Closed Loop Feedback Control System for EXOhSPEC Development

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MSc Astrophysics Master Project

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Outline

- Introduction
- System Overview
- Methodology
- Results and Analysis
  - Temperature Analysis- Box2
  - Preliminary Testing
  - Self-Mixing Interferometry: Using Glass Slip Width Variation Experiment
  - Environmental Compensation Unit(ECU) testing
- Future Work

Introduction

Closed Feedback Loop Control System for EXOhSPEC

- **EXOhSPEC,** the Exoplanet High-Resolution Spectrograph
- Focus on high-resolution spectrometry and precise radial velocity measurement.
- Design prioritizes efficiency by minimizing optical components.

Objectives:

- Project targets environmental stability with a designed control system.
- Utilizes off-the-shelf sensors in a feedback loop to calibrate the spectrograph.
- IDS3010 Displacement Measuring Interferometer provides picometer-level displacement measurements. Integration of additional sensors: BME680 for pressure and humidity, PT104 for temperature.
- Compact, low-cost, and efficient high-resolution spectrograph.

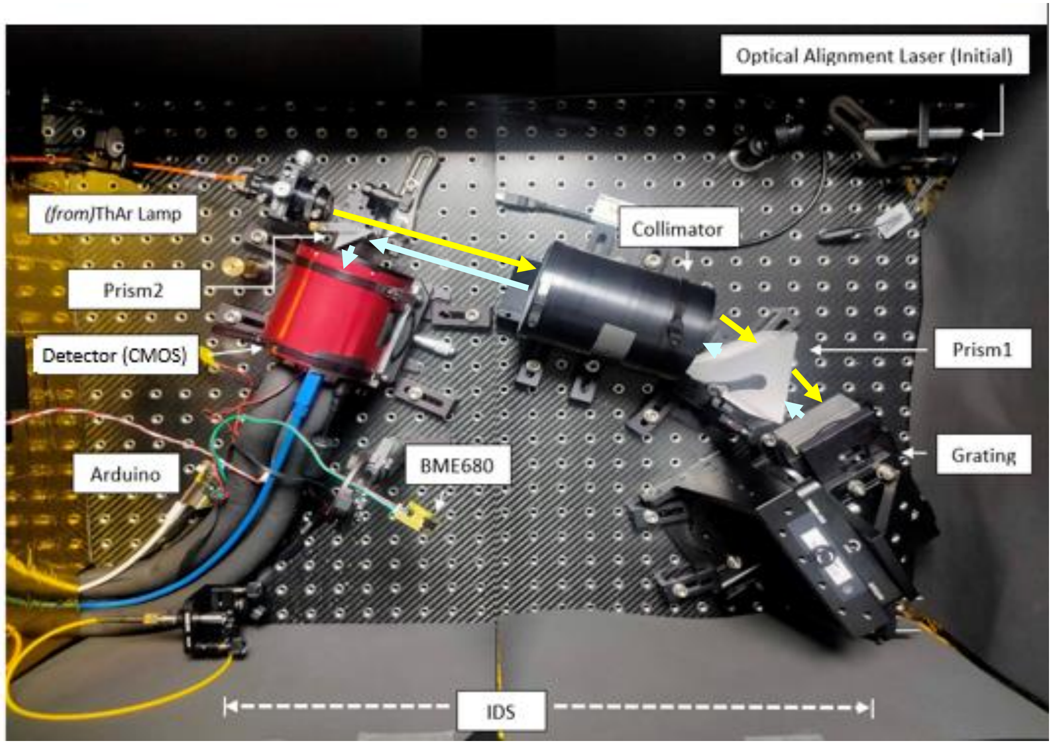
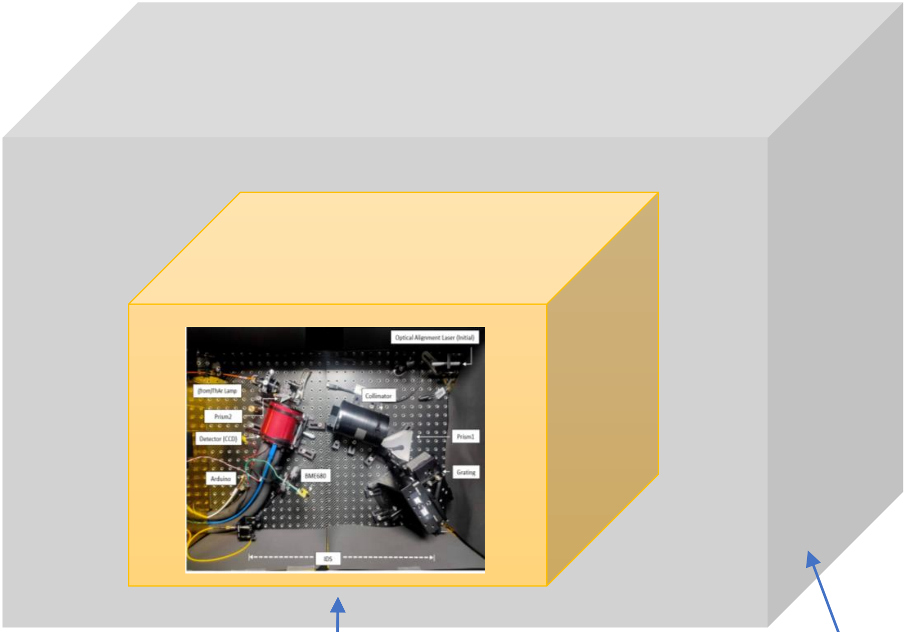


Fig 1. Internal structure of the Modified EXOhSPEC along with IDS and BME680 integrated

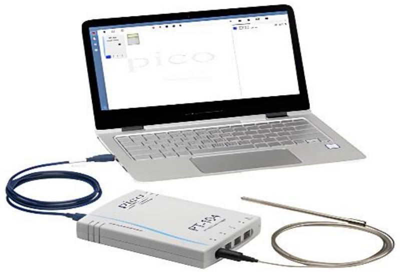
System Overview

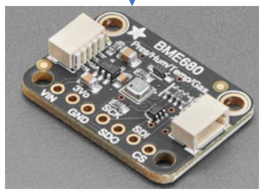
- EXOhSPEC (Spectrograph) Jones et. al.,2021
- Box1(Housing the Spectrograph)
- Box2(Housing the Box1)
- Attocube's –
  - Laser Interferometer (IDS3010)
  - Environmental Compensation Unit (ECU)
- Electronic components:
  - Microcontroller(Arduino Nano)
  - BME680 Sensor (Temperature, Pressure and Humidity)
  - Peltier Based Temperature Sensor – 4 channel

