# Advancements in Precision: LASER Interferometer Control System


*Presented By:* **Biswajit Jana**

*Supervisors:* **Prof. Hugh Jones and Prof. William Martin**

MSc Astrophysics

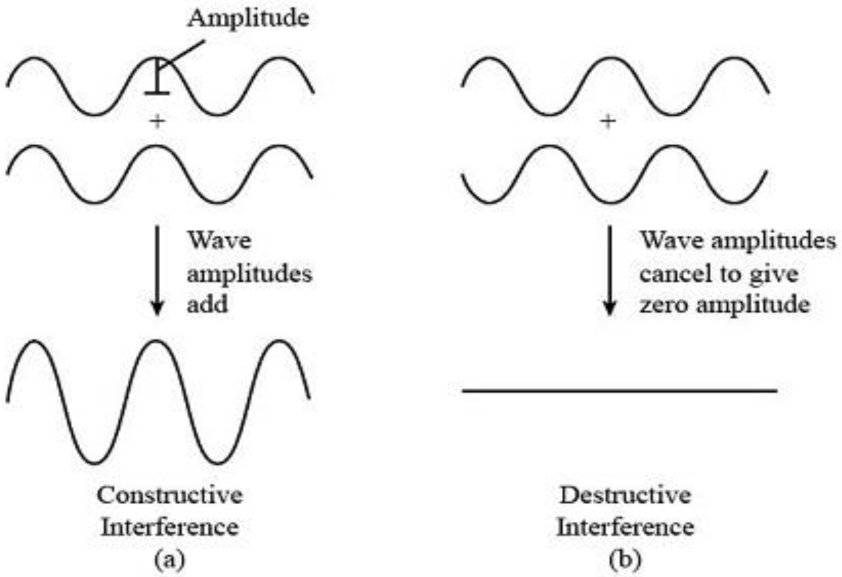

December 8th, 2023

# Outline

- Interferometry
- Types of Interferometer
  - Michelson Interferometer
  - Fabry-Perot Interferometer
  - Laser Interferometer
- Known Interferometer System
- Advantages & Disadvantages
- Connection to Project
- Results
- Summary

# Interferometry

- Measurement method utilizing wave interference, commonly with light, radio, or sound waves.
- **Scope of Measurements:** Involves assessing characteristics of waves and the materials they interact with.
- **Displacement Measuring Interferometry:** Specifically focuses on using light waves to study changes in displacement.
- **Applications in Precision Machining:** Widely utilized for calibration and mechanical stage motion control in precision machining.
- **Formation of Interference Pattern:** Achieved by superposing two light beams, allowing detection of small changes in optical path differences, especially with the precision introduced by laser technology.

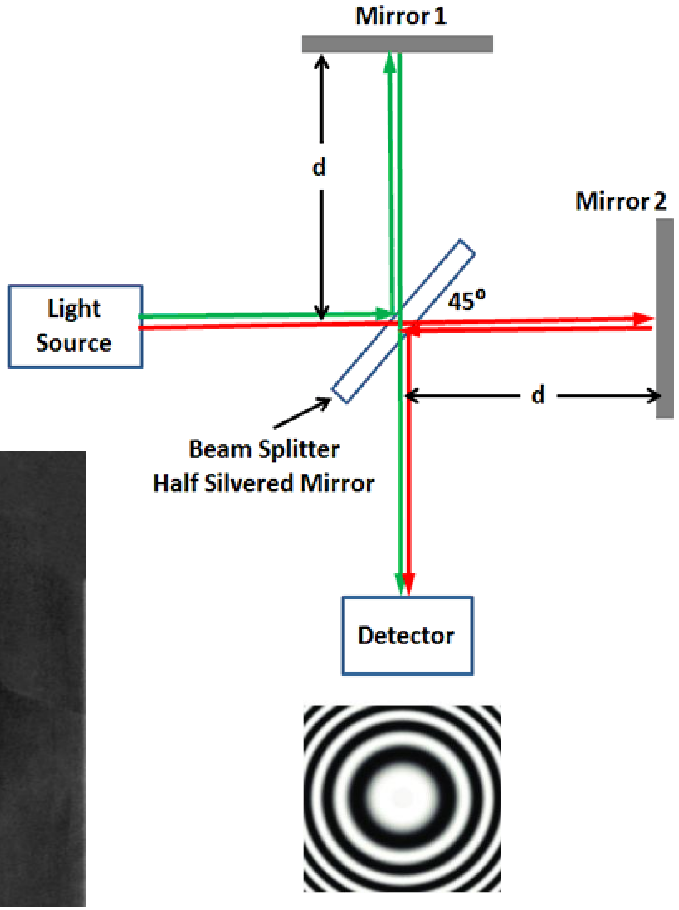


# Types of Interferometers

## *Michelson Interferometer*

- Introduced light interference for measurements in the 1880s.
- **Core Principles Persist:** Modern interferometers, including Michelson's, use a beamsplitter, two mirrors, and a detector.
- **Measurement Process:** Light splits, reflects, and recombines, creating an interference fringe pattern analyzed for various measurements, employing a coherent light source, beamsplitter, reference mirror, movable mirror, and detector.
- **Advantages:**
  - Simplicity in design.
  - Versatility for various applications.
- **Disadvantages:**
  - Susceptibility to environmental factors.
  - Limited sensitivity in certain configurations.

*Fig.:* *Michelson Interferometer design*



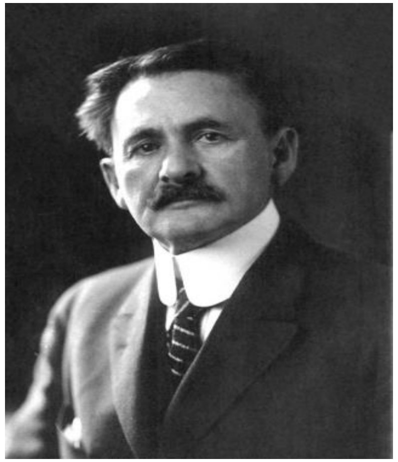



*Image:* *Albert A. Michelson*

# Types of Interferometers

## ***Fabry-Perot Interferometer***

Improved version of Michelson Interferometer, High Resolving Power Instrument. Combination of mirrors parallel to each other

- Advantages:
  - High resolution and finesse.
  - Versatile for a broad spectral range.
  - Suitable for cavity-enhanced spectroscopy.
- Disadvantages:
  - Complexity in alignment.
  - Sensitivity to temperature fluctuations.
  - Limited field of view.

