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Towards Photonic based Pascal Realization as a Primary Pressure Standard

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Abstract

New techniques using refractometry have enabled gas pressure to be measured using laser interferometry. Two key techniques have been studied at NIST which include the Fixed Length Optical Cavity (FLOC) and the Variable Length Optical Cavity (VLOC). The measurement techniques are described and the traceability of these measurements through quantum mechanics that enables them to be primary standards. This technology is critical for gas pressure metrology to move away from artifact based standards (and especially mercury based) and move to quantum based methods for realization of the pascal.

1. Introduction

The first gas pressure measurements were made in the 1640s by Evangelista Torricelli using a mercury manometer. Since then many new devices and techniques have tried, but none have been able to surpass the accuracy of the mercury manometer. An Ultrasonic Interferometer Manometer (UIM) constructed at NIST claims the lowest uncertainties in the world [1,2], however a new technique utilizing the refractive properties of gas will replace the 400 year reliance on liquid mercury for the highest accuracy pressure measurements.

The new technique relies on knowing the refractivity of the gas being used. The refractivity is the susceptibility of an electromagnetic wave to slow the down as it passes through. This change is proportional to the density of the gas molecules and therefore it is directly related to pressure via the thermal energy, k_BT, of the molecules. By using high precision lasers and a Fabry-Perot (FP) interferometer, we can easily detect changes in speed of light to a fraction of a percent and therefore determine the pressure to an accuracy approaching that of the UIM [3].

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2. The Fixed Length Optical Cavity

An optical cavity consists of a set of mirrors on a spacer with the gas filling the space between the mirrors. To improve upon this design, you can add a reference cavity that is kept at vacuum to help eliminate noise and other systematic errors. This design, referred to as a Fixed Length Optical Cavity (FLOC), was constructed and is shown in Figure 1 & 2. The FLOC was constructed out of a glass with very low thermal expansion to prevent changes in interferometer length with temperature. The upper cavity consists of a slot to allow gas to easily flow in and out where as the reference cavity is a hole drilled through the glass block and sealed at either end via mirrors.

Additionally, a vertical tube allows us to pump out the reference cavity through a vacuum pump. The glass cavity is placed inside a chamber to improve temperature stability and to ensure that the gas species is known, and therefore has a known refractivity. For gasses such as helium with simple electron structure and limited number of isotopes, the refractivity and density virial coefficients can be calculated through quantum mechanics [4]. This calculation can provide refractivity to an uncertainty better than 1 parts in 10^6. For other gasses, the values must be measured or will be calculated but with significantly larger uncertainties. Because the calculation of pressure is only dependant on refractivity and temperature, we can define the FLOC as a primary realization of pressure.

Even though the FLOC is primary, it does contain two critical drawbacks that must be accounted for when making a high accuracy measurement. The first of which is the distortion of the glass as you apply pressure. The glass experiences a bulk compression as you apply a force to the outside surfaces. In addition to the bulk compression, the glass experiences a non-uniform bending because the reference cavity is at a different pressure and the glass experiences non-uniform forces. The distortions are different for each glass cavity; however, the correction can be determined experimentally and corrected with some uncertainty. The second drawback is that helium can absorb into glass causing the glass to swell. With good interferometer data the absorption can be traced over time and extrapolated back to zero, however this does have some associated uncertainty.

Overall a FLOC standard can achieve an uncertainty of 9 parts in 10^6 in nitrogen [5], however a better determination of index would allow this to be drastically reduced. Additionally, the best method to measure pressure distortions would be to use several gasses of known refractive index at the same pressure. The distortions will be independent of gas species and can be solved to determine the magnitude of the error. This may introduce uncertainty if the refractivity is not determined precisely, so better refractivity measurements lead to better pressure standards.

3. The Variable Length Optical Cavity

For a making a high precision measurement of refraction, it is clear the FLOC’s distortions would limit its usefulness. Another concept refered to as the Variable Length Optical Cavity (VLOC), operates on similar principles to the FLOC; however, there are key differences that allow for it to measure refractivity. First, the VLOC has four cavities (three positioned at equal radius from a central cavity) as shown in Figure 3. The central cavity, or measurement cavity, will be exposed to a gas at a constant pressure, whereas the outer cavities will be at vacuum. The four cavity mirrors on each end plate will be mounted on a monolithic piece to allow for equal displacement of all cavities simultaneously as the glass expands/contracts.

