# International Conference on Space Optics—ICSO 2022

Dubrovnik, Croatia

3–7 October 2022

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ICSO 2022

International Conference on Space Optics

3 – 7 October 2022 | Dubrovnik | Croatia

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# *LISA laser head metrology*

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International Conference on Space Optics — ICSO 2022, edited by Kyriaki Minoglou, Nikos Karafolas, Bruno Cugny, Proc. of SPIE Vol. 12777, 127773B · © 2023 ESA and CNES · 0277-786X · doi: 10.1117/12.2690348

# LISA laser head metrology

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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 sources used for the distance metrological measurements. In particular, meeting the frequency noise, power stability and side band phase noise requirements reliably for multiple laser systems over the mission lifetime presents a considerable technical challenge. These constraints demand a robust state-of-the-art laser design and a particular attention to reliability and procurement strategy, which all pose a significant challenge.

Relying on its strong metrology expertise, CSEM, Swiss Center of Electronics and Microtechnology, is, in the frame of an ESA activity, upgrading all of the metrology techniques and hardware, used to characterize a previously developed non NPRO laser system for the LISA mission. These metrology systems are the baseline for assessing the performance of LISA mission laser heads, developed by NASA. Novel metrology techniques have been developed to assess the challenging laser head specifications.

The measurement of frequency stability requires combining different frequency references to cover the full frequency range spanning over more than 10 decades.

The measurement of power stability requires combining several metrology approaches to cover the full frequency range and dedicated development, in collaboration with NASA, to improve the long-term measurement capability.

As already demonstrated in the previous CSEM activity, sideband phase noise measurement is very sensitive to the environment and complex to perform. A dedicated and improved test setup has been implemented.

After a presentation of the NASA laser head, dedicated testing philosophy approaches, encountered technical challenges and obtained test results are presented.

**Keywords:** LISA, laser system, laser head, frequency stability, phase noise, power stability

## 1. INTRODUCTION

The development of the LISA Laser Head (LH), in particular the laser optical modules (LOMs), led by NASA, shall answer stringent specifications to meet the requirements of the LISA extreme distance measurement requirements. Among the key performance specifications, side band phase noise, frequency stability and output power stability are key drivers. Reliability and lifetime are also critical aspects driving the laser system design which is shown in Figure 1. Each of the three LISA spacecraft carry one Laser System which consists of a Laser Assembly for each interferometer arm. The Laser Assembly in turn consists of prime and cold redundant Laser Heads. Each Laser System also consists of one Laser Prestabilisation System, a Fabry Perot based frequency reference against which the LH can be locked.

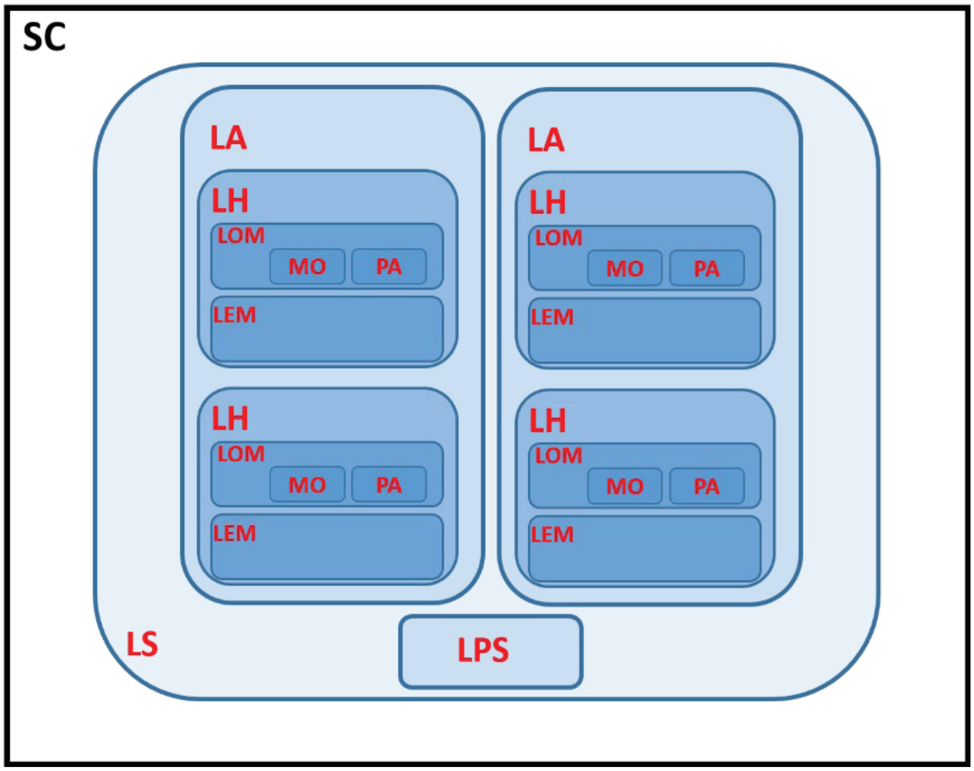


Figure 1: LISA Laser System schematic. SC = Spacecraft, LS = Laser System. LA = Laser Assembly, LH = Laser Head, LOM = Laser Optical Module, LEM = Laser Electronics Module, MO = Master Oscillator, PA = Power Amplifier, LPS = Laser Prestabilisation System.

In addition to the laser development, the metrology of such a laser is also a key challenge for the LISA mission. Thus, to validate the laser optical module development, dedicated metrology approaches have been developed or upgraded.

CSEM, under ESA contract, has been tasked with developing a metrology laboratory that will serve for the validation of the LISA Laser System elements developed by NASA and delivered to ESA for assessment. As of today, the first Technology Readiness Level (TRL) 4 model has been tested.

## 2. NASA LASER HEAD OVERVIEW

**TRL4 Laser Design and Deliverable to CSEM**

NASA Goddard Space Flight Center (GSFC) has developed prototype TRL 4 LOMs for the Laser Interferometer Space Antenna (LISA) mission by early 2021. These modules were designed and built with the form, fit and function defined in the LISA Laser System TRL 6 Demonstrator Requirements document [1]. The TRL 4 LOM was delivered to CSEM for evaluation and concurrently, we continued to advance our technology readiness level with a goal of reaching TRL 6 in late 2023.

