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B Bachman, G de Vine, J Dickson, S Dubovitsky, J Liu, W Klipstein, K McKenzie, R Spero, A Sutton, B Ware, and C Woodruff

Jet Propulsion Laboratory (JPL), California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA 91109 USA

E-mail: `Robert.Spero@jpl.nasa.gov`

Abstract. As the first inter-spacecraft laser interferometer, the Laser Ranging Interferometer (LRI) on the GRACE Follow-On Mission will demonstrate interferometry technology relevant to the LISA mission. This paper focuses on the completed LRI Laser Ranging Processor (LRP), which includes heterodyne signal phase tracking at μcycle/$\sqrt{\text{Hz}}$ precision, differential wavefront sensing, offset frequency phase locking and Pound-Drever-Hall laser stabilization. The LRI design has characteristics that are similar to those for LISA: 1064 nm NPRO laser source, science bandwidth in the mHz range, MHz-range intermediate frequency and Doppler shift, detected optical power of tens of picoWatts. Laser frequency stabilization has been demonstrated at a level below $30\,\text{Hz}/\sqrt{\text{Hz}}$, better than the LISA requirement of $300\,\text{Hz}/\sqrt{\text{Hz}}$. The LRP has completed all performance testing and environmental qualification and has been delivered to the GRACE Follow-On spacecraft. The LRI is poised to test the LISA techniques of tone-assisted time delay interferometry and arm-locking. GRACE Follow-On launches in 2017.

1. Introduction, LISA and GRACE Follow-On synergy

The Laser Ranging Interferometer (LRI) for GRACE Follow-On will measure changes in the separation of earth-orbiting satellites with nanometer-scale precision. It is the product of a joint US-German collaboration, with management shared between the Jet Propulsion Laboratory (JPL) and the Albert Einstein Institute (AEI). The US[1] subsystems are the phasemeter, laser and optical cavity. Subsystems from Germany[2] are the optical bench, photodetectors, triple mirror assembly, and baffles.

The science from earth-observing missions GRACE[1] and its successor GRACE Follow-On have no connection to science from the gravitational-wave detector LISA[2]. Nonetheless, the LRI[3] overlaps in both function and design parameters with LISA's laser metrology. Concepts essential to LISA interferometry that were developed at JPL include Time Delay Interferometry (TDI)[4], post-processing interpolation for TDI[5], the arm-locking technique for laser stabilization[6][7], and velocity-correcting TDI[8]. LISA Technology developments from JPL include the invention of the first digital phasemeter meeting the LISA performance requirements [9][10] and a demonstration of clock noise suppression[11]. These efforts culminated in the first experimental implementation of LISA-like TDI[12]. Also demonstrated on the TDI

[1] NASA/JPL

[2] GFZ Research Center for Geosciences/AEI; Spacetech Gmbh, Immenstaad; DLR

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testbed were absolute metrology with accuracy of 0.2 m rms and optical communications on the laser link at a rate of 20 kbps[13].

Much of our experience with LISA technology was transferred to the LRI. LISA and the LRI have similar phase tracking/signal readout performance, received optical power, lasers, photodetectors, and laser frequency control by either offset-frequency phase locking or reference-cavity based stabilization. The development of a frequency reference cavity suitable for flight[14] was an extension of LISA efforts. There are plans to use the LRI to test two LISA-specific techniques on orbit: an arm-locking experiment[15] and a TDI experiment[16].

