International Conference on Space Optics—ICSO 2014

La Caleta, Tenerife, Canary Islands

7–10 October 2014

Edited by Zoran Sodnik, Bruno Cugny, and Nikos Karafolas

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esa icso proceedings cnes

International Conference on Space Optics — ICSO 2014, edited by Zoran Sodnik, Nikos Karafolas,
Bruno Cugny, Proc. of SPIE Vol. 10563, 105632T · © 2014 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2304161

HIGH STABILITY LASER FOR NEXT GENERATION GRAVITY MISSIONS

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I. INTRODUCTION

With GRACE (launched 2002) and GOCE (launched 2009) two very successful missions to measure earth's gravity field have been in orbit, both leading to a large number of publications[1, 2]. For a potential Next Generation Gravity Mission (NGGM) from ESA a satellite-to-satellite tracking (SST) scheme, similar to GRACE is under discussion, with a laser ranging interferometer instead of a Ka-Band link to enable much lower measurement noise. Of key importance for such a laser interferometer is a single frequency laser source with a linewidth <10 kHz and extremely low frequency noise down to 40 $\mathrm{Hz}/\sqrt{\mathrm{Hz}}$ in the measurement frequency band of 0.1 mHz to 1 Hz, which is about one order of magnitude more demanding than LISA. On GRACE FO a laser ranging interferometer (LRI) will fly as a demonstrator. The LRI is a joint development between USA (JPL,NASA) and Germany(GFZ,DLR). In this collaboration the JPL contributions are the instrument electronics, the reference cavity and the single frequency laser, while STI as the German industry prime is responsible for the optical bench [3] and the retroreflector [4]. In preparation of NGGM an all European instrument development is the goal.

In the scope of the ESA funded "High Stability Laser (HSL)" activity, an elegant breadboard (EBB) consisting of a master oscillator – fibre power amplifier with 500 mW output power and an ultra-stable Fabry-Perot reference cavity, to which the laser is stabilised, has been developed and built and is presented here. This EBB is a significant step forward in comparison to the laboratory setups currently available. The laser system is capable of supporting both instrument concepts developed in earlier ESA missions and system studies [5, 6]

II. HSL OVERVIEW

The HSL consists of a master oscillator, a fibre amplifier with pump module, a reference cavity and the associated electronics (see Fig. 1). The critical components with the lowest technology readiness level are the fibre amplifier and the cavity and the focus of this development is therefore on these two units. The master oscillator in the EBB is a commercially available non planar ring oscillator (NPRO), as a space qualified version based on the NPRO technology is already available. The fibre amplifier increases the optical output power to at least 500 mW without significant influence on linewidth, spectral frequency noise and laser RIN. Low optical frequency noise is achieved by stabilising the laser frequency to an ultra-stable optical cavity.

As the majority of the laser parameters required for NGGM is very similar or even more stringent than the requirements on the laser for LISA/eLISA, this development is technologically also beneficial for a later LISA/eLISA mission.

