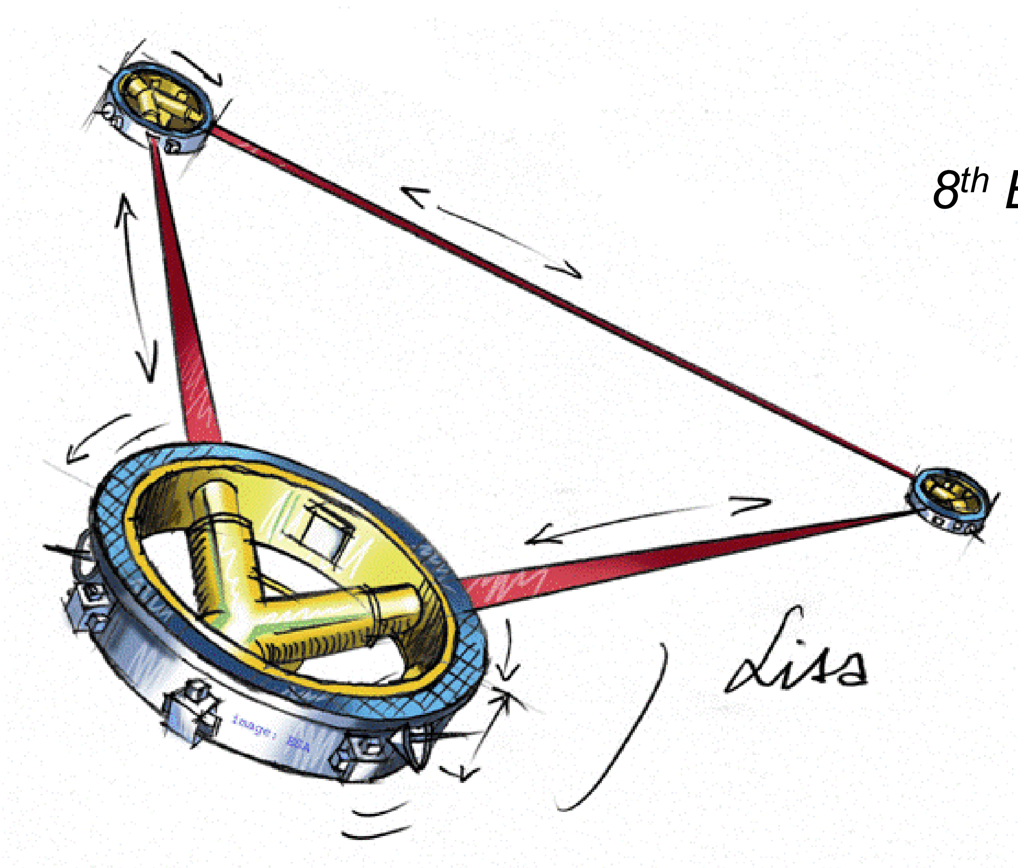
LISA Long-Arm Interferometry



J.I Thorpe, NASA/GSFC

8th Eduardo Amaldi Conference on Gravitational Waves

Columbia University
New York, New York

June 24th, 2009

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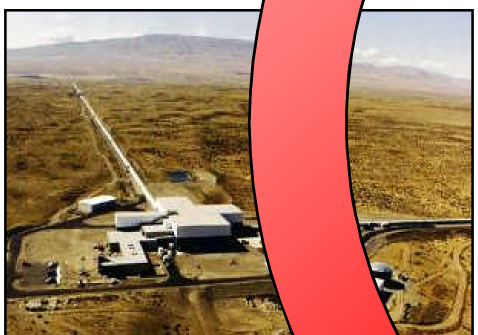

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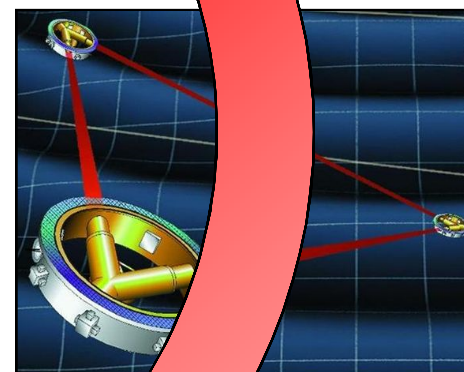
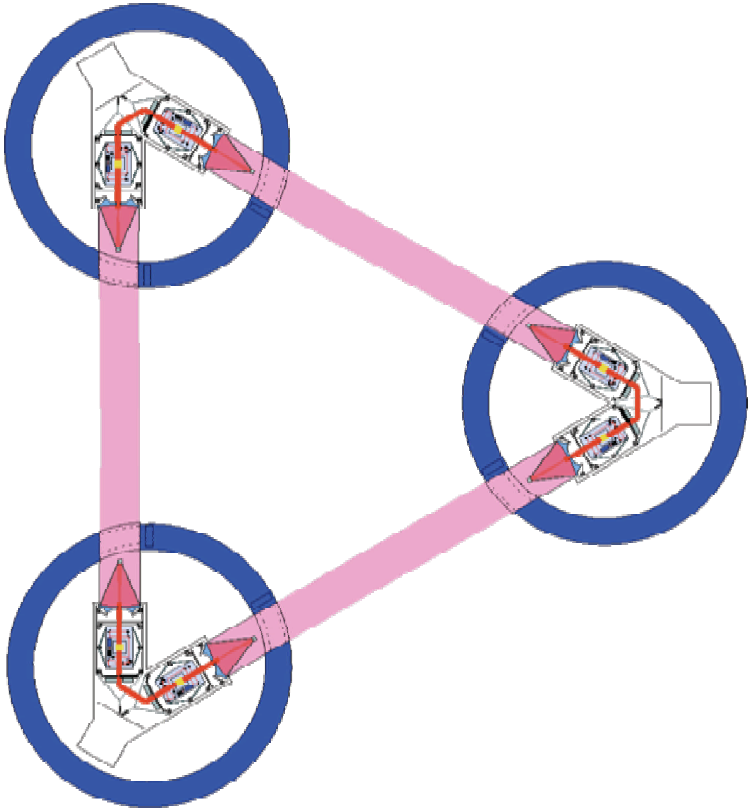