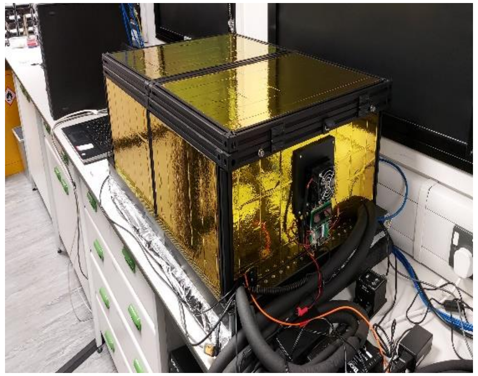


Box1

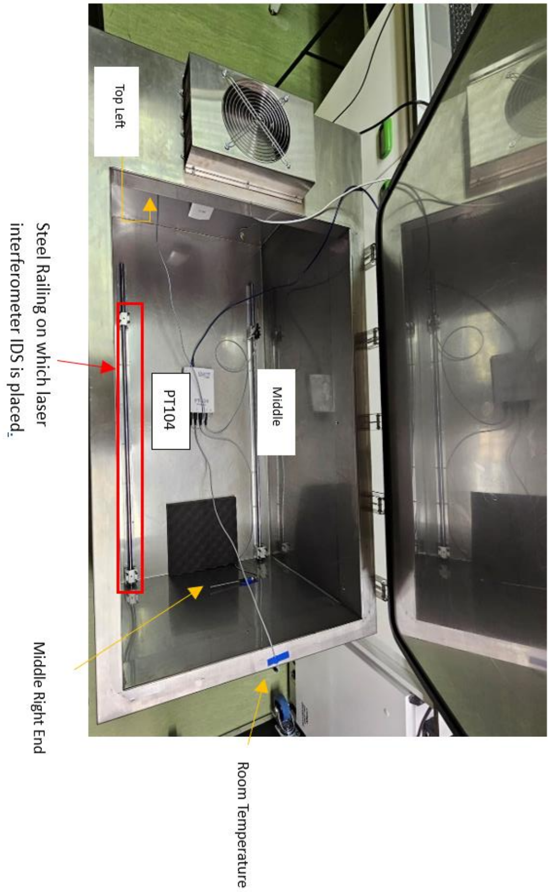
Box 2







Temperature Analysis: Box2



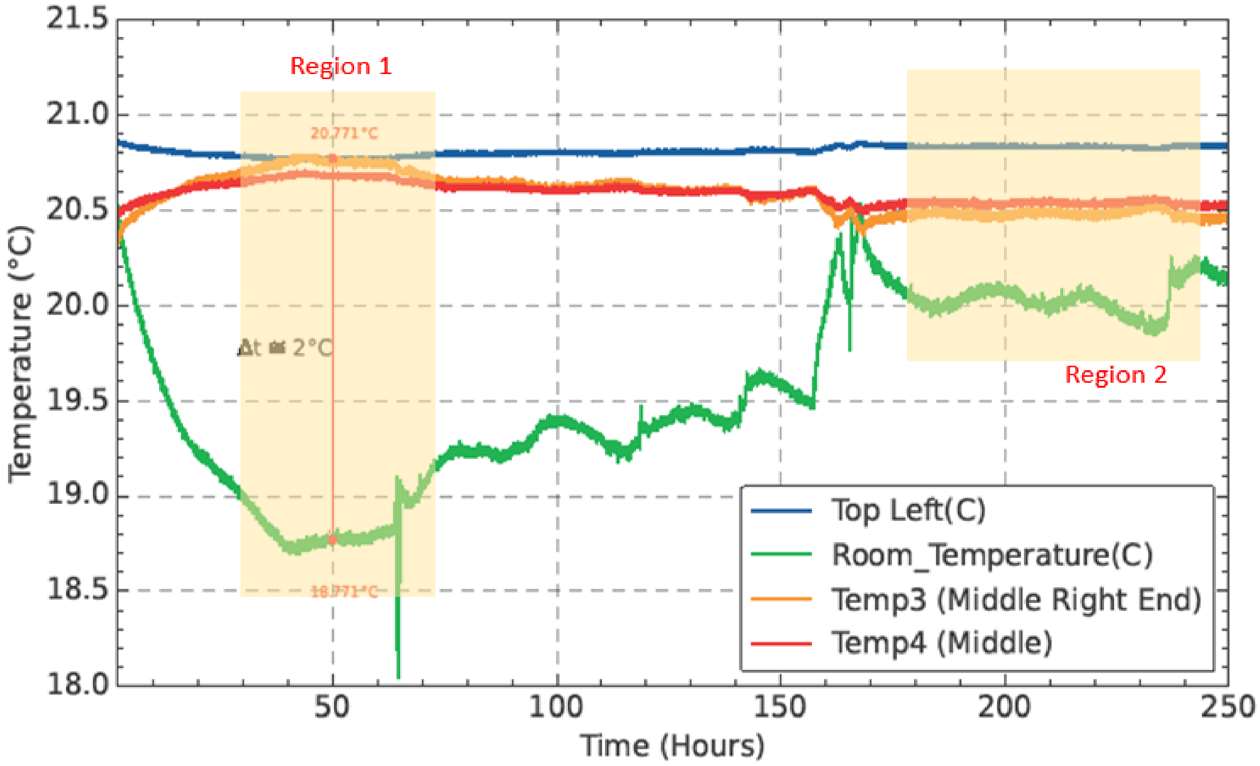


Fig 5. Region of focus: Region 1 and Region 2

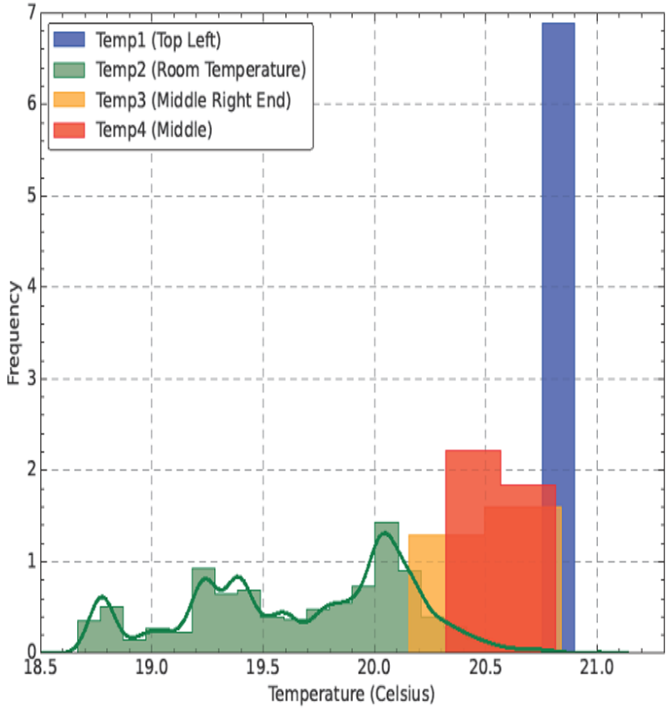


Fig. Outer Box Temperature Characteristics in 2 different regions

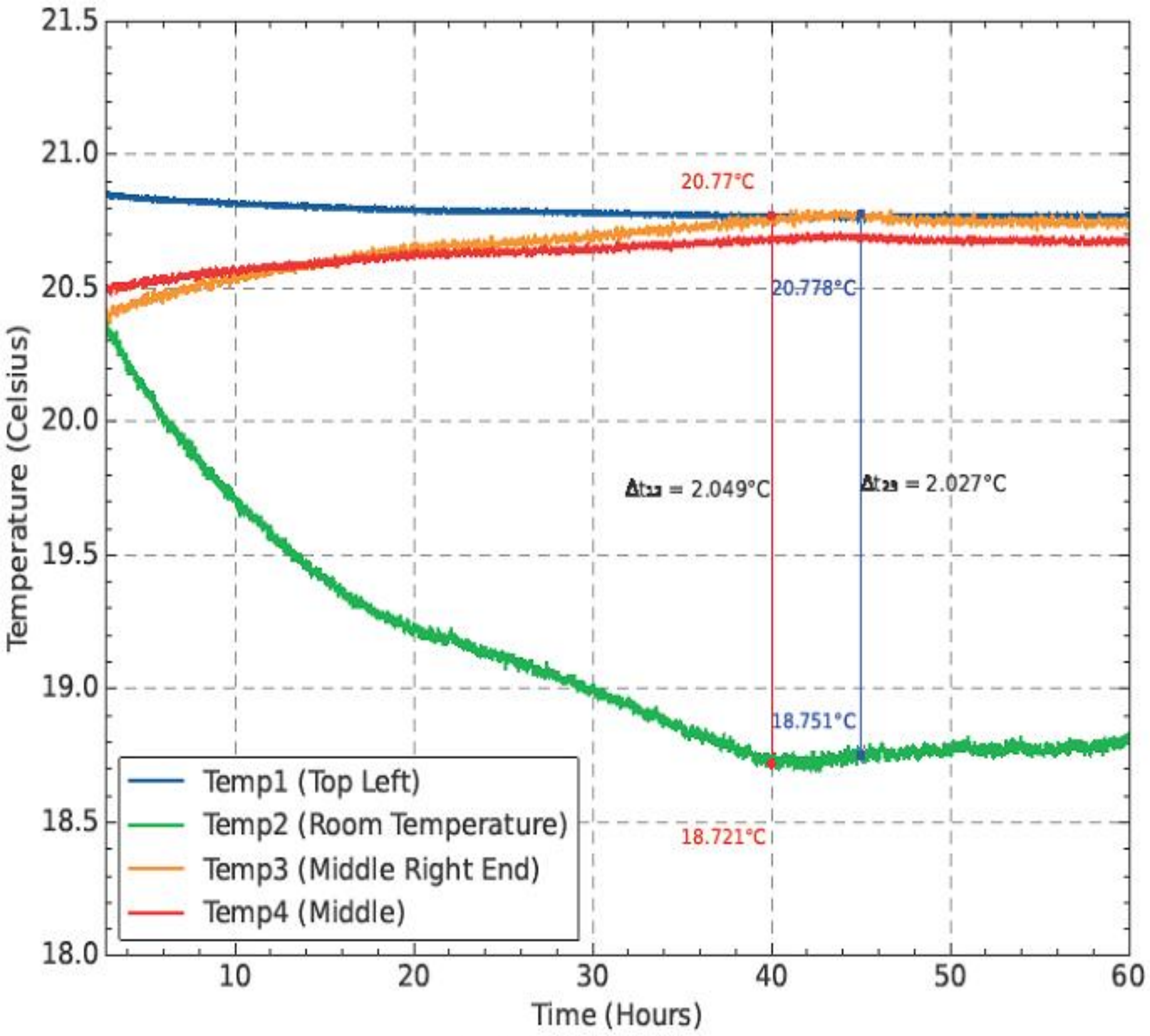


Fig 6. Region 1 analysis

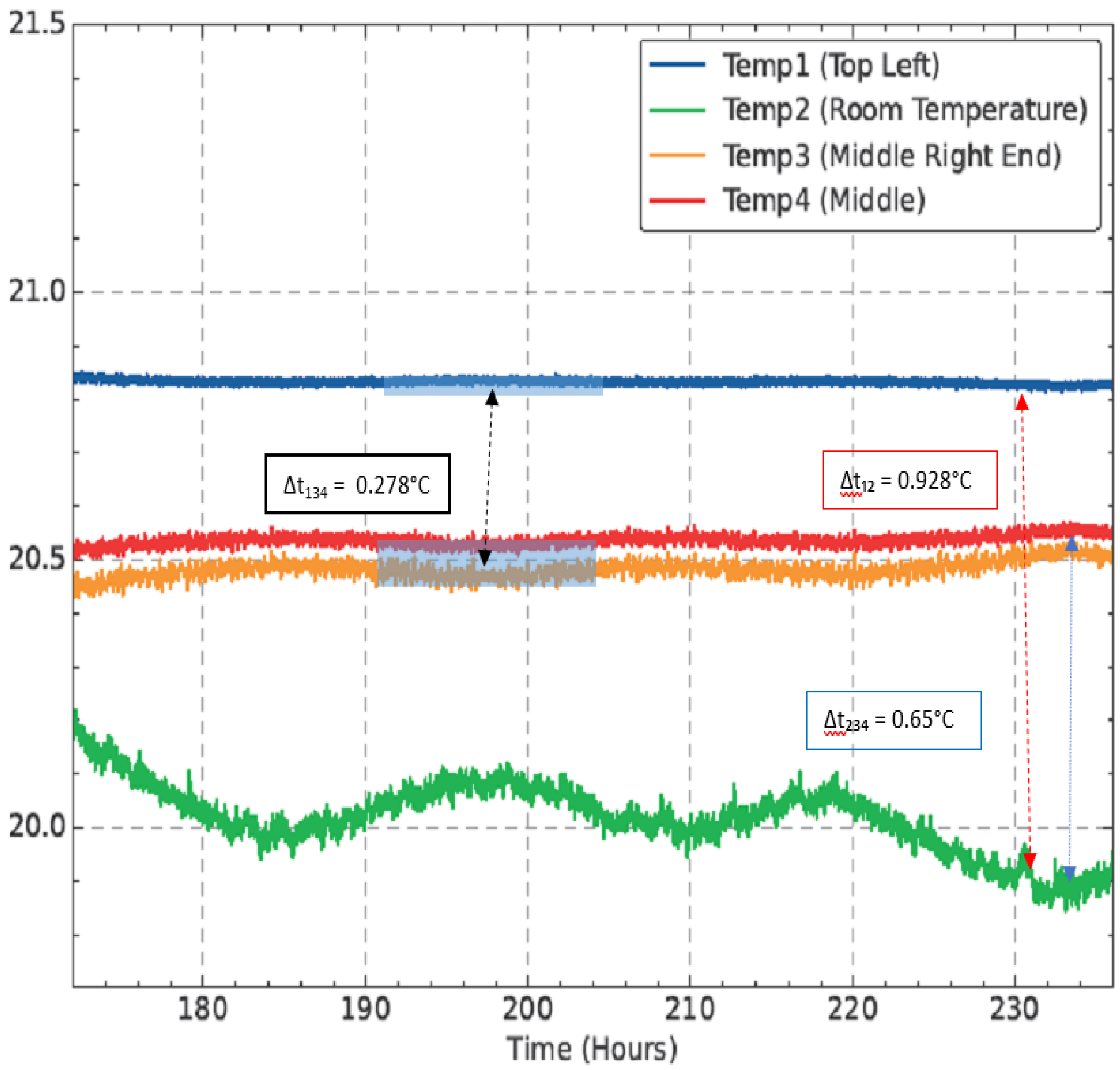


Fig 7. Region 2 analysis

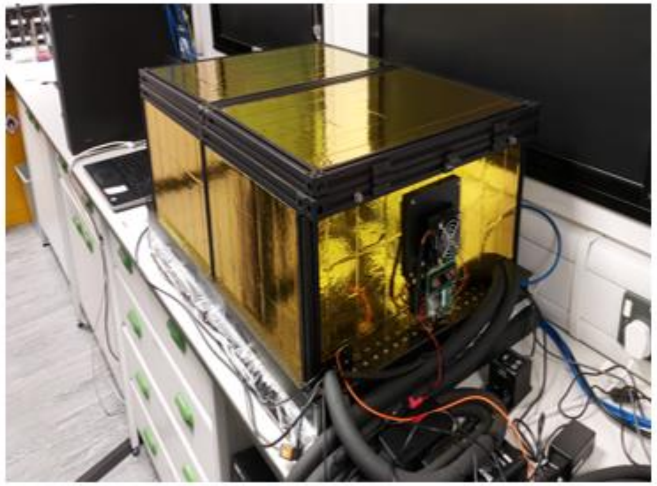


Fig. 7: The system's outer box is positioned on a carbon fibre breadboard.

