I. INTRODUCTION

Science analysis is the process by which observations are transformed into scientific insight and understanding. In the same way that even the most artful analysis cannot compensate for poor data, so even the best instruments and observational skill can compensate for an inability to adequately analyze the data. LISA is no exception.

Exactly because LISA is a pathfinder for a new scientific discipline — gravitational wave astronomy — LISA data processing and science analysis methodologies are in their infancy and require considerable maturation if they are to be ready to take advantage of LISA data. Here we offer some thoughts, in anticipation of the LISA Science Analysis Workshop, on analysis research problems that demonstrate the capabilities of different proposed analysis methodologies and, simultaneously, help to push those techniques toward greater maturity. Particular emphasis is placed on formulating questions that can be turned into well-posed problems involving tests run on specific data sets, which can be shared among different groups to enable the comparison of techniques on a well-defined platform.

The questions, from which demonstration problems can be posed, are organized by source type. Accompanying each set of questions is a short discussion meant to provide context and motivation for the questions that follow.

II. TECHNOLOGY READINESS LEVELS

One way to measure the maturity of LISA data processing and science analysis technology techniques is to use the NASA Technology Readiness Level (TRL) metric. TRLs provide a systematic measurement of the maturity of a particular technology (hardware or software) relative to mission goals. Table I describes the NASA TRLs for software. When LISA science data becomes available the software necessary for data processing and science analysis related to LISA science requirements should be at least TRL 7 and preferably TRL 8. When LISA science results are released the software should be at TRL 8.

We are aware of no LISA analysis methodologies beyond TRL 2 and the principal goal of the questions posed here is to point the way toward elevating the TRL level of LISA analysis technology. For these questions to be useful in this regard they must be attuned to the present level of analysis sophistication. Thus, the problems described here are focused on demonstrating capability at the level of TRL 2 or TRL 3. Later demonstration problems will focus on further developing data processing and science analysis technologies to higher TRLs.

III. VERIFICATION BINARIES

The verification binaries are a unique subset of the resolved galactic binaries described in the next section. Verification binaries are systems that have been identified pre-science operation and that are well characterized through more traditional astronomical observations. This characterization of the verification binaries makes it possible make it possible to accurately predict the strength, polarization, and propagation direction of the gravitational waves from the source. LISA’s response and function can thus be verified from its observations of these systems.

The verification sources will be among the first targets in a search of the LISA data. The results of those searches will be used to validate and confirm the performance and expectations for the software, instrumental noise, and hardware performance of the observatory. As such, these binaries will play a vital role in characterizing early LISA performance, and specific analysis will need to be developed to address this special population of sources. Questions of particular interest include:

- How soon after observations begin can you identify a verification binary, ignoring other sources? With other sources (binaries, supermassive black holes, extreme mass ratio inspirals, etc)?
- How does knowledge of a verification binary’s parameters change as a function of LISA observing
TABLE I NASA Technology Readiness Levels for software.

| TRL  | Description |
|------|-------------|
| TRL 1 | Basic principles observed and reported. Basic properties of algorithms, representations & concepts. Mathematical formulations. Mix of basic and applied research. |
| TRL 2 | Technology concept and/or application formulated. Basic principles coded. Experiments with synthetic data. Mostly applied research. |
| TRL 3 | Analytical and experimental critical function and/or characteristic proof-of-concept. Limited functionality implementations. Experiments with small representative data sets. Scientific feasibility fully demonstrated. |
| TRL 4 | Module and/or subsystem validation in laboratory environment. Standalone prototype implementations. Experiments with full-scale problems or data sets. |
| TRL 5 | Module and/or subsystem validation in relevant environment. Prototype implementations conform to target environment/interfaces. Experiments with realistic problems. Simulated interfaces to existing systems. |
| TRL 6 | System/subsystem prototype demonstration in a relevant end-to-end environment. Prototype implementations if the software is on full-scale realistic problems. Partially integrated with existing hardware/software systems. Limited documentation available. Engineering feasibility fully demonstrated. |
| TRL 7 | System prototype demonstration in high-fidelity environment (parallel or shadow mode operation). Most of the software is functionality available for demonstration and test. Well integrated with operational hardware/software systems. Most software bugs removed. Limited documentation available. |
| TRL 8 | Actual system completed and “mission qualified” through test and demonstration in an operational environment. Thoroughly debugged software. Fully integrated with operational hardware and software systems. Most user documentation, training documentation, and maintenance documentation completed. All functionality tested in simulated and operational scenarios. Validation & Verification completed. |
| TRL 9 | Actual system “mission proven” through successful mission operations. Thoroughly debugged software. Fully integrated with operational hardware/software systems. All documentation has been completed and users have successful operational experience. Sustaining software-engineering support in place. Actual system fully demonstrated. |

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time? How long must LISA observations last to recover the verification parameters to the level of accuracy provided by electromagnetic observations?

