Maintaining and Managing a Large Low-Cost Sensor Network

Nimit Godhani

HEI
Health Effects Institute
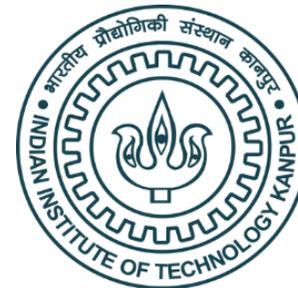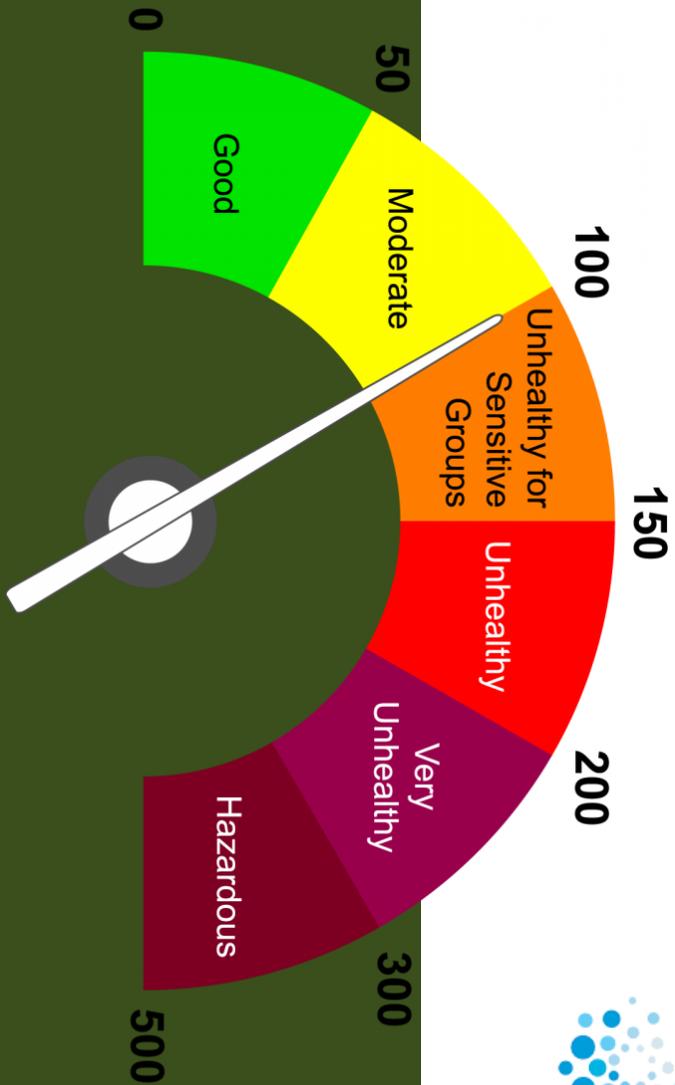
Indian Institute of Technology

Kanpur

What ? & Why ?

What are Low-Cost Sensors?
Low-cost sensors are affordable, compact sensing devices used for large-scale and dense monitoring, especially where deploying expensive instruments is not feasible.

What can they measure?
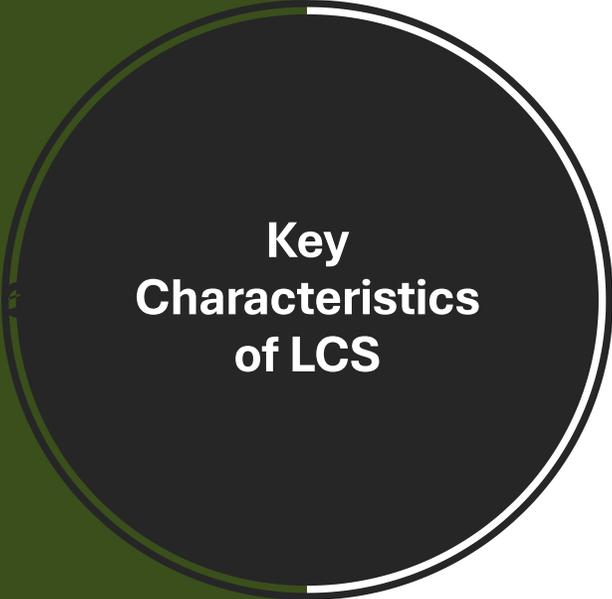- Particulate matter sensors ($PM_{2.5}$, PM_{10})
- Optical particle counters (Size Distribution)
- Gas sensors (Electrochemical sensors) for NO_2, CO, O_3 etc.

Other Domains
- Temperature and humidity sensors
- Noise sensors
- Water quality sensors
- Soil moisture sensors

Why Use Low-Cost Sensors?
- Enable city-scale monitoring
- Provide high spatial and temporal resolution
- Support research, public awareness, and decision-making
- Ideal for smart cities and IoT applications
- Complement (not replace) reference-grade stations

Comparison: Low-Cost vs Reference-Grade Sensors

Feature	Low-Cost Sensors	Reference-Grade Sensors
Cost	Low	Very high
Accuracy	Moderate	Very high
Maintenance	Frequent	Less frequent
Calibration	Essential	Periodic
Deployment	Large numbers	Limited
Use case	Dense monitoring	Regulatory compliance

LCS manual developed by IITK

Smart and Affordable

A Manual for Air Quality Monitors with Low Cost Sensors

Empowering Communities for Cleaner Air Through Accessible Technology

Sustainable Development

Awareness

Policy Intervention

Ambient Air Quality & Health Exposure

Environmental Research

Collaboration

Low Cost Sensors

Centre of Excellence - ATMAN
Advanced Technologies for Monitoring Air-quality iNdicators

Scope of handbook

The handbook aims to help people learn how to install and use low-cost sensors for monitoring air quality. It is designed for individuals with basic education and helps them understand pollution levels in their local area, track changes over time, and identify possible pollution sources. By doing so, it encourages community involvement in reducing pollution, working together with local authorities such as Gram Panchayats and Urban Local Bodies.

With a focus on cost-effective solutions and reliable air quality monitoring practices, this handbook serves as a vital resource for deploying low-cost PM sensors in professional, community, and research contexts. By equipping individuals with the knowledge and skills to engage in air quality monitoring, it contributes with building a more informed and participatory approach to pollution management and mitigation.

Overview of low-cost sensors

Low-cost sensors provides real-time measurements of $PM_{2.5}$ concentration ($\mu g/m^3$), Relative Humidity (RH) (%) and Temperature (°C). This robust device has ability to provide the real-time data at 1 minute interval with wide range of measurements listed below:

Low Cost Strategy

$PM_{2.5}$: 0 – 1000 $\mu g/m^3$.

Temperature: -10 to +60 °C.

Relative Humidity: 0 – 99 %.

