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Determination of distortion corrections for a fixed length optical cavity pressure standard

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ABSTRACT

Optical gas refractometry has enabled new pressure standards to be developed based on a dual Fixed Length Optical Cavity (FLOC) system. NIST in CRADA (collaboration research and development agreement) partnership with MKS Instruments has created a portable FLOC pressure standard based on gas refractivity. A key challenge for accurate measurements is the characterization of cavity distortions when pressurized. A method for determination of the distortion constants is presented based on using two gases of known refractive index. Using this two-gas technique, the distortions on the portable FLOC pressure standard are corrected so that this correction contributes no more than 1 μPa/Pa of uncertainty (k = 1).

1. Introduction

The field of pressure metrology has seen a revolution in new pressure standards based on optical gas refractometry. NIST has pioneered a technique known as the Fixed Length Optical Cavity (FLOC) that utilizes two Fabry-Perot interferometers where one cavity remains at vacuum and the other is pressurized. The interferometers are used to measure changes in refractive index which is proportional to pressure. This technique has proven to perform as well or better than existing pressure standards and paves the way for the elimination of mercury-based standards [1–3].

Compared to other existing technologies, the FLOC can be made compact and portable without sacrificing performance and enables end-users to have direct traceability, reduced uncertainty, and increased operating range without the downtime needed for recalibration. To help foster growth and knowledge of these optical based standards in industry, NIST partnered with MKS Instruments, Inc. under a cooperative research and development agreement (CRADA) to construct/test a portable version of the NIST FLOC.

The compact prototype uses telecom lasers and components which are small, readily available, and have commonly available frequency standards. The portable design has also implemented several improvements over the initial NIST design. The prototype was tested under numerous conditions, including commercial shipment, and was then ready for metrological characterization. This paper outlines the procedures for determining distortion corrections of a FLOC pressure standard and shows the initial results of the first prototype.

2. Overview of prototype

The first operational FLOC at NIST included 2 racks of electronics along with equipment taking up 1.5 m^2 of surface on an optical table. Leveraging compact optical design, our mostly fiber optic based system has enabled the overall system size to be reduced by a factor of five. The current operating wavelength of 1542 nm—which is in the focus of the telecom range—was chosen due to the availability of compatible frequency standards, coatings, and detectors. Additionally, due to a wide mode-hop-free tuning range of many narrow linewidth diode lasers, they can be easily coupled with small optical cavities with large Free Spectral Range. Thus the FLOC cavity can be reduced in size to 1/6 scale length. The FLOC prototype is constructed of Ultra Low Expansion (ULE)[1] Glass and mounted on a vacuum flange as shown in Fig. 1.

A major advantage of the reduced size is improved temperature uniformity. It is known that temperature effects play a large part of FLOC performance [4] and by reducing size and surface area, these temperature effects are smaller and easier to control/monitor. Additionally, the small size was designed around a standard size DN50 flange which easily allows for an all metal seal system to reduce leaks and contamination. The seals improve the performance of this prototype and are critical for operation in very low pressures/high vacuum.

The FLOC and all optical components were packaged into a tabletop prototype as shown in Fig. 2. For a FLOC to measure pressure, three quantities must be measured: distortion correction of the measurement cavity (d_m), distortion correction of the reference cavity (d_r), and the Free Spectral Range (FSR). These constant parameters are part of the measurement equation

$$P = \frac{1}{c_1 - d_{\mathrm{m}} - d_{\mathrm{r}}}\left(\frac{\Delta f}{\nu}\right) - \frac{(c_2 - c_1 c_4)}{(c_1 - d_{\mathrm{m}} - d_{\mathrm{r}})^3}\left(\frac{\Delta f}{\nu}\right)^2 + \frac{2(c_2 - c_1 d_{\mathrm{m}})^2 - c_3(c_1 - d_{\mathrm{m}} - d_{\mathrm{r}})}{(c_1 - d_m - d_r)^5}\left(\frac{\Delta f}{\nu}\right)^3, \tag{1}$$

$$\left(\frac{\Delta f}{\nu}\right) = FSR(1 + \varepsilon_\alpha)\frac{\frac{(f_{Bi} - f_{Bf})}{FSR} + \Delta m}{f_{Bf} + f_{Rf}}, \tag{2}$$

[1] Any mention of commercial products within this article is for information only; it does not imply recommendation or endorsement by NIST.

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Fig. 1. FLOC glass cavity developed under NIST/MKS CRADA. *Credit: MKS Instruments, INC.*

Fig. 2. Portable prototype FLOC developed under NIST/MKS CRADA displayed at the AVS65 vendor equipment show. *Credit: MKS Instruments, INC.*

as outlined in Ref. [1]. The following sections detail how these measurements are performed and the initial results.