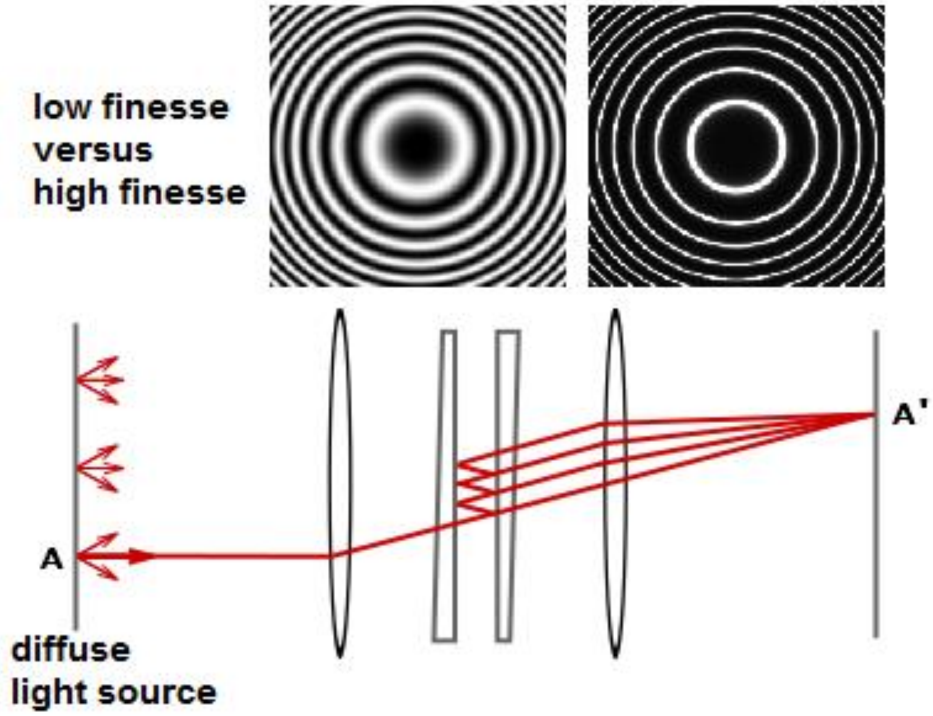



*Fig.* Using a pair of partially reflective, slightly wedged optical flats. The exaggerated wedge angle in the illustration (actual angle is minimal) avoids ghost fringes. Low-finesse (4% reflectivity, bare glass) and high-finesse (95% reflectivity) images are depicted.

# Laser Interferometer

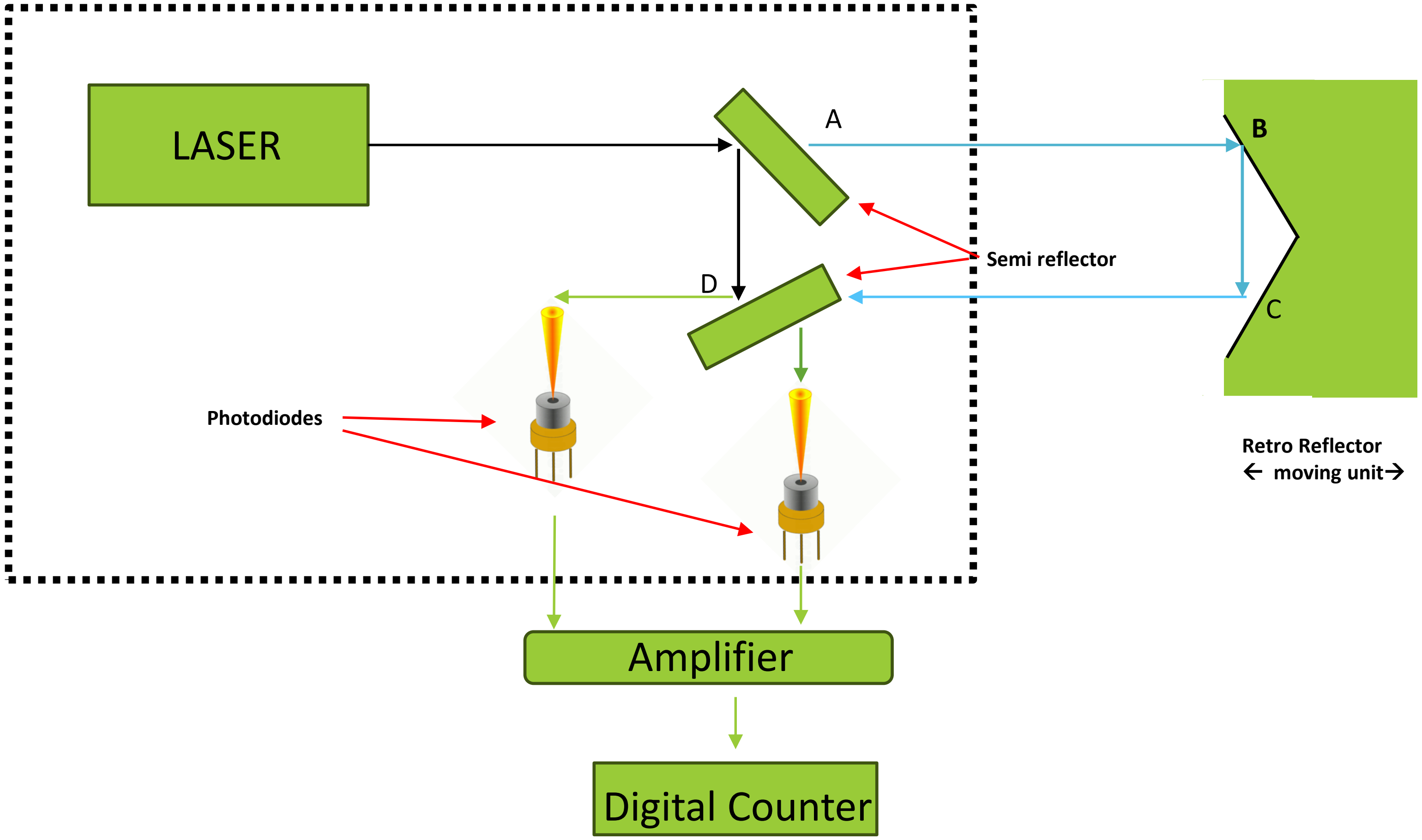



*Fig. Working Principle of Laser Interferometer*

- **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.

# LIGO (Laser Interferometer Gravitational-Wave Observatory)

- **LIGO Detection Advancements**: Michelson interferometers and Advanced LIGO upgrades enable precise measurement of gravitational waves.
- **Observatory Network:** Multiple LIGO detectors in Louisiana and Washington confirm and pinpoint cosmic events.
- **Technological Enhancements:** O3 run improvements, including squeezed light and laser power, refine high-frequency sensitivity.
- **Noise Challenges:** Correlated noise, primarily from laser frequency and intensity, poses challenges, with unknown origins at 1-2 kHz.
- **Sensitivity Limits:** Correlated noise below 100 Hz restricts sensitivity at 40 Hz, impacting certain gravitational wave detections.
- **Detailed Noise Analysis:** Comprehensive study includes visualizing noise budgets and amplitude spectral density, encompassing interferometer properties and auxiliary channels.


