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<td>John Armstrong</td>
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See page 3 for instructions for completing this form.
Synthetic LISA
simulating time-delay interferometry
in a model LISA

(presenting) Michele Vallisneri
(in absentia) John W. Armstrong
LISA Science Office, Jet Propulsion Laboratory
12/17/2003
Why Synthetic LISA?

• Simulate LISA fundamental noises at the level of science/technical requirements
  • Higher level than extended modeling (no spacecraft subsystems)
  • Lower level than data analysis tools (do time-domain simulation of TDI; include removal of laser frequency fluctuations)

• Provide streamlined module to filter GWs through TDI responses, for use in developing data-analysis algorithms
  • Include full model of TDI (motion of the LISA array, time- and direction-dependent armlengths, causal Doppler observables, 2nd-generation TDI observables)
  • Use directly or to validate (semi)analytic approximations

• Make it friendly and fun to use
A LISA block diagram (very high level!)

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

LISA noises
laser freq. fluctuations, (optical bench), 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
A LISA block diagram (very high level!)

\[
X = U^{32,322} - U^{23,233} - U^{31,22} - U^{21,33} + U^{23,2} - U^{32,3} + U^{21} - U^{31}
- \frac{1}{2}(U^{21,2233} + U^{21,33} + U^{21,22} - U^{21})
- \frac{1}{2}(U^{31,2233} - U^{31,33} - U^{31,22} + U^{31})
\]

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

\[
\alpha = U^{21} - U^{31} + U^{13,2} - U^{12,3} + U^{32,12} - U^{23,13}
- \frac{1}{2}(U^{213,2} + U^{213,3} + U^{21} - U^{21,123} + U^{32,3} + U^{32,12})
+ \frac{1}{2}(U^{223,2} + U^{23,13} + U^{31} - U^{31,123} + U^{12,3} + U^{12,12})
\]
A LISA block diagram (very high level!)

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

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

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

**photon propagation vector**
GW TT tensor

$$\Psi_l(t) = \frac{\hat{n}_l \cdot h(t) \cdot \hat{n}_l}{2[1 - (\hat{k} \cdot \hat{n}_l)^2]}$$

geom. projection factor

**GW buffeting of spacecraft**
s at emission (t-$L_t$

geom. projection factor

wavefront retard.; $p_i$ are spacecraft pos.

$$y_{l}\rightarrow (t) = y_{(s)lr}(t) = \left[1 + \epsilon_{slr} \hat{k} \cdot \hat{n}_l \right] (\Psi_l(t - \hat{k} \cdot \hat{p}_s - L_l) - \Psi_l(t - \hat{k} \cdot \bar{p}_r))$$

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GWDAW 2003: Michele Vallisneri on Synthetic LISA
A LISA block diagram (very high level!)

Doppler shift measured for reception at spacecraft 1 and emission at spacecraft 3 (laser travels along arm 2)

LISA noises
laser freq. fluctuations, (optical bench), proof mass, optical path

\[ y_{21} = C_{3,2} + 2pm^*_1 - C^*_1 + y_{21}^{\text{opt path}} \]

proof-mass 1 noise

\[ z_{21} = C_1 + 2pm_1 - C_1^* \]

fluctuations of lasers 1 and 1*

fluctuations of laser 3 at emission (t - L_2)
fluctuations of laser 1* (reference) at reception (t)

inter-spacecraft relative frequency fluctuations
intra-spacecraft relative frequency fluctuations

Doppler shift measured between optical benches on spacecraft 1

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For laser noise, use combination of Markov chain (exp(-\lambda t)) then interpolate uncorrelated white noise produced at fixed sampling time.

Covariance in the time domain by applying digital filters in

Assume Gaussian, \( f_2 \), white

LISA noises: 16 time series (6 root mass + 6 optical path + 6 laser)

LISA noises

A LISA block diagram (very high level)
A LISA block diagram (very high level!)

Motion complicates GW signals (1):
- by changing orientation of LISA plane (power spread through ~9 bins)
- by Doppler-shifting incoming GW signals (due to relative motion, dominates for f > 10^{-3} Hz; bandwidth ~ (ΩR/c)f)

Motion improves sensitivity to GW (1):
- to source position and polarization
- makes it homogeneous in the sky

Motion hinders noise suppression (1,2,3):
- need accurate knowledge of armlengths
- high-order time delays needed

1. One Solar orbit/yr; LISA triangle spins through 360°/orbit
2. Armlengths deviate from equilateral triangle at ~2%
3. Armlengths are time and direction dependent

LISA geometry
spacecraft positions → photon propagation → armlengths
The Synthetic LISA package

Implements the LISA block structure 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 $h_+, h_x$

...
The Synthetic LISA package

...things to do with it right now!

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

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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...

Check the sensitivity of alternate LISA configurations

Class **TDI(LISA, Wave)**
Return time series of noise and GW TDI observables (builds causal $y_{ii}$'s; includes 1st- and 2nd-generation observables)

**TDInoise:** demonstrates laser-noise subtraction

**TDIsignal:** causal, validated vs. *LISA Simulator*

**TDIfast:** cached for multiple sources (Edlund)

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The Synthetic LISA package

...things to do with it right now!

