Technical report

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Contenido

1. Introduction

Obtaining accurate gravity values using free fall absolute gravimeters depends strongly on the distance and time primary references used. Omitting other instrumental problems that these systems could present, the periodic checking of the components that provide these patterns is crucial to ensure the quality of the measurements.

While the time reference could be easily maintained by means of atomic clocks and their periodic synchronization with GNSS time measurements, the main problem in absolute gravimeters is checking if the distance reference remains constant. There is a large range of lasers that ensure a sufficiently good precision. However, most of them don´t guarantee very good long-term stability in the wavelength value, requiring their checking and periodic calibration.

This document summarizes the measurement of the A10 gravimeter [1] laser wavelength λ, based on the comparison with the FG5 gravimeter [1] laser WEO100 [2]. It is important to track this value as soon as it is being used as a distance reference. In fact, 1 MHz on the laser frequency deviation implies 2 µgal error when measuring gravity field value [3].

As soon as the FG-5 absolute gravimeter uses as meter pattern a Winters Electro-Optics Model 100 iodine stabilized laser, which is the same as the metrological institutes as CEM [4], typically use to calibrate other lasers wavelength as the A10 laser, the ML-1 Laser Polarization Stabilized from MicrogLacoste [5].

Aiming to compare one laser against the other one, a new system has been developed in Yebes. An interferometer has been constructed to overlap the signals of provided by the FG5 and A10 lasers. The resulting interference signal has been collected by a low-cost electronic board (purpose-built) that amplifies the signal collected from a photodiode. Finally, the signal is captured using a spectrum analyser. This enables to distinguish the relative frequency between the two signals.

The results indicate that through this low-cost development, under a not very special environmental conditions, and in just a few minutes, we are able to reproduce the results of the values provided by the recognized calibrations during 2019 by the manufacturer.

2. Laser description

Reference laser used is the Model 100 Iodine-Stabilized He-Ne Laser (WEO100). The laser, was designed in collaboration with the Bureau International des Poids et Mesures (BIPM), is commercialized by Winters Electro-Optics. It is a primary length standard based on the 1997 CIPM (Cesium time standard).

The electronic associated to the laser allows the precise detection and maintenance of 7 of the 14 iodine absorption peaks and no calibration is necessary (Table 1). At the same time, it allows unattended use, which is ideal for experiments that require long-term observations, as large gravity observations.

Laser Peak	Wavelength (nm)	Frecuency (MHz)
D	632,9911775	47361238,0
E	632,9911947	47361236,7
F	632,9912126	47361235,4
G	632,9912302	47361234,0
H	632,9913689	47361223,7
I	632,9913982	47361221,5
J	632,9914270	47361219,3

Table 1: WEO100 Laser wavelength and frequency peaks.

Regarding the laser to be examined, the ML-1 is a small, low-cost laboratory He-Ne laser designed and commercialized by Microg-Lacoste. This laser provides a linear-polarized, frequency-stabilized, or intensity-stabilized, coherent, light source of continuous wave visible (red) laser light with a nominal output power of 1 mWatt. The frequency of the ML-1 laser is stabilized and calibrated at the factory to provide an ideal light source wherever a visible calibrated light source is needed. The cavity can be locked in two distinct modes, which are defined as red and blue, based on an analogy with the frequency spectrum.

Main technical specifications of these two lasers are compared in the Table 2:

SPECIFICATIONS	WEO100	ML1
ACCURACY	2.5 parts in 10^{11} absolute frequency accuracy (12 kHz) with respect to the frequencies set by the 1997 CIPM Mise en Pratique.	better than 10MHz ($2x10^{-8}$)
FRECUENCY STABILITY (ALLAN VARIANCE)	1×10^{-11} 1 s 3×10^{-12} 10 s 1×10^{-12} 100 s 3×10^{-13} 1000 s	Short Term 10msec: <100 kHz ($2x10^{-10}$) Long Term (days) <1 C room temp changes<800kHz ($2x10^{-9}$)
OUTPUT POWER	100 – 125 µW typical output power	1 mWatt
LASER CAVITY PARAMETERS	Cavity length: 26.5 cm Iodine cell length: 10 cm Output beam waist: 0.40 mm (collimated)	The length of the laser cavity is adjusted by changing the temperature using a heater wrapped around the laser tube
PHYSICAL DIMENSIONS:	Electronics: 42.5 cm x 9 cm x 28 cm; 4.5 kg Laser Head: 10 cm x 10 cm x 39 cm; 6.4 kg	Housing dimensions 33,02 cm x 8,89 cm x 8,89 cm
ELECTRICAL REQUIREMENTS:	100/120/220/240 VAC; 50/60 Hz; 50 W max.	12-14 V DC
OPERATING TEMPERATURE RANGE:	15°C to 25°C	-18ºC – 38ºC, laser should be set at least 10ºC above the hottest ambient temperature

Table 2: Technical specifications for WEO100 and ML1 lasers.

3. Methodology

3.a Interferometry

The system consists of a similar interferometer to the Michelson's one [6] (see figure 1 to look at the details). It consists of a beamsplitter (element 4), which receives the light of the two lasers to be compared and divides the light beam in two different beams of equal intensity on each two faces (elements 1 and 3). To align properly the system, a mirror (element 2) has been used on a kinematic mount which can move the position at the beamsplitter of the first laser, and a kinematic mount holding the beam-splitter itself which can be used to move the direction of the second laser which leaves the beamsplitter can be modified, allowing to adjust the two spots to be colinear. Once the spots are collinear, a parabolic reflector (element 6) focuses them on the detector (element 7). The materials used are from Thorlabs [7] and are listed in the table 3, where quantity represent the actual quantity used, because the bought quantity could be different because some of them are sold in packs of several units.

