Synthetic LISA: simulating the future of LISA data analysis

Goddard Space Flight Center
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Tasting menu

→ The LISA response: geometric TDI
→ Simulating TDI: Synthetic LISA (w/Armstrong)

Adventures in detector characterization with SynthLISA

→ The effects of noisy armlengths
→ Post-processed TDI (w/Shaddock, Ware, Spero)
→ TDI ranging (w/Tinto, Armstrong)

A quick survey of LISA sources: status and wishlist

→ Massive-BH binaries
→ Extreme-mass ratio inspirals
→ The removal of galactic binaries

→ A conclusion on simulation for LISA
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How is LISA an Interferometer?

LISA: → A constellation of three drag-free spacecraft, separated by \(5 \times 10^6\) km and flying on an Earth-trailing solar orbit

→ Gravitational waves detected in \(10^{-5}–10^{-1}\) Hz band as modulation of distance between spacecraft by picometer interferometry

→ Sources: compact binary-star systems in our galaxy, massive and super-massive BH mergers, compact stellar objects captures by massive BHs

Interferometer: → (Noun) a device that combines signals radiating from a common source [or multiple sources], and received at different locations [or at a common location, but after traveling different paths]

TDI: → Six laser beams are exchanged between the spacecraft; each spacecraft compares the phase of the incoming and local lasers; these measurements are delayed and combined to synthesize interferometric observables
The basic GW observable

In fact, with good clocks, any time transport link is a GW detector

\[ h_{\mu\nu}^{TT} = h_+(t + x)[e_{zz} - e_{yy}] \]

\[ p_2(t) - p_1(t - L_{12}(t)) = \omega L_{12}(t) \]

\[ L_{12}(t) = L_{12}^{\text{no gw}} + \frac{1}{2} \int_1^2 h_+(t) dt \]

\[ [\dot{p}_2(t) - \dot{p}_1(t - L_{12}(t))]/\omega = \frac{1}{2} [h_+(2) - h_+(1)] \]

and in general (Estabrook-Wahlquist two-pulse response)

\[ [\dot{p}_2(t) - \dot{p}_1(t - L_{12}(t))]/\omega = \frac{1}{2} \frac{n \cdot [h(2) - h(1)] \cdot n}{1 - k \cdot n} \]
Introducing TDI

But LISA’s clocks (lasers) are not perfect: \( \text{rms } \Delta f/f = 10^{-13} \text{ Hz}^{-1/2} \)
(160 dB louder than proof-mass noise)

\[
\dot{p}_i(t) = \omega + C_i(t) + \text{g.w.}
\]

Then we can add (or subtract) single-link observables \( y_{\text{send (link) recv}} \) to cancel laser noise at common events (with six LISA lasers, we will need also backplane measurements)

The geometric TDI principle: add/subtract single-link obs. to create a closed loop that cancels laser noise at all send/recv events
Synthesized interferometers

The TDI combination of single-link observables can synthesize the phase-difference output of laser beams sent along standard interferometer paths:

- The head-to-tail sum of observables [e.g., $y_{12}(t)+y_{21}(t+L)$, or $y_{12}(t)+y_{23}(t+L)$] replaces a perfect phase-locked transponder (mirror)

- The head-to-head or tail-to-tail difference of two such sums computes their total phase difference (replacing the photodetector)

Synthesized equal-arm Michelson interferometer
The garden of TDI observables

The first-generation TDI observables, discovered algebraically by AET:
- cancel laser noise in stationary unequal-arm LISA configurations
- are built with 6 single-link obs. (using all links), or 8 single-link obs. (using 4 out of 6 links); Dhurandar et al. (2002) give generators
- can all be interpreted geometrically as synthesized interferometers with 2, 4, or 6 beams!

- Sagnac ($\alpha$)
- Unequal-Arm Michelson ($X$)
- Beacon ($P$)
- Monitor ($E$)

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The F-W TDI principle: a $2N$-beam combination can be seen as a single beam that travels forward and backward in time to meet itself back at its origin.

