

Development of spaceborne optical cavity for laser frequency stabilization

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ABSTRACT

The development of a TRL6 Laser Stabilization Unit (LSU), designed to meet the stringent frequency stability requirements of the Next Generation Gravity Mission (NGGM), is presented. The LSU incorporates several key subsystems, including a high finesse Fabry–Perot cavity, a vacuum enclosure with thermal shielding, an optical arm implementing PDH stabilization and optical coupling, and a fiber system with EOMs for PDH stabilisation. Achieving the required laser frequency stability demands a highly stable environment, with tight constraints on temperature, pressure, laser RIN, and post environmental test alignment. The work enhances European capabilities in precision spaceborne laser metrology, supporting future missions.

Keywords: Optical cavity, Fabry Perrot Cavity, NGGM, frequency noise, frequency stabilization

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1. INTRODUCTION

Ultra-precise distance measurement, using laser interferometry, open new windows in space metrology. For instance, the Next Generation Gravity Mission (NGGM) has the aim to extend and improve the earth gravity field measurement using ultra-precise inter-satellite distance measurement, based on heterodyne laser interferometry. In this architecture, frequency stability of the onboard laser sources is a dominant performance driver. To reach the measurement requirement, the laser sources need to be improved through a stabilization on an ultra-stable cavity.

The consortium designed, manufactured, characterized and tested a TRL6 Laser Stabilization Unit (LSU), reaching the NGGM requirements. The system is based on the following subassemblies:

- A 5cm high-finesse Fabry-Perot cavity with Ultra Low Expansion (ULE) spacer provided by NPL,
- A vacuum enclosure and associated thermal shielding to provide the required stable environment for the cavity,
- An Optical Arm (OA) provided by STI, coupling laser light into the reference cavity and detecting the PDH signal to perform laser stabilization
- Fiber system to couple the two redundant lasers to the OA and including Electro-Optic Modulators (EOM) to imprint the sideband for Pound-Drever-Hall (PDH) stabilization

To reach the high-demanding required laser frequency stability, the Fabry-Perot cavity shall be maintained in a highly stable environment.

2. KEY DESIGN ELEMENTS

Three key aspects are key design drivers for such a frequency reference system:

- The frequency noise requirement on the laser stabilized on the reference cavity
- The space environment mainly the mechanical load (vibration and shock)
- The required high cleanliness to keep the high reflectivity of cavity mirror and thus the high finesse

Indeed, the frequency noise is directly linked to any cavity length fluctuation. Cavity dilatation is one of the main contributors. For this reason, the spacer is selected in ULE. Furthermore, the Fabry-Perot cavity shall be thermal shielded from the outside.

The mechanical loads at the instrument level are also one of the key design drivers for the unit. The cavity shall survive to the required mechanical levels and the alignment between the cavity and the laser shall also be maintained to keep the system functionality.

The system functionality is also linked with the cavity finesse and mirror reflectivity. In the present activity, a target finesse of $38'500 \pm 6'500$ was foreseen, corresponding to a mirror reflectivity of 99.991840%. To maintain this mirror reflectivity during the whole mission lifetime, the molecular and particulate contamination shall be well controlled.

2.1 Thermal shielding

Knowing the required frequency stability, it is possible to mathematically[1] deduce the cavity length stability requirement and thus the required thermal stability at cavity level. From this information and knowing the temperature stability at the unit interface, the necessary thermal shielding transfer function can be deduced and is presented in Figure 1.

