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LASER METROLOGY FOR A NEXT GENERATION GRAVIMETRIC MISSION

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ABSTRACT

Within the ESA technology research project "Laser Interferometer High Precision tracking for LEO", Thales Alenia Space Italia is developing a laser metrology system for a Next Generation Gravimetric Mission (NGGM) based on satellite-to-satellite tracking. This technique is based on the precise measurement of the displacement between two satellites flying in formation at low altitude for monitoring the variations of Earth's gravity field at high resolution over a long time period.

The laser metrology system that has been defined for this mission consists of the following elements:

- an heterodyne Michelson interferometer for measuring the distance variation between retroreflectors positioned on the two satellites;
- an angle metrology for measuring the orientation of the laser beam in the reference frames of the two satellites;
- a lateral displacement metrology for measuring the deviations of the laser beam axis from the target retro-reflector.

The laser interferometer makes use of a chopped measurement beam to avoid spurious signals and non-linearity caused by the unbalance between the strong local beam and the weak return beam.
The main results of the design, development and test activities performed on the breadboard of the metrology system are summarized in this paper.

1. INTRODUCTION

In 2004 the European Space Agency (ESA) awarded to Thales Alenia Space Italia a contract for studying a new gravimetric mission, named Satellite-to-Satellite Interferometry (SSI), with the objective of monitoring the temporal variations of the Earth's gravity field at high resolution (up to harmonic degree ℓ = 180-240, as in GOCE [1]), over a long period of time (5 to 10 years as in CHAMP [2], GRACE [3]).

A review of medium and large-scale geophysical phenomena involving significant mass redistribution in Atmosphere (global and small-scale circulation), Cryosphere (ice mass unbalance, mountain glaciers melting), Hydrosphere (sea level changes, ocean dynamics) and Lithosphere (post glacial rebound, tectonics subduction), led to establish a requirement for the determination of the variation rate of the geoid height: error ≤ 0.1 mm/year at the degree ℓ = 200.
To achieve its objectives, the SSI mission shall make use of the so called Low-Low Satellite-to-Satellite Tracking technique, similar to that adopted on GRACE, but where the inter-satellite distance variation produced by the geopotential is measured by a laser interferometer rather than a radio-frequency ranging system. The intrinsically higher resolution of the laser interferometry allows in principle to reconstruct the Earth gravity field with a significantly higher spatial resolution, if the other relevant mission parameters and the accelerometers in charge of measuring the non-gravitational accelerations on the satellite are sized to match the interferometer performance [4], [5].
The following reference mission parameters have been established in the Laser Doppler Interferometry Mission study [4], [5]:

- Circular orbit spherical altitude h = 325 km.
- Orbit inclination i = 96.78° (sun-synchronous).
- In-flight measurement phase duration = 6 years.
- Inter-satellite distance d = 10 km.

2. PRINCIPLES OF OPERATIONS

A laser interferometer measures the distance variation between two retro-reflectors placed on the two satellites. The position offset between the satellites centre of mass (COM) and the retro-reflector implies a coupling between the satellite attitude motion and the distance variation measurement. Therefore an angle metrology must be introduced for measuring the angles of the two satellites relative to the laser beam. Wavefront errors in the laser beam couples with the laser beam pointing jitter and introduces a phase variation in the signal measured by the interferometer. This implies a precise and stable pointing of the laser beam which is achieved through a Beam Steering Mechanism (BSM), and an optical metrology measuring the lateral displacement of the satellite 2 (S2) relative to the beam sent by the satellite 1 (S1). The lateral displacement and angle metrology are both realized by means of three optical heads focusing the collected light on three Position Sensing Detectors (PSD).

In order to discriminate aerodynamic drag and other non-gravitational forces, they must be measured with an independent accelerometer, installed on each satellite, nominally centred in the COM. The accelerometers reproduced in the optical bench drawings are those developed and qualified for the Gradiometer of the GOCE project. In fact, their performances are very close to those needed for the NGGM.