2. GRACE Follow-On LRI measurement concept

The GRACE Follow-On mission will comprise a pair of satellites in identical low-earth orbit, separated by approximately $\rho = 200\,\mathrm{km}$, the same as the GRACE mission that has been operating successfully since 2002. Variations in Earth's gravitational potential measured by GRACE or GRACE Follow-On are proportional to changes in $\Delta\rho/\rho$ resulting from the satellite pair passing over regions of nonuniform gradient[17]. The measurement sensitivity of the GRACE K-band microwave ranging system [18], a copy of which will be the primary science instrument on GRACE Follow-On, is approximately $\tilde{\rho}(f) = 1\,\mu\mathrm{m}/\sqrt{\mathrm{Hz}}$, where $\tilde{\rho}(f)$ designates a root power spectral density. A similar microwave system was used to map the moon's gravity in the GRAIL mission between 2011 and 2012[19]. In addition, GRACE Follow-On includes the LRI as a technology demonstrator to perform the same measurement as the microwave system but with better sensitivity. The 1×10^4 times smaller laser wavelength enables an improvement of a factor of 10 to $\tilde{\rho}(f) = 80\,\mathrm{nm}/\sqrt{\mathrm{Hz}}$ in the fourier frequency band $2\,\mathrm{mHz} < f < 100\,\mathrm{mHz}$. Long-term variations in the absolute distance ρ are known at the level of approximately 1 cm.

Figure 1 shows how LRI1 and LRI2 on separate spacecraft are used to measure $\Delta\rho$ ($= \delta L$ in the figure). The two LRI's are identical, and provide for laser frequency to be controlled either by a local cavity or by incoming light from the opposite LRI. As shown, the LRI1 laser frequency is locked to its cavity and LRI2 phase is phase-locked to the LRI1 laser with typical offset frequency $f_o = 10\,\mathrm{MHz}$. A heterodyne signal is formed on the DWS photodetector, using leakage light of approximately 1 mW from the local laser interfering with pW-level light from the distant spacecraft. Approximately 20 mW of signal power is available at the main output. The heterodyne frequency is $f_h = f_o + f_D$ where f_D is the Doppler shift from the LRI1-LRI2 relative velocity. The phases from the 4 segments of the photodetector are separately measured by the phasemeter in the Laser Ranging Processor (LRP). Changes in the sum phase $\Delta\phi$ on LRI1 are proportional to $\Delta\rho$, and are transponded to ground as the primary science signal. The difference phases give misalignment in pitch and yaw of the local beam relative to the incoming light. A control system in the LRP uses the difference phases to control the Fast Steering Mirror (FSM), aligning the outgoing beam to the incoming beam to μrad level precision. The Triple Mirror Assembly (TMA) routes the beam within the spacecraft such that the optical vertex coincides with the spacecraft center of mass.

3. Hardware

The photographs in Figure 2 are of the LRI1 during laboratory testing and while integrated on the spacecraft at Airbus.

Below we discuss the LRI subsystems and their relevance to LISA.

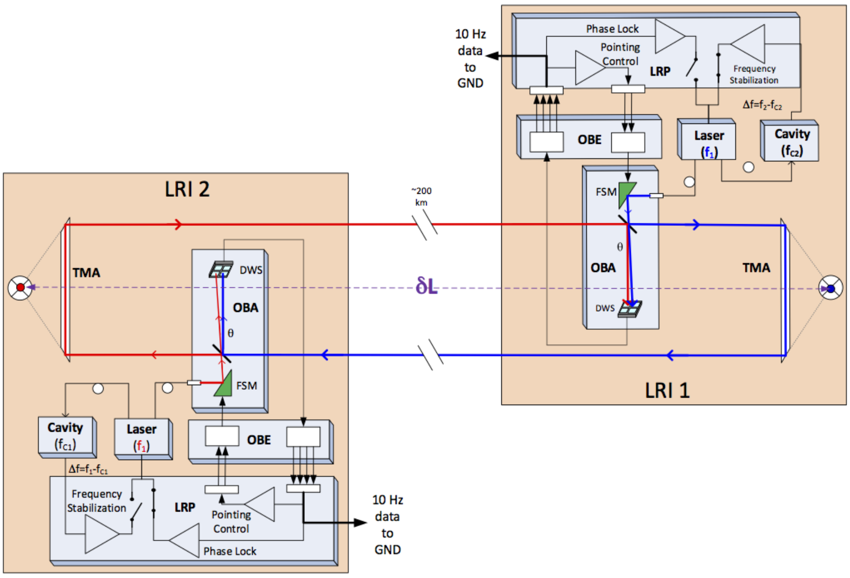

Figure 1. Block diagram of the LRI. OBA = Optical Bench Assembly, TMA = Triple Mirror Assembly, FSM = Fast Steering Mirror, DWS = Differential Wavefront Sensor, LRP = Laser Ranging Processor.

