Development and calibration of an Air Quality Monitoring (AQM) appliance based on low-cost electrochemical and laser sensors

Ioannis D. Apostolopoulos
Postdoctoral Researcher
(FORTH/ICE-HT)

FORTH INSTITUTE OF CHEMICAL ENGINEERING SCIENCES

C-STACC Center for the Study of Air Quality & Climate Change

IoT Air Quality Monitoring

Air Quality measurement devices

Regulatory Instrumentation

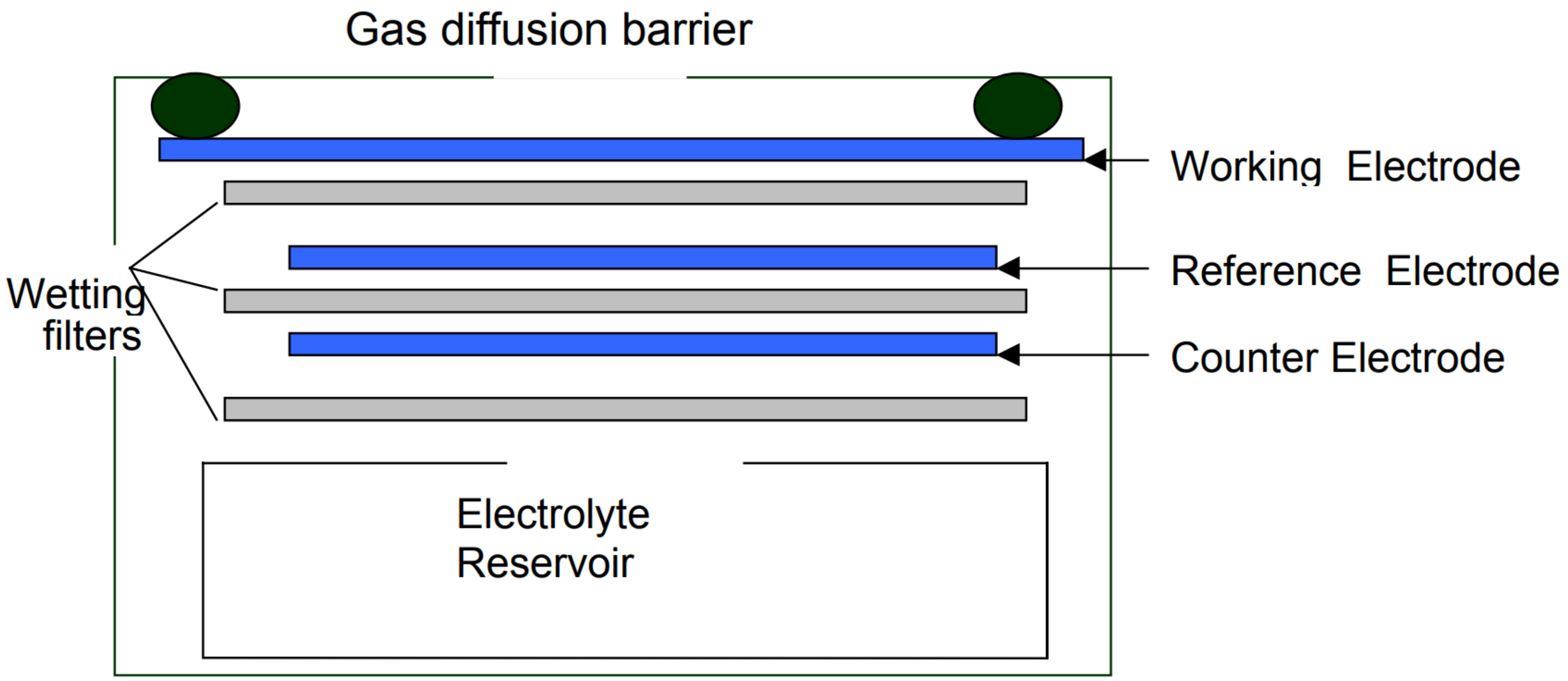
10k to 200k euros

Low-cost sensors

60 to 100 euros

Electrochemical sensors	CO, NO, NO_2, O_3
Laser sensors	$PM_{2.5}$
NDIR sensors	CO_2
MOx sensors	CO, Total VOC

Fundamental principles of electrochemical sensors



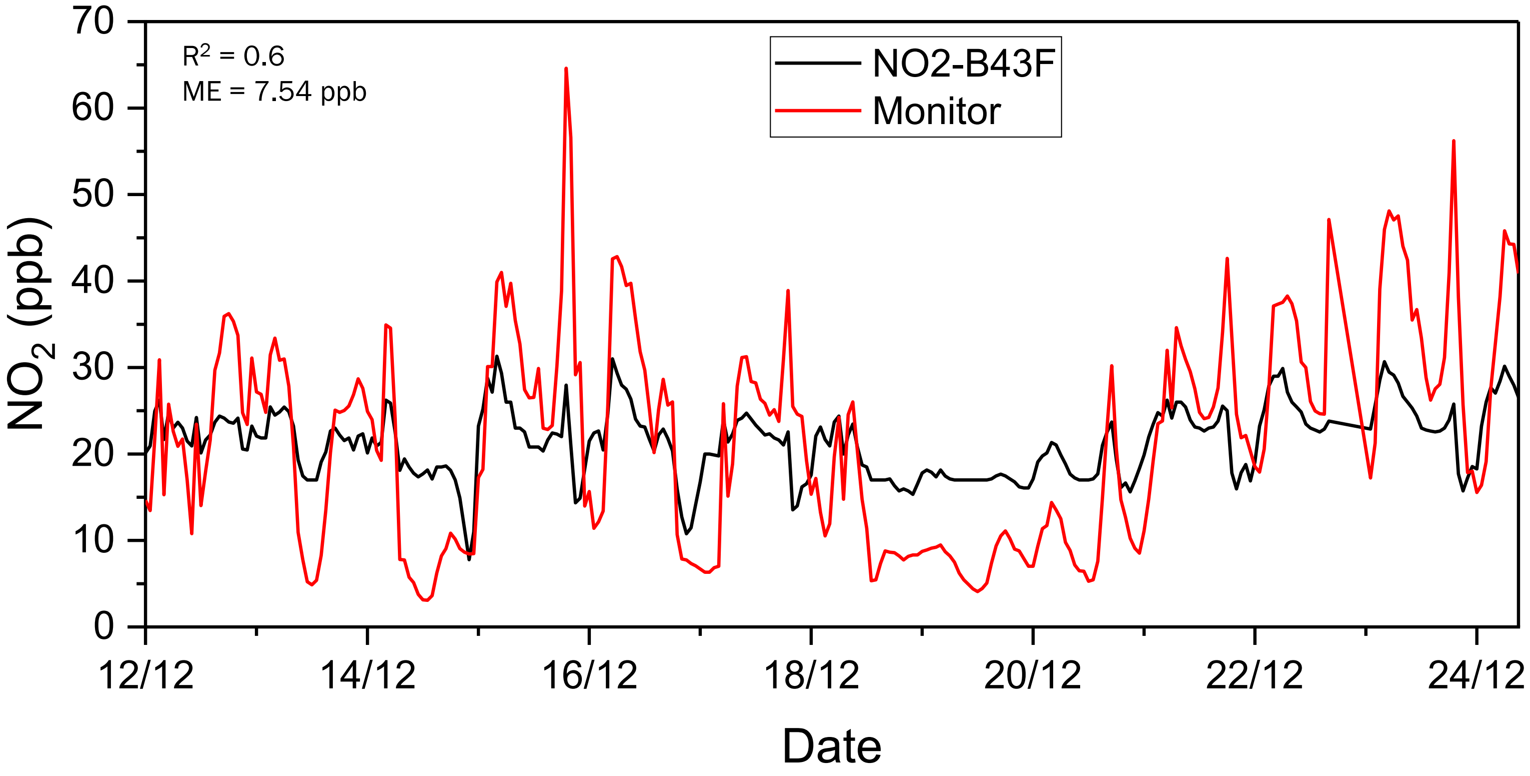
https://docs.smartcitizen.me/Components/sensors/air/Electrochemical%20Sensors/

