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Independent Reliability Assessment of the NASA GSFC Laser Transmitter for the LISA Program

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ABSTRACT

The Laser Interferometer Space Antenna (LISA) is a partnership between the European Space Agency (ESA) and NASA to build a Gravitational Wave (GW) observatory. The observatory, which consists of a three-spacecraft constellation with a nominal separation of 2.5 million km between each spacecraft, provides a tool for scientists to directly detect gravitational waves generated from various astronomical phenomena in a waveband that is not accessible from Earth. NASA is developing laser transmitters as one of the potential US contributions to LISA. The NASA laser design leverages lessons learned from previous flight missions and included the latest technologies in photonics packaging and reliability engineering to ensure a laser lifetime of >16 years covering integration and test through a possible extended mission phase.

As part of the laser development process, NASA's Goddard Space Flight Center (GSFC) requested support from the NASA Engineering and Safety Center (NESC) to independently assess the Technology Readiness Level (TRL) of the LISA Laser System (LS). The independent assessment included the following tasks: (a) assess the design for weaknesses and suggest improvements to mitigate risks, (b) assess the laser reliability plan for weaknesses and suggest improvements to mitigate risks and improve effectiveness, and (c) assess the current redundancy plan on laser subsystems for weaknesses and suggest improvements to mitigate risks and improve effectiveness. The NESC team comprised of a team of subject matter experts (SMEs) and performed a 12-month review of every aspect of the laser design.

We present the assessment findings and the current development progress of the LISA laser to meet the mission requirements with a delivery of a form, fit, and functional TRL6 laser to the LSIA mission by late 2023.

Keywords: Times Roman, image area, acronyms, references

1. INTRODUCTION

The LISA Laser System (LS) is the basis for the measurement system for the proposed LISA mission led by the ESA with a target launch date of 2035. The LS is one of the three NASA's possible contributions for LISA, the other two are the telescope and the charge management system. As part of the technology development effort, NASA GSFC requested that the NASA [1]Engineering and Safety Center (NESC) assess the Technology Readiness Level (TRL) of the LISA LS. The goal of this assessment is to determine if the LS design and development plan is on track to meet requirements provided by ESA in their TRL 6 demonstrator requirements document. This study provides an independent assessment of the GSFC laser architecture and has a direct impact on the LS TRL 6 development [1], and future flight laser production if selected by ESA.

The LISA assessment plan consisted of the following major tasks to be conducted by a team of Subject Matter Experts (SMEs) recruited by the NESC.

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The assessment tasks were identified as

- Task 1 – Assess the NASA GSFC LS design for design weaknesses and suggest improvements to mitigate risks
- Task 2 – Review the goals and structure of the LISA Program's Reliability Plan
- Task 3 – Assess the current redundancy plan on LSs including the fiber optic components and the pump laser diodes.

2. PROBLEM DESCRIPTION, MEASUREMENT DESCRIPTION, AND MEASUREMENT SYSTEM OVERVIEW

The LISA LS is the basis for the measurement system for the proposed LISA mission led by the ESA with a target launch date in 2035. The space segment for the LISA mission is composed of three satellites in an equilateral triangle formation with arm lengths of ~2.5 Mkm as shown in Figure 1. With this configuration, any two arms of the triangle represent a Michelson-type interferometer. The LISA measurement system is designed to measure GW from massive black hole binary (MBHB) systems that deform space-time and can be detected as a variation in the change in the length of the interferometer arms of ~10 pm/Hz$^{1/2}$.

Ensuring the appropriate reliability for the LISA LS is a critical challenge. A key performance requirement for the final design ESA selects will be the simultaneous and stable in-orbit operation of 6 laser heads (LH) on three spacecraft (SC) over a period of 5 years, with a goal of 11 years, without any prolonged operational interruptions. The current assessment is to determine if the LS design and development plan is on track to meet the following requirements provided by ESA in the TRL 6 demonstrator requirements document [2].