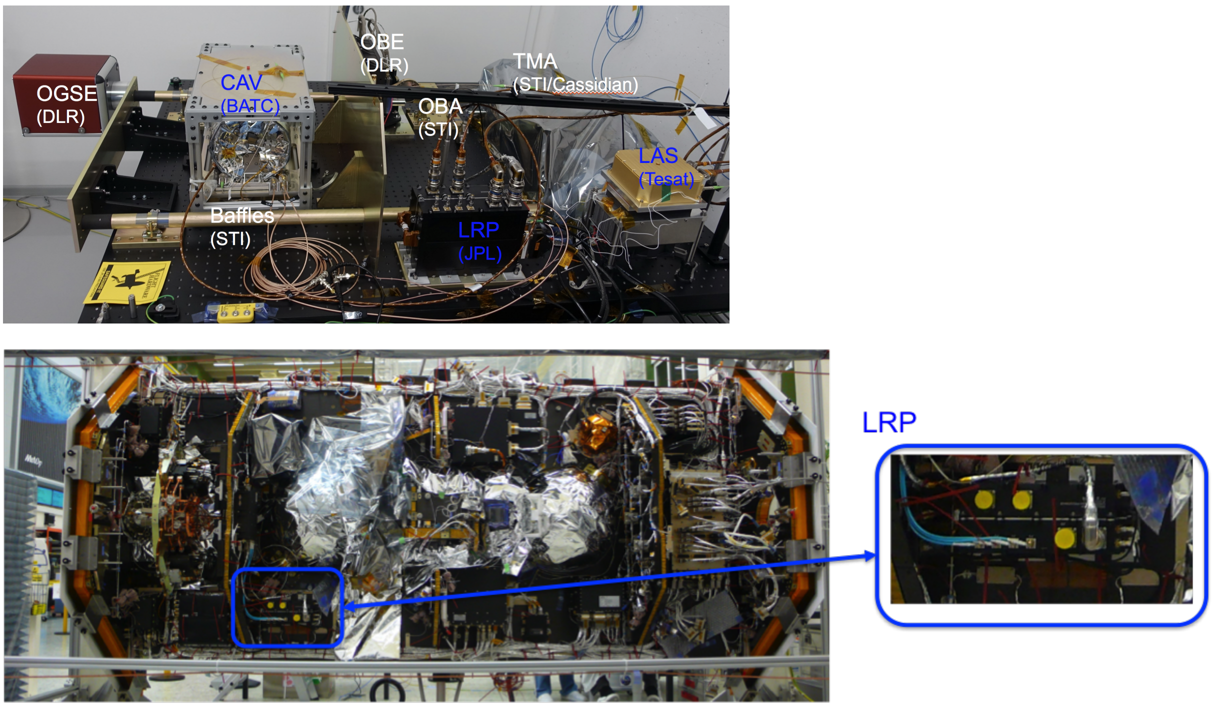

Figure 2. *Upper*: LRI flight hardware for Spacecraft 1 at Spacetech Gmbh (STI), Immenstaad, just prior to spacecraft integration. OGSE = Optical Ground Support Equipment, CAV = cavity manufactured by Ball Aerospace and Technology Corporation (BATC), OBE = Optical Bench Electronics, TMA = Triple Mirror Assembly manufactered by STI and Cassidian Oberkochen DE, LAS = Laser. *Middle*: Spacecraft 1 during integration at Airbus Defence and Space Gmbh, Immenstaad. *Inset*: Laser Ranging Processor (LRP). Photographs courtesy of Airbus and JPL.