The NASA GSFC TRL 4 prototype LOM (see Figure 2) utilizes a Master Oscillator Power Amplifier (MOPA) architecture. This design starts with a lower power seed laser source – the "Master Oscillator" (MO) - that is fiber optically coupled to a "Power Amplifier" (PA). The PA combines light from the seed laser and light from higher power pump laser diodes in Ytterbium (Yb) doped gain fiber. Pump diode light interacts with the gain fiber dopants in a manner that results in amplification of optical power at the seed laser wavelength.

LISA prototype MOPA configuration is illustrated in Figure 2. As shown in the figure, the design includes redundant MO modules, "MO1" and "MO2". Within each MO there are additional redundancies built in. For example, each MO contains two 808 nm laser diodes to pump the Nd:YAG micro non-planar ring oscillator (µNPRO) crystal. There are three thermoelectric coolers – one for the 808 nm pump subassemblies, one for the µNPRO crystal and one for the MO case and denoted as (1) laser diode baseplate TEC, (2) crystal TEC, and (3) case TEC.

The TRL 4 MO as delivered required a high voltage (HV) amplifier to frequency tune the laser emission due to the small tuning coefficient of the piezoelectric transducer (PZT) that is attached to the µNPRO crystal. The TRL 4 design had a 10X smaller PZT tuning coefficient of ~1.5 MHz/V than the TRL6 design. The HV amplifier affected the frequency noise performance at high Fourier frequency.

MO1 and MO2 outputs are phase modulated and coupled to fiber optic splitters for MO monitoring. The primary splitter outputs are routed to the PA via a 2x1 optical switch that selects which MO will be seed the PA. This switch is denoted as master oscillator switch (MO-Switch).

The PA uses three pump laser diodes, denoted as LD1, LD2, and LD3, and a TEC, denoted as Fiber TEC, to control the gain fiber spool temperature. The PA is also seeded with a “scram” laser to protect the PA in the event of loss of signal (LOS) from the MO. The PA output is transmitted to a main output fiber or auxiliary output fiber via a 1x2 output switch, denoted as power amplifier switch (PA-Switch). These output fibers are terminated with collimators for performance evaluation. In actual mission, the delivery fiber will be interfaced to the instrument optical bench via fiber connectors.

Nominal MOPA laser wavelength is 1064.5 nm and nominal output power is 2 Watts continuous wave (CW).

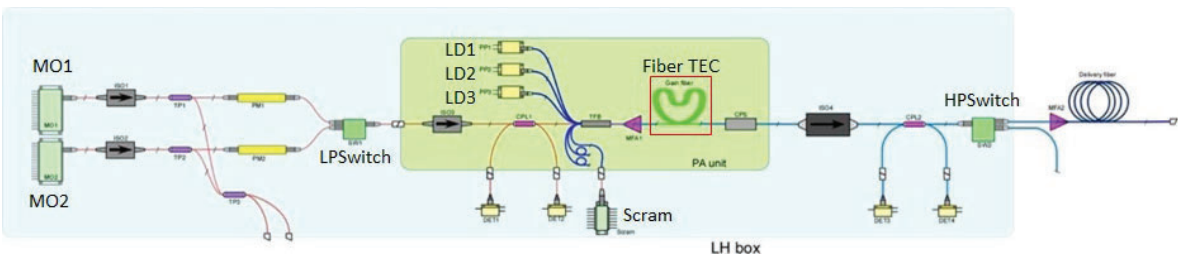


Figure 2: LISA Prototype Laser Optical Module (LOM) Layout

The TRL4 LOM is driven by a commercial-off-the-shelf (COTS) based laser electronics module (LEM). As part of the deliverables, NASA included a power stabilization optical and detector ground support equipment (GSE) for power stabilizing the MOPA laser meeting the TRL6 requirements, as well as the associated drive electronics for the GSE. Figure 3 shows the deliverables to CSEM for performance evaluation.

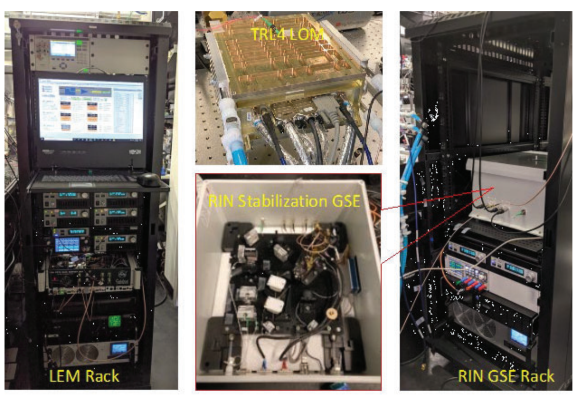


Figure 3. NASA GSFC deliverables to CSEM for performance evaluation.

The LEM rack communicates with sixteen (16) COTS instruments that are necessary to operate the laser and maintaining thermal control of critical assemblies inside the LOM. Control of the LEM is via a LabVIEW based graphic user interface (GUI) that fully control and set all the laser operating parameters.
The relative intensity noise (RIN) power stabilization is a MOPA operating mode that reduces laser intensity noise by modulating PA pump diode current with a servo signal from the stabilization GSE. The servo signal is based upon signal processing applied to a small fraction of the MOPA output tapped to the GSE and measured by stabilized optical detectors and electronics.
The GUI also captures telemetries that monitor the health of the laser and anomalies that may arise during laser operation. This function proves to be valuable and provided important clues to diagnose an event that happened during the test campaign at CSEM premises. Results of the diagnoses and lessons learned will be presented in the paper by K. Numata et al. [2].
The major performance parameters were measured prior to shipping the laser to CSEM for comprehensive performance evaluation.

## 3. KEY ELEMENTS TESTING APPROACHES

The LISA laser head shall meet stringent specifications. Key requirements are the laser frequency noise, the power stability and the sideband phase noise. For each of these requirements a dedicated test approach and the associated test bench is described in the following.

### 3.1 Side band phase noise (SBPN)

The measurement principle is presented in Figure 4. The LH, with sideband modulation on, is attenuated and combined with a Local Oscillator (LO) laser. The beat note between these two lasers is recorded with a fast photodetector. After filtering, this measurement is composed of two frequencies: the carrier-LO peak at 2.4 GHz+Δf and the sideband-LO peak at the frequency Δf. These two frequencies are isolated with an RF splitter and filters. The 2.4 GHz+Δf frequency is used to offset lock the LO laser to the carrier.

As the LO laser is locked on the carrier, the sideband-LO beat note contains the phase noise generated by the LH Electro Optical Modulator (EOM) and all other components within the signal path. This signal is sent to a phase detector for comparison to the reference signal.