- Contamination
- Temperature
- Humidity
- Sensor aging
- Cross-sensitivity
- Calibration

Low-cost sensor estimation errors

Estimation errors

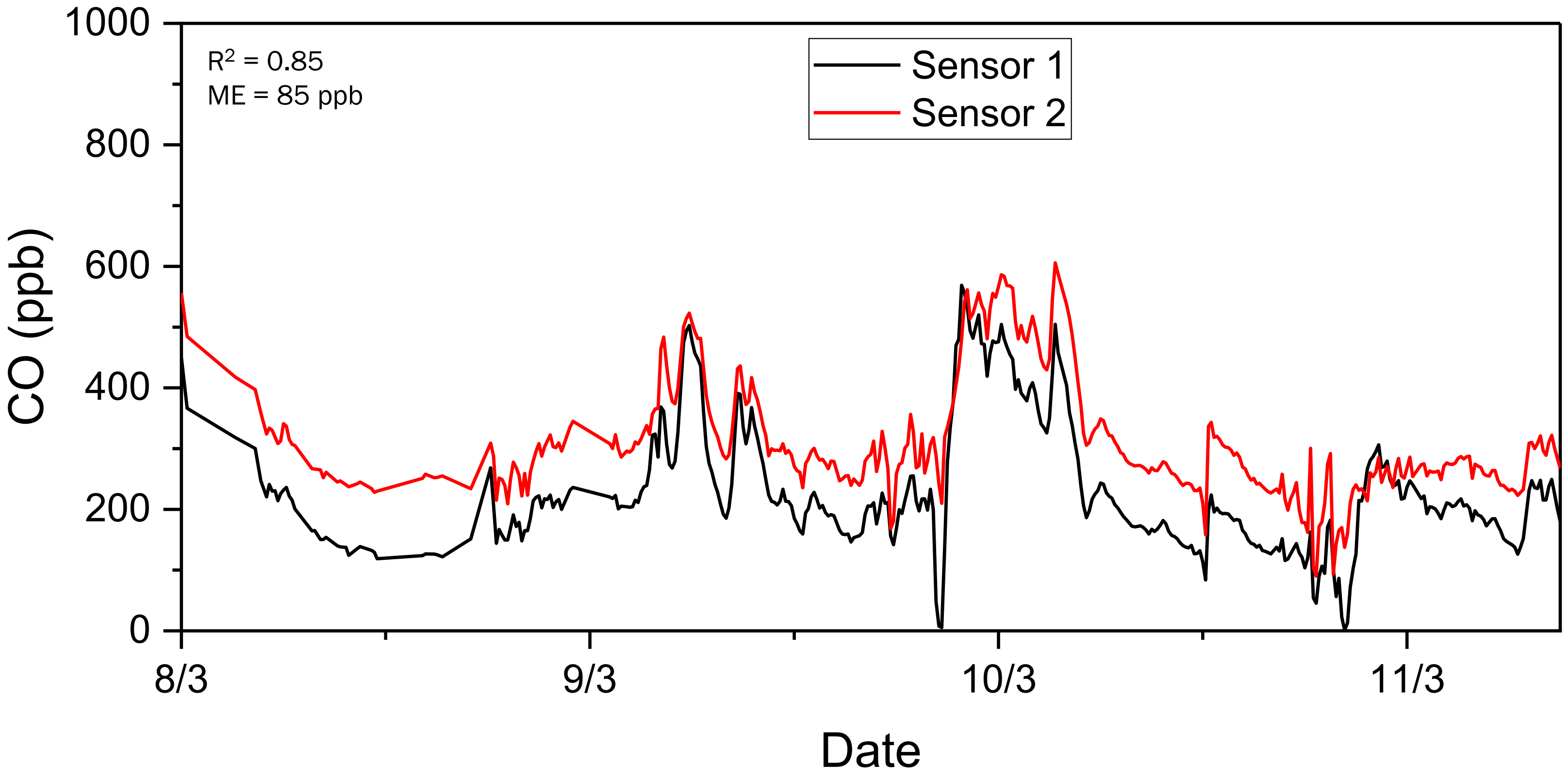
National Observatory of Athens (Ambient)
2022-12-13 to 2022-12-26
Low-cost sensor: NO2-B43F



Low-cost sensor inter-unit consistency

Discrepancy between the same sensors

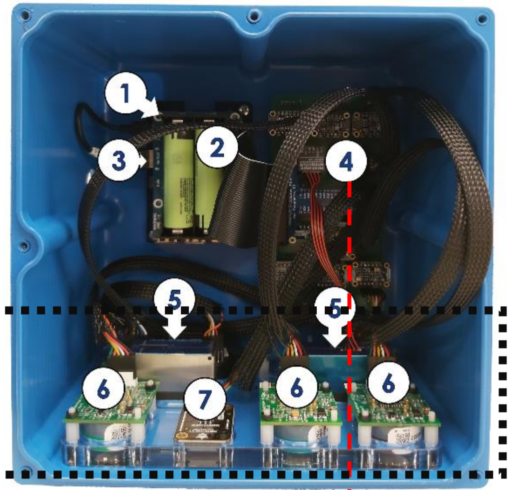
Kastritsi (Ambient)
2023-03-08 to 2023-03-12
Low-cost sensors: CO-B4



Why low-cost sensors?

- Low-cost
- Multi-sensor networks (e.g. school classes)
- Though not ideal for accurate measurements, they can give us an estimation of the general conditions
- Are easily adjusted and calibrated to provide better estimations

ENSENSIA sensors



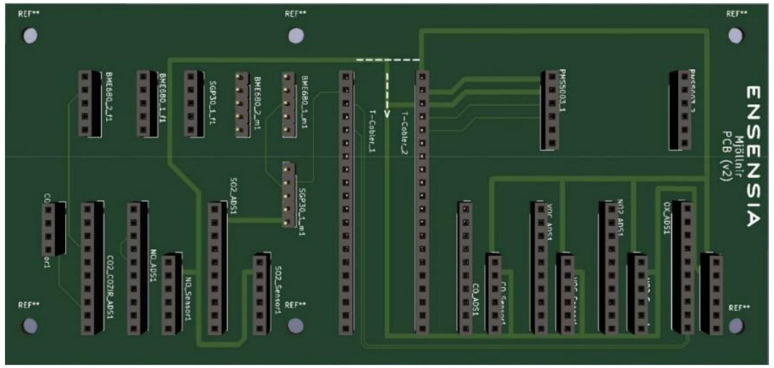
..Front Side

1. Beneath the UPS HAT is the Raspberry PI Model 4B
2. UPS HAT
3. Power supply (8.4V 2A)
4. Printed Circuit Board
5. PMS sensor
6. Analog (Electrochemical) sensor
7. Digital (Electrochemical) sensor

