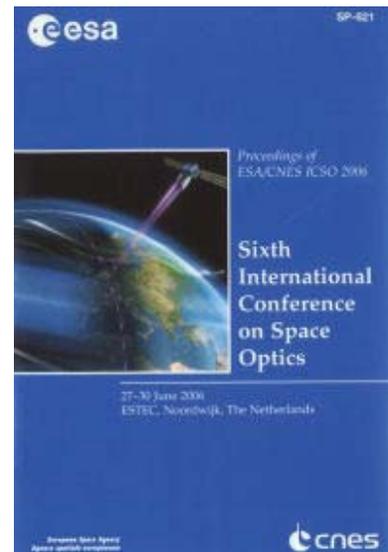# International Conference on Space Optics—ICSO 2006

Noordwijk, Netherlands

27–30 June 2006

Edited by Errico Armandillo, Josiane Costeraste, and Nikos Karafolas

Laser metrology and optic active control system for GAIA

F. D'Angelo, L. Bonino, S. Cesare, G. Castorina, et al.

LASER METROLOGY AND OPTIC ACTIVE CONTROL SYSTEM FOR GAIA

F. D'angelo [(1)], L. Bonino [(1)], S. Cesare [(1)], G. Castorina [(1)], S. Mottini [(1)],
F. Bertinetto [(2)], M. Bisi [(2)], E. Canuto [(3)], F. Musso[(3)]

[(1)]*AAS-I: Alcatel Alenia Space – Italia, strada Antica di Collegno 253, Torino (Italy); filippo.dangelo@aleniaspazio.it*
[(2)]*INRiM: Istituto Nazionale di Ricerca Metrologica (Italy)*
[(3)]*Politecnico di Torino (Italy)*

ABSTRACT

The Laser Metrology and Optic Active Control (LM&OAC) program has been carried out under ESA contract with the purpose to design and validate a laser metrology system and an actuation mechanism to monitor and control at microarcsec level the stability of the Basic Angle (angle between the lines of sight of the two telescopes) of GAIA satellite. As part of the program, a breadboard (including some EQM elements) of the laser metrology and control system has been built and submitted to functional, performance and environmental tests. In the followings we describe the mission requirements, the system architecture, the breadboard design, and finally the performed validation tests. Conclusion and appraisals from this experience are also reported.

1. THE GAIA MISSION

The ESA mission GAIA (Global Astrometric Interferometer for Astrophysics) is planned for launch in 2011 with the objective to create the largest and most precise three dimensional chart of our Galaxy by providing unprecedented positional and radial velocity measurements for about one billion stars.

The main astrometric requirement of GAIA is to measure the star position and parallax with accuracy <10 microarcsec (μas) rms at the magnitude mv = 15. The adopted observation scheme will be a continuous sky scanning with simultaneous observation of two fields of view in which the star positions are measured and compared (see Figure 1).

The GAIA astrometric instrument consists of two telescopes observing the sky in two different directions, and focusing the images of the stars belonging to the two fields of views (FOVs) on a single focal plane. The angle between the two lines of sight of the astrometric instrument (106°) is the so called "basic angle" (BA). The angular distance between any two stars belonging to different FOVs is measured on the same focal plane; the fixed offset represented by the BA is then added.

To achieve the astrometric requirement, the BA must be stable to better than **1 μas rms** over time periods **from 3.3 s** (star image integration time on a single CCD) **to 6 hours** (spin period of the satellite).
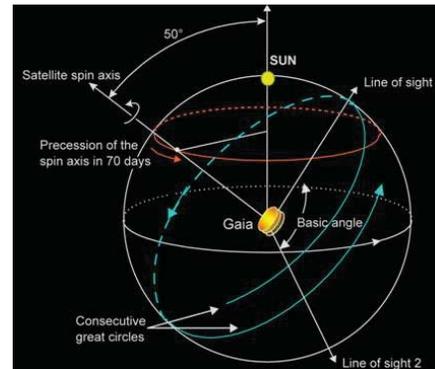

Fig. 1. GAIA sky scanning law, composed by a spin and a precession motion. The two lines of sight lie on a plane orthogonal to the spin axis.

