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LISA Laser System and European Development Strategy

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ABSTRACT

The Laser Interferometer Space Antenna (LISA), with its extreme distance measurement requirements (pm over arm lengths of 2.5 million km), imposes many stringent requirements on the laser systems used for the distance metrological measurements. In particular, frequency and power stability, sideband phase noise, and frequency reproducibility, the need of manufacturing multiple laser systems and extremely challenging lifetime (extended mission duration of 12.5 years) which demand a streamlined laser design and a particular attention to reliability and procurement strategy, all pose a significant challenge. The main requirements will be presented and analysed. Some preliminary strategies as it pertains to procurement and lot screening shall also be approached.

The current configuration and break-down of the future on-board laser systems shall be provided detailing in particular the critical interfaces.

Existing space heritage hardware (such as the LISA Pathfinder Master Oscillator) and new specialized developments are under study in both Europe and the US. European industry is developing custom Power Amplifiers to reach the end-of-life requirement of 2W (in Continuous Wave operation). In parallel alterative possible sources for a back-up Master Oscillator are also being investigated, based on off the shelf components and proprietary technologies. An overview of the development strategy shall be presented as well as some details on the specific hardware.

Keywords: Gravitational Waves, Laser Interferometer Space Antenna, laser system

1. INTRODUCTION

Gravitational Waves (GWs) are distortions of the space-time, which can be translated as a variation in the refractive index of vacuum, or in the distances between free-floating macroscopic bodies. The challenge for the observation of these phenomena is, however, the diminutive nature of the relative length changes due to passage of a GW; the periodic change in distance between two proof masses to be resolved being of the order of the (10^{-12}m) picometer (pm).

The ground-based antennas have permitted to obtain a first GW detection in 2015[1], and have managed to create in the years since a GW observatory[2], leading up to multi-messenger astronomy applications[3], [4]. However, observation of GW from the Earth is limited, mostly due to seismic noise and antenna arm length, to frequencies above the Hz. An instrument capable to measure below the tens of mHz would allow to study the most powerful GW sources. The Laser Interferometer Space Antenna (LISA) exactly aims at satisfying this objective: to detect and to observe gravitational waves from massive black holes and galactic binaries in the frequency range between 10^{-4} and 1 Hz.

A number of mission concepts dedicated to the detection of gravitational waves in space have been studied over the past three decades (e.g. LISA, DECIGO[5]) with the Laser Interferometer Space Antenna (LISA) mission concept emerging as the forerunner in Europe[6].

1.1 The LISA Antenna

The LISA observatory basic mission concept comprises three identical S/C located 2.5 million km apart and forming an equilateral triangle rotating in a Heliocentric orbit, trailing, or preceding the Earth by roughly 20° along its orbit. The arm lengths will actually be slightly unequal, as will the angle between the arms, with annual variations respectively of 10%

and less than 3°. The plane containing the three S/C is inclined by 60° with respect to the ecliptic plane. At the heart of each Spacecraft are two free-flying Test Masses (TMs). Each TM represents the end of one interferometric arm. One complete arm is constituted by two TM on opposite S/C. A passing gravitational wave will change the length of the optical path between the TMs of the three interferometric arms. The goal is to measure by optical interferometry these distance fluctuations to sub-Angstrom accuracy down to a spectral noise density of few pm/√Hz in the frequency range from 10^{-4} Hz to 1 Hz (goal: 3×10^{-5} Hz to 1 Hz). Combined with the large separation between the spacecraft, this allows the detection of gravitational wave strains down to a level of the order of $\Delta l/l=10^{-23}$ in one year of observation, with a signal-to-noise ratio of 5.

The interferometric measurement system is based on an infrared laser beam (transmit beam, Tx) which is pointed to the corresponding remote spacecraft via a telescope. The same telescope is used to receive the very weak beam (about 100 pW) coming from the distant spacecraft (received beam, Rx) and to direct the light to a sensitive photo-detector where it is superimposed with a fraction of the local light to realise an heterodyne interferometer which measures the (one-way) arm length variation. It has to be noted that due to the very low amount of received optical power (due to divergence over the large propagation distance) the complete arm measurement is obtained by combining the two one-way arm length determinations with appropriate introduced delays [7].

1.2 The Laser Assembly architecture

Each of the LISA spacecraft will require a Laser System able to ensure contact with one of the distant sister Spacecraft (S/C). The LISA observatory having three arms, dictates the need for each S/C to have two Laser Assemblies, one per interferometer arm. With reference to Figure 1 hereunder Spacecraft A will have a laser assembly for the L_{AB} arm and one for the L_{AC} arm.
Each interferometer arm will be constituted of two one way links (cf. Figure 1) and the laser sources will need to be phase locked in order to ensure that reconstitution of all possible (Michelson, Sagnac,…) interferometric configurations is possible. This reconstitution is obtained by adequately delaying and combining the single arm data-sets using Time Delay Interferometry (TDI [7]). The usage of TDI, and the knowledge of the arm length, allows for interferometer reconstruction.

