Optimizing Path Length Stability in Laser Interferometers using Air Refractive Index

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Outline

- Introduction
- Challenges in Precision Interferometry
- Calibration Techniques
  - Literature Survey
- Refractive Index of Air
- Calibration Method Implementation
- Results and Conclusion

Introduction

Choosing sensors for positioning or scanning is crucial, impacting overall instrument performance. Diverse technologies in the market make decision-making challenging for new setups.

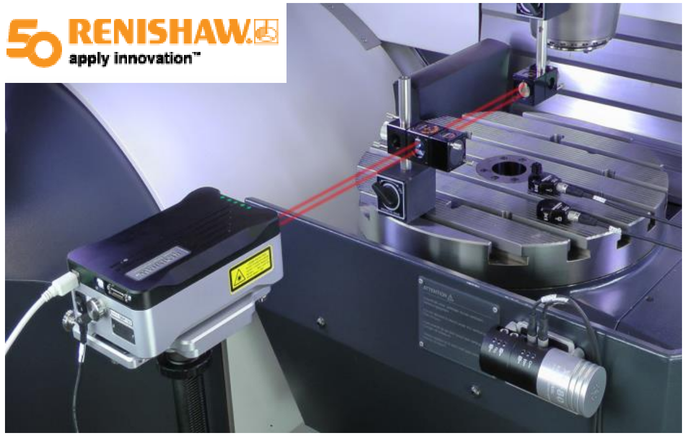
<u>However, demanding development requirements, such as</u>:

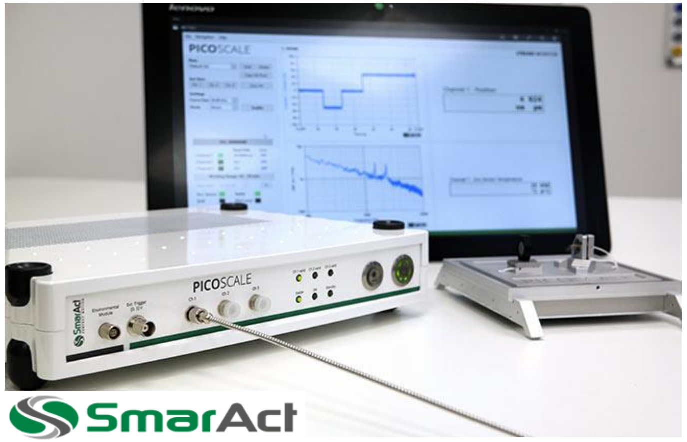
- Achieving accuracy in the nanometer range (<100 nm).
- High dynamics: sub-nanometer resolution over an extensive displacement range, atomic scale (beyond 1 meter).
- Simultaneous measurement of several degrees of freedom.
- Traceability to the International System of Units (SI).
- Long-term stability.
- Linearity of response (< a few tens of nm).
- High bandwidth (velocities up to a few m/s, sampling frequency up to a few MHz).

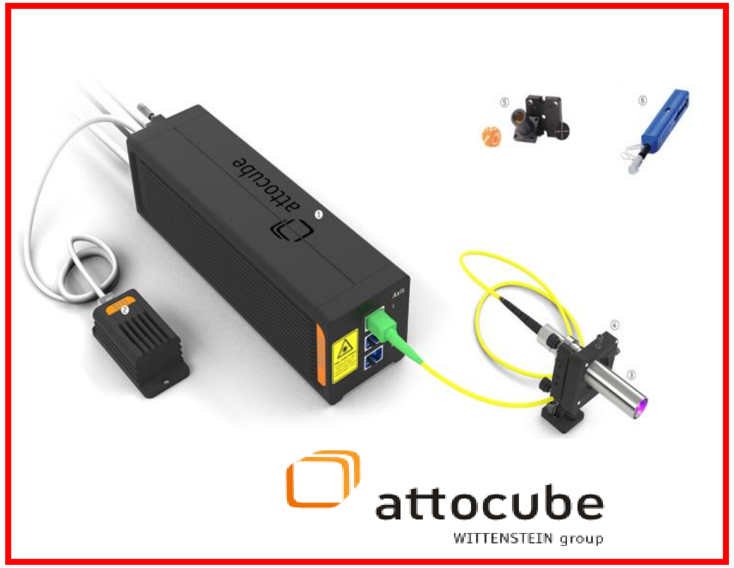
LASER Interferometers

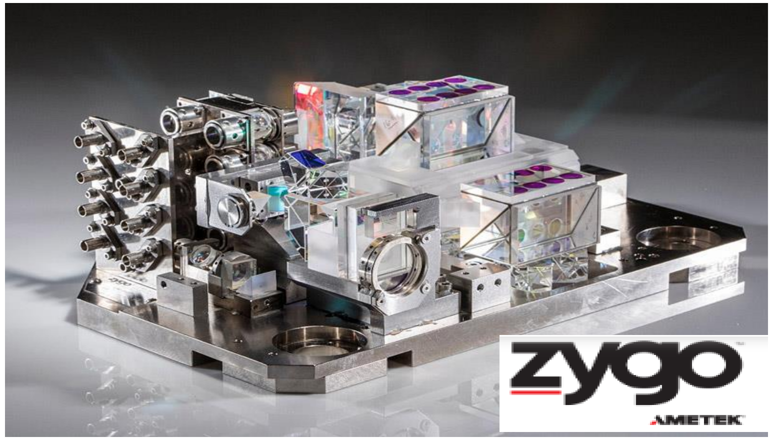
The number of eligible sensors is greatly reduced and attention generally focuses on Optical Interferometers.

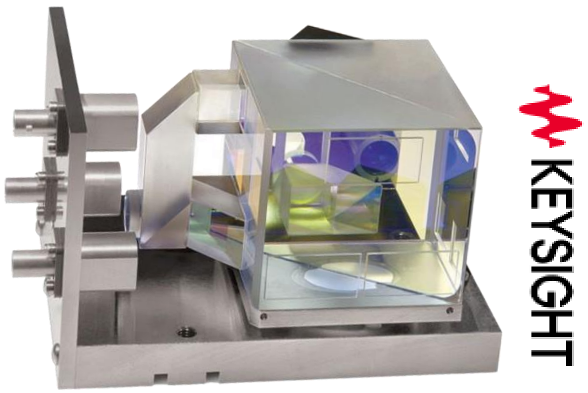
Many Interferometers are available in the market for measuring both Linear and Angular displacements











Challenges in Precision Interferometry

- Key Questions for an instrument designer:
  - How to evaluate an Interferometer?
  - What are the limitations in terms of displacement measurement?
  - What are the positioning uncertainties?
  - Identifying Main contributors to measurement uncertainties
  - Precautions to be taken.