2. LM&OAC PROGRAM OBJECTIVE

The objectives of the activity performed under the LM&OAC contract were the following:
- design, implement, validate an ultra-high resolution laser metrology system and the associated actuator mechanism for the BA monitoring and stabilization with the required accuracy;
- submit it to GAIA representative environmental testing.

The system had to be manufactured at elegant breadboard level, with some critical subsystems designed and manufactured at EQM level. These are:

(a) the Fabry-Perot laser cavity system;
(b) the mirror mount actuator mechanism.

A commercial Nd:YAG laser source was used to feed the laser metrology breadboard, being the laser source development outside the scope of the activity.

The GAIA-representative environmental tests (thermal cycling, vibrations) apply only to the EQM elements (a) and (b). For the other elements of the LM&OAC system breadboard, only functional and performance tests are applicable.

3. LM&OAC FOR THE GAIA MISSION

Each of the two telescopes of the GAIA Astrometric Instrument consists of three mirrors (M1, M2, M3).

After the mirror M3, the star light beams collected by the two telescopes are intercepted by a "beam combiner", composed by two flat mirrors (M4) arranged in single roof-top configuration prism, folded twice by two (common) M5, M6 flat mirrors and routed towards the common focal plane.

In the followings, the beam combiner will be identified with the M4 mirror, intended as a single element endowed with two flat reflecting surfaces, whose normal vectors form an angle of 106/2 = 53°.
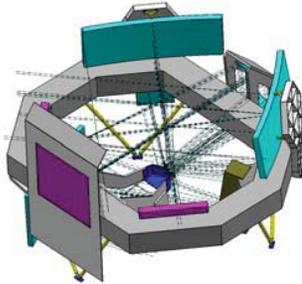

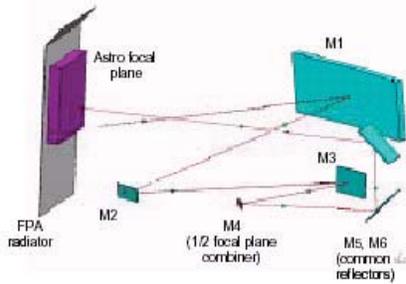Fig. 2. GAIA Astrometric Instrument mirrors

Fig. 3. Mirror layout

BA variations in the plane formed by the two LOS (the plane perpendicular to the satellite spin axis) are generated by rigid body movements of the instrument mirrors from their nominal position. Variations due to thermo-elastic deformation of the mirrors themselves are considered negligible (< 1μas).
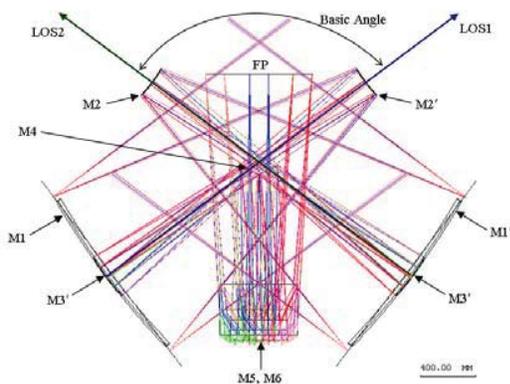

Fig. 4. GAIA Astrometric Instrument optical scheme

A variation of the BA can be caused by any movement (translation, rotation) of each of the telescope mirrors, till the combination of the beams at the level of the M4 mirror (the following mirrors M5, M6 have no effect, acting on the already combined beams). Thus there are 48 degrees of freedom (DOF) which can have an impact on the BA: (4 independent mirrors on each telescope) $\times$ (6 DOF for each mirror) $\times$ (2 telescopes).

