# The Mock LISA Data Challenges: first results and future prospects

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The LISA International Science Team Working Group on Data Analysis is sponsoring several rounds of **mock data challenges**, with the purpose of fostering development of LISA data-analysis capabilities, and of demonstrating technical readiness for the maximum science exploitation of the LISA data.

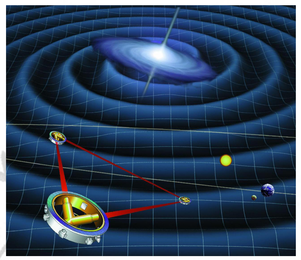
The **first round was completed** at the end of 2006, and the second round of challenge data sets is being **released now**. Here we present a critical overview of the first results and discuss the future steps in this effort.

## Introduction

The **Laser Interferometer Space Antenna** (LISA) is a spaceborne gravitational-wave (GW) observatory planned jointly by NASA and ESA, and designed for detailed studies of a wide variety of GW sources throughout the Universe, in the frequency range 0.1 mHz–0.1 Hz.

LISA is an **all-sky monitor** with the capability of measuring source parameters such as masses, spins, and distances with **unprecedented precision**. The LISA data set is expected to contain a large number (~ $10^4$) of resolvable overlapping sources, ranging from galactic subsolar-mass binary systems to high-redshift massive black-hole binaries; in addition, LISA has the potential of discovering radically new classes of GW sources, such as primordial stochastic backgrounds, cosmic strings, and exotic compact objects.

Most sources detectable by LISA are long lived (> two years) compared to the mission lifetime, and the LISA data will contain **strong GW foregrounds** generated by **abundant populations** of galactic and extra-galactic white-dwarf binary systems, and possibly of solar-mass compact objects captured by massive black holes in galactic nuclei. There is no established expertise for this kind of data, although much relevant experience has already been gained in the analysis of GW data collected by ground-based detectors. In ground-based observations GWs are rare and weak, whereas in the low-frequency band they are **numerous** and (a fair fraction of them) yield **high signal-to-noise ratios** (SNR). It is therefore vital, in preparation for the mission, to tackle these new analysis problems early, in order to develop the tools and methods necessary for the maximum science payoff from such a revolutionary data set.



*LISA is a constellation of three drag-free spacecraft, separated by* 5x$10^6$ km, *and flying on an Earth-trailing solar orbit.*

*Gravitational waves are detected in the* $10^{-5}$–$10^{-1}$ Hz *band as a modulation of the distance between spacecraft by picometer interferometry.*

The LISA International Science Team is sponsoring several rounds of **Mock LISA Data Challenges** (MLDCs), with the dual purpose of fostering the **development of LISA data-analysis tools** and capabilities, and of **demonstrating the technical readiness** already achieved by the GW community in distilling a rich science payoff from the LISA data output. The MLDCs were discussed at meetings organized by the US and European LISA Project, which were attended by a broad cross section of the international GW community.

The challenges involve the distribution of several data sets containing combinations of **realistic simulated LISA noise** with the signals from **one or more GW sources** of parameters unknown to the challenge participants, who are asked to return the maximum amount of correct information about the sources, and to produce technical notes detailing their work. These challenges are meant to be **blind tests, but not really contests**; their greatest scientific benefit comes from the quantitative comparison of results, analysis methods, and implementations.

A **MLDC Task Force** has been working since the beginning of 2006 to:

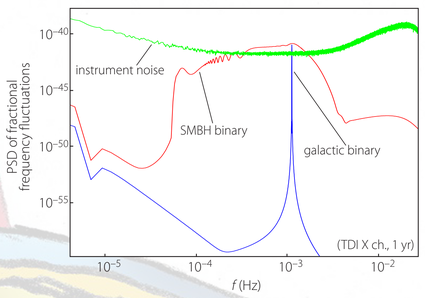
- develop a series of **progressively more difficult** MLDCs;
- select a simple set of **physical conventions** for the LISA orbits, noises, and measurements;
- choose representative theoretical models for the **LISA GW sources**;
- provide **software tools** to generate waveforms and simulate the LISA response and noises;
- create an **XML-based data format** to distribute the datasets;
- distribute **training** and **challenge data sets**;
- administer the MLDCs and **evaluate solutions**.

## Challenge 1

released June 2006, due Dec 2006

The first round of challenges was aimed at enabling the development of the building blocks necessary for simple LISA data-analysis tasks. It focused on data sets containing a **single source** (generally with moderate-to-high SNR), or a **small number of sources** that did not overlap in the frequency domain, except for two data sets containing a few tens of galactic binary systems with radiation overlapping significantly in a small frequency region (i.e., a taste of the LISA source confusion problem).