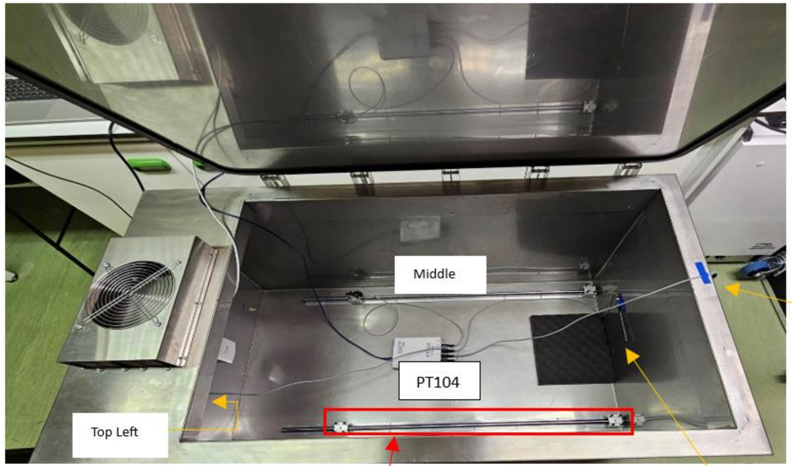
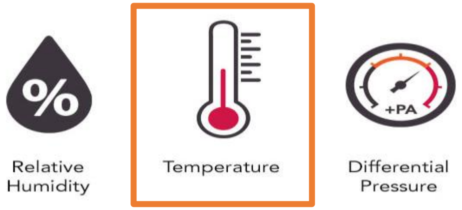
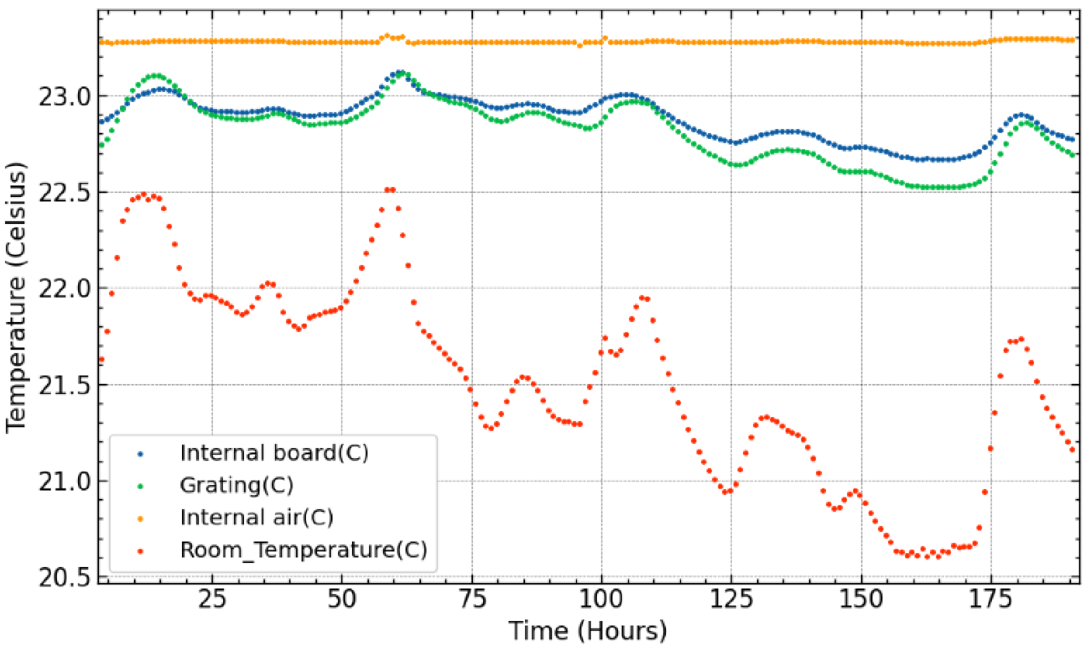


Fig. Peltier-104 Temperature Sensor 4 channel





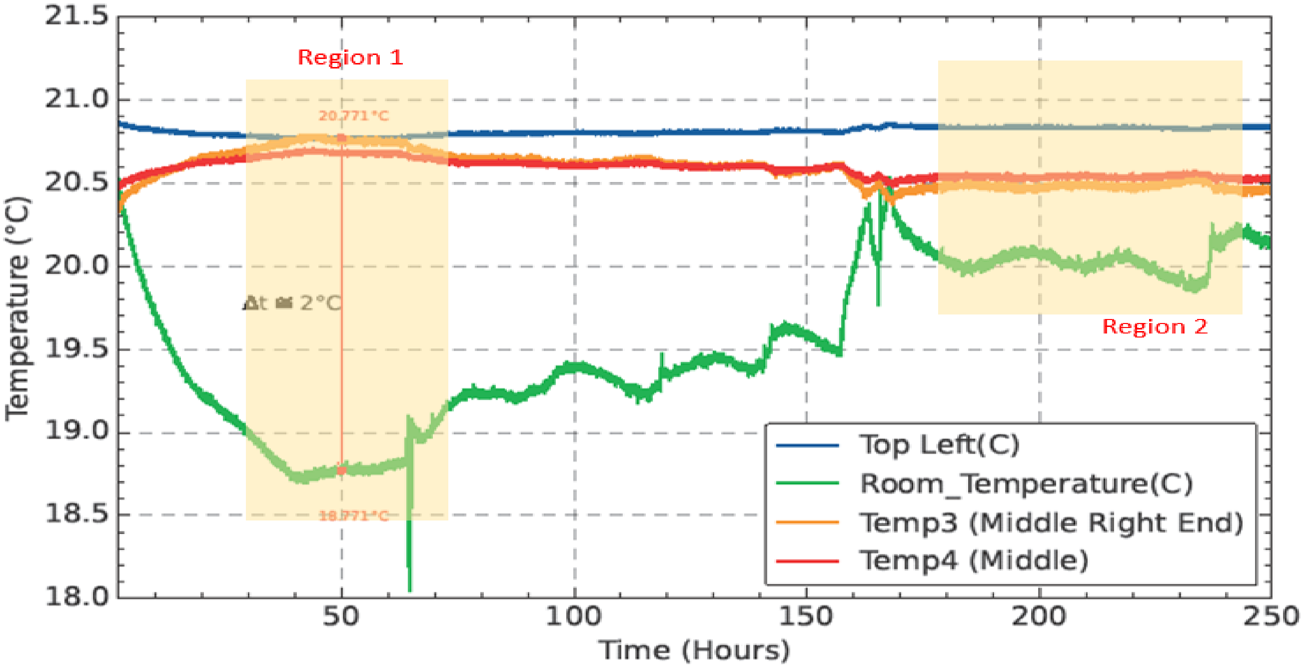
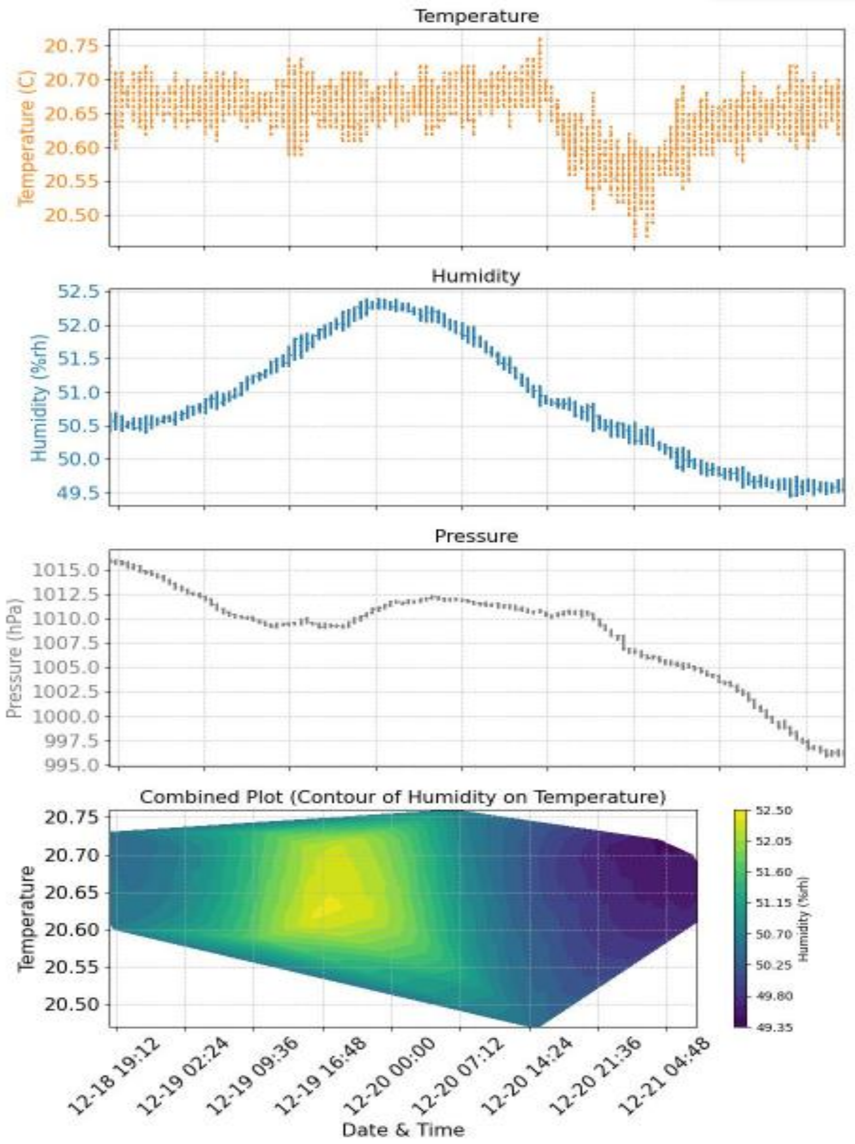
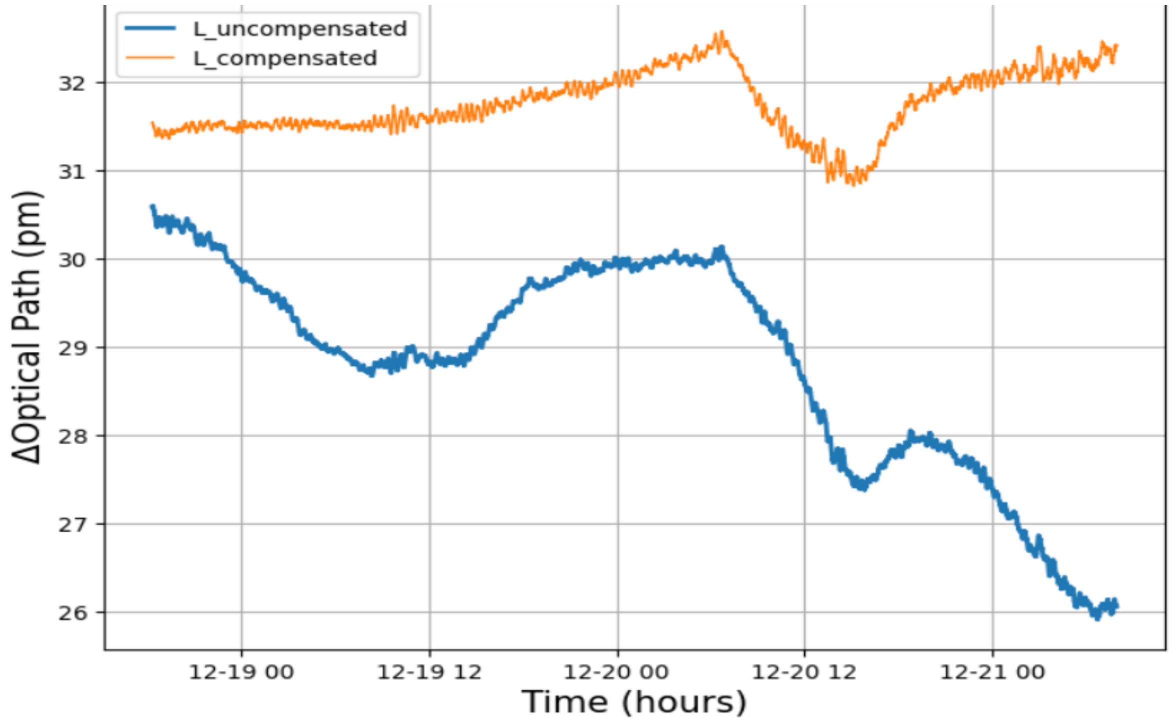