A sensitivity analysis made on the BA variation pointed out that the most relevant DOFs for the along scan variations of the BA are:

- the relative decenter ($\Delta d_i = TY_i - TY'_i$, along the axis orthogonal to the mirror normal) of the mirrors M1-M1′, M2-M2′, M3-M3′,
- the relative tilt ($\Delta \alpha_i = RX_i - RX'_i$, about the spin axis direction) of the mirrors M1-M1′, M2-M2′, M3-M3′,
- the piston ($p_4 = TZ_{M4}$, about the bisector of the normal vectors to the two reflecting surfaces) of the mirror M4.

The BA variation along the scan direction can be approximated as a linear combination of such DOF:

$$\Delta BA = \sum_{i=1}^{3} \left[K_i^d \cdot \Delta d_i + K_i^\alpha \cdot \Delta \alpha_i \right] + K^p \cdot p_4$$

(i = mirror pair index)

Mirror(s)	DOF	Coefficient	Value
(M1, M1′)	relative decenter	K_1^d	-72.933970 μas/nm
(M1, M1′)	relative tilt	K_1^α	0.409937 μas/prad
(M2, M2′)	relative decenter	K_2^d	48.558838 μas/nm
(M2, M2′)	relative tilt	K_2^α	-0.064701 μas/prad
(M3, M3′)	relative decenter	K_3^d	28.794529 μas/nm
(M3, M3′)	relative tilt	K_3^α	-0.049530 μas/prad
M4	piston	K^p	3.944044 μas/nm

Tab. 1. Basic Angle sensitivity

From the sensitivity analysis results reported in Table 1 it appears that the most critical DOF is the tilt of the primary mirrors (M1, M1′).

3.1 BA monitoring

Fabry-Perot type laser interferometers are the building blocks of the metrology system for the BA variation monitoring.

The Fabry-Perot interferometer is basically constituted by two mutually faced spherical mirrors forming an optical cavity. The electro-optic scheme of the Fabry-Perot interferometer is shown in Fig. 4.

The error signal of the Fabry-Perot interferometer is generated by means of the Pound-Drever technique. It is characterized by periodic oscillations with steep zero crossing occurring every time the laser beam is in resonance with the optical cavity.
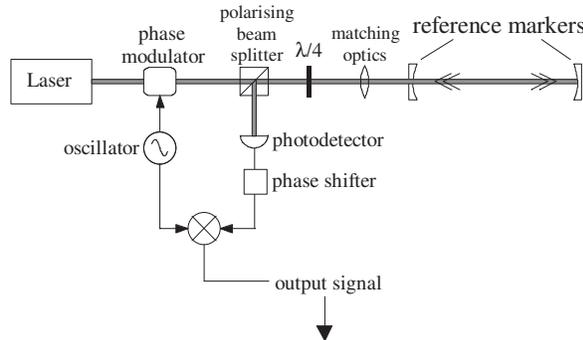
Fig. 4 - schematics of Fabry-Perot laser interferometer
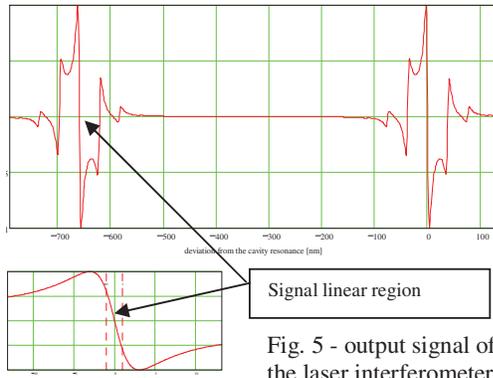

Signal linear region

Fig. 5 - output signal of
the laser interferometer

Around the zero crossing, the error signal is linear and proportional to the variation of the distance between its spherical end mirrors. Thus, the interferometer must be forced to operate only in the linear region by tuning the frequency of the laser in order to ensure the resonance condition ($L = n \cdot \lambda / 2$, L = distance between the spherical mirrors, λ = laser wavelength, n integer).