The reference signal is generated by mixing the outputs of the synthesizer generating the 2.4 GHz and the 2.4 GHz+Δf carriers-LO beat note. This signal is considered as the reference since it does not travel through the EOM and the subsequent LH system. The phase detector signal is recorded and processed to calculate the associated Power Spectral Density (PSD). To meet the requirement, the phase noise induced by the test bench shall be minimized.

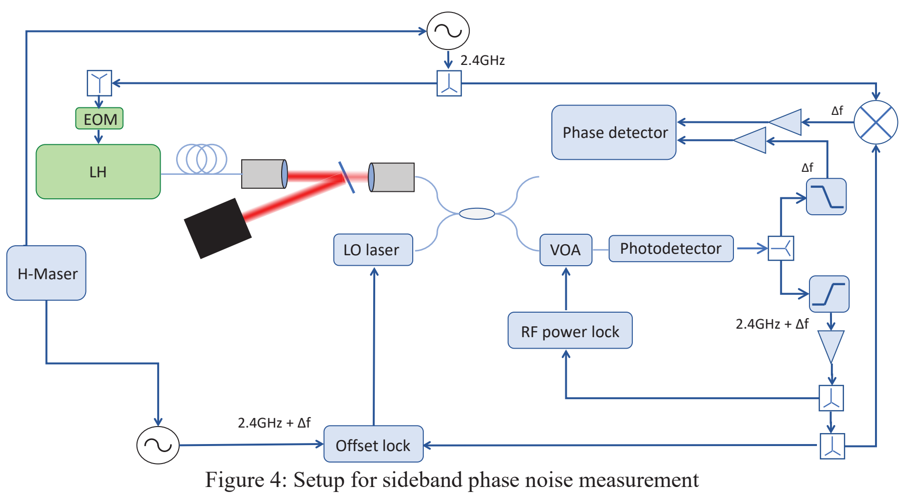


Figure 4: Setup for sideband phase noise measurement

In order to validate the test bench is verified on a MO followed by an EOM. The performed measurement is presented in Figure 5. For this measurement, the EOM is seeded with a 2.4GHz at 13.8dBm signal (cable losses not taken into account).

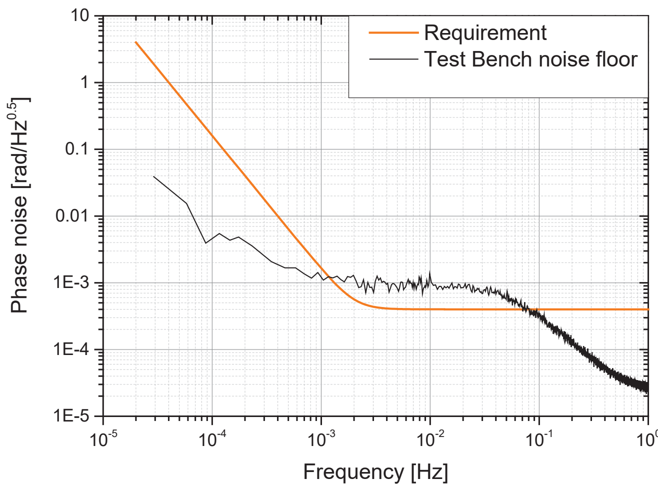


Figure 5 : Sideband phase noise test bench noise floor

The measurement depicted in Figure 5 reaches the specification at low and high frequency. Between 0.1Hz and 1mHz, the measurement setup is out of specification mainly due to thermal issue.

During the setup validation, it was noted that temperature drifts are the most frequent origin of long-term drifts. The increase of phase noise density at low frequencies is very likely due to temperature drift of the Radio Frequency (RF) components of the setup (amplifiers, mixers, splitters, filters, cables). An improved thermal stabilization should improve the test bench noise floor.

### 3.2 Frequency stability

The requirement on frequency stability spectral density limit $S_\upsilon$ for the pre-stabilized laser mode, is depicted in Figure 6.

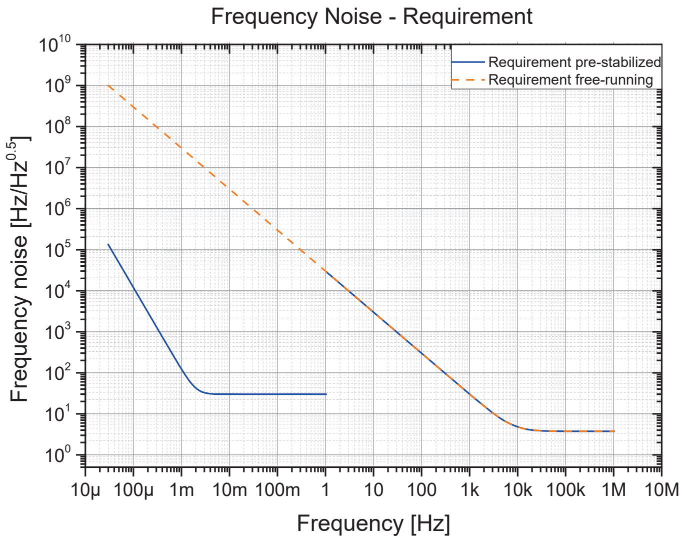


Figure 6: Frequency noise requirement

To be able to assess the achieved laser performances, two dedicated test benches had to be developed, one covering the low frequency range [30µHz; 3kHz] and one the high frequency range [3kHz; 10MHz]. Both are presented in the following.

### Low frequency range [30 µHz; 3 kHz] test bench

The setup developed for this frequency range is depicted in Figure 7. The LH is characterized by measuring the beatnote frequency noise of the NASA laser against a more stable reference laser. To obtain this reference light, we lock a self-referenced optical frequency comb to the optical frequency of a 1560 nm Continuous Wave (CW) laser (from OEwaves) locked to an ultrastable cavity and we correct the cavity drift by a reference maser leading to the combination of the best frequency stability performances of the two references (cavity and maser).

In more details, this stabilization is achieved via an offset lock of a 1560nm laser on the cavity. Then, one optical mode of a homemade 600MHz repetition rate self-referenced frequency comb (FC) is phase locked to this cavity-stabilized 1560nm laser. The phase of the frequency comb repetition frequency and the phase of a synthesizer referenced to the maser are compared. The obtained phase error signal is fed to the 1560 nm Continuous Wave (CW) laser control electronics to change its optical frequency via its offset lock to the reference cavity. In this way the long-term stability of the maser is transferred to the 1560 nm CW laser, correcting the drift of the cavity. As such the system delivers:

- the short term / best frequency stability of the reference cavity
- the long term / best frequency stability of the reference maser

Finally, to measure the frequency noise of the NASA laser, stable comb light at 1064nm is used to phase lock a 1064 nm CW laser (from Redfern Integrated Optics (RIO)) considered as local oscillator (LO). The beatnote of the LO laser and the Laser Head under test is then recorded with a photodetector and analyzed with a frequency counter and a phase noise test set.