Overview of low-cost sensors

PM 2.5: 4
PM1:2   PM10:4

CONTACT INFORMATION

📞 05122597274

✉ atman-coe@iitk.ac.in

atmos
real-time air quality

Respirer Living Sciences

Overview of low-cost sensors

IMEI 4C7525091642
Batch 2307_03

OFF/ON

Power switch

Power indicator

SD card

Overview of low-cost sensors

DC in · Solar in · Temp. & RH sensor · Air vents of PM sensor
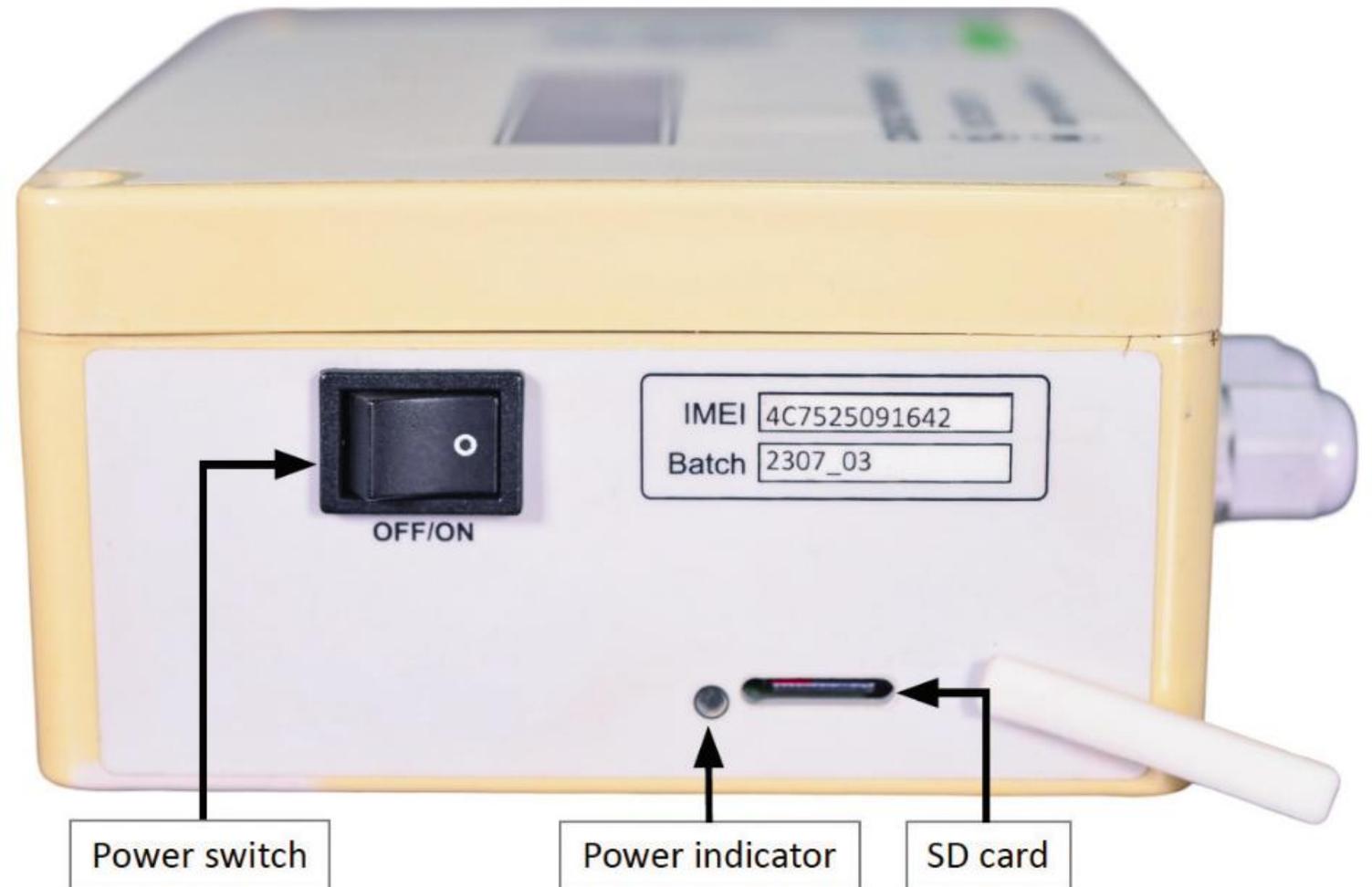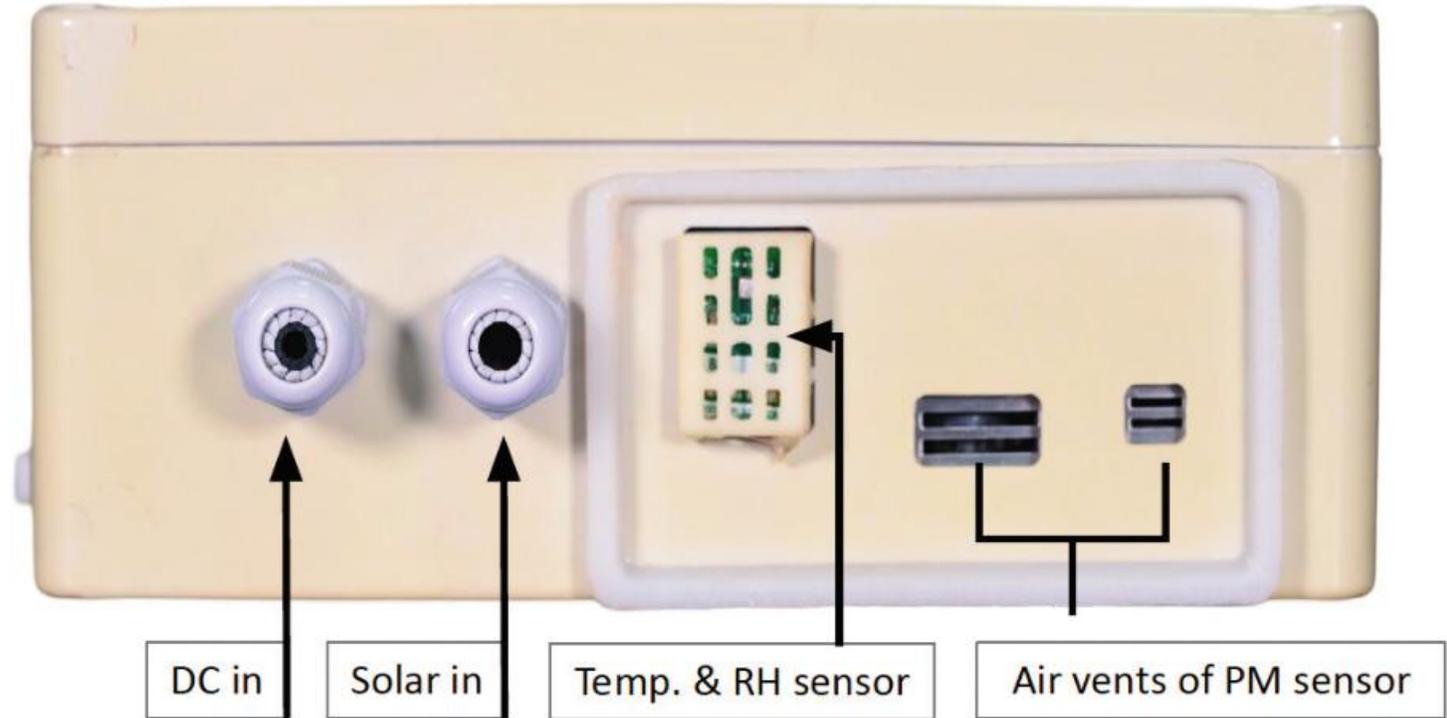
Internal parts used in the device

1) 5V DC power supply from mains (SMPS).

2) Solar power supply.

3) Battery for emergency power supply.

4) Motherboard to connect all sensors.

5) PM sensor.

6) Temperature & RH sensor.

7) GPS module for location accuracy and GSM module for internet connection; for real-time data transfer.

8) SD card for data storage. (In case of network error, still data will be stored in SD card. Which benefits of no missing data.)

9) RTC for time notation.

10) 16 segment display for live data display on device.
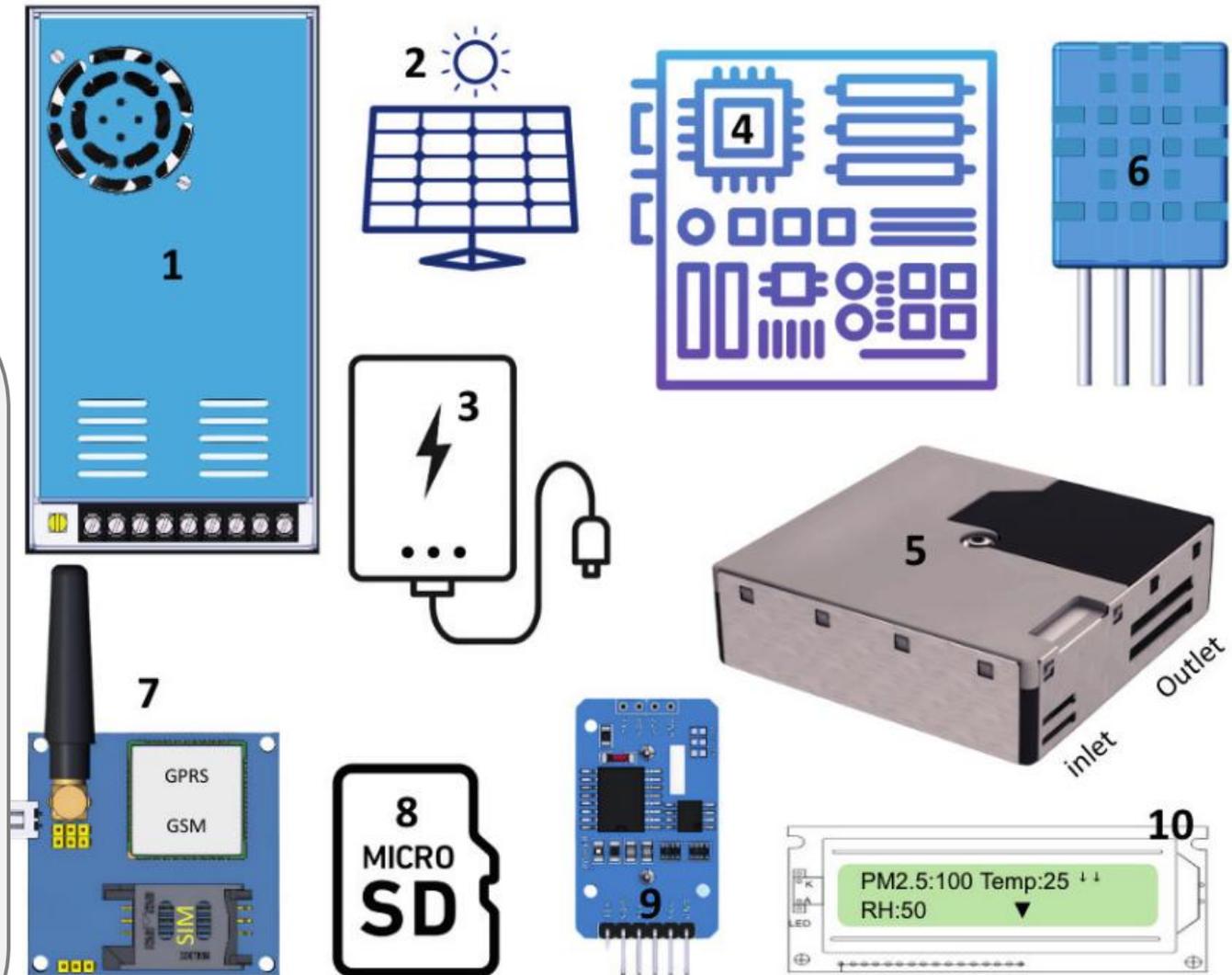
Working Principle of the Sensor

