Wavemeter improvements for laser diode calibration

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ABSTRACT

This paper shows the progress made in the wavemeter developed to give traceability to the wavelength of lasers and ECDLs (External Cavity Laser Diode). The improvements are: duplication of the optical path of the laser beams due to a double pass through the interferometer arms [1], the electronic fringe counter [2], the measurement of the refractive index of air and the uncertainty calculations of the wavelength for the case of lasers with frequencies that differs more than 10 THz from laser reference. The new measurements improve the previous results [3].

Keywords: wavemeter, Michelson interferometer, ECDL, metrology, calibration

1. INTRODUCTION

Updates made to the wavemeter developed in [3] were focused in frequency range extension and improvements in the uncertainty and accuracy of the system.

The system previously designed was formed of a Michelson wavemeter which counts the number of fringes for two counterpropagating laser beams. One laser beam is of unknown wavelength, while the other is a reference laser with a measured wavelength. Equation 1 calculates the wavelength of the unknown laser (λ_U) through the ratio of the number of fringes of the two lasers (N_R/ N_U), the wavelength of the reference laser (λ_R), and the air refractive indices of the reference and unknown wavelengths (n_R) and (n_U) [1,4-6].

$$\lambda_U = \left(\frac{N_R}{N_U}\right)\lambda_R \frac{n_U}{n_R} \tag{1}$$

Further development of this system goes on the development of a better electronic fringe counter, which design was described in detail in [2]; duplication of the optic path and a new way to compute the wavelength of the unknown laser (λ_U) with frequencies that differs more than 10 THz from reference laser frequency.

2. DESIGN IMPROVEMENTS

2.1 Optic path

Path duplication of the wavemeter, figure 1, was made with the help of two new mirrors (5, 6, 7 and 8) per arm. These mirrors are located behind and in an upper plane than the ones that guide the laser to the corner cubes

Alignment was made as described in [1], firstly the mirrors 1 and 2 were positioned and adjusted until the beam coming back from the corner cube went to a fixed point position while the carriage was moved. This point must be in an upper plane than the incoming laser beam, figure 2, and as far as possible of the corner cubes. In this new plane a pinhole was used to define the fixed point position.

After this the two turning mirrors (5 and 6 or 7 and 8) are positioned so that the returning beam from the cube corner after being reflected by the initial mirror (1 or 3) hits the same fixed point in the beam splitter while the carriage is driven. The horizontal distance of the input and output beams of the corner cubes must kept fixed and equal in the two arms and the beam splitter of the wavemeter to ensure a good beam coincidence and contrast in the interference pattern.

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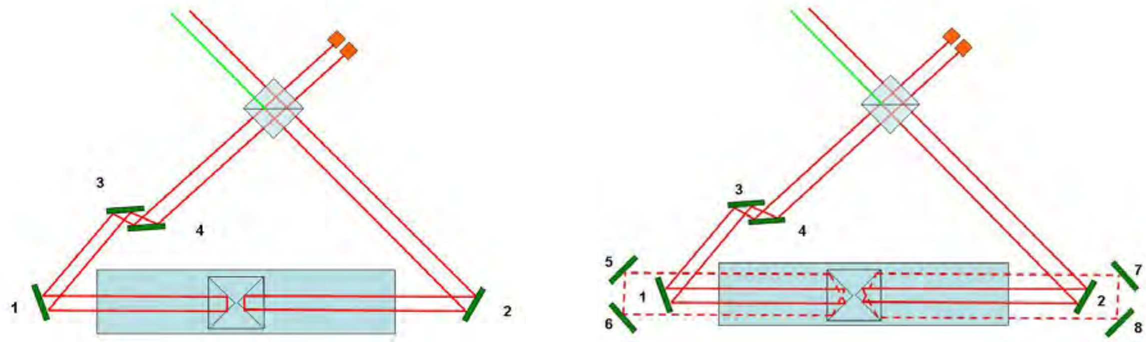
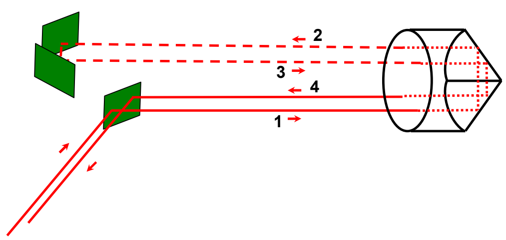


Figure 1. Schematic of the wavemeter first setup (left) and the improved (doubled, right); mirrors 5, 6, 7 and 8 allow the second travel of the laser beams through the corner cubes.