- 6 years on-ground after delivery including the accumulated operational time of 1 year for on-ground testing plus 5 years (to be confirmed (TBC)) of storage
- 1.5 years (TBC) OFF state in operational environment (cruise phase), 5 (TBC) years continuous operation in nominal science mode (nominal mission lifetime) with a goal of 11 years continuous operation in nominal science mode (extended mission lifetime)
- LS reliability of 0.92 (TBC)

This study provides an independent assessment of the GSFC LS architecture and have a direct impact on the LS TRL 6 development, and future flight laser production if selected by ESA.

Figure 1. Relative positioning of the LISA satellites.

3. APPROACH

The GSFC LISA laser team formulated a set of specific technical questions ("Statement of Work" (SOW) Questions) for each of the technology areas in the system to guide this assessment. The original assessment plan was to conduct these tasks in a serial fashion. However, as the team compared the technology specific questions, it was decided to look at the tasks in parallel to permit greater synergy among the reviewers. This was accomplished by having team-wide meetings on specific topics during the assessment period. The team held bi-weekly meetings and content were recorded to update all members on progress and to determine topics for the team-wide technical topic meetings. These bi-weekly meetings were held in lieu of progress reports.

Each technology sub-area drafted their initial reports to form the basis for this final report. These initial reports were circulated among the assessment team members for comment and technical enhancements.

4. LISA ELEMENT ASSESSMENT

Due to the length of the assessment and proprietary nature of some of the details, only selected element assessments are provided here –

Question: Review the laser architecture and provide feedback on redundancy, derating, and implementation strategies to meet the LISA lifetime and performance requirements.

Assessment Result: Given the stringent intensity, frequency, and phase stability requirements, a small non-planar ring oscillator (NPRO) is ideal. The additional steps taken by the team to make the active laser material small is commendable. A shorter cavity length provides a longer free spectral range spacing prohibiting spurious wavelength from appearing along the emission bandwidth. A master oscillator power amplifier (PA) is the best way to meet the 2 W output required.
This type of PA is a fiber amplifier.

Question: Review the µNPRO design and provide feedback on redundancy, derating, and implementation strategies to meet the LISA lifetime and performance requirements.

Assessment Result: The µNPRO provides the stable, low-noise oscillator for the system. It was selected based on the existence of a prototype that provides required performance with minimal changes to design. Key subsystems are the laser cavity formed around the µNPRO crystal; the 808-nm pump lasers; optics for forming the cavity, coupling the pump to the cavity, and coupling light from the cavity to a single-mode optical fiber; and the laser housing that includes thermal management, hermetic sealing, mechanical structure, and electrical feedthroughs. The LISA Program is working with a vendor to build a TRL 6 µNPRO that will undergo testing, at the unit level and integrated into the LS.

The LS, shown schematically in Figure *2*, provides two levels of redundancy: a 'cold' spare µNPRO for each signal chain, and two redundant signal chains. Reliability estimates suggest that the 808-nm pump lasers drive system reliability and require careful consideration. A driving consideration that has not been determined is the required pump laser operating point. Laser reliability improves with lower current, but relative intensity noise (RIN) increases. For currents below ~400 milliampere (mA), 'noise-eater' mechanisms will need to be included. A further consideration is the µNPRO output power at its operating point, and if this is sufficient to drive the PA, as discussed elsewhere in this report.

