Engineering the LISA Project: Systems Engineering Challenges

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Abstract— The Laser Interferometer Space Antenna (LISA) is a joint NASA/ESA mission to detect and measure gravitational waves with periods from 1 s to 10000 s. The systems engineering challenges of developing a giant interferometer, 5 million kilometers on a side, are numerous. Some of the key challenges are presented in this paper[1,2]. The organizational challenges imposed by sharing the engineering function between three centers (ESA ESTEC, NASA GSFC, and JPL) across nine time zones are addressed. The issues and approaches to allocation of the acceleration noise and measurement sensitivity budget terms across a traditionally decomposed system are discussed. Additionally, using LISA to detect gravitational waves for the first time presents significant data analysis challenges, many of which drive the project system design. The approach to understanding the implications of science data analysis on the system is also addressed.

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1. INTRODUCTION

Central to the development of any space mission is the function of systems engineering. The systems engineering function ensures that the system is designed, built, and operated so that it accomplishes its purpose in the most cost-effective way possible, considering performance, cost, schedule, and risk as described in reference [1]. As observatory missions become increasingly complex and more capable, we are forced to find solutions to issues and error sources that we could once ignore [2].

In this paper, examples of the challenges facing the systems engineers on the Laser Interferometer Space Antenna (LISA) Project are presented. As we continue to open up new regimes for observing and further the collaborative efforts across centers, agencies, and nations, the lessons learned and techniques developed by the LISA project may prove useful to other projects.

2. MISSION OVERVIEW

The LISA mission will be the first space-based gravitational wave observatory, opening a new window on a Universe unseen by conventional electromagnetic radiation. LISA will observe some of the most violent events in the Universe, including merging black holes over a wide mass range, closely orbiting stellar remnants, as well as cosmological backgrounds and bursts. Observations of these signals will help us to understand the structure of the Universe from its origins to its ultimate fate, to explore the limits of extreme gravity and energy, and to understand how galaxies and compact objects form, interact, and evolve.

Gravitational waves cause minute changes in the separation between freely falling bodies (*ripples* in space-time). The LISA mission concept requires continuously measuring minute changes in the separation of freely falling proof masses contained within three spacecraft orbiting the Sun in a triangular formation. LISA measures picometer-scale changes in five million kilometer separations using laser interferometry. LISA is a joint project of the European Space Agency (ESA) and the National Aeronautics and Space Administration (NASA) to design, build and operate the first space-based gravitational wave observatory.

Gravitational waves are strains in space-time caused by the rapid acceleration of large masses in extremely energetic astrophysical events. They are the radiative form of gravity, as light is the radiative form of electromagnetism. Because of the technical challenges, gravitational radiation has never been directly detected, though there is indirect evidence for its existence. Gravitational wave detection is a major goal of physics worldwide, and there are several significant efforts to build ground-based gravitational wave detectors.

Gravitational wave sources involve the close interaction of very compact objects and are often shrouded from electromagnetic observation. LISA is expected to detect signals from merging supermassive black holes, compact stellar objects spiraling into supermassive black holes in galactic nuclei, thousands of close binaries of compact

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[2] IEEEAC paper #1408, Version 1, Updated October, 18 2005

objects in the Milky Way, and possibly backgrounds of cosmological origin.

LISA's science goals are to determine the role of massive black holes in galaxy evolution, make precision tests of Einstein's Theory of Relativity, determine the population of ultra-compact binaries in the Galaxy, and to probe the physics of the early universe.

As previously stated, gravitational waves are detected by measuring extremely small changes in the separation of fiducial (proof) masses. The measurement concept is:

(1) The time-varying change in three arms 5 million kilometer long is measured by laser interferometry in the frequency band of $3x10^{-5}$ to 10^{-1} Hz

(2) The three arms are defined by six proof masses that form an equilateral triangle with pairs of proof masses located at the vertices of the triangle. A spacecraft at each vertex houses the two proof masses and interferometry equipment

(3) The constellation of three spacecraft orbit the Sun 20° behind the Earth

(4) The proof masses are protected from disturbances by careful design and "dragfree" operation (i.e., the mass is free-falling, but enclosed and followed by the spacecraft)

(5) Lasers at each end of each arm operate in a "transponder" mode. Optical path difference changes, laser frequency noise, and clock noise are determined

(6) The three arms enable the measurement of both polarizations of the quadrupolar gravitational waves. The source direction is decoded from amplitude, frequency, and phase modulation caused by annual orbital motion

3. Systems Engineering Organization

The interest in, and complexity of, the LISA mission has led to the endeavor being undertaken jointly between ESA and NASA. Additionally, within NASA, two centers carry significant roles. In August 2004, an international agreement was signed between ESA and NASA establishing an equal role in the management and performance of the mission-level systems engineering function on LISA across ESA, NASA Goddard Space Flight Center, and the Jet Propulsion Laboratory. Stated another way, "there are three systems engineering managers...each with equal authority and responsibility." The LISA organizational structure, as defined in the international agreement, is show in Figure 1. Note too that the project management function is shared equally between two people (one ESA and one NASA).