The laser frequency variation $\Delta\nu$ is so modified to chase the distance variation ΔL between the mirrors:

$$\Delta\nu = \nu_0 \frac{\Delta L}{L_0}$$

(ν_0, L_0 = frequency and F-P cavity length initial values)

Each interferometer provides an ultra-high resolution measurement of the distance variation between the two spherical mirrors of its optical cavity; these mirrors are suitably installed on the Astrometric Instrument mirrors. Each optical cavity is therefore a "metrology line" (ML). The metrology system for the BA variation monitoring consists of a network of 12 metrology lines arranged to capture univocally all mirror movements affecting the BA.

In this way the variation of the mirror DOF relevant for the BA variation (Δd_i, $\Delta\alpha_i$, p_4, $i=1,2,3$) can be expressed as a linear combination of the variation of the metrology lines length (ΔL_j, $j = 1, \ldots, 12$).
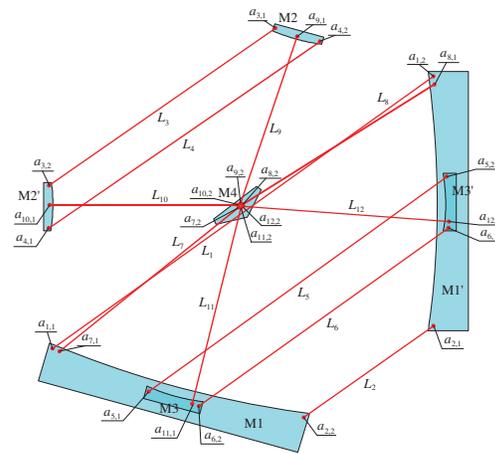

Fig. 6 - Layout of the metrology line network for the BA variations monitoring

Thus it is possible to obtain an estimate of the BA variation (BAV) as a linear combination of ΔL_j:

$$\Delta\hat{\mathrm{BA}} = \sum_{j=1}^{3} \boldsymbol{k}_j \cdot \mathbf{A}_j^{-1} \cdot \boldsymbol{\Delta L}_j$$

where the coefficient:

- $\boldsymbol{k_j}$ is related to the mirror movements

- $\boldsymbol{A_j}$ depends on the metrology lines layout

- $\boldsymbol{\Delta L_j}$ is a vector the elements of which are the single variations of the metrology lines lengths

In order to obtain an estimate of ΔBA with a resolution ≤ 1 µas rms, the variations ΔL_j of the lengths of each metrology line must be measured with a relative error:

$$\delta L_j / L_j \leq 10^{-12}$$

The system must therefore guarantee a resolution < 1 pm for an optical cavity length of the order of 1 m.

3.1.1 Laser source and frequency stabilisation

The reference laser source considered for feeding the Fabry-Perot interferometers consists of a diode-pumped Nd:YAG crystal emitting at $\lambda = 1319$ nm (near infrared). This wavelength has been selected for metrology on GAIA to avoid stray light effects on GAIA measurement, due to generation of background photons on the focal plane. In fact the CCD detectors of the astrometric instrument are insensitive to a wavelength $\lambda = 1319$ nm.

In order to measure the variation of the metrology lines with a relative error $\delta L / L \leq 10^{-12}$, the frequency of the laser source feeding the Fabry-Perot interferometers

must have a relative stability $\frac{\delta\nu}{\nu} < 10^{-12}$ over the same time scale (from 3.3s to 6 hours).

This cannot be achieved by a free-running laser (Nd:YAG lasers are limited to $\frac{\delta\nu}{\nu} \sim 10^{-8}$): stabilisation is obtained using as frequency reference a Fabry-Perot resonant optical cavity.