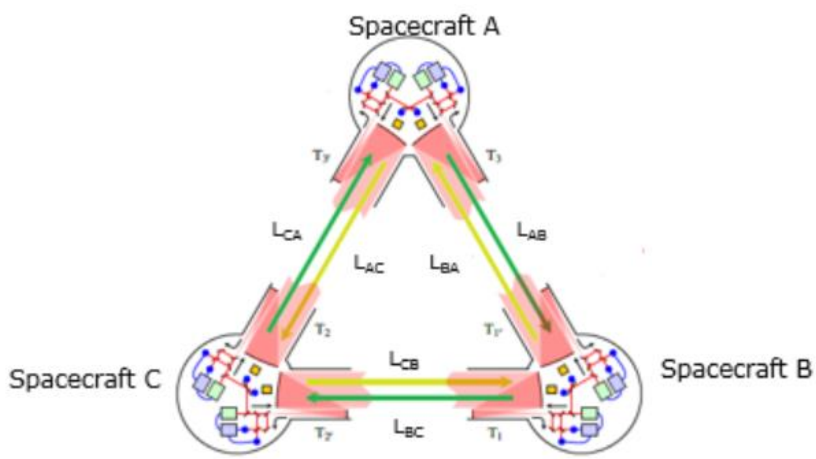

Figure 1. LISA antenna laser links. Three S/C in constellation, 3-arm interferometer, 6 1-way links.

It has to be noted that due to the unequal arm lengths the laser frequency noise will not cancel out and will need to be taken into account. To ensure pm sensitivity over millions of km would in theory require stabilities better than state of art by more than 3 orders of magnitude. Through the use of TDI and the possibility it affords to equalise the interferometers arms, the required frequency stability requirement can be relaxed to a level achievable with today's technology .

The loss of one laser source would effectively result in the loss of one arm, with corresponding decrease in mission science return but without mission loss. A Laser Assembly is therefore required to be robust with respect to single point failure. The preferred redundancy strategy currently envisaged foresees complete redundancy of each arm's Laser Head (LH) as shown in Figure 2.

The LH is composed of a Laser Optical Module (LOM) and a Laser Electronics Module (LEM). Cross-strapping (i.e. allowing LEM nominally to operate in conjunction with LOM redundant, and vice versa as well as nominal units and redundant units together) of these two modules is currently being investigated and is the preferred solution, provided it does not result in a single point failure mechanism.

The LOM can be broken down in turn in two separate sub-units a Master Oscillator (MO) determining, together with the LPS, the LS frequency performance and a Power Amplifier (PA) ensuring the required power (2W, CW and measured at the fibre output on the LISA Optical Bench) is made available to the LISA interferometers. While the MO could, in principle, be a laser very similar to the LISA Pathfinder (LPF) development, the PA is a new development. For this reason, as shown in the following, the PA will be the source of multiple parallel technological developments. Alternatives to the LPF MO are also studied to account for significantly increased lifetime and to reduce the risk of obsolescence.

The LOM includes all optical functions required for the generation and modulation of the laser light; it also includes a switch for turning on and off the laser output ideally with minimum perturbation of the thermal environment. The main optical output of the Laser Head is a linearly polarized and continuous wave laser beam at a wavelength of 1064nm. This beam is sent to the optical bench via a polarization maintaining (PM), single-mode (SM) optical fibre.

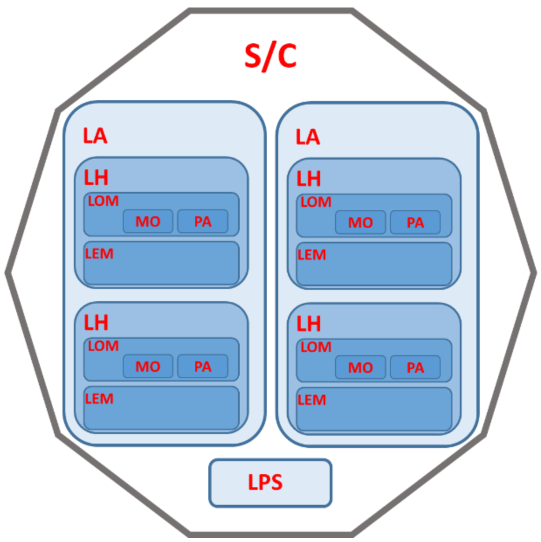

Figure 2. Laser system on board of each of LISA spacecraft. Two Laser assemblies, one for each arm, containing two Laser Heads. LH including Laser Optical Module, Laser Electronics Module. LOM composed of Master Oscillator and Power Amplifier. Frequency characteristics guaranteed by the Laser Pre-stabilisation System.

Finally, in order to guarantee the laser frequency stability, a frequency reference and its associated control loop will also be required. The laser frequency stability is a demand at constellation level only. During science operation, six of the twelve Laser Heads are operative with one of the six Laser Heads acting as the Master being phase-locked to its Laser Pre-stabilisation System (LPS). The other five active Laser Heads operate in Slave mode, whereby they are offset-locked to the Master in an active transponder scheme. Typical offset frequencies are in the range of 5 - 20 MHz. All six Laser Systems are identical and can be switched from Master to Slave or vice-versa during the mission lifetime as needed. As such, with a single LPS per spacecraft (S/C), a triple redundancy at instrument level is in place. If, as is currently under study, both laser assemblies on each S/C were in a position to be locked to its LPS the frequency locking would maintain its redundancy even in the event of the loss of an interferometer arm.