Detector ▶

Processor ▲

Air-Inlet ▶

Air-Outlet ▶

Laser ▶

Reflector ▶
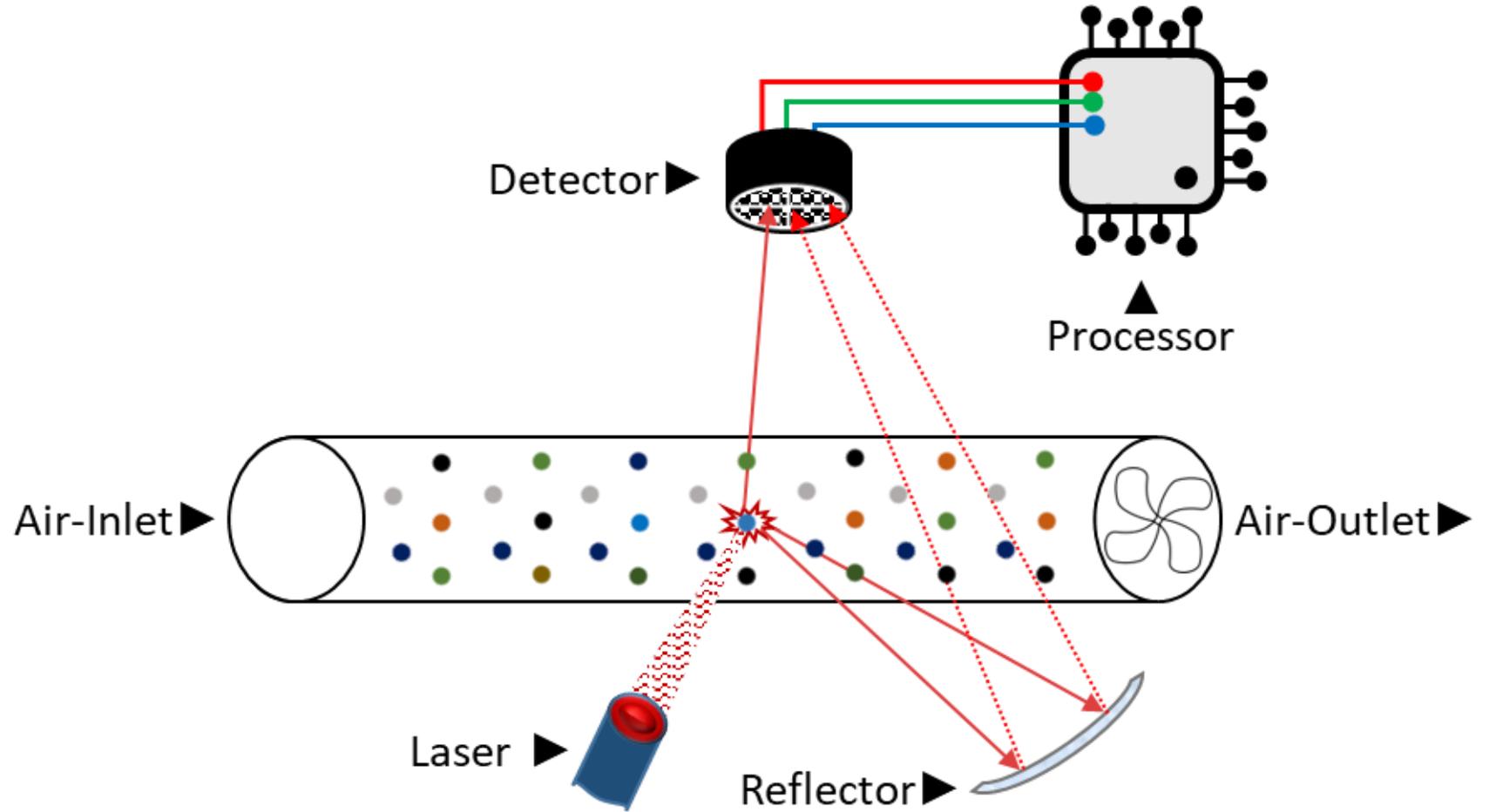
When dealing with low-cost PM sensor, it's important to handle its power supply carefully to ensure reliable operation and avoid damage. Here are some key points and cautions must be taken care of:

Caution and Safety for Sensors

V — The Low-cost sensor typically operates at 5V DC. Ensure that your power supply provides a stable 5V output within the sensor's specifications to avoid damaging it

A — The sensor may draw a varying amount of current depending on its operation mode. Check the datasheet for the current consumption requirements and ensure your power supply can handle this without significant voltage drops.
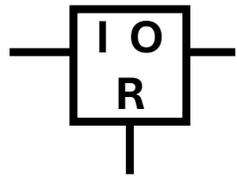
I O R — Use a regulated power supply to avoid fluctuations that could affect sensor performance. Voltage spikes or drops can lead to inaccurate readings or even damage the sensor.
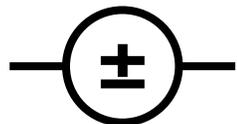
± — Double-check the polarity of your power connections. Reversing the power supply connections can cause permanent damage to the sensor.

Caution and Safety for Sensors
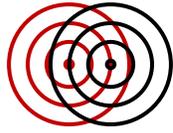
Ensure that the power supply is clean and free from electrical noise. Noise can affect sensor readings or cause erratic behavior.

If possible, use fuse protection or similar safeguards to protect the sensor from overcurrent situations that could arise from power supply failures.

Use appropriate gauge wiring and secure connections to avoid issues related to poor connectivity or electrical noise.

Ensure that the sensor and its power supply operate within their specified temperature ranges. Excessive heat can affect performance and longevity.

US – EPA criteria

Measurement Methods

Federal Reference Method (FRM):
This involves a specific type of air sampler and filter analysis. The most common FRM for $PM_{2.5}$ uses a tapered element oscillating microbalance (TEOM) or a filter-based gravimetric method.

Federal Equivalent Method (FEM):
These methods are similar to FRM but can include variations that are still considered equivalent in performance. They may use different types of samplers or analytical techniques but must be validated to meet EPA performance specifications.

Sampling Frequency

24-Hour Averaging:
PM2.5 is often measured with a 24-hour averaging period, which means that samples are collected over a 24-hour period and the concentration is averaged over this time.

Continuous Monitoring:
Some methods allow for continuous monitoring and real-time data collection, providing more frequent updates on air quality; which are varies from 1 to 60 minutes intervals.

US – EPA criteria

Calibration	Regular calibration of equipment and sensors to maintain measurement accuracy.
Performance	Periodic performance audits and precision checks.
Validation	Review and validation of data to check for consistency and reliability.
Sensitivity	The ability to detect low levels of particulate matter.
Accuracy	The closeness of measurements to the true concentration.
Precision	The consistency of measurements under the same conditions.

For more derails, please refer: https://www.epa.gov/criteria-air-pollutants

Colocation & Calibration

*Performance evaluation tests over a period of 15 to 30 days.
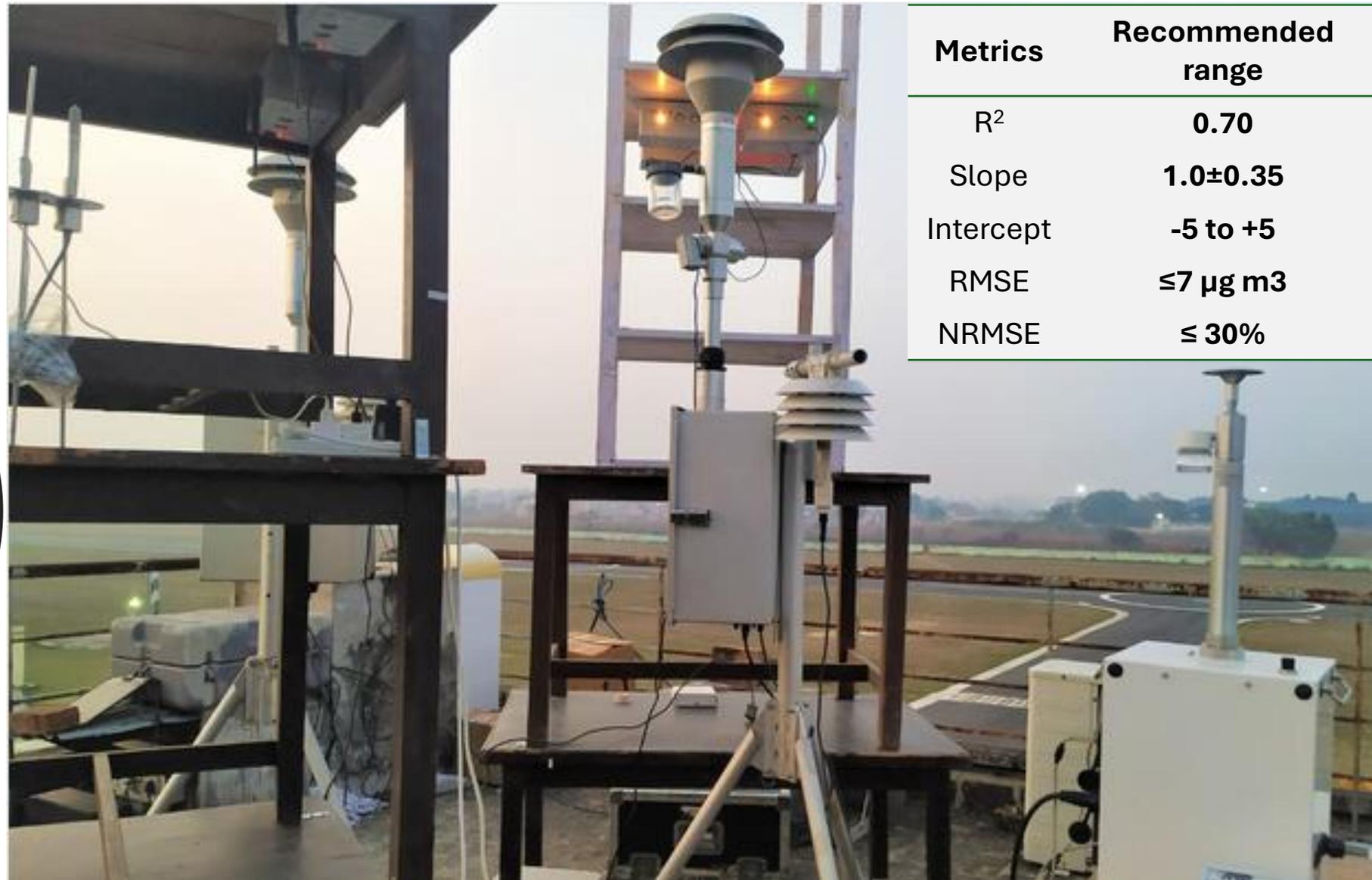
Metrics	Recommended range
R^2	0.70
Slope	1.0±0.35
Intercept	-5 to +5
RMSE	≤7 µg m3
NRMSE	≤ 30%

Only sensors that demonstrated good performance in comparison to the reference grade monitors were deployed in the field; the other sensors were returned to the factory for further calibration.