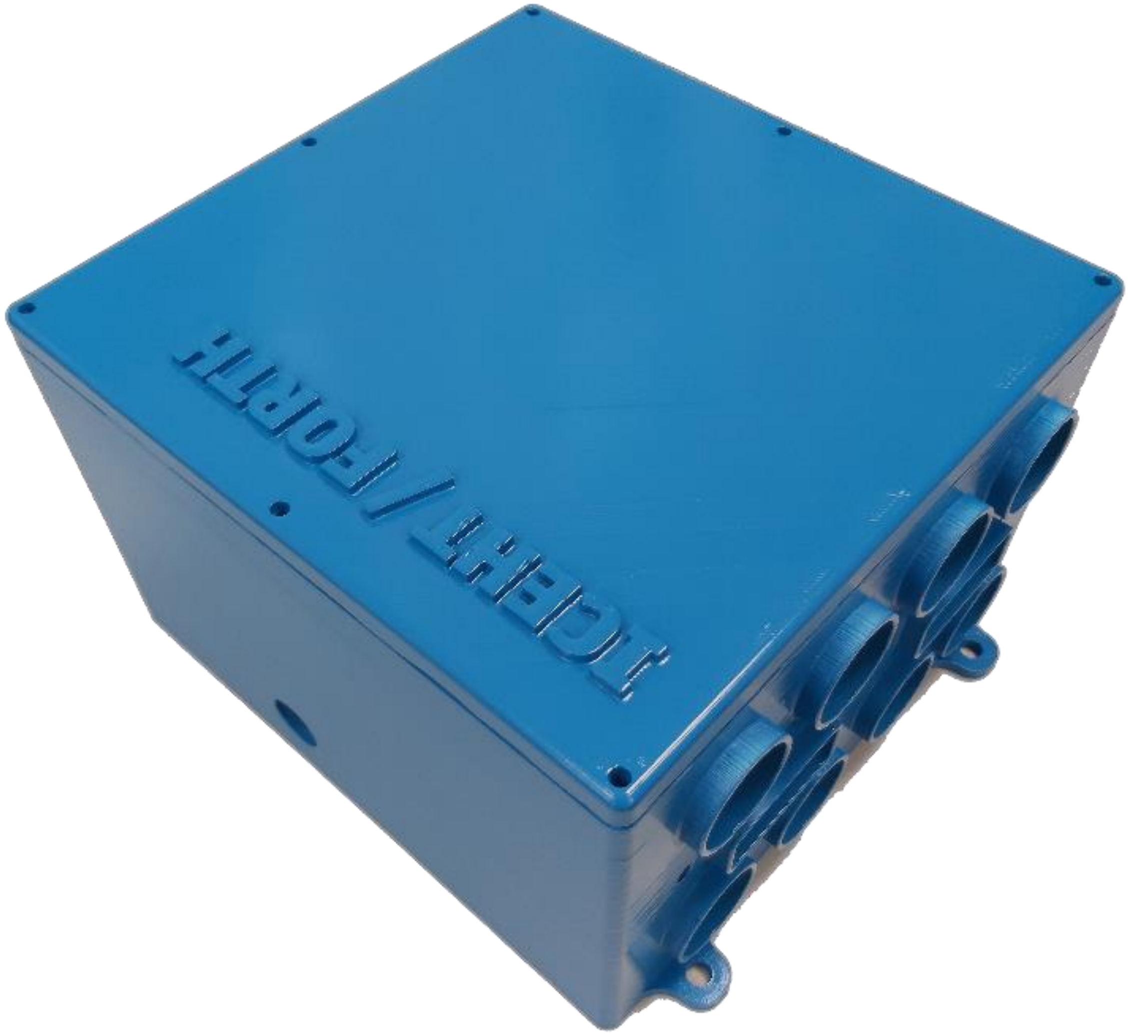
EC sensors
NO2-B43F
NO-B4
CO-B4
OX-B431
SO2-B4
VOC-B4