LISA Interferometry

3 Spacecraft x 2 proof-masses = 6 links

- Transmitted laser power ~ 1W
- Transmit/Receive Telescopes ~ 40cm
- Received Power ~ 1 pW



Measurement Principle

- Interfere transmitted/received beam
- Measure phase difference on each SC
- Combine data from all SC to form 'virtual' interferometers

The Long and Short of It

"Short Arm"*

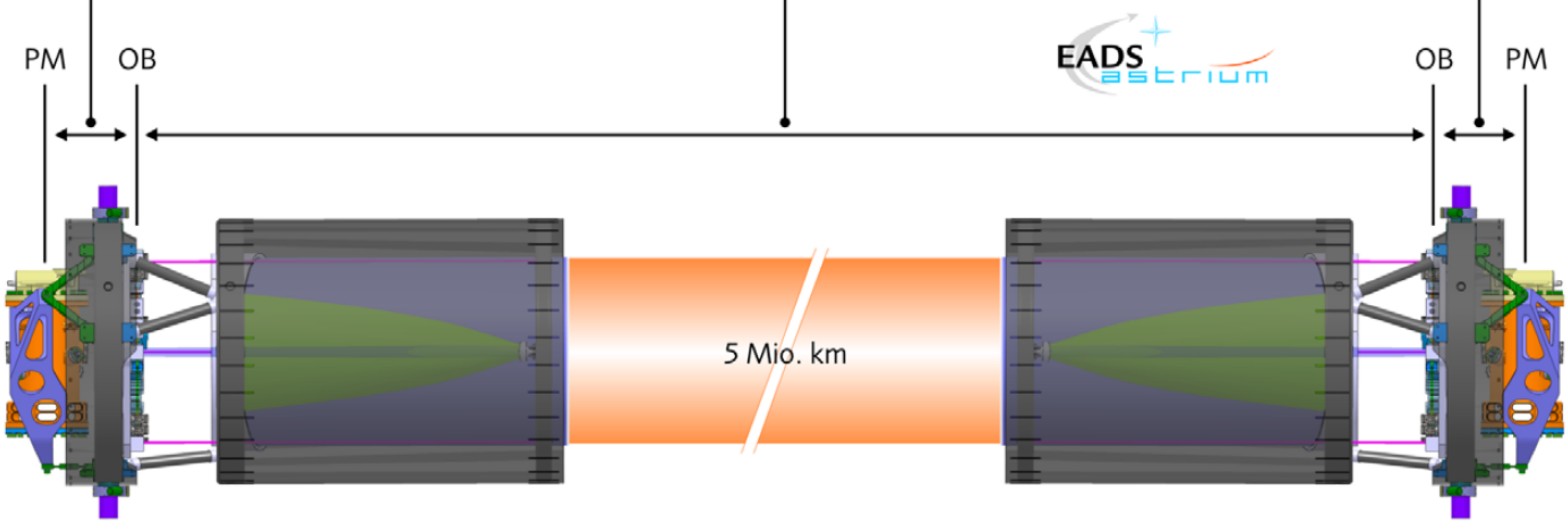
Proof Mass to Optical Bench

"Long Arm"