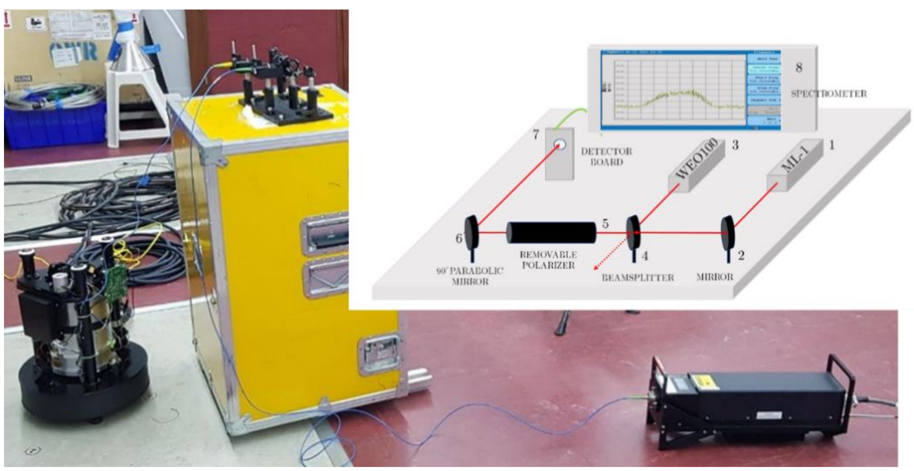


Figure 1:Image and scheme of the assembly carried out

As soon as perpendicular polarizations do not interfere, one of the lasers must be rotated to align their polarizations. Thus, a removable polarizer is inserted between the beamsplitter and the parabolic mirror (see figure 1) and a piece of white paper at the output of the polarizer is positioned. The polarizer is rotated to find out the minimum transmission with the first laser. After that, the second laser is rotated to align its minimum transmission when traversing the polarizer with the other one.

This way, as soon as both lasers are linearly polarized, they will have the same polarization.

Last part of the path (between elements 6 and 7) is the superposition of two polarized waves. Equation 1 describes the resulting wave:

$$A = A_1 \cos(k_1 x - \omega_1 t) + A_2 \cos(k_2 x - \omega_2 t + \varphi) \qquad \text{(eq.1)}$$

In this case frequencies and wavelengths are closer, producing a signal characterized by a main frequency is modulated by another one, similar to the Figure 2. As soon as their frequencies are so close, the number of periods before decaying is very large, so the figure is just an example with very different frequencies:

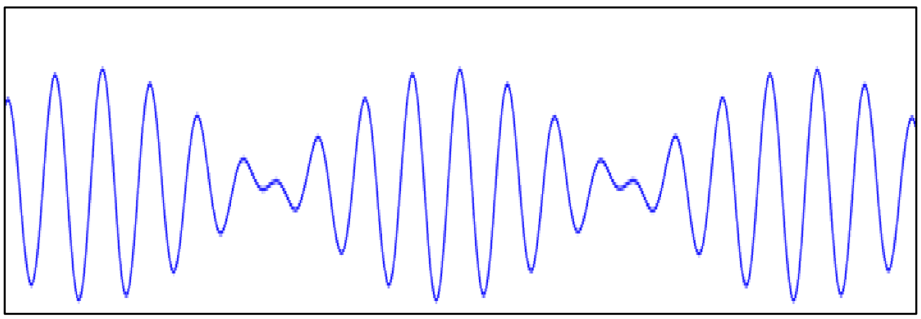


Figure 2: Superposition of waves with different amplitudes, wavelengths and frequencies

Reference	Quantity	Description
PH50/M-P5	6	Ø12.7 mm Post Holder, Spring-Loaded Hex-Locking Thumbscrew, L=50 mm
TR50/M-P5	6	Ø12.7 mm Optical Post, SS, M4 Setscrew, M6 Tap, L = 50 mm
BA1S/M-P5	6	Mounting Base, 25 mm x 58 mm x 10 mm
MB1530F/M	1	Aluminium Breadboard, 150 mm x 300 mm x 12.7 mm, M6 Taps
RDF1	4	Rubber Damping Feet
KM100	2	Kinematic Mirror Mount for Ø1" Optics
KM05/M	1	Kinematic Mirror Mount for Ø1/2" Optics, M4 Taps
VC3C/M	2	Large V-Clamp with PM4/M Clamping Arm, 63.5 mm Long, Metric
ME1-G01	1	Ø1" Round Protected Aluminium Mirror, 3.2 mm Thick
EBS1	1	Economy 50:50 Beamsplitter, Ø1", AOI: 45°
MPD029-G01	1	Ø1/2" 90° Off-Axis Parabolic Mirror, Prot. Aluminium, RFL = 2"

Table 3: Bill of materials

3.b Photodetector

The detector 3 and 4 has been made with a photodiode (D2) (Hamamatsu S5973) which can receive up to 500 MHz, amplified with two transistors in Darlington configuration (Q1 and Q3), with a cascode transistor (Q2) at their output to increase bandwidth. All the transistors are Infineon BFQ19SH6327XTSA1. The board has been manufactured at Yebes Observatory (Figure 3).

The photodetector receives the "signal wave envelope", as soon as the "carrier" frequency is inside the visible or infrared (according to the Hamamatsu datasheet) wavelengths.

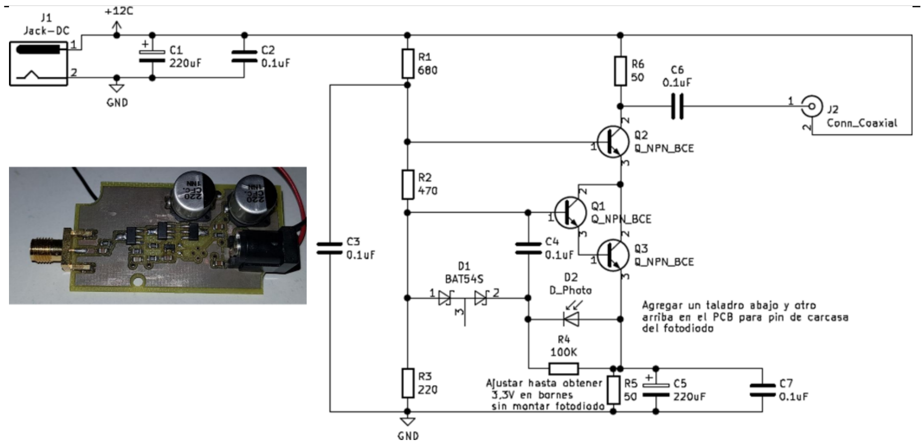


Figure 3: Photodiode PCB design a picture inset

The output current from the photodiode is proportional to the incoming optical power. As soon as we have two waves, with angular speeds ω1 and ω2, the output, assuming infinite bandwidth, would be (eq.2):

$$I = \alpha[V_1\cos(\omega_1 t + \delta_1) + V_2\cos(\omega_2 t + \delta_2)]^2 = \\ = \alpha V_1^2\cos^2(\omega_1 t + \delta_1) + \alpha V_2^2\cos^2(\omega_2 t + \delta_2) + \\ + 2\alpha V_1 V_2 \cos(\omega_1 t + \delta_1)\cos(\omega_2 t + \delta_2) \qquad \text{(eq.2)}$$