3. Measurement of free spectral range

As the FLOC is pressurized, the resonant frequency of the sample cavity changes based on the refractive index. At a wavelength of 1542 nm, the frequency of light changes by approximately 50 GHz or roughly 9 modes when pressurized from vacuum to atmospheric pressure. Measurements are made by re-locking the laser system to the nearest high intensity Transverse Electric and Magnetic mode, specifically TEM00. The mode number (integer number of resonant peak changes from vacuum) can be counted or determined from other means such as reference frequency change. However the Free Spectral Range (FSR) must be precisely known to determine the overall frequency change of the measurement.

In our setup two lasers are locked to a single cavity. Using the two tunable lasers and a fiber splitter/combiner, as shown in Fig. 3, the FSR is measured as the beat frequency between two lasers locked to the same cavity. This measurement technique only relies on cavity stability and doesn't depend on stability of a frequency standard. For the prototype FLOC the FSR was measured to be 5537.58426(20) MHz where the number in parentheses is the numerical value of the combined standard uncertainty. The uncertainty was determined by the standard deviation of the measurement taken over several hours.

4. Measurement of cavity distortions

When pressurized, the FLOC is subjected to significant forces causing a bulk compression of the cavity along with an inward bending of the reference cavity mirrors. These distortions are large compared to the FLOC uncertainty and therefore must be accurately corrected prior to pressure measurements. The distortions are proportional to pressure and are directly included in the measurement equation [1].

Since bulk compression affects the entire ULE block, the length change is common to both the reference cavity and measurement cavity which limits the error caused by this effect. However, the reference cavity is always at vacuum which causes a non-uniform distortion of the spacer. Thick cavity mirrors and small diameter cavities are used to minimize mirror distortion effects, limit hysteresis, and provide constant results over long timescales.

The distortions can be modelled by Finite Element Analysis (FEA); unfortunately this has large uncertainties due to non-uniformity of the material properties, so it is preferable that the distortions be measured.

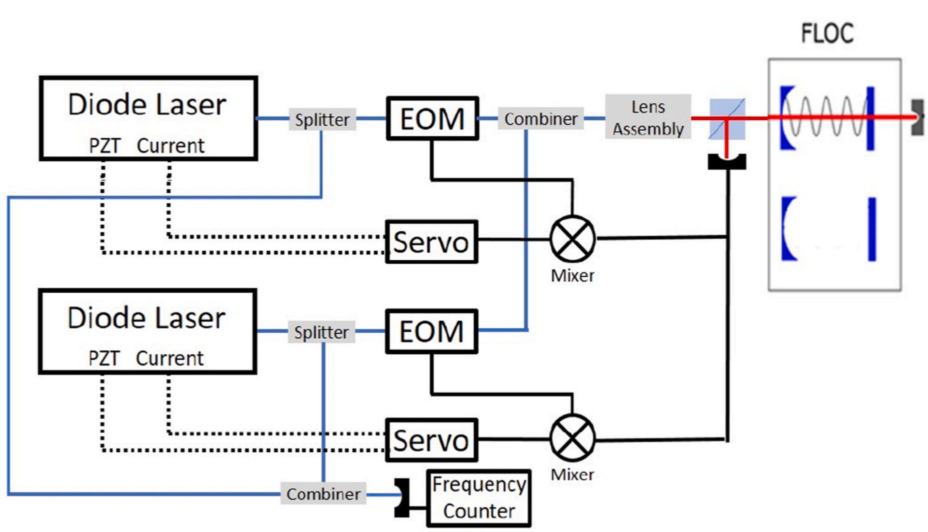

Fig. 3. FLOC FSR Measurement using two lasers in single cavity.