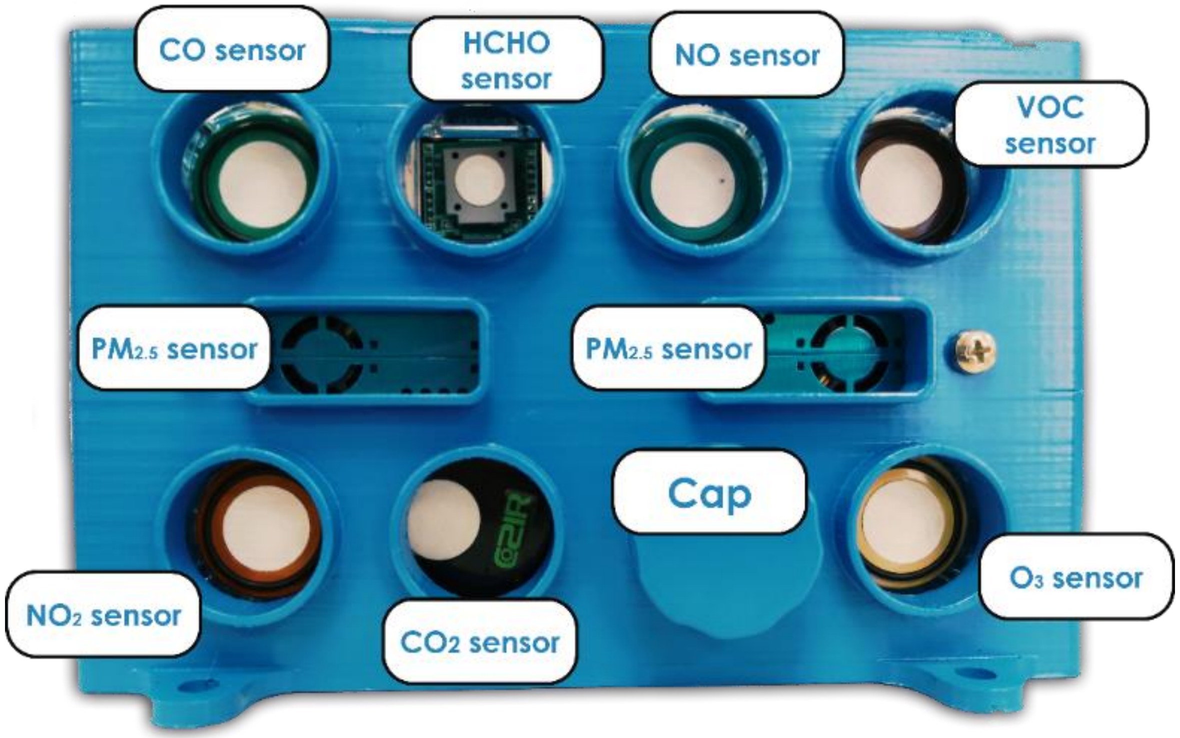
Laser sensor
PMS5003

Printed Circuit Board



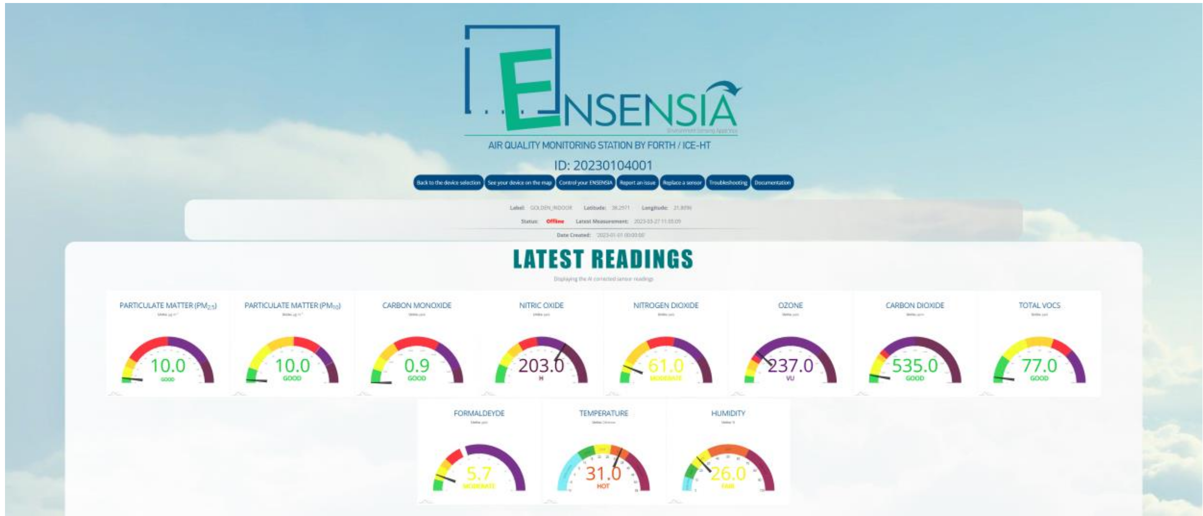
ENSENSIA packaging

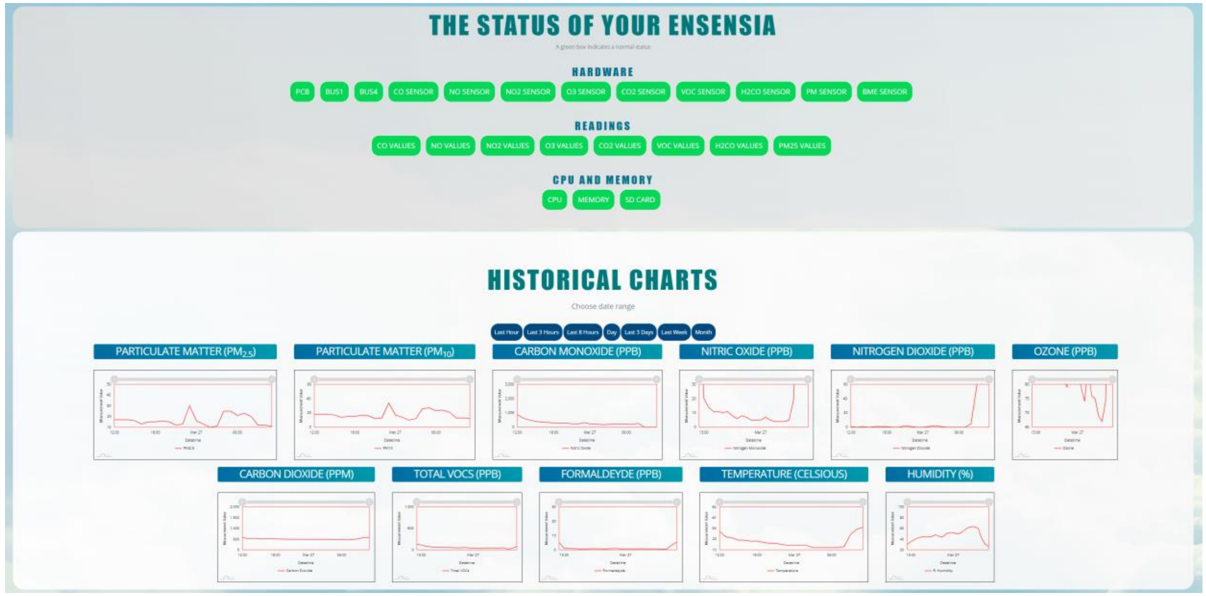




Visualization web-based platform

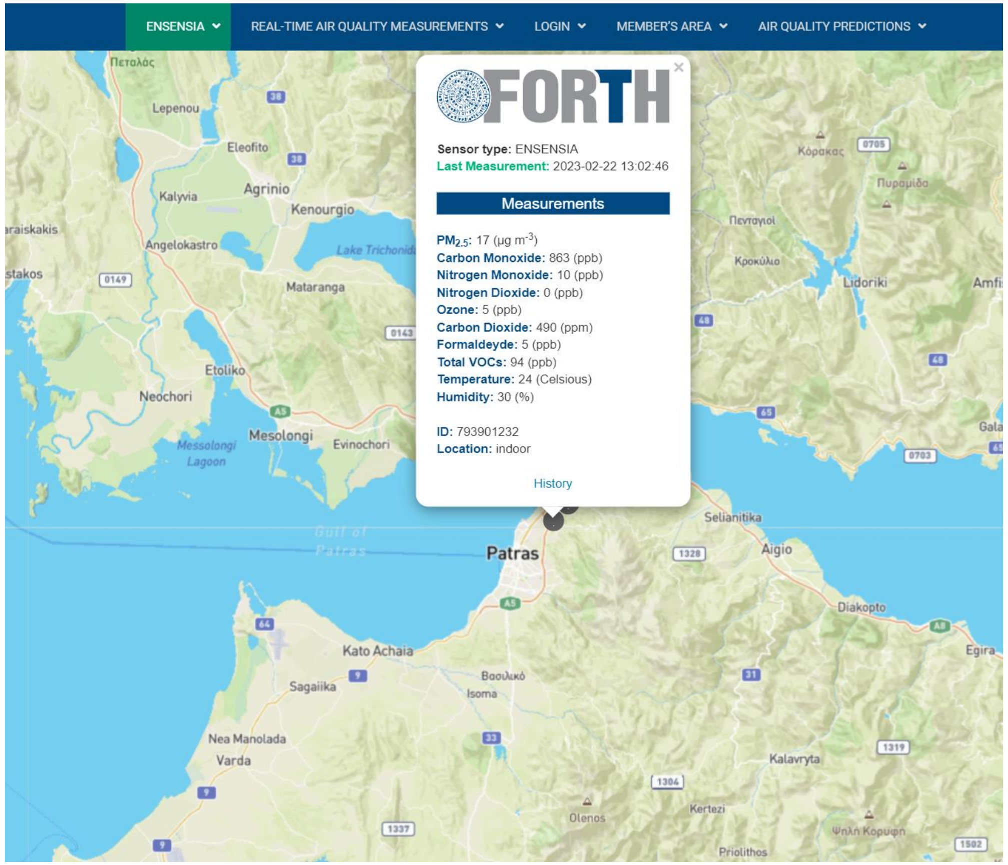
Air Quality Monitoring
http://aqmmon.iceht.forth.gr/





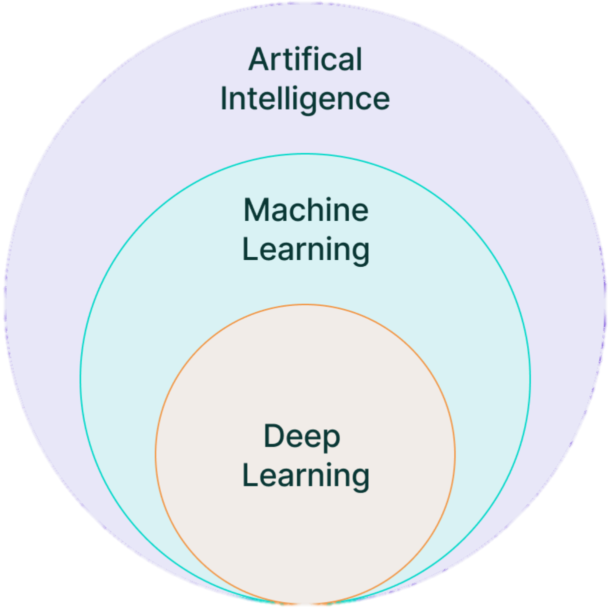
AIR QUALITY MONITORING STATION BY FORTH / ICE-HT