Only sensors that demonstrated good performance in comparison to the reference grade monitors were deployed in the field; the other sensors were returned to the factory for further calibration.

IITK Colocation Facility

Colocation performance evaluation

$R^2 = 0.93$
y = 1.21x 5.5
RMSE=50.4

$R^2 = 0.91$
y = 1.15x 9.0
RMSE=44.9
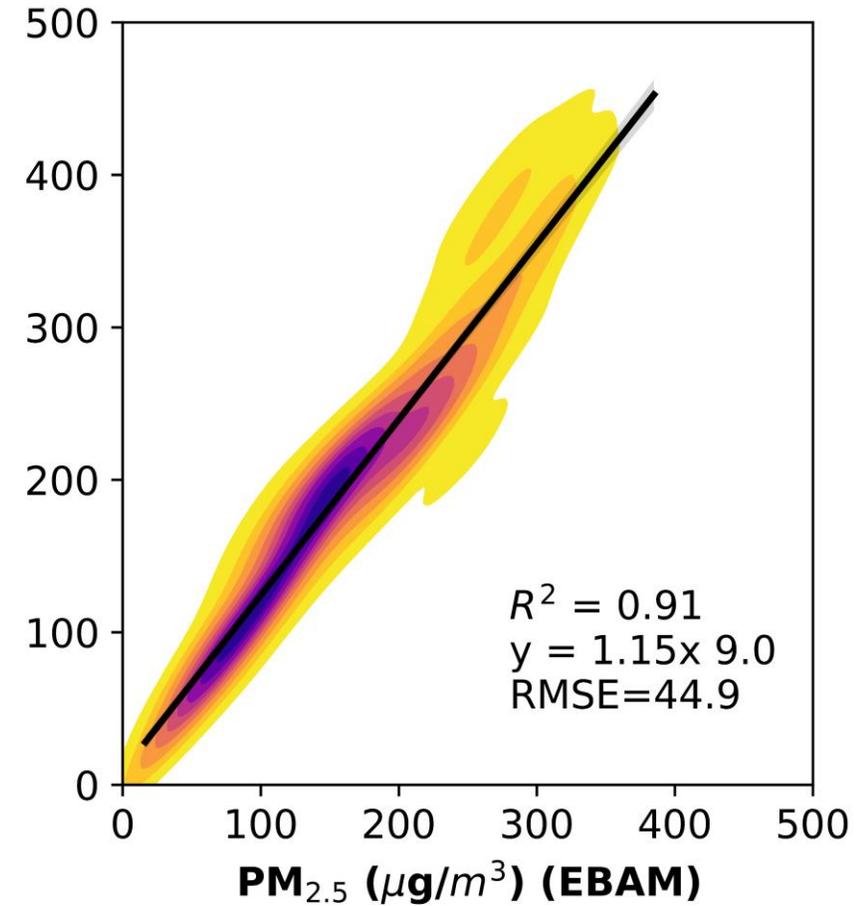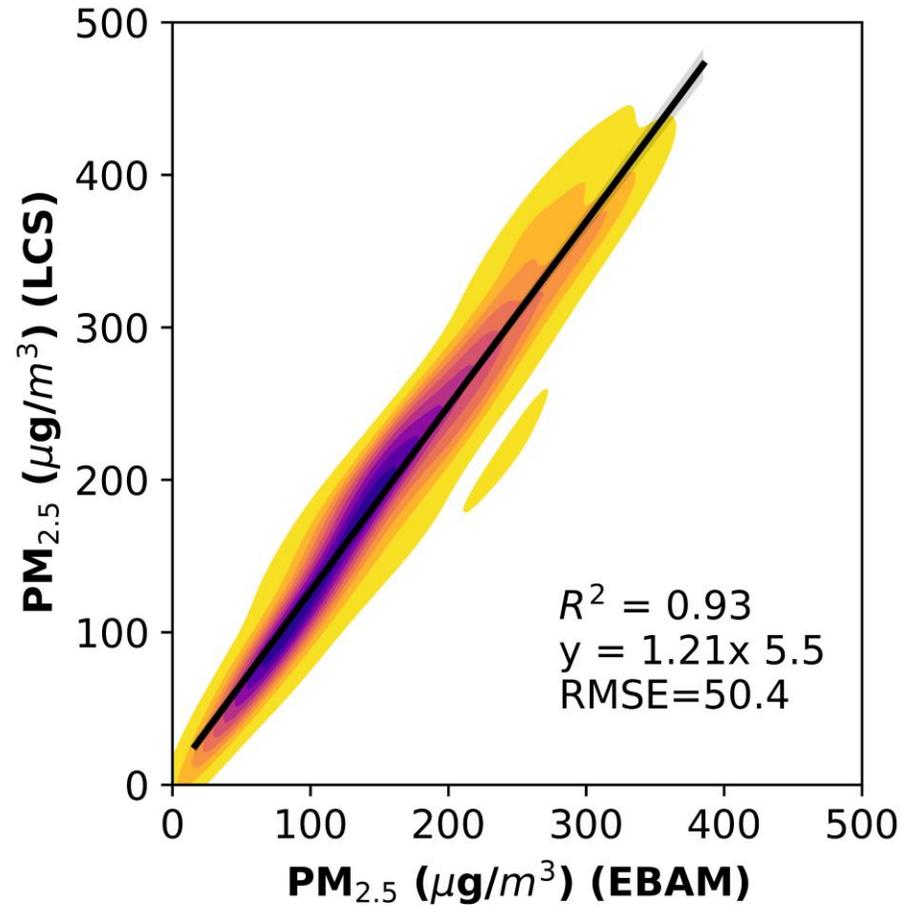
Every sensor has been evaluated similar to this.
The correction factor fed individually to every sensor.
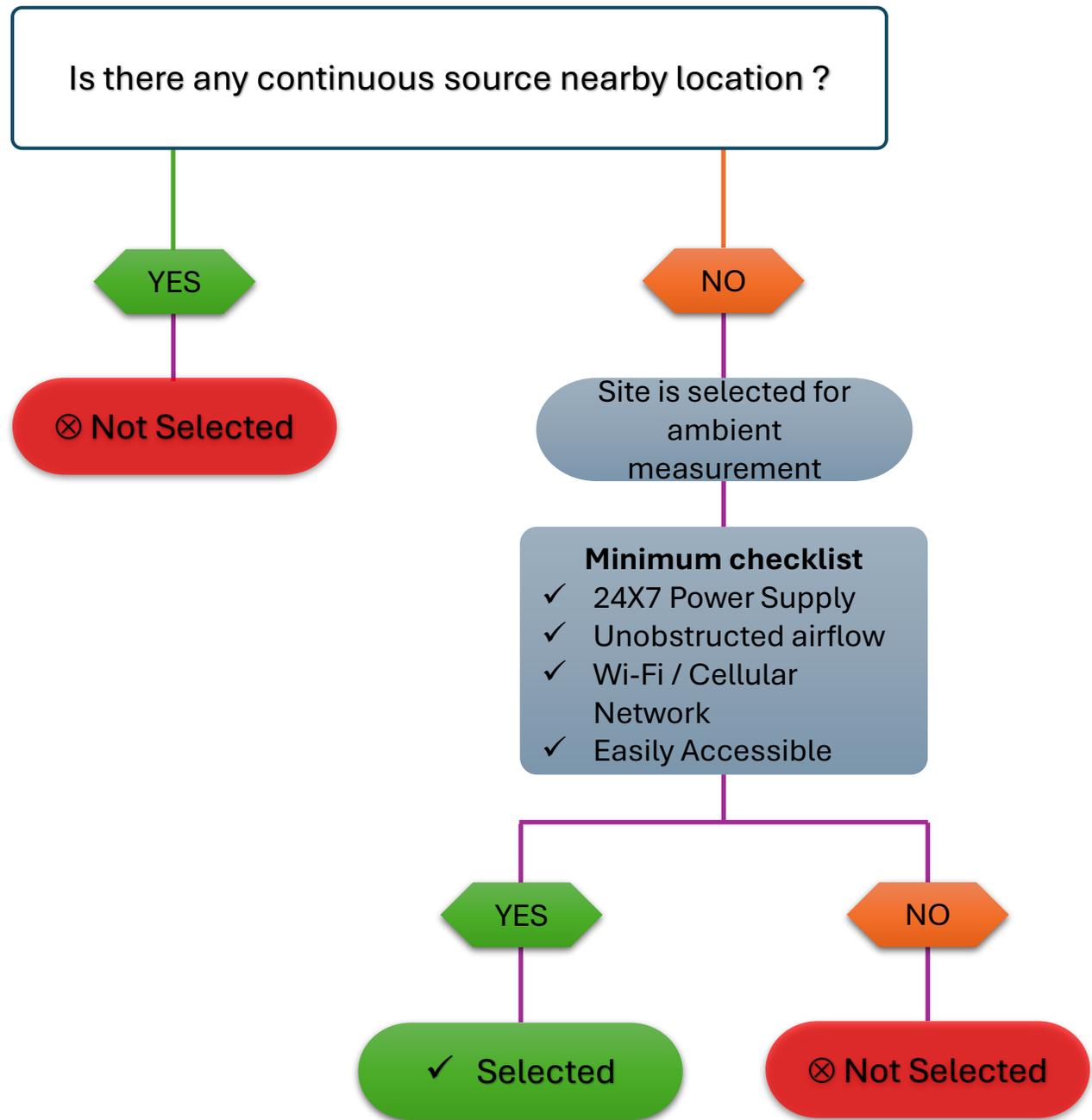
Device Installation Procedure

Solar Panel   Device

- Install the monitor on rooftops, terraces, or balconies of buildings, or at community.