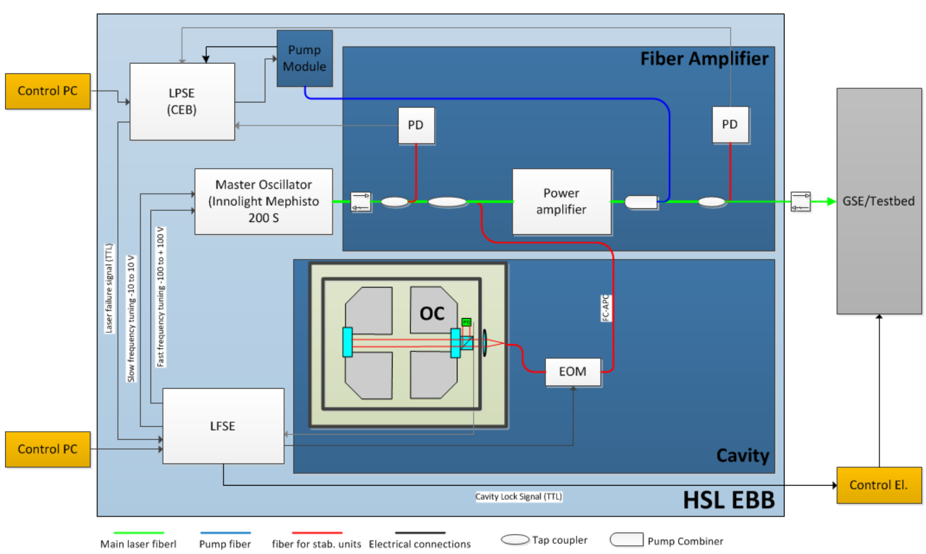

Fig. 1 HSL setup (LPSE=laser power stabilisation electronics; LFSE=laser frequency stabilisation electronics)

Starting from the available existing technologies the HSL EBB has been designed, undergone thermal (static and transient), structural and performance analysis, and successfully passed PDR and CDR. All components have been procured, assembled and operated. At the component level several tests, including thermal performance tests and radiation tests, have been performed on selected components (fibres, pump diodes, test cavity, cavity mounting technology). First measurements have been performed with the laser head (seed source with amplifier) and the fully assembled EBB and are presented below.

III. KEY REQUIREMENTS AND ENVIRONMENT

The key and driving requirements for the high stability laser are the diffraction limited laser output power of 500 mW, the output power noise of

$$RIN < \frac{10^{-3}}{\sqrt{\text{Hz}}}\sqrt{1+\left(\frac{10\text{ mHz}}{f}\right)^4}\text{for } 0.1\text{ mHz} < f < 1\text{Hz} \qquad (1)$$

and the optical frequency noise $\sqrt{S_\nu(f)}$ of

$$\sqrt{S_\nu(f)} < \frac{40\text{ Hz}}{\sqrt{\text{Hz}}}\sqrt{1+\left(\frac{10\text{ mHz}}{f}\right)^2}\text{for } 0.1\text{ mHz} < f < 1\text{Hz}, \qquad (2)$$

which is about one order of magnitude more demanding than the corresponding requirement in LISA/eLISA.

Apart from the demonstration of the optical performance requirements, the EBB critical components are required to be representative in terms of power consumption, mass and dimensions with respect to a later flight model and to allow environmental testing without major redesign.

When designing the HSL EBB the assumed environment (that is, the operational temperature ranges, temperature stability, and vibration and shock loads) was that of the GOCE mission.

Of key importance for the RIN and the frequency noise is the thermal noise (or temperature linear spectral density) of the environment. For this development actual GOCE measurement data from the regulated platform, on which the GOCE gradiometer is located, are taken. Fig. 2 shows the temperature time series used in the thermal modelling, the corresponding linear spectral density and in comparison the required temperature linear spectral density of the reference cavity to meet the frequency noise requirement.

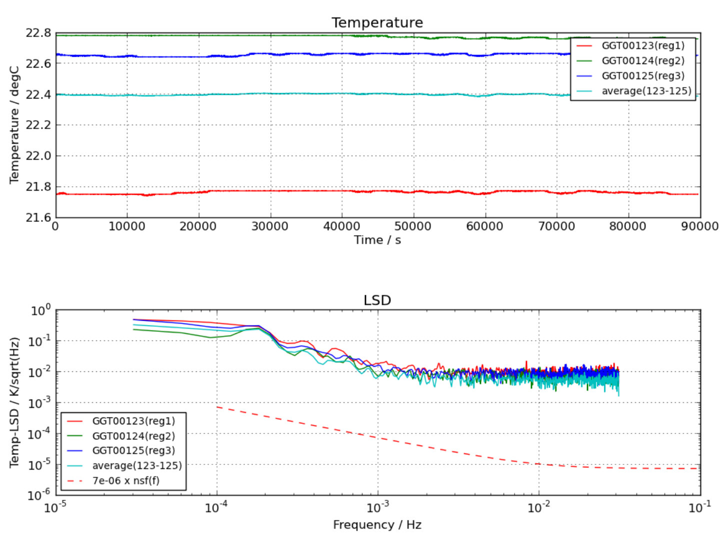

Fig. 2 GOCE thermal noise environment of regulated platform, measured time series and linear spectral density