3. METROLOGY SYSTEM DESIGN

The measurement scheme is shown in Fig. 1. The distance variation metrology consists of a heterodyne Michelson interferometer fed by a frequency-stabilised Nd:YAG laser (λ = 1064 nm). Two laser beams with slightly different frequency (ν_1, ν_2) and orthogonal linear polarization are generated by means of a fiber-coupled frequency shifter (*FS*) coupled with an amplitude modulator (*AM*). They are first mixed and their beat signal is used as reference signal. Then, one of the two beams (said "reference beam", ν_2) goes directly on the photodiode pd_2 while the other beam (said "measurement beam", ν_1) is sent towards the Satellite 2.

A Beam Steering Mechanism (BSM), based on Risley prisms, adjusts the orientation of the outgoing beam.

The measurement beam back reflected by the remote retroreflector is collected by the same transmitting telescope, and reaches the local retroreflector. After this second reflection, the measurement beam is deflected to superimpose again to the reference beam and to form a measurement beat signal, with frequency $|\nu_2 - (\nu_1 + \nu_D)| = |\nu_M - \nu_D|$, where ν_D is the Doppler frequency shift due to the satellite relative motion.

The measurement beat signal is then mixed with the reference beat signal directly and after the addition of a $\pi/2$ phase shift. These operations generate two signals in quadrature that are the two orthogonal coordinates of the rotating phase vector, this being the phase difference $\delta\varphi$ between the interferometer arms, from which the distance variation δL is computed. The incremental distance between the satellites derived from the phase vector can be then temporally derived once and twice to get the relative velocity and accelerations along the laser beam direction.

The frequency difference $|\nu_1 - \nu_2|$ between the measurement beam and the reference beam is set to 30 MHz, suitable to track relative velocities between the satellites up to 15.9 m/s (in the mission scenario defined in the LDI Mission study, the maximum relative velocity is just about 3.6 cm/s [5]).

The interferometer makes use of a chopped measurement beam to avoid spurious signals and non-linearity caused by the unbalance between the strong local beam and the weak return beam. In the proposed laser interferometer the measurement beam is chopped with 50% duty cycle, i.e. the carrier RF wave is modulated by a square wave (with the AM) with period $T = 2 \cdot Th$, being Th the round-trip time of the measurement beam between the two satellites (Th = 66.7 µs for an inter-satellite distance of 10 km, corresponding to an ON-OFF modulation frequency of 7.5 kHz). This allows avoiding the simultaneous presence on the measurement photodiode of the portion of the measurement beam which has completed the round-trip path between S1 and S2 and of that portion (more than 1000 times larger, but not carrying any information about the distance measurement) which leaks through the polarizing beamsplitter (Figure 1).

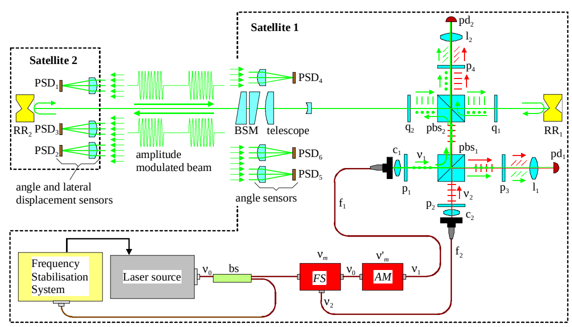

Figure 1: Functional scheme of the metrology system for the NGGM

Voltage Controlled Oscillators (VCO) locked in phase to the beat signals detected by photodiodes provide the synthetic signals that allows feeding the phase measurement during the half of the modulation cycle in which the measurement beam is OFF. This measurement scheme allows to track the phase (distance) variation until the variation occurring in the period when the signal is off is less than $\pi/2$ ($\lambda/4$ = 266 nm), a condition which is widely satisfied for the mission scenario.

The metrology measuring the orientation angles (θ, ψ) and the lateral displacements (ΔY, ΔZ) consists of a set of three small telescopes, arranged at the vertices of an equilateral triangle, and endowed with PSDs. Each PSD measures the coordinates and the optical power of the light spot focused on its plane. The incidence angles of the laser beam relative to each telescope are obtained from the light spot coordinates (ξ_Y, ξ_Z) and the telescope focal length F.

The lateral displacements are obtained from the optical powers measured by PSDs, exploiting the property of the laser beams of having a power distribution with a Gaussian profile in any cross section.