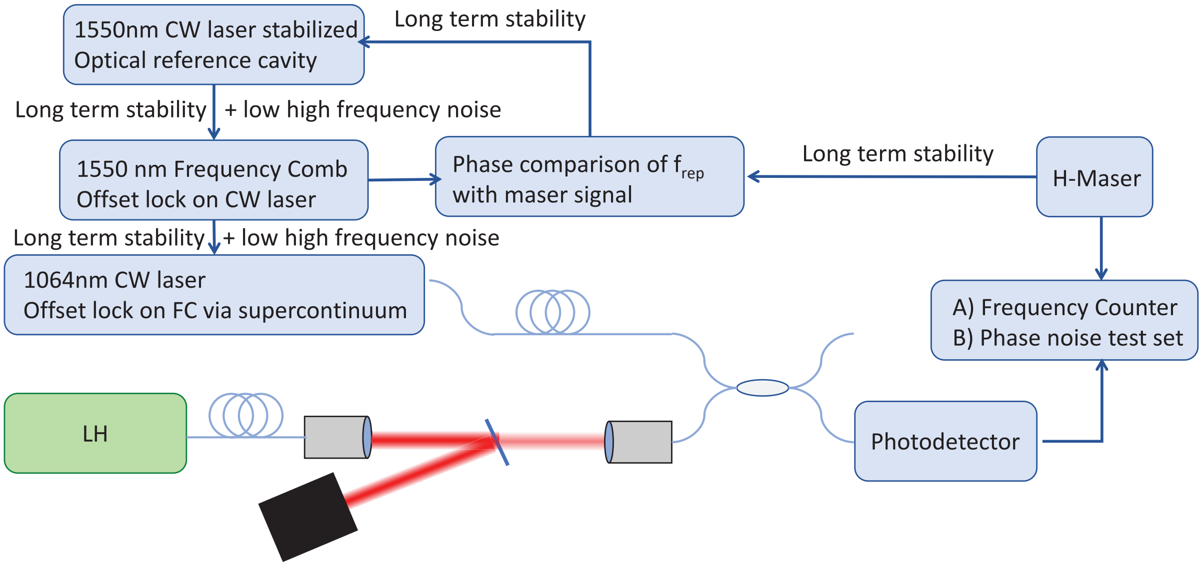


Figure 7: Architecture of frequency noise measurement setup for the [30 µHz; 3 kHz] frequency range.

The developed cavity and the frequency comb are depicted in Figure 8.

Figure 8: CSEM reference cavity and frequency comb

In Figure 8, on the left, the optical reference cavity is shown. The cavity is a 1560nm Fabry Perot cavity with a finesse of 200,000 and maintained at its zero coefficient of thermal expansion temperature. To reach the required stability, the cavity is maintained under vacuum, thermally stabilized via active temperature stabilization and passive thermal shields. The CSEM design is based on [3] and [4]. The cavity stabilization digital electronics including the offset lock and the referencing on the maser through the frequency comb repetition rate was developed by CSEM in the framework of the ESA OSRC project [5].

In Figure 8 right, the frequency comb setup is represented. The 600 MHz diode-pumped solid-state frequency comb shown on the top left of the picture was designed and manufactured by CSEM. The output light of this comb is split to seed two independent fiber amplifiers. The first amplifier is used to self-reference the frequency comb with a standard f-2f interferometer. The stabilization is performed via the frequency comb pump diode current with home-made ultralow noise electronics. The second amplifier arm is used to generate the 1064nm light to phase lock the 1064nm CW LO.

### High frequency range [3 kHz; 10 MHz]

At high frequencies, the measurement approach relies on a Michelson interferometer that converts laser frequency fluctuations into intensity fluctuations. The optical schematic of the Michelson interferometer is depicted in Figure 9. The light from the LH is attenuated and sent to a non-polarizing beam splitter. In both interferometer arms, retro reflectors based on right angle prisms are used. Reflections from both arms interfere in the beam splitter and the two outputs are sent to a balanced photodetector having the appropriate bandwidth. To cover the needed range of the measurement, an interferometer with an arm length difference of 2m and a related Free Spectral Range (FSR) of 75 MHz is used. Balanced photodetection is used to remove the noise due to the Relative Intensity Noise (RIN)

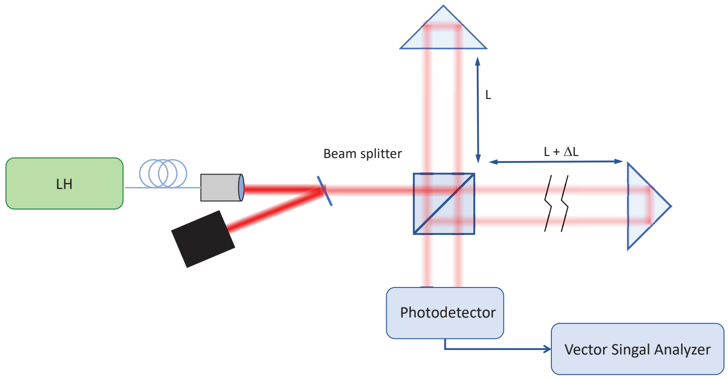


Figure 9: Michelson interferometer for frequency noise measurement in the [3 kHz; 10 MHz] range.

To validate the setup, a measurement performed using an OEwaves MO is presented in Figure 10. This MO does not reach the specification but was the lowest high frequency noise laser available at CSEM premises before the NASA μNPRO arrived. It is thus not possible to fully validate the test bench limit with this laser.