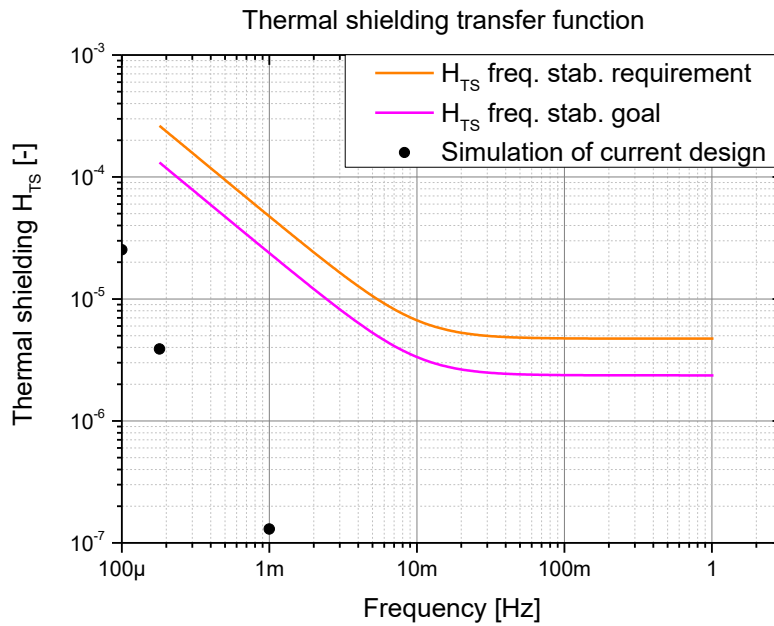


Figure 1: Thermal shielding transfer function required for the activity (orange and purple line) and simulation result of the current design (black dots)

To achieve the required thermal shielding, we shall work on all potential parameters. The convective aspect is already minimized as the system is under vacuum. The radiative and conductive path of the assembly shall then be designed and optimized to reach the required transfer function. The proposed concept relies on the usage three layers of conductive and radiative shielding one inside the others.

To reduce the conductive path, two main concepts are used: the combination of isolating components in PEEK material and thin metallic blades. However, both concepts have drawbacks as PEEK generates outgassing in the enclosure (see chapter 2.4) and thin blades decrease the mechanical eigenfrequencies of the system. For that reason, a compromise between both options should be found. A picture of the blade and isolation pad of one isolation layer is shown in Figure 2



Figure 2: Blade and PEEK pad for conductive decoupling of the different thermal shielding layers. Picture was taken during the system blank assembly. Part on the right is a dummy part mimicking the cavity interface.

The second aspect is to shield the system against radiation. To do so, one cube and two cylindrical radiative shields are added in the design. To improve the emissivity, the thermal shields are polished and gold plated on both sides. Figure 3 shows, on the left, the first cubic shield and first cylindrical shield and, on the right, the first and second cylindrical shield. A hole is implemented in middle of the covers to allow the laser beam propagation.

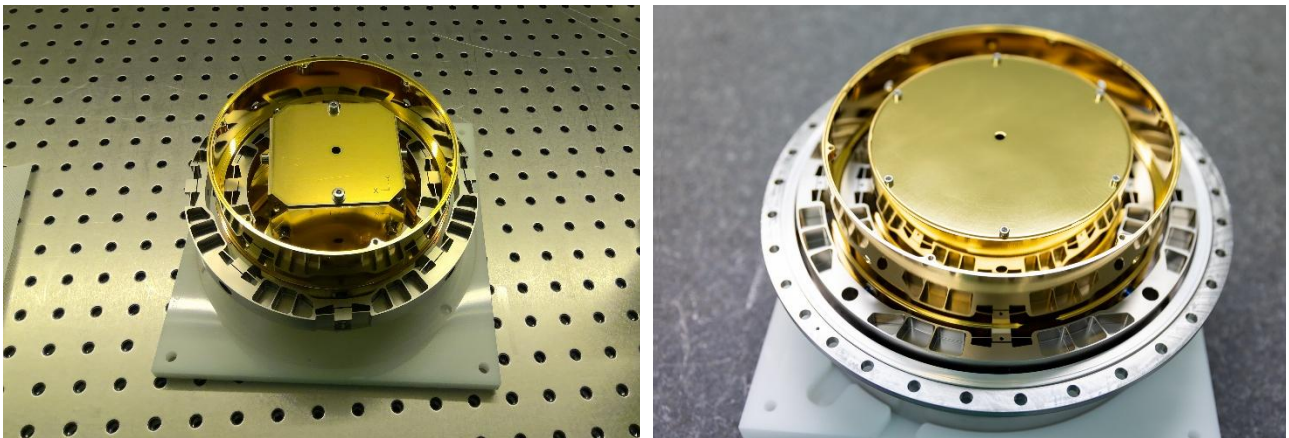


Figure 3: left: Cubic cavity mounted in the cubic frame with a first thermal shield and assembled in the first cylindrical frame. Right: next assembly step, first cylindrical shield is assembled in the second thermal shield.