Using trigonometric formulas, it can be shown that:

$$\begin{aligned} I = 0{,}5\alpha(V_1^2 + V_2^2) & \quad (DC\ component) \\ -0{,}5\alpha V_1^2\cos(2\omega_1 t + 2\delta_1) & \quad (2nd\ harmonic\ wave\ 1) \\ -0{,}5\alpha V_2^2\cos(2\omega_2 t + 2\delta_2) & \quad (2nd\ harmonic\ wave\ 2) \\ +\alpha V_1 V_2\cos[(\omega_1 - \omega_2)t + (\delta_1 - \delta_2)] & \quad (difference\ frequency) \\ -\alpha V_1 V_2\cos[(\omega_1 + \omega_2)t + (\delta_1 + \delta_2)] & \quad (sum\ frequency) \end{aligned}$$

The DC component is filtered out by the circuit. The 2nd harmonics are in the range of ultraviolet, so they are well above the cutoff frequency of the photodiode (1 GHz). The difference frequency term is the only one which can be seen with the spectrum analyzer. The sum frequency is also above the cutoff frequency of the photodiode.

3.c Data Acquisition

Once total amount of light rising from the interference of both lasers over the photodetector is enough to collect the data, a Keysight N9344C spectrum analyser is used. It is directly connected to the photodiode PCB with a SMA-SMA cable. The circuit was powered with a laboratory power supply, being its consumption around 20 mA.

Locking the ML1 laser in one of its modes (blue or red), peaks from WEO 100 are changing respectively, recording, and saving data of the relative frequency between lasers. The procedure is repeated, now locking the ML1 laser to the opposite mode to the previous one (red or blue). As soon as the" peaks" from the interferometric signal are so wide, they are just centred on the screen and the frequency centre value is noted down (Figure 4).

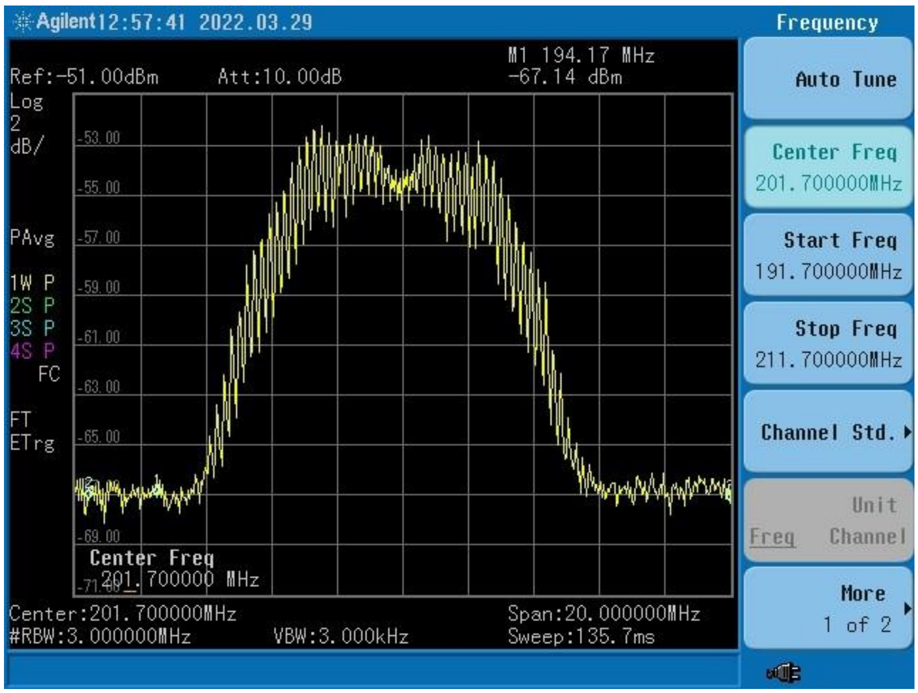


Figure 4: Example of the peak width interference zoomed.

3.d Data processing

As stated before, the FG5 laser is used as reference. Peak frequencies are listed in Table 4. As stated before, the result at the spectrum analyser is the relative frequency between the two-superimposing light beams. Table 4 shows the results from a previous calibration from the manufacturer in 2019, which has been used as reference. To transform frecuency to wavelengths equation 3 has been employed:

$$\lambda = \frac{c}{\upsilon} \quad \text{(eq. 3)}$$

where λ is the wavelength in m, c is the light speed c=299792458 m/s and υ is the frequency value in Hz.

Peak	Absolute frequency [MHz]	Relative frequency to i peak [MHz]	Blue Lock Offsset (MHz)	Red Lock Offset (MHz)
d	473612379,821	165,116	161,0	534,8
e	473612366,960	152,255	174,0	521,8
f	473612353,597	138,892	187,4	508,5
g	473612340,399	125,694	200,2	495,6
h	473612236,644	21,939	304,3	391,6
i	473612214,711	0,000	325,8	369,7
j	473612193,140	-21,565	347,4	347,8

The results are obtained simply by adding or subtracting the values obtained from the relative frequency with the corresponding value of the WEO 100 peak in which it has been measured. In this way seven values for each ML1 mode are obtained. These data can be treated statistically, obtaining a mean value with its corresponding standard deviation. Equation m shows the basic formulas to calculate de statistical parameters (equation 4 and equation 5)

$$\bar{\nu} = \frac{1}{n}\sum_{i=1}^{n} \nu_i \qquad \text{(eq. 4)}$$

$$\overline{\Delta\nu} = \frac{1}{n-1}\sum_{i=1}^{n} (\nu_i - \bar{\nu})^2 \qquad \text{(eq. 5)}$$

3.e CEM calibration methodology

The CEM2 reference laser is a Helium-Neon laser stabilized by means of Iodine absorption cell, emitting at 473.612 THz. It is the same model to the WEO laser used by the IGN. The design complies with the 1983 recommendations of the International Committee for Weights and Measures, revised in the Mise en pratique (MEP 2003). The frequency of reference laser emission is known with a typical uncertainty of 2.1 parts in 10^{11} complying with the specifications of the BIPM (International Committee for Weights and Measures).