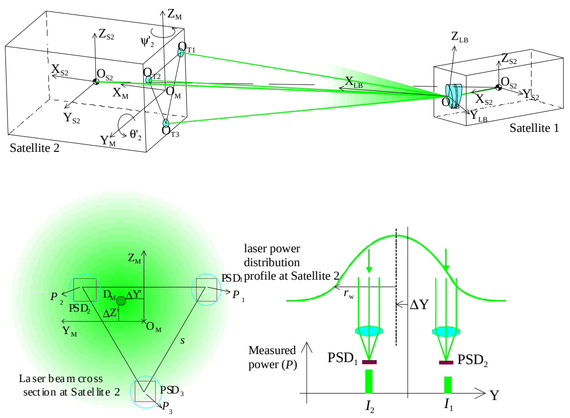

Figure 2: Measurement principle of the laser beam orientation and lateral displacements

3.1. Optical Bench Configuration

The optical bench is designed in such a way to accommodate on a same common and stable platform the units belonging to the laser interferometer and to the angle and lateral displacement metrology. The two accelerometers are also installed on the optical bench, since they must be in a close and stable position with respect to the satellite COM, where also the laser retro-reflector is located.

The structure of the optical bench has been proposed to be a sandwich panel made in Carbon-Carbon (C/C) composite material, due to its high thermal stability and low density properties.

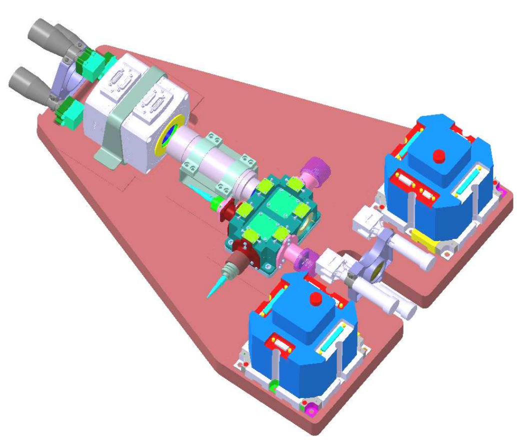

Figure 3: Optical bench configuration: 3D views

Since there are optical elements crossed by the measurement beam only, the optical path variation due to the temperature stability of the optical bench shall be a fraction of the specified distance variation measurement error.

The optical bench is surrounded by a thermal protection with an active control of the temperature between the two layers (based on thermistors and heaters).

The reference and the measurement laser beams are brought to the optical bench by two optical fibres (Figure 4).

The electronics of the metrology system is grouped in three boxes:

- The FS, AM Driving Unit contains the oscillators generating the RF signals sent to the FS (110 MHz), and to the AM (80 MHz).
- The Laser Control and Driving Electronics, which implements the stabilization of the laser frequency ($\delta\nu/\nu \leq 1.4{\cdot}10^{-13}$ 1/Hz$^{1/2}$ above f = 0.01 Hz) by means of the Pound-Drever technique and the stabilization of the laser optical power acting on the Nd:YAG pump diodes current.
- The Metrology Electronic Unit, which collects the signals and computes distance variation angles and lateral displacements. It also drives the BSM, controls the optical bench temperature and provides the data interface with the S/C.

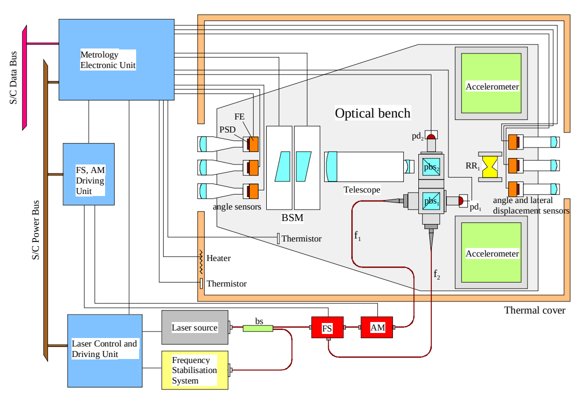

Figure 4: Functional scheme of the metrology system installed on each satellite

3.2. Optical Design

All the optical elements distributed along the laser interferometer path on the optical bench have been designed and optimized by means of the CODE V optical analysis tool.