**Combinatorial recipe** for $n$-link combinations:

Starting at arbitrary spacecraft, repeat $n$ times:

- (randomly or exhaustively) choose *left or right*, choose *future or past*, lay down arrow

For $n$ links, $3 \times 2^{2n}$ combinations possible

**Closure rules** to verify laser noise cancellation:

<p>| | | |</p>
<table>
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|L|-closure (first-generation TDI, unequal-arm LISA): & $(1$ or $1')$, $(2$ or $2')$, $(3$ or $3')$ must be same under $\rightarrow$ and $\leftarrow$
|L|-closure (modified TDI, rotating unequal-arm LISA): & $(1)$, $(1')$, $(2)$, $(2')$, $(3)$, $(3')$ must be same under $\rightarrow$ and $\leftarrow$
|L|-closure (second generation TDI, flexing LISA; actual $dL/dt=10^{-8}$ s/s): & even more restrictive, will fit in a few lines of code
Geometric TDI!
[MV, in preparation]

- Geometric TDI is a powerful (and pedagogical!) way to understand TDI
- It provides the first **systematic method** to explore the space of 2nd-gen. TDI observables. For instance:
  - the **shortest** 2nd-gen. obs. has length 16
  - there is no ζ-type obs. up to (at least) length 20
  - the search recovers TEA’s 16-link, 2-beam $X_1, X_2, X_3$ but also news 4-beam and 6-beam X-type obs.
- The new combinations have the same sensitivity, but employ both time delays and advancements, with **reduced temporal footprint**

<table>
<thead>
<tr>
<th>links</th>
<th>combination space</th>
<th>unique observables</th>
<th>$X$</th>
<th>$P, E$</th>
<th>$U$</th>
<th>$\alpha$</th>
<th>2 beam</th>
<th>4</th>
<th>6</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>$4 \times 10^9$</td>
<td>45</td>
<td>9</td>
<td>18</td>
<td>18</td>
<td>0</td>
<td>3</td>
<td>24</td>
<td>0</td>
<td>18</td>
</tr>
<tr>
<td>18</td>
<td>$7 \times 10^{10}$</td>
<td>168</td>
<td>0</td>
<td>12</td>
<td>12</td>
<td>144</td>
<td>6</td>
<td>24</td>
<td>90</td>
<td>48</td>
</tr>
<tr>
<td>20</td>
<td>$1 \times 10^{12}$</td>
<td>618</td>
<td>24</td>
<td>12</td>
<td>18</td>
<td>564</td>
<td>12</td>
<td>114</td>
<td>264</td>
<td>84</td>
</tr>
<tr>
<td>24</td>
<td>$3 \times 10^{14}$</td>
<td>6,534</td>
<td>29</td>
<td>24</td>
<td>40</td>
<td>6,440</td>
<td>48</td>
<td>536</td>
<td>1,540</td>
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Why simulate TDI?

The time-delay structure of the TDI observables generates complicated many-pulse responses to GW signals, making for burdensome analytical signal models.

The LISA orbital motion modulates GW signals:
- by changing the orientation of the LISA plane
- by Doppler shifting incoming signals

The successful subtraction of laser phase noise must be verified w.r.t. the practical implementation of TDI and the realistic time dependence of the armlengths.
Synthetic LISA
[by MV & J. W. Armstrong; MV, *PRD*, in review, gr-qc/0407102]

- Simulates the LISA fundamental noises and GW response at the level of science/technical requirements; can be adapted and extended to the analysis of systems-engineering questions
- Includes a full model of the LISA science process (shearing LISA motion, causal light propagation, second-generation TDI, laser-noise subtraction, phase locking)
- Contains standard noise and GW-signal objects, but it’s easy to implement or load new ones
- Is conceived as a modular and steerable package, to allow easy interfacing to extended modeling and data-analysis applications
- Is user-friendly, and extensible (C++, Python, XML), to allow easy interfacing to extended modeling and data-analysis applications
- Is award-winning (NASA Space Act) software, (to be) released in the public domain
A Synthetic LISA Block Diagram

GW sources
for plane waves, work from $k, h_+ (t), h_\times (t)$ at SSB

LISA noises
laser freq. fluctuations, proof mass, optical path

LISA geometry
spacecraft positions → photon propagation → armlengths

Doppler $y_{ij}$
inter-spacecraft relative frequency fluctuations

Doppler $z_{ij}$
intra-spacecraft relative frequency fluctuations

TDI observables
time-delayed combinations of $y_{ij}$ and $z_{ij}$
laser-noise and optical-bench-noise free
3 independent observables

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The Synthetic LISA Package

Implements the LISA science process as a collection of C++ classes

**Class LISA**
Defines the LISA time-evolving geometry (positions of spacecraft, armlengths)

- **OriginalLISA**: static configuration with fixed (arbitrary) armlengths
- **ModifiedLISA**: stationary configuration, rotating with T=1yr; different cw and ccw armlengths
- **CircularRotating**: spacecraft on circular, inclined orbits; cw/ccw, time-evolving, causal armlengths
- **EccentricInclined**: spacecraft on eccentric, inclined orbits; cw/ccw, time-evolving, causal armlengths
- **NoisyLISA** (use with any LISA): adds white noise to armlengths used for TDI delays