Laser Interferometer

$$\text{Displacement in optical path (L)} = \text{Wavelength}(\lambda) \times \frac{N}{2}$$

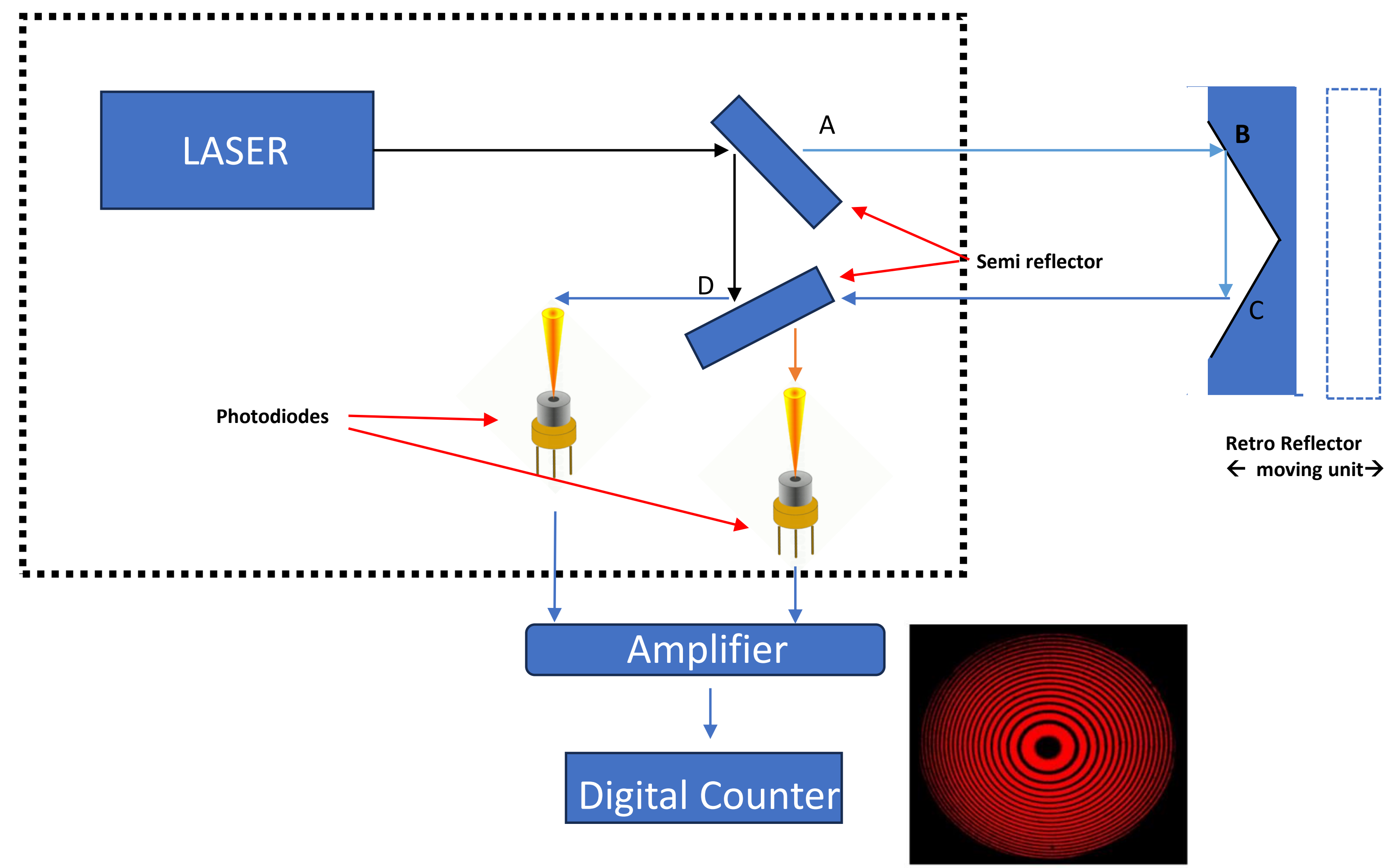
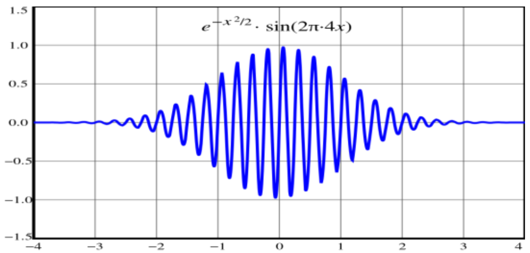


Fig. Working Principle of Laser Interferometer

- **Interferometric Precision:** Instruments rely on interferometry for highly accurate measurements.
- **Light Source:** Utilizes a laser as a coherent and monochromatic light source.
- **Semi-Reflectors:** Directs laser beams to semi-reflectors, splitting them into two perpendicular paths.
- **Path Splitting and Rejoining:** One path reflects, the other transmits, rejoining to create an interference pattern.
- **Interference Pattern:** Changes in optical path lengths result in a detectable interference pattern.
- **Displacement Detection:** Photodetector captures shifts in the interference pattern due to mirror displacement.
- **Digital Counter and Calibration:** Amplified signal sent to a digital counter, calibrated for precise displacement measurements.
- **Applications:** Widely used for high-precision measurements in metrology, machining, astronomy, and environmental monitoring.