The interferometer has been designed according to the following requirements/criteria:

1) far-field divergence (1-m beam radius at 10 km)

2) curvature error in the far-field < λ/10 PTV (to minimise the error term arising from the

wavefront curvature error coupling with beam pointing stability);

3) wavefront error < λ/10 rms on the reference signal and < λ/20 rms on the measurement one (to minimise the fringe visibility degradation);

4) match the size of the reference laser beam to that of the measurement beam in the interference regions;

5) collect enough light to fulfil the minimum optical power requirements on the detectors

The telescopes for the angle measurement has been designed to focus the laser beam on the PSD active area (10×10 mm^2) within a FOV = ±1° and a 30 mm (on S1) or 10 mm (on S2) entrance pupil diameter, obtaining light spots of minimum size on the detector and maximum radial symmetry associated to low distortion (< 0.1% max at field edges) to insure higher linearity in centroid motion across the field of view (Figure 5).

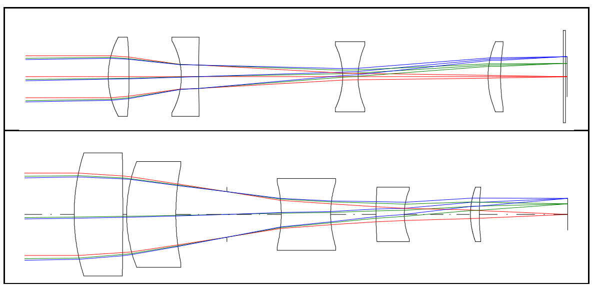

Figure 5: Optical configurations of the telescopes for the angle metrology on S1 (top) and for the angle and lateral displacement telescopes on S2 (bottom).

4. METROLOGY BREADBOARD

The central body of the Interferometer Core is a machined Aluminium block on which all the optical elements and the detectors of the laser interferometer are integrated and aligned. The fully integrated Interferometer Core is shown in Figure 6.

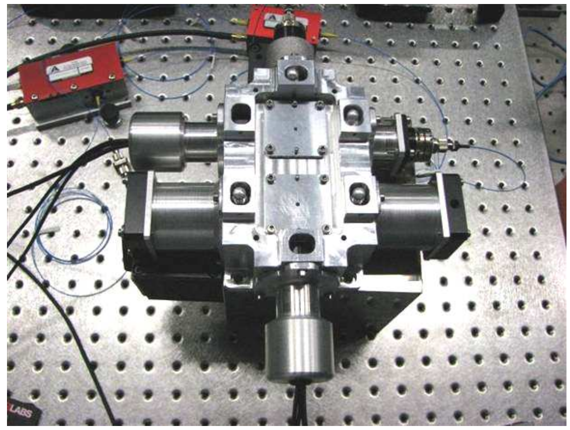

Figure 6: Interferometer Core breadboard fully integrated.

The interferometer electronics implemented in the metrology breadboard utilizes a single VCO phase locked to the reference beat signal (the one with the largest amplitude and stability) for keeping the continuity of the measurement signal when the measurement laser beam is temporarily switched off. Instead than using a second VCO phase locked to the measurement beat signal, the signal coming from this photodiode is simply discarded after the A/D conversion in the period in which the measurement beam is off.
The workstation utilized in the metrology breadboard is a Dell Dual Quad Core Intel® Xeon® X5365. A 14-bit ADC National Instrument PXI-6132 samples and digitizes at 2.5 MHz the sin(ϕ), cos(ϕ) signals produced by the analogue phase meter. The workstation computes the phase variation.

The three telescopes of the Rear Telescopes Assembly integrated on their mounting frame are shown in Figure 7. The telescope body and the mounting frame are in anodized aluminium.