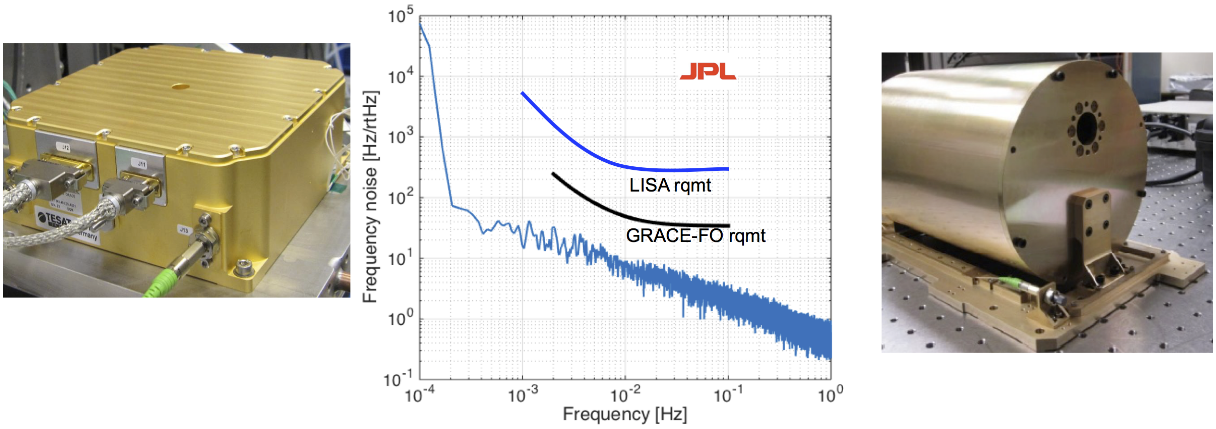

Figure 3. *Left*: NPRO laser manufactured by Tesat Spacecom, Gmbh, Backnang *Mid*: Measured frequency stability is better than requirements for both LISA and GRACE Follow-On. Right Reference cavity assembly from Ball Aerospace, Boulder Colorado.

3.1. Laser and laser stabilization

The laser, Figure 3, is a Nd:YAG Non-Planar Ring Oscillator (NPRO) of wavelength of 1064 nm, similar to the laser on LISA Pathfinder. Its output power is adjustable between 20 and 30 mW. The output frequency is stabilized to a resonance of a thermally isolated reference cavity with free spectral range = 1.9 GHz using the Pound-Drever-Hall technique implemented in the LRP. The residual frequency noise $\tilde{\nu}(f)$ limits performance according to $\tilde{\rho}(f) = \rho\tilde{\nu}(f)/\nu_0$ where $\nu_0 = 281$ THz. $\tilde{\nu}(f)$ was measured by stabilizing two flight lasers to flight cavities and measuring the interference phase between the lasers with a flight phasemeter, showing performance that meets the LRI requirement with margin.

3.2. Phase tracking

Figure 4 shows performance of the digital part of the phasemeter in response to synthesized noise that simulates a free-running laser. The noise in the difference between two such stimuli is below the phasemeter requirement, demonstrating that the dynamic range and the noise floor meets the LRI requirements. The residual is equal to the more stringent requirement on the LISA phasemeter: no accident, since the LRI phasemeter is based on the LISA design.

Table1 summarizes phase tracking performance of a heterodyne signal at the limit of low signal power. The carrier-to-noise ratio is defined as CNR $= V_{\text{carrier}}/\tilde{V}(f)$ where V_{carrier} and $\tilde{V}(f)$ are respectively the signal (carrier) amplitude and the noise floor at frequencies adjacent to the signal. CNR of 68 dB-Hz results from optical signal power of 3 pW with nominal laser intensity noise and photoreceiver electronic noise. The LRI phasemeter satisfies the LISA requirement of no cycle slipping for CNR as low as 75 dB-Hz, with margin of 7 dB, in the presence of laser frequency noise at the requirement level of $150\,\text{kHz}/\sqrt{\text{Hz}}\cdot(\text{Hz}/f)$.