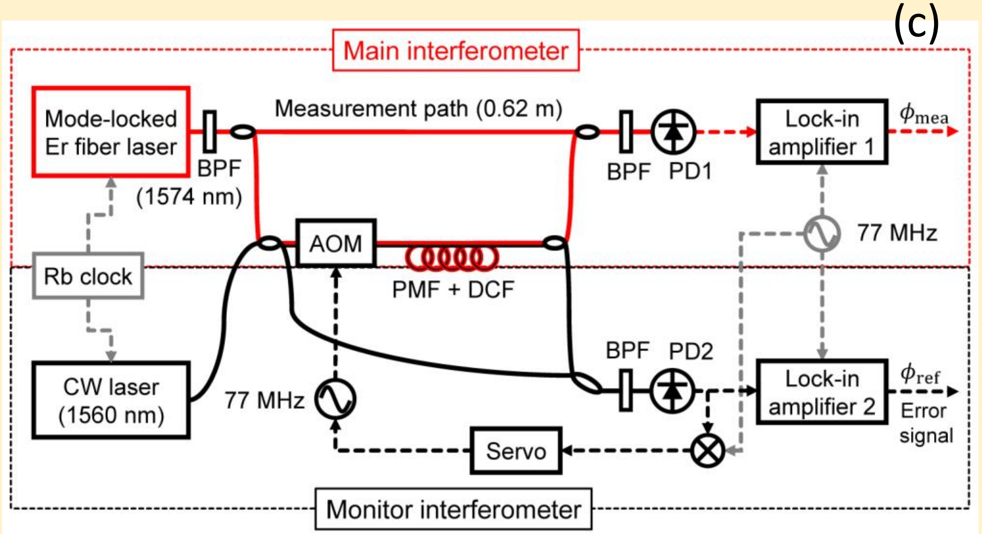
Calibration Techniques in Precision Interferometry

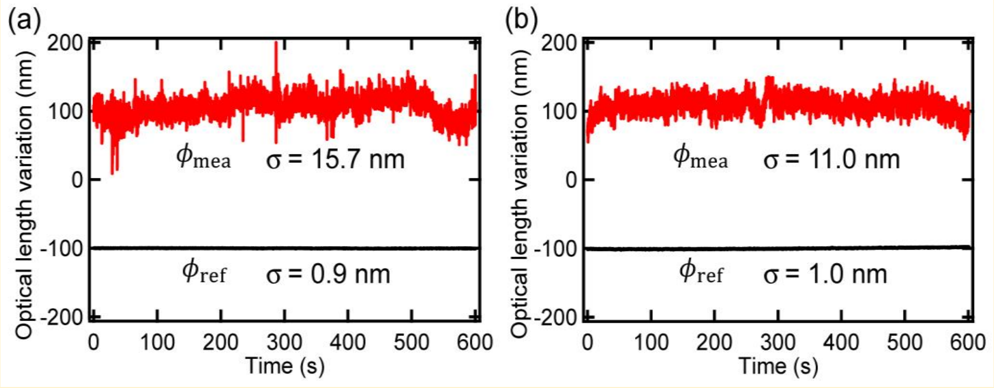
- Ensures accuracy and reliability in interferometric measurements.
- **Adaptive approaches**: Require Sophisticated selection tailored to specific system aspects.
- Ciddor/Edlen equations are fundamental tools, correcting optical path length based on environmental factors.
- **Real-time Adaptation**: Crucial for addressing dynamic changes in temperature, pressure, and humidity.
- **Integrated Accuracy**: Integration into closed-loop systems ensures real-time adjustments for ongoing precision.

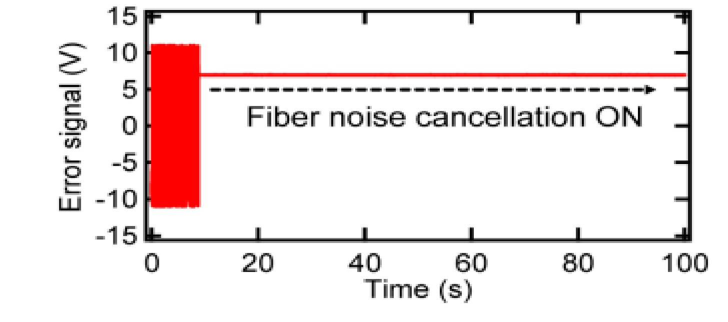


Highly Stabilized Optical Frequency Comb Interferometer(Nakajima et. al., 2015)

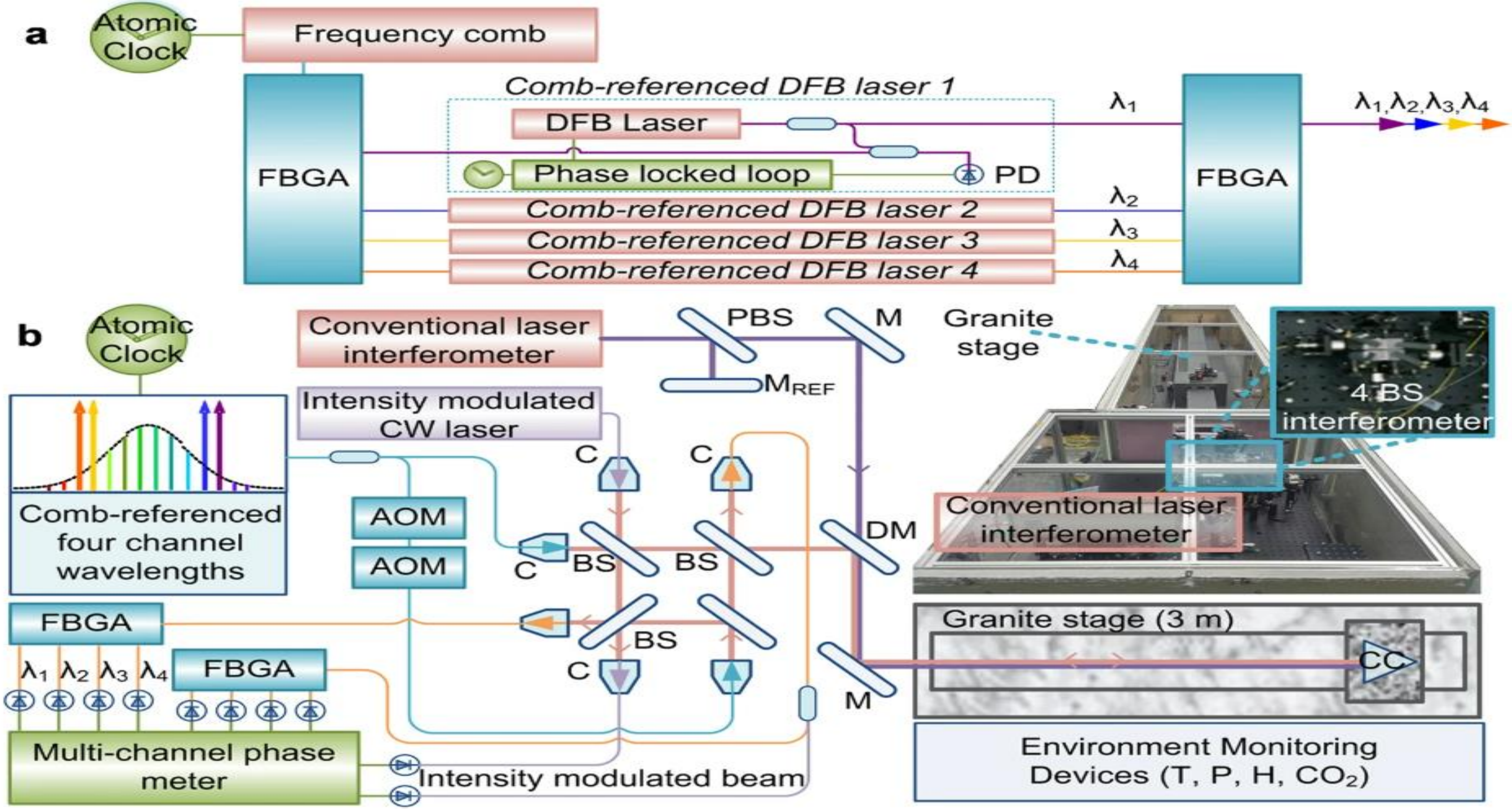
- Developed a highly stable optical frequency comb interferometer with a 342-m-long fiber-based reference path.
- Fig (c) Illustrates the setup of the optical frequency comb interferometer with components like mode-locked laser, fiber-based reference path, and interferometer.
- Shows interferometric fringe scanning in Fig(a),(b) with effective optical path length variation for different optical path differences of 168 m and 342 m.
- In summary, the interferometer setup, with advanced laser control and noise cancellation techniques, allows for highly accurate and stable measurements of displacements at the nanometer level.