IV. DESIGN, ANALYSES AND EBB HARDWARE

The HSL development is based on the available lab technologies of fibre laser amplifiers and of the reference cavity [7]. From this basis a dedicated design process was run, including evaluation of the space compatibility of materials and design approaches. Detailed static and transient thermal as well as structural modelling was applied to achieve a design compatible with the assumed GOCE mission environment. Tests on selected components have been performed to acquire the necessary data for the thermal design and a first indication on radiation hardness of critical components. Fig. 3 illustrates the development flow from existing units via analysis and tests to the HSL EBB hardware. In the following sections the individual units are described in more detail.

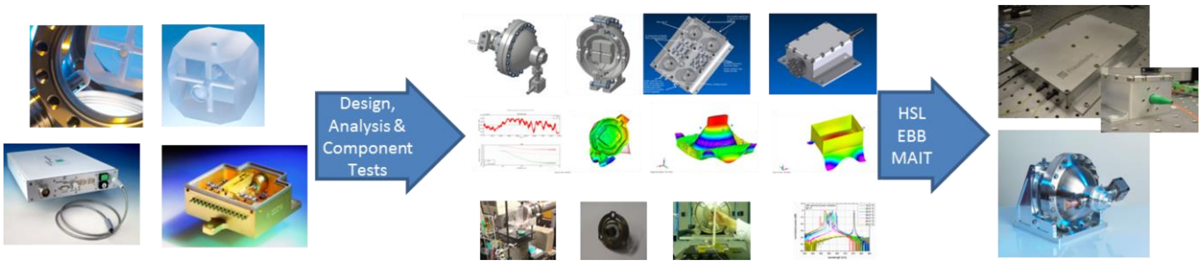

Fig. 3: Illustration of development flow of the HSL EBB. Left: existing technology before activity; middle: CAD models, analysis illustrations and pictures from component tests; right: HSL EBB hardware

A. Laser Head

The laser head (LH) consists of a master oscillator and fibre amplifier, and the associated power stabilization electronics. The master oscillator baseline for a later flight model is the space qualified NPRO from TESAT (delivering 25 mW), but the HSL EBB is modular and allows other seed sources to be used in the future. For the EBB an Innolight Mephisto 200 S is used.

The fibre amplifier is based on single-mode polarization maintaining fibres. All fibre components are placed inside one box, the fibre component box (FCB), with optical fibre interfaces to the master oscillator (PM980 fibre, spliced), the pump diode (multimode fibre, spliced) and the reference cavity (PM980, FC-APC connector). The FCB on a flight model will be evacuated.

The pump diode for the fibre amplifier is placed in a separate box (the pump diode box (PDB)) which will be pressurized during flight due to known lifetime issues with laser diodes in vacuum operation.

The separation of FCB and PDB has been introduced due to the significantly different thermal dissipation, the different pressure needs and for pump diode redundancy considerations. The fibre interface makes the placement of the units on a later spacecraft highly flexible.