The first round of challenges concentrated on sources currently listed as minimum science requirements: **galactic binaries** (including **verification** binaries), and **supermassive black-hole (SMBH) binary systems**. All data sets were one-year long, and contained instrumental noise modeled as Gaussian and stationary, with the assumption that laser frequency noise had been removed perfectly. For simplicity, no foreground radiation from the Galactic binary population was included.




*In addition to the* blind *challenge data sets,* training *sets with known parameters, with and* without instrument noise, *were also provided to allow participants to validate their searches.*

*This figure shows power spectral densities for the* ~1 mHz–*binary and strong–SMBH-binary training sets, and for representative instrument noise.*

participating collaborations per challenge data set

| | | Albert Einstein Institut Golm | NASA Ames | APC Paris | NASA Goddard | Glasgow–Carleton–Auckland–Birmingham | IMPAN Warsaw | NASA JPL–Caltech | Montana–AEI | Montana–NASA JPL | U. Texas Brownsville |
|---|---|---|---|---|---|---|---|---|---|---|---|
| individual binary | ~ 1 mHz | • | • | • | | | • | | • | • | |
| | ~ 3 mHz | • | • | | | | • | | • | • | |
| | ~ 10 mHz | • | | | | • | • | | • | • | |
| 5 known, 15 mock **verification binaries** | 0.5–12 mHz | • | • | | | | | | • | • | |
| 20 non-overlapping **resolvable binaries** | 0.1–1 mHz | • | • | | | | • | | • | • | |
| **source confusion**: ~ 50 binaries | ± 15 μHz band around 3 mHz | • | | | | | | | • | • | |
| **severe source confusion**: ~ 40 binaries | ± 1.5 μHz band around 3 mHz | • | | | | | | | • | • | |
| **nonspinning SMBH binary**, coalescing ~ 6 months | $m_1, m_2 < 5\times10^6$ $M_\odot$, SNR ~ 500 | | | • | | | • | • | | | |
| **nonspinning SMBH binary**, coalescing ~ 1 month beyond dataset | $m_1, m_2 < 5\times10^6$ $M_\odot$, SNR ~ 20–100 | | | • | | | | • | | | |

**Ten collaborations submitted results** for Challenge 1 (a few other groups developed analysis pipelines, but did not make the deadline). Each MLDC data set, including the two containing an unknown number of overlapping sources, was analyzed by at least two groups.

Several techniques were pursued, including matched filtering (in **bank**-based, **Markov Chain Monte Carlo**, and **genetic** varieties), **tomographic reconstruction**, the **Hilbert transform**, and other **time-frequency** methods. In some cases these were used in hierarchical combinations.

Most reports emphasize that the participating groups have **just begun the process** of implementing these searches. Nonetheless, **for each data set at least one entry** (in several cases more than one) **produced correct results**, including the most challenging data set containing overlapping sources.

A comparison of techniques is not yet possible (or wise), but the results of the initial MLDC are reassuring on the wealth of information that will become available in further challenges to compare and assess different approaches.

Because instrument noise skews the estimates of source parameters, simply comparing the parameter values provided by the participants to their true values is not sufficient to **evaluate search-algorithm performance**. (Nevertheless, the errors are reassuringly small, and comparable to theoretical predictions.)

Instead, we can rely on **metrics** that measure the amount of signal power recovered by the reconstructed signal,

$$\mathrm{SNR} = (s|h_{\mathrm{rec}}) \,/\, (h_{\mathrm{rec}}|h_{\mathrm{rec}})^{1/2},$$

(noise-weighted correlation products)

the normalized correlation between the true and reconstructed noise-free signals,

$$C = (h_{\mathrm{key}}|h_{\mathrm{rec}}) \,/\, [\,(h_{\mathrm{key}}|h_{\mathrm{key}})^{1/2}\,(h_{\mathrm{rec}}|h_{\mathrm{rec}})^{1/2}\,],$$

and a $\chi^2$-like quantity that compares the discrepancy between the true (noisy) and reconstructed (noise-free) signal to what is statistically expected from noise,