(d) Evaluation of fiber noise cancellation



(a) Comb-referenced four wavelength light source. **(b)** Hardware design of the comb-referenced multi-wavelength interferometer. Abbreviations are; FBGA: fiber Bragg grating array, OFG: optical frequency generation, DFB: distributed feedback laser, PD: photo-detector, AOM: acousto-optic modulator, C: collimator, BS: beam splitter, M: mirror, DM: dichroic mirror, CC: corner cube, T: temperature, P: pressure, H: humidity and CO_2: carbon dioxide concentration.

Precision Air Refractive Index Correction with Two-Color Interferometry(G Wu et. al., 2013)

- Presents a high-accuracy correction method for air refractive index using two-color heterodyne interferometry of optical frequency combs.
- Achieves stability of 10^{-10} in measuring optical distance and correcting for refractive index changes.
- Figure illustrates 10h measurement:
    - (a) Measured Difference: Obtained from interferometers with a monitor arm.
    - (b) Ciddor's Equation: Calculated indices using Ciddor's equation and environmental parameters.
    - (c) Difference: Discrepancy between measured and calculated indices.
    - (d) Without Monitor Arm: Measured difference without using a monitor arm.
    - Vertical Adjustments: Aligned averages in (a) & (b) and set average in (c) at -6×10^{-9} for clarity.

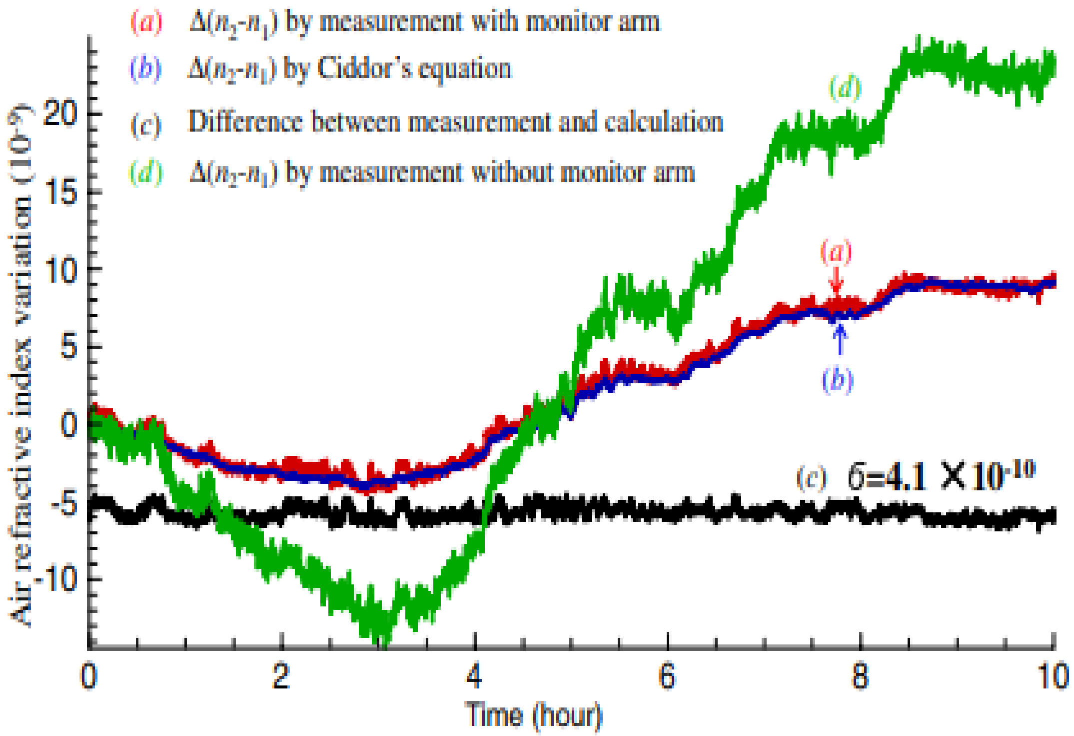
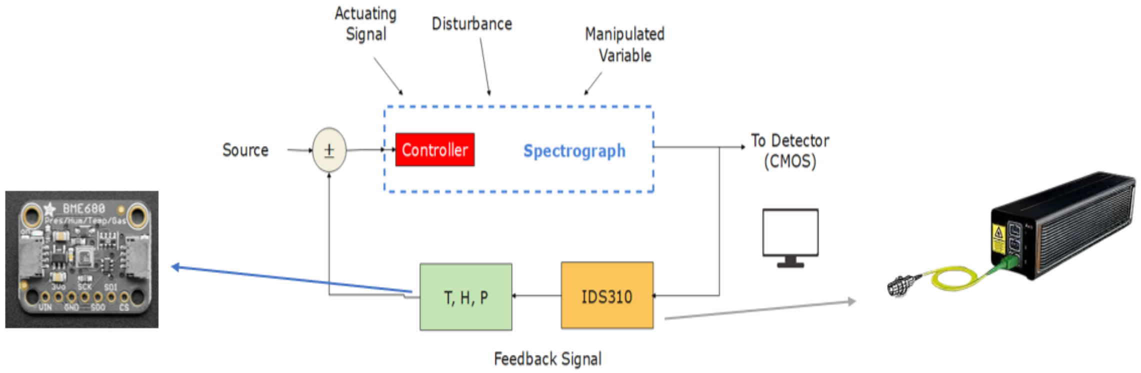