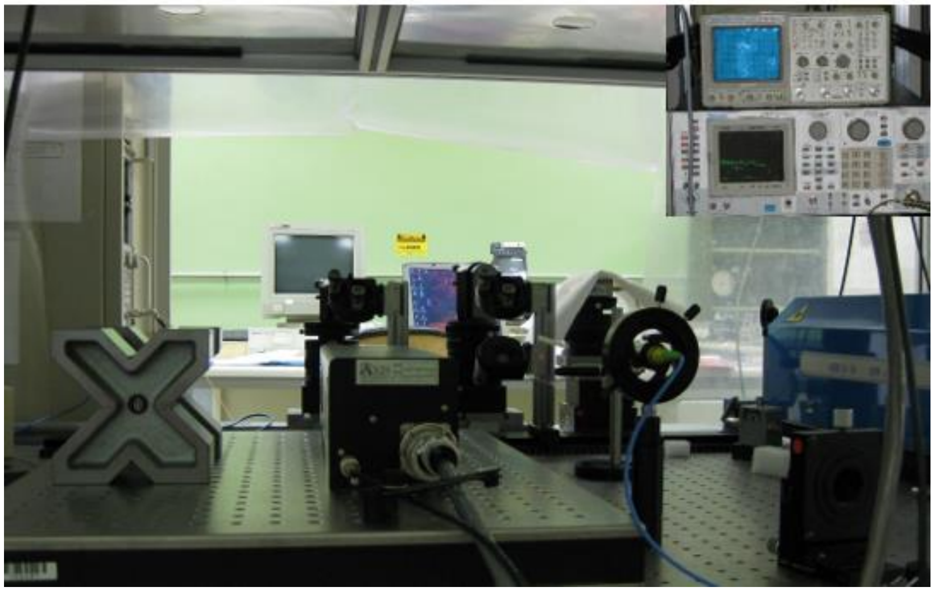


Figure 5: Picture in CEM during ML1 2008 calibration

Aiming to calibrate the laser, the Spanish Metrological Centre (CEM), use the frequency beating technique. The beat frequency is detected using an avalanche photodiode, amplifying the output signal by 40 dB, over a 500 MHz bandwidth, so that it can be correctly observed by a spectrum analyser, guaranteeing the purity of the signal. The frequency has been determined using a frequency counter coupled to a computer.

4. Results

Results for ML1 laser in blue and red mode configurations are summarized in table 5 and table 6, accordingly. There, the first column comprises the WEO100 peaks, the second one is the relative frequency between WEO100 and ML1 laser in their respective configurations. The third column contains the sum of these values with the FG5 laser absolute frequency peaks and the fourth one is the wavelength obtained applying equation 1. The mean wavelength is 632.990960838367 nm.

	ML1 Blue mode		
WEO100 Peak	Relative frequency $\Delta\upsilon$ [MHz]	Absolute frecuency υ [MHz]	Wavelength λ [nm]
d	162,2	473612541,971	632,99096082
e	175,0	473612541,960	632,99096084
f	188,5	473612542,097	632,99096065
g	201,7	473612542,099	632,99096065
h	305,0	473612541,644	632,99096126
i	327,2	473612541,905	632,99096091
j	348,9	473612542,040	632,99096073

Table 5: Results for the comparison between ML1 Blue mode laser and different peaks from WEO100

	ML1 Red mode		
WEO100 Peak	Relative frequency $\Delta\upsilon$ [MHz]	Absolute frequency υ [MHz]	Wavelength λ [nm]
d	535,0	473611844,821	632,99189258
e	522,2	473611844,760	632,99189266
f	508,5	473611844,997	632,99189234
g	495,6	473611844,799	632,99189261
h	391,9	473611844,744	632,99189268
i	369,5	473611845,205	632,99189206
j	348,3	473611844,840	632,99189255

Table 6: Results for the comparison between ML1 Blue mode laser and different peaks from WEO100

CEM results are displayed in Figure 6:

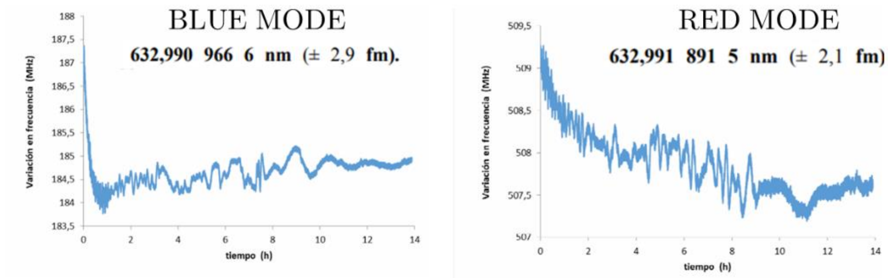


Figure 6: Graphical results from CEM laser comparison

Finally, table 7 and Figure 7 contain the different result for the comparison between 2019 ML1 laser values obtained fo MicrogLacoste, results obtained in the CEM in 2022 and values obtained in 2022 with the new system.