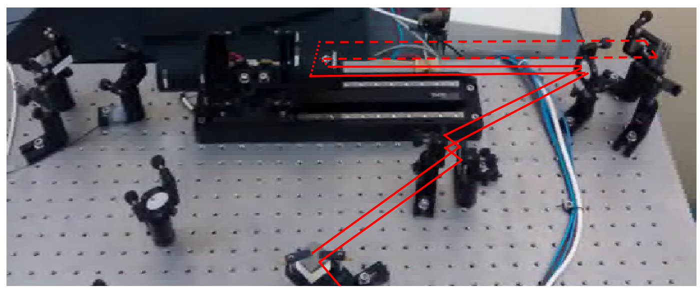


Figure 2. Detail of the beams paths in one wavemeter arm, one beam schematic (left) and one beam plot in the wavemeter assembly (right).

Three different laser sources were tested in this new design, to get this three turning mirrors were used to align each laser source with the wavemeter as need for the measurements, figure 3.

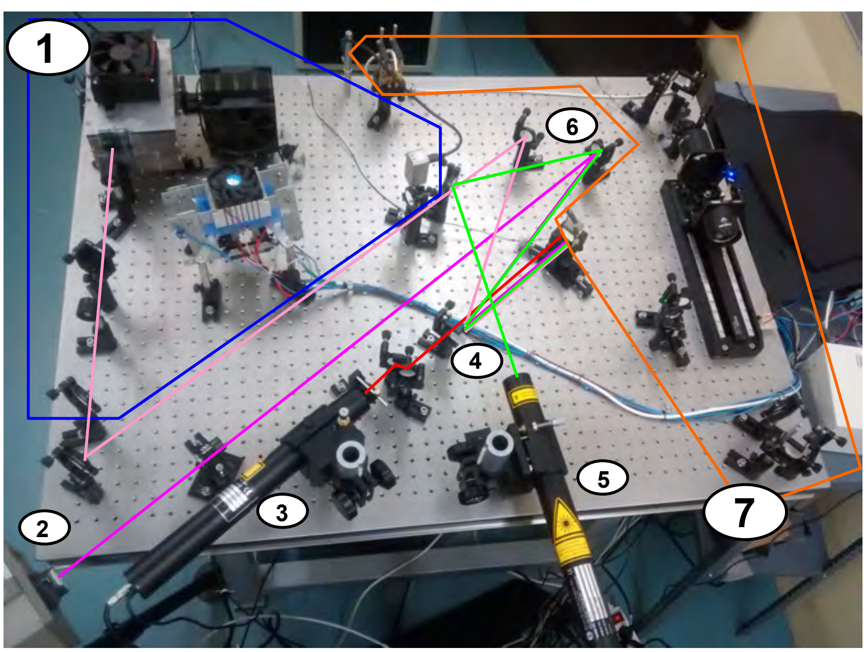


Figure 3. Experimental assembly of the ECDL and Michelson wavemeter. 1 ECDL stabilization system, 2 He-Ne HP red laser, 3 Reo green laser 543 nm, 4 and 6 turning mirrors to align ECDL, HP and Reo green lasers, 5 Reo red reference laser, 7 wavemeter assembly.

2.2 Wavelength calculation

Unknown wavelength depends of the refractive index of refraction of air, equation 1. When the two wavelengths, λ_R and λ_U, are close, less than 1 nm, the difference between the refractive index, calculated with the Edlén equation [7-9], is less than 10^{-8}, at the same the order of precision of the Edlén equation, ten times smaller than the precision of our wavemeter, so it is negligible. However when this don't happen, for example when a 543 nm and 633 nm laser sources were used the difference between the refractive index goes to 10^{-6}, which is a significant one.

So the refractive index of air for the unknown laser was needed to be known to achieve a good wavemeter precision. The problem arises when the unknown laser wavelength it's needed to calculate the refractive index of air for the unknown laser in the Edlén equation (2).

$$
\begin{aligned}
n_s &= 1 + 10^{-8}\left\{8342{,}54 + \frac{2406147}{\left[130 - \left(\frac{1}{\lambda^2}\right)\right]} + \frac{15998}{\left[38{,}9 - \left(\frac{1}{\lambda^2}\right)\right]}\right\} \\
n_x &= \frac{\left[1 + \left(10^{-8} 0{,}601 - 0{,}00972t\right)p\right]}{\left(1 + 0{,}003661t\right)} \\
n_{tp} &= 1 + p\left(n_s - 1\right)\left(\frac{n_x}{96095{,}43}\right) \\
n &= n_{tp} - 10^{-10}\left(\frac{292{,}75}{\left(t + 273{,}15\right)}\right)\left(3{,}7345 - \frac{0{,}0401}{\lambda^2}\right)p_v
\end{aligned}
\qquad (2)
$$

Where, t is the air temperature in Celsius, p is the pressure in Pascal, λ is the wavelength of the laser, and p_v is the water vapour partial pressure.