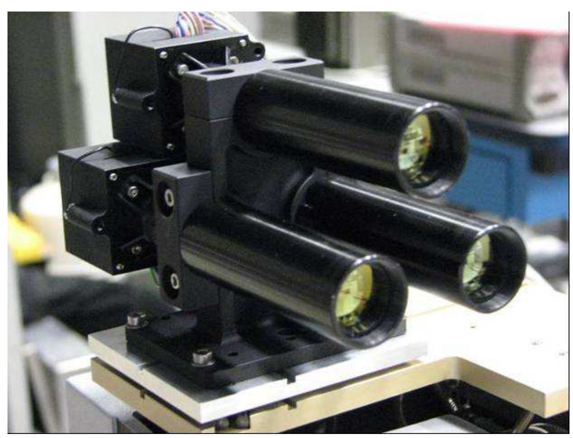

Figure 7: Telescope assembly breadboard fully integrated

Each PSD is endowed with a front end electronic board accommodated inside the detector box of each telescope. The front end amplifies and combine the signals of the PSD into two sum signals (Σ, proportional to the incident optical power *P*) and into two difference signals (ΔY and ΔZ, proportional to the light spot coordinates ξ_Y, ξ_Z).
An 18-bit ADC National Instrument PXI-6289 M samples and digitizes at 500 kHz the output signals of the three PSD.
Since the signal is chopped, the demodulation signal is provided by a local VCO phase locked to the sum output signal of the PSD. The effectiveness of this technique of "self generation" of the demodulation signal has verified by specific laboratory tests.
After the demodulation, the sum and difference signals of the three PSDs are utilized to compute the angles and lateral displacements.

The data acquisition and processing computer programs have been realized in LabView environment.

5. TEST RESULTS

Laboratory prototypes of the most critical and new elements of the optical metrology (laser interferometer, angle and lateral displacement metrology) have been implemented and submitted to preliminary proof-of-concept tests to validate the measurement models of these metrologies, utilized for the performance prediction. Here the main results are summarized.

5.3. Interferometer measurements

It has been verified the efficacy of the amplitude modulation (chopping) of the measurement laser beam enabling the correct operation of the interferometer when the power of the measurement beam back-reflected from the S2 (P*m*) is much weaker than the power fraction (P*s*) of the same beam leaking through the polarizing beam-splitter pbs_2 (actual situation for an inter-satellite distance = 10 km).
The test set-up (Figure 8) has been implemented in the underground gallery of INRIM. Here an optical path between RR_1 and RR_2 extendible up to ~90 m has been realized through three round-trip paths with an intermediate retro-reflector installed on a motorized carriage running on a 30 m rail. At the maximum distance, the chopping frequency applied to the measurement beam is about 830 kHz (with 50% duty cycle).

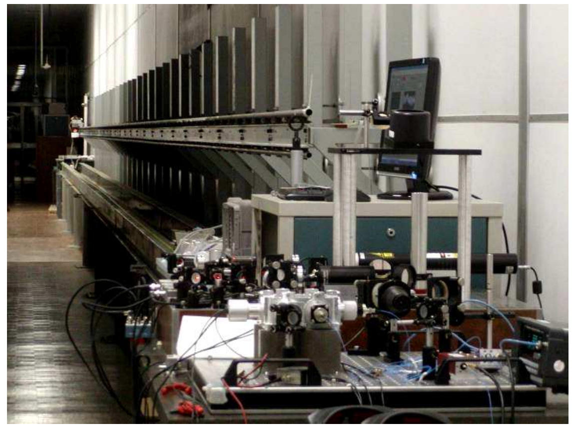

Figure 8: Test set-up at INRIM

The results of this test are summarized in Figure 9, showing the sinusoidal distance variation with ~±1 mm amplitude measured by the interferometer in various conditions:

- Time period T = 0÷30 s: continuous (not chopped) measurement beam; optical power set to get a measurement signal larger than the spurious signal (P*m* > P*s*).
- T = ~30 s: the optical power is attenuated until the spurious signal dominates (P*m* << P*s*). The interferometer output becomes flat.
- T = ~40 s: the amplitude modulation of the measurement beam is activated, without changing the optical power ⇒ the distance variation is measured again as in the period T = 0÷30 s.

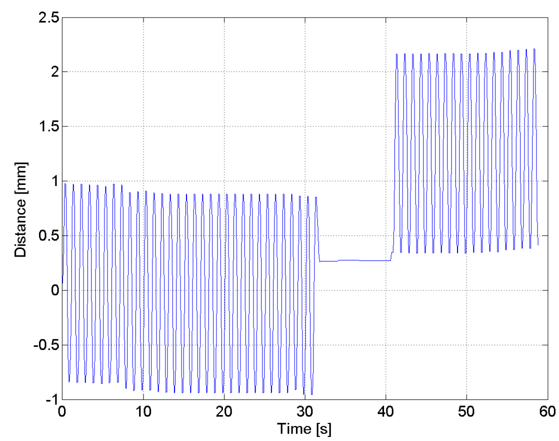

Figure 9: Distance variation measured by the laser interferometer.