$$\chi^2 = (s - h_{\mathrm{rec}}|s - h_{\mathrm{rec}}) \,/\, (N - D).$$

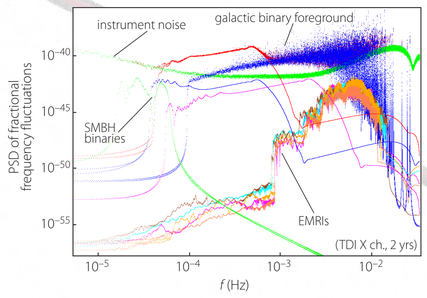
(dimension of parameter space)

| | $\Delta f$ (nHz) | $\Delta\theta$ (rad) | $\Delta\varphi$ (rad) |
|---|---|---|---|
| Montana–JPL (MCMC) | –1.37 | –0.015 | –0.0083 |
| Montana–JPL (genetic) | –1.04 | –0.013 | –0.0027 |
| AEI | –1.21 | –0.018 | –0.0008 |
| IMPAN | 0.98 | 0.028 | –0.0077 |
| APC | 1.34 | 0.030 | 0.0106 |
| Ames | –1.89 | –1.159 | 3.1270 |
| Brownsville | –3.21 | 0.142 | 0.6030 |

*Source parameter errors for the* 1-mHz–*binary data set.*

| | $\chi^2$ | SNR | C |
|---|---|---|---|
| Key file | 0.926 | 529.4 | 1.0000 |
| Montana–JPL (MCMC) | 0.934 | 523.4 | 0.9885 |
| Montana–JPL (genetic) | 0.951 | 505.0 | 0.9539 |
| AEI | 1.114 | 330.4 | 0.6250 |
| Ames | 0.956 | 501.7 | 0.9479 |

*Statistical assessment of solutions to the verification-binary dataset.*




*Power spectral density of a representative Challenge-2 dataset, broken up by GW source type.*

## Challenge 2

released Jan 2007, due Jun 2007

The second round of challenges will be a key milestone in this program. The goal is to build on the standard, tools, and experience of Challenge 1 to tackle the **global-analysis problem** of LISA data analysis: **sources overlap and interfere** in the time and frequency domains, so it can become difficult or impossible to distinguish them without skewing the estimates of their parameters; a strong signal may even obscure a weaker signal entirely.

Challenge 2 consists of two data sets, each two years long: the first includes a **full-scale Galactic model** (**30 million** white-dwarf binaries, drawn from a Nelemans–Yungelsen–Zwart population model, and approximated as circular and monochromatic), plus instrument noise; the second adds **4–6 SMBH binaries**, coalescing at different times and building up different SNRs, and **5 extreme–mass-ratio inspirals** (EMRIs), chosen within a restricted parameter space to obviate computational cost, and represented by the analytic Barack–Cutler waveforms.

## And on...

Later challenges will include **new LISA source classes**, such as cosmic-string bursts and cosmological stochastic backgrounds; they will feature **increasingly accurate waveforms** (e.g., chirping galactic binaries, SMBH binaries with spins and numerical-relativity–inspired mergers and ringdowns) in more extensive parameter ranges; and they will contain **more realistic instrument noise** (e.g., including data gaps, non–Gaussianity and non-stationarity).

"**Re-dos**" of previous challenges are also being envisaged, to allow more research groups to get into the game at a later time, without having to immediately tackle the complexity of the later challenges.

**You are all invited to participate!** For info, e-mail **vallis@caltech.edu**.

## Web resources

NASA LISA site:
**lisa.nasa.gov**

LISA International Science Community:
**www.lisascience.org**

MLDC official site:
**astrogravs.nasa.gov/docs/mldc**

MLDC taskforce wiki:
**www.tapir.caltech.edu/listwg1b**

MLDC software repository:
**sourceforge.net/projects/lisatools**

## Bibliography

K. A. Arnaud et al. (the MLDC Task Force), "The Mock LISA Data Challenges: An overview," and "A how-to for the Mock LISA Data Challenges," in proceedings of the 6th International LISA Symposium, Jun 19-23 2006, GSFC, Greenbelt, MD (AIP, 2006). gr-qc/0609105, gr-qc/0609106

K. A. Arnaud et al. (the MLDC Task Force and the Challenge-1 participants), "Report on the first round of Mock LISA Data Challenges," in proceedings of the 11th Gravitational-Wave Data-Analysis Workshop, Dec 18–21 2006, Potsdam, Germany. In preparation.

K. A. Arnaud et al. (the MLDC Task Force), "An overview of the second round of Mock LISA Data Challenges," in proceedings of the 11th Gravitational-Wave Data-Analysis Workshop, Dec 18–21 2006, Potsdam, Germany. In preparation.

## Image credits

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