A thermal simulation was performed on the current design and thermal shielding transfer function was calculated and presented with black dot in Figure 1.

2.2 Mechanical isolator and cavity holding structure

The cavity space has a cubic design with truncated corners to a depth that enables a null-sensitivity to accelerations when held properly [2]. The spacer is supported at four truncated corners in a configuration which corresponds to the vertices of a tetrahedron and is arranged symmetrically with respect to the optical axis. The four supports create Hertzian contacts at each corner between the glass cavity and plastic mounts. This mounting structure also minimizes the conductive path to the cavity.

Two risks were identified with this assembly:

- The spacer material failure during shock or vibration due to the small contact area
- A slippage of the spacer in its mounting frame leading to a cavity misalignment

To minimize those risks, mechanical isolators are designed and implemented outside of the mechanical enclosure. The mechanical isolator design shall be precisely performed to react in the expected frequency range. Figure 4 shows mechanical isolator testing on a dummy enclosure.

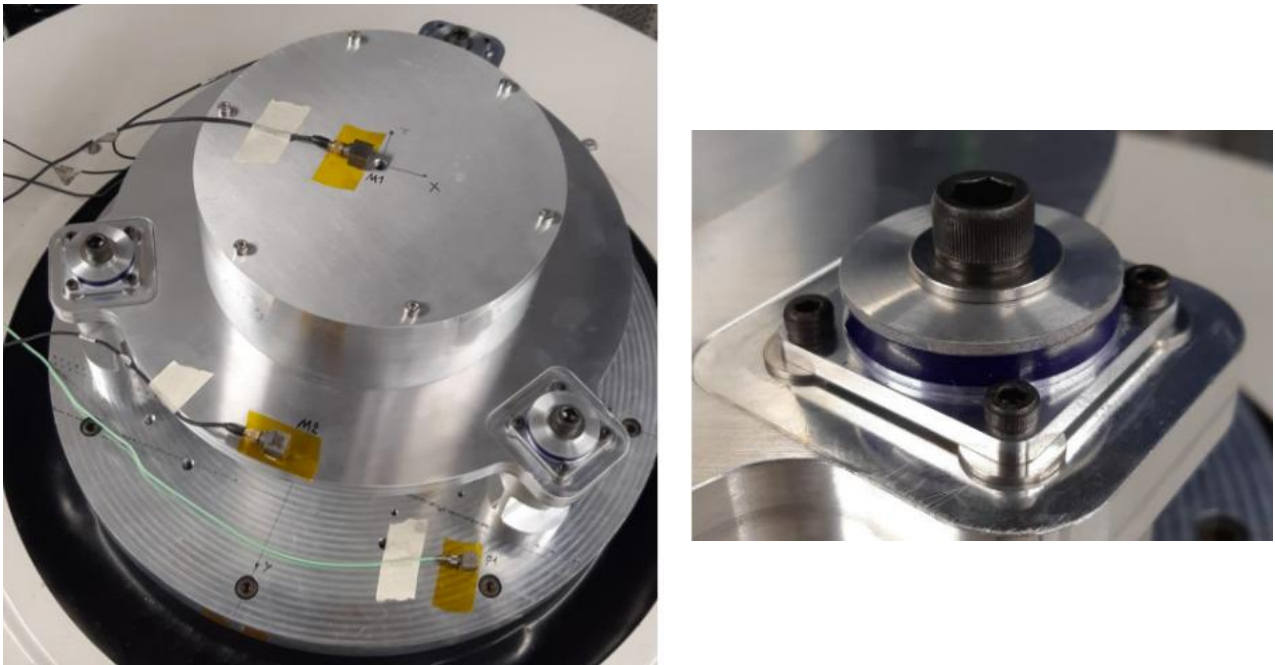


Figure 4: Left: mechanical isolator testing on a dummy. Right: mechanical isolator part.

As a second risk mitigation, a preliminary vibration and shock test campaign was performed on a dummy cavity mounted in a representative structure (see chapter 3).

