GRAVITATIONAL-WAVE DATA ANALYSIS FROM EARTH TO SPACE: COMPUTATIONAL AND THEORETICAL CHALLENGES

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The Laser Interferometer Space Antenna (LISA) is a joint NASA–ESA deep-space mission consisting of three drag-free spacecraft, separated by 5×10^6 km and following an Earth-trailing solar orbit;[1] LISA will use picometer interferometry to measure the modulations in the inter-spacecraft distances induced by gravitational waves (GWs) of frequency between 10^{-5} and 1 Hz. LISA will seek to detect GWs from binary systems of compact stellar objects in our galaxy,[2] from the inspiral and merger of binaries of massive and supermassive black holes,[2] and from the capture of compact stellar objects into the supermassive black holes at the center of galaxies;[3] it will also set new constraints on background GWs from the early universe,[4] and naturally (but perhaps most interestingly) it will be sensitive to GWs from previously unknown sources within its frequency band.

LISA is expected to start collecting data around 2013 (two years after its launch); thus, its deployment will trail by at least ten years the beginning of science operations for ground-based GW interferometers[5] such as LIGO, GEO, Virgo, and TAMA. At the time of writing, these experiments have begun generating result papers with upper limits[6] on the distribution of sources and GW events; more importantly, they can rely on highly developed technical literature and individual expertise on the characterization and operation of detectors, the handling and analysis of data, and the astrophysics and waveform modeling of sources. It follows that the theoretical activity on LISA is likely to be modeled, at least initially, on the tools and techniques developed for the ground-based detectors (henceforth, GBDs).

LISA and GBDs have remarkable similarities, but crucial differences. They look at the same (or similar) sources from different windows in the frequency spectrum (10^{-5}–1 Hz for LISA, 10–10^3 Hz for GBDs): consequently, the LISA data set will consist of $\sim 10^7$ samples/year, while the GBDs are now collecting a rather more daunting $\sim 10^{11}$ samples/year. Thus, the search for continuous, quasi-monochromatic sources of unknown position (e.g., galactic binaries for LISA, and spinning, asymmetric neutron stars for GBDs), will be much less computationally taxing for LISA than it is for GBDs. This asymmetry is partially offset for chirping sources such as inspiraling binaries, which will transit slowly through the LISA frequency band, while they move rapidly (in hours or minutes) in and out of the

GBD frequency band.

As soon as it is switched on, LISA is expected to be sensitive to many GW sources; so many, in fact, that at some frequencies they will cease to be resolvable individually, and they will instead conspire to create a stochastic background[2] that will act as *confusion noise* to complicate the detection of sources in the foreground. By contrast, waveforms detectable by GBDs will be sparse and well separated[7] (in time, frequency, or functional space). Last in this comparison, GBDs in different geographic locations can be operated *as a network*, enhancing the signal-to-noise ratio of single-detector observations, and their sensitivity to source distance, position, and GW polarization;[8] while LISA is not likely to be joined by other space-borne detectors in the near future, the interferometric measurements between the three spacecraft can be combined into three independent observables with different antenna patterns,[9] creating in effect a virtual network of detectors with increased signal-to-noise ratios, and improved position and GW polarization sensitivities.

The LISA International Science Team has compiled a list of computational challenges for LISA data analysis,[10] which span all the major classes of GW sources. Here we review them briefly, with an eye to what can be learned from the experience gained on GBDs. For the galactic binaries of compact objects, the computational challenge is to formulate efficient data-analysis algorithms to subtract[a] a thick superposition of these sources from the LISA data; the efficiency of subtraction will set the *confusion-limit* frequency (probably around a few mHz) where these sources merge into unresolved background noise.[11]

For massive and supermassive black-hole binaries, the computational challenge is to develop reliable models for the waveforms from the inspiral and merger of the binary. In fact, the same models, scaled up to higher frequencies, are necessary to detect stellar-mass black-hole binaries with GBDs. The inspiral is well understood in its early stages, if the effects of black-hole spins are negligible; less so in the late stages that precede the final plunge, and when the spins induce significant precession of the orbital plane.[12] On the other hand, the simulation of black-hole mergers continues to present formidable obstacles for numerical-relativity codes.[13]

For extreme–mass-ratio capture sources,[3] the computational challenge is to obtain accurate signal templates for the very complicated GW signals generated by these system, and to reduce the prohibitive computational burden of a full matched-filtering search[14] by breaking apart the signal into short *stacks*, in analogy to pulsar searches for GBDs.[15] As for stochastic GW backgrounds, LISA will not search for them by cross-correlating the output of independent detectors, as commonly done for GBDs:[16] while LISA does offer multiple independent interferometric channels,

[a]In fact, it is probably misleading to frame this problem in terms of source *subtraction*: galactic-binary waveforms will not be functionally orthogonal to other signals in the same frequency band (such as the chirping waveforms of supermassive black-hole inspirals), so inconditional subtraction would remove also the foreground signals. Rather, effective searches will probably need to look *simultaneously* for background and foreground signals in the same band.

these have essentially orthogonal responses with respect to isotropic signals. An alternative proposed method[17] would compares the standard LISA interferometric combination to a peculiar combination (ζ) that is not sensitive to GWs.

We conclude by emphasizing that LISA poses peculiar challenges and promises exciting opportunities, which we should address using all the experience gained on GBDs, but looking ahead and beyond.

Acknowledgments. This research was supported by the LISA Mission Science Office at the Jet Propulsion Laboratory, California Institute of Technology, where it was performed under contract with the National Aeronautics and Space Administration.

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