A series of tests have been performed at the component level, ranging from tests on temperature dependencies of fibre components to total dose gamma (20 krad) and trapped proton ($4x10^{10}$ protons/cm² at 36 MeV) radiation tests. The test results were used for component selection and to provide the required thermal coupling factors needed for the transfer from thermal noise to RIN and frequency noise in the analysis. All components under test and built into the HSL EBB passed all tests successfully. The EBB features power stabilisation loops after the master oscillator as well as after the fibre amplifier. Measurements of the RIN of the master oscillator and the pump diodes -- as well as the analysis of thermally caused RIN due to the temperature dependency of other components -- predicted that an active power stabilization of the pump diode may be required, while the RIN of the master oscillator meets requirement (1) without active stabilization (see Fig. **4**)

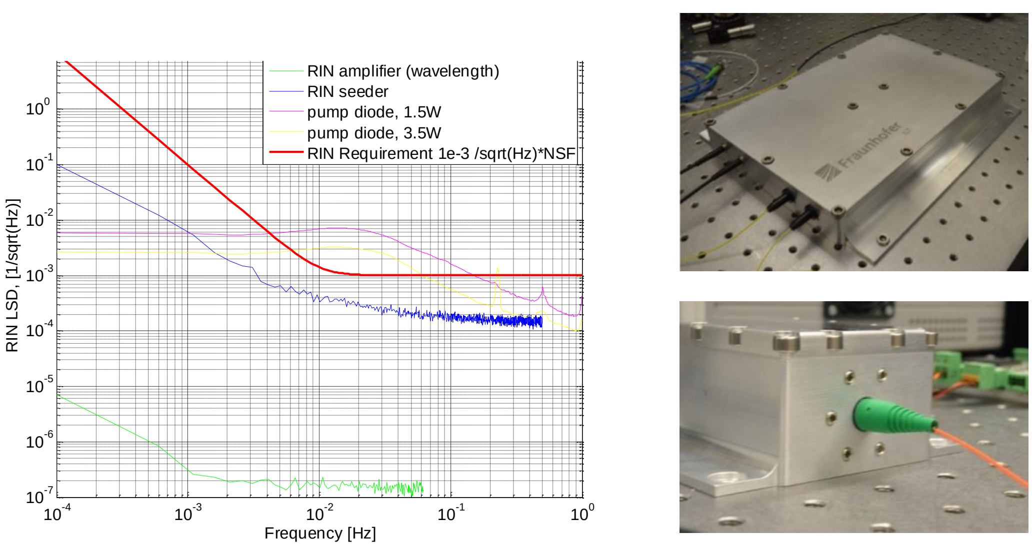

Fig. 4 Left: RIN of the Laser head due to different sources; right: LH EBB boxes

B. Laser Stabilisation Unit

The laser stabilisation unit (LSU) consists of a Fabry-Perot reference cavity, an electro-optical modulator and the associated Pound-Drever-Hall control electronics. The cavity is maintained in a vacuum environment which eliminates convection as a source of heat transfer and prevents pressure fluctuations from affecting the frequency stability. The cavity is made from Ultra-Low Expansivity glass (ULE) and the coupling factor between temperature and frequency noise is approx. $6.3\text{x}10^{6}$ Hz/K for an assumed worst case ULE coefficient of thermal expansion (CTE) of $2.25\text{x}10^{-8}$. To achieve the required frequency spectral density stated in (2) the requirement on the thermal noise $\sqrt{S_T(f)}$ in the cavity is therefore given by

$$\sqrt{S_T(f)} < \frac{7\ \mu\text{K}}{\sqrt{\text{Hz}}}\sqrt{1+\left(\frac{10\ \text{mHz}}{f}\right)^2}\ \text{for } 0.1\ \text{mHz} < f < 1\text{Hz} \qquad (2)$$

To achieve this noise in the GOCE environment (see Fig. 2) the design needs to provide a noise reduction of at least three orders of magnitude. A transient thermal analysis with the GOCE temperature time series and the detailed design of the cavity has been performed resulting in a design of the vacuum chamber with an inner thermal shield, and low thermal conductivity interconnects (see Fig. 5, right). In the analysis different surface coating and MLI configurations were considered. Fig. 5 (left) shows the result of the transient thermal analysis. It can be seen that for all cases the temperature stability requirement is well met above $2\text{x}10^{-4}$ Hz, while between $1\text{x}10^{-4}$ Hz and $2\text{x}10^{-4}$ Hz the requirement may not be met. Given the remaining uncertainties of the model (e.g. due to ULE CTE, exact thermal conductivities) a definitive statement for performance in the low frequency region cannot be made based on the analysis alone.