Figure: Long-Term Variation in Two-Color Air Refractive Indices

Drawing Conclusions from the Literature

- Fiber-based reference paths and advanced interferometry techniques contribute to achieving high stability and accuracy in optical measurements.
- Calibration of laser interferometer systems is crucial for industrial applications, emphasizing the need for comprehensive system calibration.
- Frequency comb-based interferometers show promise for high-precision distance measurements and correction of air refractive index.
- The two-color heterodyne interferometry method effectively corrects air refractive index variations with high accuracy and stability.
- Overall, advancements in interferometry techniques enhance the precision and reliability of optical measurements for various applications.

Refractive Index of Air



- Changes in environmental condition during the measurement are the largest source of error in interferometry.
- By modified empirical Ciddor/Edlen equation,

$$\eta = 1 + 7.86 \times 10^{-4} \frac{P}{273.15+T} - 1.5 \times 10^{-11} RH(T^2 + 160)$$

(https://emtoolbox.nist.gov/Wavelength/Edlen.asp)

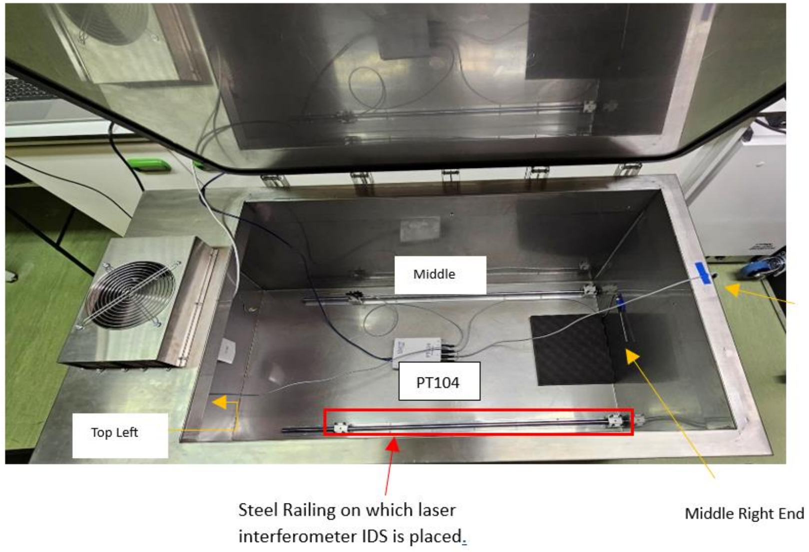
where, T (0 to 35°C) is temperature, P(50kPa to 120 kPa) is pressure, H(0 to 100%) is relative humidity . Now using the values and plugging into the equation.

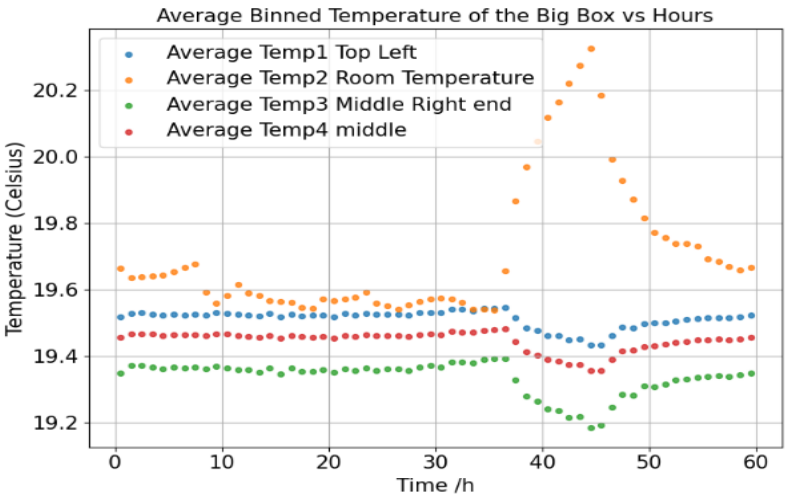
$$\eta_{sa} = \eta_{\text{standard air}} = 1 + 7.86 \times 10^{-4} \frac{101.325}{273.15+T} - 1.5 \times 10^{-11} \times 50(20^2 + 160)$$

∴ Will solve for Lcompensated, as Lcompensated is the geometric optical path length,

$$L_{\text{compensated}} = L_{\text{uncompensated}} \times \frac{\eta_{standard\ air}}{\eta_{air}} = L_{\text{uncompensated}} \times \frac{1.0002713938}{\eta_{air}}$$