The noise spectral density of the distance variation measurement is adequate to the mission needs (Figure 11). The requirement, $<2.256 \cdot 10^{-9}$ m/Hz$^{1/2}$ from 10 to 100 mHz, with 1/*f* increase below 10 mHz, has been achieved with an optical power contributing to the beat signal on the photodiode $pd_2 \cong 20$ nW. The set-up utilized for this test has been realized by installing the two retro-reflectors directly to the central body of the interferometer in order to maximise the dimensional stability of the measured distance. The interferometer block has been enclosed in a thermally insulated box (Figure 10). The fiber-coupled frequency shifter and amplitude modulators have been included in the insulated box too, after having verified their significant temperature sensitivity (the interferometer noise with the *FS* and *AM* outside the box was significantly higher).

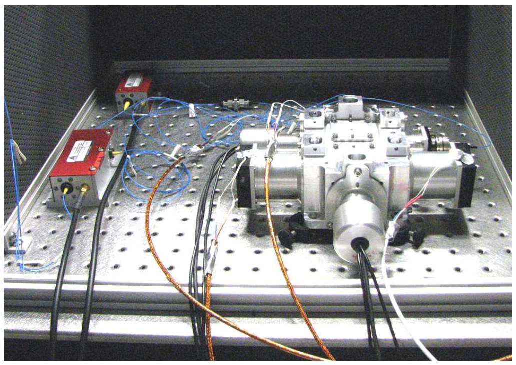

Figure 10: Thermal insulated box for distance noise measurement

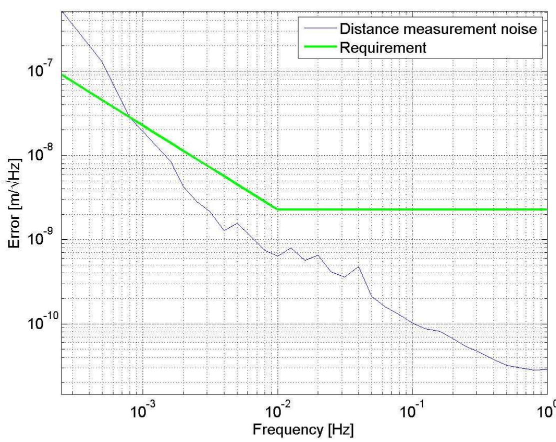

Figure 11: Spectral density of the distance variation measurement compared to the requirement.

The maximum distance variation rate that the interferometer has been able to track is 9.2 cm/s, being the result limited by the amplification of the beat signals entering the phase meter and by the sampling frequency of the ADC that digitizes signals produced by the analogue phase meter.
The result must be compared with the maximum distance variation rate of two co-orbiting satellites produced by the gravity field harmonics (3.6 cm/s): the attained performance is largely sufficient to satisfy the needs pertinent to this mission scenario.

5.4. Angular Metrology Measurements

Figure 12 show the spectral density of the angle measurement error obtained with ~0.95 µW on the PSD. The requirement for S2 ($<1.5\cdot10^{-7}$ rad/Hz$^{1/2}$) is exceeded across the whole (1÷100 mHz) frequency range mainly because of the source power instability, largely exceeding the 10 ppm/Hz$^{1/2}$ requirement. The Nd:YAG laser passed through the *FS* and *AM* was found particularly noisy at low frequency, due to the temperature sensitivity of these devices, and was then replaced in these by a modulable fiber-coupled diode laser (Figure 13). Although this latter laser was not stable enough for achieving the angle measurement noise limit, it was enough to get a 3σ value smaller than $2.5\cdot10^{-5}$ rad (requirement for the angle metrology on S1) with an optical power ≥45 nW.