*Image Credit: Aerial view, [LIGO Lab, Caltech | MIT]()*

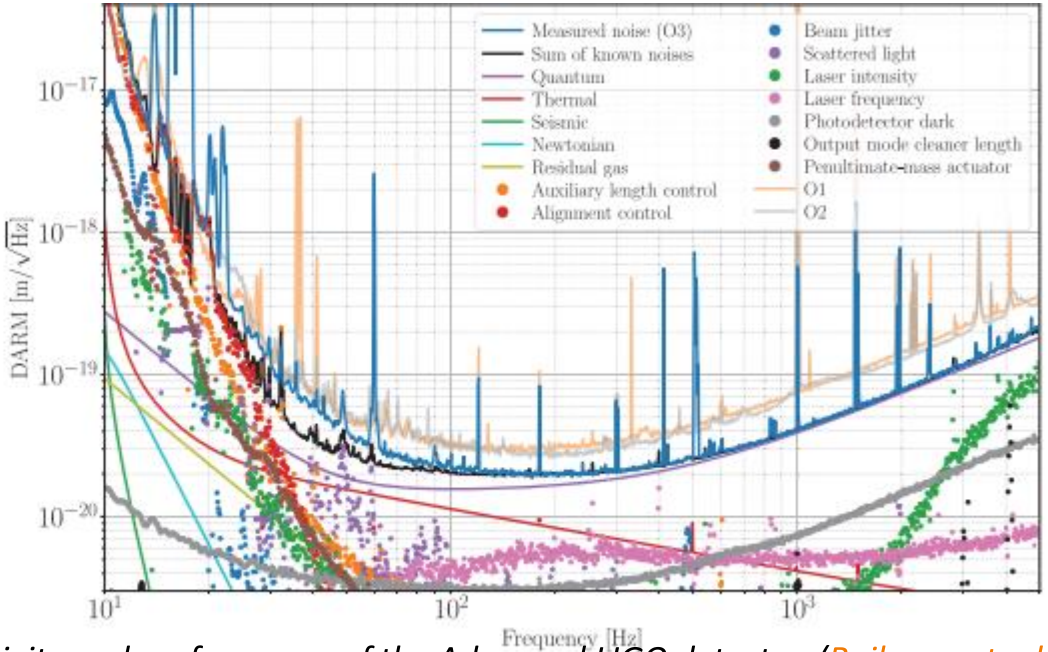
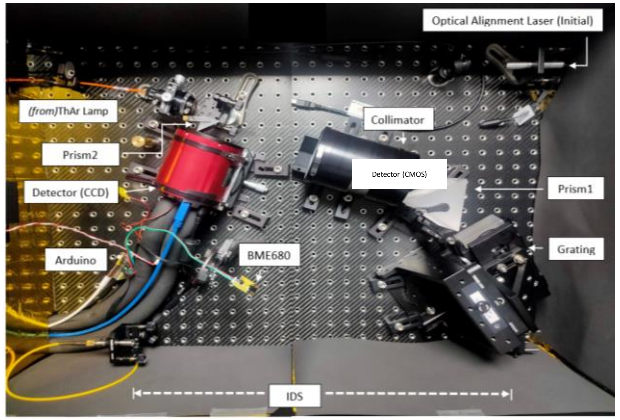



*Fig. Sensitivity and performance of the Advanced LIGO detectors([Buikema et. al. 2020]())*



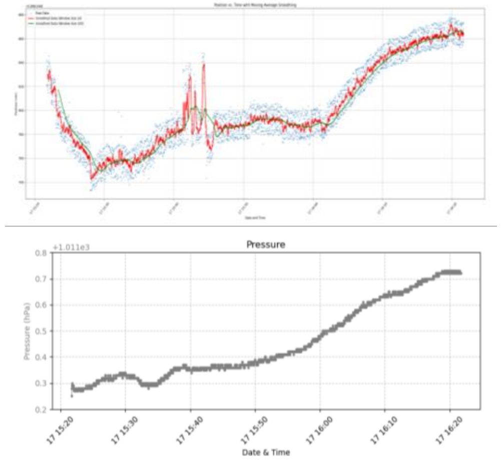




Image: Exohspec Design. The graph illustrates the pressure-dependent nature of the optical path.

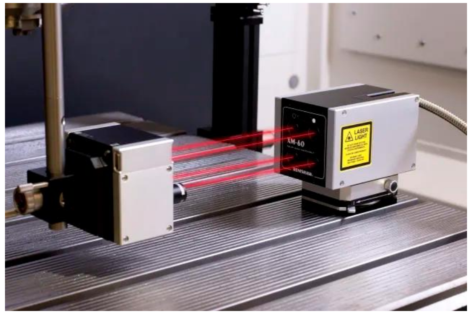


Image courtesy of Renishaw

Precision Metrology

Environmental Monitoring For Spectroscopy

Industrial Machining and Calibration

Application

Semiconductor Manufacturing

Astronomical Observations - GW

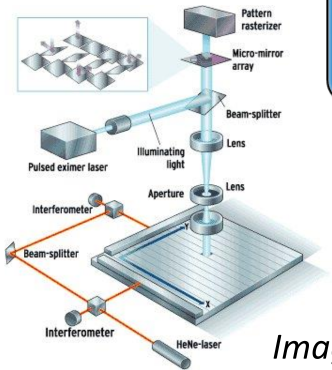
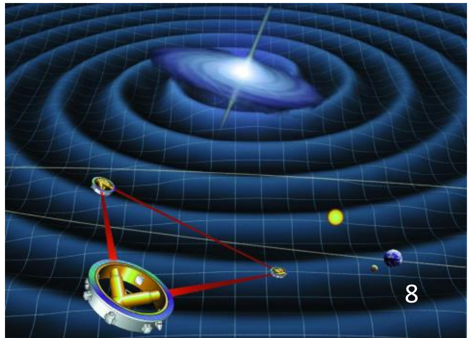



Image Credit: Wana C.,2013

Image Credit: LISA Observatory



# Advantages of Laser Interferometers

| | |
|---|---|
| **Picometer-level Accuracy:** | Precision at the picometer scale for accurate measurements. |
| **Real-time Measurement Capabilities:** | Ability to perform dynamic, real-time measurements. |
| **Non-invasive Nature:** | Non-intrusive measurements are suitable for delicate systems. |
| **Reliability and Stability:** | High reliability and stability for continuous monitoring. |
| **Broad Applicability:** | Versatility across various scientific domains |

# Disadvantages of Laser Interferometers

| | |
|---|---|
| **Susceptibility to Environmental Factors:** | Sensitivity to external factors like temperature, pressure, and vibrations. |
| **Sensitivity to Mechanical Vibrations:** | Impact of mechanical vibrations on measurement accuracy. |
| **Complexity and Cost Factors:** | Intricate design and associated costs. |
| **Calibration Challenges:** | Difficulty in achieving and maintaining calibration. |
| **Limited Field of View:** | Constraints on the observable field in certain configurations. |

# Connecting with my Master Project

- Implementation of Laser Interferometer for Spectrograph focus on achieving picometer precision in Optical path and calibrating the overall system.

