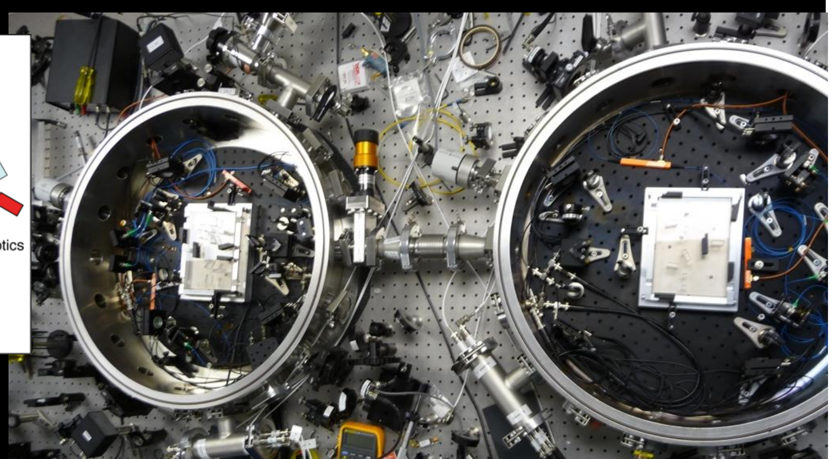
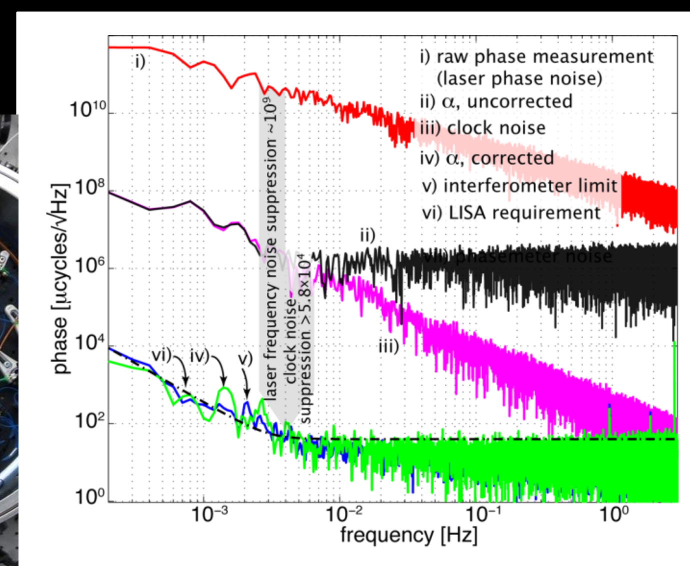


- Retired the highest LISA phase measurement risk[1]
- Frequency noise removal to interferometer displacement limit
- Clock Tone Transfer via GHz phase modulation
- Interpolation of data streams onto common time-base







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

JPL LISA Interferometry Contributions

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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]
- 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]
- Track very low light power (<3pW)
- Design of the GRACE Follow-On LRI[9] (2012)
- Differential Wavefront Sensing Demonstrated
- Interferometer system engineering (US Co-Chair of Interferometry ITAT)
- 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]
- LISA Phasemeter on LRI

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)
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).

