

TDI Ranging *for the GRACE-FO* Laser Ranging Interferometer

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LEGOP Activities



- Funded NASA ROSES APRA (Dec. 2012)
 - Research Opportunities in Space and Earth Sciences, Astrophysics Research and Analysis Program 11-APRA11-0029



- Develop interesting LISA technology experiments that can be demonstrated on GRACE-FO.
 - Time Delay Interferometry with Optical Ranging, and
 - Arm Locking.
- Simulate/demonstrate experiments with the GRACE-FO conditions and hardware.
 - Utilise existing LISA Interferometry Testbed,
 - Prototype algorithms & hardware.

Time Delay Interferometry





TDI combinations rely upon relaying frequency noise between links. -- '**synthetic**' interferometer arms --

GRACE-FO LRI





Time Delay Interferometry





$$\phi_1(t) = \phi_{l1}(t) - \phi_{l2}(t-\tau) - \phi_{path}(t),$$

$$\phi_2(t) = \phi_{l2}(t) - \phi_{l1}(t-\tau) - \phi_{path}(t).$$

TDI combines phase measurements with delays determined by optical-ranging. Required error in delay $\Delta \tau < 6$ ns.

 $\phi_{DOWR}(t) = D_{\hat{\tau}}(\phi_1(t)) + \phi_2(t),$



Recover `active transponder' architecture in post-processing

Time Delay Interferometry



 TDI is limited by delay knowledge *GRACE-FO allows testing of TDI algorithms with a significant delay (~ms) & delay fluctuations (~30%) >> requirement (~ns)*

$$\phi_{DOWR}(t) = \underbrace{\left[\phi_{l1}(t-\hat{\tau}) - \phi_{l1}(t-\tau)\right]}_{\text{free-running}} + \dots \Rightarrow \tilde{x}(f) = c\Delta\tau(\tilde{\nu}(f)/\nu_0) \quad \text{m}/\sqrt{\text{Hz}},$$

- LRI has NO explicit absolute ranging (GPS...)
- TDI Ranging (TDIR)

TDIR: Time-Delay Interferometric Ranging for Space-Borne Gravitational-Wave Detectors

Massimo Tinto,* Michele Vallisneri,[†] and J. W. Armstrong[‡] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109 (Dated: February 7, 2008)

- Implicit TDI Ranging
 - Minimise RMS over regions without range signal (laser freq. noise limited)
- Tone Assisted
 - Minimise 'In-band' frequency modulation upon noisy laser.

TDI in GRACE-FO





GRACE-FO Numbers: $x(f) = 20 \text{ nm} / \sqrt{\text{Hz}}$









 $\Delta \tau \ll 6 \text{ ns}$

















- SC₁ Range
- SC₂ Range
- Un-interpolated DOWR
- Interpolated DOWR
- DOWR Residual
- Theory Residual







- Structure in the ranging error is imposed onto the TDI tone.
 - Range delay \Rightarrow Changing phase delay \Rightarrow Phase modulation
 - Structure from orbital tone & harmonics.
 - Broadband error from white noise + smoothing filter.



TDI Testbed



- Stablised Master + free-running Slave
- Generate signals with real optical delay.
 - Add a displacement signal.
 - Sense the delay using TDI Ranging.
 - Sensitive to optical path length
- α Zero-area Sagnac Interferometer
 - Fiber delay: 150 ns
 - P₀ '*Truth*' frequency measurement





Dummy Spacecraft B

G. de Vine et al. Phys. Rev. Let. 104(21) (2010)



Dual One-Way Range $\phi_{DOWR}(t) = D_{\hat{\tau}}(\phi_1(t)) + \phi_2(t),$

Truth $\alpha(t) = p_{12}(t) + p_{21}(t) - (1 + 2D_{dowr}(t))p_0(t)$

TDI Testbed



- LRI prototype phase measurement & locking
- Displacement injected via Sagnac phaselocking
 - ULE bench.

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Operating LISA as a Sagnac interferometer

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, 91109. (Dated: February 22, 2007)



TDI Testbed:

RESULTS





- Master A cavity stabilized
- Slave A Free-running with a 0.85Hz tone.

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 - **DOWR** has a 0.18mHz tone added through Sagnac phaselock.
- TDIR finds Interpolated DOWR.

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- Master A cavity stabilized
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 - **DOWR** has a 0.18mHz tone added through Sagnac phaselock.
- TDIR finds Interpolated DOWR.
- Delay used to Interpolate Alpha
- Corrected Alpha is formed by subtracting the injected displacement.

Δτ<6ns: Meets GRACE-FO Phaselocking Requirement

Conclusion



..develop in-flight tests of core-techniques and high-risk elements of laser interferometry for a future space-based gravitational-wave astronomy mission for deployment on the GRACE Follow-On (GRACE-FO) mission, using that mission's optical technology package as a 'Mission of Opportunity'.



Simulation

- •Shows operation of Tone-Assisted TDI ranging for GRACE-FO.
- •Demonstrated suppression of laser frequency noise.

Experiment

- •Demonstrated < 6ns ranging error using Tone-Assisted TDI Ranging.
- •Displacement signal injection via Sagnac phase locking.
- •Non-reciprocal displacement noise limited

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