Optical Bench to Optical Bench

"Short Arm"*

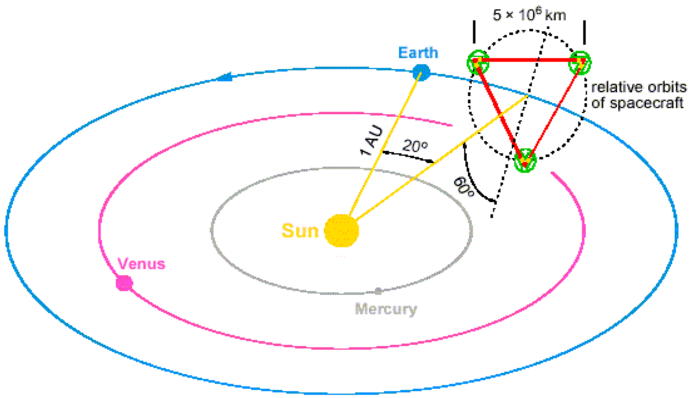
Proof Mass to Optical Bench

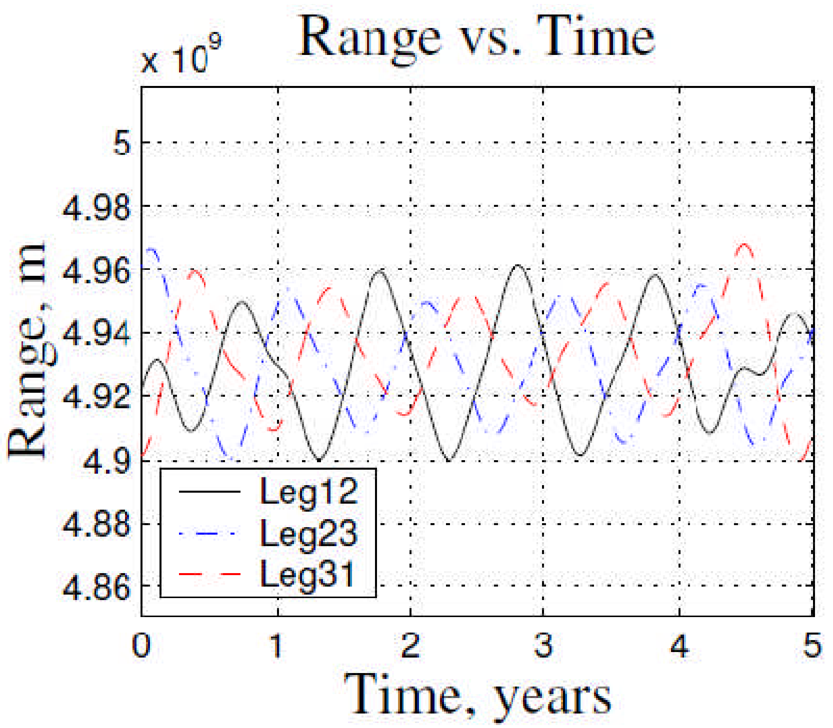


* Following Talk By A.F. García Marín

Constellation Design

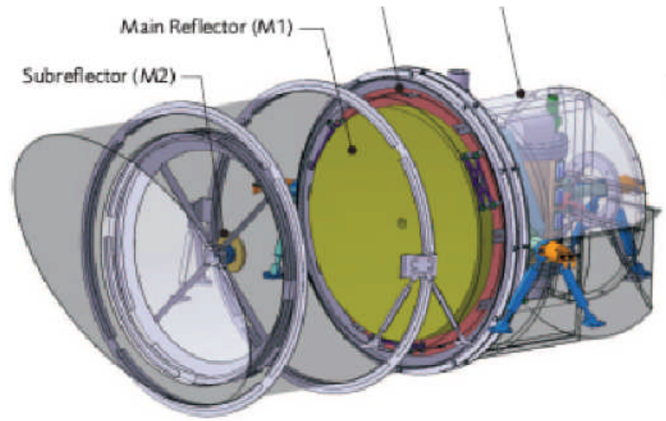
- Passive orbits, no active station-keeping
  - Varying arm-lengths
  - Varying constellation angles
  - Varying Doppler Shifts
- Different Optimizations Possible
  - Geometry
  - Doppler
  - Longevity
  - Delta-V

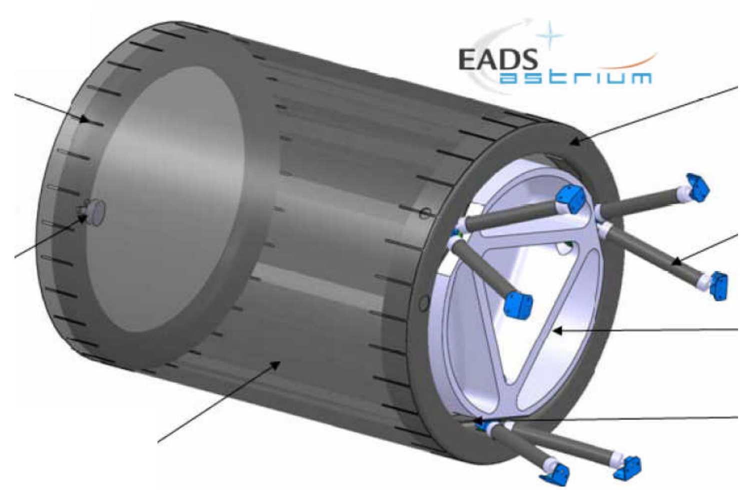




Telescope Design

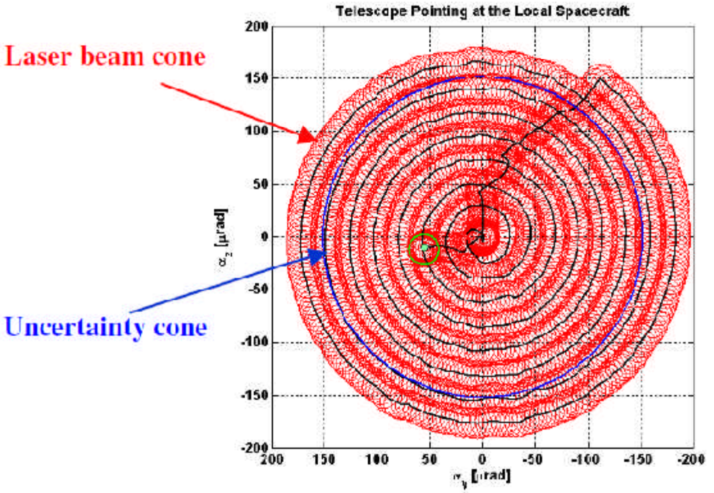
- Transmit/Receive beams
- Nominal 40cm dia
- Picometer Stability
- Off-Axis & On-Axis Designs
- Current Work
  - Fused Silica Spacer Stability (UF & GSFC)
  - ???

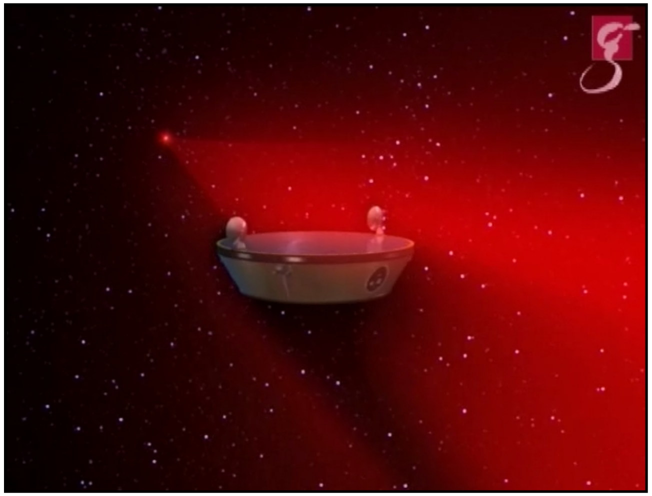


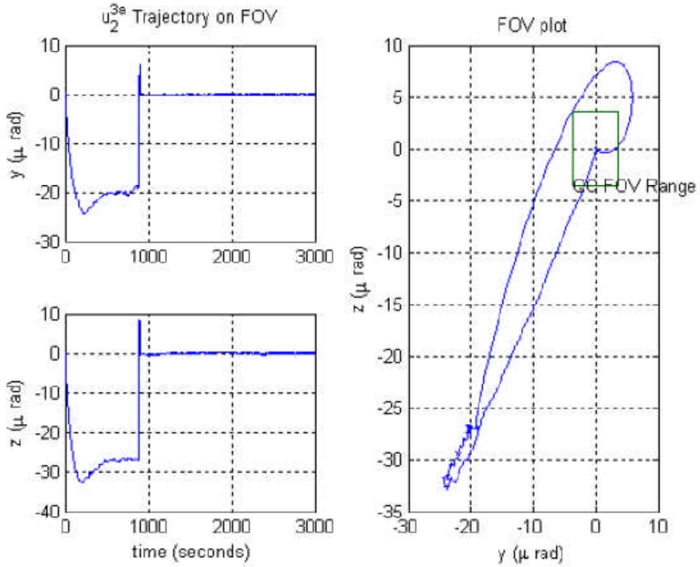


Constellation Acquisition

- Initial Uncertainty
  - Orbital Ephemeris
  - Star Trackers
- Active Acquisition
  - Defocus
  - CCD
  - Wavefront Sensing