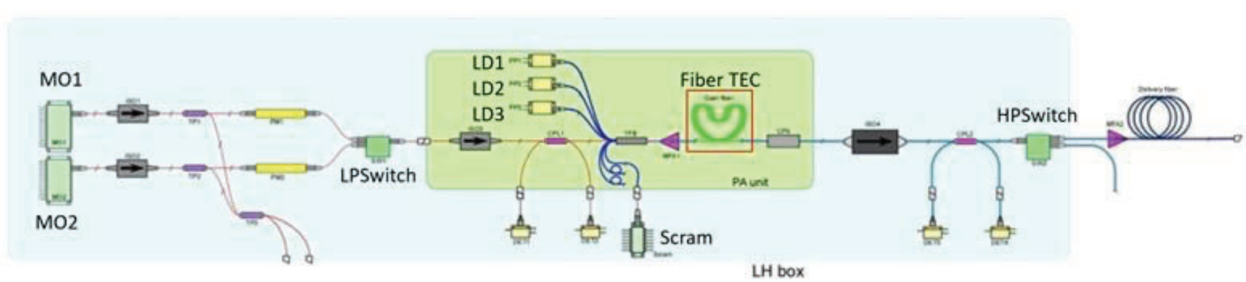

Figure 2. MO and PA Elements in Assembly

The laser cavity includes a PZT controlled by external driver electronics. There is a tradeoff between PZT tuning, drive voltage, and laser cavity tuning sensitivity.

The LISA LS design team should identify the target µNPRO operating current and determine if noise-eater circuitry will be included in the baseline design. Pump laser reliability testing should be focused on showing adequate reliability for the target operating point given program resources and timelines. The TRL 6 units should be tested for functionality. As part of this testing, it would be advisable to track the operating time for the units, using this metric as a check for unexpected mechanisms that could limit lifetime under use conditions. It will be important to finalize the design with sufficient documentation and manufacturing controls such the future flight units can be built with similar expected reliability. Finally, it is important to conduct operational-like environmental testing on the TRL 6 units.

Question: Identify any risks for the master oscillator (MO) subsystem with associated components and include potential mitigations where possible.

Topic A – Coupling the Optical Signal
Assessment Result: A concern raised during the review is the method for coupling the optical signal from inside to outside the device. Because the unit is hermetically sealed, the approach uses an optical window with free-space coupling to an optical fiber external to the package. It is important to recognize that an advantage of using COTS telecommunications-grade fiber and electro-optic components is that the designs receive some level of qualification and testing through volume production. To the extent that this approach is a unique design, it should be thoroughly evaluated and tested during the TRL 6 phase. A specific concern is the role of contamination at the fiber facet, where 100s of mW of optical fiber will be focused into the fiber core. Contamination in that location could lead to reduced CE and/or optical facet damage. Given these concerns, the Program should continue to track this risk item as Avo manufactures and tests the µNPRO.

Topic B – PZT Use
Assessment Result: Currently, the circuit is designed to supply ±100 V to the PZT epoxied to the µNPRO crystal. This design specification seems to be the worst-case scenario. The function of the PZT is tied to the fast, high-resolution, tuning of the µNPRO to meet the two of the LISA laser requirements [2].

The LISA design team reports that they used PiezoDrive PD200 for the TRL 4/5 demo. With a new µNPRO crystal design and new piezo material, they have demonstrated ~15 MHz/V, with a factor of 10 improvement from other NPROs. The high-voltage amp will no longer be needed for a TRL > 5 µNPRO MO.

Question: Identify risks for the PA subsystem and associated components and include potential mitigations where possible.

Assessment Result: The main risks for the fiber-based PA in any subsystem excluding the pump diode reliability noted is the occurrence of fiber nonlinearities arising from energetic pulses that leads to high peak power. However, the current modulation scheme and power levels are within the range that can be supported by the specified single-mode fiber configuration.

Other fiber-based component risks have been identified (e.g., with phase modulators, isolators, connectors, TFBs, filters, and optical switches). Mitigation options include testing to ensure that the amplifier is shutdown in a timely manner if no seed signal is present or that the alternate SCRAM source is switched on as required. Thermal management of the fiber assembly in the packaging design is with stress analysis and mechanical shock and vibration testing at the assembly and component levels if they do not come certified from the vendor. Excess phase noise is an issue in the PA performance, and it was not clear if that is a significant risk.

The program should perform a risk analysis on the dropout of the seed laser while the amplifier is operational to ensure safe shutdown is possible. A thermal and mechanical stress analysis of the PA design should be performed to ensure thermal management at the component and assembly levels based on vendor data. The PA design should be analyzed for all sources of excess phase noise.