	Parameters	Blue lock		Red lock	
2022 Yebes	ν [MHz]	473612541,96	0,16	473611844,88	0,17
	λ [nm]	632,99096084	0,00000023	632,99189248	0,00000024
2019 MG	ν [MHz]	473612540,77	0,21	473611845,07	0,17
	λ [nm]	632,99096240	0,00000030	632,99189220	0,00000020
Dif.	Δν [MHz]	-1,189	0,056	0,1891	0,0047
	Δλ [nm]	0,000001559	0,000000071	-0,000000283	-0,000000039

	Parameters	Blue lock		Red lock	
2022 Yebes	ν [MHz]	473612541,96	0,16	473611844,88	0,17
	λ [nm]	632,99096084	0,00000023	632,99189248	0,00000024
2022 CEM	ν [MHz]	473612537,70	2,2	473611845,6	1,5
	λ [nm]	632,9909666	0,0000029	632,9918915	0,0000021
Dif.	Δν [MHz]	-4,3	2,0	0,7	1,3
	Δλ [nm]	0,000005759	0,000002671	-0,000000983	0,000001861

Table 7: Wavelength and frequency comparisons between distinct procedures and calibration Epochs

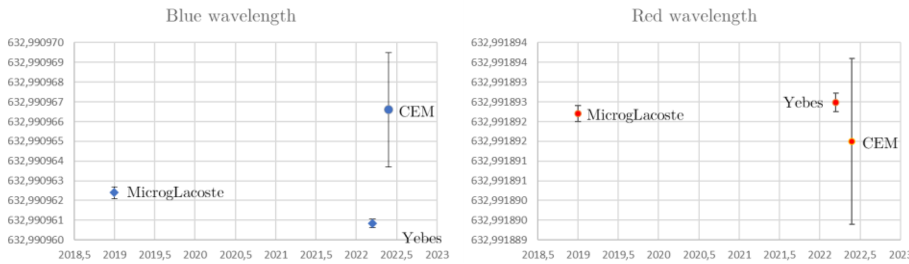


Figura 7: Graphical comparison of final values

5. Discussion and conclusion

Aiming to obtain a more periodic calibration control of the laser of the A10 gravimeter which help to remove doubts emerging during observations with this gravimeter, a fast system to check its behaviour is developed, to be used before the next calibration can be carried out in the CEM

Starting from the advantage of taking the FG5 laser (WEO100), which is the standard used by metrology centres and which does not need to be calibrated, it has only been necessary to create a comparison mechanism and methodology. This mechanism consists of the construction of a small interferometer that leads the superimposing signal of the two lasers over a photodiode inserted in an electronic board that amplifies the signal and can be measured. Signal is received by a spectrum analyser to read the relative difference in frequency.

Results obtained show a very good concordance between the values provided by the calibration carried out in the factory in 2019. The only thing that was not expected is that the linewidth of the signals is too wide, but it can not be discerned if the laser is manufactured this way or it is a problem which should be fixed. Additionally, there is a very low frequency drift (around 0.5 Hz), probably due to the closed loop heating stabilization.

Several advantages have been found with this methodology:

- It is not necessary an expensive laboratory equipment or ideal laboratory conditions. Although it is understandable that the better the conditions, the better the measures are.
- Time needed to set up the interferometer, as well as to carry out measurements, took about three hours, and the precision is enough for the calibration purposes. Moreover, the part corresponding to the interferometer can be fixed, avoiding having to do the alignment from scratch every time the calibration is needed, greatly reducing the measurement time.

The current system is a prototype that can be improved, further amplifying the signal. The spectrum analyser can be replaced by a relative low-cost electronic card connected to a computer. Finally, the interferometer can be mounted on a fixed structure that allows a non-specialized user to make the corresponding comparisons.

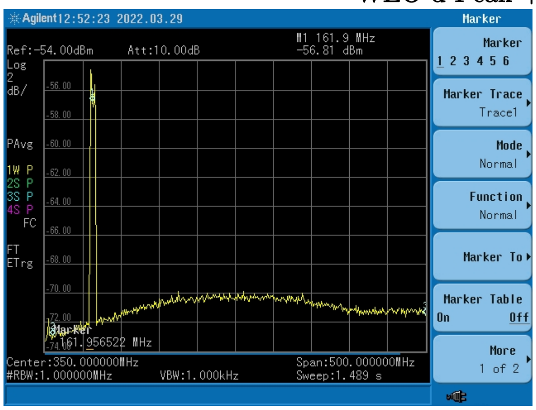
This methodology presents several advantages and some disadvantages. On the one hand, this methodology is comparable to the one used by the manufacturer (moreover, it has been verified, as the values obtained are closer to that calibration). On the other hand, values for the frequency and the wavelength are obtained from 7 independent measurements, what gives a greater statistical weight to the result. Timing procedure can be reduced considerably, since the comparison with different peaks is what provides more confidence in the process and not the measurement time. Against this system is the need to calibrate the frequency meter to be sure that the measurements are correct.

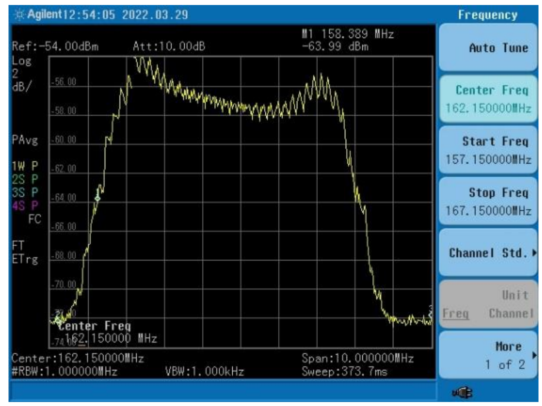
Anyway, both the assembly and the developed methodology allows to isolate possible problems in the equipment. Therefore, it can be a useful tool in which it would be a good option to continue working. to verify the status of the equipment before and after field work.