2.3 Misalignment Study

Cavity and laser beam alignment play a fundamental role in the system performance. To evaluate their impact, simulations have been conducted with the OSCAR [1] (Optical Simulations Containing Ansys Results) software. OSCAR is a MATLAB toolbox designed to simulate optical resonators such as Fabry–Perot cavities in presence of imperfect optics. The software allows us to identify the different cavity propagation modes and the misalignment impacts. In this respect four main misalignment situations have been simulated.

- Radial misalignment
- Angular misalignment
- Combined radial and angular misalignment
- Waist position misalignment

In Figure 5, three first misalignment cases are presented. The waist position misalignment is a misalignment along the cavity axis, i.e. the z direction in the following graph, where the position of the laser beam does not correspond anymore to the cavity waist position. For all simulations, the misalignment study was performed considering a perfect coupling before misalignment.

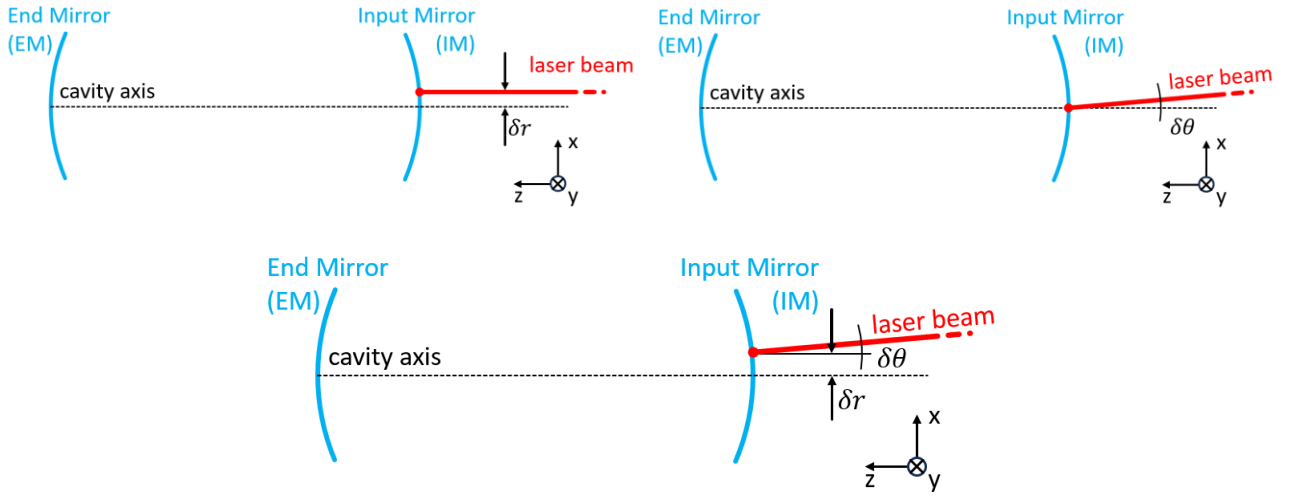


Figure 5: Three misalignment cases studied: top left is the radial misalignment, top right is the angular misalignment, and bottom is the combined misalignment

In the simulation results presented hereafter, not only the coupling losses related to the central (main) mode of the cavity are presented, but also the fluctuation (most likely the increase) of the secondary peaks. In fact, besides the main problematics of signal losses due coupling degradation on the main peak and the increase of the DC signal component on the detector, secondary peaks rise and may cause issues for the acquisition and the laser stabilization.