The design is optimised to provide a high alignment stability of the optical system over the full operational temperature range, to reduce stress on critical components during launch, and to have sufficiently high resonance frequencies (above 140 Hz).

As the cavity is a high finesse cavity with a finesse in excess of 200,000, the reflectivity of the mirrors is of key importance. The cavity mirrors (on a test cavity) have been irradiated with total dose gamma (500 rad) and proton ($4\text{x}10^{10}$ protons/cm² at 36 MeV) radiation. The tests have been passed successfully, with both tests showing a reduction in the cavity ring down time (corresponding to a loss in finesse) of around 10%.

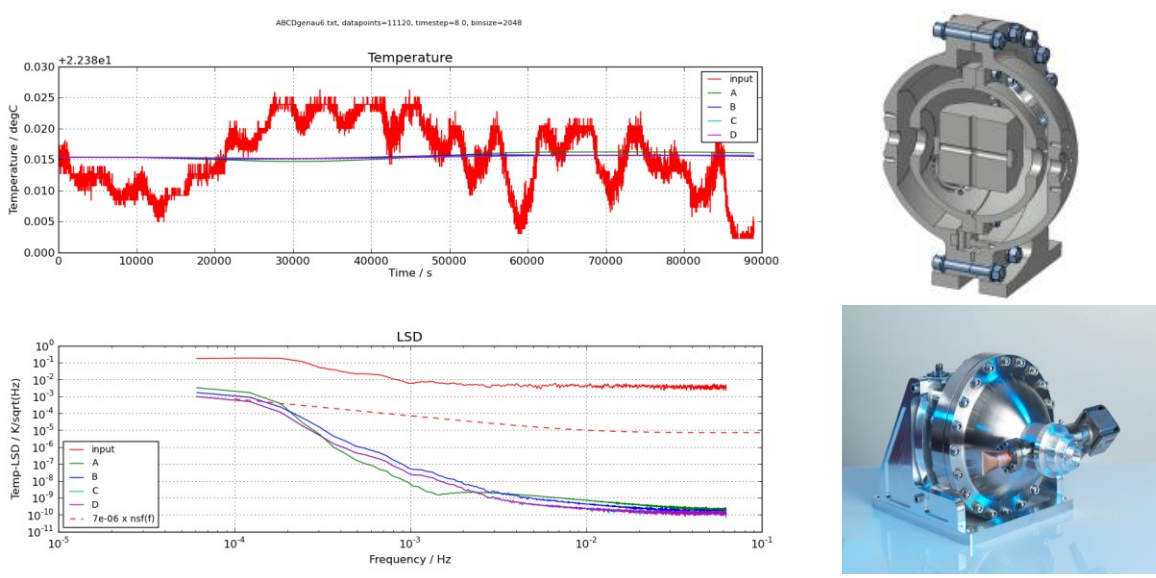

Fig. 5 Top left: GOCE Temperature time series (input) and temperature time series of the cavity for different coating variants. Bottom left: The corresponding linear spectral densities (A - no gold coating, no multi layer insulation(MLI); B – no gold coating, MLI; C – all surfaces gold coated, MLI; D – all surfaces but cavity gold coated, MLI). Right: schematic cross section through the cavity and a picture of the constructed EBB LSU

V. TEST SETUPS AND RESULTS

An extensive test campaign of the HSL EBB is currently in progress. This entails a full experimental characterization of the key requirements listed in section III, and also testing of parameters such as wavelength, spectral linewidth, spectral purity, wavelength tunability, polarisation, spatial mode and overall power consumption.

At this point preliminary results of the key and driving requirements are available. Fig. 6 shows the achieved output power of 500 mW and the corresponding RIN of the free running LH are well below the RIN requirement (1).