6. Annexes

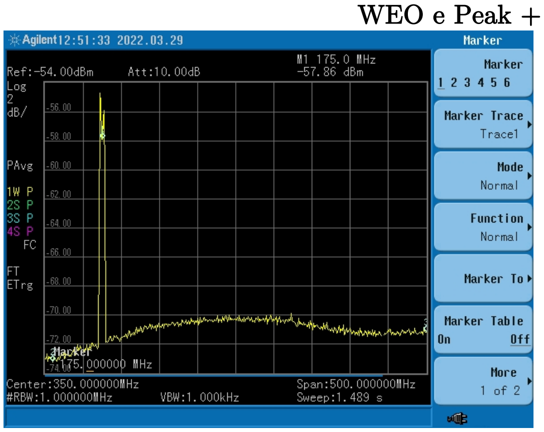
6a. Spectrum analyser screenshots

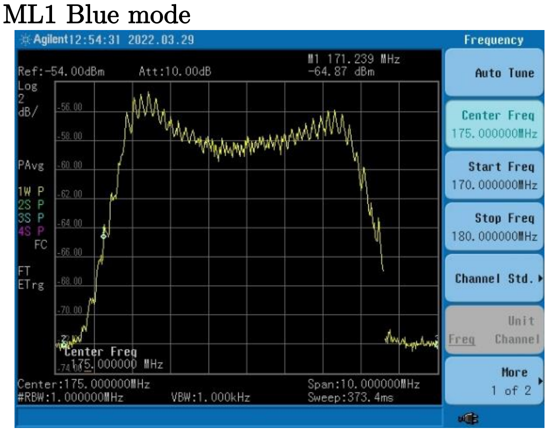
WEO d Peak + ML1 Blue mode



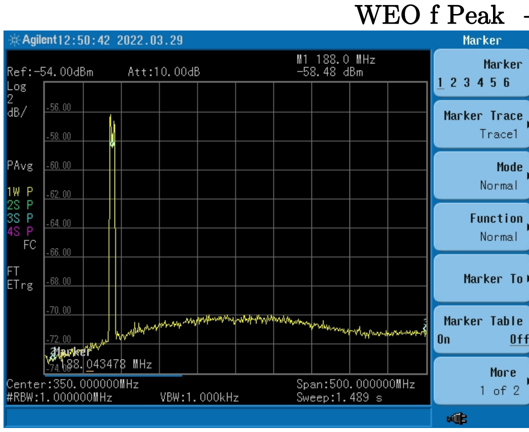


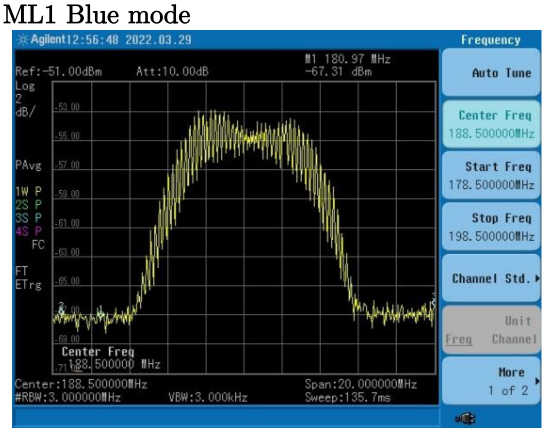
WEO e Peak + ML1 Blue mode



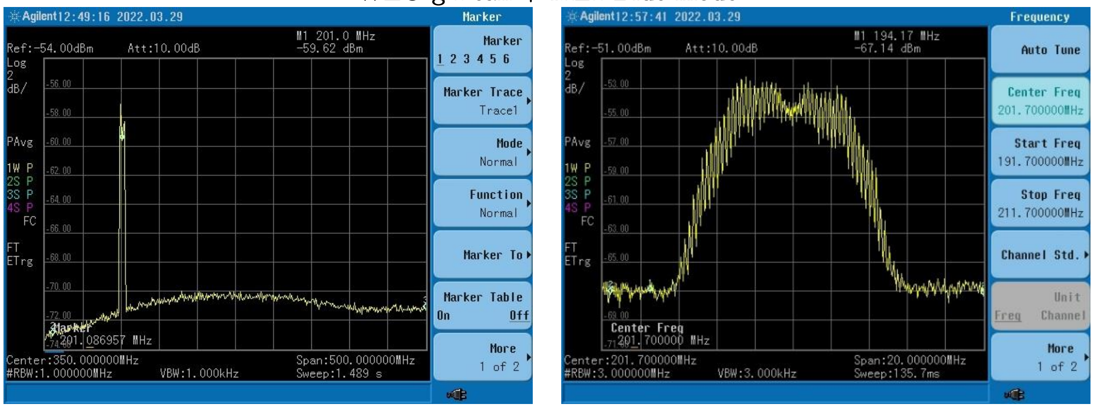


WEO f Peak + ML1 Blue mode

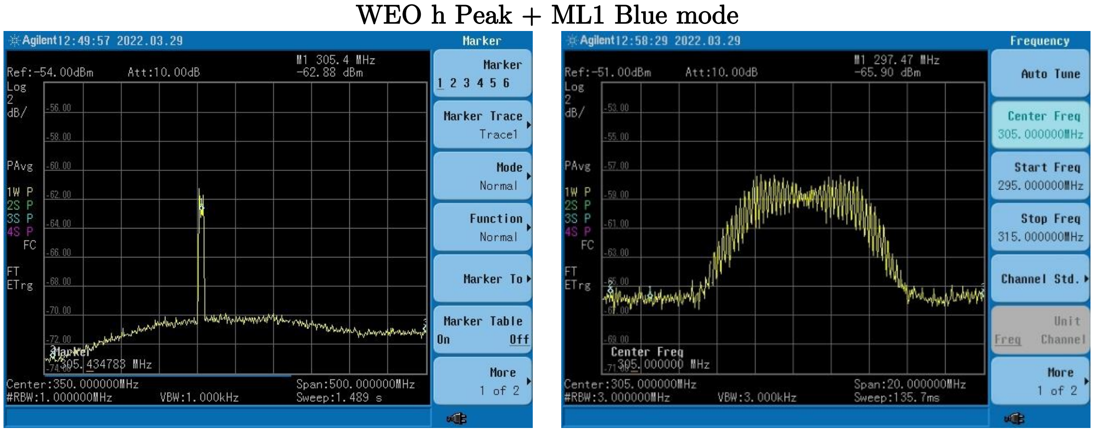




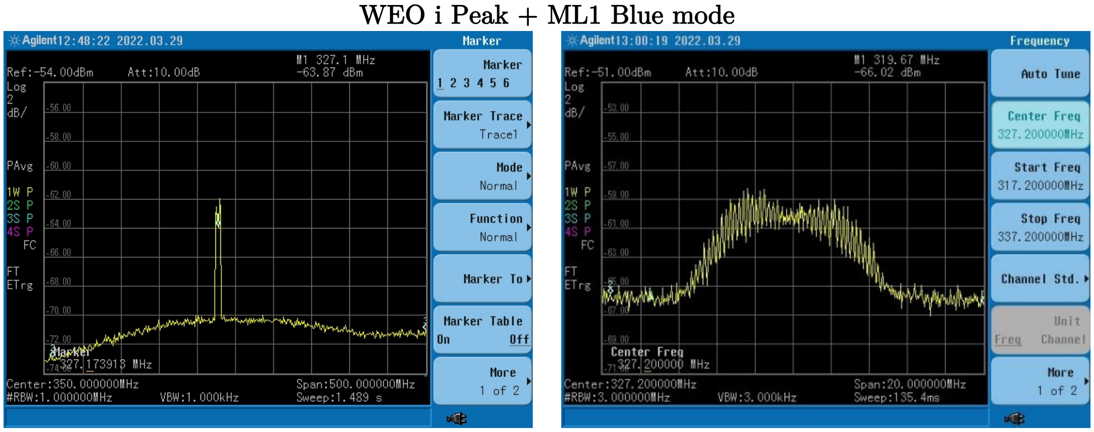
WEO g Peak + ML1 Blue mode