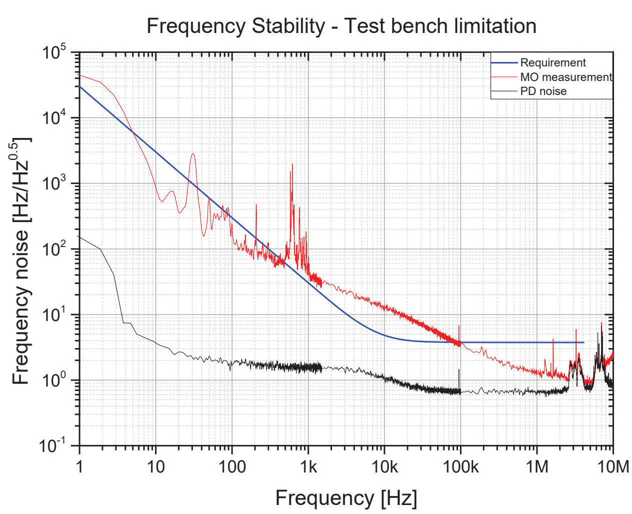


Figure 10: Blue curve represent the high frequency, frequency noise requirement. The red line is the measurement realized on a MO laser (OE-waves). The black curve represents the dark noise of the photodetector.

Figure 10 shows that, between 100kHz and 1MHz, the test bench can measure the LISA specification. Between 1kHz and 100kHz, the measurement is limited by the OEwaves laser that does not reach the specification. It is thus impossible to fully conclude if the test bench can measure at the specification level over the full bandwidth. This being said, later a measurement of the NASA µNPRO will show that the bench is well capable to meet the specification. Below 1kHz, the setup is governed by mechanical noise and the measure is limited by the test bench itself. An improvement on the mechanical isolation should improve the measurement in the future.

### 3.3 Output Power Stability

Output power stability is one of the most important performance requirements of the LH. The specified output power stability spectral densities are depicted in Figure 11.

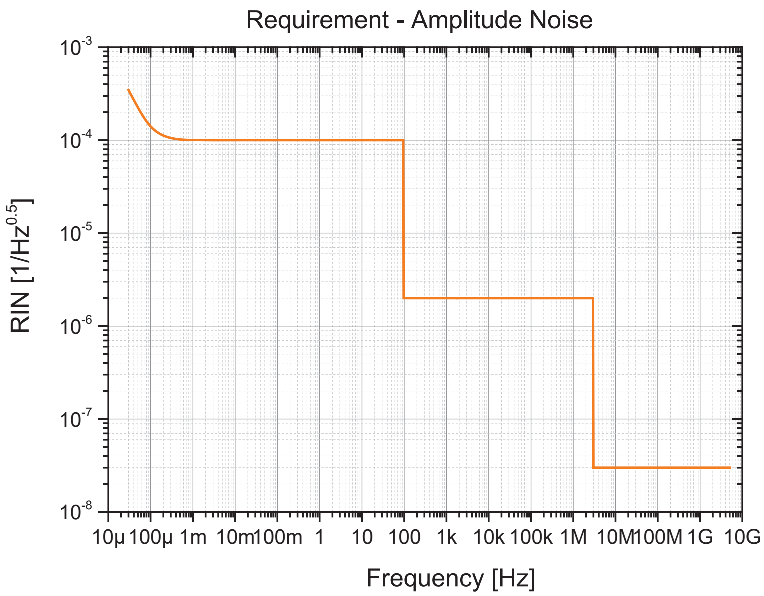


Figure 11 : Output power stability RIN from the development requirement specification in orange

As this requirement covers more than 10 orders of magnitude of frequency range, three different setups corresponding to the low frequency range [100 µHz ;1 Hz], the intermediate frequency range [100 mHz ;10 MHz] and the high frequency range [100 kHz ;5 GHz] of RIN were required. They are presented separately in the following.

### Low frequency [30 µHz ;1 Hz]

To reach the low frequency range requirement, an active stabilization of the amplifier is required. NASA developed a stabilization test bench and duplicate the measurement photodiode (PD) and light picking stage to perform an out of loop measurement as well. NASA made available its low frequency power test / stabilization bench for the test campaign at CSEM. A picture of the bench is shown in Figure 12.

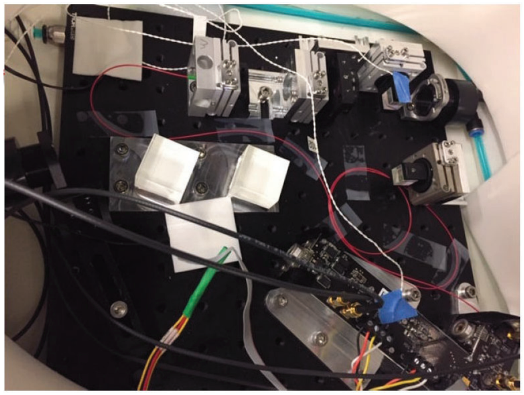

Figure 12: Picture of NASA power test / stabilization bench

The power stability depicted in Figure 13 was measured with the out of loop detector of the NASA measurement setup. This measurement shows that the test bench is able to measure the requirement.

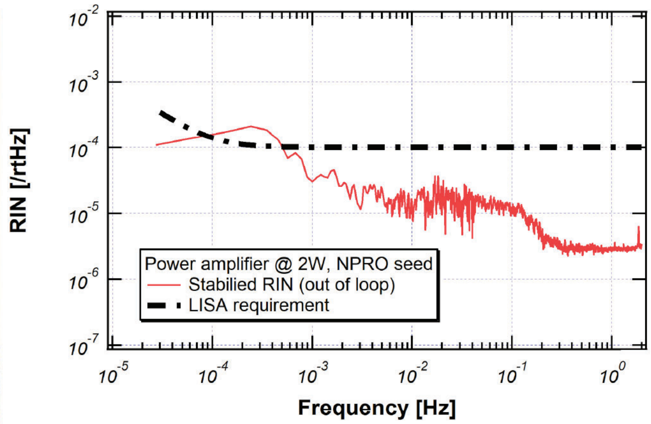


Figure 13: Measurement of power stability with out of loop detector

### Intermediate frequency [100 mHz ;10 MHz]

The intermediate frequency measurement setup is presented in Figure 14. The LH output is first attenuated with an output coupler and then focalized on an off-the-shelf photodetector and the signal is recorded with a vector signal analyzer.