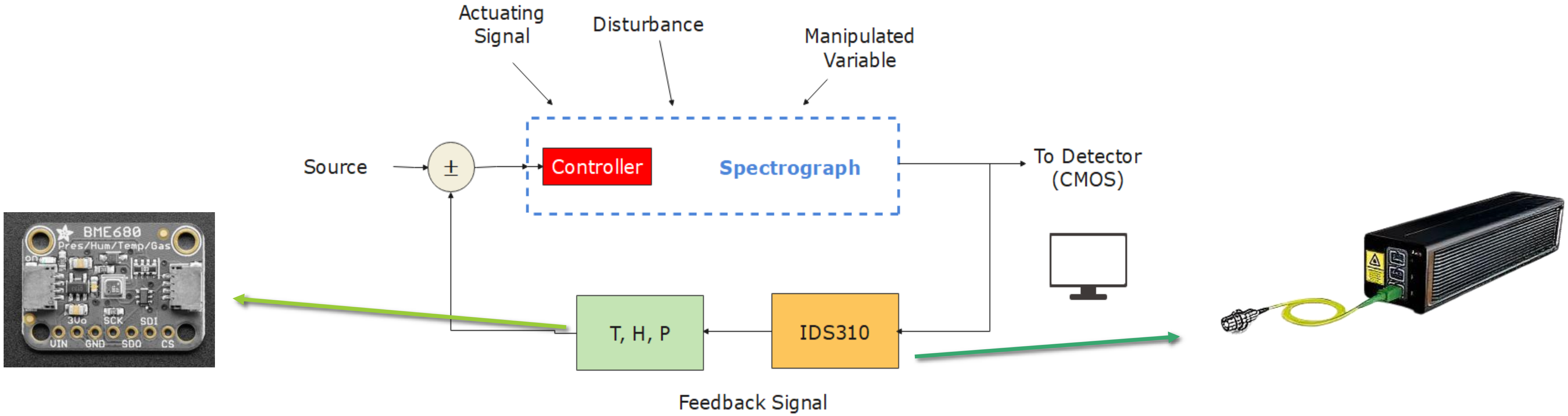



*Fig. 1. Schematic Block Diagram of the Spectrograph Control Feedback System*

Machinery  tool

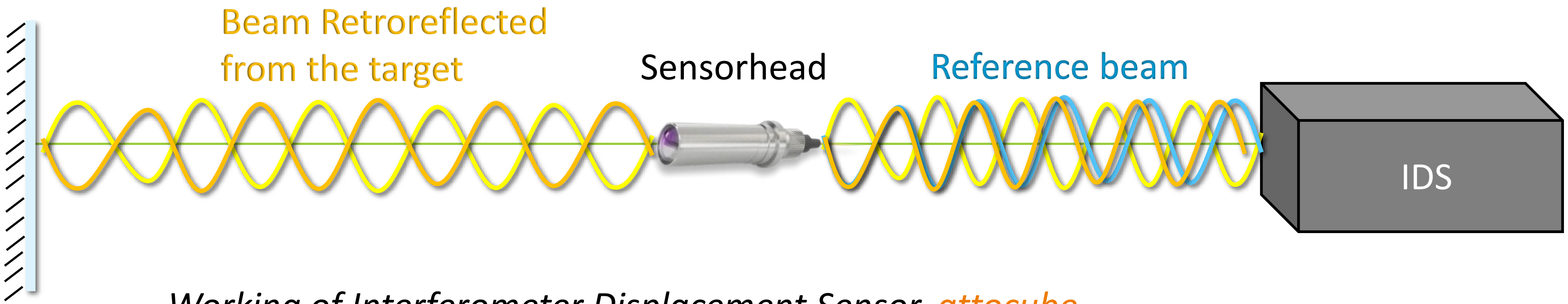
<u>Specification of IDS310</u>-

Fibre-coupled laser diodes, compact modular design
Number of sensor axes: 3
Sensor resolution: 1 pm
Distance coverage: mm to 30 m
Signal Stability: 0.11nm(2s)
Measurement bandwidth: 10MHz
Measurement mode: Displacement

*Working of Interferometer Displacement Sensor*

Retroreflector

[Fixed]




*Working of Interferometer Displacement Sensor, attocube*

# Experimental Results Highlights

- **Control System Laser Interferometer Experiment:**
    - 2-hour experiment examining interferometer and environmental sensor impact.
    - Identified temperature and pressure as key factors affecting optical path length.
    - Noted initial decrease and subsequent increase in optical path length with temperature changes.
    - Implemented a nanometer-scale control feedback loop instrument for precise monitoring.
    - Instrument crucial for spectrograph calibration, addressing noise susceptibility.
- **Outer Box Temperature Variation Experiment:**
    - Explored temperature variations in the designated outer box.
    - Insights gained into the box’s effectiveness in maintaining a specific temperature.
    - Results contribute to evaluating the stability and functionality of the temperature maintenance system.
- **Slid Variation Experiment:**
    - Aim to monitor the variation in the optical path.