In this "reference cavity" the spherical mirrors are mounted on a structure made in ULE™, (CTE = 0 ± 10^{-8} K^{-1}), to be stabilised in temperature within 0.1 mK over time scale between 3.3 s and 6 hours.

$$\frac{\delta\nu}{\nu} = \frac{\delta\ell}{\ell} = CTE \cdot \delta T \ \leq 10^{-8} \text{ K}^{-1} \ \cdot 10^{-4} \text{ K} \leq 10^{-12}$$
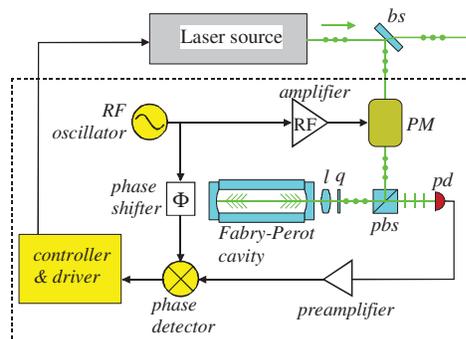

Fig. 7 – Laser frequency stabilisation system

3.2 BA control

The sensitivity of the BA to the astrometric instrument mirrors DOF points out a very interesting feature: the BA value can be changed by just moving in piston the M4 mirror.

In fact this movement changes the relative position on the focal plane of the stars images collected by the two telescopes (coming from the two FOV). A relative displacement Δs between the star images on the focal plane is equivalent to a basic angle variation $\Delta BA = \Delta s/f$, being f the focal length of the astrometric instrument.

Therefore, the control of the BA value can be simply achieved by a single-DOF linear translation mechanism (based on a PZT actuator) operating on the smallest mirror of the optical train: the focal plane combiner. For a BA control at 1 μas resolution level, the linear translator must have a resolution of ~250 pm, while its stroke must be up to ~25 μm for recovering BA variations up to 100 mas.

Since there are six metrology lines ($L_7,...,L_{12}$) having one end mirror placed on the M4, the movement of the latter affects also the lengths of these lines. This length variation must be subtracted from the length variation

measured by the laser interferometers in order to estimate the BA variations produced by astrometric instrument geometry perturbations.
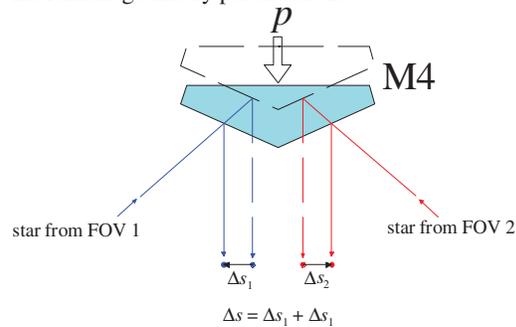

Fig. 8 - Relative displacement on the focal plane of star images coming from the two FOV, produced by M4 piston.

3.2.1 Control Electronic Unit (CEU)

The CEU of the LM&OAC for GAIA performs three different functions:
1. Provides the frequency command for keeping the laser beams of each ML in resonance with its optical cavity. It also measures the ML length variation, derived from the commands provided to the frequency shifters.
2. Provides the real-time variation of the BA from the ML lengths variations measured.
3. Commands the M4 mirror mechanism so to force the BA variation to zero, on the basis of the estimated variations of BA.

4.   LM&OAC SYSTEM ARCHITECTURE

The LM&OAC flight model architecture is thought to reduce to the minimum the elements to be mounted on the Payload Module. These are:
-   the 12 Fabry-Perot cavities;
-   the M4 translation mechanism

while the others are mounted in the Service Module. The yellow area in Fig.8 represents the Payload Module.

The optical components designed to inject/extract the laser beam into/from each F-P cavity are concentrated in a monolithic assembly, the **Optical Head**, mounting also one of the two cavity mirrors (the opposite is mounted on a support). Tip-tilt adjusters are provided on each cavity mirror for fine alignment.

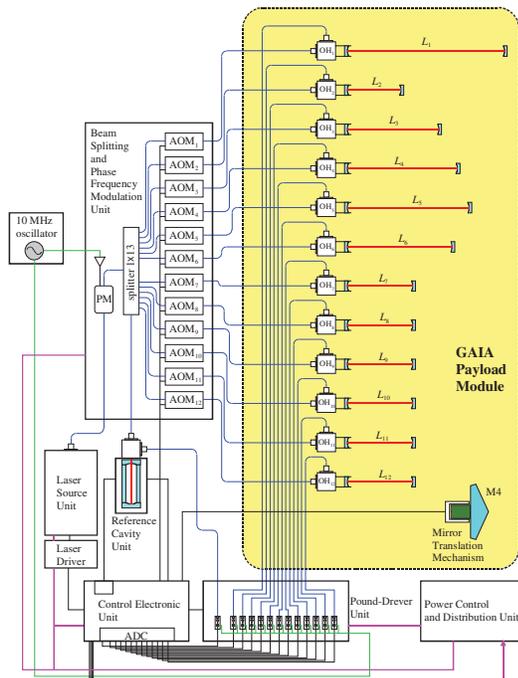The OH is designed at flight level, in order to be submitted to EQM test.