LRI Phasemeter is LISA-lite Phasemeter

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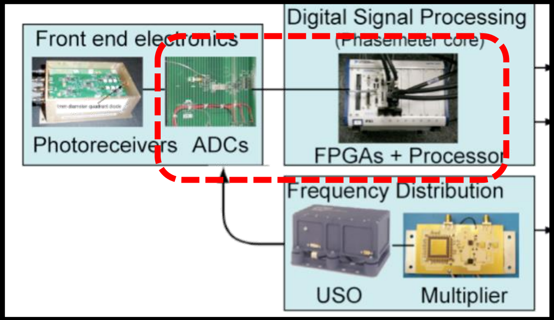
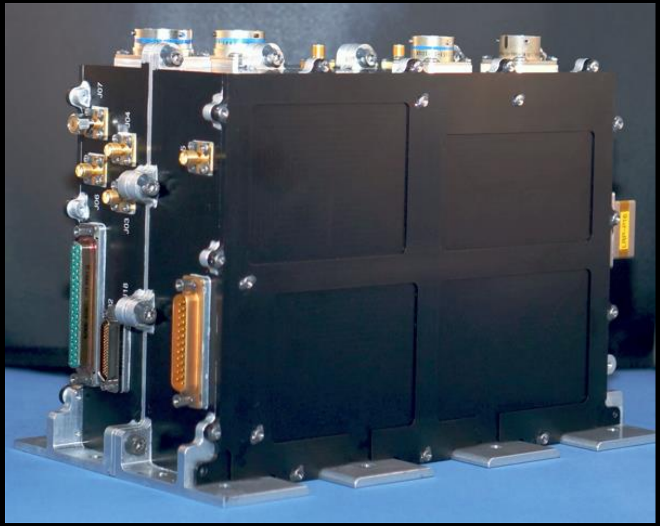
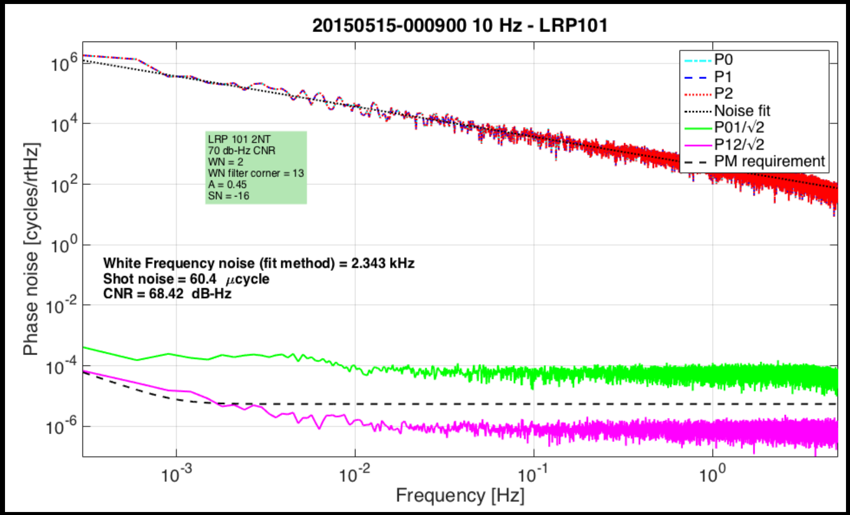


TRL 4 unit stress tested in all-digital tests and in interferometer testbed

GRACE Follow-On Laser Ranging Processor implements for flight LISA phase tracking and frequency control algorithms, including:

- Phase tracking
- differential wavefront sensing (and control)
- Laser Phase Locking
- Laser frequency stabilization
- Multi-tone tracking to be added under SAT
- Has only 4 input channels (vs 18 for LISA)