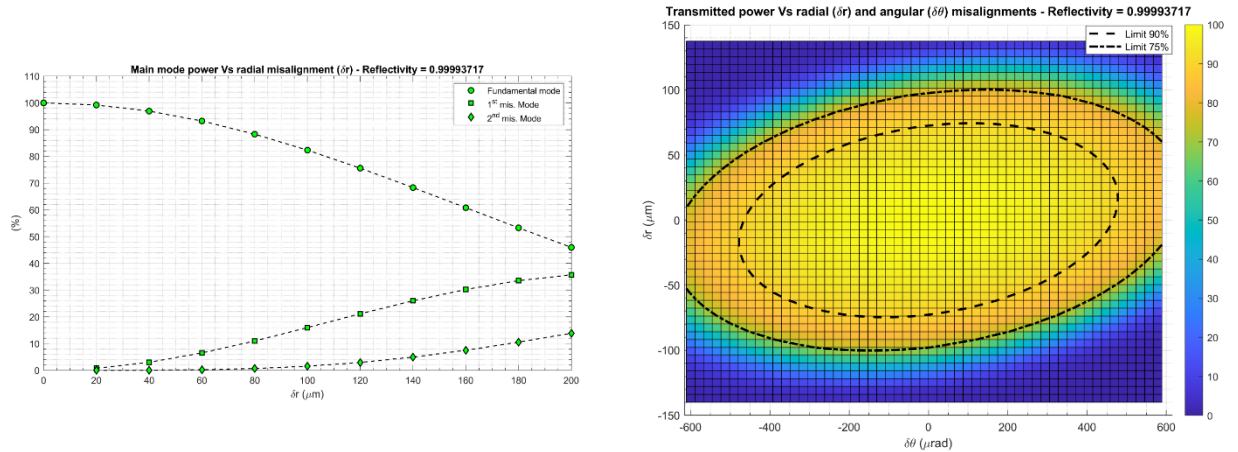


Figure 6: left, radial misalignment analysis showing the main mode coupling reduction and the increase in secondary third mode coupling. Right: combined radial and angular misalignment study with representation of the main peak coupling reduction

Figure 6, left shows the main mode power decrease (as percentage with respect to the maximum value achieved with perfect alignment) depending on the radial misalignment: a maximum radial misalignment of 120 μm allows to maintain a transmitted power of 75.1%. The value of 75% should allow the system to still be automatically stabilized on the main resonance peak as the secondary peaks stay at a low value. In Figure 6 right, the combined radial and angular misalignment

coupling analysis is shown. This provides a target value for system design. The waist position simulation shows a very small power coupling variation for such misalignment.

2.4 Cleanliness and contamination

Two different cleanliness requirements for different surfaces shall be foreseen. On one side, the most critical parts are the two cavity mirrors facing each other. These two mirrors determine the cavity finesse and thus the frequency discriminator of the cavity. For a targeted finesse of 38'500, the mirror's reflectivity is 99.991840%. As presented in Figure 7, a change in reflectivity of 50ppm already deteriorates the finesse drastically. This surface is thus very sensitive to contamination. On the other side, the optical path between the laser and the cavity is less demanding in terms of cleanliness as they affect the coupling efficiency but not the cavity finesse itself.

These elements could be deteriorated by particular and molecular contamination. To limit the molecular contamination, all outgassing materials shall be minimized in the vacuum vessel. For the particulate contamination, the system is integrated into a clean environment and shall then be protected against external contamination.

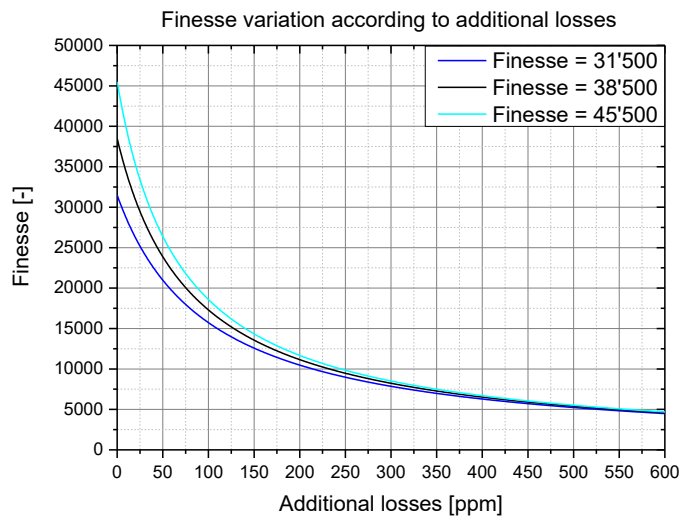


Figure 7: Finesse degradation according to additional losses inside the cavity. Black curve represents the targeted finesse. Dark and light blues curves represent the lower and higher finesse range.