So a solution to this problem was the application of intermediate value theorem (Bolzano's theorem) to a rearranged wavemeter equation (3).

$$
f(\lambda_U) = \lambda_U - \left(\frac{N_R \lambda_R}{N_U n_R}\right) n_U = 0 \qquad (3)
$$

Edlén equation is continuous over the wavelength, figure 4, the term $N_R\ \lambda_R\ /\ N_U\ n_U$ is constant, and equation 3 changes sign before and after the unknown wavelength so the convergence is assured. So with the help of a fixed-point iteration method the refractive index of air for the unknown laser can be calculated for each measurement along with the unknown wavelength.

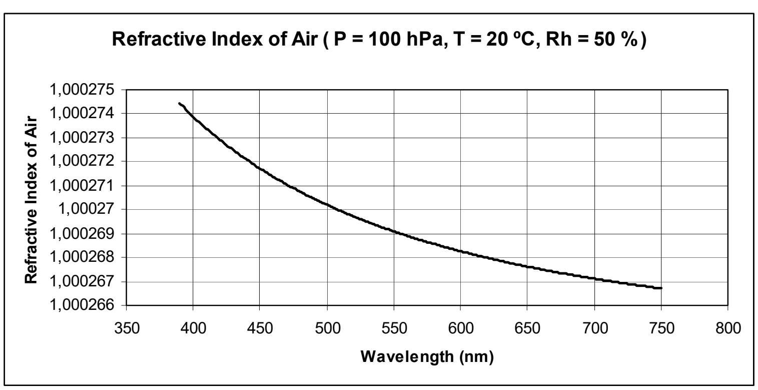


Figure 4. Refractive index of air over the light visible range.

3. MEASUREMENTS

After the improvements made in the design, new measurements were made with three unknown laser sources, an ECDL, a HP red laser and a Reo green laser. [3]

Measurements for each laser source are in the next tables:

Table 1. Uncertainty components of Reo red reference laser and wavemeter.

Quantity	**Symbol**	**Value**
Reference laser wavelength	λ_R	632,991 032 5 nm
Reference laser wavelength uncertainty	$U(\lambda_R)$	0.000 003 1 nm
Reference laser deviation per year	$D(\lambda_R)$	0.000 007 nm
Reference laser beam divergence	$\Delta\delta_R$	0.2 mrad
Reference and unknown wavelength fringe error	ΔN_R *and* ΔN_U	0,1 fringe
Reference and unknown position misalignment	Δx_R *and* Δx_U	0.1 mm
Alignment distance	L	4000 mm
Direct drive stage misalignment	$\Delta\theta_{DS}$	0,25 mrad
Corner cubes misalignment	$\Delta\theta_{CC}$	0,015 mrad
Standard deviation of the measured wavelength	$\sigma(\lambda_U)$,	0,000031 nm
Air diffraction index uncertainty	Δn	0,01 ppm
Corner cube base lineal expansion coefficient	α	22 µm/Km
Temperature gradient	ΔT	0,5 K
Corner cube distance	d	62 mm
Vibration amplitude	ΔA	50 nm

Table 2. Additional uncertainty components values for Reo green laser.

Quantity	**Symbol**	**Value**
Unknown laser beam divergence	$\Delta\delta_U$	2.0 mrad
Reference wavelength fringe count	N_R	364 304,1 fringes
Unknown wavelength fringe count	N_U	424 272,9 fringes
Standard deviation of the measured wavelength	$\sigma(\lambda_U)$,	0,000 743 nm

Table 3. Additional uncertainty components values for ECDL red laser.

Quantity	**Symbol**	**Value**
Unknown laser beam divergence	$\Delta\delta_U$	1.0 mrad
Reference wavelength fringe count	N_R	2 606 402,8 fringes
Unknown wavelength fringe count	N_U	2 606 401,7 fringes
Standard deviation of the measured wavelength	$\sigma(\lambda_U)$,	0,000 000 3 nm

Table 4. Additional uncertainty components values for HP red laser.