LRI Flight Hardware just prior to spacecraft integration

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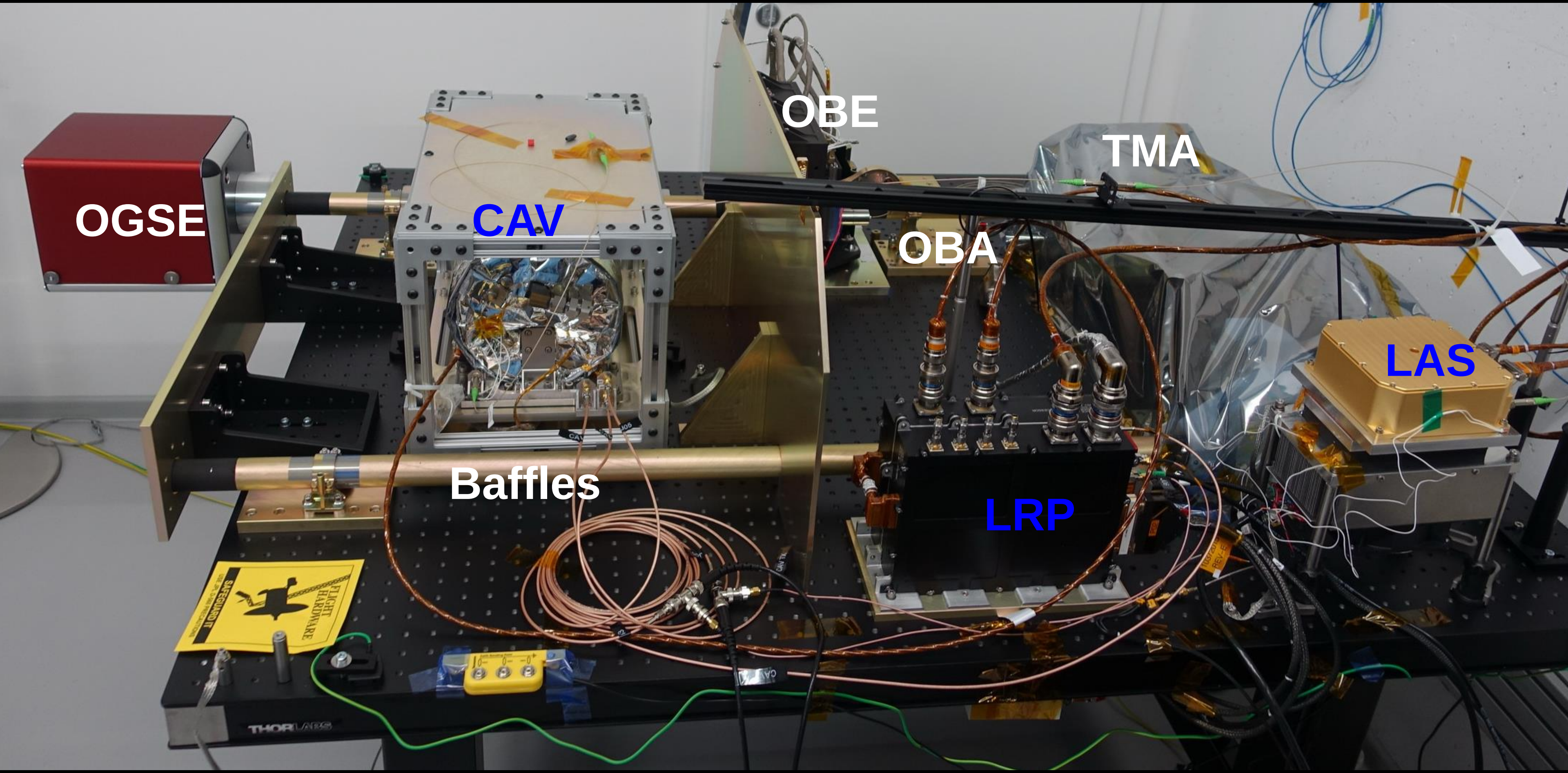