- Device is positioned to have an unobstructed airflow of at least 270 degrees, with no less than 180 degrees.

- The monitor should be placed at least 6 feet above the ground to better represent exposures at the breathing zone level.

Caution

The device should be protected from direct rain.

The monitor must be positioned so that it is shielded from rain, but it must also be sufficiently exposed to the atmosphere to obtain useful readings.

The ambient air at sensor inlet without any interference.

Checklist for Device Installation

1 Check AC mains power supply using multimeter (should be 220-240 V).

2 Check DC power supply from solar panel (~ 12 V).

3 Make proper connections with respective sockets.

4 Turn ON the device.
(green LED must be glowing, if not then check all power connection)

5 Check Wi-Fi/cellular signal.

6 Check whether data is also recorded on SD card.
(by plugging SD card in laptop)

7 Connect the device with laptop or mobile phone using Wi-Fi and check the real-time data is transmitted on a given IP address.

8 Install the device as described above on prefixed location.

9 Check the data is correctly transmitted on a server via internet.

10 The real-time data of PM, RH and Temperature can be seen on dashboard.

Note:
If the data is not transmitted on the server, please reset the device and repeat the above checklist. If there is any firmware or software issue occurs, re-installed the software and restart the device. Before installing the device, no errors should be displayed.

Data Analysis & Data Management

Data Analysis
Data Visualization
Scientific Results

Field Deployment

Data From devices with time & id

LEVEL-0 datasets

DATA ARCHIVES

QA/QC as per limitations

Sudden spikes removal process

LEVEL-1 datasets
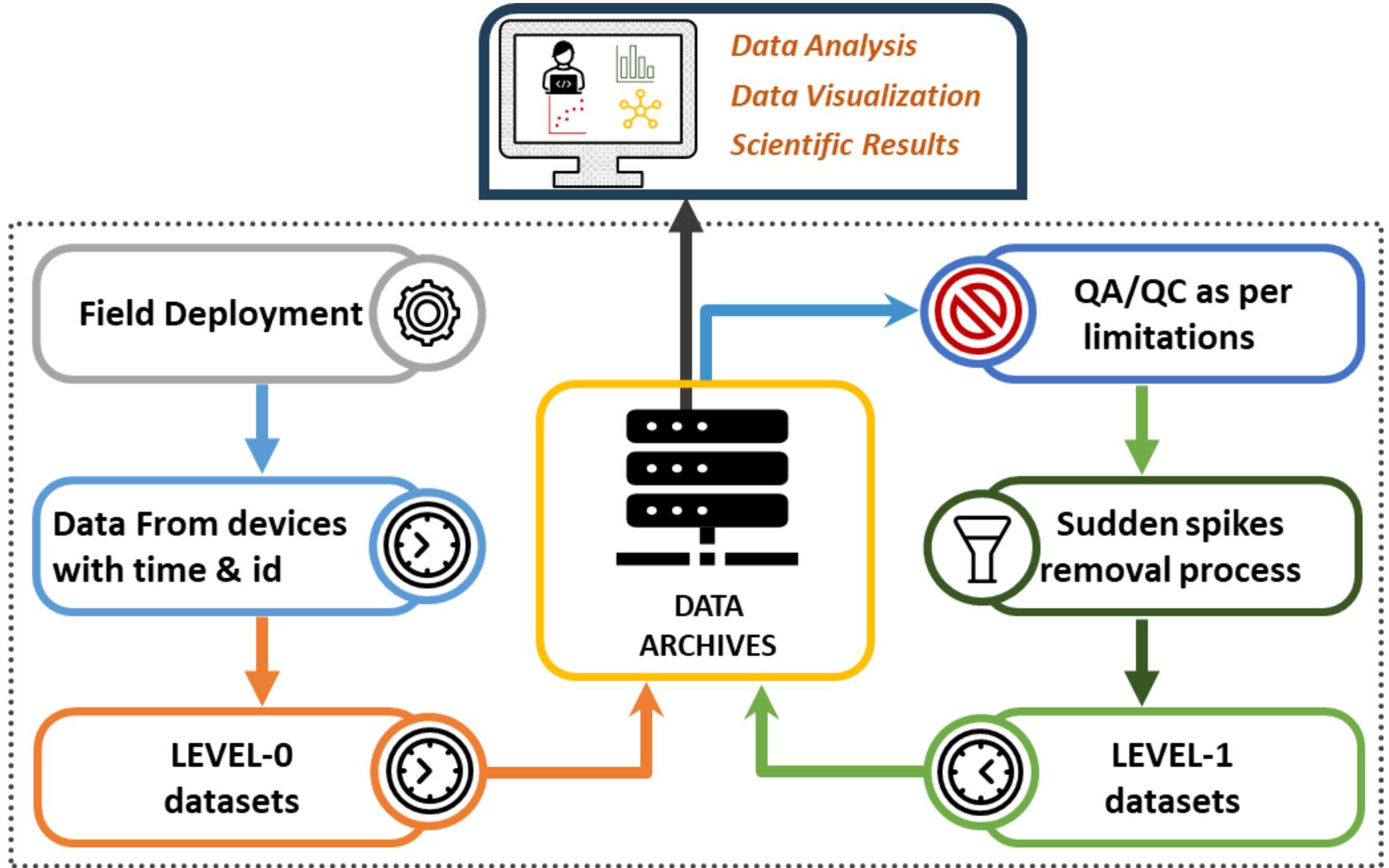
Troubleshooting & maintenance

1 — The dashboard provides real-time data visibility, allowing users to monitor various sensor readings continuously.

2 — Users can identify and flag sensors that may be malfunctioning directly through the dashboard interface.

3 — The raw data collected at one-minute intervals; After the QA/QC process, the data is aggregated and averaged into hourly mean values, facilitating a more comprehensive analysis of sensor performance and fault detection.

4 — Technicians visit the locations of identified faulty sensors to perform the necessary repairs or adjustments to restore data transmission and bring the sensors back online.

5 — The faulty sensors which are giving inappropriate values are replaced with new one.

6 — Mostly the low-cost sensors have a short life span for the accurate measurements than claimed by the manufacturers. So, in this project we are replacing the new PM sensor after one year of measurement in the field from date of installation.

If the sensor if giving a continuously constant or zero values of $PM_{2.5}$, RH or Temperature for more than 72-hours, it requires to replacement of sensor.

Case - 1 Device is not working

Carefully dismantle the device from the installation site

Open the device carefully

Take a new sensor, connect the connector to the new sensor

Now place the new sensor such that the Inlet and Outlet of the sensor should properly place to the locknut opening

Repeat as described in section "Checklist for Device Installation"

Cleaning the device: On the right side of the device there are two locknuts, to clean the sensor blow some air from the 2nd (down) locknut

Clean solar panel time to time for better power efficiency

**Case - 2
Data is not being transmitted**

Step 1:

If the battery is 0% in last transmitted data; it means that the device is not getting power.

- Please check if the device is properly connected to power supply.
- The red LED next to the switch should be glowing.
- If the red light is not on, then switch on the unit using switch at the bottom of the device. Make sure the Red light next to the switch is switched on.

Step 2:

Device is on, red light is on but data is not being sent

- Remove the top cover and open the device and connect AC mains to the device.
- Red LED on the Red PCB (where SIM card has been placed) should be blinking. If no network, this blink is faster than once a second. Once network is found, the blinking becomes slower (once in 2-3 seconds).
- It takes about 2 minutes for the network to be found. The unit then starts transmitting data. "Data transmitted" message is displayed whenever data is transmitted. If not, "Network error" or "Server Disconnect" messages may appear.
- Restart the device and see if "Data Transmitted" starts coming.
- If "CHECK MODEM" message keeps appearing and data is not being transmitted, contact manufacturer support.

Case - 2
Data is not being transmitted

Step 3:

Check the SIM card

- If above practice does not solve the problem, switch off the unit, remove the SIM card.
- Put the SIM card in your phone and check if you are able to connect to the internet using your SIM card. Please make sure your phone is not connected to Wi-Fi. (It may take up to 5 minutes for a SIM to register on the network.)
- Specifically for m2m SIM, also check APN setting.
- Please check that data roaming is turned on.
- Please check that data roaming is turned on.
- Now put the SIM back in the slot and ensure it is not loose.
- If this still does not work try to replace the SIM card and see if that works.