It has to be noted that the laser beam will also be used for arm length measurement (with a precision of the order of less than a m), and transmission of data between spacecraft, the latter in order to reduce the number of repointing of both ground station and spacecraft antennas for communication and data retrieval from the constellation. Therefore, an RF modulation signal (pure sine tone at 2.4 GHz) and a Pseudo random Noise (PN) modulation (symbol rate of 1 Mbps tentatively) will be applied as phase-modulation to the laser beams either at MO (current baseline), or at PA level within the Laser Optical Module.

2. CRITICAL LASER SPECIFICATIONS AND JUSTIFICATION

The LISA laser system has numerous requirements defining the architecture, interfaces and performances. In the following we shall concentrate on the most critical for antenna performance, that is to say spectral and power requirements. Before these requirements are presented a few definitions have to be set down.

Rather atypically, in the case of LISA, the frequency stability is defined as a (linear $S_x(f)$ in units/√Hz) Power Spectral Density (PSD) rather than in terms of Allan variance/deviation. While Allan variance is the preferred estimator for oscillators presenting non-Gaussian (e.g. flicker) noise, as it converges allowing for repeatability of the measurement, the power spectral density can be directly related to the antenna performances without any transformation requiring knowledge of the noise type (e.g. white, flicker). The PSD is the Fourier Transform of the autocorrelation of a signal, and its integral over frequency will yield the variance:

$$S_x^2(f) = \int_{-\infty}^{+\infty} E[x(t)\, x(t+\tau)\,] \cdot e^{-2\pi i f \tau} d\tau \qquad (1)$$

A complementary requirement on the excess noise δpp is then specified, as PSD estimators are ill suited in the presence of single spectral lines, or, in general, non-Gaussian noise (as mentioned above). In particular, the estimated probability $\hat{p}$ for a measurement $x_i = x(t_i)$ of the time varying quantity $x(t)$ to be located in the interval with maximum deviation δ_{pp} around the mean value $\langle x \rangle_T$ is requested to be at least 99% for all measurement times, as expressed in the formula hereunder:

$$\hat{p}\left(\langle x \rangle_T - \frac{\delta_{PP}}{2} \leq x_i \leq \langle x \rangle_T + \frac{\delta_{PP}}{2}\right) \geq 99\% \qquad (2)$$

Note that this requirement uses estimated quantities, and that δ_{pp} is computed by evaluation the Root-Mean-Square-noise of the quantity over the relevant frequency band and multiplying it by 6.

2.1 Laser central wavelength

The centre wavelength, $\lambda_{0,}$ in vacuum for the Laser Head (LH) shall be as close as possible to 1064.5 nm to maximize the reuse of LISA Pathfinder [8] developed technology.

2.2 Tuning Range commonality

All Laser Heads shall possess a common tuning range to ensure that sets of operating parameters can be chosen such that the respective tuning intervals have an overlap of at least 2 GHz.

These overlapping tuning intervals are needed to ensure that all lasers in the antenna can be offset locked to one another.

2.3 Laser wavelength coarse tuning range

The emission wavelength of the free-running LH shall be tunable by at least ± 2 GHz around λ_0. For any frequency within the Coarse Tuning Range, the Laser Head shall provide mode-hop free operation throughout the mission lifetime. The prescribed tuning range is required for initial alignment of the emission frequency of the Master laser to a LPS cavity resonance, and to offset-lock the Slave lasers to the Master in order to establish beat notes.

2.4 Laser wavelength tuning accuracy

For the free-running Laser Head, the emission wavelength shall be tunable to an absolute accuracy of 50 MHz, with a step resolution of 1 MHz over the full Coarse Tuning Range.

The stated absolute tuning accuracy (which applies to all 12 LH) ensures a rapid fringe acquisition. The stated tuning step resolution allows adequate control of the beat note frequency.

2.5 Frequency stability (free running)

The requirements for the frequency stability of the laser are given below. The laser frequency is denoted by ν and measurement band frequency by f. An illustration of the requirement is given in Figure 3.

The frequency stability requirement for the free-running laser is given by:

$$S_\nu \leq 3.75 \frac{Hz}{\sqrt{Hz}} \cdot \sqrt{1 + \left(\frac{8kHz}{f}\right)^2} \; for \; 3 \times 10^{-5} Hz \leq f \leq 1Hz \, (3)$$

With excess noise for the free running laser

$$\delta_{\nu PP} \leq 33MHz\ for\ 3\times 10^{-5}Hz \leq f \leq 1Hz$$

$$\delta_{\nu PP} \leq 200kHz\ for\ 1Hz \leq f \leq 1MHz \qquad (4)$$

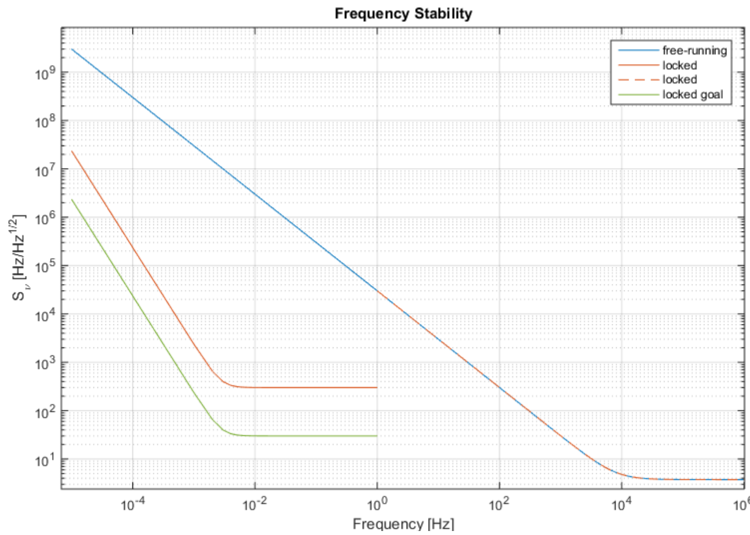

Figure 3. Laser system frequency stability characteristics free-running (blue), locked (orange), locked goal (green)