# Control System Laser Interferometer Experiment Results(inside box):

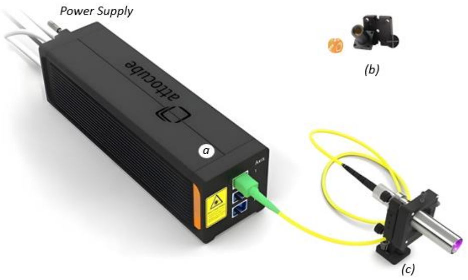



*Fig. 4. (a) IDS including Accessories, (b) Sensor head selection and alignment simplified with advanced mounting kits, (c) Optical items: glass target, plane mirror, and retroreflector*

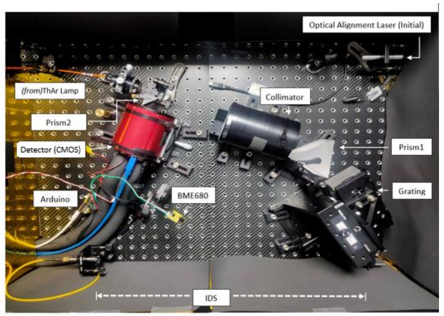
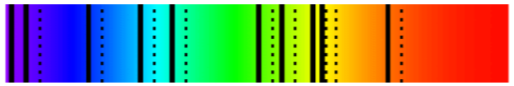



*Fig. 3. Internal structure of the Modified EXOhSPEC along with IDS and BME680 integrated*

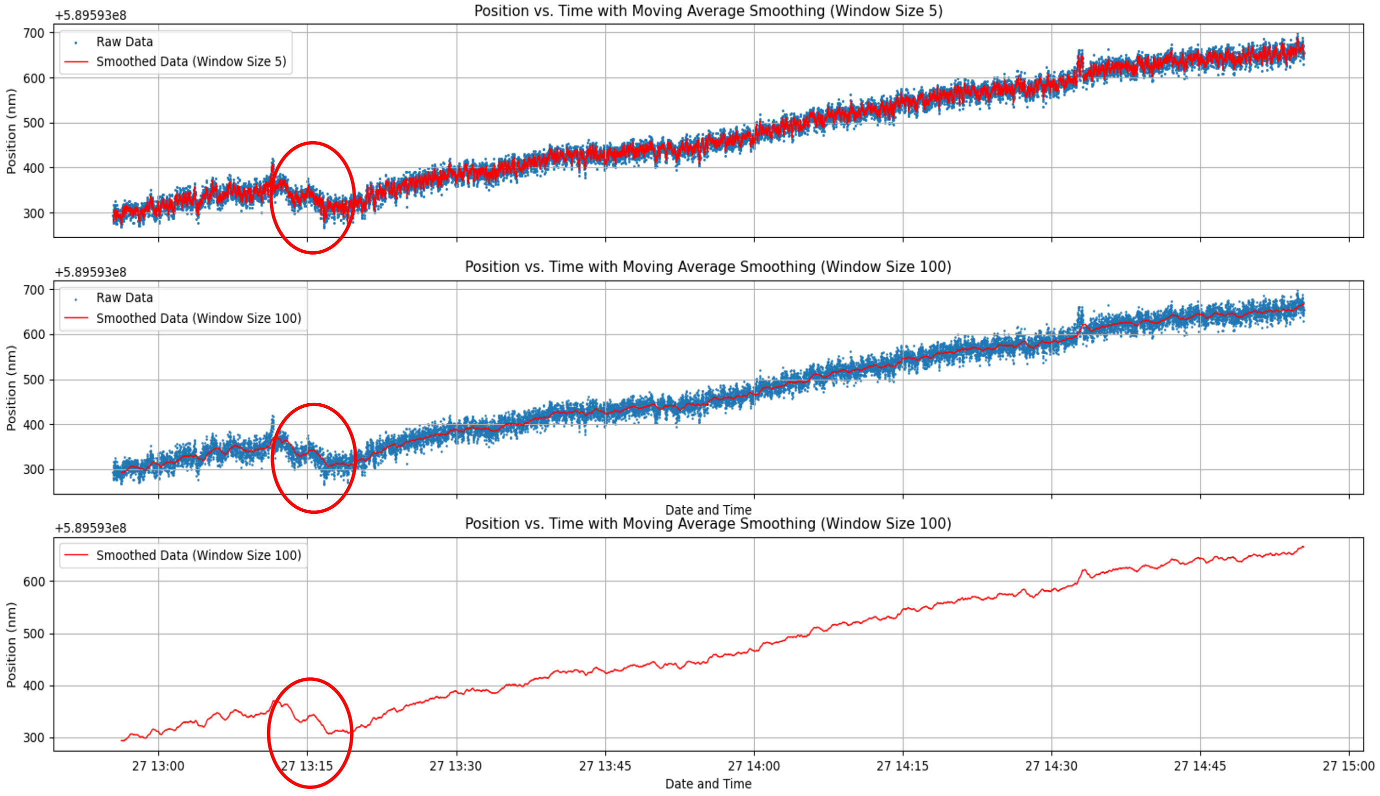
Wien's Displacement Law:

$\lambda_{max} \propto 1/T$



(a)

(b)




(c)

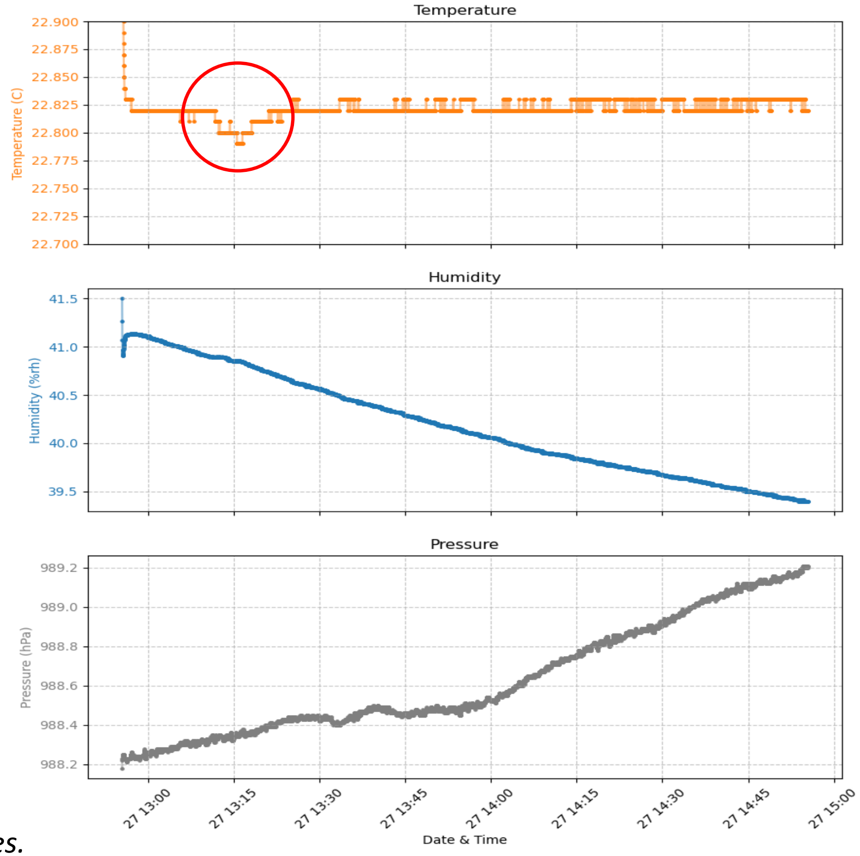



*Fig. (a) Position vs Time (Raw Data): Raw IDS displacement data over 1 hour, revealing trends in optical path changes. (b) Moving Average Smoothing: High-frequency data smoothed with moving averages, enhancing trend visibility. (c) Temperature, Pressure, Humidity vs Date & Time*