Quantity	**Symbol**	**Value**
Unknown laser beam divergence	$\Delta\delta_U$	0.2 mrad
Reference wavelength fringe count	N_R	2 389 021,9 fringes
Unknown wavelength fringe count	N_U	2 389 020,8 fringes
Standard deviation of the measured wavelength	$\sigma(\lambda_U)$,	0,000 000 1 nm

4. ANALYSIS AND RESULTS

4.1 Uncertainty evaluation

Uncertainty can be calculated for the measurements made with: the data of section 3; the uncertainty analysis developed [10], equation 4; and the addition of a uncertainty term for the Reo green laser that takes into account the lack of precision of the iterations values, equation 5.

Moreover, calibrated values for the wavelength of Reo green and HP are available trough external calibrations, so the precision of the system can be assessed, table 6.

$$U(\lambda_{U}) = \sqrt{U^2(N_R)+U^2(N_U)+U^2(\lambda_R)+U^2(\lambda_{WCR})+U^2(\lambda_{WCU})+U^2(\lambda_{ALIGR})+ U^2(\lambda_{ALIGU})+U^2(\lambda_S)+U^2(\lambda_{EDLEN})+U^2(\lambda_{ITER})+U^2(\lambda_{TEMP})+U^2(\lambda_{VIB})} \quad (4)$$

Table 5. Uncertainty contributions for the unknown wavelength λ_U measurement.

$U(N_R)$	Uncertainty of the number of fringes counted in the reference laser
$U(N_U)$	Uncertainty of the number of fringes counted in the unknown laser
$U(\lambda_R)$	Calibration uncertainty of the reference laser
$U(\lambda_{WCU})$	Wavelength uncertainty from wavefront curvature of the unknown laser
$U(\lambda_{WCR})$	Wavelength uncertainty from wavefront curvature of the reference laser
$U(\lambda_{ALIGU})$	Wavelength uncertainty from unknown laser beam misalignment
$U(\lambda_{ALIGR})$	Wavelength uncertainty from reference laser beam misalignment
$U(\lambda_S)$	Standard deviation of the measurements
λ_{EDLEN}	Wavelength uncertainty from air refractive index, (Edlén equation)
λ_{ITER}	Wavelength uncertainty from wavelength calculations (fixed-point iteration)
λ_{TEMP}	Wavelength uncertainty from thermal expansion
λ_{VIB}	Wavelength uncertainty from optical system vibration

$$U^2(\lambda_{ITER}) = (10^{-7}/\sqrt{12})^2 \quad (5)$$

Table 6. Calibration and measured wavelength of HP red and Reo green lasers.

Laser	Measurement (nm)	Uncertainty (nm)	Calibration value (nm)	Uncertainty (nm)
HP red	632.991 30	0.000 07	632.991 368 7	0.000 013
Reo green	543.528	0.019	543.514 1	0.003 0
ECDL	632.991 3	0.000 4		

4.2 Allan analysis

Moreover Allan analysis [11-12] of the measurements shows a good stability of the ECDL and HP laser sources and the wavemeter, as can be displayed in the next figures obtained with AlaVar®; where four standard deviations are computed: ADEV, Allan deviation; MDEV, square root of the modified Allan deviation; TDEV, time Allan deviation; and HDEV, Overlapping HADAMARD standard deviation.