Step 4:

Device is still not connecting to Internet

- Try changing the location of the device (preferably outdoors) for better connectivity.
- Check the antenna to be tight in its holder on the Red PCB.

Case - 3
Other Issue

Device is connected to power, but data is not showing on the display. This means there is some loose wire.

- Remove the top cover and open the device.
- Connect AC mains to the device.
- Switch on the unit using the on/off switch at the bottom of the device, The Red light next to the switch should also switch on.
- The internal Red Light next to the USB socket should come on. If this does not come on, check the green light on the SMPS (inside metal cage on top right corner of the enclosure). If this also does not come on, check if any wire is loose either from the AC mains plug side or the 5 wires at the terminal strip of the SMPS.
- Please note while checking these wires, switch off the device and remove the AC mains plug to avoid shock. If wires are found ok, switch the unit back on. If some wires seem to be loose, please contact manufacturer for support.
- For power supply issue, please check the continuity of the wire, if damaged wires were found, then replace with new wires.

Accessories required for installation & maintenance

Drill machine with 6.5 mm bit

Solar Panel

Solar Panel mount

Screws, Nuts & washers

Clamp for pole mount

Wires & sockets

Rawls Plug & screws

Screwdriver

Hammer

Multimeter

Laptop
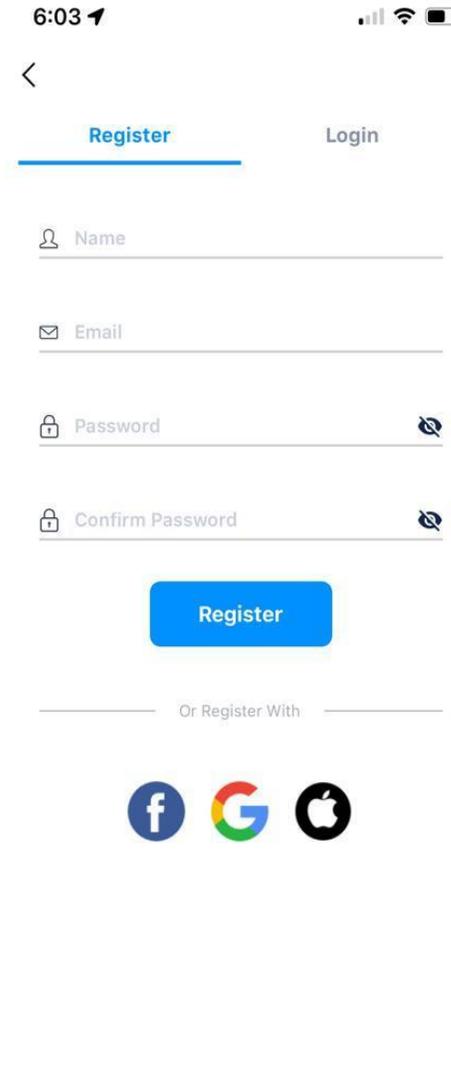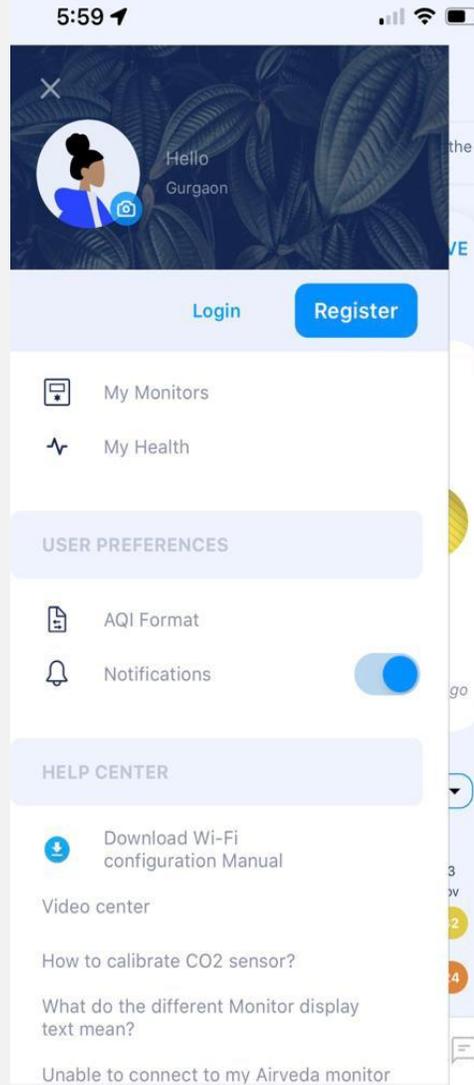
Ladder

Application overview

Application overview

Search & Manage Monitors

Application overview

Temperature Calibration

Advanced Settings

This will clear any data that is currently stored locally on the monitor's memory. It will not affect any data for the monitor on already the server.

Set Device IP

By default a device's IP is set dynamically. If you wish to change it to Static IP then you can set it here.

Calibrate Temperature

You can use this feature to add an offset to Temperature value to calibrate against a reference.

Calibrate Humidity

You can use this feature to add an offset to humidity value to calibrate against a reference.

Modbus Settings

Please use the settings below to set configuration settings for Modbus.

APN Setting

Calibrate Temperature

Please enter current temperature value you are seeing on the device.

Current Temperature: 27 °C

Please enter the reference temperature value. This will be used to calibrate the device.

Note: You may set Temperature value in range: 9.0°C to 39.0°C.

Reference Temperature: 29 °C

Based on your input we will be incrementing the temperature value by:

Offset: +2.0°C

Submit Calibration

Please confirm this calibration

By default, the GSM module picks up the APN from the network, however if you wish to set a specific APN for connecting to a particular network then you may enter it here.

Humidity Calibration

Advanced Settings

This will clear any data that is currently stored locally on the monitor's memory. It will not affect any data for the monitor on already the server.

Set Device IP

By default a device's IP is set dynamically. If you wish to change it to Static IP then you can set it here.

Calibrate Temperature

You can use this feature to add an offset to Temperature value to calibrate against a reference.

Calibrate Humidity

You can use this feature to add an offset to humidity value to calibrate against a reference.

Modbus Settings

Please use the settings below to set configuration settings for Modbus.

APN Setting

Set Device IP

By default a device's IP is set

Calibrate Humidity

Please enter current humidity value you are seeing on the device.

Current Humidity: 75 %

Please enter the reference humidity value. This will be used to calibrate the device.

Note: You may set Humidity value in range: 50% to 99%.

Reference Humidity: 66 %

Based on your input we will be decrementing the humidity value by:

Offset: -9%

Submit Calibration

Please confirm this calibration

By default, the GSM module picks up the APN from the network, however if you wish to set a specific APN for connecting to a particular network then you may enter it here.

Drift detection & analysis

What is Sensor Drift in Low-Cost Sensors?
Sensor drift is the gradual change in a sensor's output over time, even when the actual pollution level remains the same. As a result, the sensor may start giving higher or lower readings than the true value.

Why Does Drift Occur?
- Aging of sensor components
- Continuous exposure to pollutants
- Effects of temperature and humidity
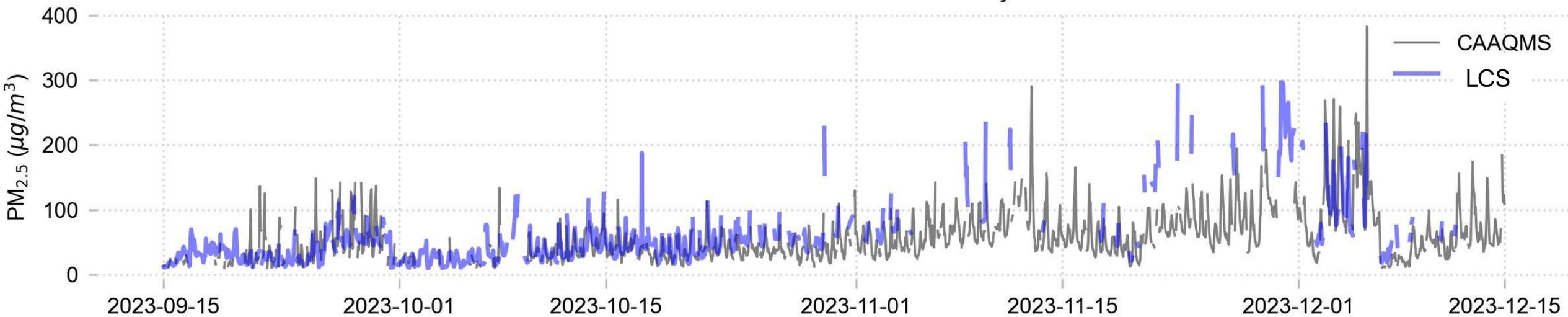- Dust, moisture, or chemical contamination
- Power supply and electronics degradation

