LISA Long-Arm Interferometry

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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°
- 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

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