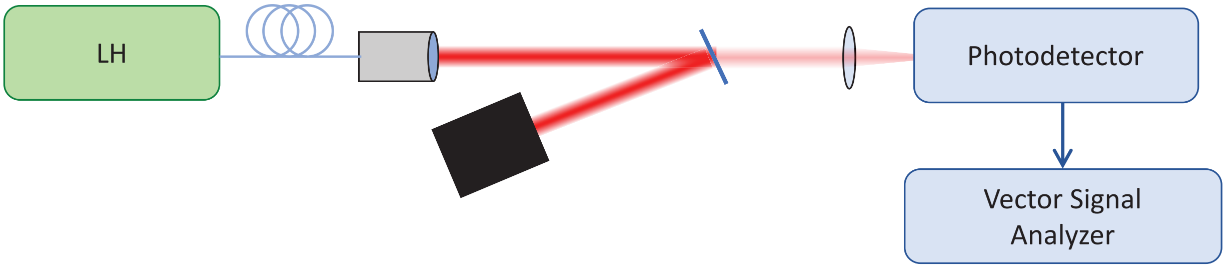


Figure 14 : Intermediate frequency power stability test bench.

For the test benches validation, a measurement shall be performed on a laser within in specification. Such a laser is available from the previous ESA activity Monalisa where the CSEM developed a LH BB and test two different seed lasers [6][7].

Figure 15 shows the intermediate frequency RIN test bench validation performed with the measurement of the CSEM LH BB seeded with a RIO laser.

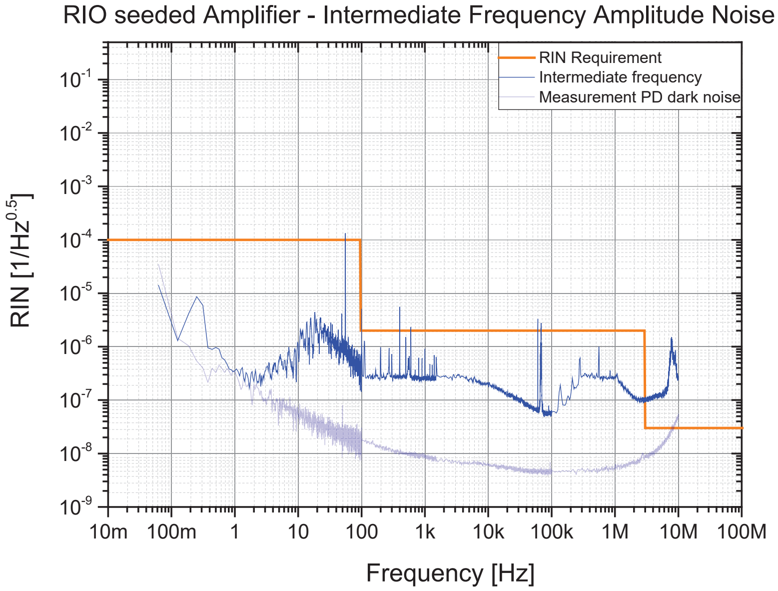


Figure 15 : Power stability intermediate frequency measured wit CSEM LH BB with RIO seed laser

As one can see in Figure 15, the noise floor is sufficient for RIN detection below the noise density specifications from 100 mHz to 3MHz. At higher frequency the measurement is limited by the laser noise. A measurement performed on CSEM LH BB with OEwaves seed laser (Figure 17) shows that the intermediate frequency measurement test bench can reach the specification at frequency higher than 3MHz. The light blue curve represents the PD dark noise and thus the measurement limitation.

### High frequency [100 kHz ;5 GHz]

The bench is depicted in Figure 16. The LH is first attenuated with an output coupler and coupled in a fiber. The signal is detected with a 13 GHz bandwidth photodetector. Its output signal is analyzed by an electrical signal analyzer.

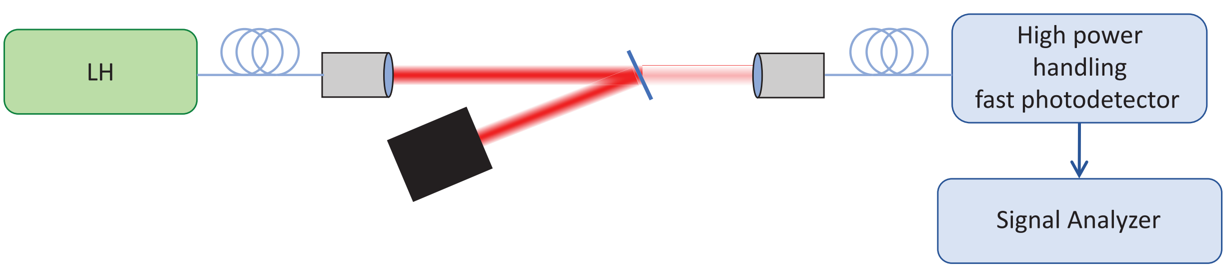


Figure 16: High frequency test bench

The proposed test bench was validated using CSEM LH BB with OEwaves seed laser. The measurement is shown in Figure 17.

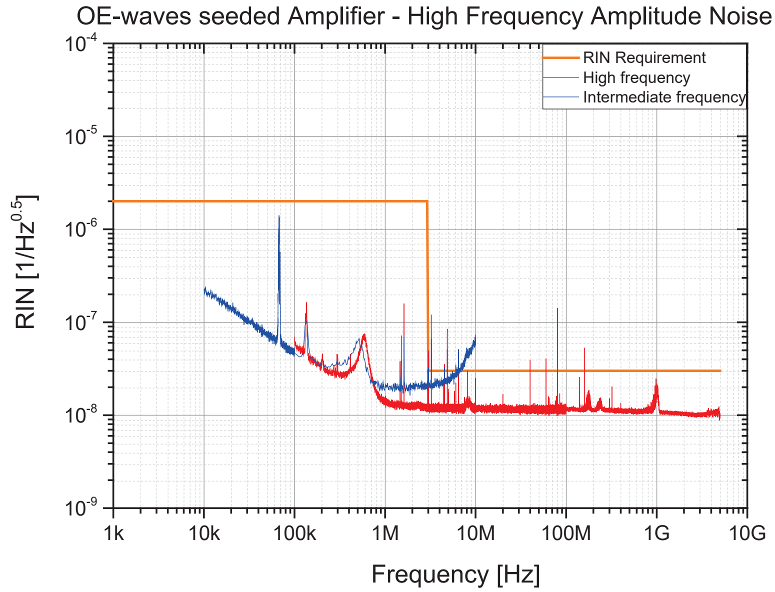


Figure 17: Power stability high frequency measured wit CSEM LH BB with OEwaves seed laser

As one can see in Figure 17, starting from 100 kHz the measurement overlaps with the one from the intermediate frequency range. At high frequency the power stability measurements reach the $10^{-8}/\sqrt{\text{Hz}}$ level are obtained. This is in line with the power stability requirement from the ESA specification.