# Outer Box Temperature Variation Experiment:

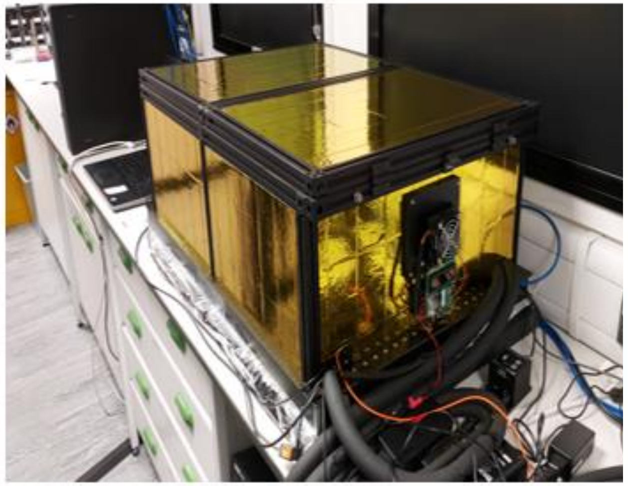
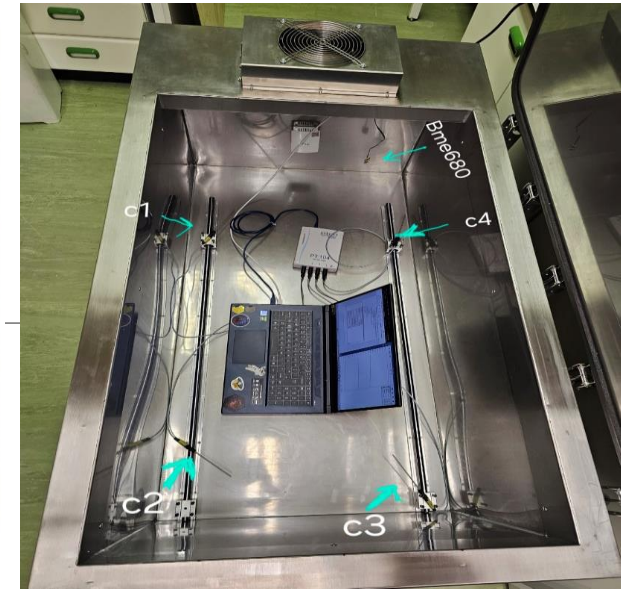


Fig. 7: The system's outer box is positioned on a carbon fibre breadboard.

Fig. 8. Modified protective box designed to shield the system from environmental factors, primarily focusing on temperature control.