The VLOC allows for the refractivity to be measured at one length, then the cavity length will be changed, and the refractivity will be measured at the second length. Any systematic errors, such as bending, distortions, or helium absorption will be the same at both lengths. Therefore, if we subtract the two readings we can obtain the refractive index as described by:

$$n = \frac{\mathrm{OPL}_2 - \mathrm{OPL}_1}{L_2 - L_1}$$

Where $(L_2 - L_1)$ is the displacement distance and (OPL_1 , OPL_2) is the optical path length defined at the two positions.

The VLOC can be used to measure the refractive index of helium and then transfer the value to nitrogen through a pressure balance. The balance will be used to generate a stable pressure first in helium and then nitrogen. Therefore, the quantum traceability of helium can be used to publish a refractivity for nitrogen, establishing a quantum traceability via the refractivity (Figure 5). Because the refractivity is an unchanging property of the gas, this experiment only needs to be completed once and then any refractometer can be used to measure pressure and achieve traceability through the quantum properties of the gas. The VLOC under construction at NIST should be able to measure helium refractivity to an uncertainty of 1 part in 10^6 [6], and therefore will reduce the uncertainties for FLOC pressure measurements using nitrogen by a factor of five or more. Refractivity measurements will also be available on other gases enabling use of argon or other gasses for use in a FLOC.

Construction of a VLOC for measurement to 1 part in 10^6 requires several difficult requirements to be met. First of which is that the gas must be extremely pure, and for gasses like helium with very different refractivity, the purity must be better than 50 parts in 10^9. The second critical requirement is that the cavity must be designed to change lengths. The longer the movement the more resolution, so cavities that extend 15 cm are optimal. The final major constraint is that the mirrors must not be affected by the movement. Since you want the mirrors to be identical at both locations it is not possible to use different mirrors or swap out components. It is nearly impossible to add something to modify pathlength without imparting errors above the dimensional tolerance of 3 pm that is easily detectable with this system. Additionally, the movement must not impart any forces that would modify dimensions by 3 pm.

The VLOC constructed at NIST is the first of its kind in the world and was constructed as described above to accomplish the uncertainty goal of 1 part in 10^6. The final prototype, pictured in Figure 6 & 7, should be fully operational by end of 2018. The design features a neutral axis mount to prevent strain on mirrors and can compress from 30 cm to 15 cm. The

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entire system is contained in a vacuum chamber and will be evacuated to 10^{-5} Pa. A hand crank provides movement to the linear stage that compresses a 15 mm diameter bellows which holds the measurement gas. The purity inside the bellows is insured by using a continuous flow of pure helium (via cryostat purification) and maintaining all metal seals and ultra-high purity tubing. A commercial pressure balance that is capable of providing stability of better than 0.5 ppm will be used to transfer between helium and other gasses. The refractivity will be measured using a laser at a wavelength of 633 nm.

4. Conclusion

The VLOC enables a primary realization of refractive index that will support traceability of the pascal through refractometry. Utilizing a FLOC, this realization has the potential to be more accurate than traditional standards. This will be the essential cornerstone to eliminating the use of mercury in pressure standards, a technique that has been around for nearly 400 years. As with other units such as the kilogram, gas pressure metrology is moving away from artifact based standards and physical calibrations and moving to quantum based methods. Refractometry will allow pressure to be realized anywhere in the world and will be traceable via quantum mechanics and the gas being used to calibrate.