## 4. TEST RESULTS

**Sideband phase noise.**

The NASA LH SBPN measurement is represented in the Figure 18.

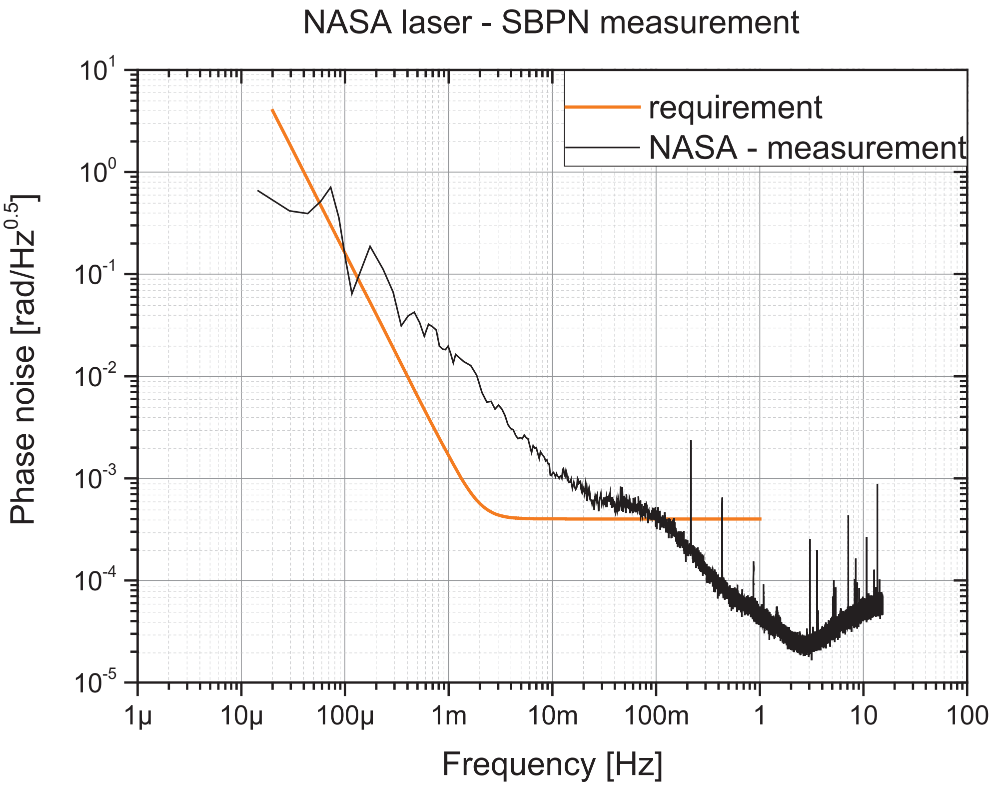


Figure 18: Measurement of the SBPN on the NASA laser

The measurement is in specification from 1Hz to 100mHz and bellow 100µHz. From 100mHz to 10mHz, the measurement is limited by the measurement test bench. At lower frequency, the measurement is driven by the NASA LH. This measurement is above the requirement and is considered to be a real effect within the LOM. The physical origin of this effect is being investigated.

**Frequency noise: free-running:**

This NASA LH frequency noise in free-running mode, that is not frequency stabilized to a frequency reference, with piezo grounded is represented in Figure 19.

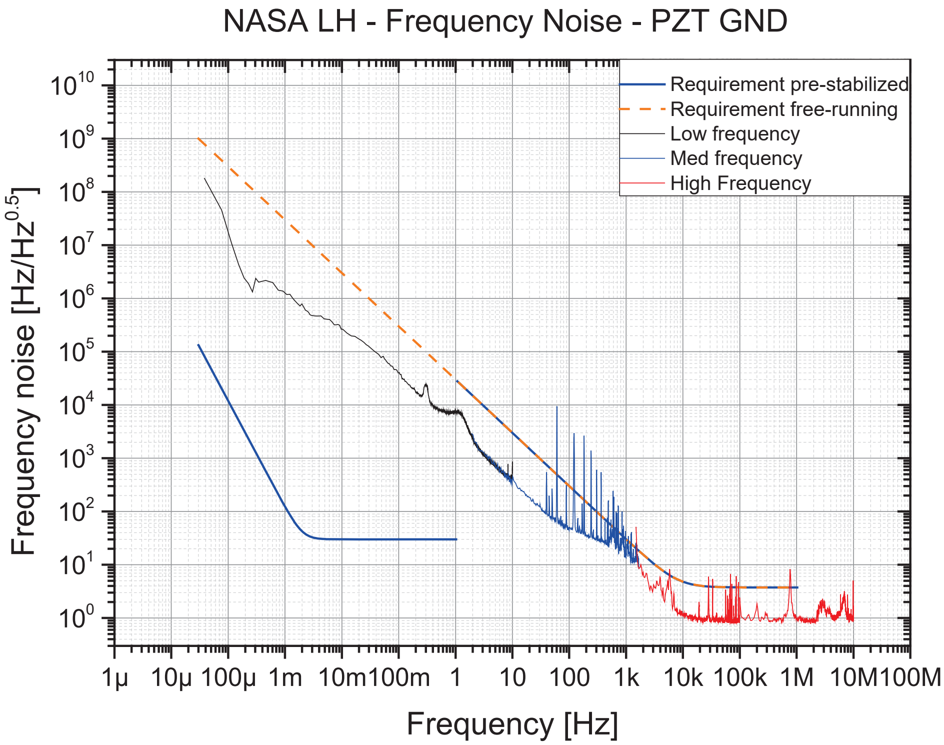


Figure 19: NASA LH piezo grounded frequency noise measurement (black / blue / red curve). Measurement (excepting spikes) is fully in specification.

The measurement shows a result that fully (excepting spurs) reaches the requirement represented in orange in Figure 19. The black and blue curves represent the low frequency range measurement performed with the counter and with two different gate times. The red curve is the high frequency range measurement performed with the interferometer.

**Frequency noise: master**

The measurement is depicted in Figure 20.