Early studies on LISA observations of verification binaries have started (2). Prospective LISA verification binaries have been identified and a database of the current known parameters for these binaries is being maintained (3) for use by the LISA community.

**IV. GALACTIC BINARIES**

Stellar mass galactic binary systems are the most abundant of the sources LISA is capable of observing. Crude estimates place the number of binaries that LISA can resolve as distinct sources in the tens of thousands (4; 5), with millions more forming an unresolvable background at lower frequencies. The large population of resolvable binaries provides opportunities to develop a more complete map of the galaxy, study the mass distribution of binary components, and study the population and evolution of mass transfer systems. The unresolvable binary background provides additional information about the number of binaries and their galactic distribution. Finally, because the signal from binaries is ever-present, signals from other sources must be identified and characterized in the forest of resolvable binaries and the fog of the confusion background. The ability to identify and characterize isolated binaries and the confusion background is thus a crucial first challenge for LISA science analysis.

**A. Isolated binaries**

In addition to the verification binaries described in §III there will be several thousand resolvable binaries which will be unknown and uncharacterized before LISA begins observations. The ability to identify, characterize, and extract science from observations of these binaries will depend largely on the analysis technique used. Specific questions which are of interest for an individual binary analysis algorithm are:

- Given a realistic galactic model, how many individual binary sources can be resolved? How accurately can resolved binaries be characterized? How does the characterization change as observing time increases? Does the method mistakenly identify “false binaries”?
- How accurately can the different binary parameters (sin i, amplitude, etc) be determined as function of...
SNR, sky location and observing time?

- Given a particular analysis technique, what is LISA’s “resolving power”? How well can the technique spatially resolve individual binaries on the sky? How well can individual binaries be resolved in frequency?

A number of analysis techniques targeting isolated binaries have appeared in the literature. These techniques have explored a variety of approaches with regard to identification and parameterization of binaries; they have yet to be compared and contrasted directly.

**B. Confusion background**

Below some frequency every analysis techniques targeting individual binary sources will break down as overlapping signals from the millions of short period binaries in the galaxy merge to form a confusion-limited background.

The confusion-limited background is both a boon and a bane. The background amplitude, shape, and angular distribution depends on the astrophysics of binary evolution, the total number of binaries contributing to the confusion, and the shape of the galaxy. By measuring this background amplitude, spectrum and angular distribution on the sky we are measuring these characteristics of our galaxy. On the other hand, the confusion-limited background is an astrophysical source of noise that limits our ability to identify other sources at low frequencies. Understanding the onset of confusion will play an important in understanding the low-frequency science that is possible with LISA observations. Interesting questions that can be posed of techniques targeting the confusion limit include:

- How well can the spectrum (shape and level) of the confusion noise be determined as a function of frequency and the confusion spectral density?
- How well can the spatial distribution of the confusion be determined?
- How does the characterization of the confusion spectrum evolve with increased observing time?

A great deal of astrophysical analysis has gone into predicting the possible populations that will contribute to the confusion limited background. A variety of techniques have been considered to begin to approach the question of how LISA will view the background.

**C. From isolated to confused**

The number density of galactic binaries increases rapidly with decreasing frequency; thus, at high frequencies we have isolated binaries while at low frequencies the binaries are unresolvable and we will not be able to identify the signal from a single binary. How the fraction of resolvable binaries decreases with decreasing frequency directly affects our ability to observe sources that may be situated in the transition band.

- Given a realistic model of the galactic binary distribution, how does confusion “emerge” as a function of frequency (binary period)?
- How does the “fog” of confusion “lift” as LISA observations progress?
- There will always be exceptionally bright sources, which stand out above the confusion. How does the number of such exceptional binaries vary with frequency?

An important element in research studies that target problems relating to the galactic binaries is the availability of galactic realizations. Several different realizations exist, such as those built from binary distribution functions, and those derived from population synthesis models.