2.6 Frequency stability (locked)

The frequency stabilised laser shall satisfy the following requirements (the low frequency part represents the goal requirement rather than the specification which is currently set at 300Hz/√Hz with a goal at 30Hz/√Hz):

$$\left.\begin{array}{c} S_\nu(f) < 300\dfrac{Hz}{\sqrt{Hz}} \times \sqrt{1+\left(\dfrac{2.8mHz}{f}\right)^4} \\ \delta_{PP}(\nu) < 50Kz \\ S_\nu(f)_{goal} < 30\dfrac{Hz}{\sqrt{Hz}} \times \sqrt{1+\left(\dfrac{2.8mHz}{f}\right)^4} \end{array}\right\} for\ 3E-5Hz \leq f < 1Hz$$

$$\left.\begin{array}{c} S_\nu(f) < 3.75\frac{Hz}{\sqrt{Hz}} \times \sqrt{1+\left(\frac{8kHz}{f}\right)^2} \\ \delta_{PP}(\nu) < 200Kz \end{array}\right\} for\ 1Hz \leq f < 1MHz \qquad (5)$$

The laser frequency stability specifications are provided visually once more in Figure 3.

2.7 Spectral purity (broadband)

The integrated power in a 10 nm bandwidth around the main laser line, excluding the laser line and a ± 5 GHz frequency band centred on it, must be smaller than:

- 0.1% of the output power for light in the nominal polarization
- 0.01% of the output power for light in the orthogonal polarisation

The integrated power outside the 10 nm wavelength band around the main laser line must be smaller than 2 mW.

2.8 Spectral purity (narrowband)

The power excess noise δ_{PP} in the frequency band ± 5 GHz centered on the laser line must be smaller than 0.6 mW for a laser output power of 2W.
The power excess noise in the band ± 5 GHz around the laser wavelength must be small enough to not affect the ranging codes and the clock transfer. Note that this power excess noise scales linearly with laser output power

2.9 RF modulation

The laser shall allow a phase modulation of the laser light at (2.4 ± 0.5) GHz. The phase noise $S_{\phi}(f)$ and the excess noise $\delta_{PP}\phi$ in the frequency band 3×10^{-5} Hz to 1 Hz shall be smaller than:

$$S_{\phi}(f) < 400 \cdot u_{PL}(f)\frac{crad}{\sqrt{Hz}} \quad (6)$$

$$\delta_{PP}\phi < 66mrad$$

in which

$$u_{PL}(f) = \sqrt{1 + \left(\frac{2.8mHz}{f}\right)^4} \quad (7)$$

The power P_{sb} in the produced sidebands at the chosen modulation frequency shall contain at least 15 % of the total output power P_{out} of the laser. Simultaneously, the remaining power in the carrier P_c must not be reduced by more than 17 % with respect to the total output power.
Assuming a sinusoidal phase-modulation, this requirement can be fulfilled by choosing the appropriate modulation index m.
The sine tone represents the Ultra-Stable-oscillator clock and is used for USO calibration. Excess phase noise on the optical signal would manifest as a differential phase noise between the carrier and one 2.4 GHz sideband. The stated phase fidelity is required for correct cancellation of USO noise in post-processing.

2.10 Code modulation

The laser shall allow a phase modulation of the laser light with a PN code. The modulated sidebands shall carry 1% of the total laser optical power.

2.11 Output power

The output power of the laser P_{out}, delivered to the optical bench in the nominal spatial mode and the nominal polarisation state at end-of-life, shall be, $P_{out} \geq 2\ W$.

2.12 Power stability

The output power stability is expressed in terms of Relative Intensity Noise (RIN). The RIN at the output of the LH optical interface to the Optical Bench shall be, under all operating conditions, better than (values are to be confirmed):

$$\left.\begin{aligned} S_{RIN}(f) &< 1E-4/\sqrt{Hz} \\ \delta_{PP}RIN &< 0.06 \end{aligned}\right\} for\ 3E-5Hz \leq f < 10kHz$$

$$\left.\begin{aligned} S_{RIN}(f) &< 1E-5/\sqrt{Hz} \\ \delta_{PP}RIN &< 0.02 \end{aligned}\right\} for\ 10kHz \leq f < 100kHz$$

$$\left.\begin{aligned} S_{RIN}(f) &< 1E-4/\sqrt{Hz} \\ \delta_{PP}RIN &< 0.02 \end{aligned}\right\} for\ 100kHz \leq f < 700kHz \quad (8)$$

$$\left.\begin{aligned} S_{RIN}(f) &< 3E-7/\sqrt{Hz} \\ \delta_{PP}RIN &< 1E-4 \end{aligned}\right\} for\ 700kHz \leq f < 5MHz$$

$$\left.\begin{aligned} S_{RIN}(f) &< 1E-8/\sqrt{Hz} \\ \delta_{PP}RIN &< 5E-4 \end{aligned}\right\} for\ 5MHz \leq f \leq 50MHz$$