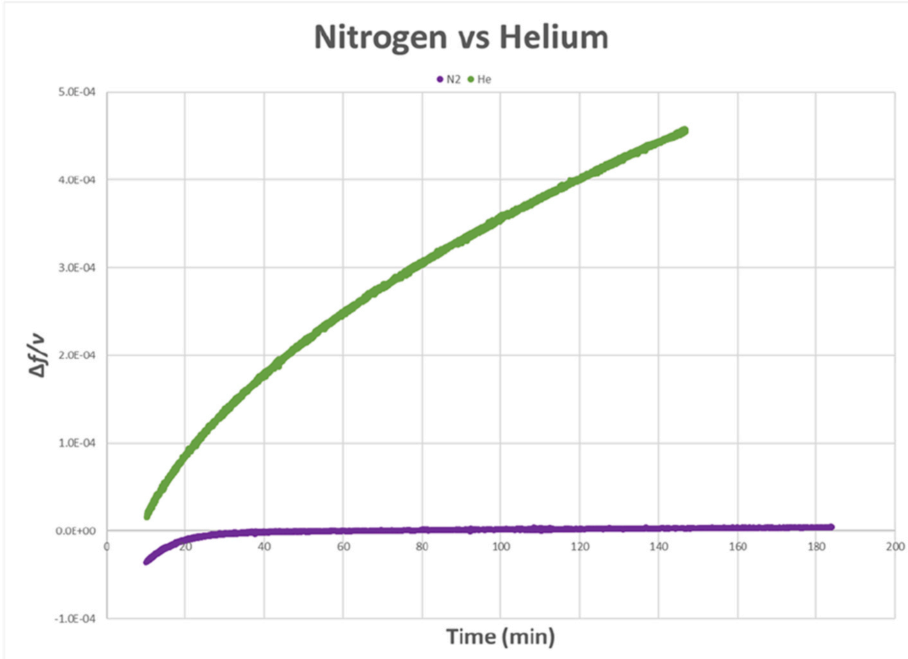

Fig. 4. Relative frequency change over time with FLOC filled with helium vs nitrogen.

The distortion correction terms can be measured by several different techniques [5]. The technique described in this paper for measuring d_m is referred to as the "two-gas method". NIST has also developed the "two-color method" which utilizes two different optical frequencies to measure distortions based on optical dispersion [6].

4.1. Reference cavity distortions

The reference cavity is kept at a vacuum below 0.1 mPa and therefore has a refractive index of 1. When the FLOC is pressurized, the frequency change of the reference cavity can be measured directly. For our test we used a fiber splitter to beat the laser frequency against an acetylene stabilized laser. The beat note is measured by a detector and frequency counter.

The distortion term d_r can then be calculated by measuring at two distinct pressures and using the formula:

$$d_r = \frac{\frac{\Delta f}{P}}{f_{RF}} \tag{3}$$

where Δf is the change in frequency, P is the pressure and f_{RF} is the optical frequency. The uncertainty of this measurement depends on the accuracy of the reference laser being used. Our measurements had a standard deviation of 1 MHz due to the instability of the acetylene lock. The final value of d_r was measured to be 1.441(5) x 10^{-11}/Pa.

4.2. Measurement cavity distortions

The two-gas method relies on having two gases of known optical refractivity. For helium, the virial refractivity coefficients and density virial coefficients have been computed using advanced quantum chemistry calculations to better than a 1 part in 10^6 [5]. Due to the complexity of the calculation and rapid scaling with size of the atom or molecule, no other gases have been calculated to this level of accuracy. The index of refraction for certain gases, such as nitrogen, cannot be calculated and therefore must be measured. For such gases, the index of refraction can be determined as a measurement ratio to known refractive index (i.e. n_{N_2}/n_{He}) or with an independent pressure standard such as the NIST Ultrasonic Interferometer Manometer (UIM) or other equivalent standard [7].

For the cavity distortion measurements of the FLOC prototype we used helium and nitrogen. It should be noted that although helium has the lowest index of refraction uncertainty, it is not an optimal gas to use because helium is known to diffuse into glasses such as ULE [8]. This effect causes the ULE cavity to slowly expand over time, causing errors in the measurement. For the second gas, nitrogen was chosen due to the ease of availability and existing refractivity work. For this work, the refractivity of nitrogen at a wavelength of 1542 nm was measured using the FLOC to measure refractive index and the UIM was used to measure pressure [Reference in preparation].

To determine distortion constants, the FLOC was connected to a gas admission system and a constant pressure generator. A piston gauge was used as the pressure generator because it can provide a constant pressure and has very little gas dependency, usually less than 1 part in 10^6 [9]. A linear pressure gauge can be used in place of a pressure generator however this may increase uncertainty. The pressure generator ensures that the pressure applied when using nitrogen is equal to that of helium, $P_{N_2} = P_{He}$, and so the absolute pressure is not needed; only repeatability and gas dependency factor into the uncertainty. Because the distortion corrections should be the same for all gases, setting the measurement equation (1) for nitrogen equal to that for helium allows us to calculate d_m.

The measurements for the prototype FLOC were taken at 100 kPa and a constant temperature of 29.821(1) °C. To correct for the helium drift, the measurements were collected over time and extrapolated back to $t = 0$, where t is the elapsed time. This however was complicated by the rapid temperature change that occurs immediately following a pressurization [6]. The temperature effects stabilized after approximately 30 minutes and are similar for nitrogen and helium, however with helium the cavity continued to drift as seen in Fig. 4. The fill was initialized at $t = 0$ and took less than 60 s. The piston gauge was then allowed to thermally stabilize and rotated before measurements were collected starting around $t = 10$ minutes.