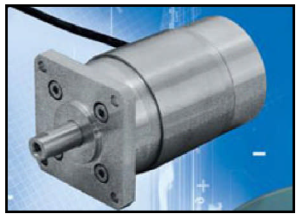


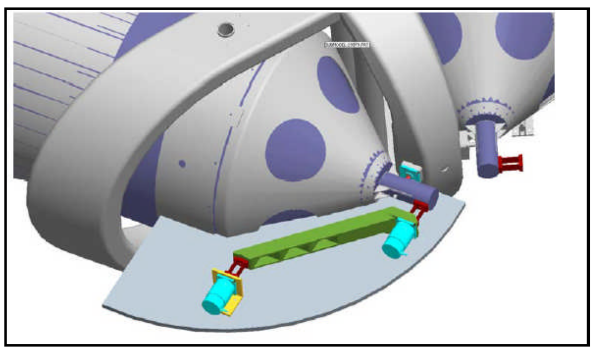


Mechanisms

Optical Assembly Tracking Mechanism

- Keeps far SC in FOV as constellation ‘breathes’
- Dynamic Range ~ 1^{o}
- Not in optical path
- Piezo ‘inch-worm’

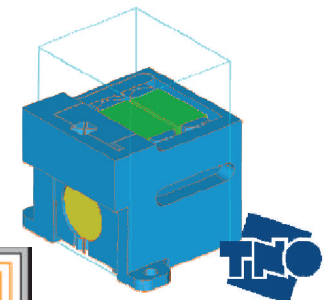


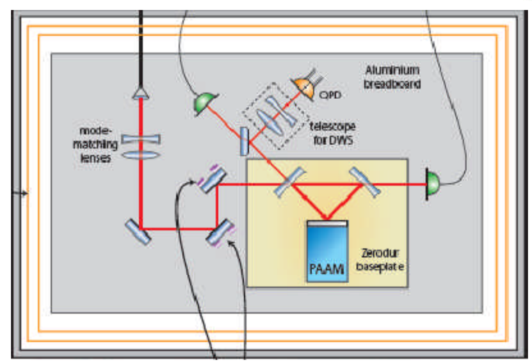


- Designs from Astrium & NASA
- Actuator test underway at GSFC

Point Ahead (Look Behind) Actuator

- Angle between transmitted and received beams
- Two axis (in/out of plane)
- Dynamic Range ~ 3μrad
- In optical path (pm stability)