Fig. 9: LM&OAC System functional architecture

Fig. 10: Optical Head   Fig. 11: M4 translation mechanism

The M4 mirror movement is actuated by a piezoelectric (PZT) translator which is constrained to slide inside a linear guide by flexible hinges. The expansion/shrink of the PZT is transmitted to the mirror through a shaft as a piston motion. The PZT translator full stroke (38 µm) is sufficient to control a BA variation up to ~ 150 mas.

5. LM&OAC BREADBOARD

5.1 LM&OAC Breadboard Design

The LM&OAC breadboard has been designed to simulate the function of one of the 12 metrology lines. The breadboard elements are:

- *Metrology Line Breadboard*, including **Optical Head** (OH), **Mirror Translation Mechanism** (MTM) with its Locking Device, **end mirrors** and **base plate**.

- *Metrology Optical Bench*, including the **Laser Source**, the **Optical Cavity** for the frequency stabilization**,** a **Phase Modulator,** a **Frequency Shifter** and other optical elements.

- *Metrology Electronics Rack* and *workstation* for all functions related to unit driving and data/power management.
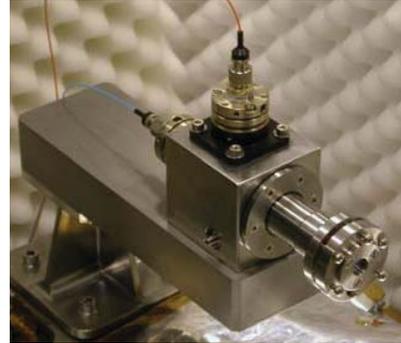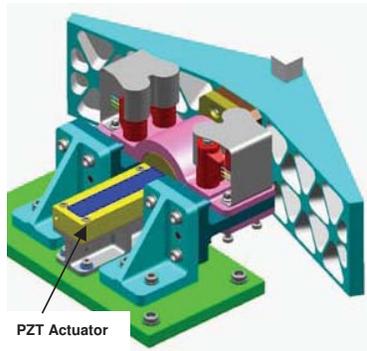

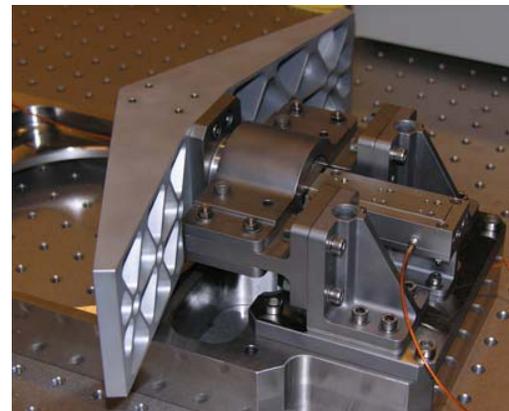Figure 12: OH on the Metrology Line Breadboard

Figure 13: MTM on the Metrology Line Breadboard

5.2 LM&OAC Breadboard Testing

A test sequence as listed in tab. 2 was foreseen in order to verify the suitability of LM&OAC system for application on GAIA.