Types of Drift
- Baseline drift
     Sensor shows non-zero readings even in clean air
- Sensitivity drift
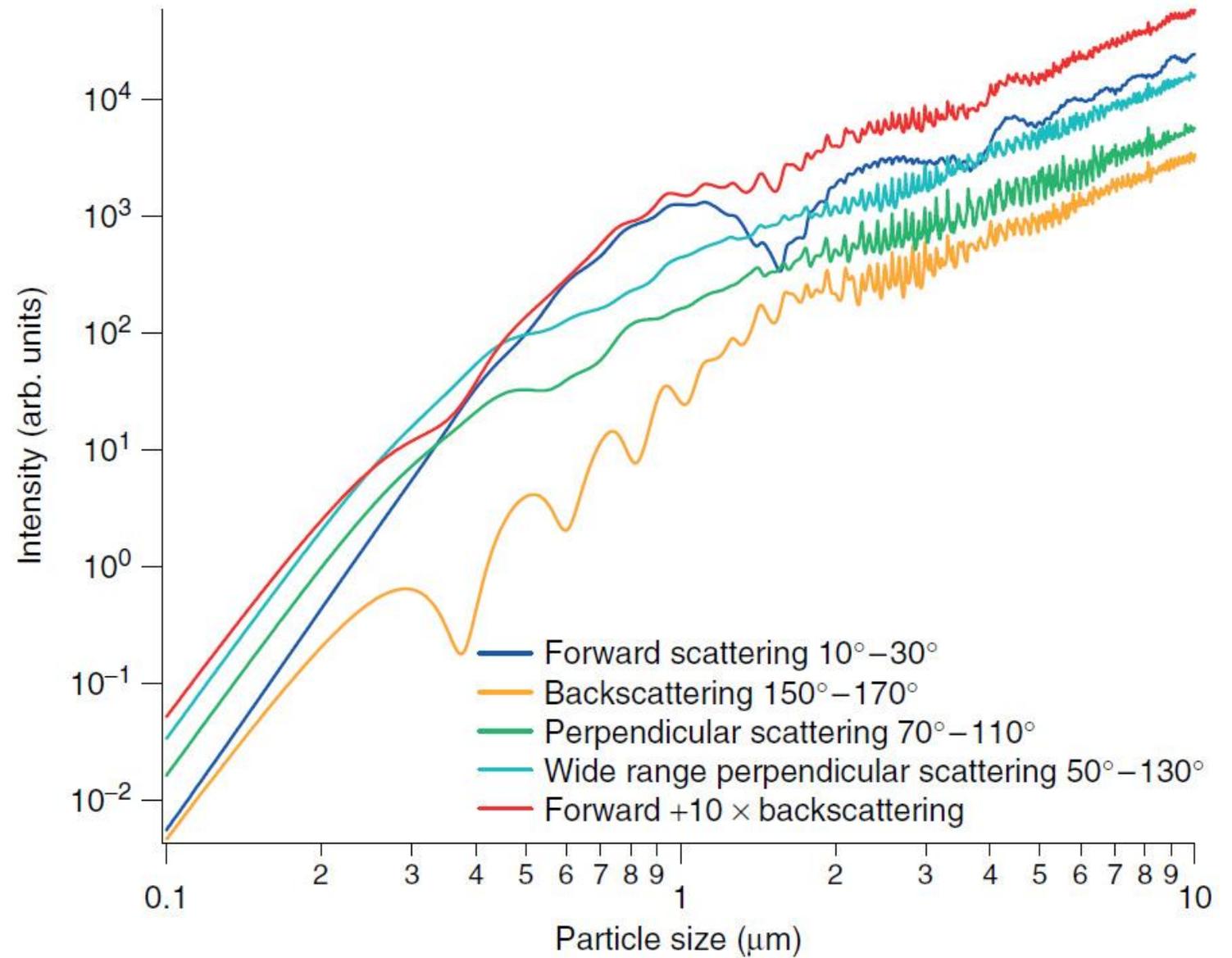   Sensor response becomes weaker or stronger over time

Drift detection & analysis

Sample plot of Drift in PM2.5 measurement

μ (CAAQMS) = 43.43 μ (atmos) = 51.75 σ (Reference) = 31.76 σ (atmos) = 32.57

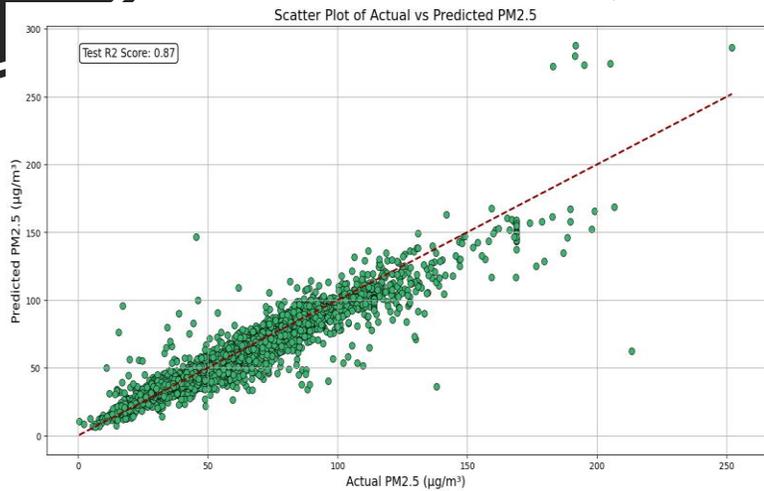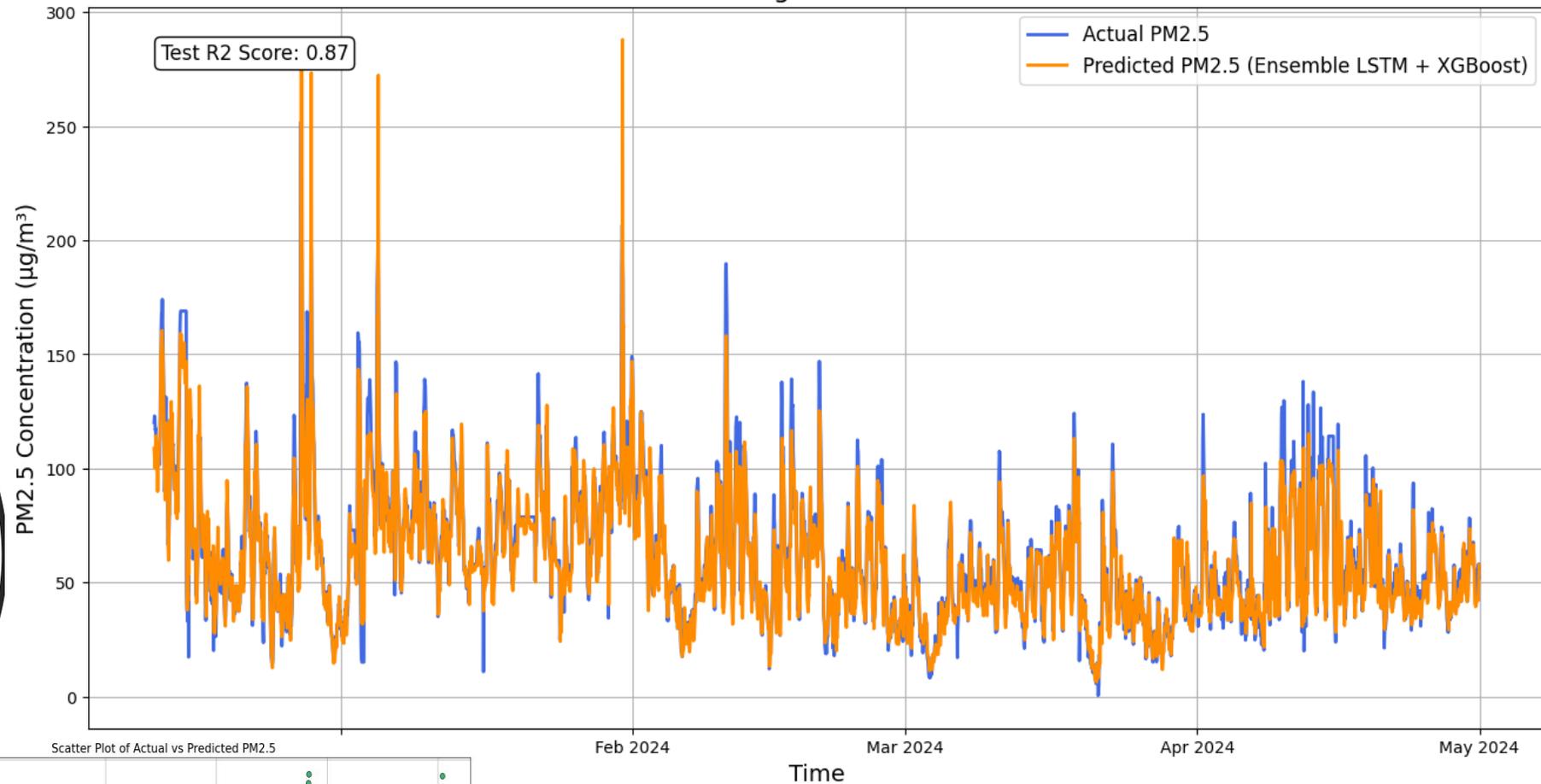R^2 = 0.73   RMSE = 16.4   MAE = 14.0   y = 0.95x + 10.0
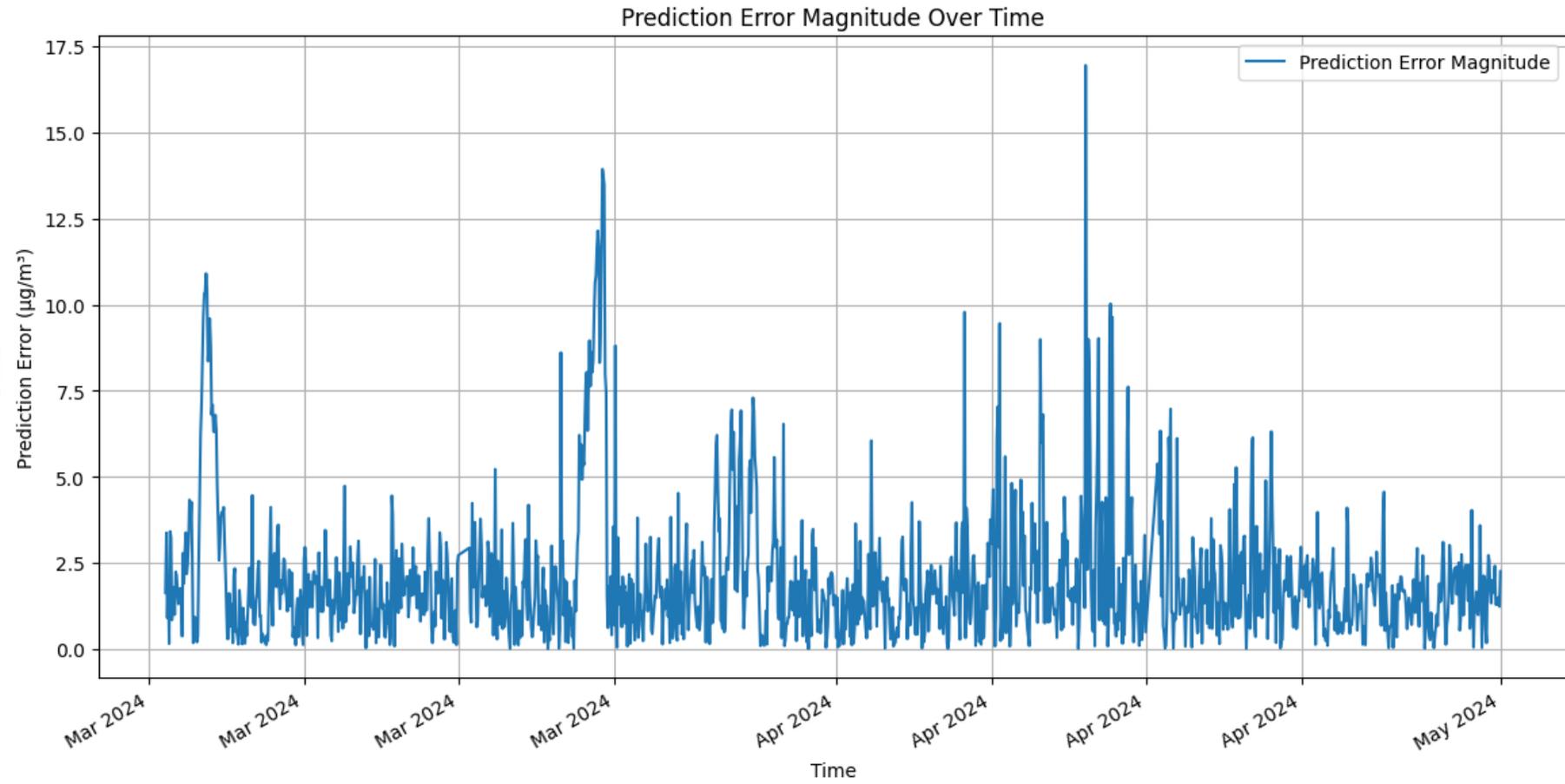
Drift detection & analysis