Since the temperature effects should cause a similar relative frequency change for both gases, the value for nitrogen is subtracted from helium. The resulting exponential curve provided a measurement of cavity drift vs time. A polynomial fit was used for simplicity and all

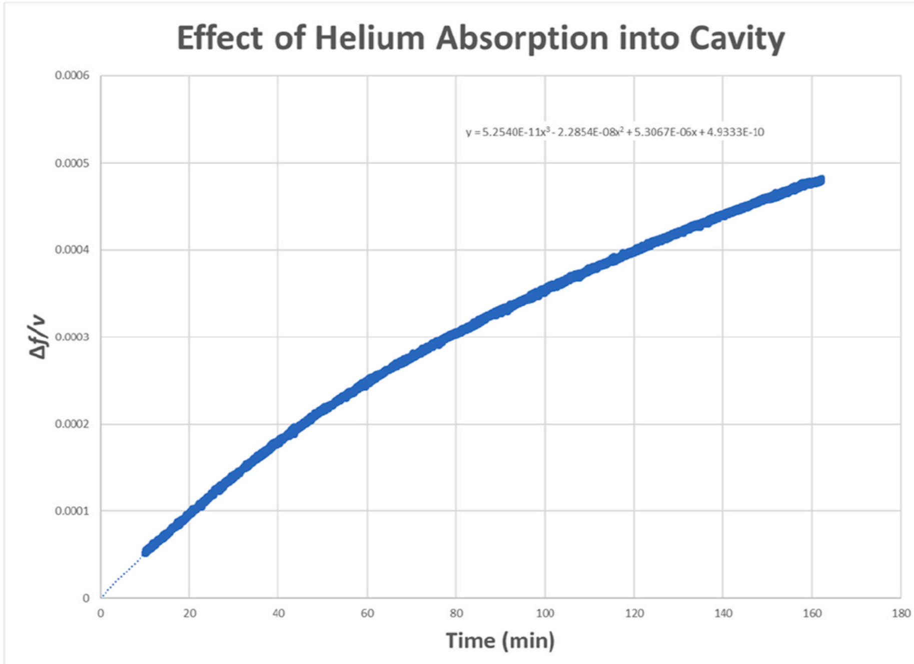

Fig. 5. Corrected relative frequency change of cavity containing helium over time. Dashed line shows polynomial equation fit.

Table 1
FLOC distortion correction uncertainty ($k = 1$).

Uncertainty Source	Contribution (parts in 10^6)
He absorption correction	0.6
Thermal drift correction	0.3
Piston Gauge Gas dependency	0.5
Piston Gauge Temperature	0.4
Piston Gauge Bell Jar Pressure	0.1
Gas Purity/Outgassing	0.3
Total ($k = 1$):	1.0

helium data was corrected using this equation to extrapolate to t = 0 (Fig. 5). The corrected frequency was then entered into the measurement equation (1) and iteratively solved for d_m until $P_{N_2} = P_{He}$. The final value of d_m was measured to be $-1.9081(5) \times 10^{-11}$/Pa.

5. Uncertainty of the distortion corrections

Using the measurement technique outlined above, the FLOC distortion terms d_r and d_m are correlated, and an error in the reference frequency distortion term would be corrected by an equivalent change in the measurement frequency distortion term. Therefore, it is difficult to determine the individual uncertainties of d_r and d_m, and is significantly easier to just determine a combined uncertainty term to cover both distortion correction terms. Additionally, many of the Type B uncertainty terms including those for refractive index and temperature are correlated and will be excluded from this calculation but must be accounted for in the overall uncertainty budget. The uncertainty for determining distortion correction via two gas is shown in Table 1.

6. Results VS calibrated standard

To prevent a circular comparison, the FLOC was then compared against an independent piston gauge with a manufacturer calibration that does not achieve traceability directly through NIST. The comparison was done at pressures of 50 kPa, 100 kPa, and 150 kPa. The thermal effects were allowed to stabilize prior to measuring frequency. Using the distortion corrections, FSR, and temperature, the pressure was calculated, and the results are shown in Table 2.

Table 2
Pressure measurement results.

Piston Gauge Pressure (Pa)	FLOC Pressure (Pa)	Difference (Pa, [parts in 10^6])
49844.19	49844.44	0.25 [5.0]
100810.51	100810.55	0.04 [0.4]
151819.95	151820.33	0.38 [2.5]

The final uncertainty of the prototype FLOC system is currently being determined as the system is improved and components finalized. The uncertainty of the two-gas distortion method (estimated in the previous section) is not expected to be a dominant uncertainty term and the above FLOC and piston gauge pressure values agree to within the expected final uncertainty.

7. Conclusions

A method for the determination of distortion coefficients using two gases of known index of refraction has been presented. The two-gas method was used in the portable FLOC prototype system. The FLOC distortion correction contributes an uncertainty of 1 μPa/Pa ($k = 1$) to the overall pressure uncertainty. The two-gas method will enable the FLOC portable prototype and similar devices to measure and correct for distortions to the optical cavities with high accuracy, thereby ensuring their practicality as deployable pressure standards.

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