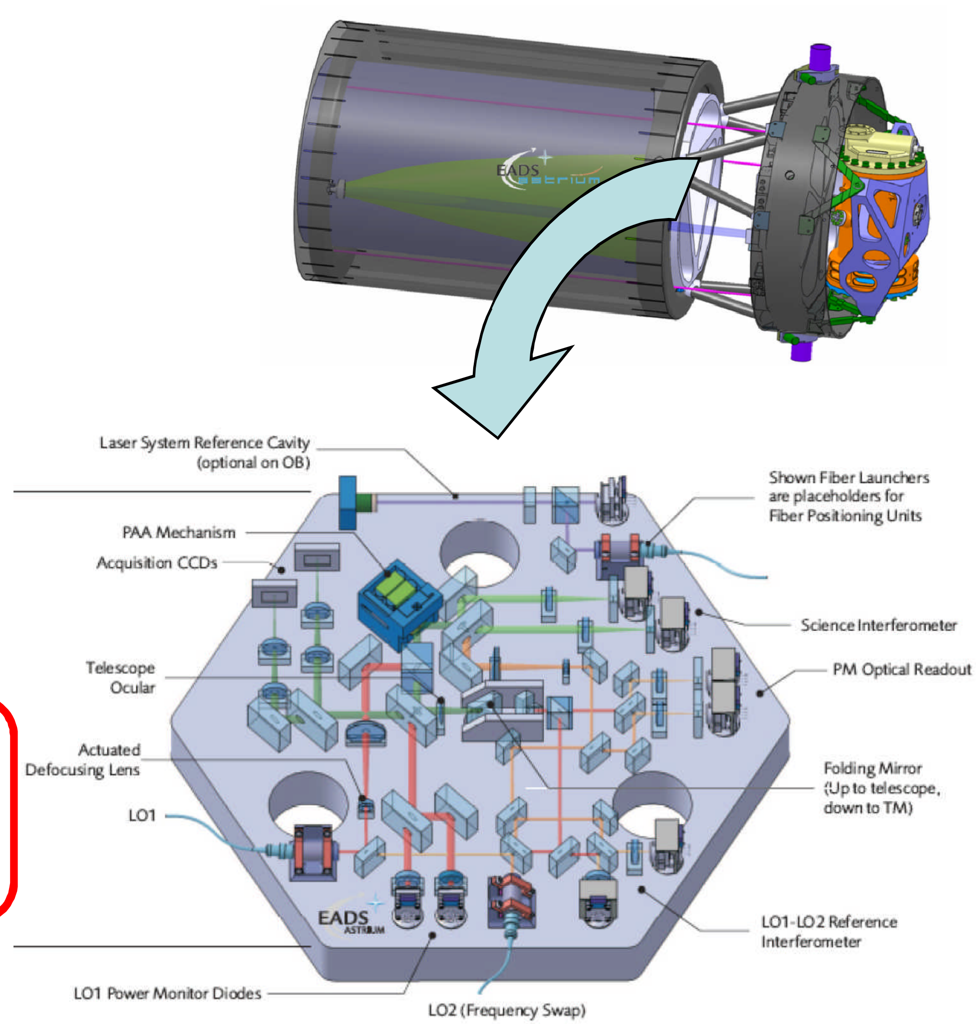


- Stability tests underway at AEI using Fabry-Perot Cavity

Optical Bench Design

- Three Beams Per Bench
  - Local Beam (L)
  - Adjacent Beam (A)
  - Received beam (R)
- Measured Signals
  - L – A
    - *phase noise*
  - L_{PM} – A
    - *bench motion, phase noise*
  - L - R
    - *bench motion, phase noise, gravitational waves*

Long Arm Interferometry



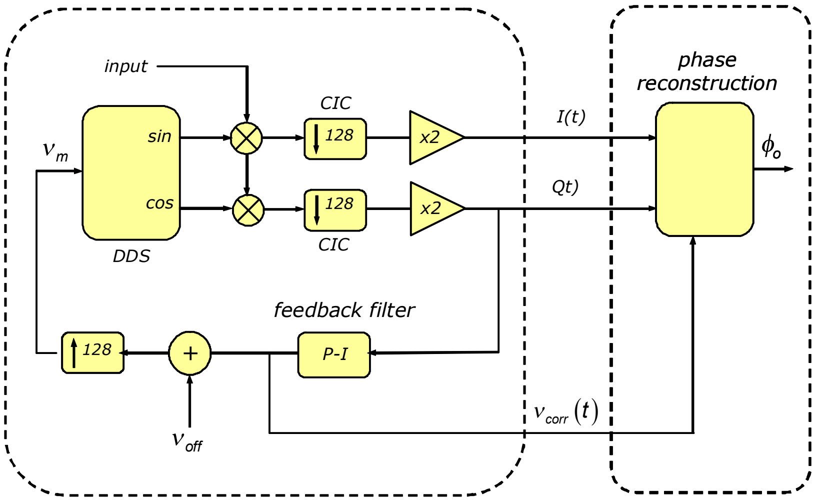
Phase Measurement Subsystem

Requirements

- Large Dynamic Range
  - Laser Frequency Noise
  - Varying Doppler Drifts +/- 10 MHz
- High Fidelity
  - Phase error ~ μCycles/rtHz
- Laser Frequency Control
  - Phase locking
  - Frequency Control
  - Frequency Stabilization

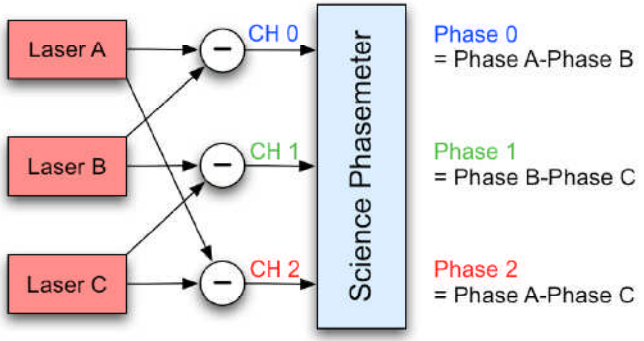
Design

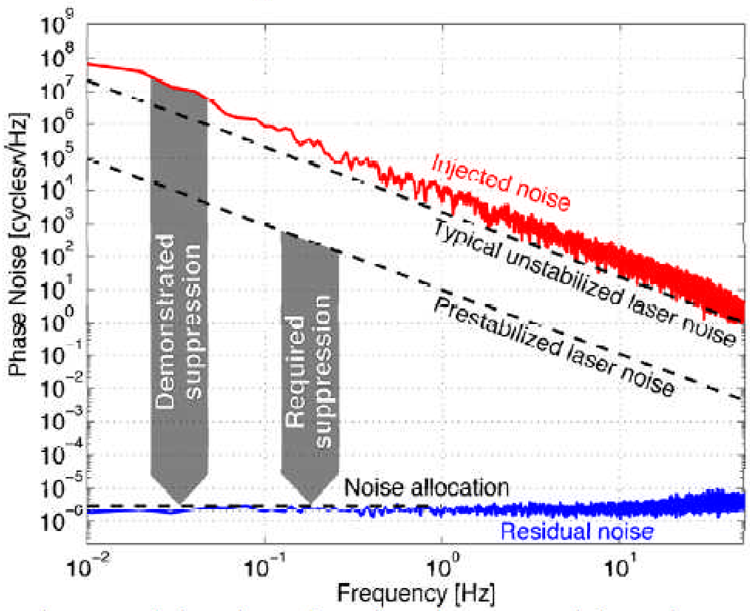
- Digital Quadrature Demodulation
- Digital PLL for frequency-tracking
- Phase reconstruction from oscillator commands