$$S_{RIN}(f) < 5E-5/\sqrt{Hz}\ for\ 50MHz < f \leq 5GHz$$

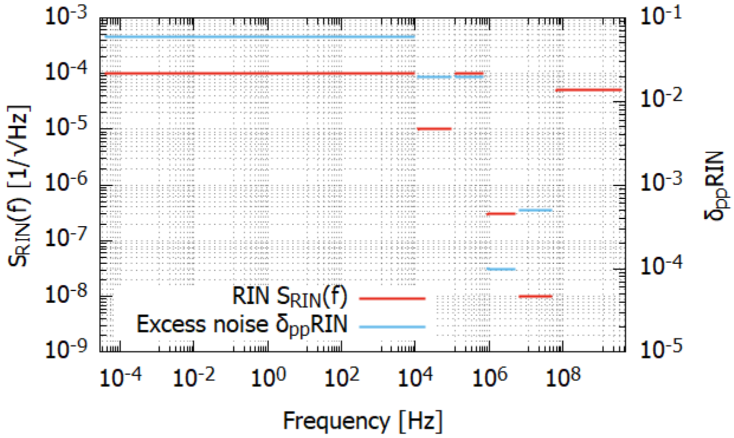

Figure 4. Laser system RIN stability characteristics plotted as a function of the frequency

2.13 On/Off switch

The Laser Head shall contain a mechanism to switch the main laser optical output from the "ON" state (i.e. full laser output power delivered to optical bench) to the "OFF" state. In the "OFF" state, the output of the main laser optical output at the OB optical interface shall be suppressed by at least 60 dB.

The switching time from "ON" to "OFF" and vice versa shall not be more than 100 ms.

The switching mechanism shall be single-point failure tolerant.

The switching is required for the initial laser beam acquisition procedure. The perturbation of the thermal environment of the laser must be minimised (e.g. the conductive load into the spacecraft) and correspondingly the LH frequency and output power settings are preserved.

3. OVERALL STRATEGY AND DEVELOPMENTS

The LISA mission has a technology programmatic requirement of TRL 6 by 2022. In order to meet this requirement, the Agency is funding technology development activities (TDAs) addressing a number of areas including the telescope, phasemeter and laser system.

For the LS the European activities include three parallel contracts developing or investigating two possible alternative Master Oscillators (as the LPF heritage MO is considered as the nominal solution) and three possible Power Amplifier designs.

A contract has been awarded to CSEM, in order to investigate commercial off the shelf external cavity diodes Master Oscillator Solutions and to develop a custom PA.

A second contract awarded to SpaceTech that is investigating a proprietary Master Oscillator design and custom Power Amplifier solution.

Last but not least, LusoSpace has developed a custom power amplifier to be tested in conjunction with a Tesat like Non-Planar-Ring-Oscillator (NPRO).

All activities are addressing the development Engineering Model (EM) level hardware which will be used to demonstrate the required performance in the relevant LISA environment.

3.1 CSEM development

CSEM has based its laser head (LH) development on reliable technologies with key optical components being either space-qualified or with proven reliability (like Telcordia qualification). Some of them have even space-heritage. Two non-NPRO commercial seed laser technologies are investigated. Of critical relevance is the frequency noise and with this respect one technology is close to the requirements and offers space-heritage while the second technology is not yet space-qualified (but offers good prospects) and is very much meeting the frequency noise specifications. The main other key specifications (like tunability, spectral purity, etc.) are essentially met. In terms of optical amplifiers, they are based on standard fiber technology and so far have shown excellent amplitude noise properties with output power level ≥ 2 W. In order to be limited by the intrinsic noise of the selected lasers (seed and pump lasers), dedicated low-noise electronics has been developed. This electronics already involves key components that have space-qualified equivalents. This will ensure a smooth transition to space-qualified electronics. In addition, the electronics has also been designed with low compliance voltages to reduce as much as possible the LH power consumption.

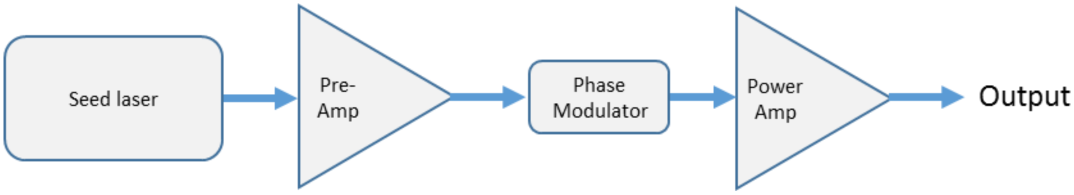

Figure 5. Schematic of CSEM laser head for LISA

In order to achieve the long-term frequency noise specifications in the pre-stabilized state, an optical reference cavity is used. The cavity has been mounted in an appropriate system including vacuum, temperature stabilization and vibration isolation features. The well-known Pound-Drever-Hall stabilization technique is utilized to servo the LH frequency to one cavity resonance. Long-term frequency metrology measurements by comparing the LH against an active-maser stabilized optical frequency comb have shown compliance with the long-term specifications down to 30 μHz. Power stabilization is another key and challenging aspect of the system. At the time of writing, further optimization of the power stabilization is under way such that the low-frequency specifications can be met as well. So far this is the case down to a frequency of 1mHz.