German
US

LRI 1 at STI

Immenstaad am Bodensee

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

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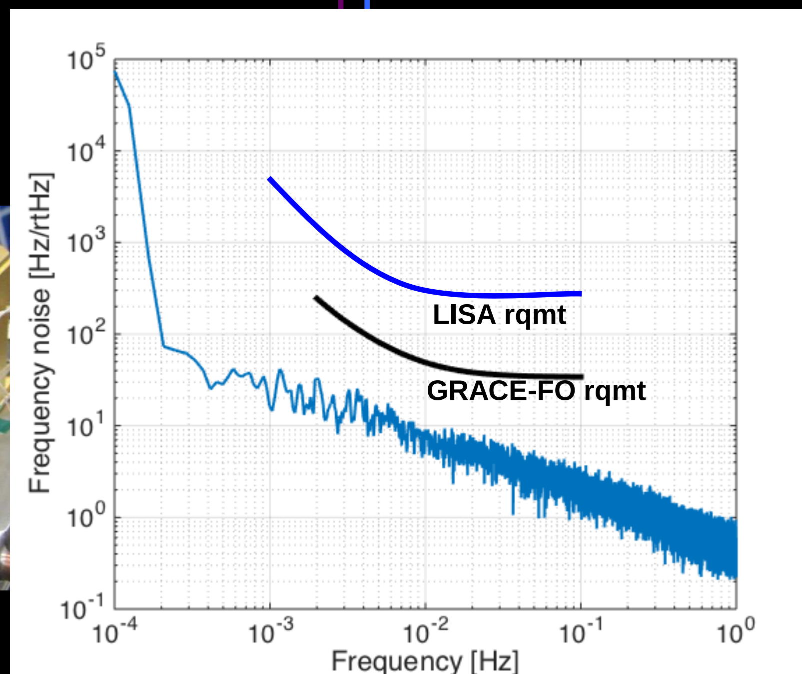
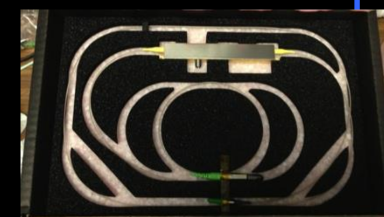
- Similar to Laser on LISA Pathfinder
  - Wavelength: 1064 nm
  - Nd:YAG Non-Planar Ring Oscillator
- Laser output power: 25 mW +/- 20%

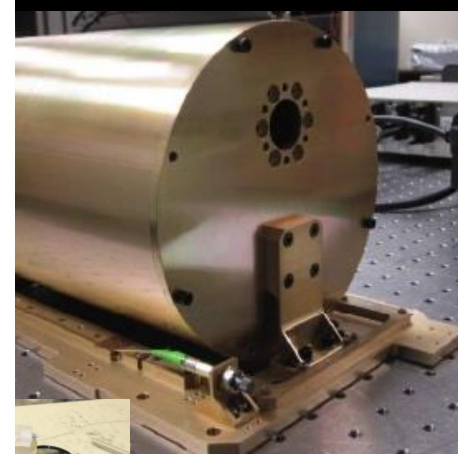
- LRP implements laser frequency control (locks laser to cavity assembly)

Laser

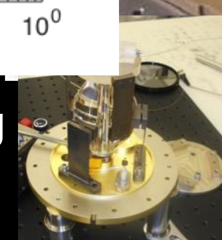
TESAT SPACECOM







- Flight phasemeter controlling flight laser to flight cavity, x2



Optical Cavity

Ball

Photoreceiver Prototype: TRL 4/5

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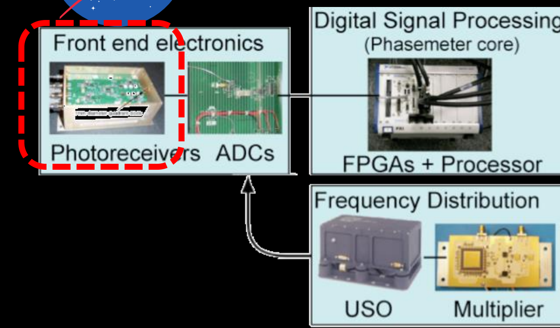
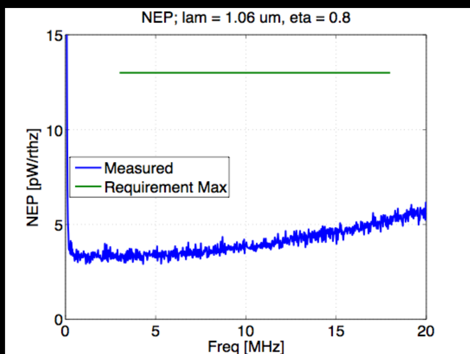
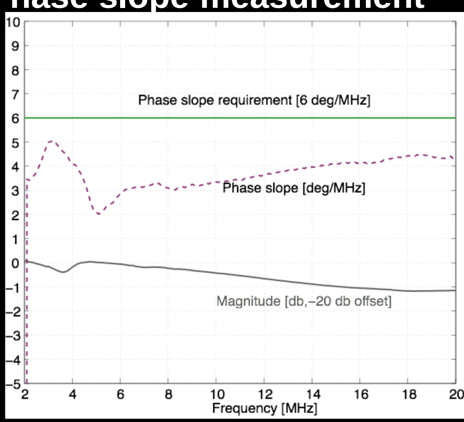