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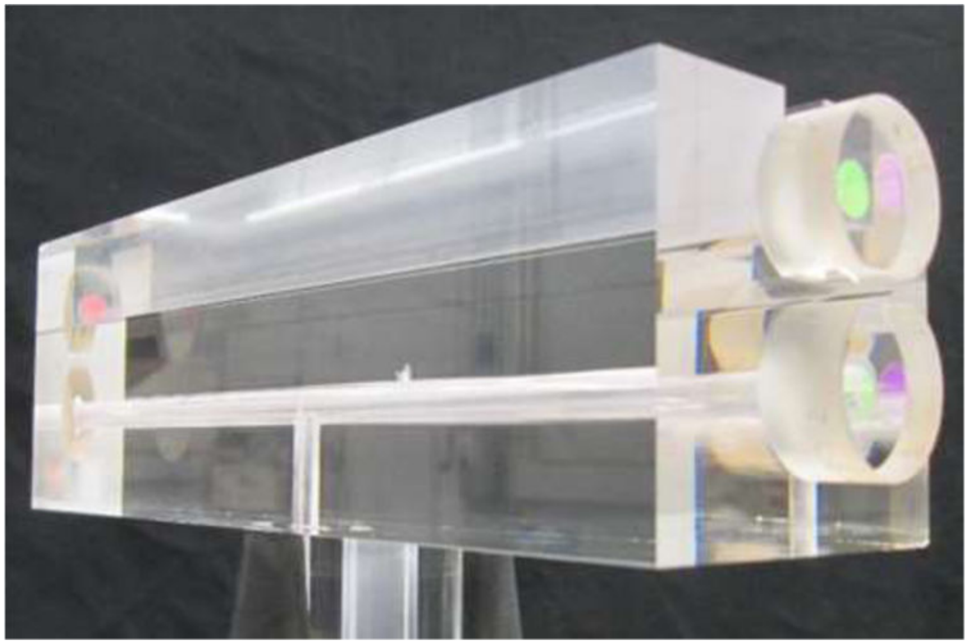

Figure 1:
FLOC prototype at NIST

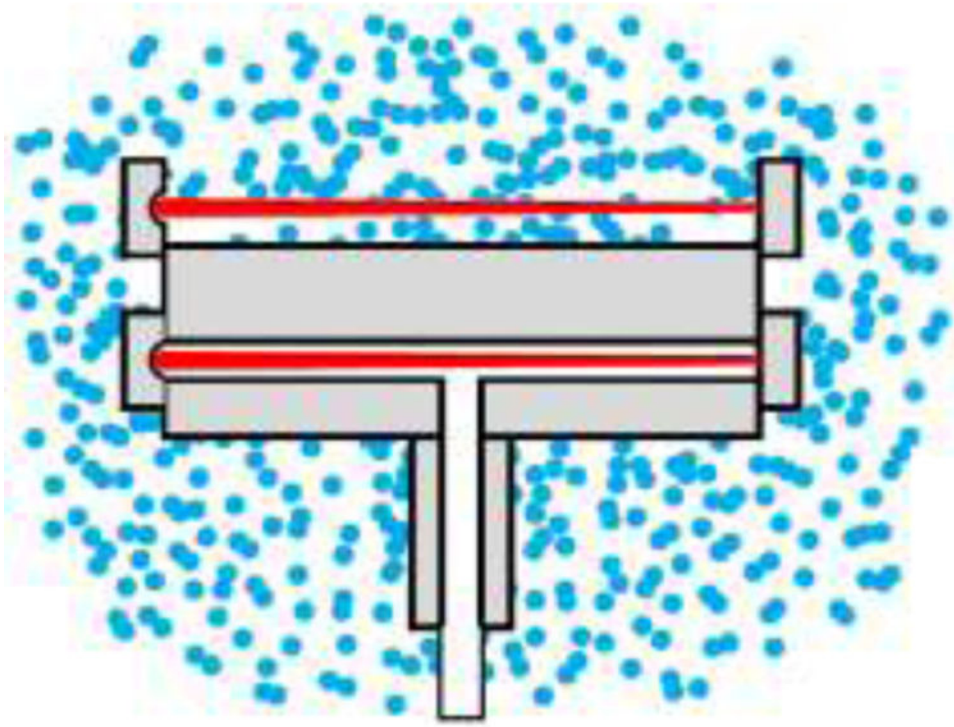

Figure 2:
FLOC sketch (dots represent gas molecules)

