The LISA Integrated Model

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Abstract

LISA has unique needs that argue for an aggressive modeling effort. These models ultimately need to forecast and interrelate the behavior of the science input, structure, optics, control systems, and many other factors that affect the performance of the flight hardware. In addition, many components of these integrated models will also be used separately for the evaluation and investigation of design choices, technology development and integration and test. This article presents an overview of the LISA integrated modeling effort.

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Introduction

The LISA mission is to detect and observe gravitational waves from astrophysical sources in the frequency band 0.1 mHz to 1 Hz. There are many potential sources within this band that are easily detectable given the design sensitivity of LISA. Possible sources include galactic binaries, massive black holes in distant galaxies, and primordial gravitational waves. LISA is comprised of three identical spacecraft separated by 5 million kilometers forming an equilateral triangle. Each spacecraft encompasses two freely floating proof masses. Each leg of the triangle acts as a single arm of an interferometer that is used to measure any change in the distance between the proof masses.

LISA is a unique mission in several ways. First, it seeks to detect gravitational waves, a manifestation of gravity that has never been directly detected before by any means. Second, it involves precision measurements at a level previously unknown in space science. Third, the apparatus cannot be deployed and tested at full sensitivity on the Earth. Fourth, the baseline design calls for very tightly integrated spacecraft and payloads, in essence a sciencecraft where all of the spacecraft systems can affect the scientific performance. Further, the constellation of three sciencecraft cooperate to function as a single instrument.

Each of these challenges requires that modeling be employed to ensure mission success. For that modeling to be effective, it must encompass geometric, structural, thermal, optical, control systems, and gravitational analyses in various combinations at various times. This requires the analyses to be integrated to a high degree.

The LISA conceptual design, as it now exists, is a complex instrument based on advanced measurement technology that cannot be fully tested on the ground. Integrated modeling of gravitational wave sources, the payload, the spacecraft, the constellation, as well as the data reduction and analysis will be required for the many purposes outlined below. This effort will incorporate existing modeling tools (e.g., geometric, structural, controls, thermal, orbital), but it will also need to create some new tools such as gravity field modeling.

Modeling of the LISA mission is challenging for the following reasons: first, the level of interactions between disciplines and subsystems for LISA are much more complex than traditional space missions. For example, we must expand traditional STOP analysis (structural, thermal, optical) to include changes in the self-gravity of the spacecraft due to thermal deformations. Second, the precision and accuracy required from the modeling is more strict than for most missions. For example, in some parts of the spacecraft we need to understand the behavior to picometer length changes and microKelvin temperature fluctuations. Finally, since much of the LISA performance cannot be validated on the ground, we must complement our test-beds with good models. Without adequate models we will not be able to accurately predict the on-orbit performance of the LISA instrument.

Requirements

The purpose of the LISA integrated modeling effort is to apply our analytical understanding of the sources, disturbances, measurement noise, and data analysis to understand the behavior of the instrument and forecast its performance. In this section we expand on this statement and discuss the overall requirements and functions that the models must perform.

Since the effects of gravitational waves are so small, the experimenter needs to measure very carefully. Precision measurements of this type always demand extensive analysis of potential systematics. Much modeling of disturbances and measurement noise has already gone into the formulation of the LISA baseline design, but much more will be needed. However, to date these models have been examined within the context of a single subsystem. These models need to be incorporated into conventional integrated modeling of structural, thermal, optical, and control systems to assess their effects on the interactions of subsystems throughout the sciencecraft. For example, thermal variations can have widespread effects through dimensional changes affecting the spacecraft gravitational field, changing primary-secondary separation in the telescope, and unbalanced thermal photon pressure on the proof mass.

An extensive integrated modeling effort will be needed to evaluate the flow down of requirements to subsystems and components. The inability to realistically verify the sciencecraft performance before launch will necessitate limited testing in conjunction with integrated modeling to verify system performance.

Finally, the combined performance of the three-spacecraft instrument and data analysis can only be assessed by an end-to-end model. This will be necessary to verify that the instrument as launched can meet the ultimate science requirements.