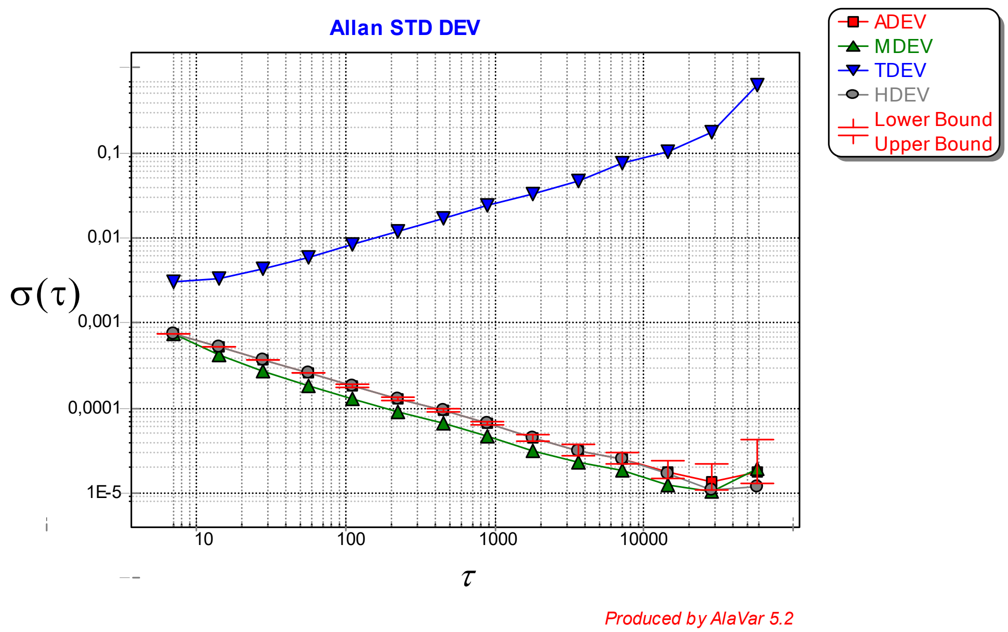


Figure 5. Allan variance for Reo green laser, measurement interval τ = 7 s. ADEV(τ =1) = Stability =0.0018587 nm

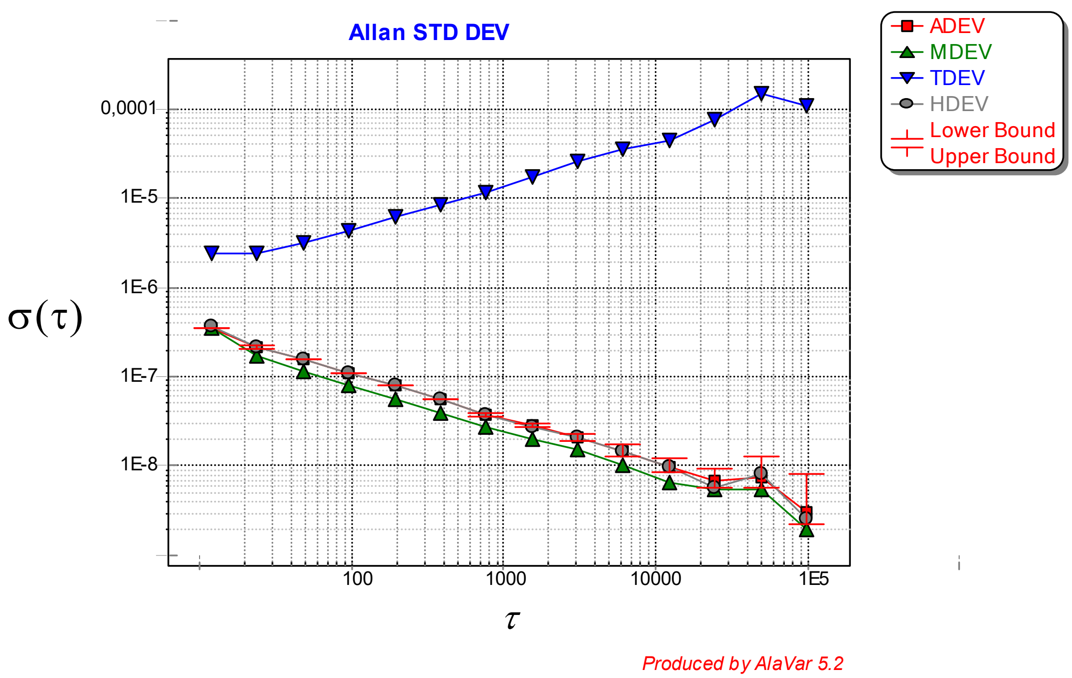


Figure 6. Allan variance for ECDL laser, measurement interval τ = 12 s. ADEV(τ =1) = Stability =0.0000010 nm

