Quantification of Uncertainty in Identifying and Extracting Gravitational Wave Signals from Astrophysical Sources using LISA

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Earth environments are very noisy and mask the ultra-low frequency and amplitudes of gravitational wave signals from space. Some of the more catastrophic astrophysical events may produce gravitational waves that are detectable at ground level at the various LIGO observatories. But the bulk of sources from white dwarf binaries and inspiraling extreme mass ratio systems emit gravitational radiation at frequencies and amplitudes that are undetectable on Earth. Hence, NASA plans to launch, as part of its Beyond Einstein programmatic plans, a group of three satellites that make up the Laser Interferometer Space Antenna [LISA] to acquire the fainter signals prevalent throughout the more quite universe. The target amplitudes spectral density of these events are on the order of 10^{-21} in the units of "per root square Hertz." The frequencies run between $3x10^{-5}$ and 10^{-1} Hertz. Some source noise is understood in these ranges; some physics and signal production is also understood there; LISA instrument and shot noise is very well documented and modeled there. The LISA Mission as planned consists of three dual-interferometers arranged as a "floating" equilateral triangle, with each spacecraft [s/c] separated by 5 million kms [roughly 16 light seconds]. LISA resides on Earth's solar orbit, trailing Earth by 20 degrees in heliocentric coordinates, and at an inclination of 60 degrees to the ecliptic. It "cartwheels" fully once per orbit [year], with the zero coordinate being the Vernal Equinox [first point of Ares]. The equilateral triangle is maintained by laser ranging and very quiet orbit adjustments in each s/c. This configuration detects both gravitational radiation plus galactic noise.

There are generally three types of uncertainty involved in detection of gravitational waves with LISA, some of which will be resolved following launch. However in preparation for launch [roughly 2010], uncertainty must be understood and managed on these three fronts. First, there is an *Uncertainty in the Physics* of astrophysical source gravitational radiation production, and this is being regularly improved through funded projects that create better models and synthetic data. Second, there is an *Uncertainty in the Simulators* themselves – two main simulators are part of the LISA Science Team toolkit, one that produces data sets relative to frequency [LISA Simulator] and the other that produces data relative to signal phase [Synthetic LISA]. These systems are the basis of the continuing Mock LISA Data Challenges by which scientist develop and test algorithms for both signal extraction and parameter search methods. Our Team works primarily with LISA Simulator data; but we do not have control of the simulated datasets by which to establish uncertainty methods or quality belief methods. Third, there is an *Uncertainty in the Signal Extraction* from the Mock LISA s/c datasets. These simulation datasets consist of 1 year of LISA 3-s/c data at 15 second cadence. Parameter extraction includes source frequency [center for search], sky location [right-ascension and declination], then various parameters relative to the orientation and phase of the binary source. Inspiraling systems add several other time-dependent parameters. In this paper we focus on our methods of quantifying the uncertainty in our signal identification and extraction methods in the Simulations, and in regulating our iterative search through parameter space, usually driven by signal-to-noise ratios and maximum log-likelihood.

Identifying a complex signal is a key challenge because of the ultra-low frequencies and amplitudes. However, once the signal frequency-group is identified, the direction of the source, type of the source, phase and inclination of the source are vital to fill out the parameter space. The simplest form of identifying a signal is based on FFT. The "center" frequency of the signal must be identified to at least 8-digit accuracy in order to search other source parameters unambiguously. A probable frequency bin is identified to constrain parameter search for sky-location, phase, inclination, and amplitude. This process is highly CPU and memory intensive, and is constrained by SNR and log-likelihood surfaces in the parameter space. The uncertainty involved in identifying the signal and its frequency-structure, even based on FFTs, is a great challenge. FFTs cannot separate complex interfering signals or chirps from time-dependent events [like extreme mass ratio inspirals]. These time-evolving events create chirp signals. Complex chirp signals are identified using Wigner-Ville distribution. The Wigner distribution provides time and frequency evolution contour plots that provide details of the evolving chirp signals. The start and end of a chirp [coalescence, merger, and ringdown], time-varying chirps, and various multiple interleaved chirps have to be identified and extracted from each detected signal f-bin. Various ancillary windowing techniques are applied to extract and characterize chirp signals. The above signal processing techniques identify and extract the signals, but in reality they may not represent true signals from the sources due to knowledge-variability and uncertainty. In this paper, we apply Dempster-Shafer theory of evidence and belief network concepts to existing waveforms databases and the simulated datasets. Knowledge of these probability distributions reduce the inherent uncertainty and lend confidence to the analysis.

The probabilities are derived using the existing waveforms and sources databases maintained by LISA Team. Probabilities have to be reassigned when more information is available regarding specific waveforms or sources. This constitutes a validation approach and reduces the uncertainty; the validation of reduction of uncertainty is an iterative procedure. The specific techniques, lessons learned, and novel solutions for both gravitation radiation waveform extraction and the attendant additional parameter search is described, and the uncertainty management discussed, in the full paper.