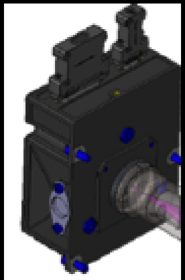
- 1 mm diameter quadrant diode with pre-amp
- Meets performance requirements for noise and phase stability



Phase slope measurement

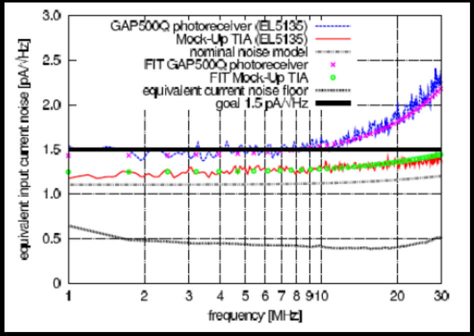


- Our LRI partners in Germany (DLR, STI, AEI) developed a similar design to FLIGHT for LRI



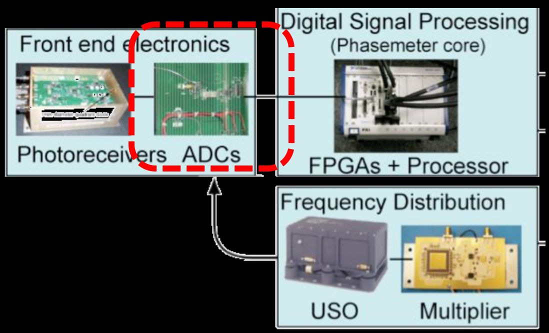
- GSFC investigated a hybrid photoreceiver

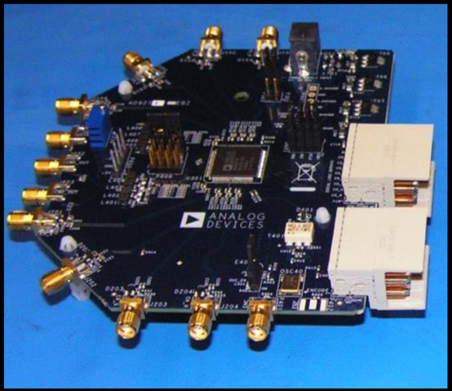
FIG. 3. Photograph of a prototype quadrant photoreceiver manufactured by Discovery Semiconductors.



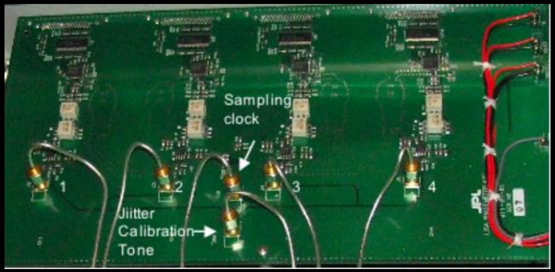
Analog-to-digital signal chain: TRL 4

- Amplifies, filters and digitizes signals from photoreceiver quadrants
- 50 MSamples/S, 12 bits: not driving
- Includes sampling time jitter calibration tone from USO
- Demonstrated to TRL 4 in interferometer testbed with commercial components
- Flight amplifier/filter chain built for LRI by German partners (AEI, STI, DLR)
- Flight samplers included in LRP on GRACE-FO