(INSERT FIGURE 1 OF ORG CHART FROM BELOW)

How does a team take direction from three managers all dealing with the same scope of work? How can three people from different organizations agree in such a way as to keep the project moving? How can collaboration occur on technical activities such as trade studies when the team is spread across nine time zones? These are a few of the challenges imposed by LISA organizationally.

A fundamental need in any collaboration, but certainly when the function being collaborated on is the systems engineering leadership of a space mission, is the need for regular and direct communication. For LISA, it has been clear that the project functions best when the three systems engineering (SE) managers are in frequent contact with each other. This frequent communication does have its price. The amount of time spent in dialogue with the other SE managers has been significantly higher than any previous mission the author has worked, making each SE manager less "efficient" when it comes to producing tangible engineering products for the project.

The overlap in the SE responsibility on the LISA project also reinforces the need for a single name to be tied to any deliverable. This is considered good practice on all projects but it is particularly important when roles and responsibilities are overlapping. The need for a "responsible individual" to be identified extends to less formal products such as action items or meeting agendas. The chances of an item not being addressed are significantly increased when a name is not explicitly tied to a required action on the project.

The processes that have been developed and are continuing to be developed on LISA also must be tailored to support this three-organization, nine time zone team. One significant lesson learned is that LISA processes require more intermediate milestones in them than the author's experience on past projects would indicate. These intermediate milestones help keep the team on track when they may not be able to communicate with each other in real time. One example of this is our trade study process, which contains several intermediate steps to foster communication and maintain synchronization.

The single-most important item to coordinating the systems engineering efforts on LISA is a detailed schedule that is not only coordinated across ESA and NASA, but within NASA (GSFC and JPL) as well. Like many techniques or lessons learned, this seems intuitively obvious on the surface. In reality, systems engineers do not tend to create and maintain detailed schedules the way an engineer producing a Command and Data Handling subsystem would. The scheduling of trade studies, dates for reaching joint decisions on elements of the baseline, and the intermediate steps to getting there are all elements of the coordinated LISA systems engineering schedule. This schedule also is used to negotiate work between NASA and ESA. Given the fiscal realities of the LISA project budget, we cannot afford to duplicate work between the two agencies

or between the two NASA centers. The systems engineering schedule allows the team to stay coordinated and prevent duplication from occurring.

4. Allocating LISA Performance

The strain sensitivity required by LISA to detect gravitational waves is the fundamental performance requirement on the project. To achieve this sensitivity, the strain measurement must be broken down into three separate performance parameters, measurement sensitivity, acceleration disturbance, and arm length. The measurement sensitivity is the requirement of how well the LISA instrument must measure the changes in distance between each of the sciencecraft (in the measurement band). The acceleration disturbance is the "quietness" of the LISA system for making these distance measurements. The acceleration disturbance is really the noise in the system that could manifest itself as a proof mass motion and, therefore, a perceived strain in space-time. The arm length is much simpler than the other two parameters as it is merely the distance between each of the three sciencecraft. A top-level performance tree, illustrating the decomposition, is provided as Figure 2.

(INSERT PERFORMANCE TREE FROM BELOW AS FIGURE 2)

While the measurement sensitivity side of the performance tree does present its own challenges, it largely decomposes in a fairly traditional manner and won't be discussed in detail in this paper. Many of the challenges that are unique to the LISA mission come in trying to decompose and achieve the performance defined by the acceleration disturbance branch of the performance tree. Two interesting examples will be summarized below.

Self-Gravity

The concept of self-gravity is a good illustration of an area where new missions are presenting systems engineers with interesting challenges that must be addressed. Since LISA is fundamentally trying to measure the weak gravitational forces acting on the proof mass at each end of the interferometer arms, the spacecraft itself cannot be disturbing the proof masses with its own mass attraction beyond the levels allocated in the acceleration disturbance budget. This is not a phenomenon that is typically of concern on space missions.

Levying a requirement on the flight system or on subsystem providers to limit their uncertainty in the DC acceleration influence on the proof mass to less than 10^{-11} m/s^2 is not reasonable. While the two-body mass acceleration equation is straightforward, asking a subsystem lead to determine the influence of their hardware on another element of the system is not. This is truly a "system" problem.