A summary of the NESC SME team findings and recommendations is presented in Table 1.

Table 1. Brief summary of findings and recommendations from the NESC SME team.

Findings	Recommendations
The TRL 6 µNPRO design and operating point is being finalized (e.g., TBCs and TBRs).	• Develop a specific set of requirements and hardware block diagrams representing the planned TRL 6 configuration against which design performance and any necessary changes can be tracked. • Identify the target µNPRO operating current and determine if noise-eater circuitry will be included in the baseline design.
The TRL 6 units have challenging reliability and noise performance requirements that can be impacted by design decisions that have not been finalized.	The TRL 6 units should be tested functionally and environmentally to show compliance with requirements.
A reduced voltage needed to meet the required Doppler tuning range and resolution can have a significant impact on the PZT drive electronics indicating the selection of a thinned crystal may present a design risk.	Continue working with the µNPRO vendor to achieve a thinned crystal that will reduce the required PZT tuning voltage.
The reliability of the optical components in the MOPA design leverages other programs' development.	Baseline the flight design and test of representative optical components at elevated operational levels.
There is a risk of optical fiber damage during I&T, which requires an increased fiber length to allow for damage repair.	Outline the test plan for integration of the fiber connectors with the optical head to ensure a low insertion loss and a high temperature rated fiber coating.
The gain fiber performance is sensitive to thermal management and potential radiation effects, and rad-hard fiber is only available from a non-US source.	Provide a thermal analysis of the gain fiber thermal management requirement to within 0.05°C.
Ionizing dose susceptibility in the Yb gain fiber in a passively irradiated, high dose rate test is unclear	Repeat ionizing dose testing on flight lots to quantify variance of degradation and bound worst case analysis
Rad-hard electronics have not been selected for laser electronics module update and laser pre-stabilization system electronics	Enabling COTS components (e.g., PZT driver) have unknown susceptibility to radiation effects and no clear radiation hardened replacement. Conduct a SEE test campaign on enabling COTS components

5. OVERALL ASSESSMENT SUMMARY

The SME assessment team was asked to determine if the LS design and development plan is on track to meet the requirements provided by ESA in the TRL 6 demonstrator requirements document. The overall NESC team's assessment conclusion is that there are no fundamental problems or major design issues that will prevent the LISA team from meeting the ESA requirements for the TRL 6 demonstrator.

However, it must be acknowledged that the LS design is challenging and there will be technical risks that must be addressed moving forward especially if ESA selects this design for the flight program. The LISA team has established a technically sound risk mitigation plan, but there are items that the assessment team believes need further consideration, including:

- Several design alternatives to improve performance and reliability were discussed by the assessment team members and they are provided in the assessment text, Findings, Observations, and NESC Recommendations
- The LISA design team needs an overall better tracking of requirements and hardware configuration in the LS subsystems, e.g., COTS versus rad-hard parts, to ensure that the design closes at the end stages
- Testing protocols for components and subsystems needs to be developed (e.g., functionality, aging, thermal, radiation, etc.) to ensure measurements are made and that the design is not affected
- The assessment team has two major concerns that will need oversight if ESA selects the design for a mid-2030s launch and the effort proceeds beyond TRL 6: (1) the TRL 6 design is primarily based on COTS parts and the

performance specifications or operating characteristics of the replacement radiation-hardened (rad-hard) parts for beyond TRL 6 may perturb the design, and (2) rad-hard part lead times and obsolescence may affect the design's viability.

6. SUMMARY

NASA GSFC is developing the laser transmitter for the LISA project. In 2020, GSFC requested help from NESC to perform an independent assessment of the laser design and approach to meet the laser requirements for LISA. The SME team from NESC performed a 12-month study of the laser design. During this study, the SME team interact closely with the LISA laser team. The independent assessment provided valuable information, findings, and recommendations for the laser team with findings and recommendations to achieving TRL6 with a goal of flight deployment. A final report was presented to stakeholders at the end of the study period [3].

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