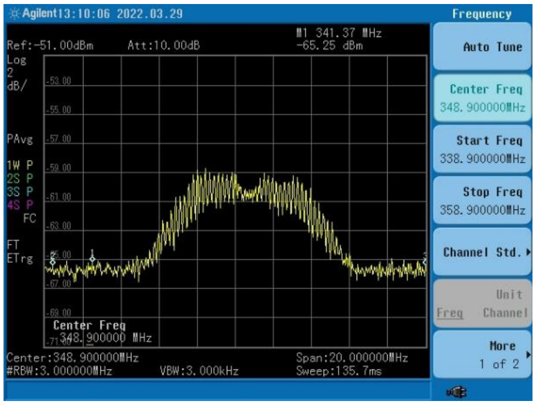
WEO h Peak + ML1 Blue mode

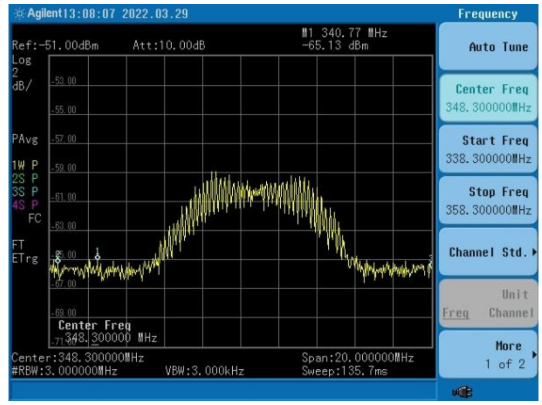


WEO i Peak + ML1 Blue mode

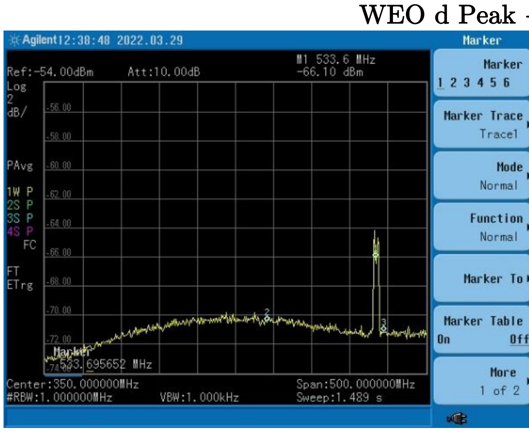


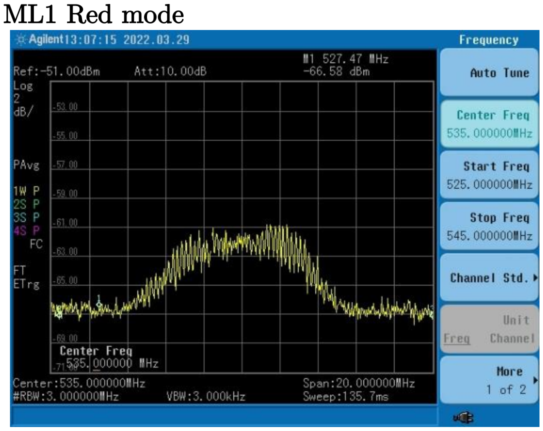
WEO j Peak



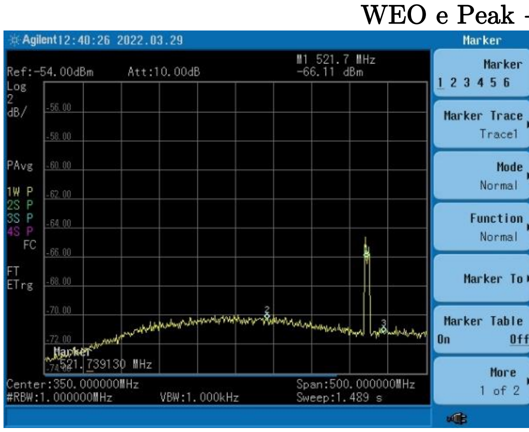


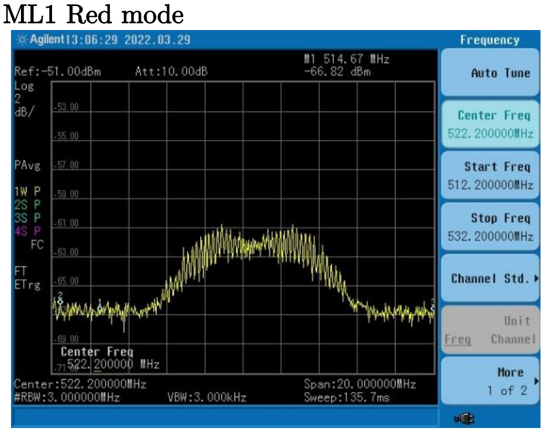
WEO d Peak + ML1 Red mode



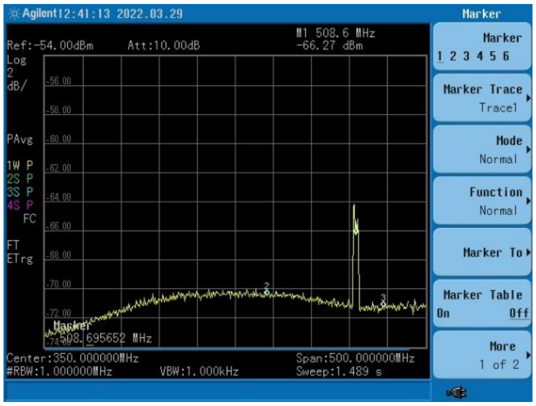


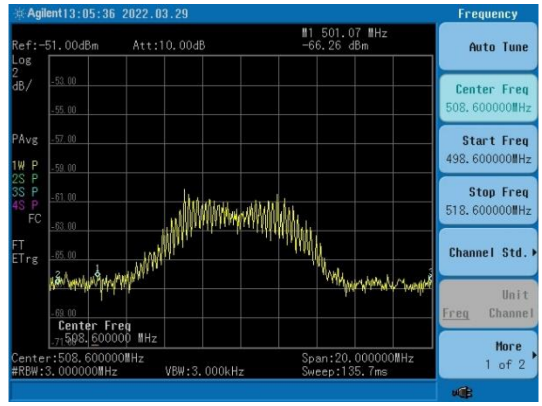