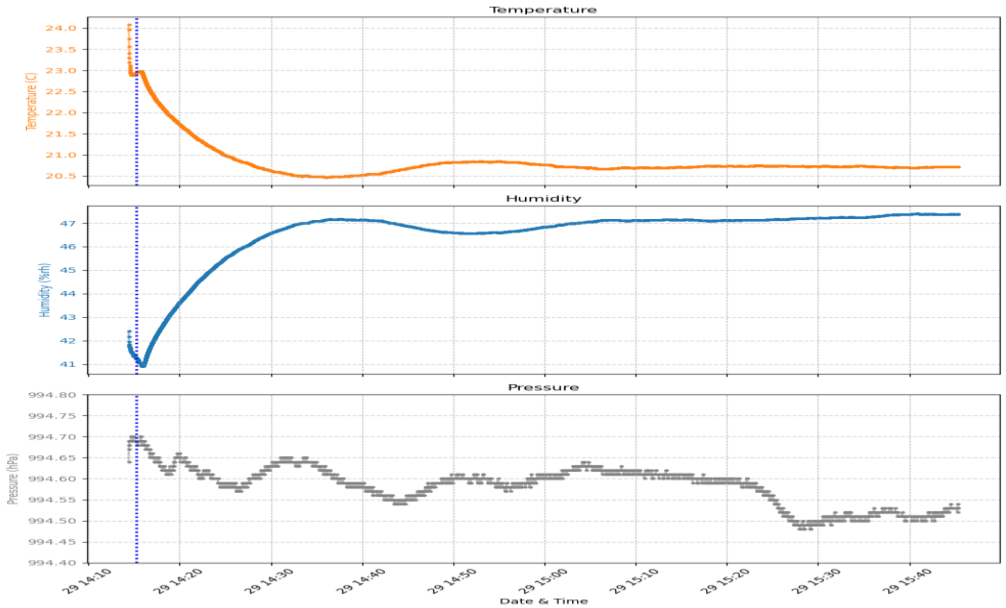




Fig. Bme680 Tempereature, Humidity, Pressure readings vs time

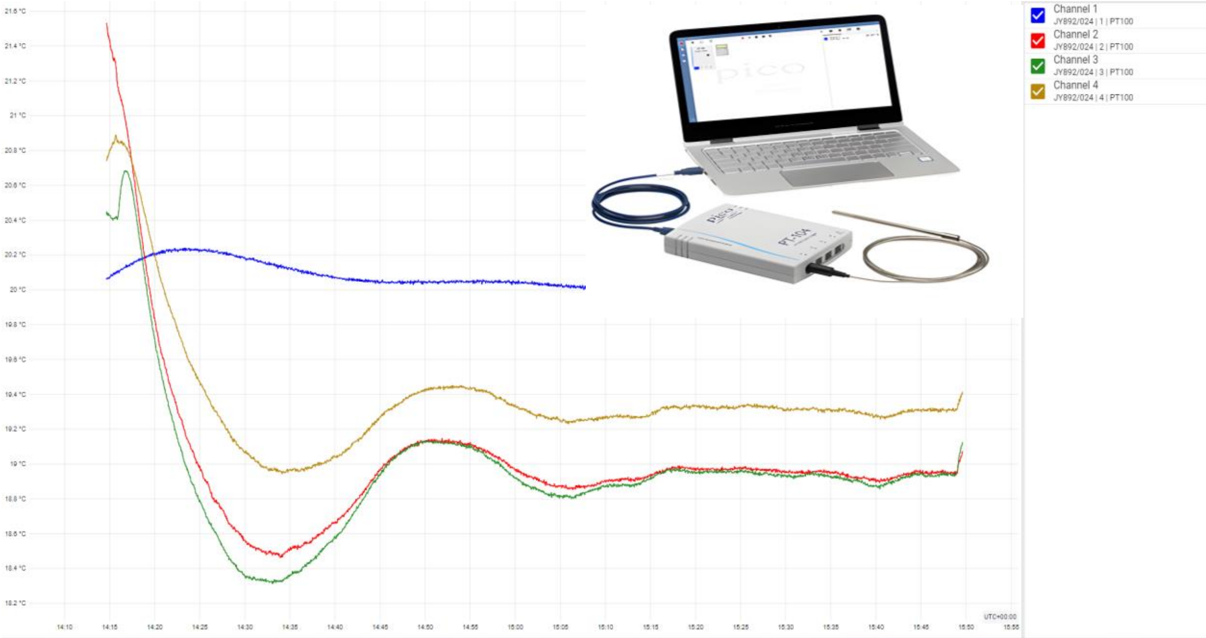
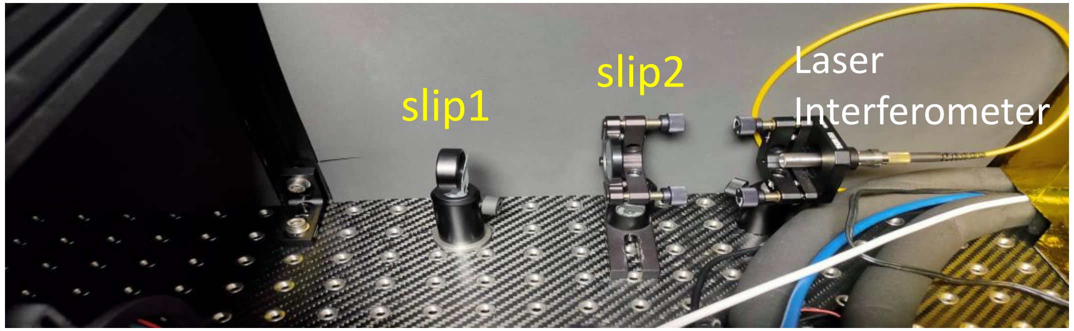
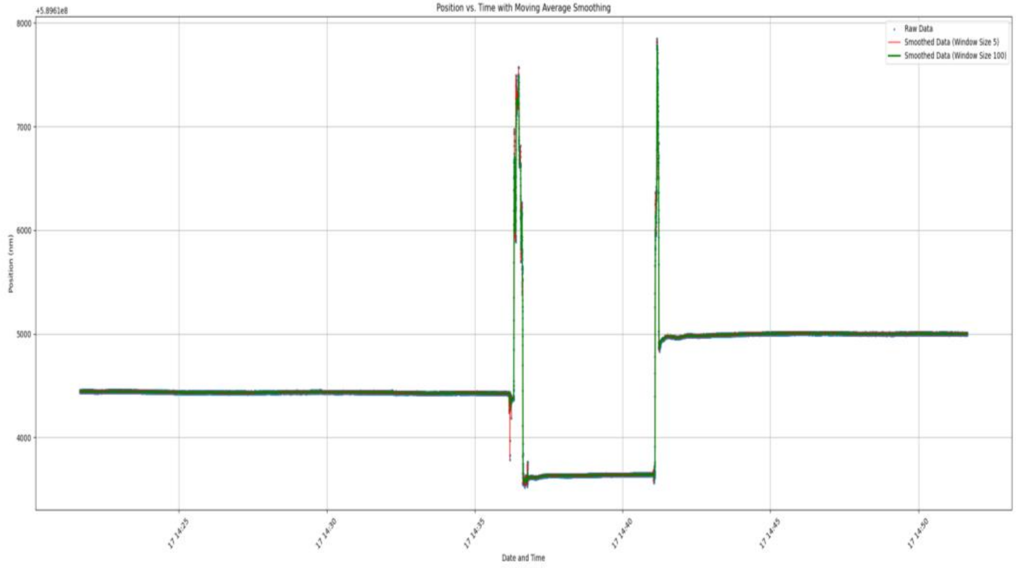



Fig. Peltier-104 Temperature Sensor 4 channel readings vs timeFig

# Slid Variation Experiment:




- Initial experiments use 0.12-0.16mm glass slip1.




- Repeating the experiment, and introducing another glass slip2 of thickness in μm.