The approach used by LISA is to break down the acceleration disturbance requirement into something that is "implementable" (and verifiable) by the hardware developers. The uncertainty in the acceleration influence can be equated to the combined mass knowledge and location knowledge of the system. By allocating an overall uncertainty to the system, lower level allocations were developed and levied on each subsystem in terms of mass knowledge and location knowledge [3].

Asymmetric Outgassing

Another example of where error terms that can be ignored on other missions must be recognized and captured in a way that is readily understandable and able to be implemented is the asymmetric outgassing portion of the acceleration disturbance budget. Many projects deal with outgassing for contamination reasons or in an attempt to maintain high vacuum inside an enclosed volume. LISA must be concerned with the very small forces that outgassing could impart on the proof mass.

The asymmetric outgassing element of the acceleration disturbance budget is decomposed into several "implementable" requirements. These requirements include limiting the total outgassing of materials (which decomposes further into volume, collected volatile condensable material (CVCM) and total mass loss (TML) of those materials) and designing symmetric hardware in close proximity to the proof mass (such as $\leq$ 4mm).

The approach illustrated by these examples of decomposing the requirement until an element provider can implement it is key to writing good requirements in general. There is added vigilance necessary when the decomposition is not straightforward due to the crosscutting or unfamiliar nature of the requirement. The awareness of this point is critical to bringing complex missions like LISA to reality.

5. Science Data Analysis Implications

The science data analysis needs of the LISA project represent an additional set of systems engineering challenges.

Extracting the science signal from LISA is akin to placing a microphone and tape recorder in the middle of a cocktail party and then trying to identify the content and location of each of the conversations in the room. All of the conversations are of scientific interest and therefore the room can be thought of as a lot of signal and very little noise. This "cocktail party problem" is a fundamental challenge for the LISA science data analysis activity. The plan is to develop many templates that represent the anticipated signal from merger events of various size ratio black holes along with other expected sources of gravitational waves. The number of these templates may easily surpass 10,000.

Given the fundamental challenge of so many signals, the sheer number of templates provided, and the need for fundamental validation that this will work (validation early in the mission development process), LISA is addressing

the science data analysis in a similar manner to technology development. Identified risks within the science data analysis activity have been assigned a likelihood and consequence to prioritize and focus the work required. These early data analysis "technology development" activities are being carried out as risk mitigation plans.

An additional challenge of the science data analysis activity is the characterization of LISA instrumental noise. The science community expects that this will require significant amounts of housekeeping data, beyond what is typical of a space mission. By asking the right questions of the science community and looking for "soft spots" in the approach to characterization of instrumental noise, LISA systems engineering has been able to quantify the housekeeping data needs in such a way that provides what the scientists need, has appropriate margin for this early phase of the mission, and is typical of other missions so as not to drive LISA to exotic RF communications systems or Deep Space Network (DSN) costs.

Systems engineering must push against requirements creep such as the desire for "more data, more often" and work to discover the true requirements to successfully implement the project. The more complex the mission, the more likely the requirements are to creep.

6. SUMMARY

This paper has provided several examples of how the NASA/ESA LISA Project is handling the challenges of a complex mission. While the science of LISA is currently unique among space missions, some of the solutions developed and lessons learned by the LISA systems engineering management team may be applicable to other projects.

(1) A fundamental need in any collaboration, but certainly when the function being collaborated on is the systems engineering leadership of a space mission, is the need for regular and direct communication.

(2) Ensure a "responsible individual" is identified for formal and less formal products such as action items or meeting agendas. The chances of an item not being addressed are significantly increased when a name is not explicitly tied to a required action on the project.

(3) When a team is distributed geographically, processes require more intermediate milestones in them than is typically necessary. These intermediate milestones help keep the team on track when they may not be able to communicate with each other in real time.

(4) Of fundamental importance to coordinating systems engineering efforts is a detailed schedule that is coordinated across all partners. The scheduling of trade studies, dates for reaching joint decisions on elements of the baseline, and the intermediate steps to getting there are all elements of the coordinated systems engineering schedule.

(5) Added vigilance in decomposing requirements until they can be implemented by an element provider is necessary when the decomposition is not straightforward due to the crosscutting or unfamiliar nature of the requirement.

(6) Systems engineering must push against requirements creep such as the desire for "more data, more often" and work to discover the true requirements to successfully implement the project. The more complex the mission, the more likely the requirements are to creep.