**Class Wave**
Defines the position and time evolution of a GW source

- **SimpleBinary**: GW from a physical monochromatic binary
- **SimpleMonochromatic**: simpler parametrization
- **InterpolateMemory**: interpolate user provided buffers for $h_+, h_x$

**Class TDI(LISA, Wave)**
Return time series of noise and GW TDI observables (builds causal $y_{ij}$'s; includes first- and second-generation observables)

- **TDInoise**: demonstrates laser-noise subtraction
- **TDIsignal**: causal, validated vs. LISA Simulator
- **TDIfast**: cached for multiple sources (Edlund)
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Check the sensitivity of alternate LISA configurations...
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<tr>
<td>→ 1st-generation TDI</td>
</tr>
<tr>
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</tr>
<tr>
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<td>→ degradation of subtraction for imperfect knowledge of arms</td>
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Implements the LISA science process as a collection of C++ classes

**Class LISA**
Defines the LISA time-evolving geometry

- Produce synthetic time series to test data-analysis algorithms
- **ModifiedLISA:** stationary configuration, rotating with $T=1$yr; different cw and ccw armlengths
- **CircularRotating:** spacecraft on circular, inclined orbits, cw/ccw, time-evolving, causal armlengths
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Return time series of noise and GW TDI observables (builds causal $y_{ij}$'s; includes first- and second-generation observables)

- **TDI_noise:** demonstrates laser-noise subtraction
- **TDI_signal:** causal, validated vs. LISA Simulator
- **TDIfast:** cached for multiple sources (Edlund)
Running Synthetic LISA

Synthetic LISA is steered with simple Python scripts
What can we do with ten lines of code?

1. from lisaswig import *
2. from lisautils import *
3. lisa = EccentricInclined(0.0, 0.0)
4. noise = TDI_noise(lisa, 1.0, 2.5e-48, 1.0, 1.8e-37, 1.0, 1.1e-26)
5. wave = SimpleBinary(1e-3, 0.0, 0.0, 1e-20, 1.57, 0.0, 0.0)
6. signal = TDI_signal(lisa, wave)
7. noiseX = getobsc(2**16, 1.0, noise.Xm)
8. signalX = getobsc(2**16, 1.0, signal.Xm)
9. writearray('noise.txt', spect(noiseX, 1.0, 64))
10. writearray('signal.txt', spect(signalX, 1.0))
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Case study: laser-noise cancellation for noisy armlengths

In accordance with analytical estimates, the armlength-measurement tolerance needed for first-generation TDI is $\sim 50$ m, or $1.7 \times 10^{-7}$ s (residual laser noise is still present because of flexing).

But much depends on the model of the armlengths used to assemble the TDI observables. Using only linear extrapolation from the last two measurements… Paradoxically, it’s bad to measure too often!
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Signal Interpolation for TDI!

[D. Shaddock, B. Ware, B. Spero, MV, PRD 70, 081101(R) (2004)]

Suppression of laser noise to 1 part in $10^8$ with TDI requires arm-length delays to be specified with a precision of 100 ns. How do we get phase measurements at the right times?

The current approach is to trigger the phasemeters at the TDI delays:

- Knowledge of the arm-lengths is needed on the spacecraft and in real time
- Spacecraft clocks must be synchronized to 100 ns
- Errors in arm-length knowledge or synchronization lead to irreversible corruption of TDI combination

**Interpolation/post-processing** is the way:

- Sample phase measurements at (low) uniform rate; transmit the time series to Earth; apply the TDI delays by interpolating the time series; Assemble the TDI combinations in postprocessing
- Combining $n \sim 20$ Lagrange interpolation with oversampling (10 Hz for 2.5 Hz-bandlimited phasemeter output), only 2 s of data needed to form observables
- Ranging information not needed in real time
- TDI implemented in postprocessing allows flexibility to choose TDI schemes
- Might require higher data rates (larger dynamical range)
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Time-Delay Interferometric Ranging

[M. Tinto, MV, J. W. Armstrong, gr-qc/0410122]

As we said, the effective suppression of laser noise with TDI (to 1 part in $10^8$) requires knowledge of the armlength delays to 100 ns.

The current LISA baseline assumes that a dedicated inter-spacecraft ranging subsystem will provide the armlengths with the required precision.

Enter TDIR: since laser noise cancels in the TDI combinations assembled with the correct armlengths, find them by minimizing noise power in the TDI combinations!