Phasemeter Demonstration

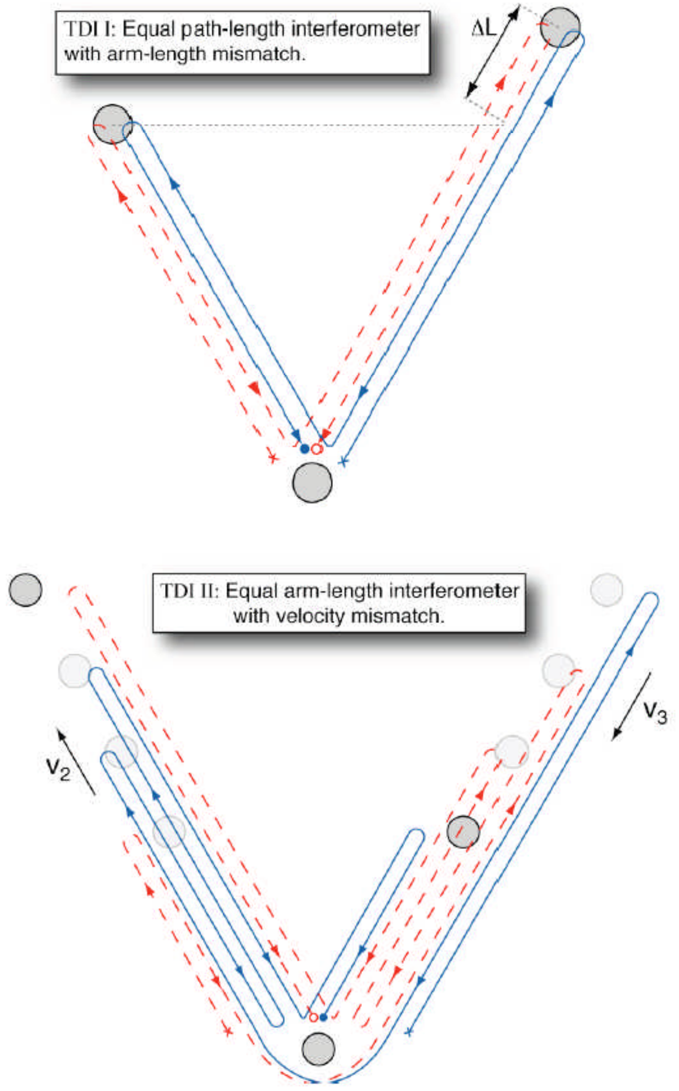
- JPL Phasemeter at TRL4
  - Inject three correlated noise streams
  - Read phase noise
  - Form noise-free combination
  - Exceeds requirements
- TRL 5 version in development
- Other Implementations
  - U. Floirda
  - AEI





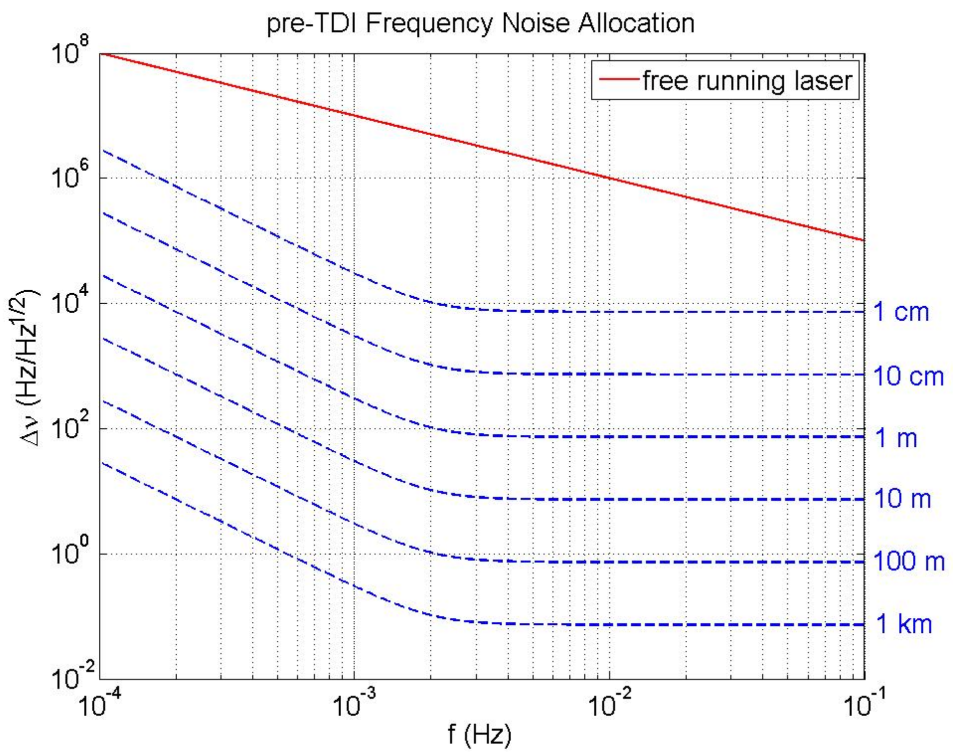
Time Delay Interferometry

- 18 phase measurements
  - 3 per bench
  - 2 benches
  - 3 spacecraft
- 18 unknowns
  - 6 long-arm link lengths
  - 6 short-arm lengths
  - 6 laser phase noises
- Time-Delay-Interferometry
  - Combine individual measurements with time-delays to suppress phase noise



TDI Limitations

- Ranging Error
  - Includes optical path and analog chain
- Ranging System Options
  - DSN tracking + Ephemeris
  - PRN code modulation
  - Doppler tracking of Science Signal

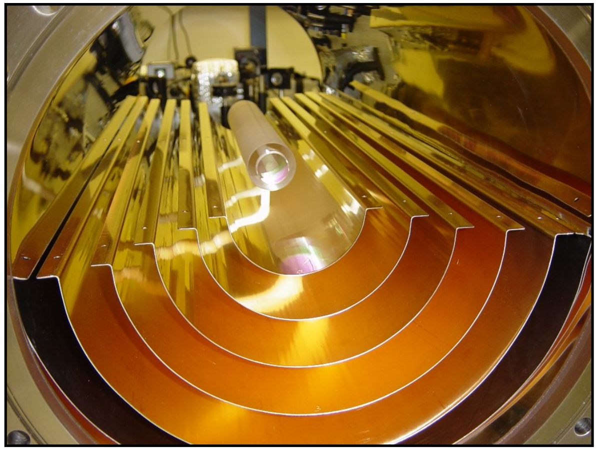


Effect	Assumption	Suppression Factor
Ranging Error	1 m ranging error	$2.4 \times 10^{7} \times (1\ \mathrm{Hz}/f)$
Algorithm limitations	Velocity correcting TDI	$2 \times 10^{9} \times (1\ \mathrm{Hz}/f)$
Interpolation	21 s kernel, 3 S/s	$3.2 \times 10^{9} \times (1\ \mathrm{Hz}/f)^{2}$
Analog Chain Errors	Measurement	$5 \times 10^{7} \times (1\ \mathrm{Hz}/f)$
Phasemeter DSP	TRL 4 Phasemeter	$10^{10} \times (1\ \mathrm{Hz}/f)^{2}$
Scattered Light	Amplitude 2×10^{-5}	$1.5 \times 10^{13} \times (1\ \mathrm{Hz}/f)$