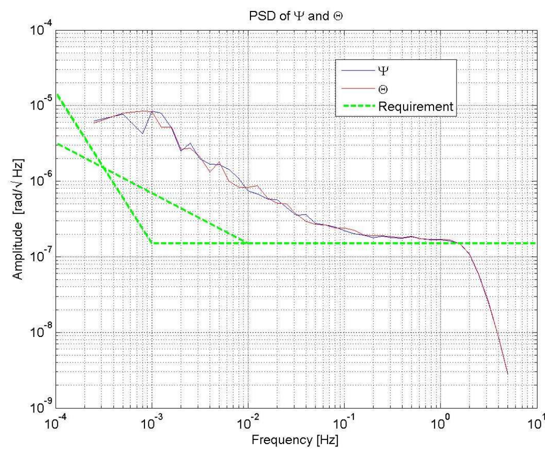

Figure 12: Spectral density of the θ, ψ angle measurement compared to the requirement.

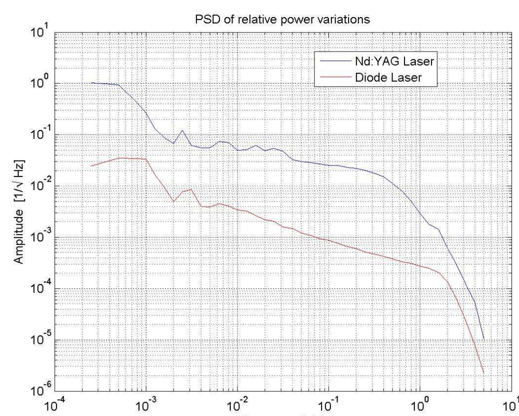

Figure 13: Relative power variation spectral density of the two lasers utilised in the angle metrology test: the Nd:YAG laser passed thorough the FS and AM (upper curve) and a fibre coupled diode laser (lower curve).

Figure 14 shows a series of decreasing angular steps of ~180 arcsec height applied to the Telescopes Assembly and measured by the optical metrology (with an optical power of 0.16 μW on each PSD) and cross-verified by an autocollimator.
The maximum difference between autocollimator and metrology measurement is 24 (mean+3σ), beside a requirement of 50·μrad.

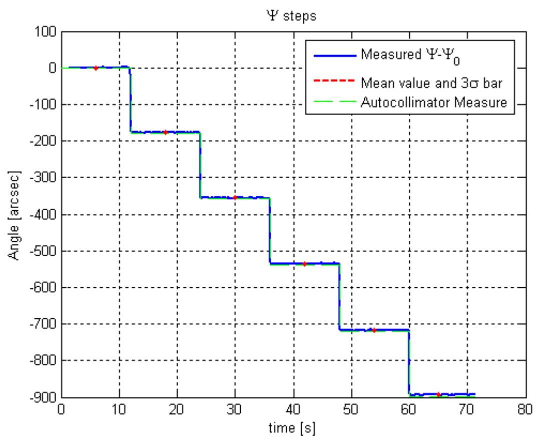

Figure 14: Decreasing angular steps of ~180 arcsec height applied to the Telescopes Assembly and measured by the optical metrology and by the autocollimator

5.5. <u>Lateral Metrology Measurements</u>

The lateral displacement measurement noise spectral density has been successfully measured and its smaller than 10^{-4} m/√Hz in the frequency range 10 ÷ 100 mHz.
The spectral density of the lateral displacement measurement error shown in Figure 15 has been achieved with ~0.34 μW on the PSD. The requirement is fulfilled across the operative frequency range. The peak at 2 mHz visible on the left side of the plot is related to the laboratory temperature variation and air conditioning system.

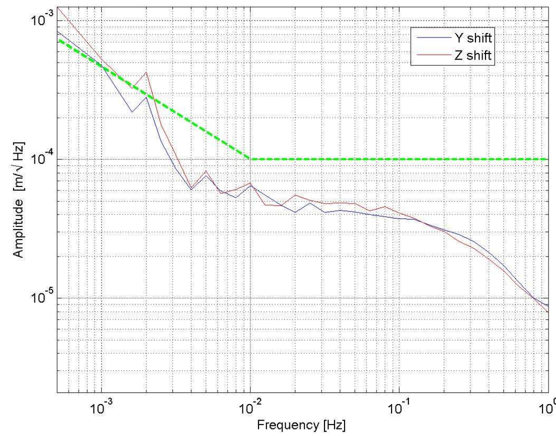

Figure 15: Spectral density of the ΔY, ΔZ lateral displacement measurement error compared to the requirement.