**V. BURST SIGNALS OF ASTROPHYSICAL ORIGIN**

LISA can be expected to observe bursts of gravitational waves from relativistic fly-bys of compact objects about supermassive black holes. More speculative is the radiation from the disruption of a main sequence or white dwarf via a too-close encounter with an intermediate mass black hole. Still more speculative is radiation from topological defects in cosmic strings. Specific questions of interest for analysis methods that target burst gravitational wave sources include:

- How well are individual bursts resolved in the LISA data as a function of signal-to-noise and burst duration?
- Is it possible to distinguish a noise burst in the measurement or sensing functions of the constellation from a burst arising from an astrophysical source?
- Can burst sources of radiation be characterized well enough that they can be distinguished by source or source type?

**VI. EXTREME MASS RATIO INSPIRALS**

When studying spacetimes, it is natural to discuss the motion of a test particle in the background spacetime of interest. Nature has been kind enough to provide systems that strongly approximate the test body case in the extreme mass ratio inspirals (EMRIs): the capture of a stellar mass compact secondary object by an intermediate or supermassive black hole. With each orbit gravitational waves carry away energy and angular momentum
and, at least while the rate of loss of energy and angular momentum is small, the secondary can be thought to evolve along a trajectory of geodesics. By studying this evolution it may be possible to reconstruct a broad family of geodesics and thus “map” the spacetime in the neighborhood of a black hole [18].

EMRI radiation is not necessarily continuously observable in the LISA band. When the orbits are relativistic the radiation is beamed, leading to large amplitude variations as the beam follows the secondary in its orbit. Additionally, many EMRIs may be in high eccentricity orbits, in which case the radiation may only be in the LISA band during a small fraction of the orbit.

Besides being natural laboratories for conducting tests of general relativity, the event rate and characteristics of EMRIs can lead to insights into the structure and evolution of galactic centers. EMRIs allow high precision estimates for the central black hole’s mass and spin [19]. The event rate alone gives an indication of the stellar density in the cores of galaxies.

The apparent difficulty associated with detecting EMRIs is that each system is parameterized by up to fourteen parameters. The high dimensionality of the parameter space hinders the blunt use of standard template matching techniques. Consequently, alternative approaches to the EMRI detection and characterization problems are required. Early analysis methods have included semi-coherent searches [20], and the use of time-frequency methods [21, 22]. These approaches are promising, but are still in the early formulation stages.

Central issues in EMRI data analysis are:

- For EMRIs that lead to periodic bursts of radiation in the LISA band (owing either to orbital eccentricity or beaming) can multiple bursts from a single EMRI system be linked with each other?
- What features of an EMRI signal (i.e. location, black hole spin, secondary mass, etc.) become “in focus” with increased waveform model complexity, signal-to-noise ratio, and/or observation duration?
- How well can a complete EMRI signal be identified and characterized in the presence of instrument noise? A confusion-limited background? A confusion-limited background of EMRIs?

VII. MASSIVE BLACK HOLE BINARIES

Observing the inspiral, coalescence and ringdown of massive black hole binaries will provide critical clues to the order in which the large scale structure in the Universe evolved: did stars evolve and then galaxies, or galaxies and then stars? Did supermassive black holes form hierarchically from run-away collision of lower-mass black holes, or were they massive at birth, forming from the collapse of primordial clouds of gas? LISA can help answer these questions by producing a census of merger events mass and luminosity distances. To obtain luminosity distances it will be necessary to have accurate sky positions. For gravitationally “bright” sources this may come from the gravitational wave observations themselves [23, 24]; however, for dimmer sources the gravitational wave estimates of position may be too crude for an accurate distance determination, in which case the observation of an optical counterpart (i.e., the galaxy host of the merger) will be necessary to get an accurate redshift [25].

While the inspiral, coalescence and ringdown of a supermassive black hole will always be detected in the presence of the galactic binaries, if we can’t identify and characterize a MBH binary source all by itself we’ll never be able to identify and characterize a MBH binary in the presence of the galactic binary forest and confusion background. Therefore, each of the following three questions should be answered at three levels: (1) in the absence of a galactic binary confusion background, (2) in the presence of an artificially “cleaned” background with all bright sources removed, and (3) in the presence of a full galactic binary background:

- How well can an SMBH binary be identified and characterized?
- How “bright” must a MBH binary be to be identified? How does the accuracy of the MBH characterization scale with “brightness”?
- How well, as a function of observation time, can you determine where and when the binary will coalesce? (i.e., what precision a month from coalescence? a week? a day?)