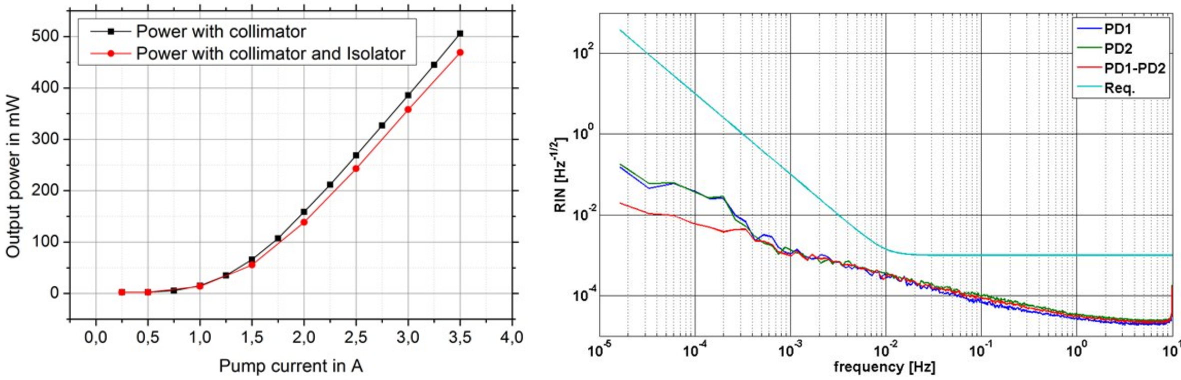

Fig. 6 Left: LH output power; right: LH Output power stability

After the initial LH characterization at ILT, the LH was shipped to NPL for interface testing and initial performance measurements. Fig. 7 shows the HSL fully assembled during interface testing.

The first frequency spectral noise measurement against a reference frequency stabilised laser system already yielded a frequency stability below frequency noise requirement over the full frequency range, even in a thermal environment significantly worse than GOCE. The noise dropped to about 3 Hz/√Hz at 0.5 Hz, indicating that the cavity is capable of a frequency stability of some Hertz in a suitable temperature environment.

After these initial measurements the HSL EBB was shipped to Airbus D&S, where the full performance test campaign is being performed. The test setup configuration is shown in Fig. 8. In this configuration each unit is mounted on a temperature-stabilised baseplate to allow testing at different operational temperature levels,