The physical phenomenon of molecular contamination is caused by material that outgasses organic contaminants (in general glue and plastic). This contaminant will then move around and deposit on optics and thus induce additional losses. The phenomenon is mainly increased under vacuum as the outgassing rate increases for lower pressure. It is also increased when the laser is stabilized on the cavity as the beam will trap molecules. The way forward is thus to minimize outgassing material quantity inside the vacuum chamber and close to the cavity. The risk is decreasing with a distance increase between sensitive components and outgassing components. If possible, a bakeout of components should be performed before their implementation.

Particulate contamination could also be detrimental to the mirror reflectivity and finesse. The whole assembly phase is thus performed in an ISO5 environment, and a particular care is taken for the parts cleaning. The integration time is minimized as much as possible. Furthermore, the different thermal shield works as a labyrinth for particles and reduces the contamination risk at the cavity position.

3. VIBRATION AND SHOCK BREADBOARDING ACTIVITY

As described in chapter 2.2, one major risk during this activity is the vibration and shock survival and misalignment of the cubic cavity in its holding structure. For this reason, a derisking activity was performed. In this activity, a dummy cubic cavity was mounted in a holding structure and then vibration, and shock test campaign was performed. The test levels were derived from the system input to the cavity position. Figure 8 shows the assembly during vibration test.

The objective of the vibration test on the dummy cubic cavity is to assess the misalignment of the spacer cavity with respect to the holding structure. CMM measurements of the space and holding structure were performed before and after the vibration test. A plane is generated for the holding structure and the spacer for each principal direction. Then, the distance and the orientation between each pair of planes is compared before and after the vibration test.

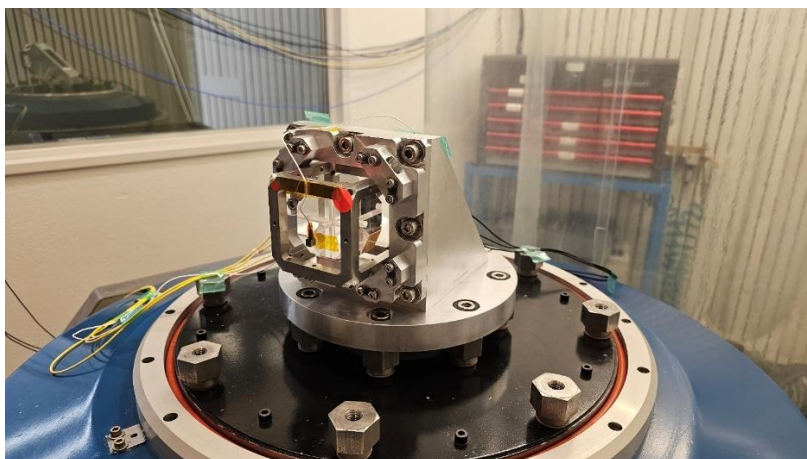


Figure 8: Vibration test performed on a dummy cavity

The outcome of the vibration test gave us confidence that with a proper mechanical isolator design, the holding structure and its alignment will survive the mission mechanical environment.

4. CONCLUSION

The development of the TRL6 Laser Stabilization Unit is ongoing and the design as well as the analysis demonstrated the feasibility of achieving the stringent frequency stability requirements for future space laser interferometry missions such as NGGM. The activity addressed the main technological challenges associated with cavity-based laser stabilization in space, namely thermal stability, mechanical robustness, alignment preservation, and contamination control.

A dedicated thermal shielding architecture combining radiative and conductive isolation was developed to provide the cavity with the extremely stable environment required to minimize frequency fluctuations. Mechanical analyses and breadboarding activities confirmed the suitability of the cavity mounting concept and increased confidence in the ability of the system to withstand the expected launch and operational environments while preserving optical alignment. Optical simulations allowed the identification of alignment tolerances and their impact on cavity coupling efficiency, providing valuable inputs for the system design and integration process. Finally, strict contamination control measures were implemented to preserve the high mirror reflectivity and cavity finesse required throughout the mission lifetime.

The analyses, design activities, and manufacturing activities were performed. The assembly and characterization are ongoing. Environmental testing is planned for the end of the year and shall demonstrate that LSU architecture is capable of meeting the demanding performance requirements of next-generation spaceborne laser metrology systems. The results obtained during this program provide a solid basis for future developments and contribute to the maturation of ultra-stable laser frequency reference technologies for space applications.

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