Fig 5. Region of focus: Region 1 and Region 2

Thermal Coefficient(α)





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

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

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

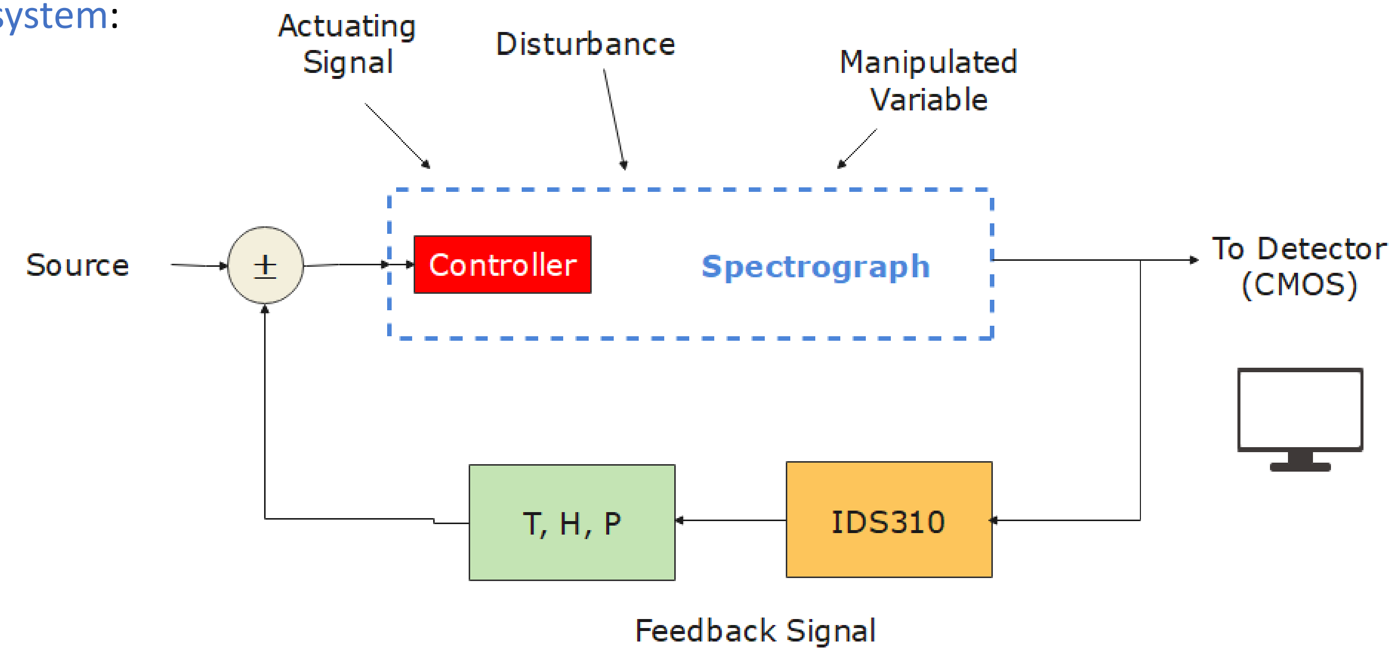
Plugging the values, we get, α = 7.25025605241059e-06 K^{-1}

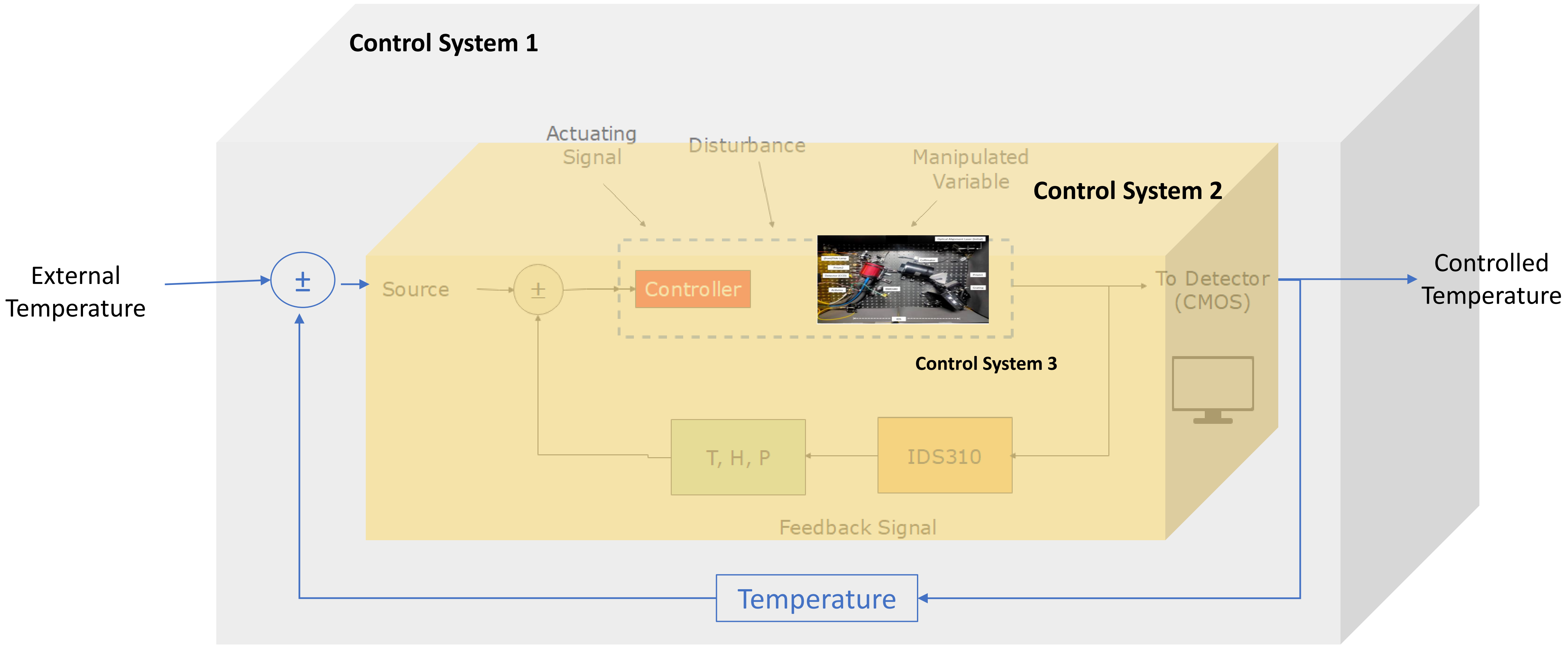
That is close to mean coefficient of thermal expansion of **Stainless Steel 304**, with which our box2 is made up of 17.25e-06 K^{-1}.

Methodology

The key steps in the closed-loop feedback control system:

- Initiation
- Data Acquisition
- Sensor Data Processing
- System Calibration
- Spectral Data Reception
- Feedback Loop
- End the process after desired iterations.