**Class LISA**
- Defines the LISA time-evolving geometry (positions of spacecraft, armlengths)
  - **OriginalLISA**: static configuration with fixed (arbitrary) armlengths
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  - **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**
- Demonstrate laser-noise sub.:
  - 1st-generation TDI
  - modified TDI
  - 2nd-generation TDI
  - degradation of subtraction for imperfect knowledge of arms with armlocking

**Class TDI(LISA, Wave)**
- Return time series of noise and GW TDI observables (builds causal y's; includes 1st- and 2nd-generation observables)
  - **TDInoise**: demonstrates laser-noise subtraction
  - **TDIsignal**: causal, validated vs. LISA Simulator
  - **TDIfast**: cached for multiple sources (Edlund)
The Synthetic LISA package

...things to do with it right now!

Class **LISA**
- Produce synthetic time series to test data-analysis algorithms
  - **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 $h_\nu$, $h_x$

Class **TDI**(LISA, Wave)
- Return time series of noise and GW TDI observables (builds causal y_i's; includes 1st- and 2nd-generation observables)
  - **TDInoise**: demonstrates laser-noise subtraction
  - **TDISignal**: causal, validated vs. LISA Simulator
  - **TDIfast**: cached for multiple sources (Edlund)
Using Synthetic LISA

The preferred interface to Synthetic LISA is through a simple script in the language Python.

This is a Python script!

```python
#!/usr/bin/python
import lisaswig;
unequalarmlisa = lisaswig.OriginalLISA(15.0,16.0,17.0);
Create a LISA (geometry) object;
use static LISA, with unequal arms
Armlengths (s)
unequalarmnoise = lisaswig.TDInoise(unequalarmlisa,
1.0,2.5e-48,1.0,1.8e-37,1.0,1.1e-26,1.0);
Create a TDI object based on our chosen LISA
Laser correlation (s)
lisaswig.printtdi("noise-X.txt",unequalarmnoise,1048576,1.0,"X");
Print X TDI noise to disk!
Noise sampling time (s)
Proof mass S_n x f^2 (Hz^{-1})
Opt. path S_n x f^2 (Hz^{-1})
Laser S_n (Hz^{-1})
File name # samples requested, sampling time
TDI variables to print
```
Example: unequal-arm 1st-gen. noises

Note laser noise subtraction!

\[
\begin{align*}
lisawig.printtdi("noise-a.txt",unequalarmnoise,1048576,1.0,"a"); 
lisawig.printtdi("noise-z.txt",unequalarmnoise,1048576,1.0,"z"); 
lisawig.printtdi("noise-E.txt",unequalarmnoise,1048576,1.0,"E");
\end{align*}
\]
Example: noisyLISA subtraction

\begin{align*}
\text{originallisa} &= \text{lisawig.OriginalLISA}(16.6782, 16.6782, 16.6782) \\
\text{noisyli} &= \text{lisawig.NoisyLISA}(\text{originallisa}, 1.0, \text{measurement noise}) \\
\text{originalnoise} &= \text{lisawig.TDINoise}(\text{originallisa}, \quad \text{measurement noise } S_n (s^2 Hz^{-1}) \\
&\quad 1.0, 2.5e-48, 1.0, 1.8e-37, 1.0, 1.1e-26, 0.1) \\
\text{noisynoise} &= \text{lisawig.TDINoise}(\text{noisyli}, \text{originallisa}, \quad \text{Use different LISA for noise and TDI delays} \\
&\quad 1.0, 2.5e-48, 1.0, 1.8e-37, 1.0, 1.1e-26, 0.1) \\
\end{align*}
Example: monochromatic binary

- $f = 2 \, \text{mHz}$
- $T = 1 \, \text{yr}$

- Ecliptic latitude: $\pi/2$
- Ecliptic longitude: $0$

- Lat.: $\pi/5$
- Long.: $\pi/3$

---

```python
mylisa = lisawig.CircularRotating(0.0, 0.0, 1.0)  # LISA array parameters
mybinary = lisawig.SimpleBinary(frequency, initial_phase, inclination, amplitude,
                                ecliptic_latitude, ecliptic_longitude, polarization_angle)

mysignal = lisawig.TDIsignal(mylisa, mybinary)    # samples requested, sampling time
lisawig.printtdi("signal-X.txt", mysignal, secondsperyear/16.0, 16.0, "X")
```
Comparison with LISA Simulator

TDI X (no noise), T = 1 yr

\[ f = 1.94 \text{ mHz} \]
\[ \text{inc} = 1.60 \]
\[ \text{ecliptic lat.} \approx 0, \text{ long.} = 0 \]
Case study: S/Ns for extreme-mass ratio inspirals

Hughes-Glampedakis-Kennefick integrator (C++): output \( h_+ \), \( h_x \)

(Python)

Synthetic LISA: generate A, E, T, X GW & noise time series

Matlab: compute S/Ns

12/17/2003

GWDAW 2003: Michele Vallisneri on Synthetic LISA
Summary!

- *Synthetic LISA* is the package I would have wanted to download and use, had I not written it.
- *Synthetic LISA* simulates LISA fundamental noises and GW response at the level of science/technical requirements.
- *Synthetic LISA* includes a full model of the LISA science process (2nd-generation TDI, laser-noise subtraction).
- *Synthetic LISA*’s modular design allows easy interfacing to extended modeling and data-analysis applications.
- *Synthetic LISA* is user-friendly and extensible (C++, Python, other scripting languages).
- *Synthetic LISA* is planned for open-source release in Jan/Feb (NASA permitting).
Synthetic LISA
simulating time-delay interferometry
in a model LISA

Michele Vallisneri
Jet Propulsion Laboratory
12/17/2003