It is difficult to set specific performance requirements on an integrated model. Instead, we choose to define requirements as functions that the model must perform. The model fidelity that each function requires will be quite varied. The integrated model will have different modes of operation to perform the different tasks. The major tasks required of the model are:

- Support trade studies
- Optimize the design before construction
- Develop/validate instrument requirements
- Support technology test beds
- Validate technology flight demonstrations
- Support payload and mission level integration and test
- Support flight operations
- Support ground calibrations
- Support flight calibrations
- Support science data analysis

Not all of these functions will be utilized nor fully developed during the early development phase; for example, "support flight operations" need not be fully developed in this phase. However, it is important to recognize that the model will eventually support these activities so that their implementation can be properly designed into the model architecture.

Model Elements

We envision this facility not as a single monolithic model, but rather a library of modeling tools and data which can be configured by users for their purposes. There will be designated model configurations that represent the reference design.

The top level elements for the integrated model are: the modeling environment, quasi-static models, dynamic models, phase propagation models, and end-to-end models. We briefly summarize these elements below:

The modeling environment, often referred to as an advanced engineering environment, supports the development, execution, user interaction, and archiving of the models. The design of this environment draws upon the experience of the James Webb Space Telescope [1] and the 2nd Generation Reusable Launch Vehicle [2] integrated modeling efforts. The environment houses the collection of modeling tools, including relevant analysis packages, model configurations, input data sets, and an archive of previous model runs. It has a user interface supporting access to the modeling tools and collaboration by the user community, and provides administration for user access, configuration control, etc.

The quasi-static models element contains all models that are independent and quasi-independent of time. One purpose of the element will be to determine how the space-environment effects the instrument. This will include not only the traditional structural, thermal, and optical models, but also non-traditional elements like self-gravity and cosmic ray charging. By integrating these disciplines we will be able to study effects such as how changes in shape due to ground-to-orbit cool-down effects the optical path and gravitational field.

The dynamic models element contains models that are time-dependent. It combines structural, optical, gravitational, orbits, and controls. An example analysis is to study the effect of telescope articulation on the optical path.

The phase propagation models element contains the models describing the interferometer measurement system. It models the propagation of the phase and phase noise of the laser beam starting from the laser, through the optical chain and into the receiving photo-detector combining it with the reference beam. These models can be used to study different time delayed interferometry schemes [3].

The end-to-end models element has two main components: the system error trees and the science data simulator. The error trees will be used for requirement flow-down and trade studies. The science data simulator will be used to test the science data analysis package and perform science based requirement flow-down.

The four classes of models described above are not independent. Many of the models developed in each class will be used for different analysis within other classes. The models will be "anchored" by the laboratory test-beds; part of the model validation and verification plan is constant comparisons with test-bed and ST-7 results [4]. In some cases where laboratory measurements are not possible, independent models will be built for verification purposes.

Heritage

A number of attempts at building an integrated model of this complexity have been made with varying degrees of success. A few successful examples are the James Webb Space Telescope [1] and the 2nd Generation Reusable Launch Vehicle [2] integrated modeling efforts, as well as the control system modeling for the LIGO ground based interferometer [5]. None of these environments meet all of the LISA integrated model requirements, however, they serve as possible good examples to study during the design of the modeling environment.

Many of the tools for building model elements are available as commercial packages. The ability to integrate these packages varies considerably. In addition, commercial packages do not exist for a few of the elements. The two main missing elements are self gravity and phase propagation. Custom codes exist for these elements, but they currently are not developed enough to meet the LISA requirements.

Development Strategy

Past experience shows that some integrated model failures occurred because of a broad scope and lack of focus. Our approach focuses on defined and specific near term goals, with long-term goals on the horizon. It is envisioned that the model will increase in breadth and depth over time.

The development of the models will progress in three phases. The first phase is to establish a baseline, which will evolve to include higher fidelity and more detailed models. The models will provide the basis for analysis that ensures the system requirements are meaningful, self-consistent, and verifiable. Sensitivity analyses will be performed to determine which requirements are drivers and risk analysis will identify those that are high risk. During this phase many of the traditional engineering trades will be performed. Only a low degree of model integration will be implemented at this stage.

The second phase of the modeling effort is a period of trade studies. Models will be built that deviate from the baseline in systematic ways. The models will be exercised by system engineering to help drive the design of the instrument. A higher level of integration will be implemented to help understand the complex interactions between subsystems.