From a similar idea by Gürsel and Tinto [1989]

TDIR is made possible by post-processed (interpolated) TDI

$$X_1 = \left[ (y_{31} + y_{13;2}) + (y_{21} + y_{12;3'})_2 + (y_{21} + y_{12;3'})_3 + (y_{31} + y_{13;2})_3 \right] + \cdots$$

TDI-imposed delays: for good noise removal, must match the physical propagation delays

$$y_{31} = C_{13;2} - C_{31} + S_{31}$$
A TDIR algorithm

→ Choose a TDI observable: 

\[ X_1 = X_1^{(0)} + X_1^{(n)} \]

Laser noise

→ The minimum of the laser-noise-only \( X_1 \) power gives the physical delays:

\[ I^{(0)}(\hat{L}_k) = \frac{1}{T} \int_0^T [X_1^{(0)}(\hat{L}_k)]^2 \, dt \]

→ The presence of secondary noise (and GWs)...

\[ I^{(n)}(\hat{L}_k) = \frac{1}{T} \int_0^T [X_1(\hat{L}_k)]^2 \, dt \]

\[ = I^{(0)}(\hat{L}_k) + \frac{1}{T} \int_0^T [X_1^{(n)}]^2 \, dt + \frac{2}{T} \int_0^T X_1^{(n)} X_1^{(0)}(\hat{L}_k) \, dt \]

...introduces an error \( \sim 30 \, \text{ns} = 9 \, \text{m} \) for \( T = 10,000 \, \text{s} \)

\[ \delta L_k \sim \left( \frac{\sigma X_1^{(n)}}{\sigma X_1^{(0)}} \right) \sqrt{\rho/T} \]

rms power

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TDIR: simulation results

True armlengths:

\[
L_k(t) = L + \frac{1}{32}(eL) \sin(3\Omega t - 3\xi_0) - \left[\frac{15}{32}(eL) \pm (\Omega RL)\right] \sin(\Omega t - \delta_k)
\]

Linear model (LM): intrinsic error 0.25-2.60 m

\[
\hat{L}_k(t) = \hat{L}_k^0 + \hat{L}_k^1(t - t_0)
\]

Orbital-dynamics model (ODM): search on \(eL, \Omega RL, \xi_0\)

Nelder-Mead search, initial errors \(\sim 50\) km (Earth-based ranging)

\[
\Delta L_k = \sqrt{\frac{1}{T} \int_{t_0}^{t_0+T} \left(\hat{L}_k(t) - L_k(t)\right)^2 dt.}
\]
TDIR: simulation results

- Secondary noise
- Laser-noise residual

Monochromatic sources

\[ \sim 5 \times 10^3 \]

\[ \sim \sqrt{2} \approx 2 \]
TDIR: conclusions

- With $T \sim 10,000$ s, TDIR allows the determination of the armlength delays with accuracy sufficient to suppress the laser noise $\sim 10^3$ below the secondary noises.

- The error induced in the reconstruction of GWs and secondary noises is:
  \[
  \sim \frac{dX_1^{(n)}}{dt} \times \delta L = (2\pi f \delta L) \times X_1^{(n)} \\
  \sim 2 \times 10^{-8} X_1^{(n)} (f / 1 \text{ Hz}) (\delta L / 1 \text{ m})
  \]

- Although an independent ranging system will probably be included in the LISA design, TDIR provides backup and fault tolerance.

- The armlength-delay determination can be optimized over the space of TDI observables.

- TDIR is conceptually distinct from conventional one-way and two-way ranging: it employs a phase-closure relation between the measurements of three spacecraft.

- Applicable in other missions that rely on formation flying?
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Black-hole binaries

- Total mass $10^3$–$10^6 \, M_\odot$, detectable out to $z \sim 5$–10
- In conjunction with EM detection, provide standard candle to measure equation of state of dark energy [Holz and Hughes, 2003]; accuracy limited by lensing
- If cosmological params well determined, study galaxy-MBH coevolution [Hughes, 2002]; “golden binaries” (insp.+ringdown) yield $E_{GW}$ [Hughes and Menou, 2004]
- Post-Newtonian inspiral and perturbative ringdown well understood, at least for nonspinning binaries
- Spin effects in adiabatic inspiral: Buonanno, Chen, Pan, Vallisneri [PRD, 2004 (two papers)] developed a family of physical signal templates to search for precessing, strongly spin-influenced NS-BH and BH-BH inspirals