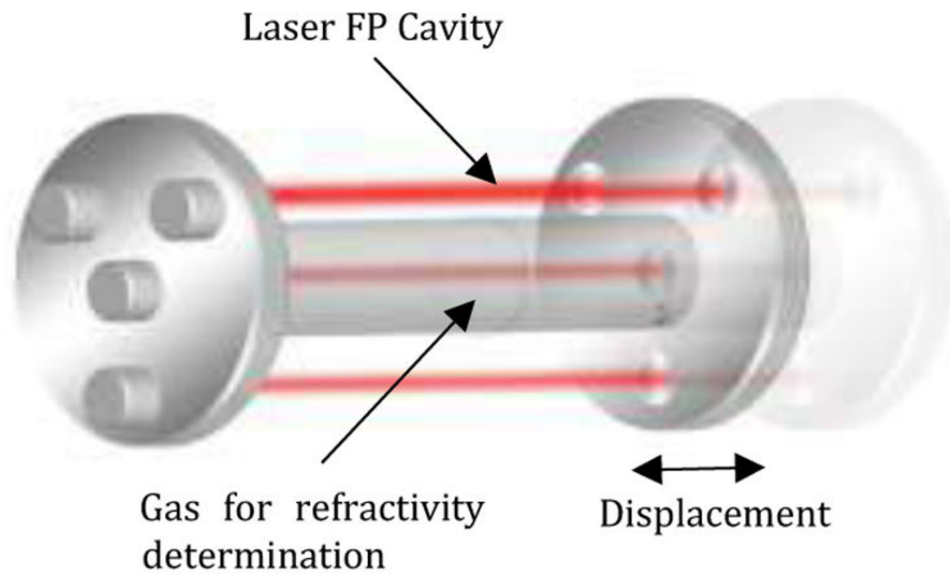

Figure 3:
VLOC 3-D Drawing

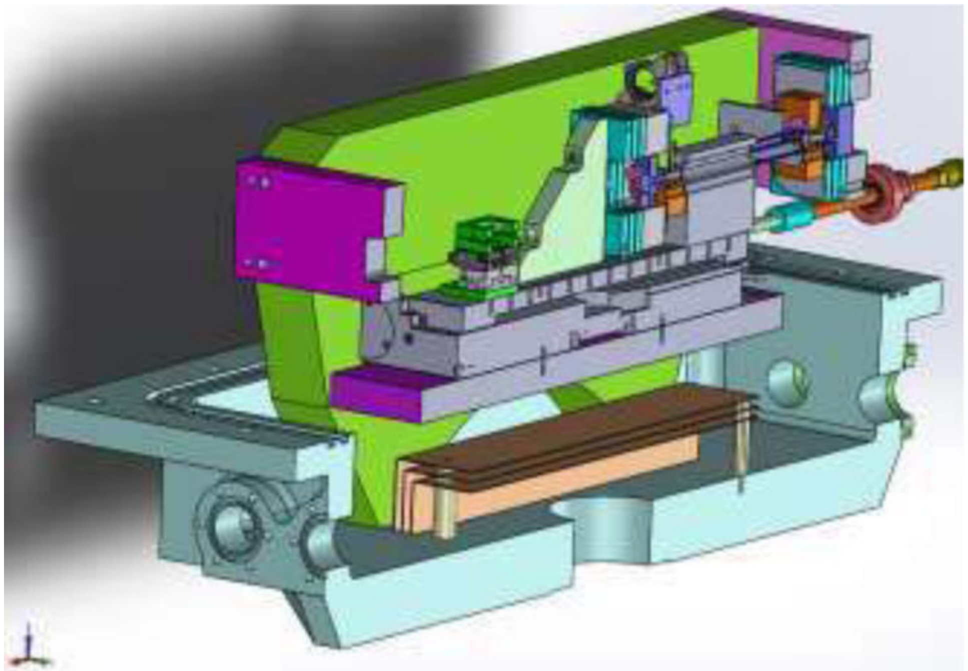

Figure 4:
VLOC 3-D Drawing

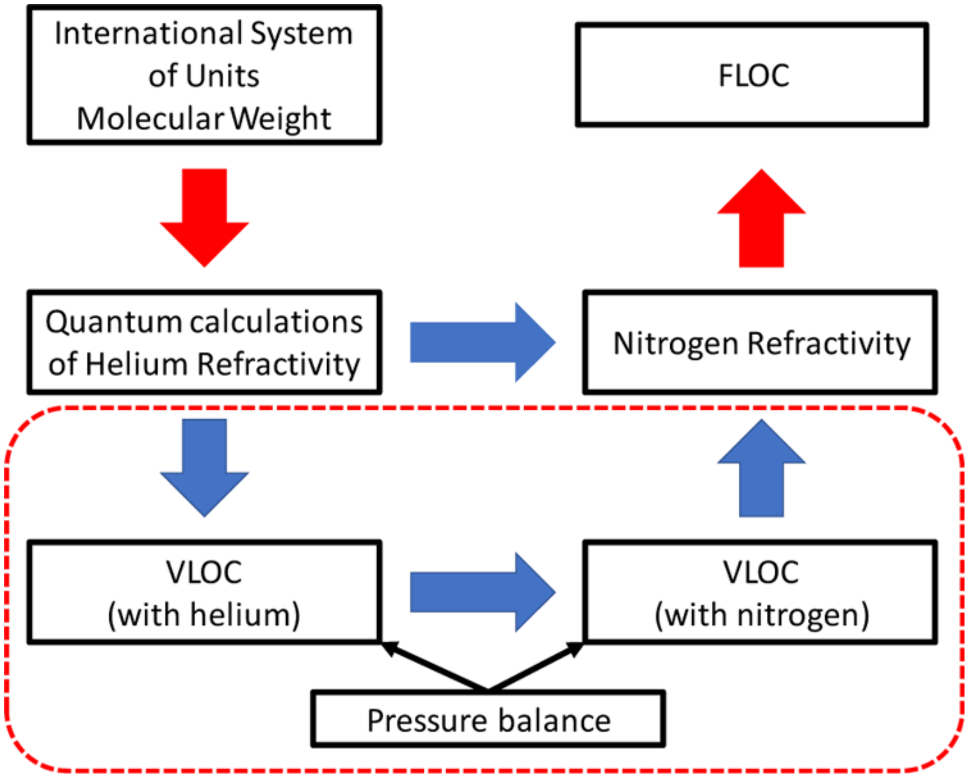

Figure 5:
The traceability of optical refractivity