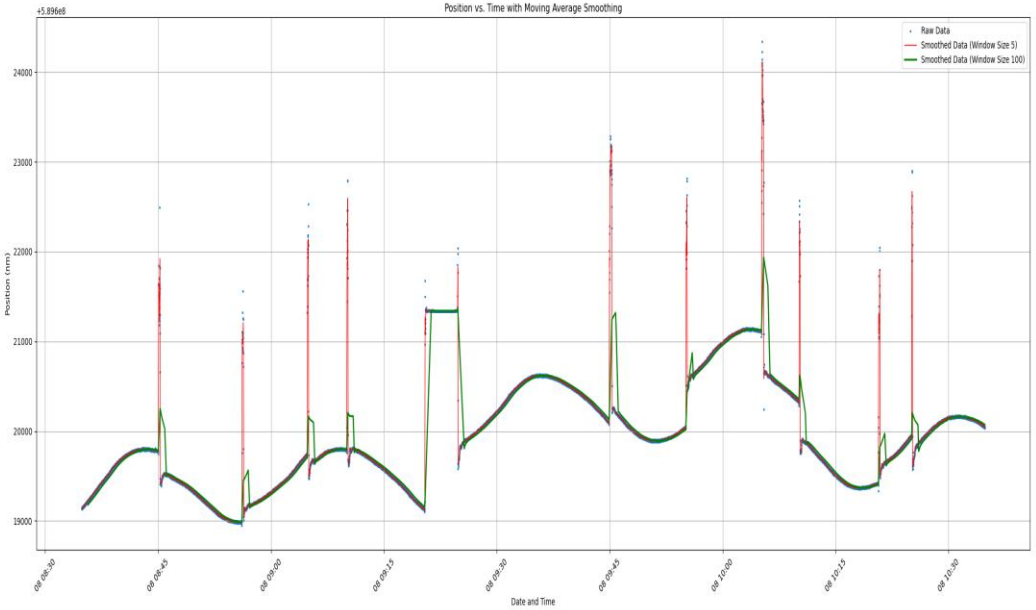
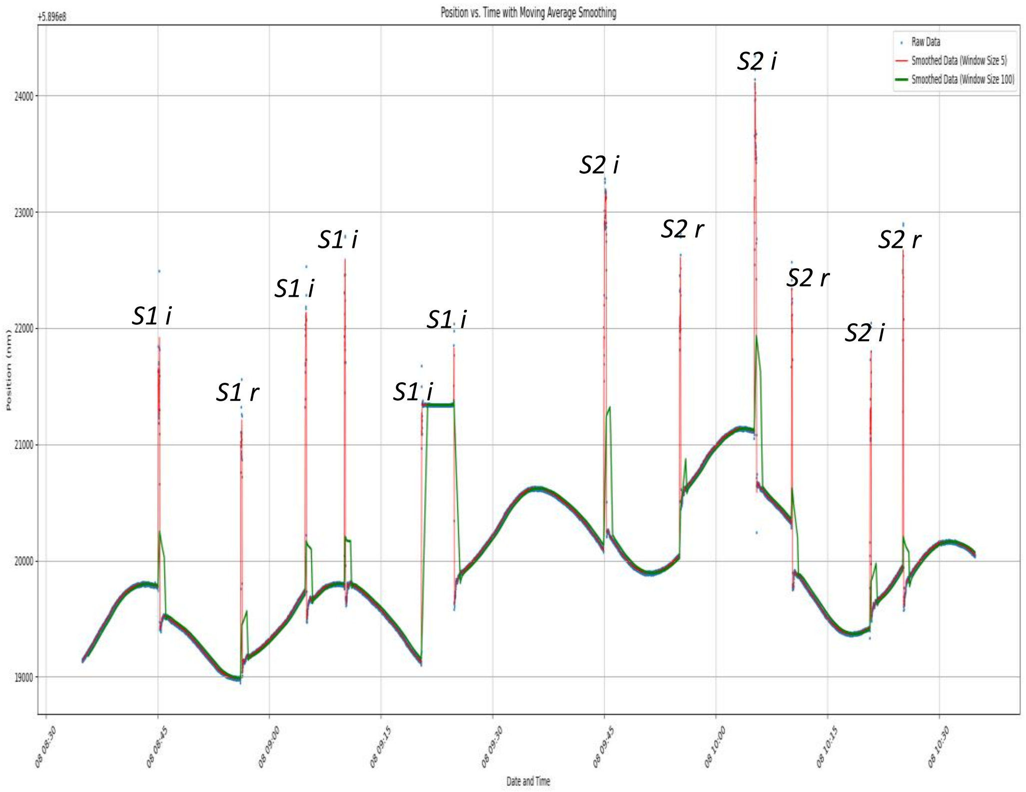
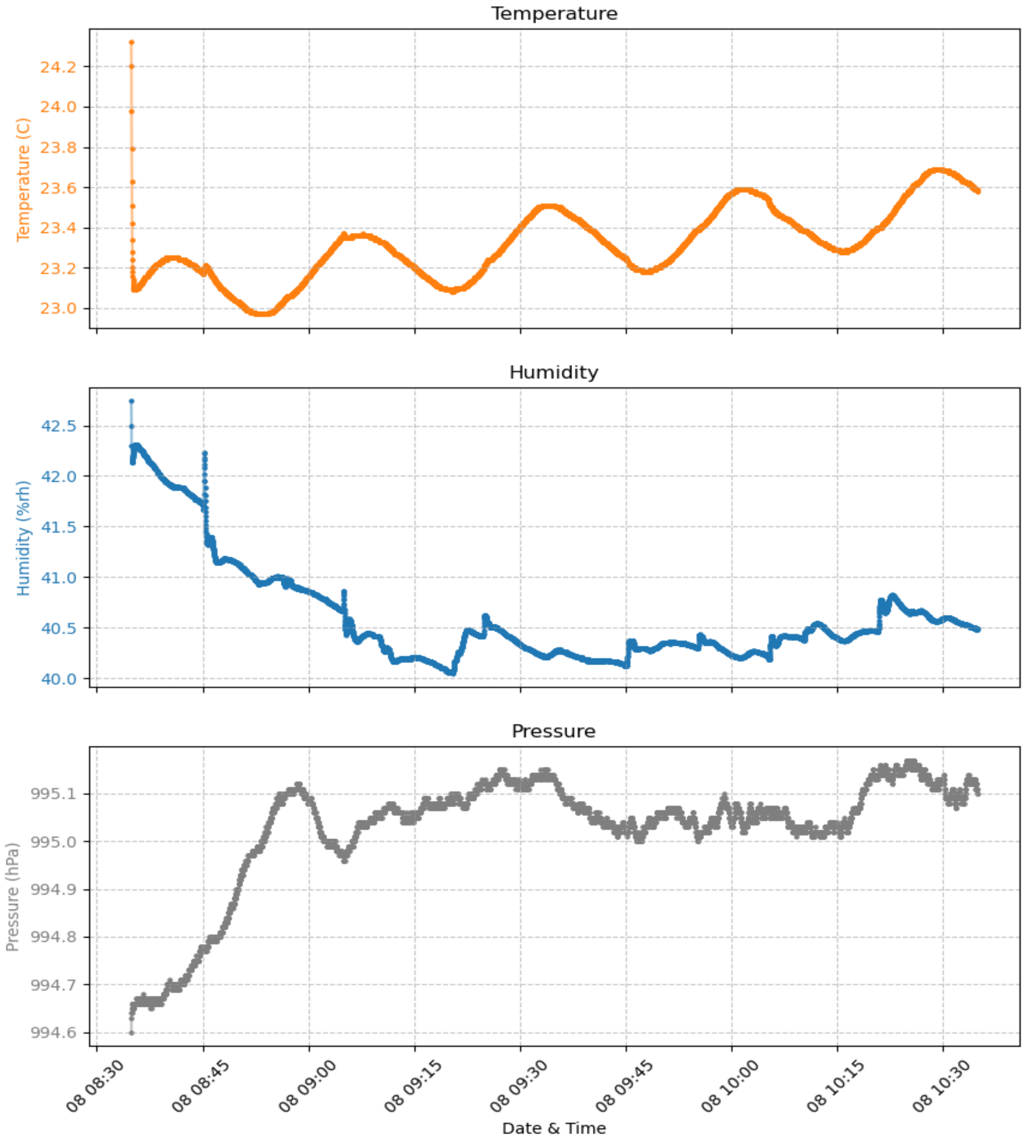



*Fig. Position vs Time (Raw Data): Raw IDS displacement data over 1 hour, revealing trends in optical path changes on the introduction of glass slip*

*Fig. Position vs Time (Raw Data): Raw IDS displacement data over 2 hrs, s1 and s2 represent slips, and i & r represents insert and removed*



# Summary

- Laser interferometry is a pivotal tool in precision measurements, from gravitational wave detection to high-precision spectroscopy.
- Explored notable systems like LIGO focused on gravitational waves.
- Various types of interferometers, including Michelson, and Fabry-Perot were discussed, each with distinct advantages and challenges.
- Application to My Project:
  - Implementing a laser interferometer for a high-precision spectrograph.
  - Acts as a crucial calibration tool, ensuring stability at the picometer level amid environmental changes.
  - Opens a research area in the field of High-Resolution RV Spectrograph Development.