Amplifier/filter chain developed for FLIGHT for GRACE-FO by LRI partners in Germany (DLR, STI, AEI)



Frequency Multiplier/synthesizer

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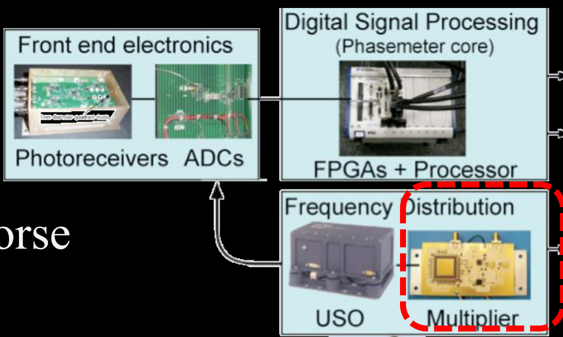
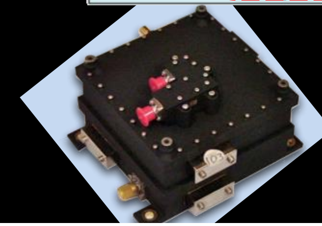
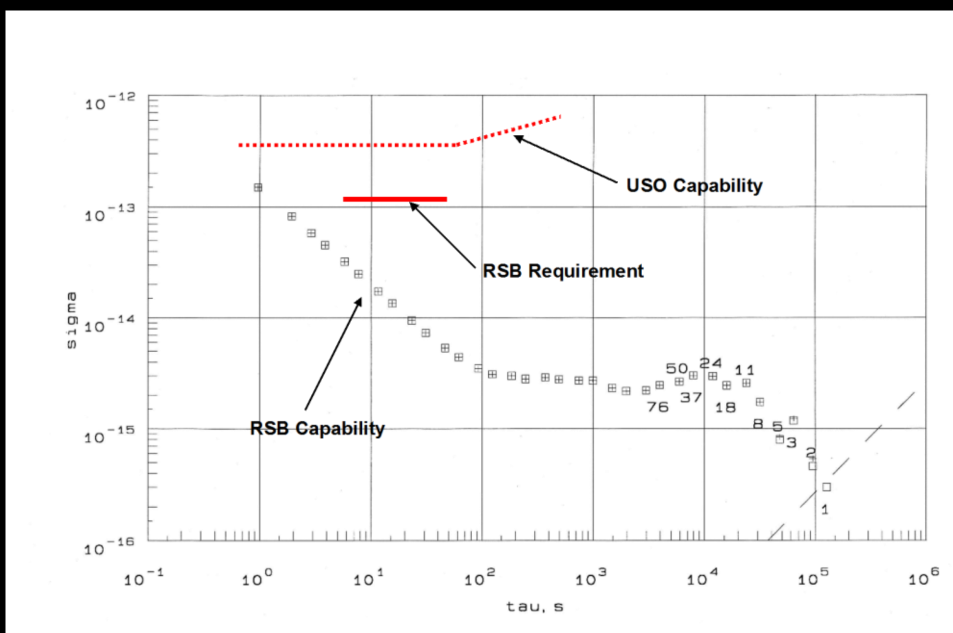
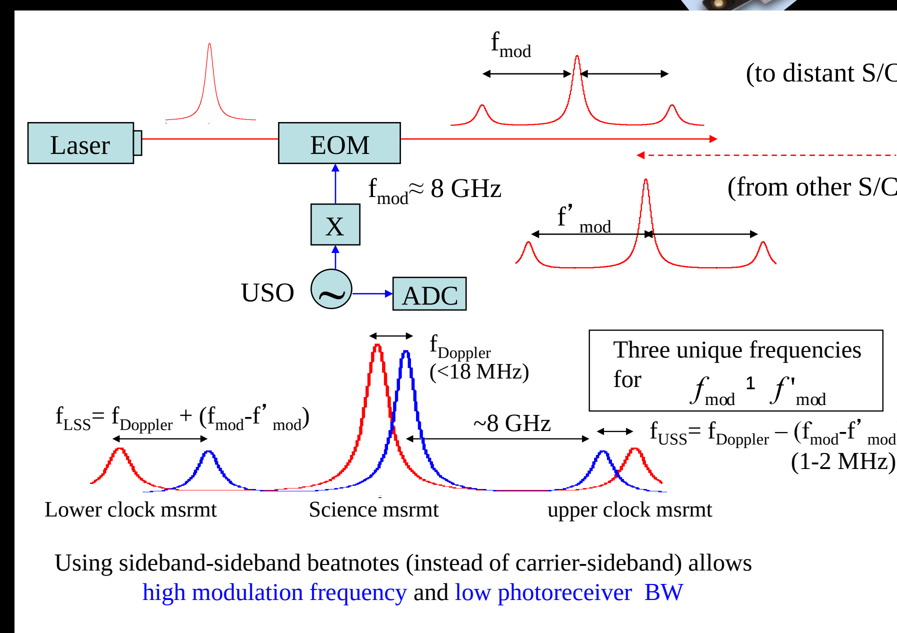
- Purpose: produces synthesized microwave copy of USO frequency to transfer noise via light
  - Used to measure and correct for clock noise
  - Technique demonstrated in our testbed with "USO" 100x worse than a USO[1]
  - Requirements met by GRAIL radio science beacon
- Easily meets LISA requirements (requirements are off the charts)