pressure measurements (dotted line indicates experiments that only need to be completed once per gas species).

Figure 6:
VLOC image at extended length

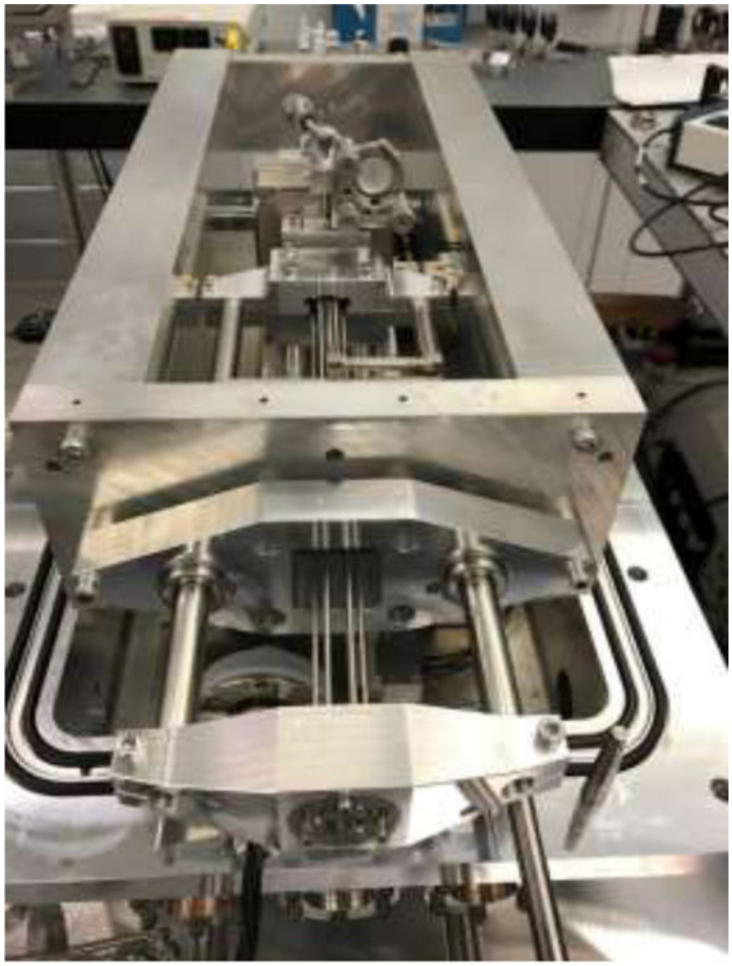

Figure 7:
VLOC image at compressed length