Agranovski, I. Aerosols: Science and Technology; John Wiley & Sons: Hoboken, NJ, USA, 2011.

Drift detection & analysis

PM2.5 Calibration Using Ensemble LSTM + XGBoost

Test R2 Score: 0.87

Scatter Plot of Actual vs Predicted PM2.5

Value of R² is improved from 0.76 to 0.87

Drift detection & analysis

Prediction Error Magnitude Over Time

Iterative Process for Anomaly Detection in Low-Cost Sensors

Drift detection & analysis

Take Corrective Actions

Calibrate Sensor Data

Use Calibrated Data for Predictions

Analyze Prediction Errors

Set Anomaly Thresholds

Detect Anomalies
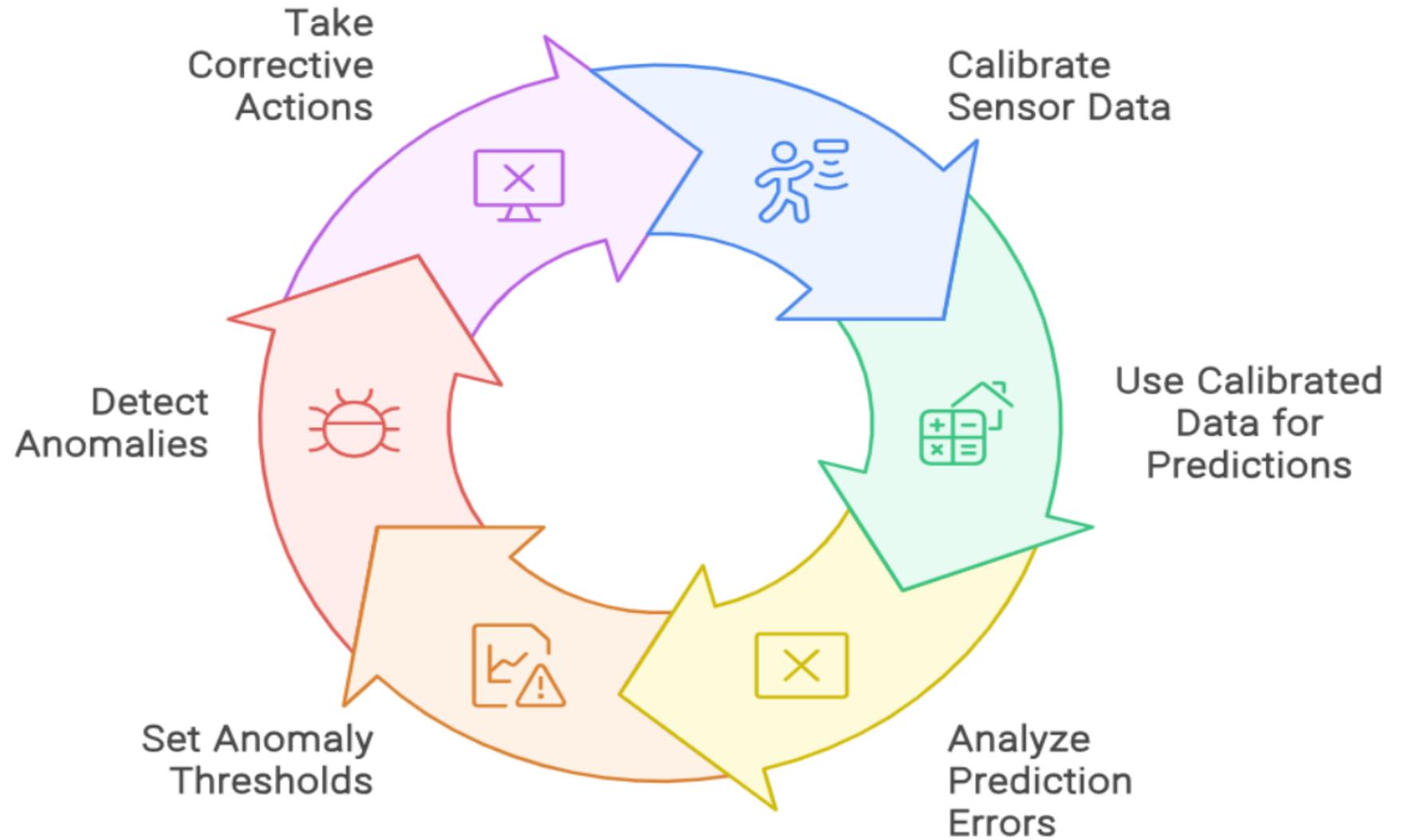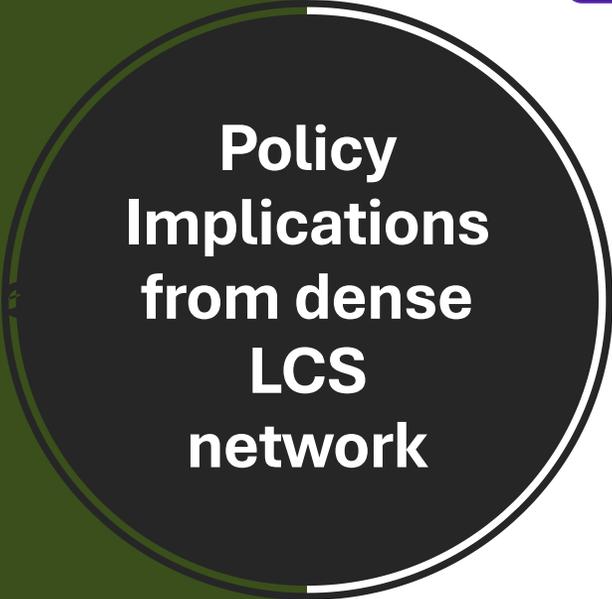
Policy Implications from dense LCS network

➤ **Regional Coordination**

Air-shed framework enables multi-jurisdictional collaboration for pollution control measures targeting shared atmospheric basins.

➤ **Targeted Interventions**

High-resolution data identifies specific hotspots requiring immediate action, optimizing resource allocation for maximum impact.

➤ **Evidence-Based Regulation**

Continuous monitoring provides robust evidence for setting standards, evaluating compliance, and measuring policy effectiveness.

The data-driven approach transforms air quality management from reactive to proactive, enabling policymakers to design interventions based on actual pollution dynamics rather than administrative convenience.