VIII. MULTI-SOURCE CHALLENGES

The identification of every LISA source will take place in the simultaneous presence, in the LISA data, of millions of long-period galactic binaries, myriads of distinctly resolvable short-period galactic binaries, and multiple extreme-mass-ratio inspirals and supermassive black hole inspirals. A critical challenge for LISA analysis is the ability to identify and characterize these sources in each others presence. Central questions in multi-source analysis include

- How well can different source types in the data be searched for sequentially? For example, can SMBH binaries be found and subtracted out of the data before galactic binaries or EMRIs are searched for?
- How well can different source types in the data be searched for simultaneously?
- What fidelity is required of theoretical source models for a given multi-source science analysis procedure to work? How does the effectiveness of the analysis method scale with source simulation fidelity?
IX. DATA SETS FOR SCIENCE ANALYSIS CHALLENGES

Science analysis demonstrations and feasibility studies require the use of simulated data that is well-characterized and of sufficient fidelity that the feasibility demonstration is meaningful. Trade studies or evaluations and qualification of different technologies are best performed under identical conditions; so, there is great value in archiving and sharing data sets used for different studies so that different analysis methods can be characterized under the same conditions and their results compared. An additional advantage of shared data sets for science analysis demonstrations and feasibility studies is that comparison among studies carried out on the same data but with different techniques provides practice for the day when real LISA data will be available and there is only one LISA data set and all studies will take place on the same data.

Every demonstration or feasibility study has a goal that determines the appropriate degree of fidelity (in noise characteristics, LISA simulation approximations, etc) that the simulated data set must satisfy. The fidelity of the data used in a study should not substantially exceed that required for a meaningful demonstration in order to avoid complications in the study’s interpretation. So, for instance, data sets designed to probe the ability of an analysis technique to resolve pairs of binary star systems need not be of full bandwidth. To be sharable, the data sets should also be complete and fully documented. Completeness, in this case, means that the data set should contain everything necessary to carry-through the analysis: no assumptions about, e.g., the approximations made in the simulation (rigid adiabatic LISA? second order eccentricity orbits? constellation position and phase at the initial epoch?) or in the constellation response (what are the observables? low-frequency approximate response, or exact response?) should need to accompany the data sets.

Data sets that can be used as a common platform for addressing these challenges are currently being developed, produced, and distributed by two groups. The Testbed for LISA Analysis (TLA) Project, spearheaded by the Center for Gravitational Wave Physics, has developed a data container (the Simulated LISA Data Product, or SLDP), which was developed to meet the goal of completeness as described above. The Mock LISA Data Challenges (MLDC) group, organized by the LISA International Science Team Working Group 1B, has developed the LISAxml data container that is complete in a different sense: LISAxml files include a full description of the source content of the data they contain. Both groups, which share many members in common, provide software for reading and writing data sets in these two different formats; additionally, the TLA Project will provide SLDP versions of the simulated data content of LISAxml files provided by the MLDC effort.

Data sets suitable for addressing several of the science analysis issues presented in this paper, and in the recommendations that emerge from the LISA Science Analysis Workshop, will be made available as SLDP files through the Testbed for LISA Analysis web site <http://tla.gravity.psu.edu>. The TLA Project invites the participation of scientists in all aspects of its work, from developing software to support collaborative work in LISA science analysis, to generating and providing sample data sets for analysis studies, to contributing to an annotated bibliography of analysis study results, and many things in between. For more information on how to become involved in the TLA Project visit the TLA website at <http://tla.gravity.psu.edu/getinvolved/>.</p>

The MLDC effort has developed a systematic series of “challenges”, which are available through their collaborative wiki hosted at Caltech, <http://www.tapir.caltech.edu/dokuwiki/> (click on LISA Science Team Working Group 1B). The MLDC Group will provide data sets suitable for addressing these challenges as LISAxml files through Astrogravs at <http://astrogravs.nasa.gov/>. People interested in participating in the MLDC effort should visit their working wiki for contact information.

X. FINAL THOUGHTS

The principal goal of the LISA Science Analysis Workshop is to encourage the development and maturation of science analysis technology in preparation for LISA science operations. The principal outcome of the workshop will be a report, written by the workshop participants, that

- articulates specific demonstrations of analysis capabilities that can (and should!) be addressed by
the LISA science analysis community in the next 1-2 years;

- defines the specific data sets needed to make these demonstrations;
- identifies the support structure (software tools, community forums and meetings) that simplify the completion of these studies; and
- provides a forum for the effective communication and dissemination of the results of these studies.

LISA’s best advocates are the scientists whose blood, toil, tears and sweat will carry-out the LISA science program, from technology through analysis and science interpretation. If you are not already involved in LISA science analysis we urge you to become involved, by joining one or both of the TLA and MLDC projects.

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