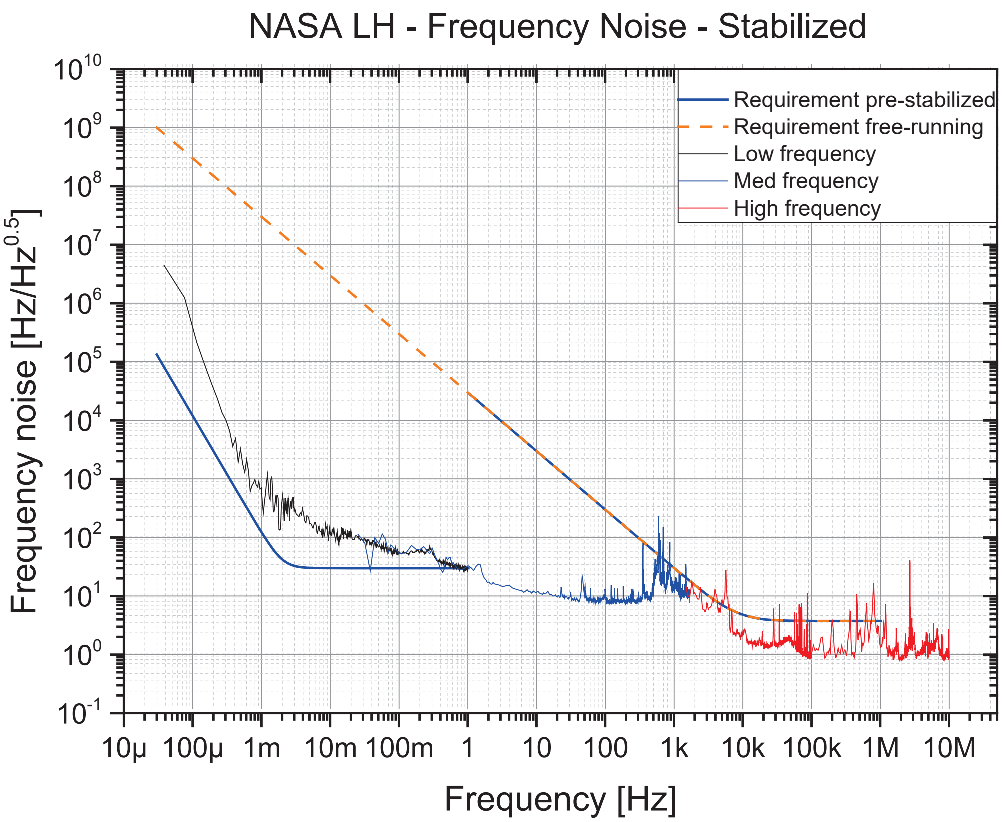


Figure 20: NASA LH cavity stabilized frequency noise measurement (black / blue / red curve). The black and blue curves represent the low and intermediate frequency range measurement performed with a counter with two different gate times. The red curve is the high frequency range measurement performed with the interferometer.

Figure 20 shows the measurement of NASA LH stabilized on a 4 cm optical cavity with finesse of 10,000 at 1064 nm. This measurement shows that the laser (excepting spikes) is in specification from 1Hz up to 1MHz. At low frequency [30μHz; 1Hz] the measurement does not reach the specification and is limited by the thermal drift of the 4cm reference cavity used here.

**Power stability, Master**

The measurement is depicted in Figure 21.

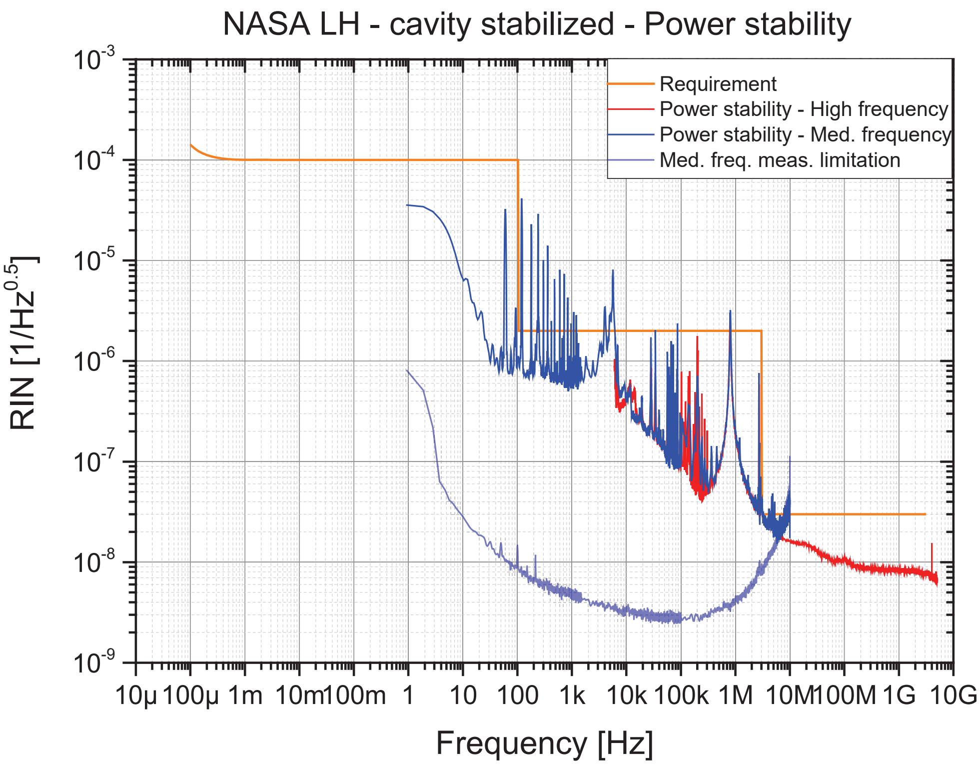


Figure 21: NASA LH cavity stabilized power stability measurement (blue / red curve). The blue curves represent the intermediate frequency range measurement performed with a counter with a vector signal analyser. The red curve is the high frequency range measurement performed with a signal analyser.

The measurement of the NASA laser stabilized on a cavity is represented on the Figure 21. The low frequency power stability was not yet performed. For intermediate and high frequency measurement, except some spikes, the laser is fully in specification.

## 5. CONCLUSION

In the frame on the LISA mission, NASA has developed a TRL 4 laser head designed to meet the requirements of the LISA mission. Dedicated metrology approaches to assess all requirement of the NASA TRL 4 laser head have been developed, implemented, and verified at CSEM.

The test benches design covering the most important requirements have been presented here. Verification and limitation of these test benches have been performed and are generally within specification.
The NASA TRL 4 LOM was tested at CSEM. The results obtained for the main requirements in term of frequency noise and power stability are in specification. The side band phase noise shows an, as yet not understood effect which is being investigate. The test bench needs to be further improved at lower frequency range. A particular care will be taken to thermally stabilized it.

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