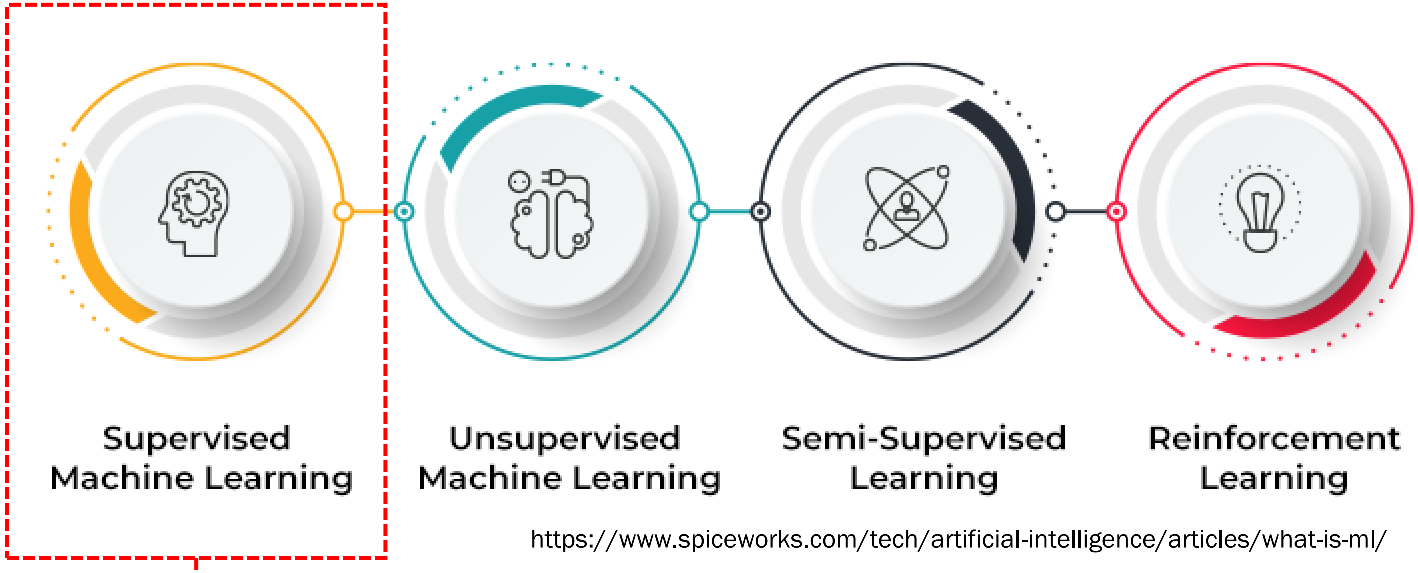
Live Map



Machine Learning methodology for low-cost sensor calibration

Supervised Machine Learning

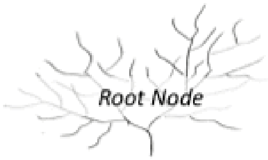


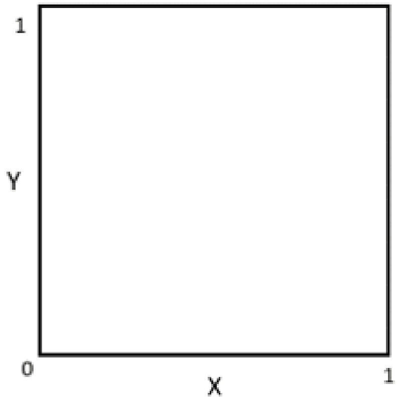


https://www.spiceworks.com/tech/artificial-intelligence/articles/what-is-ml/

- Support Vector Machine
- Decision Trees
- Neural Networks
- Ensemble methods

The Decision Tree algorithm





NO

CO

NO_2

RH

O_3

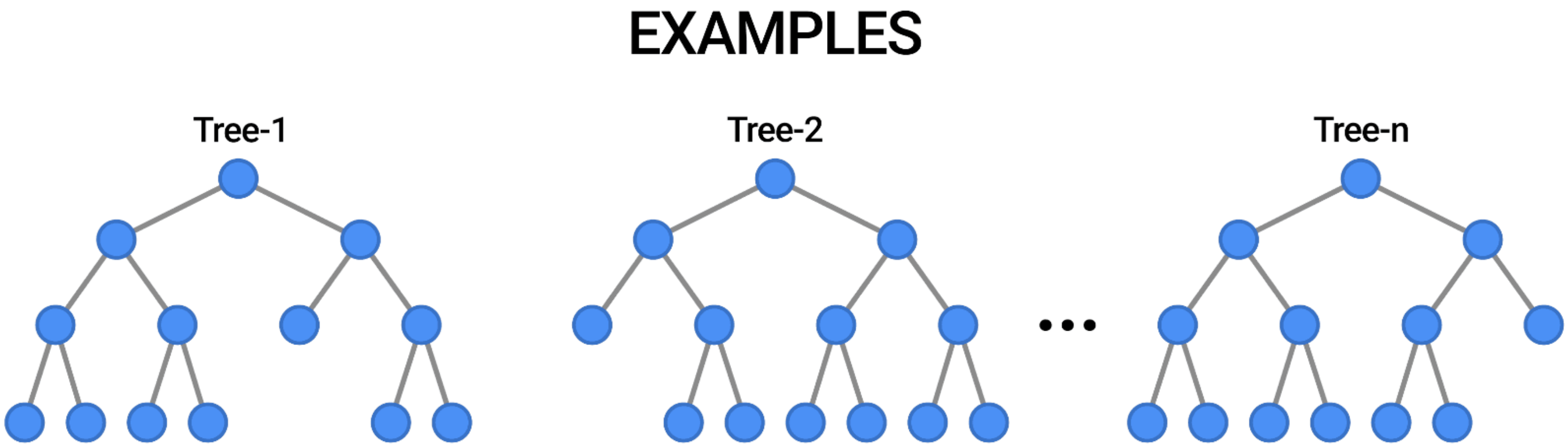
Features

NO_2

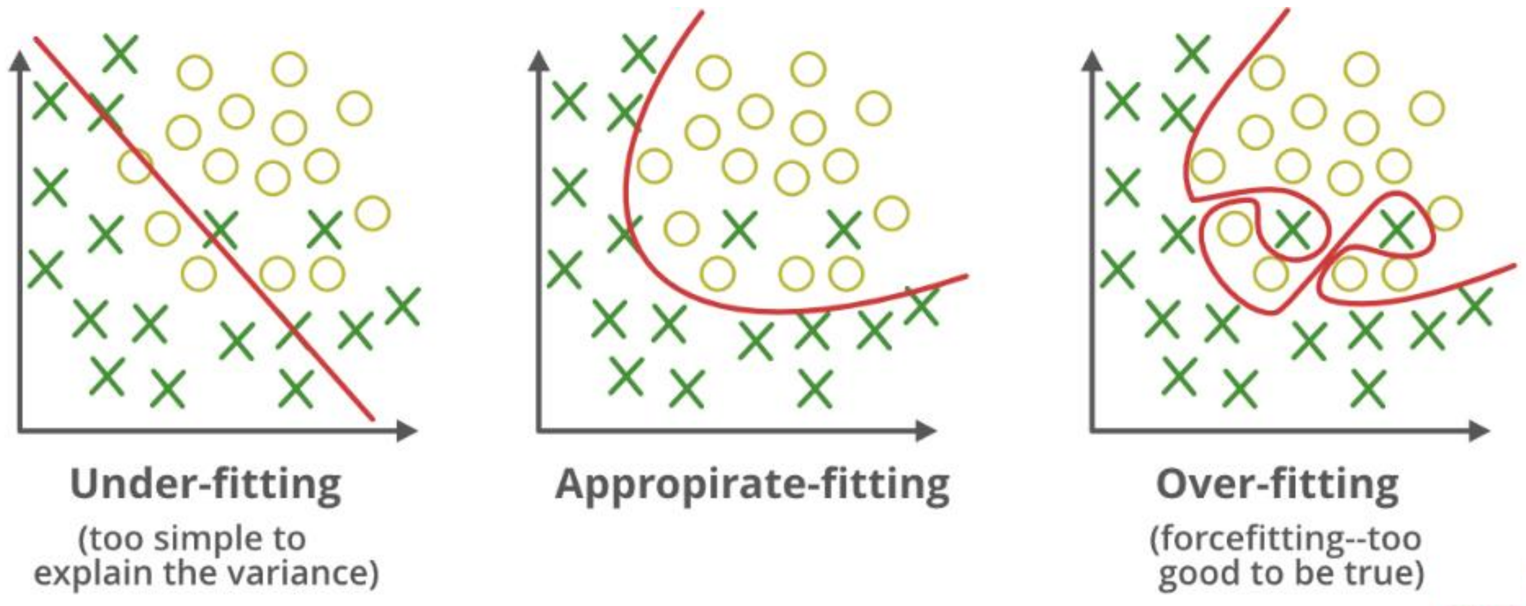
Ground Truth

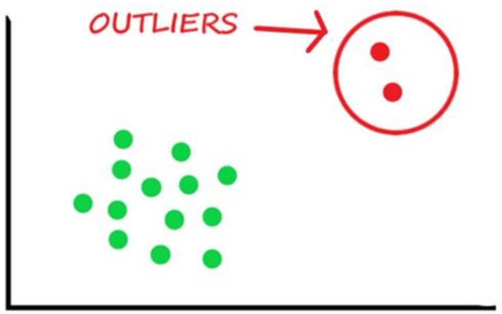
For more tutorials: annalyzin.wordpress.com