Control System 1
Actuating Signal
Disturbance
Manipulated Variable
Control System 2
External Temperature
±
Source
±
Controller
To Detector (CMOS)
Controlled Temperature
Control System 3
T, H, P
IDS310
Feedback Signal
Temperature

Preliminary Test Results

BME680 Temp Analysis

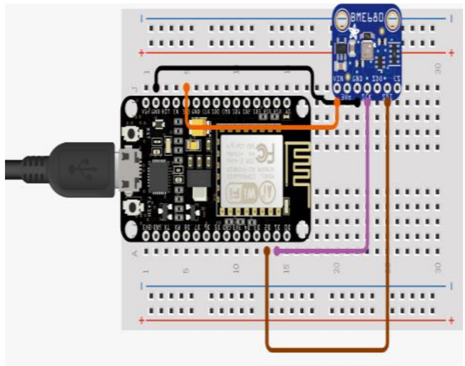
- Problem:
  - $\boxed{\rho = \rho_0 (1 + \alpha \Delta T),}$

where ρ_0 represents the original resistivity,

α is the temperature coefficient of resistivity, and

ΔT is the temperature change.

- Solution:
  - Change sampling rate



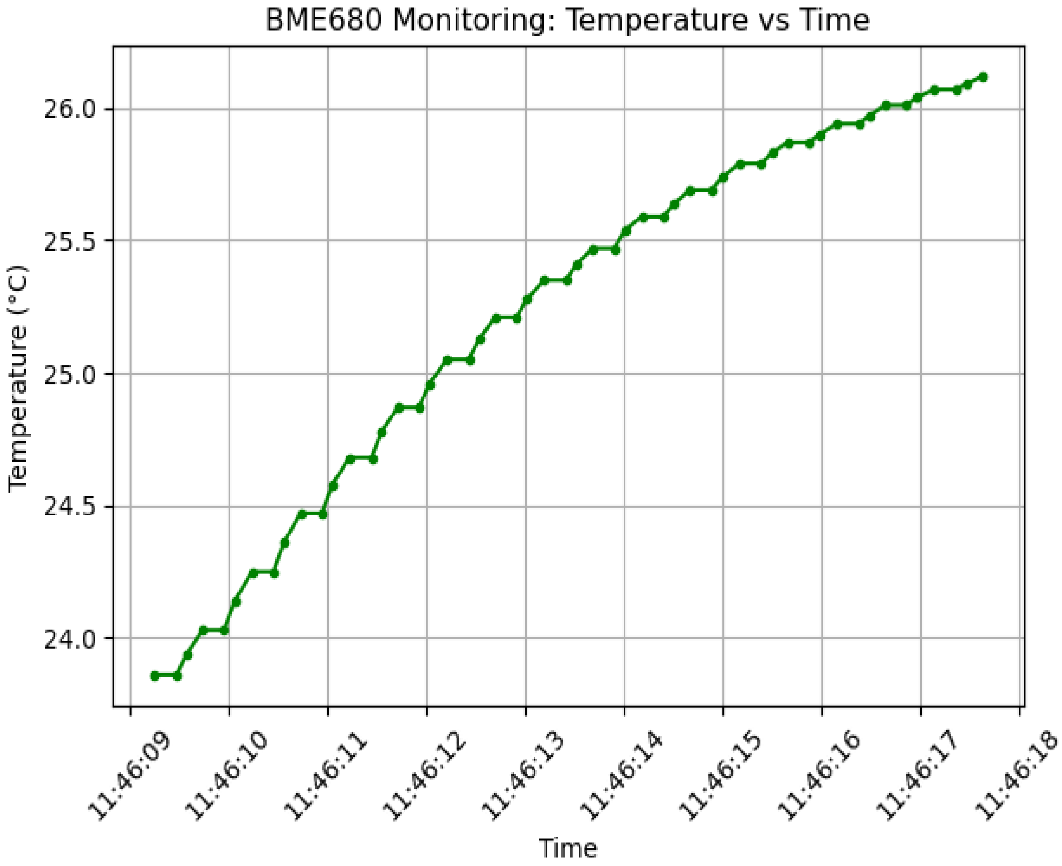
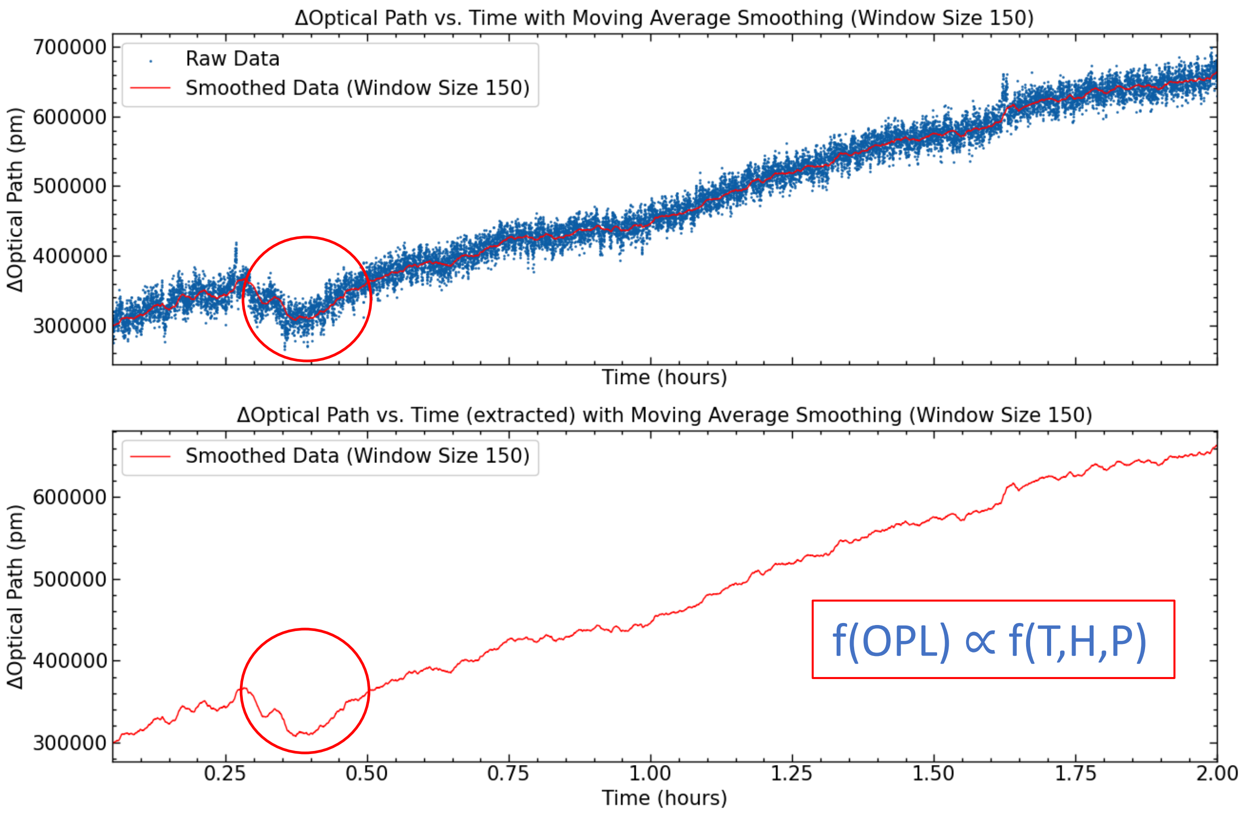


Fig (a) Circuit Design of Nodemcu ESP8266 a microcontroller development along with BME680 sensor, (b) Temperature (°C) vs Time

Preliminary Test Results

ΔPressure ∝ ΔOPL
1hpa -> 0.4 µm

Dependencies(Problem)? ---> Need Calibration (Solution)