Active Frequency Stabilization

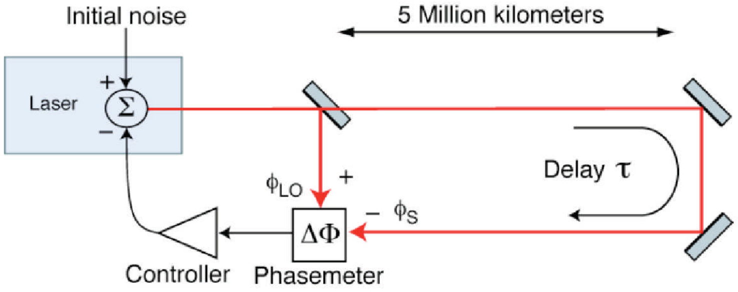
Spacecraft Level

- Lock laser to local frequency reference
  - Optical Cavity
  - Mach Zender Interferometer (LPF)
  - Spectroscopic Line



Constellation Level

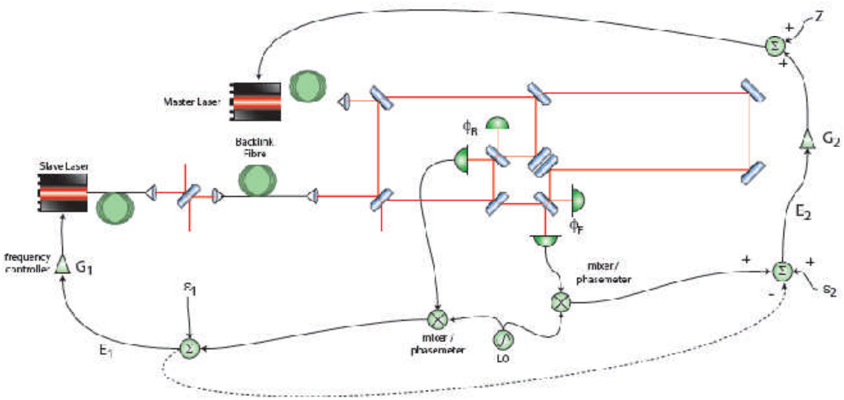
- Lock laser to combination of LISA arms
  - Arm Locking