In conclusion, the LH breadboard developed by CSEM integrates mature and reliable optical and electrical components that are, for the majority of them, Telcordia or even space-qualified. CSEM also developed the necessary metrological test equipment to be able to fully characterize the LH. The LH performances are so far reaching, for most of them, the demanding specifications of the mission.

3.2 SpaceTech development

We – a consortium consisting of Airbus Defence & Space; DELOS Space; DLR Bremen; Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik; Fraunhofer ILT; Humboldt Universität zu Berlin, and SpaceTech as a prime contractor to ESA – design, build and test a Laser Head to fulfill the LISA requirements using another, new seed laser technology. The MO is an external cavity diode laser (ECDL) with resonant feedback from an additional external cavity for further linewidth narrowing (approx. a factor of ten compared to regular ECDLs). This laser comprises a master oscillator power amplifier (MOPA) concept, where the output of the ECDL with resonant optical feedback, the MO, is (pre-)amplified by means of a power amplifier (PA), a semiconductor optical amplifier (SOA) delivering 300 mW of optical power at the fiber output. The ECDL MOPA is a hybrid micro-integrated device based on a micro-integrated laser platform already flown on several sounding rocket experiments, highly suitable for space missions.

Figure 6 shows a photograph of the ECDL Breadboard with external cavity during integration without SOA. For the Breadboard (BB) phase a dedicated SOA BB is set up (see Figure 7) as existing hardware had to be used for the ECDL micro-bench due to the time constraints.

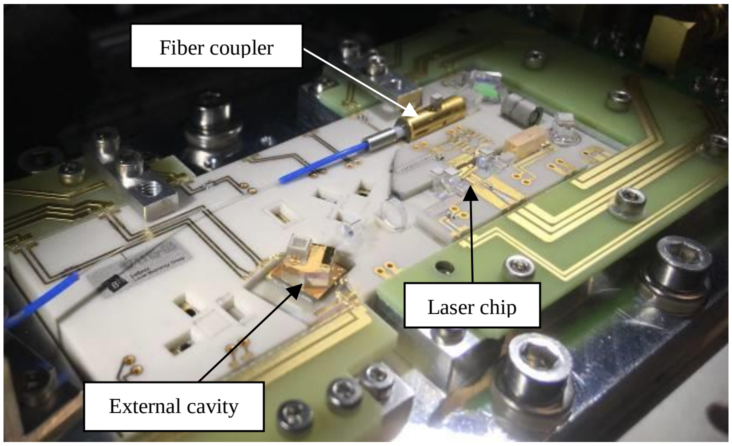

Figure 6. Micro-integrated ECDL BB with external cavity during integration.

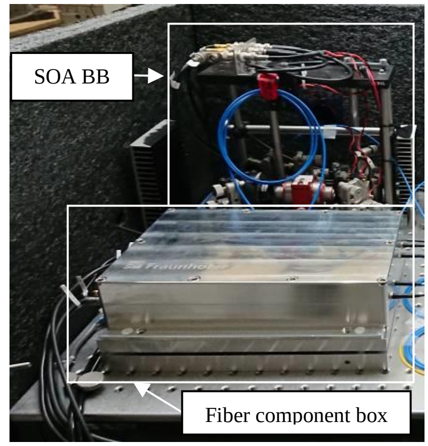

Figure 7. Fiber component box of Fiber Amplifier (front) and SOA BB setup (back).

The ECDL with external cavity delivers about 4.5 mW of optical power out of the fiber. This is sufficient to seed the SOA to deliver 300 mW of optical power.

This light is coupled into an EOM for PN code modulation and amplified by a single-stage fiber amplifier with an amplification factor of about 20 dB. The amplifier utilizes an active Yb-doped fiber that is contra-directionally pumped by three wavelength-stabilized pump diodes to deliver 2.1 W of optical output power to the LISA Optical Bench. 7 depicts the fiber component box of the amplifier. The single-stage amplifier is designed to introduce only very low noise, which could mainly arise from amplified spontaneous emission and stimulated Brillouin scattering. The design is based on the design of the fiber amplifier for a high-stability laser for a potential Next Generation Gravity Mission (NGGM) which successfully passed an environmental test campaign to demonstrate TRL5 on system and TRL7 on component level.

All breadboards are currently undergoing final tests showing promising results that an ECDL with external cavity in conjunction with a single-stage fiber amplifier can meet the demanding laser requirements for LISA [9].

3.3 LUSO Space development

Lusospace's Laser Head Amplifier (LHA) development is a 3-phase project and is currently at the end of phase 2. Phase 1 focused on the LHA general architecture design and on the critical photonic components market survey and screening for space use. During phase 1, several photonic components (pump lasers, splitters, photodiodes, optical isolators, erbium doped fibres, and optical switches) were procured and environmentally tested with respect to vibration, radiation, thermal and vacuum environment. A trade-off was made between: required performance, supplier heritage on space-grade manufacturing, testing survivability and degradation assessment.

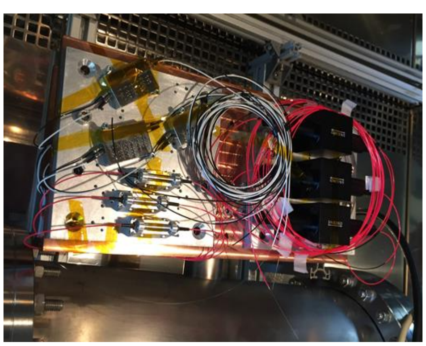

Figure 8 - Photonic devices under TVAC test.