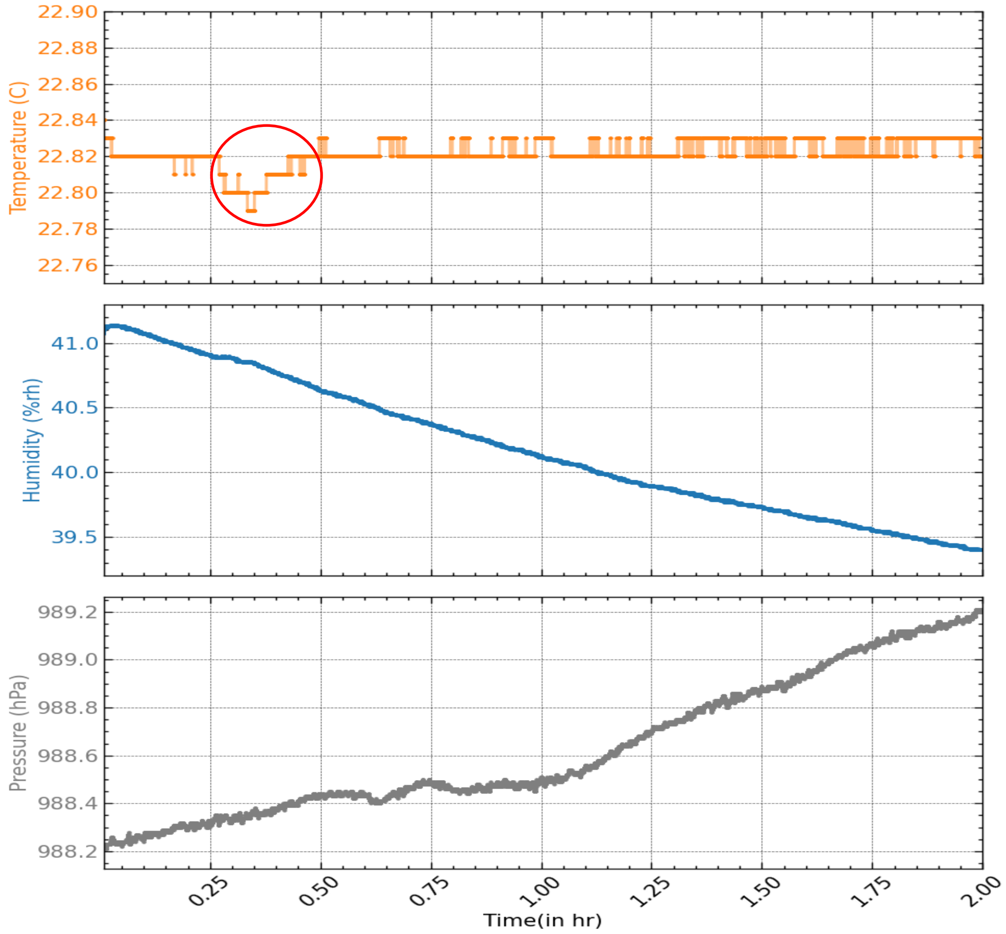
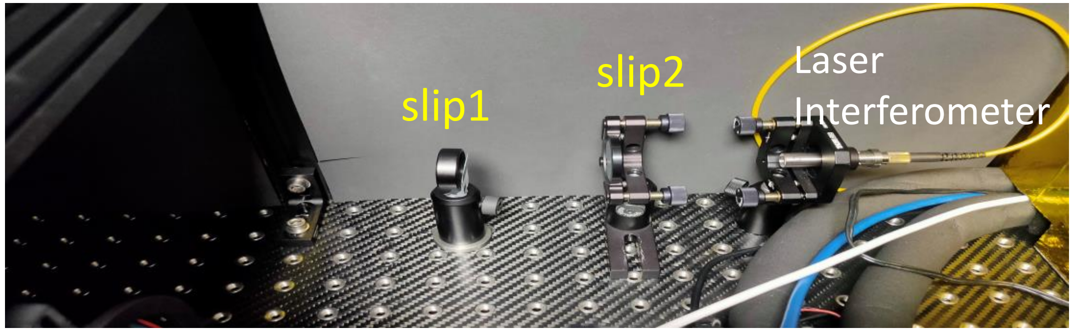
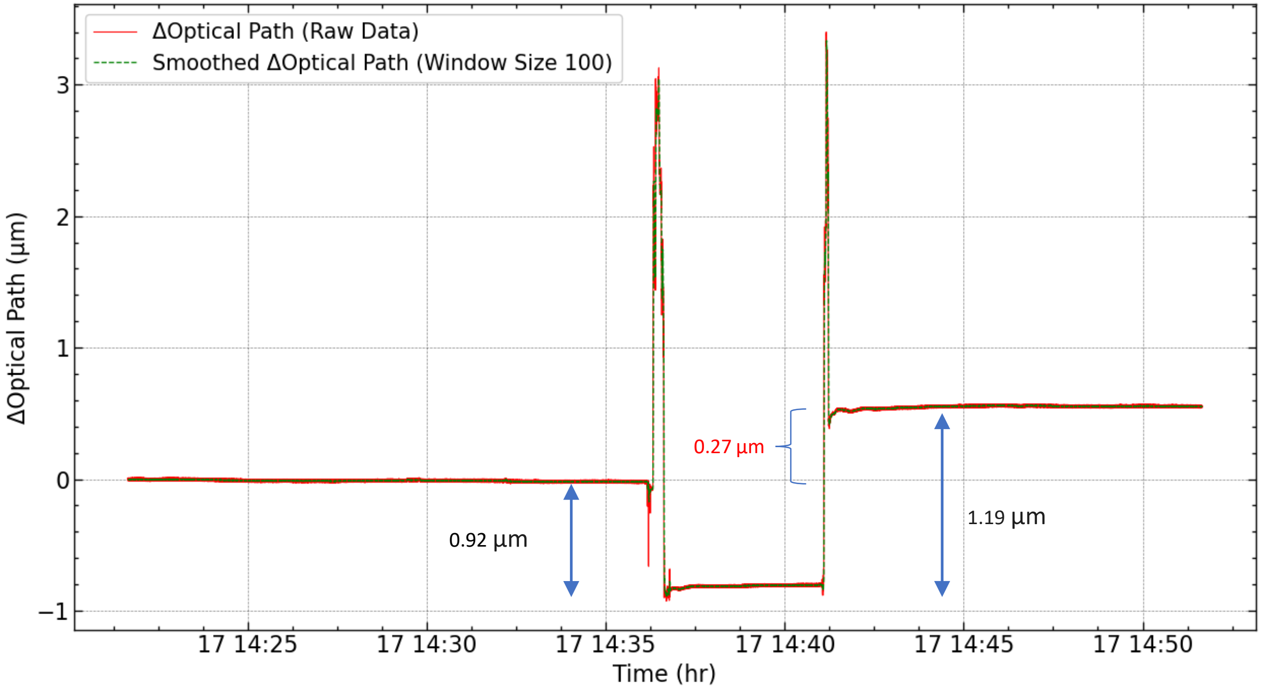


Fig. (a) Position vs Time (Raw Data): Raw IDS displacement data over 2 hours, revealing trends in optical path changes.
(b) Moving Average Smoothing: High-frequency data smoothed with moving averages, enhancing trend visibility. (c) Temperature, Pressure, Humidity vs Date & Time

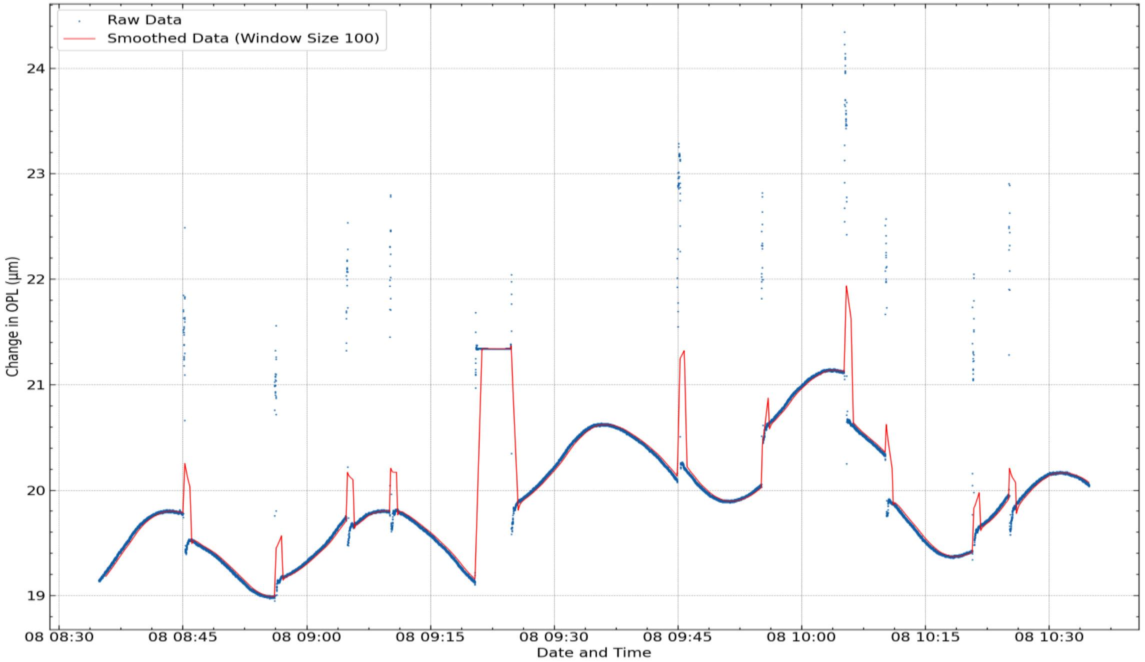
Glass Slip Variation Experiment



- Initial experiment use 0.12-0.16mm glass slip1.



- Repeated experiment using slip 1 + slip 2



- Outcome: Not Robust in extreme, found undocumented feature as per the manufacturer documentation.

Self Mixing Interferometry (Yuanlong F.,2011)

Calibration Technique

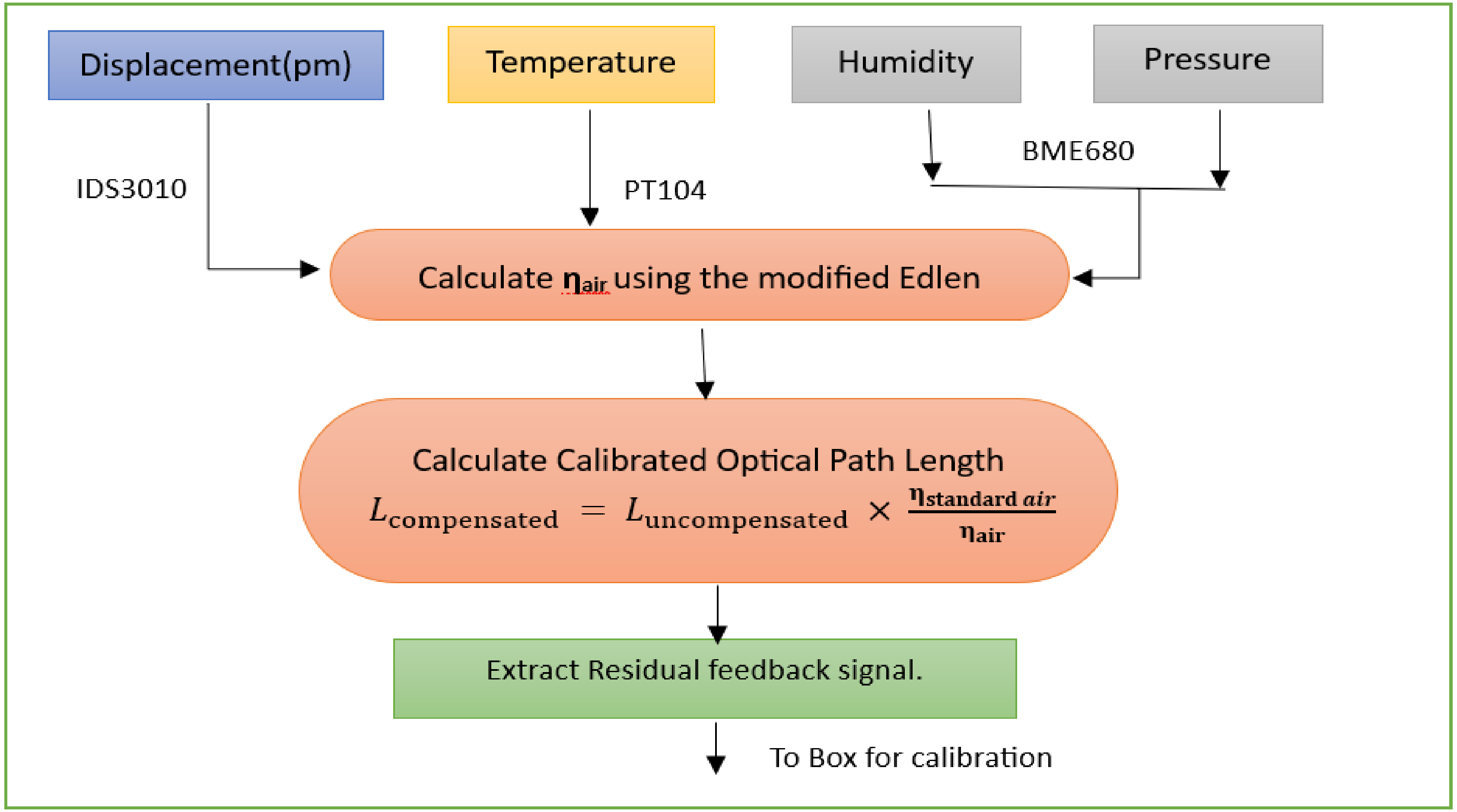
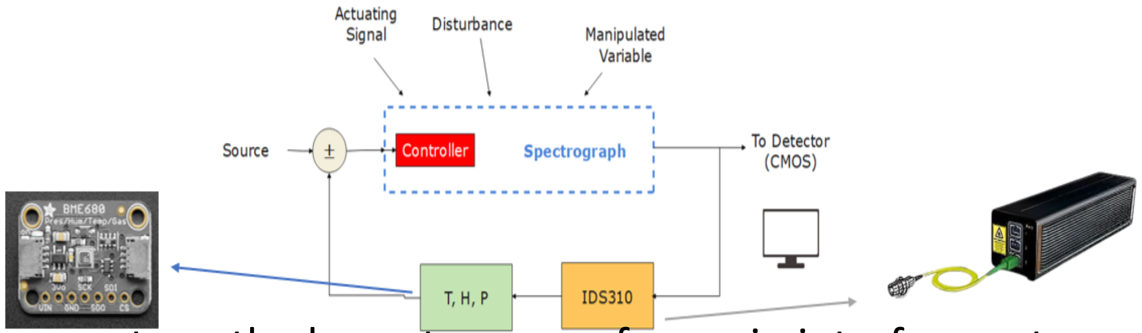