Lateral displacement steps of increasing height (up to 40 mm) and lateral displacement steps of 4 mm constant height have been measured by the lateral displacement metrology with an optical power of ~ 33 nW. The maximum difference between the translation stage encoder and lateral displacement metrology measurement is 2.6 mm (mean + 3σ) in the first test (Figure 16, horizontal direction) and 0.17 mm (mean + 3σ) in the second test (Figure 17, vertical direction).
In both cases the specified requirement of 1 cm is fulfilled.

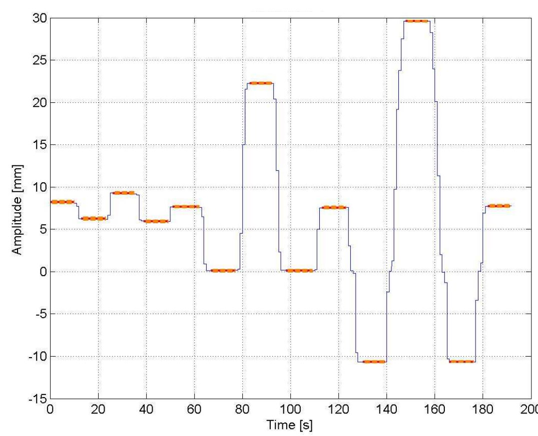

Figure 16: Lateral displacement horizontal steps of increasing height (up to 40 mm) measured by the lateral displacement metrology.

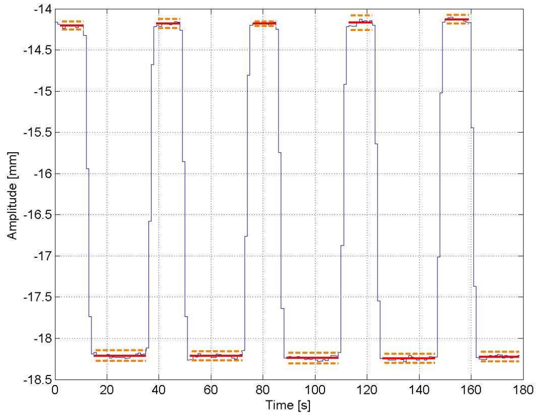

Figure 17: Lateral displacement vertical steps of constant height (4 mm) measured by the lateral displacement metrology. The mean value and the 3σ errors of the measured steps are shown.

The ultimate capabilities of the angular/lateral metrology are absolutely superior according to a specific validation campaign that preceded these tests. But the effects of air turbulence through 2.5 meters of optical path, from the source to the telescopes, are the limiting factor in performances achievement.

6. CONCLUSIONS

A possible solution for the optical metrology suitable for the realization of a Next-Generation Gravimetric Mission, as defined in the Laser Doppler Interferometry Mission study, has been identified, designed, breadboarded and tested to a level of detail sufficient to assess its feasibility.

The laser interferometer capability of measuring the distance variation with the required resolution (noise level) has been verified, as well as the its innovative operational feature (the chopped measurement beam) which is essential to enable the proper functioning of the interferometer with a retro-reflector placed at large distances (~10 km) from the source.

Strength elements of the designed interferometer are fibre-coupled frequency shifter (for the heterodyne frequencies generation) and amplitude modulator (for the measurement beam chopping). They enable to realize a fibre routing of the laser beam from the source to the interferometer body with great benefits for the alignment. On the other hand these elements and the optical fibres carrying the laser beam were found very sensitive to the temperature variations. Further investigations are necessary to identify the cause of this sensitivity and to properly address their development.

The solution of integrating all the optical elements and the detectors of the interferometer in a monolithic and compact body has been verified capable to guarantee a good alignment stability and repeatability through all the test campaign.

The possibility of achieving both the frequency and optical power relative stability requirements specified for the NGGM has been already demonstrated in the technology developments of the laser source for the LISA project [6].

In conclusions, no technological show stoppers that can prevent the implementation of a flight model of this optical metrology capable to fulfill performance requirements suitable for a NGGM have been found in this study.

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