Calibration Method Implementation





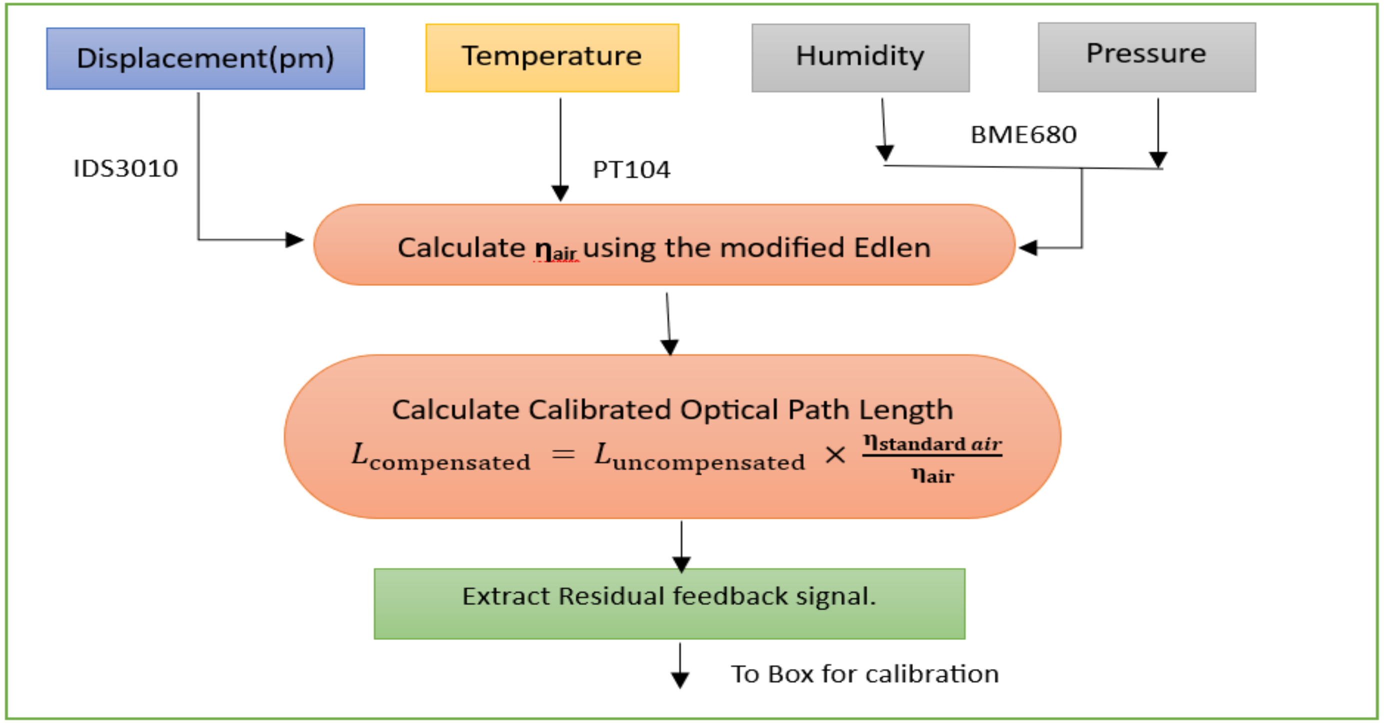
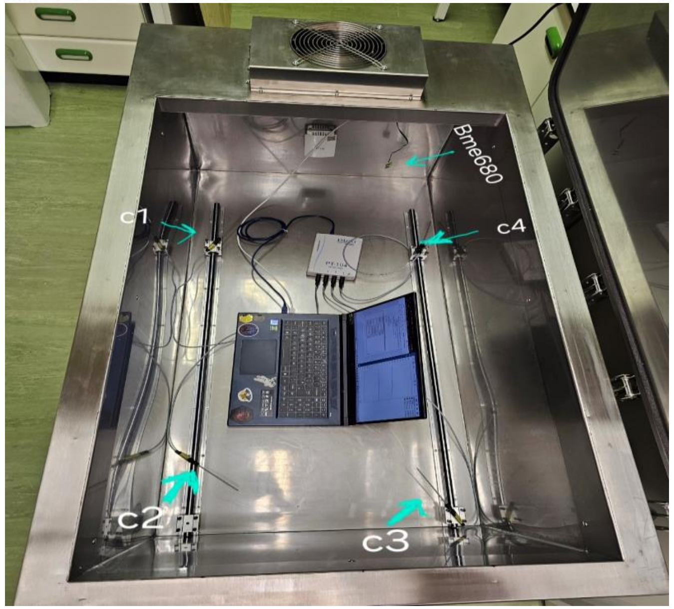


Fig. Flowchart: Algorithm to calculate the calibrated path.



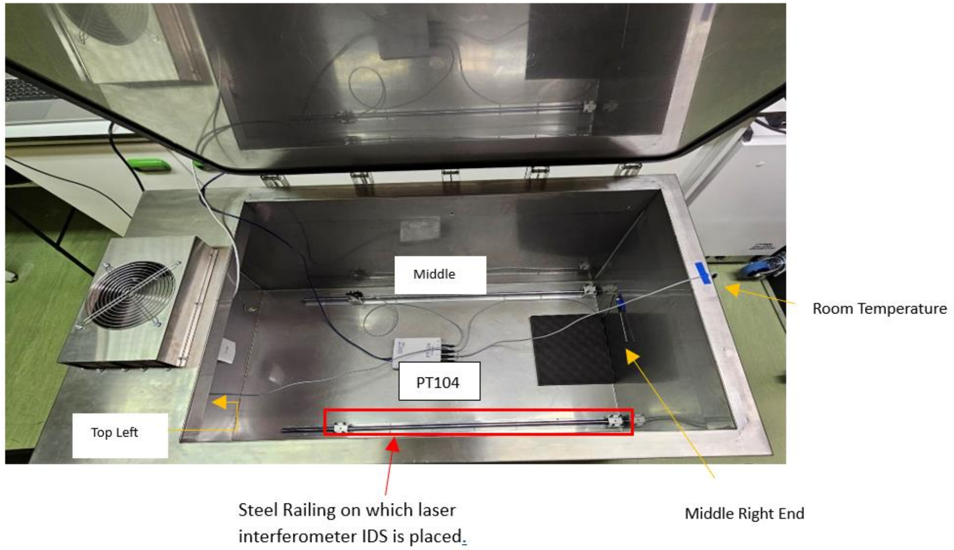
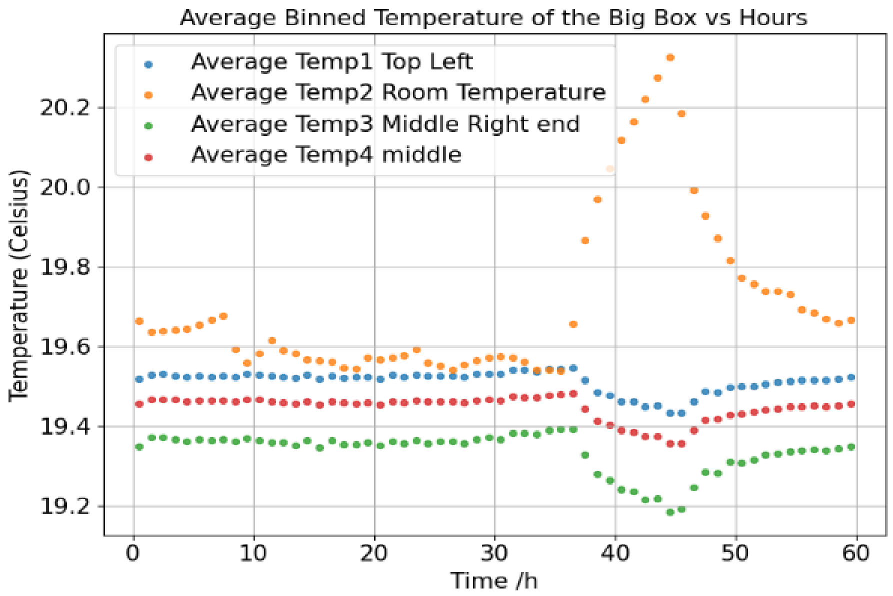