Fig. Flowchart: Algorithm to calculate the calibrated path.

(Edlen, 1996)
(Ciddor,1999)

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,

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

(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.

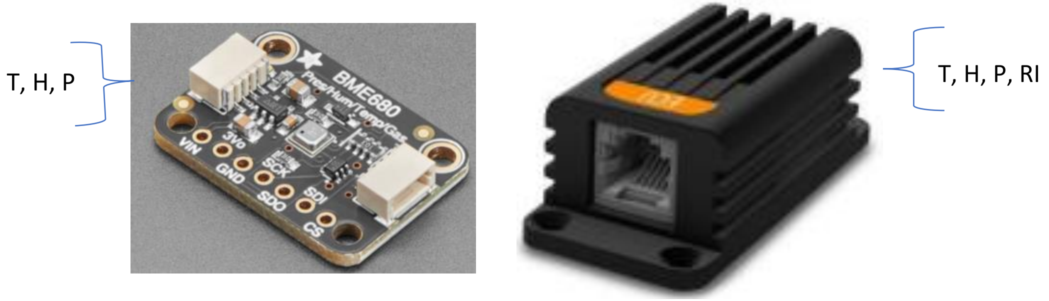
$$\boxed{\eta_{sa} = \eta_{\text{standard air}} = 1 + 7.86 \times 10^{-4} \frac{101.325}{273.15+T} - 1.5 \times 10^{-11} \times 50(20^2 + 160)}$$

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

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

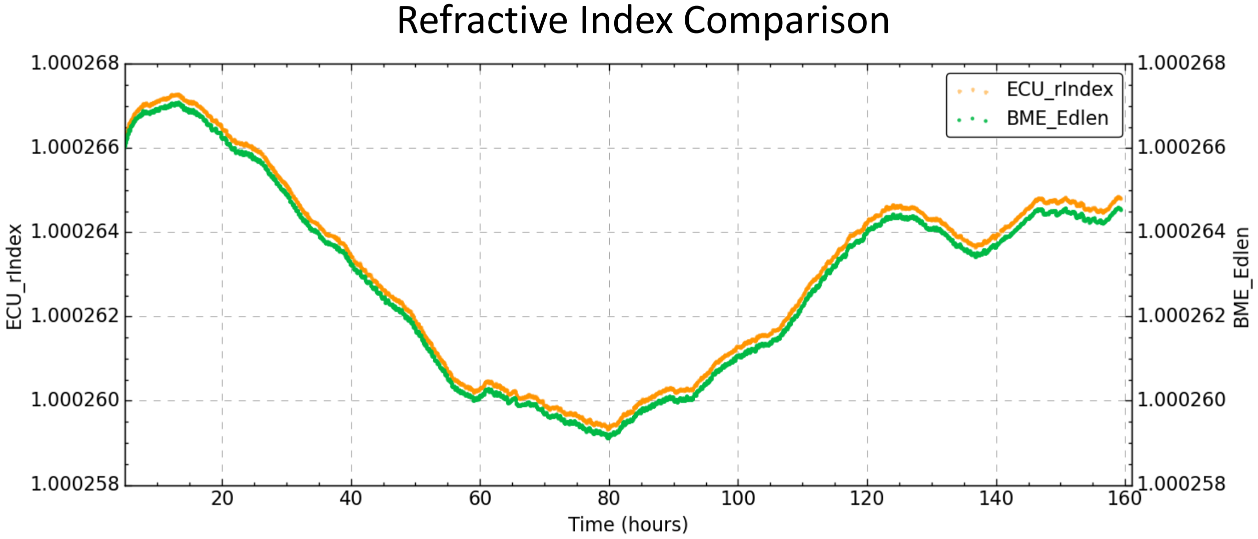
ECU vs BME680 Test

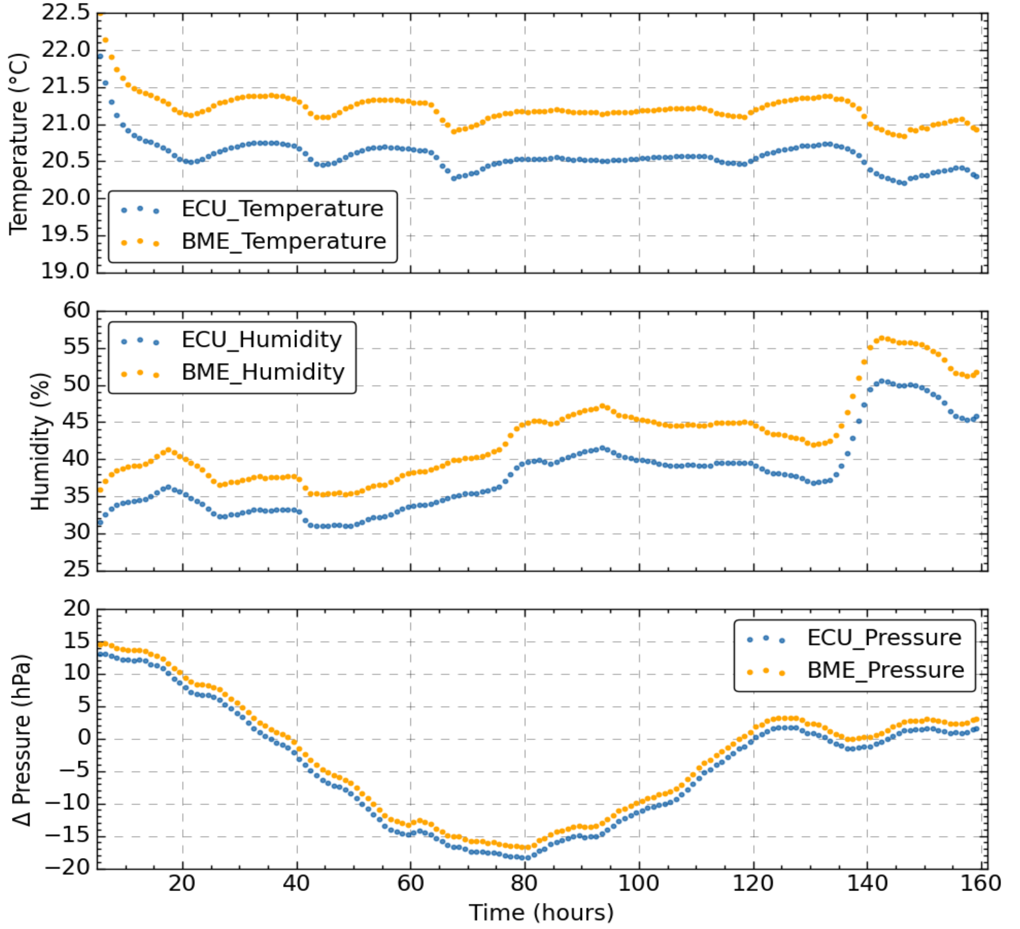
Fig. BME680 and Attocube Environmental Compensation Unit