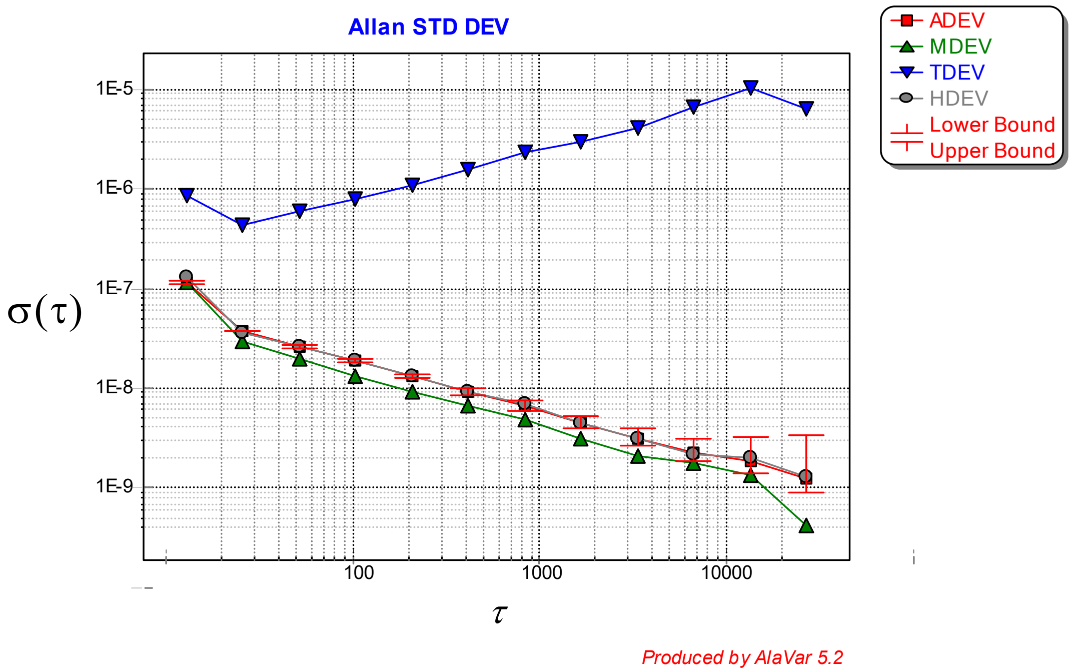


Figure 7. Allan variance for ECDL laser, measurement interval τ = 13 s. ADEV(τ =1) = Stability =0.0000003 nm

5. DISCUSSION

The results show the improvements made in the precision of the Michelson wavemeter and the wavelength range extension in the measurement achieved due to the new calculation method.

Reo green laser poor stability, figure 8, is the result of its small (≈70 mm) coherence length, and high beam divergence which raise the uncertainty of the measurement and worsen the precision of the wavemeter so a new green light source is needed to get more accurate results. Moreover the fixed-point iteration method is suitable to expand the calibration range of Michelson wavemeters.

Furthermore, with a good laser source, as the HP red laser, the wavemeter achieves a good precision and uncertainty, 0.11 ppm, so a suitable measurement system for ECDL lasers was developed.

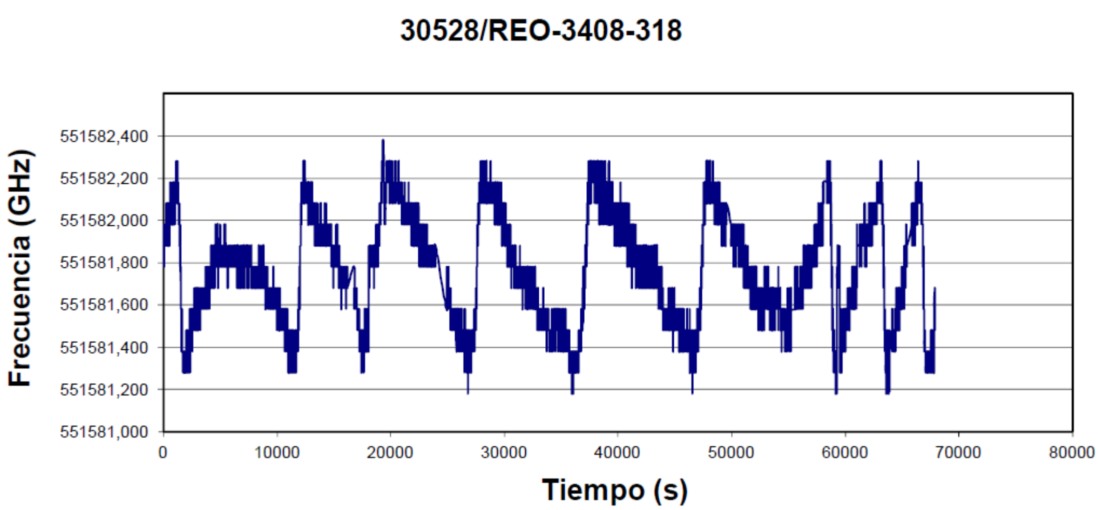


Figure 8. Reo green laser frequency plot over time, extracted from the calibration certificate.

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