Figure 9 -Optical Switches and pump lasers under vibration testing.

Within phase 2, a LHA delta-design was made to include the selected components from phase 1. This phase included the LHA Engineering Model manufacturing, integration and testing in the laboratory environment.

The LHA general architecture can be described as being an optical power amplifier composed by two stages of erbium doped fibers amplifiers, a pre-amplifier and a power amplifier. The general specifications of the developed LHA are the following:

- 1064 nm NPRO seed laser (Lusospace used a Mephisto NPRO Laser 1064 nm);
- 10 to 40 mW input optical power;
- >1,2 W output optical power (can go up to 2W at Beginning of Life, BOL)
- Standalone system with internal electronic circuits and critical photonic devices redundancy.
- Master mode and free-running mode operation.
- RIN suppression circuits; Frequency tuning and stabilization circuits; Thermal management circuits;
- Space wire interface; 28 V input voltage;
- 80 W power consumption;

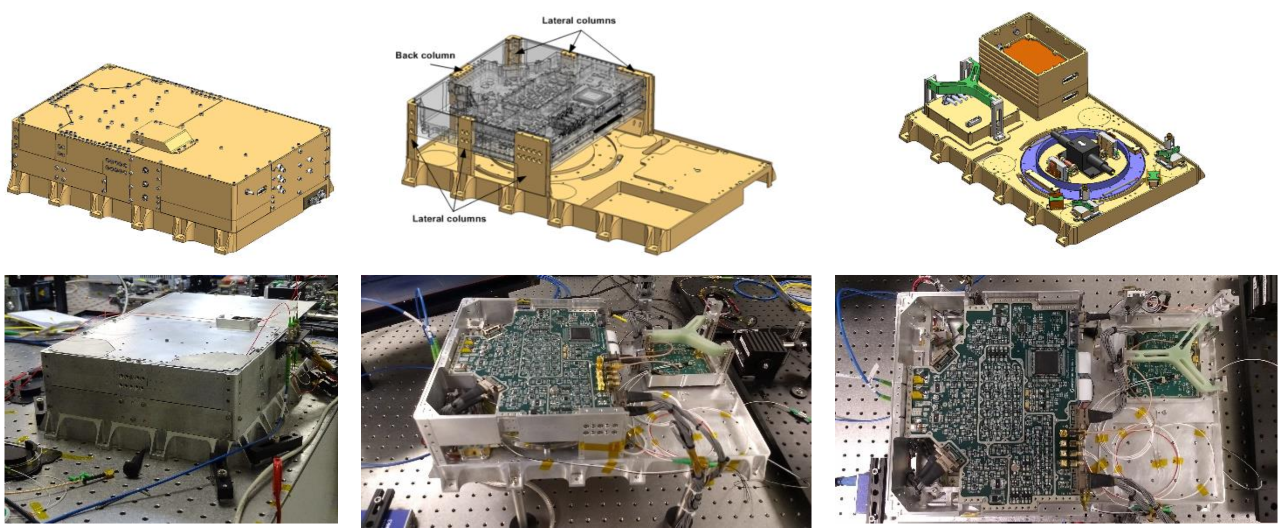

Figure 10 – Several views on the LHA 3D CAD design and the LHA EM manufacturing and integration.

For the LHA performance testing Lusospace and its partners developed several test setups to verify the system compliance with respect to the LISA specifications. The critical specifications to be measured include: Relative Intensity Noise at the 1.2W optical power, laser frequency stability noise and sideband phase fidelity noise.

Figure 11 – Verification test setup for the LHA laboratory environment testing.

Custom hardware was developed to support the measurements: a very stable digital optical power meter, an Optical Reference System (ORS) for the frequency noise measurement (which included an optical cavity for laser reference at 1064 nm) plus a custom verification setup for the sideband phase fidelity noise acquisition.

The Laser Head Amplifier test results are promising, showing that most of the LISA specifications can be achieved and integrated in a complex amplifier system, the following pictures show some of the results:

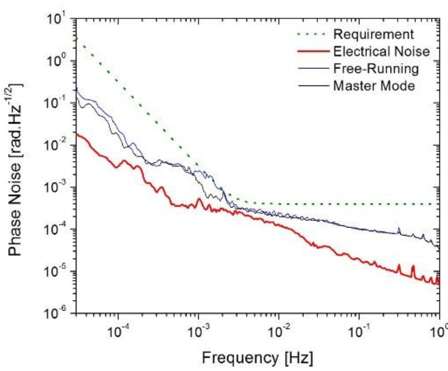

Figure 12 - Sideband Phase Fidelity Noise.

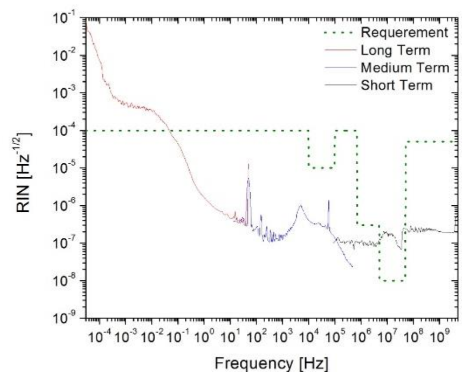

Figure 13 - RIN measurement for 1.2 W output optical power.