The third stage of the modeling effort strives towards full integration of the models. A complete science data simulator will be developed and the error trees will be fully mature. Trade studies will be performed that require understanding the subtle interactions between normally independent subsystems. As PDR approaches, the models will be used to refine technical options relative to cost and risk.

The modeling environment will evolve in a way that complements the development of the models. During the first phase of development we will define the requirements of the environment and build the basic framework of the environment. Once the model baseline is established the environment will support configuration control. The environment will then evolve to support the running of the trade studies. Process management will be implemented as the number of parallel analysis increases. As the level of model integration increases the environment will support the exchange and translation of model data and configurations.

The models will produce "synthetic" science data products representative of the real telemetry that can be used to test candidate data reduction techniques. An end result of this effort is and "analytical justification of the LISA mission." That is to say, the sources, instruments, spacecraft, ground system, and detection algorithms have operated in concert to demonstrate the detection of individual sources as anticipated.

As the technology test beds are developed, they will need modeling support initially to set performance goals and to forecast the test bed's performance. Further, the results from the test beds need to be folded back into the integrated models to reflect lessons learned.

Some of the models will eventually be tested using ST-7 [4]. Prior to launch, the integrated model will be modified to study on-orbit scenarios of ST-7. These models will then be compared to the on-orbit performance. This test will help bridge the gap between the technology test-beds and the LISA on-orbit performance.

Current Status

We are currently in the first phase of development, establishing the baseline from which all trade studies will deviate. The bulk of the effort is defining in detail the structural and thermal design along with the control systems. The control system model is discussed in the paper by Maghami in these proceedings [6].

An example solid geometry model is shown in Figure 1. We are currently performing a finite element structural analysis derived from this model. At the same time we are building a thermal model from this geometry. An integrated analysis is also currently underway where we are studying thermal deformations of the sciencecraft. A first generation version of a self-gravity tool is written and is currently being validated.

In conclusion, an aggressive modeling effort is currently under way for the LISA project. The level of integration between the various models goes beyond what is traditionally done for space missions. By building detailed models that have strong ties to technology test-beds and the flight demonstration mission, we give ourselves confidence that we will be able to meet the LISA science goals.

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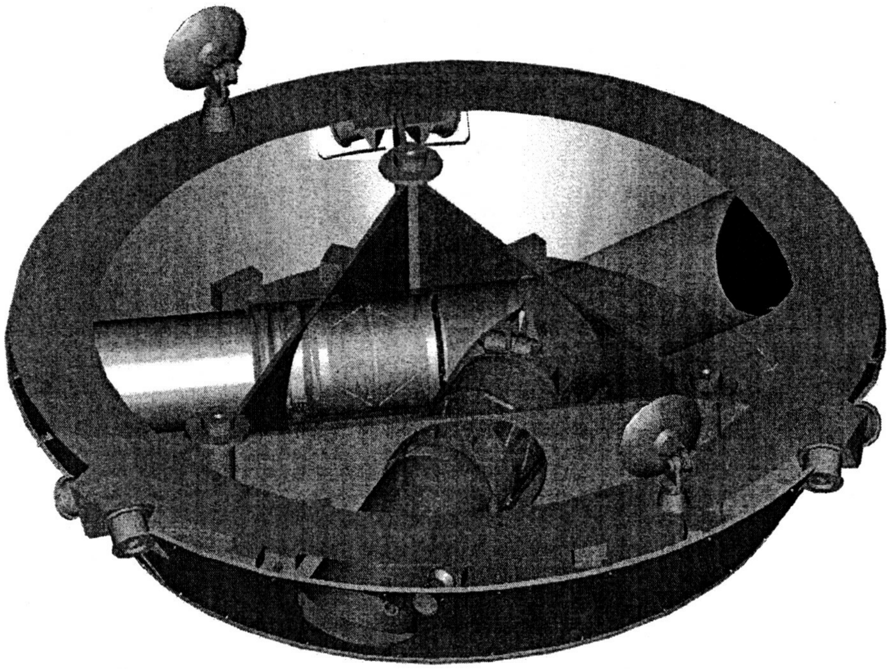

Figure 1: Example solid model of the LISA sciencecraft.

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[4] ST-7 is a NASA mission that will demonstrate a number of critical LISA technologies. It is currently scheduled to launch on the European spacecraft SMART-2 in 2006.

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