Fig. [Peltier-104](#) Temperature Sensor 4 channel



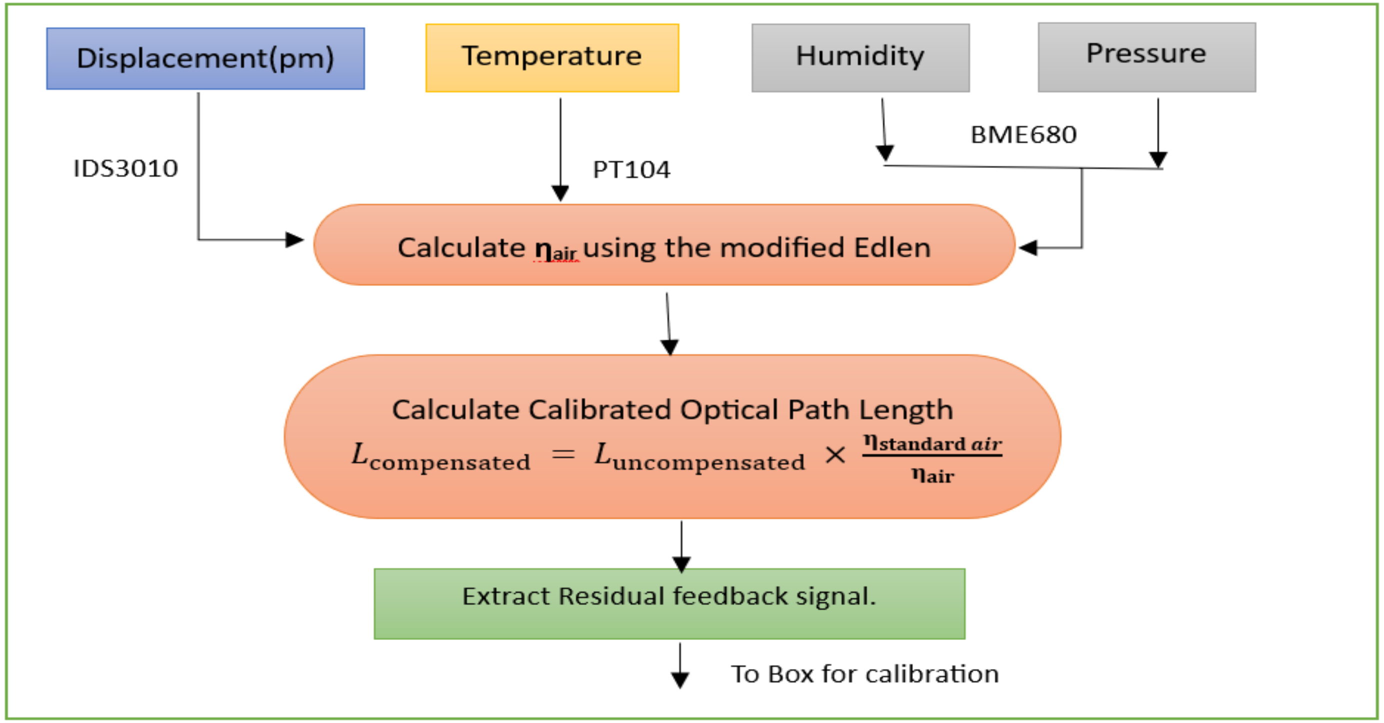
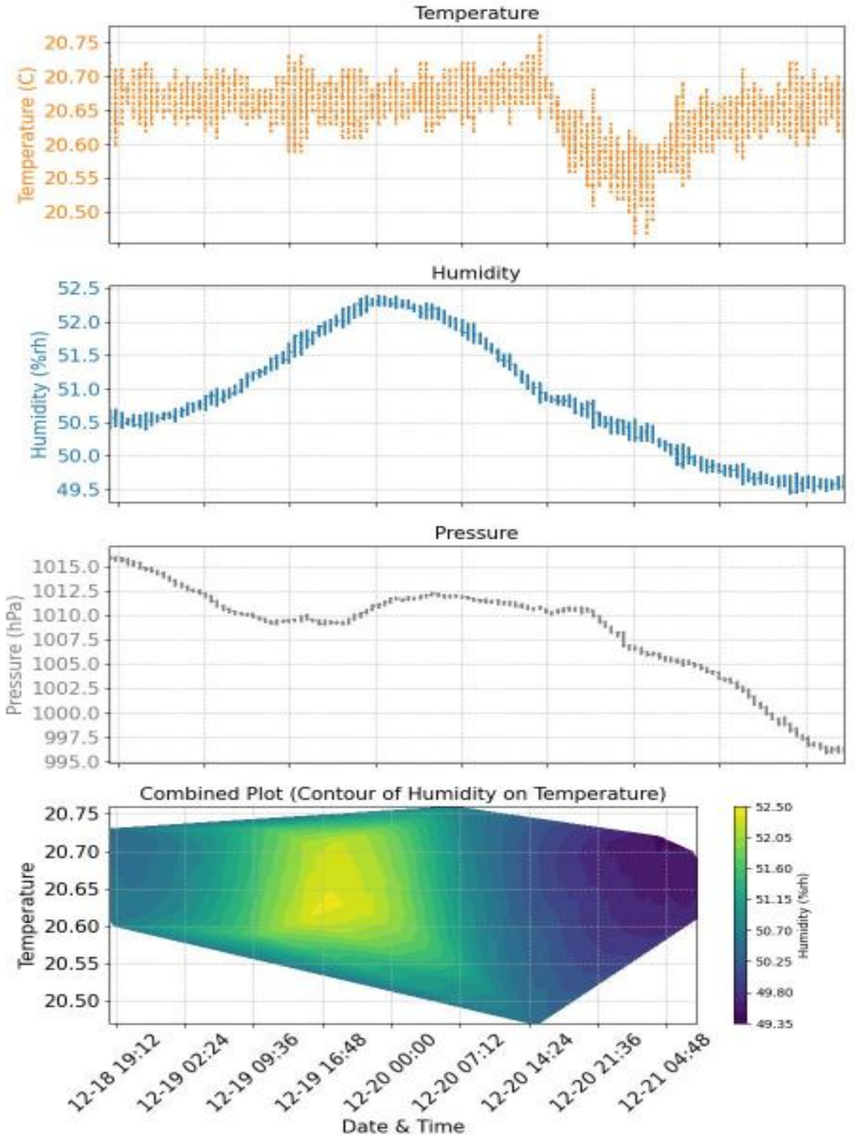
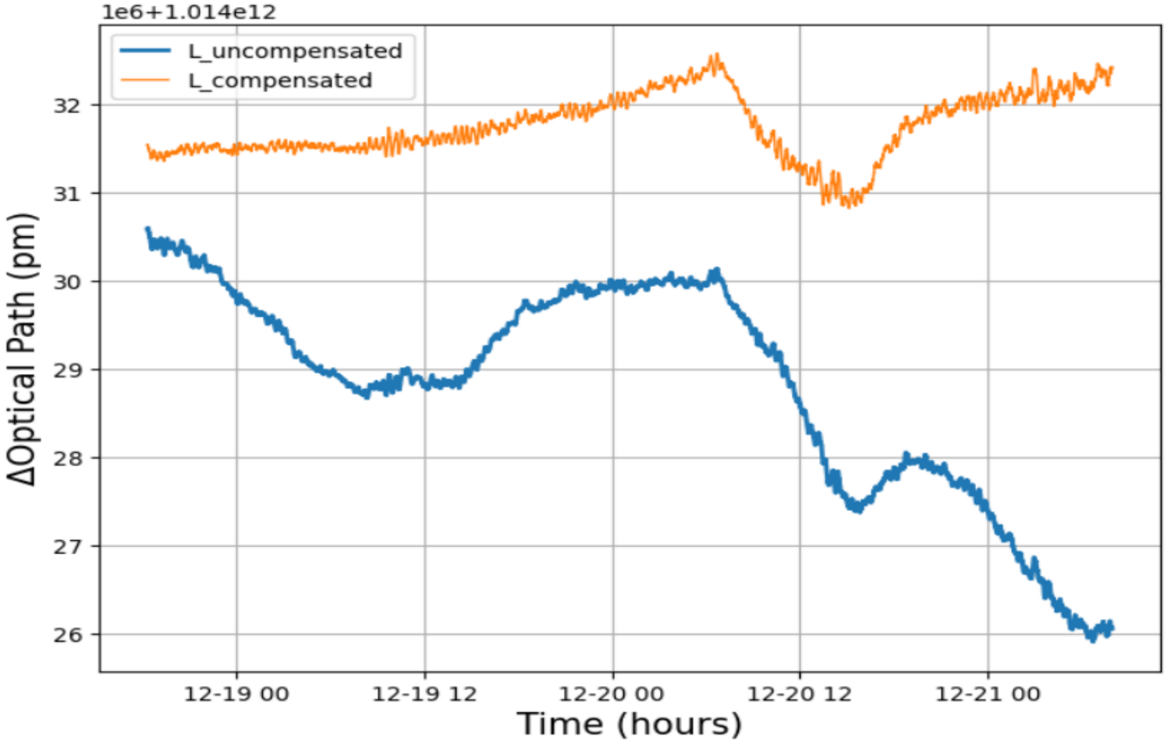