WEO e Peak + ML1 Red mode



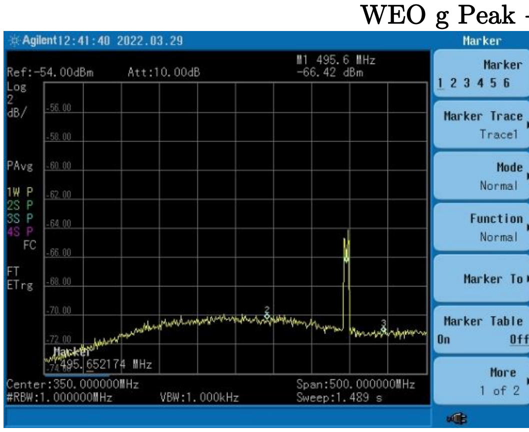


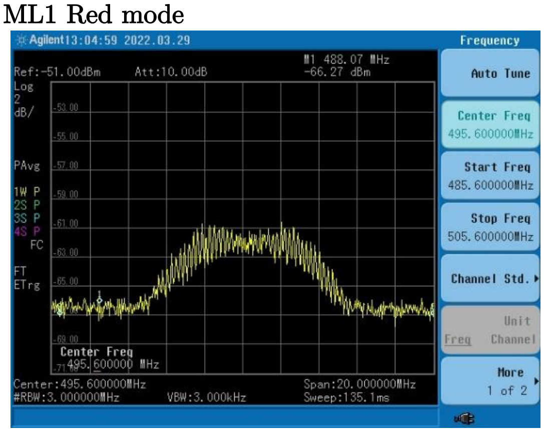
WEO f Peak + ML1 Red mode



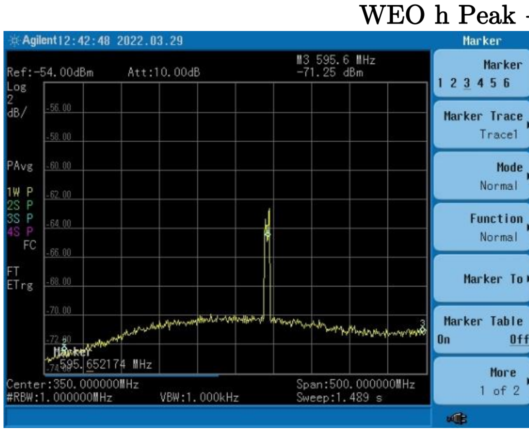


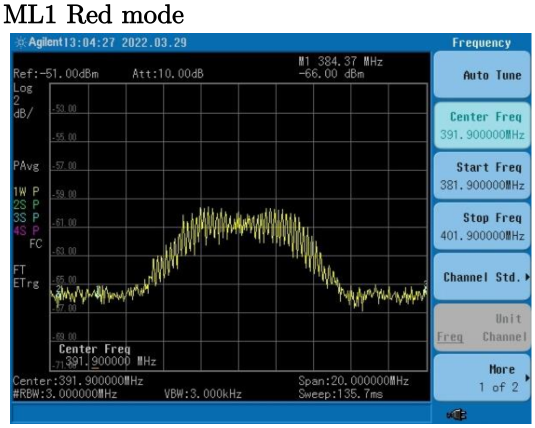
WEO g Peak + ML1 Red mode



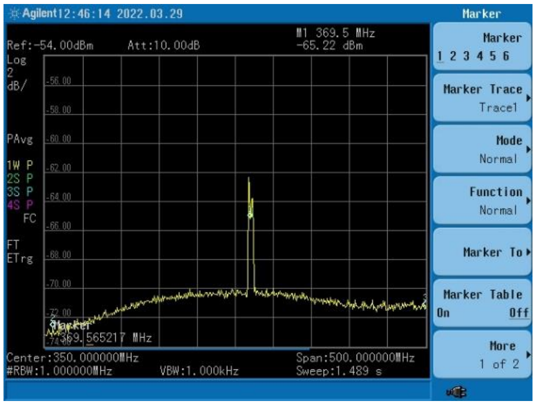


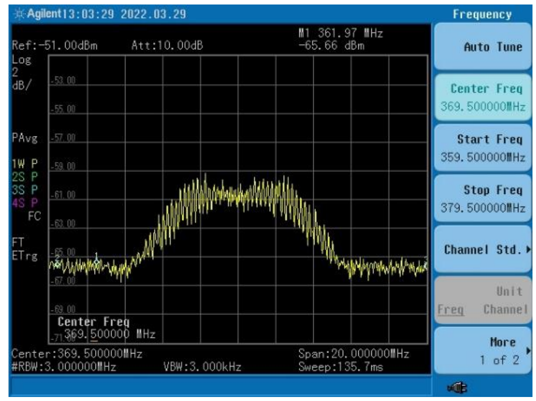
WEO h Peak + ML1 Red mode





WEO i Peak + ML1 Red mode





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