The Random Forest algorithm



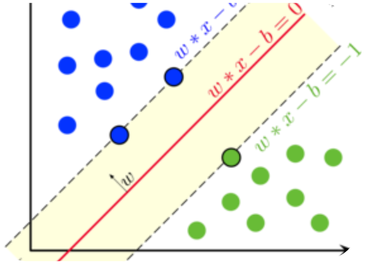
Random Forest weaknesses



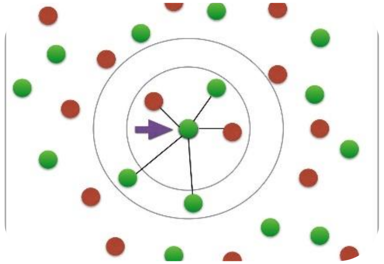


https://www.geeksforgeeks.org/underfitting-and-overfitting-in-machine-learning/

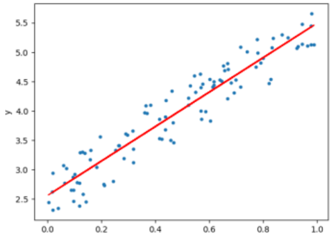
Why we chose Random Forest



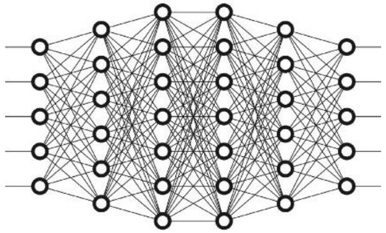
Support Vector Machines



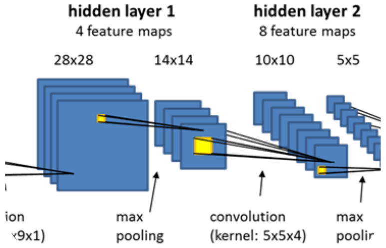
K-nearest Neighbors



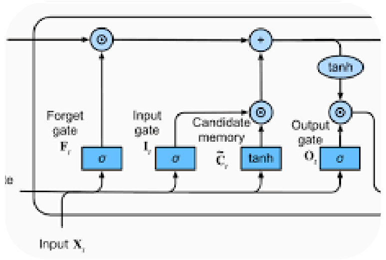
Linear Models



Neural Network



2D Convolutional Neural Networks



Long-Short Term Memory Networks

Better results with RF

LSTM performed similarly, but is a black-box and requires many resources to operate in real time. RF provides more explainable decisions and is lightweight

Field calibration experiment and results

Field calibration experiment

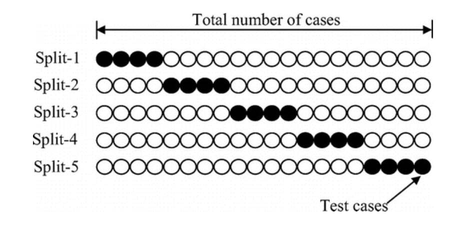
- Location: Patra (center)
- Period: 2021-2022
- Time resolution: hourly average values
- Training Set: 2021
- Gas sensors for calibration: NO_2, O_3
- Test Set: 2022 (same location)

Data Clean

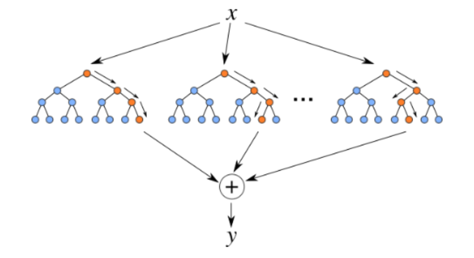
- Remove Zeros
- Remove Negatives
- Average (1H)

Training Data
2021
Drosopoulou Sq.

Training - Validation



Trained Model



Test Data
2022
Drosopoulou Sq.