Fig. Flowchart: Algorithm to calculate the calibrated path.

Results & Conclusion





The thermal coefficient of expansion (or contraction) can be calculated using the formula:

$$\boxed{Thermal\ Coefficient(\alpha) = \frac{Final\ Path\ Length - Intial\ Path\ Length}{Initial\ Path\ Length\ \times (Final\ Temperature - Initial\ Temperature)}}$$

From the data collected, we have,

Uncompensated or Initial Path Length(L1) = 1.01375730e+12 pm

Compensated or Final Path Length(L2) = 1.01375583e+12 pm

Initial Temperature(T1) = 20.7 °C; Final Temperature(T2) = 20.5 °C

Plugging the values, we get, α = 7.25025605241059e-06 K^{-1}

That is close to mean coefficient of thermal expansion of Stainless Steel 304, with which our box2 is made up of 17.25e-06 K^{-1}.

Summary

- **Significance of Position Accuracy:**
  - Recognized the crucial role of precise position measurements in instrument design.
  - Emphasized the importance of reliable position sensors for accurate and dynamic applications.
- **Laser Interferometers in Precision:**
  - Explored the pivotal role of laser interferometers in achieving nanometer-level accuracy.
  - Discussed their key contributions to addressing challenges like long-range displacement and high dynamics.
- **Calibration Techniques in Industrial Interferometry:**
  - Examined various calibration methods used in industrial interferometers.
  - Reviewed approaches for calibrating individual components and entire systems.
- **Proposed Correction Method:**
  - Introduced a novel approach for correcting the optical path using the refraction of air.
  - Outlined the implementation of Ciddor/Edlen equations within a closed-loop feedback control system for ExoSpec development

Future Work

Fig Attocube Environmental Compensation Unit

- **Error Analysis for Robustness:**
  - Conduct a comprehensive error analysis, considering factors such as vibrations and Abbé error.
  - Address Abbé error resulting from parasitic rotations during displacement and an offset between interferometer axis and the point under investigation.
- **Dead Path Error Resolution:**
  - Tackle dead path error, focusing on minimizing the difference in optical path length when the interferometer electronics are zeroed.
- Conduct a thorough comparative analysis to validate the system's stability against existing environmental compensation units.