Desiderata

- Merger waveforms! In the meantime: robust merger analysis algorithms [Brady and Majumdar 2004]; attention to reliability of waveforms [Miller 2003, 2004]
- Study entanglement of spin and distance measurements [MV+PBC, in progress]
- Study practicality of coherent matched-filtering detection: watch out for response modulation and confusion noise
Very complicated waveforms ($10^5$ cycles/y, 14 params) to be computed using BH perturbation theory, and event rates exceedingly uncertain

Very rich science payoff: map curvature of black-hole spacetimes, test no-hair theorems, get census of galactic cusp population

Study of detection prospects [Gair et al. incl. MV, CQG 21 (2004)]:

- assume matched filtering detection, evaluate CPU burden using kludge waves
- coherent search not possible: >$10^{13}$ templates for one month of integration
- stacked search: eliminate phases, thread dynamical parameters through stacks
- conclude $\sim 1000$ detections/lifetime probable out to $z = 1$

Recent developments

- Simpler TF power-excess detection for strongest events [Gair + Wen, in progress]
- IMBHs from runaway mergers in young stellar mass clusters [C. Miller, 2004]: IMBH-SMBH mergers (few/year?) visible without templates, test strong gravity
- Confusion noise from unresolved inspirals [Barack and Cutler, 2004]: weak to modest reduction of LISA sensitivity
Galactic binaries

- Guaranteed verification source, but their ensemble generates confusion noise between $10^{-4}$–$10^{-2.5}$ Hz
- Low number of cycles/year: when sources resolvable, coherent detection possible
- Analytical expression of the TDI responses and ML detection scheme available [Królak, Tinto, and MV 2004]

- Rule of thumb: confusion limit at one binary/bin ($f \sim 2 \times 10^{-3}$ Hz)
- gCLEAN [Larson and Cornish 2003]
- In practice: parameter uncertainty grows exponentially with # of binaries in bin; five-bin rule [Crowder and Cornish 2004]
- However: directionality of WD background [Seto and Cooray 2004, Tinto et al. 2004]

Desiderata

- Problem of orthogonality (baby/bathwater) in background subtraction
- Information-theoretical understanding of LISA resolving power
- Maximum-entropy/Bayesian methods
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→ A conclusion on simulation for LISA
Mock LISA Data Archive

- Hosted at astrogravs.nasa.gov (GSFC)
- Steering Committee: N. Cornish, J. Baker, M. Benacquista, J. Centrella, S. Hughes, S. Larson, M. Vallisneri
- Collect realistic time series of GW strains and of the LISA outputs, for use in developing and testing data-analysis algorithms

Formulate standard parameter conventions:
- Where is the source?
- Whence the LISA orbits?
- Which is the plus polarization?
- What is X?

As more contributions become available, will develop DB search and indexing capabilities

Organize mock data challenges

11/18/04  M. Vallisneri, Jet Propulsion Laboratory
The Mock LISA Data Input Format

```xml
<?xml version="1.0"?>
<!DOCTYPE XSIL SYSTEM "xsil.dtd">

<XSIL Name="GWPlaneWaveSource">
  <Param Name="EclipticLatitude" Unit="Degree">40.0</Param>
  <Param Name="EclipticLongitude" Unit="Degree">180.0</Param>
  <Param Name="SourcePolarization" Unit="Degree">0.0</Param>

  <Time Name="StartTime" Type="ISO-8601">2004-07-15 06:30:00.0</Time>
  <Param Name="Cadence" Unit="s">1.0</Param>
  <Param Name="Duration" Unit="s">65536.0</Param>

  <Array Name="hp" Type="double">
    <Dim Name="Length">65536</Dim>
    <Dim Name="Records">1</Dim>

    <Stream Type="Remote" Encoding="Bigendian">
      hp.bin
    </Stream>
  </Array>
</XSIL>
```

→ An application of **XSIL** (extensible scientific interchange language; also used as **LIGO_LW**)

→ Easily parsed by machine and human (web browsers, DBs)

→ Inline or externally linked data

→ Read/written by **LISA Simulator** and **Synthetic LISA**
Why simulations?

- The LISA response is **complex**
- **Honest** time-domain simulations can:
  - Take over where analytical treatments become unwieldy
  - Increase our trust in analytical insights
  - Point out the unexpected
- **Uses of simulation:**
  - Development and testing of data-analysis schemes and algorithms
  - **Performance** characterization and architecture tradeoffs
  - Interface between scientific and technical mission requirements
  - Time-domain studies of noise and vetos
- **The future of simulation:**
  - Waveform repositories (astrogravs), data formats, mock data challenges
  - Interface/incorporate technical simulations, experimental measurements
  - Requirement flowdown automation?
  - LISA stand in: prototyping of data-management system
  - Investigate other missions and geometries