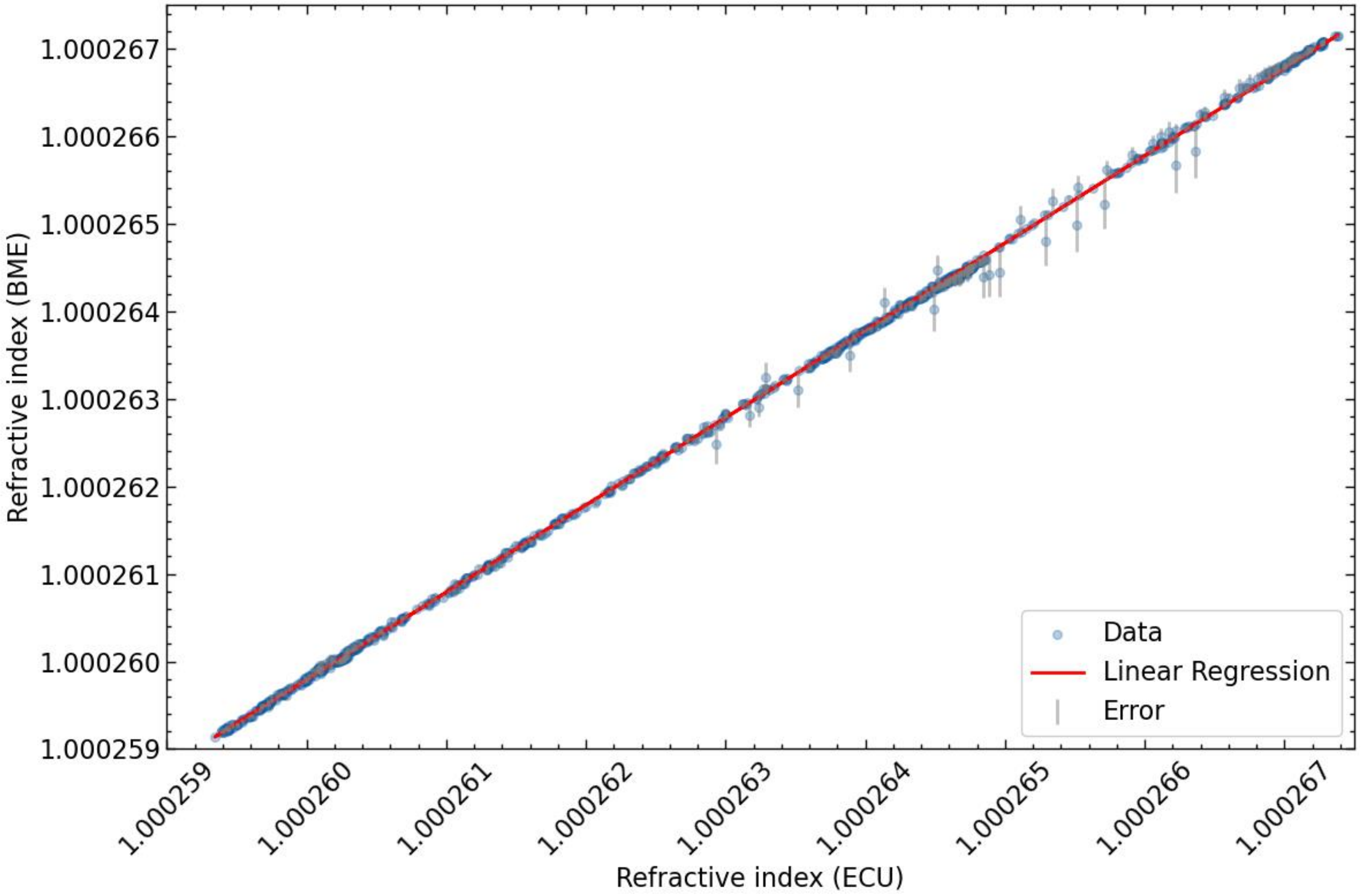
Parameters	BME	ECU	Δ change
Temperature (°C)	22.61	20.63627	1.97373
Humidity (%rh)	40.11	35.04	5.07
Pressure (hPa)	1013.47	1011.87	1.6

Parameters	BME Accuracy	ECU Accuracy	PT104 Accuracy
Temperature (°C)	±1	±0.1	0.001
Humidity (%rh)	±2%	±2%	
Pressure (hPa)	±1	±1	





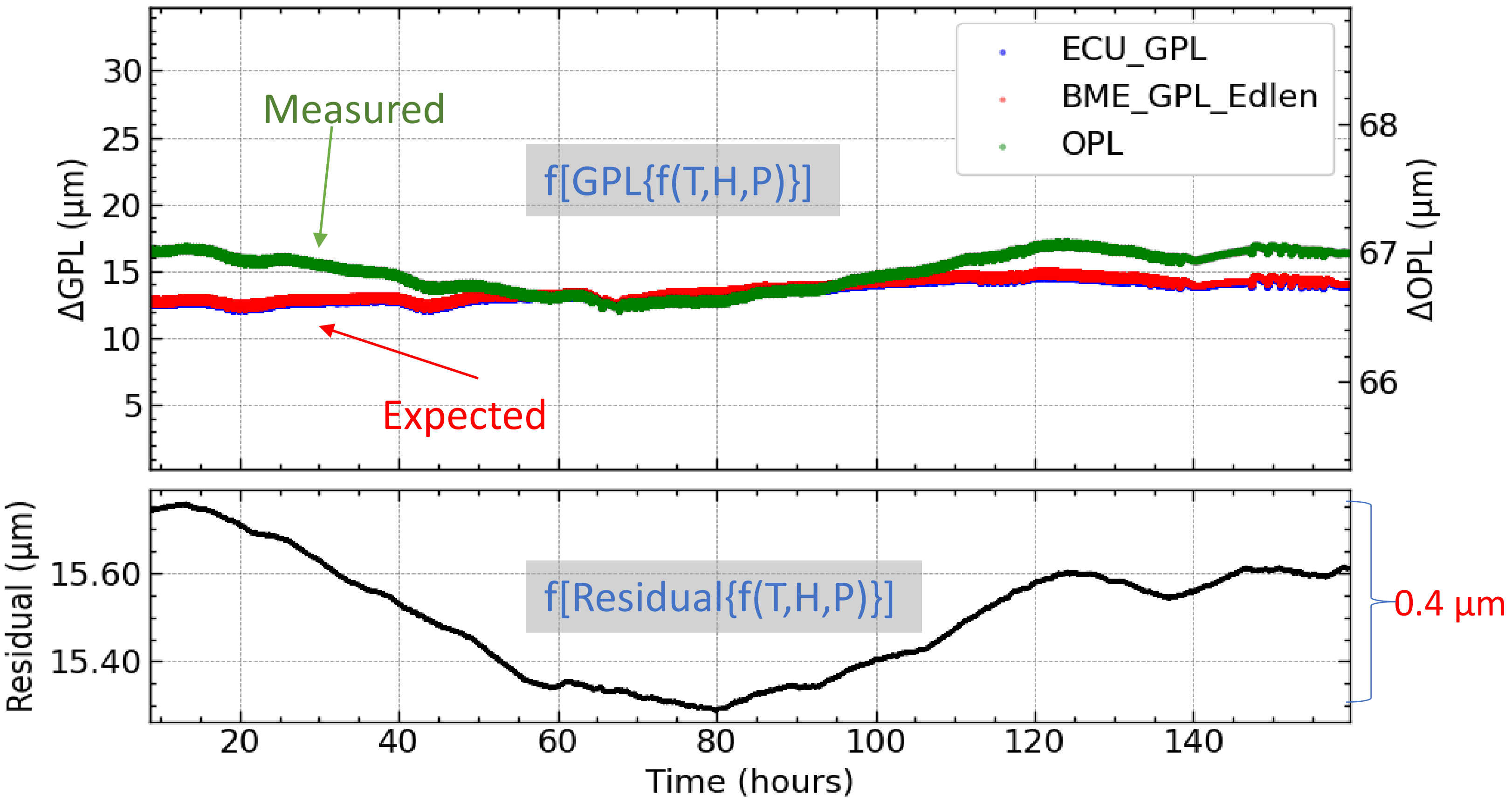
ECU vs BME680 Refractive Index Analysis

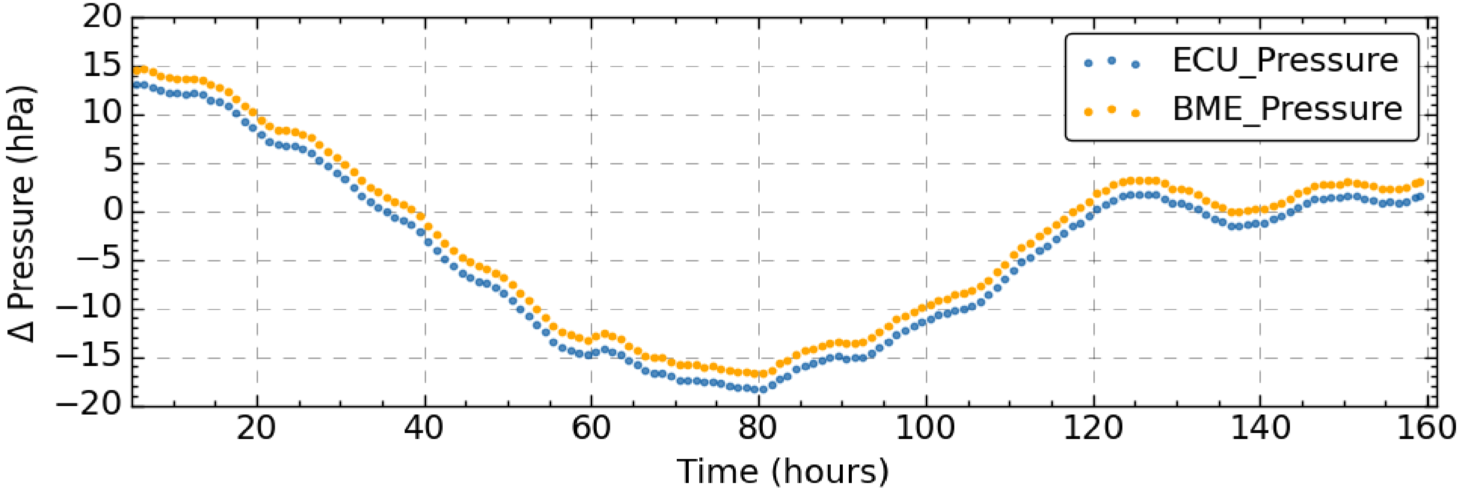


Correlation between BME_Edlen and ECU_rIndex: 99.78% ± 0.06%

Results and Analysis

- Geometric Path Length, or GPL (Expected/Compensated)
- Optical Path Length, or OPL (Measured/Uncompensated)
- $GPL = \dfrac{OPL}{Refractive\ Index}$
- Residual (or, Feedback Signal)
  = Measured – Expected
- Shows Residual trends correlation with Pressure change.
- Our adapted Model compensated the Pressure term.





Future Work

Fig. XYZ precision piezo nano-positioning system with picometer positioning resolution, Nano HS3M

- Implement Feedback Signal
- Box2 Integration: Implement the system within Box 2 and assess its stability with the developed algorithm.
- Pressure Stability: Integrate a pressure valve mechanism into Box 2 for consistent pressure levels.
- Implementing Real-time Monitoring, building web interface/app.

Key Milestones

PHASE 1: Equipment Orientation and System Introduction
- Familiarize with system components, and execute basic code for IDS using Python language

Completed

PHASE 2: Closed-Loop Feedback System Development
- Establish the foundation for the closed-loop system using IDS, BME680, and Peltier 101
- Integrate BME680 with ESP8266, design a webpage interface, and implement refractive index correction.

Completed

PHASE 3: System Integration and Optimization
- Assemble the integrated setup and conduct preliminary tests.
- Precisely calibrate optical components, implement Nano-HS3M, and conduct experiments for system validation.

In Progress

PHASE 4: Advanced Integration and Testing
- Subject the system to environmental robustness testing.
- Enhance interferometer configuration, refine calibration, and conduct extensive testing with various light sources.

Fig. Real Time Monitoring Web Interface for Spectrograph Functionalities and Sensor Control