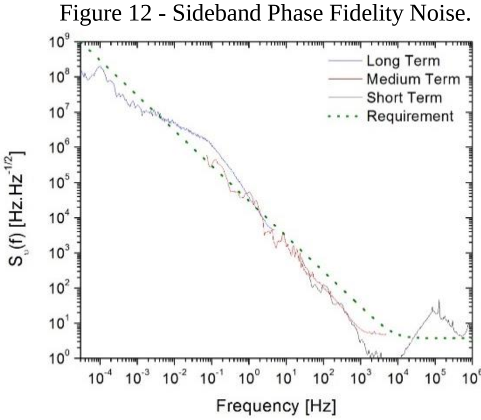

Figure 14 - LHA Frequency noise in Free-Running Mode operation.

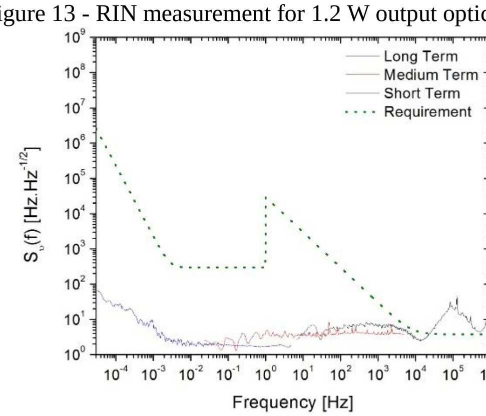

Figure 15 – LHA Frequency noise in Master Mode (locked with the ORS) operation.

The goal of the following phase (phase 3) is to increase the technology readiness to TRL 6 and verify the system performance in relevant space environment (vacuum, representative thermal interfaces). Also some improvements in the verification setups will be implemented.

4. CRITICAL DEVELOPMENT CHALLENGES

Aside from the performance challenges, detailed in the previous sections, a few additional delicate constraints affect the LISA laser system. These are related the very long mission development phase (more than 15 years), long mission duration (in excess of a decade) and verification of performances with interfaces spanning several different sub-systems (e.g. Phasemeter (PM), Optical Bench , and LPS.

4.1 Obsolescence, storage and aging

The long development phase for LISA implies that a real risk exists for components used for EM (engineering model) and QM (qualification model) testing to no longer be available at the time of flight lot procurement. The photonics market being continuously and rapidly evolving, obsolescence is a very present concern.

Advance procurement of flight lots for the critical components and technologies could be a potential solution. This however opens questions of how better to evaluate the impacts of storage and potential aging (e.g. seal of hermetically enclosed sub-systems) of the procured components.

Currently the baseline is to start evaluation of critical components to evaluate their robustness to environment for both on-ground land in-orbit life-cycles of the laser system. Depending on the results of these preliminary tests an advance flight lot procurement may be started as soon as mission adoption is formalised in the early years of the next decade.

4.2 Lifetime

The laser Flight Model (FM) lifetime includes:
- a three year period on-ground after delivery to the S/C prime contractor, with at least one year operational during AIT/V activities (including alignment, integration and testing)
- at least 6 months (and as much as 1.5y) of cruise
- 4 years of nominal science operations
- 6 years of extended science operations

The lifetime for the Laser Head is thus well in excess of 13 years. This is extremely challenging and will require both careful choice of critical components and accelerated verification to prove lifetime, without engendering non-realistic failure mechanisms due to the accelerated quality of the aging.

Once more the evaluation campaigns, currently in their planning phases, will allow to assess the criticality of the different laser components and the preferred way forward for the qualification phase.

4.3 Interfaces, Metrology and Ground Support Equipment

A last difficult point to master are the interfaces. This is a generic difficulty for LISA, a very complex mission in which platform and payload work together, in close accord, to deliver the science performances.

For the LS the critical interfaces involve the phasemeter (PM) which is providing the signals to ensure that the phase lock across the antenna Laser Heads is possible. Whether the creation of an adequate error signal will be placed within the LEM (laser electronics) or the PM is yet undefined. For verification purposes a self-contained laser would be preferred. In both cases a PM simulator (Ground-Support Equipment) will be required. The development thereof is considered to be non-trivial, as the flight configuration test may occur very late in the project life-cycle.

Analogously the interfaces between the LH and the LPS, which may be just a passive frequency reference or could include error and correction signal generation, have to be carefully assessed. Currently, the proposed solution is to include the LPS in the laser system development to avoid additional split of control loops across different sub-systems.

A last interface which will be tested only at spacecraft level testing, involves the Optical Bench on which the fibre emanating from the laser will be placed; as will be the fast photodetectors used for the long term power stability control. Here the interface is considered to be less critical as the creation of an adequate GSE is more straightforward control loop functions being expected to be included in the LEM.

5. CONCLUSIONS AND WAY FORWARD

The LISA laser system development is a challenging and rather unique one, due to the demanding performance requirements, coupled with the long development and operation phases.

The path forward includes the down-selection of two MO and two PA concepts by the end of the 2018 in time to present a consolidated preliminary laser concept for the Mission Consolidation Review which will take place toward the end of the first quarter of 2019.

Evaluation activities will proceed apace with the engineering development and characterization ones to pave the path to a Technical Readiness Level of 6 for mission adoption in 2022.

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