4. LRI and LISA phase measurement comparison

Table 2 compares parameters for the LRI phase measurement system to those for LISA. The top level phase noise requirement in LRI is relaxed compared to LISA, and the laser frequency

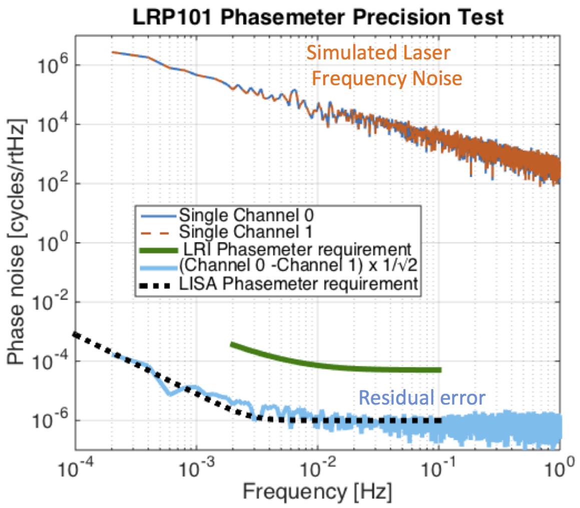

Figure 4. Electronic test of the digital part of the LRI phasemeter shows suppression of laser frequency noise to the requirement level for LISA.

Table 1. Phasemeter performance at CNR limits, tracking a flight laser.

CNR	Performance
61 dB-Hz	Acquire DWS with cycle slips ∼ 1 per second. DWS algorithm is resilient to cycle slipping
64 dB-Hz	Lock and track for hours with some cycle slips, ∼ 1 per few hundred seconds
66 dB-Hz	Lock and track for hours without cycle slips

stabilization is tightened. The Doppler shift, signal Intermediate Frequency (IF), received optical power, and science frequency band are all similar. Both LRI and LISA require phase tracking with low optical power and a DWS system to maintain alignment. The similarities demonstrate that the LRI provides a relevant technology demonstration for LISA and represents a valuable step towards LISA technology development.

5. Acknowledgment

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Table 2. Comparison of LRI and LISA phase measurement parameters

Parameter	LRI	LISA
Measurement noise total	$80\,\mathrm{nm}/\sqrt{\mathrm{Hz}}$	$20\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$
Shot noise	$0.01\,\mathrm{nm}/\sqrt{\mathrm{Hz}}$	$7\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$
Phasemeter noise $\cdot\lambda$	$1\,\mathrm{nm}/\sqrt{\mathrm{Hz}}$	$1\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$
Optical pathlength noise	$30\,\mathrm{nm}/\sqrt{\mathrm{Hz}}$	$3\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$
Laser frequency noise	$35\,\mathrm{nm}/\sqrt{\mathrm{Hz}}$	$1\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$
USO noise	$1\,\mathrm{nm}/\sqrt{\mathrm{Hz}}$	$1\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$
Phasemeter noise	1×10^{-3} cycles/$\sqrt{\mathrm{Hz}}$	1×10^{-6} cycles/$\sqrt{\mathrm{Hz}}$
Satellite separation	170–270 km	5×10^{9} m
Satellite relative velocity	$< \pm 3$ m/s	$< \pm 15$ m/s
Laser Wavelength λ	1.065×10^{-6} m	1.065×10^{-6} m
Nominal carrier-to-noise ratio	$>$ 75 dB-Hz (single channel)	$>$ 75 dB-Hz (single channel)
IF signal frequency	4–16 MHz	2–18 MHz
IF signal dynamics (at 1 Hz)		
Before frequency stabilization	5×10^{3} Hz/$\sqrt{\mathrm{Hz}}$	5×10^{3} Hz/$\sqrt{\mathrm{Hz}}$
After frequency stabilization	30 Hz/$\sqrt{\mathrm{Hz}}$	30 Hz/$\sqrt{\mathrm{Hz}}$
Science bandwidth	2 mHz–100 mHz	0.1 mHz–1 Hz
Received optical poser	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
Frequency-offset laser phase locking	Required	Required
Beam pointing sensing	Wavefront sensing	Wavefront sensing
Pointing noise	$1\,\mu\mathrm{rad}/\sqrt{\mathrm{Hz}}$	$80\,\mathrm{nrad}/\sqrt{\mathrm{Hz}}$