Features

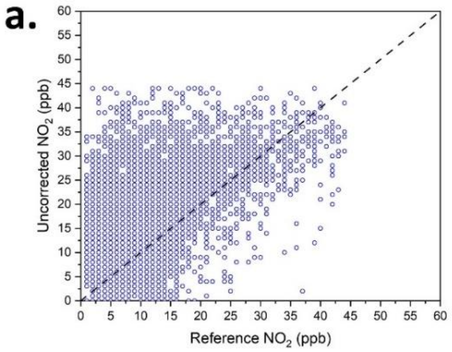
NO, CO, O_3, NO_2, $PM_{2.5}$, T

Ground truth

Either O_3 or NO_2

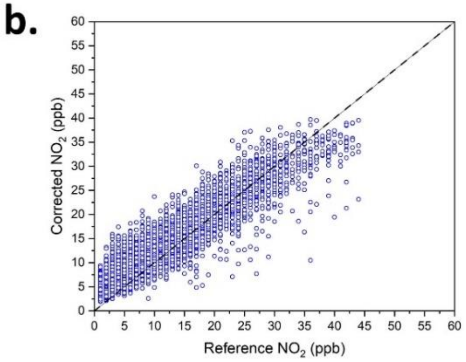
RF performance on the test data

Uncorrected

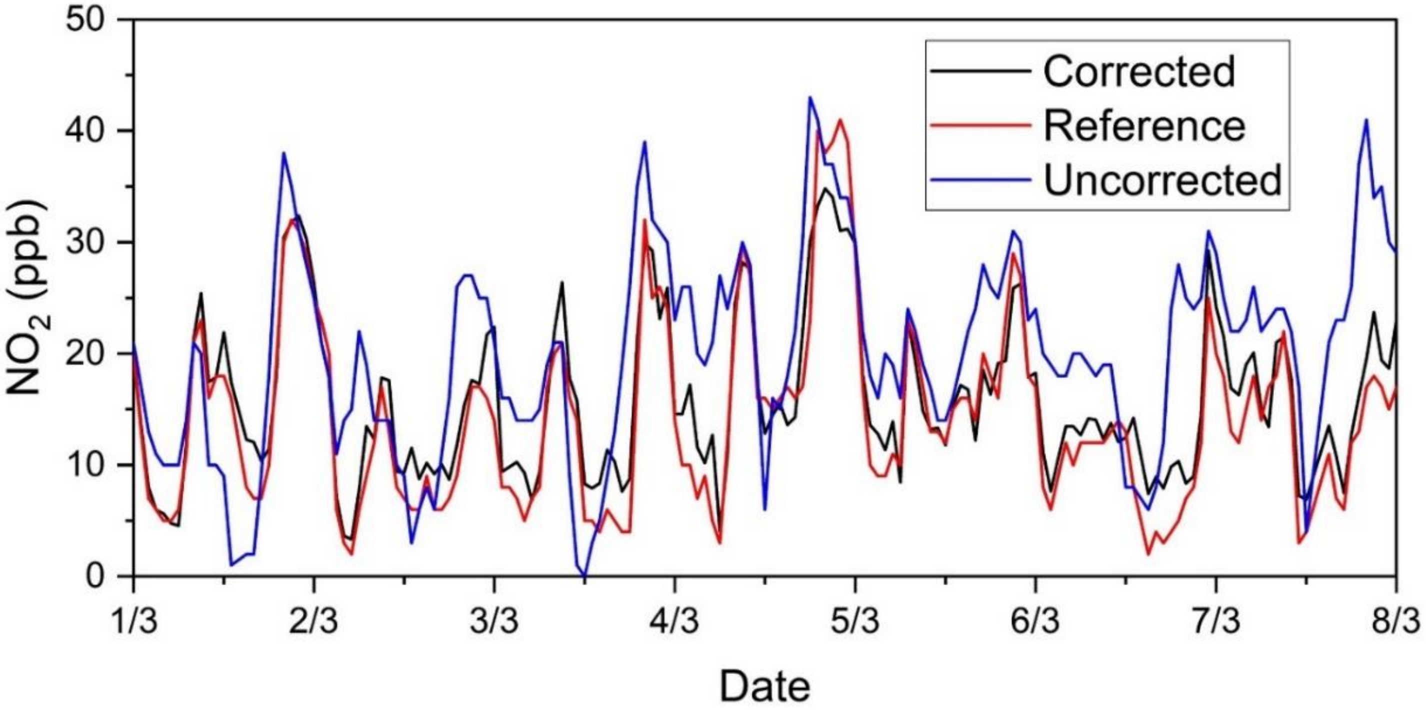


R^2: 0.22
ME(ppb): 9.4
MB (ppb): 7.3
nME: 0.67

Random Forest

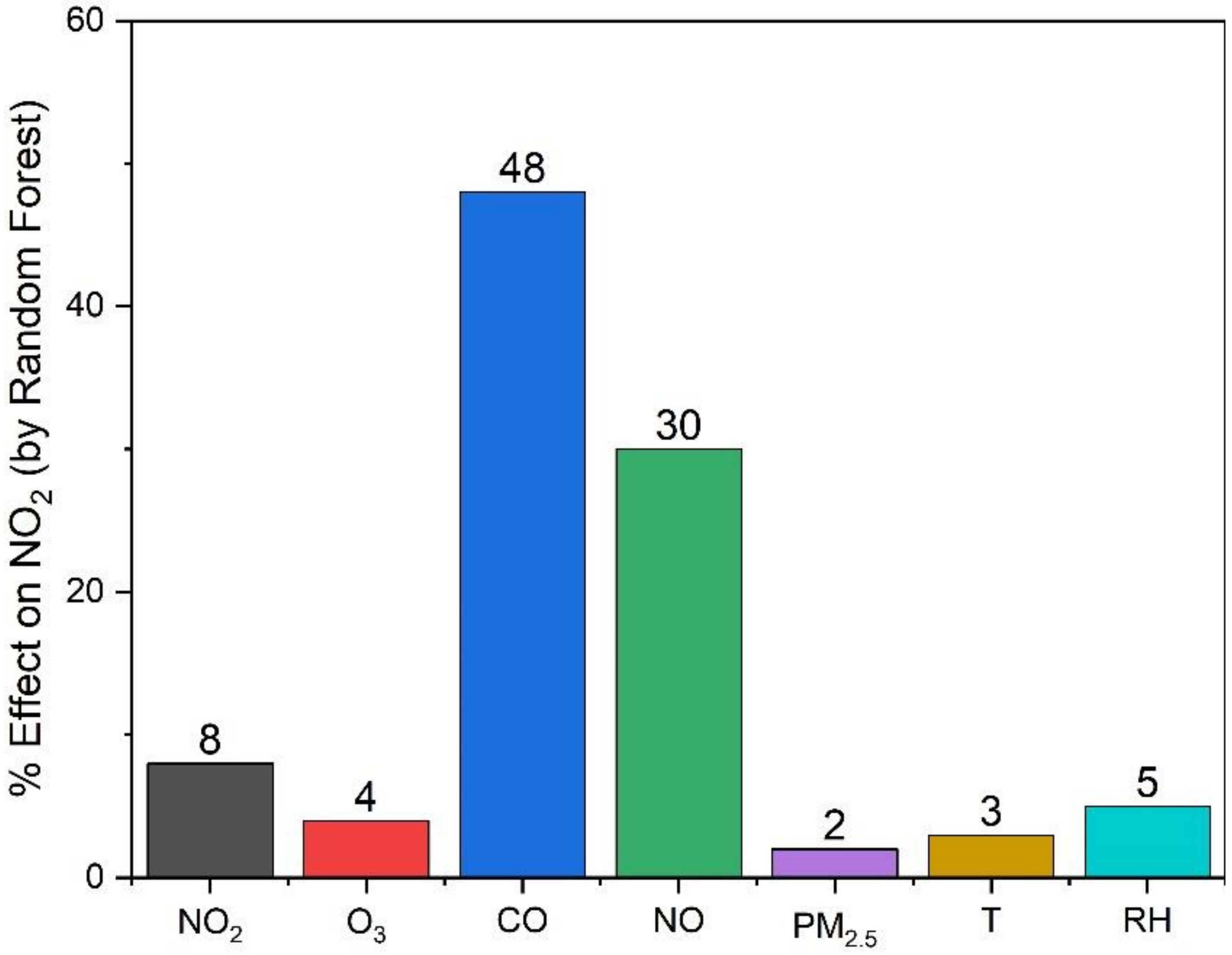


R^2: 0.86
ME(ppb): 3
MB (ppb): 1.7
nME: 0.3



Apostolopoulos ID, Fouskas G, Pandis SN. Field Calibration of a Low-Cost Air Quality Monitoring Device in an Urban Background Site Using Machine Learning Models. Atmosphere. 2023; 14(2):368.

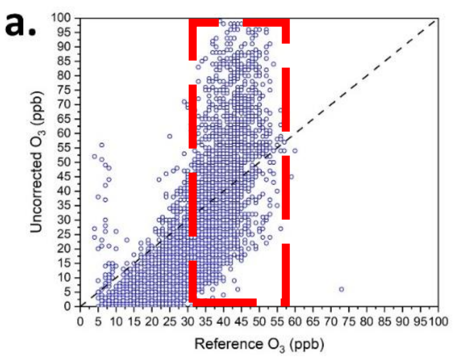
RF feature importance



Apostolopoulos ID, Fouskas G, Pandis SN. Field Calibration of a Low-Cost Air Quality Monitoring Device in an Urban Background Site Using Machine Learning Models. Atmosphere. 2023; 14(2):368.