7. ACKNOWLEDGEMENTS

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BIOGRAPHY

Jordan Evans is the Systems Engineering Manager for JPL on the LISA Project and also serves as the supervisor of the JPL Observatories System Engineering Group. He

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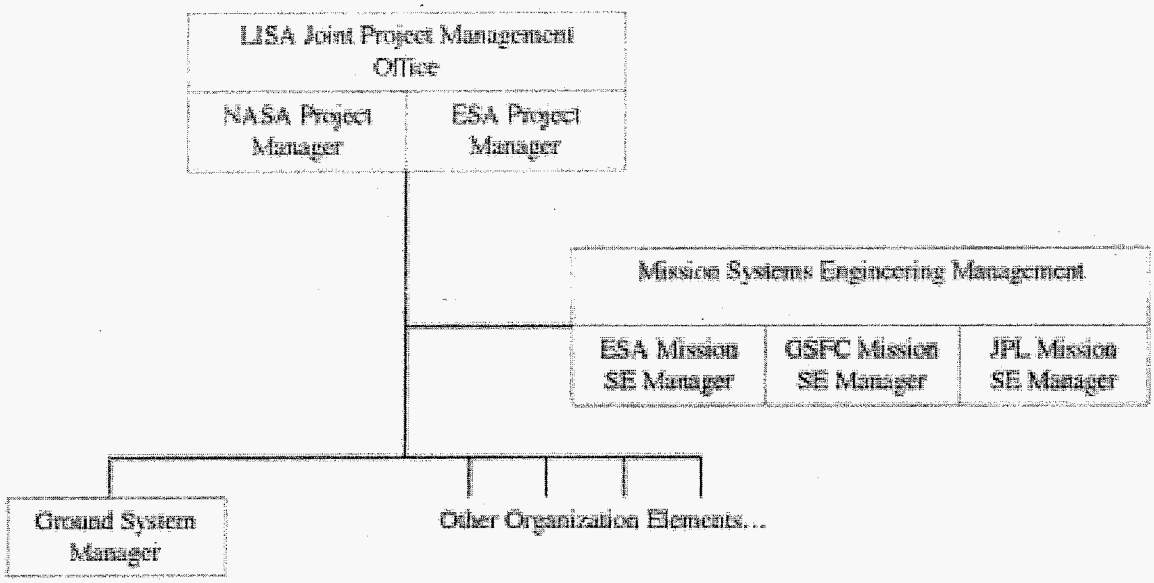

Figure 1 – LISA Project Organizational Structure

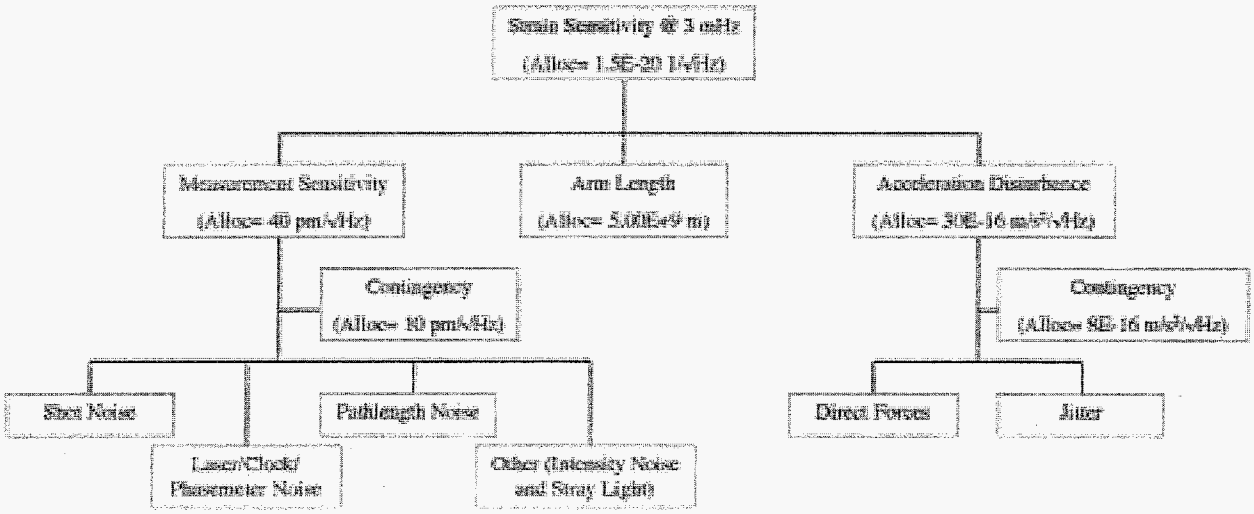

Figure 2 – LISA Top-Level Performance Budget