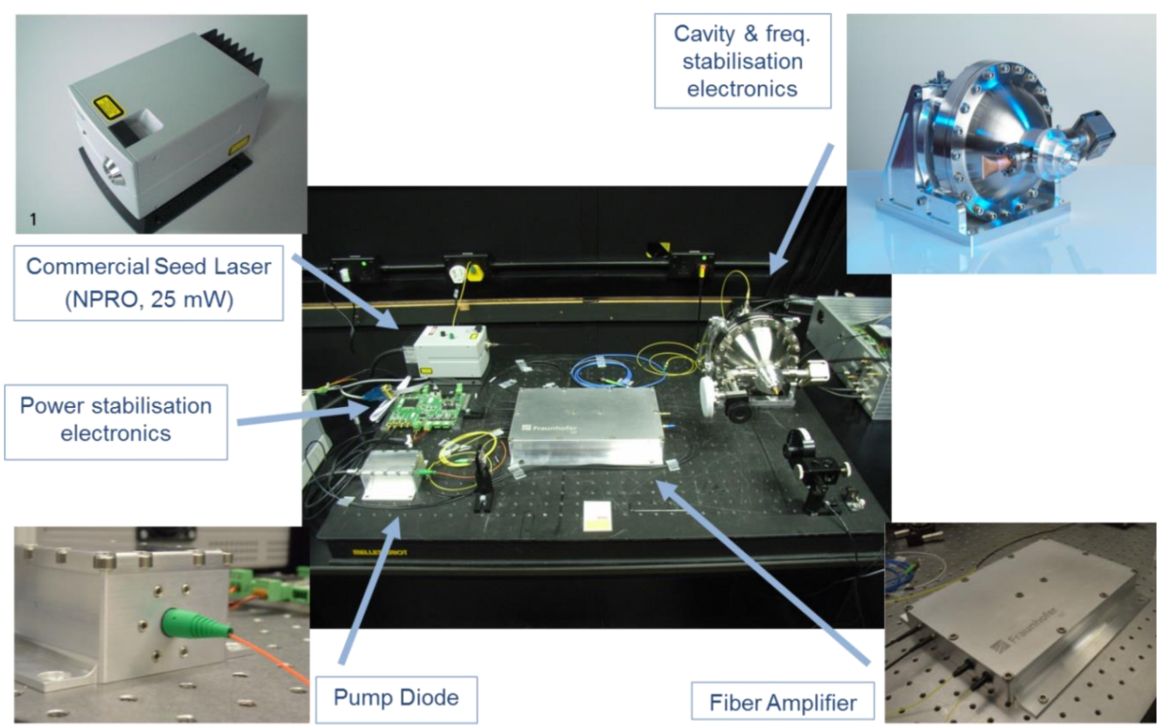

Fig. 7 HSL EBB setup at NPL laboratories

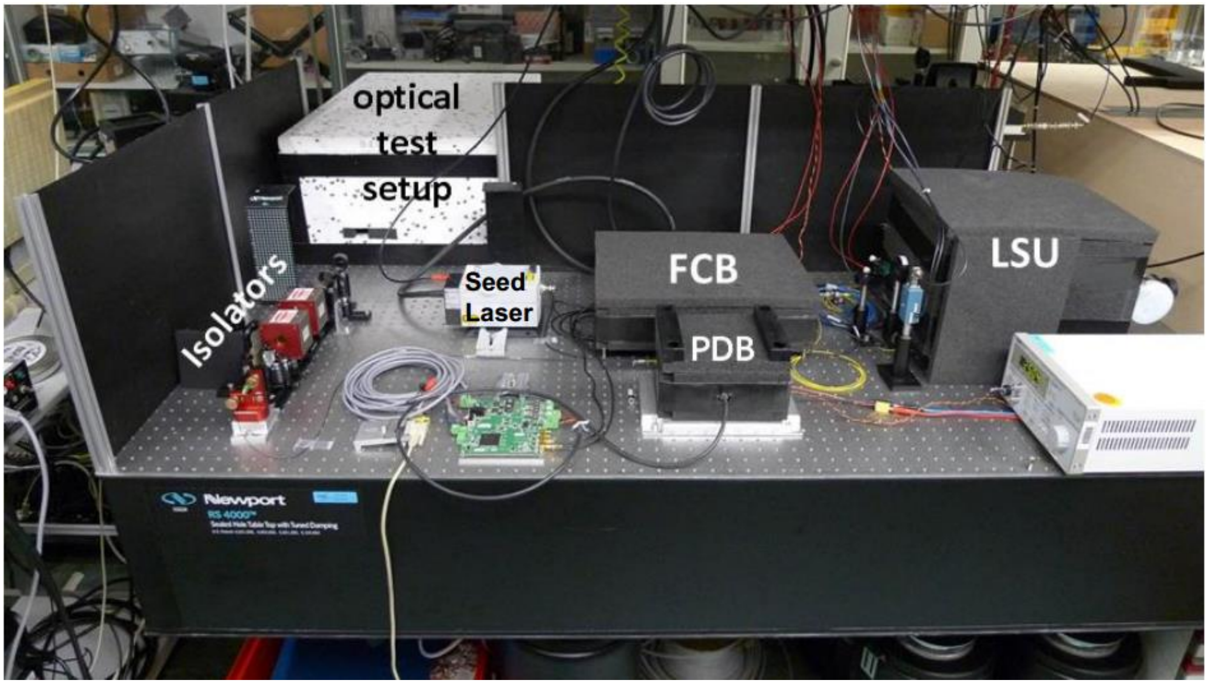

Fig. 8 HSL EBB test configuration in Airbus D&S lab

which are 18-22°C for the FCB and PDB and 20-30°C for the LSU. As the thermal noise in the Airbus lab is also not as stable as the GOCE environment all units are placed in thermal covers to reduce the thermal noise, reduce convection and to limit the required power for temperature stabilization.