Test N.	Test Type	Test Purpose
1	Performance	Laser frequency stability, thermal control of the reference cavity ON
2	Performance	Laser frequency stability, thermal control of the reference cavity OFF
3	Performance	Temperature stability of the reference optical cavity, thermal control ON (freq. stability indirect verification)
4	Design validation	Determination of the misalignment tolerance of the metrology line
5	Characterization/ calibration	Measurement of the characteristics of the Frequency Shifter driver
6	Functional	Capability to lock the laser beam to the optical cavity of the metrology line in ambient conditions
7	Functional	As per Test 6 in vacuum
8	Functional	As per Test 7 in cool-down condition
9	Performance	As per Test 7 at T= 160 K (GAIA operational temperature)
10	Environmental	OH and MTM thermal cycling
11	Functional	As per Test 6, after thermal cycling
12	Environmental	OH and MTM sine+ random vibration
13	Functional	As per Test 6, after vibration

Tab. 2 – LM&OAC Breadboard tests

5.3   Outcome of the test campaign

Laser frequency stability

Applicable requirement: $\frac{\delta\nu}{\nu} < 10^{-12}$ rms over time scales from 3.3 s to 6 hours. The requirement has been verified with the indirect method (Test 3), by measuring the thermal stability of the ULE cavity. The spectral density of the cavity temperature is mostly below 10^{-4} K/√Hz in the frequency band from $4.6 \cdot 10^{-5}$ Hz (1/(6 hours)) to 0.3 Hz (1/(3.3 s)), as required

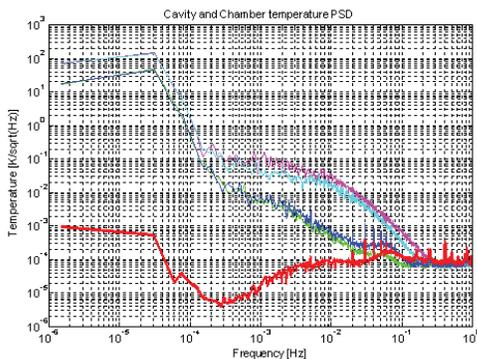Figure 14: Spectral density of the reference cavity temperature (red line) with the active control on

Tolerance to misalignments

A test carried out on a dedicated setup (controlling the rotation of one cavity mirror by means of a piezo-electric actuator) showed a misalignment tolerance of ± 0.1 arcmin at cavity mirrors level

Frequency Shifter (FS) characterization

Several FS driver output measurements performed along its useful frequency range showed non-linear response, requiring to be compensated by means of a suitable voltage-to-frequency look-up table.

The frequency shift range (~40 Mhz) is not sufficient to cover the whole frequency range between two resonances of the optical cavity (Free Spectral Range ~ 300 MHz). The lock-in condition is not guaranteed with the FS only: it can be guaranteed with the aid of physical motion of one mirror (PZT actuator).

A specific development activity may be necessary to have a FS suitable for this type of application.

Functional and performance verification

The tests have shown the capability of the system to follow distance variation at the level of 1 pm in the range 3.3 s to 6 hours (Fig. 15). Problems have been encountered at low temperature (< -40 °C) due to the loose of efficiency of the elastomeric dampers, with introduction of mechanical noise. Once back at ambient temperature, the performance was restored.
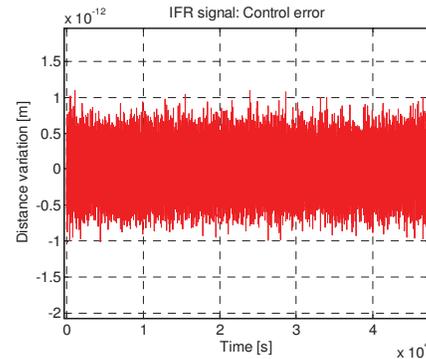

Figure 15: Fabry-Perot interferometer signal expressed in length variation of the ML

6.   CONCLUSIONS

The results of the project activities proved that the designed LM&OAC is able to:
- ❑ monitor all the degrees of freedom contributing to the Basic Angle Variation
- ❑ actively control BAV within 1 µas RMS over periods from 3.3 sec to 6 hours
- ❑ withstand the specified vibration levels and thermal cycles without internal misalignments and performance degradation (EQM elements: Optical Head and Mirror Translation Mechanism) .