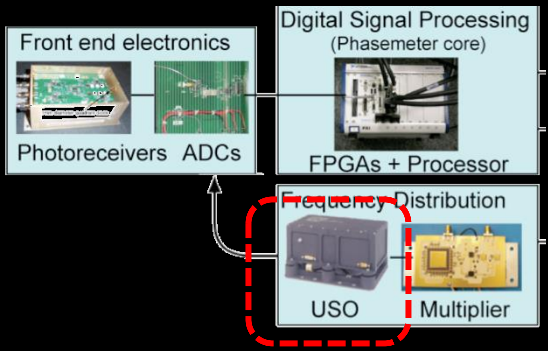


1 W. Klipstein et al., AIP Conf. Ser. No. 873 (2006)



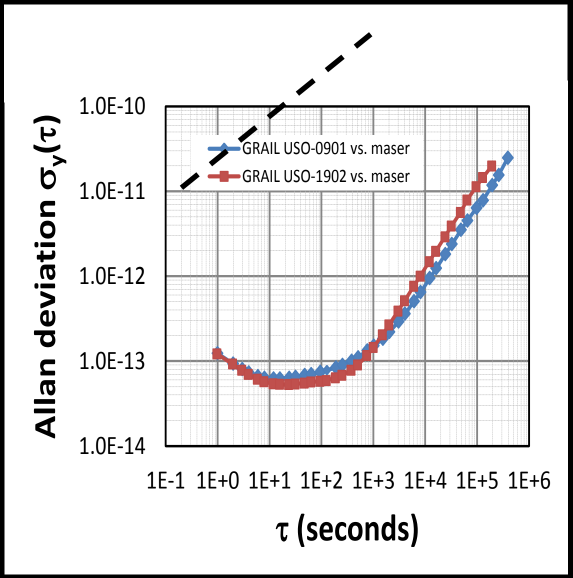


Ultra-stable oscillator



USO provides a reference for the ADCs in the phasemeter

- flight USOs exist (GRAIL shown). LISA does not need state-of-the-art performance. This is just a procurement
- On GRAIL the RSB (prev. slide) used one USO output



GFO LRI Team

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Martin Hinz
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Andreas Eckardt
Thomas Mangoldt
Bernd Zender
Burkhardt Guenther
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Josep Sanjuan
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Claus Braxmaier

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