Fig. 9 (left) shows the first measurement of the frequency noise of the LSU against the reference frequency stabilised laser system, which was performed with only the master oscillator in operation. The frequency noise of this configuration meets the requirement over the full frequency range. The temperature stability at the LSU is very close to the GOCE environment in the low frequency range, while the resolution of the temperature measurement system is not sufficient to resolve the actual noise in the higher frequency region. The measurement system will be improved to enable a better comparison between analysis and testing.

The M² measurement of the full HSL EBB in operation yielded an M² value of 1.08 and 1.07 in x and y direction. The tests with the whole HSL EBB in operation have just started and more results are expected in the next weeks.

Furthermore the FCB, PDB and LSU will undergo thermal cycling with the system non-operational over a temperature range from -40 to +50 °C for the FCB and the PDB and -20 to +50°C for the LSU.

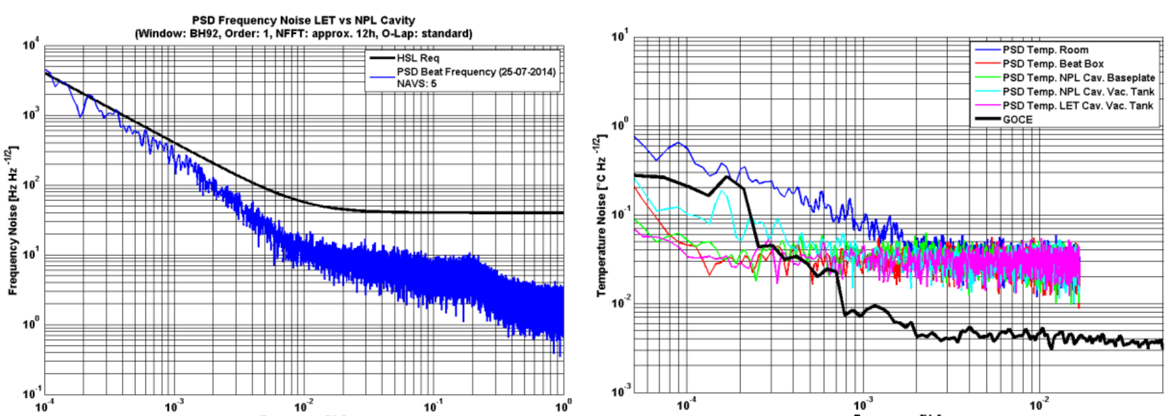

Fig. 9 Left: Frequency stability measurement(master oscillator and cavity only) ; right: temperature environment in the lab, compared to the GOCE thermal environment

VI.SUMMARY

An elegant breadboard of a frequency stabilized laser source has been developed. The fibre amplifier and the reference cavity are highly representative in form, fit and function of a later flight model. The key performance requirements of power, RIN and frequency noise already have been demonstrated, and the full test campaign is ongoing. Thermal cycling to survival temperatures will also be part of the test campaign.

The HSL EBB is considered a significant step forward compared to the lab breadboards currently available and, together with the German activities on the LRI on GRACE FO, provides an important contribution for an all European laser ranging interferometer on missions like NGGM or LISA/eLISA

ACKNOWLEDGEMENT

The development of the HSL EBB has been funded by ESA in the frame of activity AO /1-6906/11/NL/SFe "High-Stability Laser with Fibre Amplifier for Interferometric Earth Gravity Measurements - Laser Stabilisation Unit for Interferometric Earth Gravity Measurements"

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