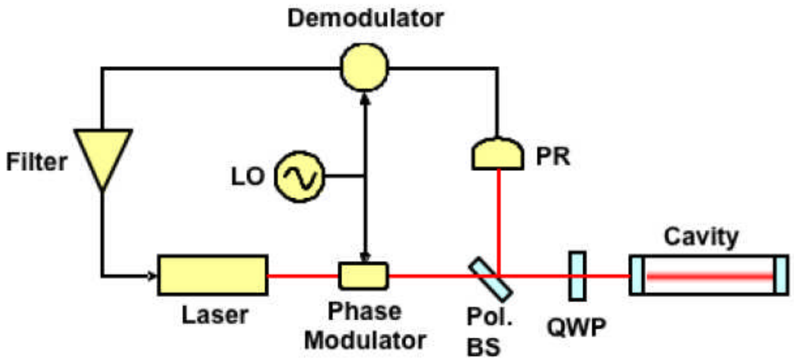


Spacecraft Level Stabilization

Mach-Zender Interferometer

- Optical pathlength used as frequency reference
- LTP flight heritage



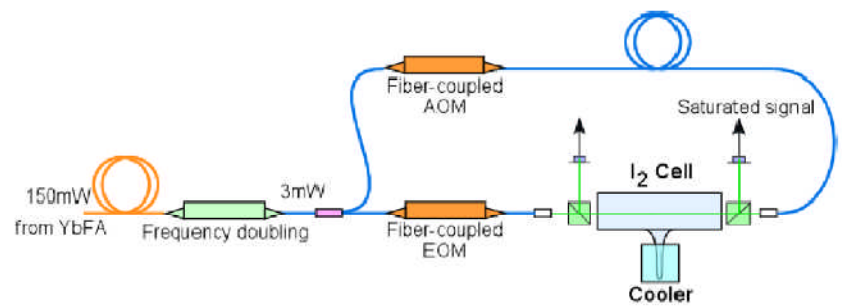


Optical Cavity

- Resonant optics improve performance
- Demonstrated in laboratories worldwide

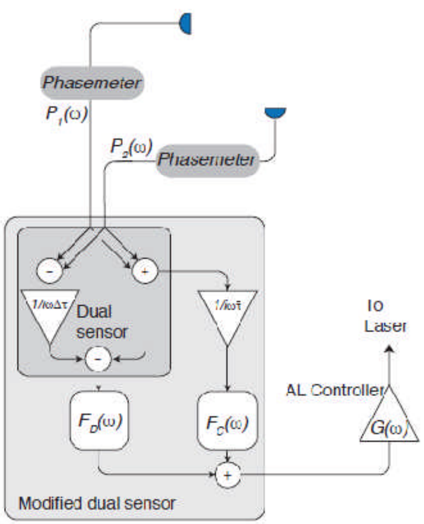
Molecular Iodine Line

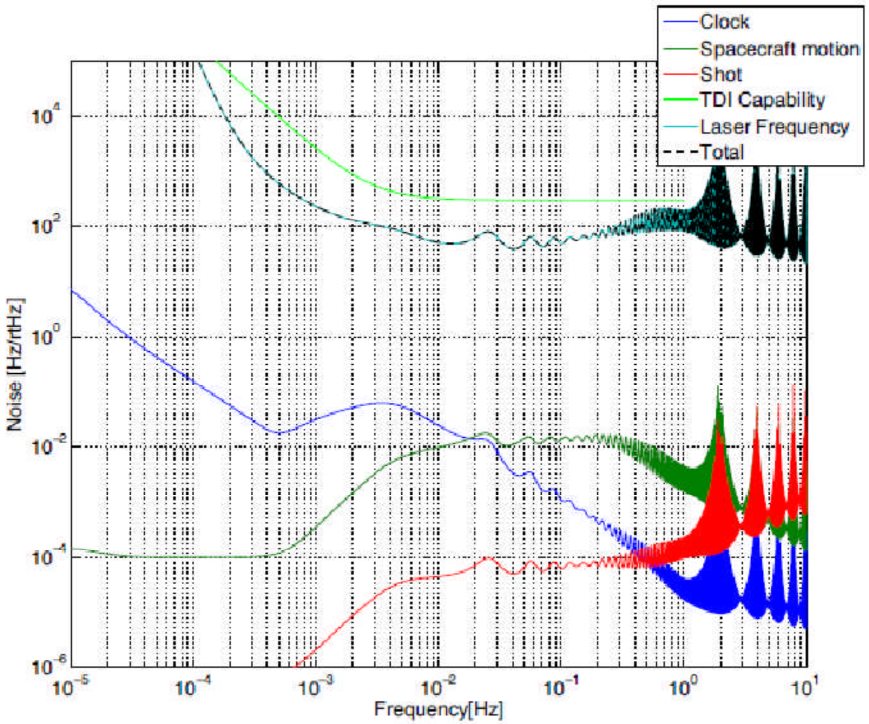
- Hyperfine transition as frequency reference
- Absolute frequency information available



Arm - Locking

- Use two LISA arms as frequency sensor
- Improved performance over cavities/iodine
- Performance depends on orbital parameters





Embarrassment of Riches

- Old Story
  - Frequency Noise mitigation is *hard*
  - Need to throw everything at it
- New Story
  - Multiple viable solutions
  - Selection based on secondary considerations (cost, complexity, interfaces, etc)

- Frequency Control Study Team
  - Ad hoc group of worldwide experts
    - Agencies
    - Universities
    - Industry
  - Telecons
  - 3 day workshop
  - Whitepaper in progress

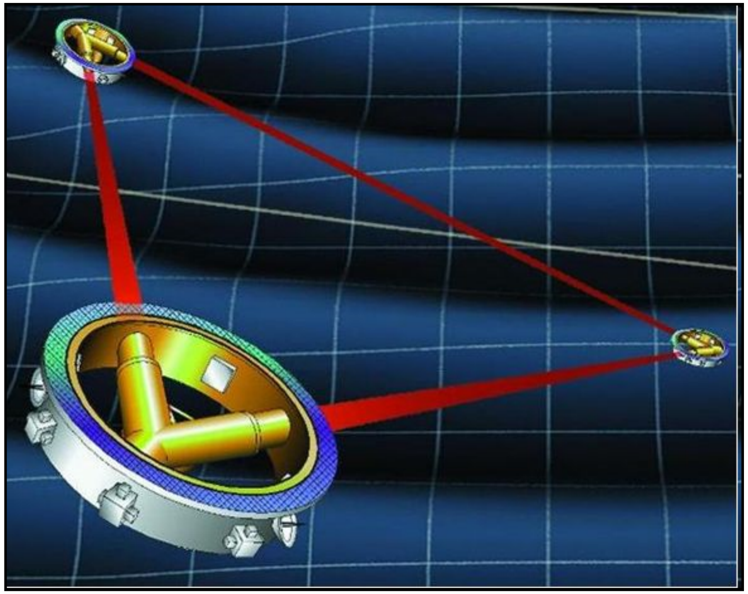
LISA Frequency Control Study Team - Meeting Notes
Millikan Board Room, California Institute of Technology
October 28-30, 2008

Meeting attendees:

Peter Bender [Univ of Colorado]	Jeffrey Livas [GSFC NASA]	Robert Spero [JPL NASA]
Jordan Camp [GSFC NASA]	Kirk McKenzie [JPL NASA]	Robin (Tuck) Stebbins [GSFC NASA]
Luigi d'Arcio [ESA/ESTEC]	Paul McNamara [ESA/ESTEC]	Dylan Sweeney [Univ of Florida]
Glenn de Vine [JPL NASA]	Stephen Merkowitz [GSFC NASA]	James Ira Thorpe [GSFC NASA]
Roger Diehl [JPL NASA]	Shawn Mitryl [Univ of Florida]	Vinzenz Wand [Univ of Florida]
Peter Gath [Astrium EADS]	Guido Müeller [Univ of Florida]	Henry Ward [Univ of Glasgow]
Alberto Gianolio [ESA]	Kenji Numata [GSFC NASA]	Brent Ware [JPL NASA]
Felipe Guzman [AEI]	Marcello Sallusti [ESA]	Danielle Wuchenich [JPL NASA]
Gerhard Heinzel [AEI]	Hans-Reiner Schulte [Astrium EADS]	Yinan Yu [Univ of Florida]
William Klipstein [JPL NASA]	Daniel Shaddock [JPL NASA]	

Summary

- LISA Interferometry Design is Mature
- Concept Stable for > 10 yrs
- Technologies / Techniques continue to be refined
- Large community of researchers pushing the envelope



Related Talks & Posters

Parallel 2, this afternoon

Gerhard Heinzel *LISA long arm interferometry*

Daniel Shaddock *Demonstration of Time Delay Interferometry for LISA*

Robert Spero *Range measurement for LISA*

Shawn Mytirk *Time Delay Interferometry at the UFLIS*

Parallel 4, Thursday afternoon

Kirk McKenzie *Implementation of arm-locking on LISA*

Kenji Numata *Fiber Laser Development for LISA*

Kakeru Takahashi *Low Frequency Stabilization of Laser Intensity and Frequency Using Optical Fiber*

Poster Session

Tim Lam *??????????*