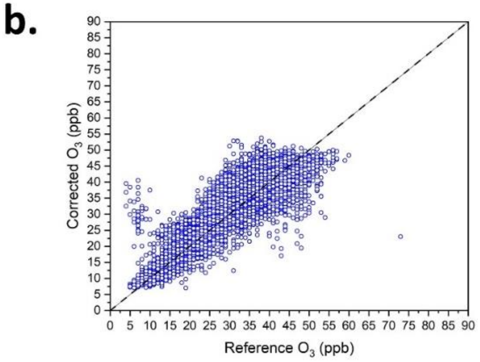
RF performance on the test data

Uncorrected

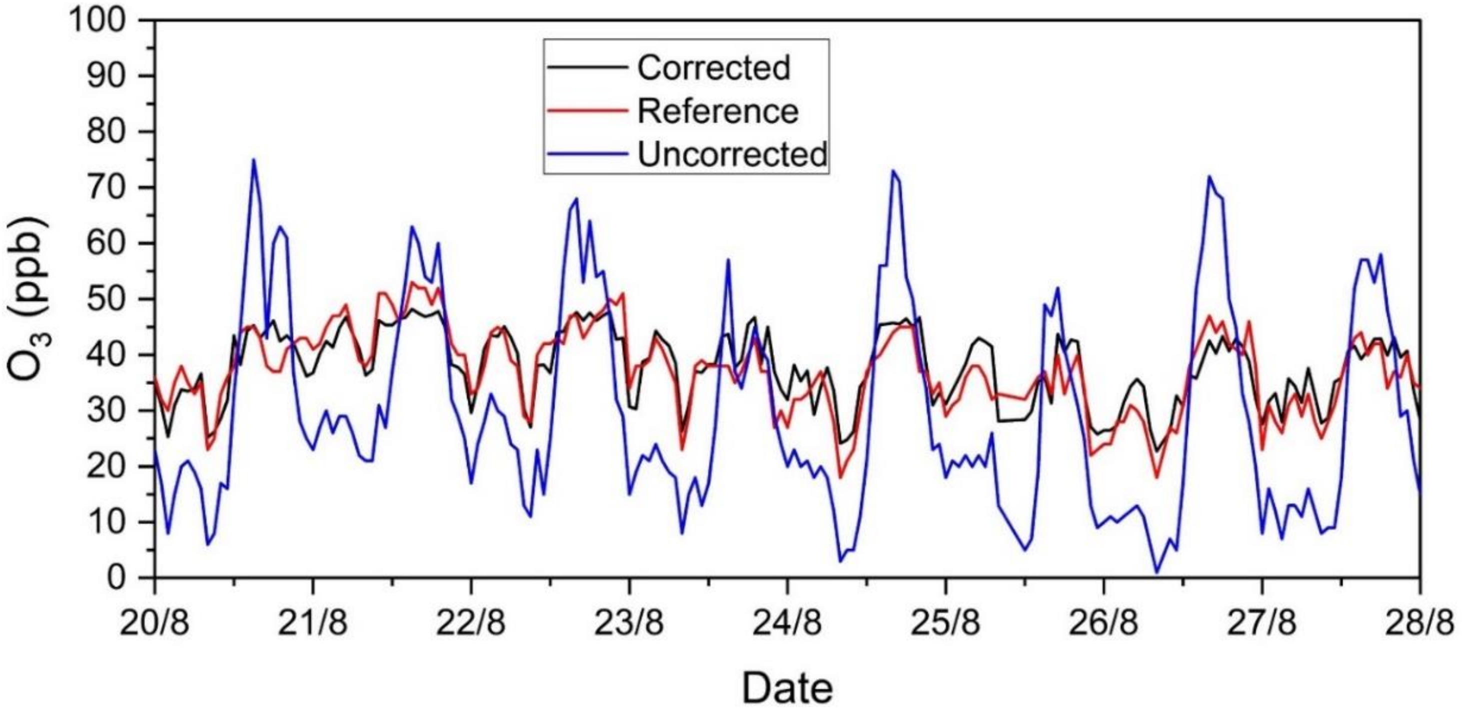


R^2: 0.52
ME(ppb): 13
MB (ppb): -5.9
nME: 0.55

Random Forest

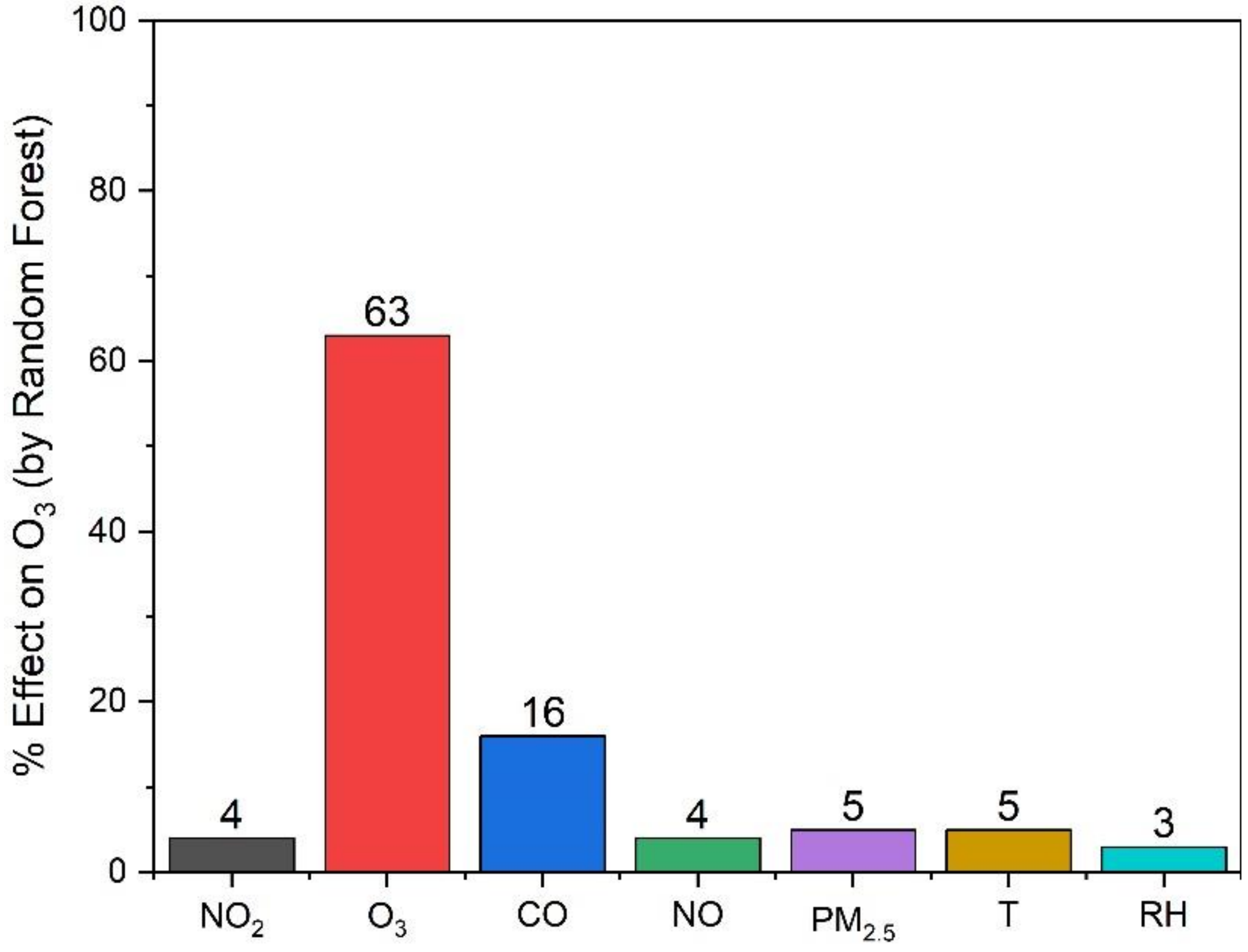


R^2: 0.69
ME(ppb): 4.3
MB (ppb): 1.3
nME: 0.15



Apostolopoulos ID, Fouskas G, Pandis SN. Field Calibration of a Low-Cost Air Quality Monitoring Device in an Urban Background Site Using Machine Learning Models. Atmosphere. 2023; 14(2):368.

RF feature importance



Apostolopoulos ID, Fouskas G, Pandis SN. Field Calibration of a Low-Cost Air Quality Monitoring Device in an Urban Background Site Using Machine Learning Models. Atmosphere. 2023; 14(2):368.

Conclusions

- Low-cost sensors exhibit errors and need calibration
- Utilizing all sensor readings besides the gas under examination for building the algorithm shows promising results
- Random Forest seems to perform well at least for NO_2 and O_3 sensors
- One-year training data are adequate for at least one year correction (on the same site)
- Machine Learning can help in field calibration of low-cost sensors

Work in progress

Work in progress

- **EC Sensors Under Investigation:**
  - NO sensor
  - CO sensor
  - CO_2 sensor
  - VOC sensor

- **General Calibration model**

- **Indoor applications**

Acknowledgements

- Professor Spyros Pandis, Chemical Engineering Department University of Patras, Collaborating Faculty Member FORTH/ICE-HT

- George Fouskas, Head of the Informatics & Communications Centre Principal Appl. Scientist, FORTH/ICE-HT

- Vasilis Bartzelas, Computer Systems Technician, FORTH/ICE-HT

- Region of Western Greece

- C-STACC members and especially Christos Kaltsonoudis, Angeliki Matrali, Eleni Dovrou, and Silas Androulakis

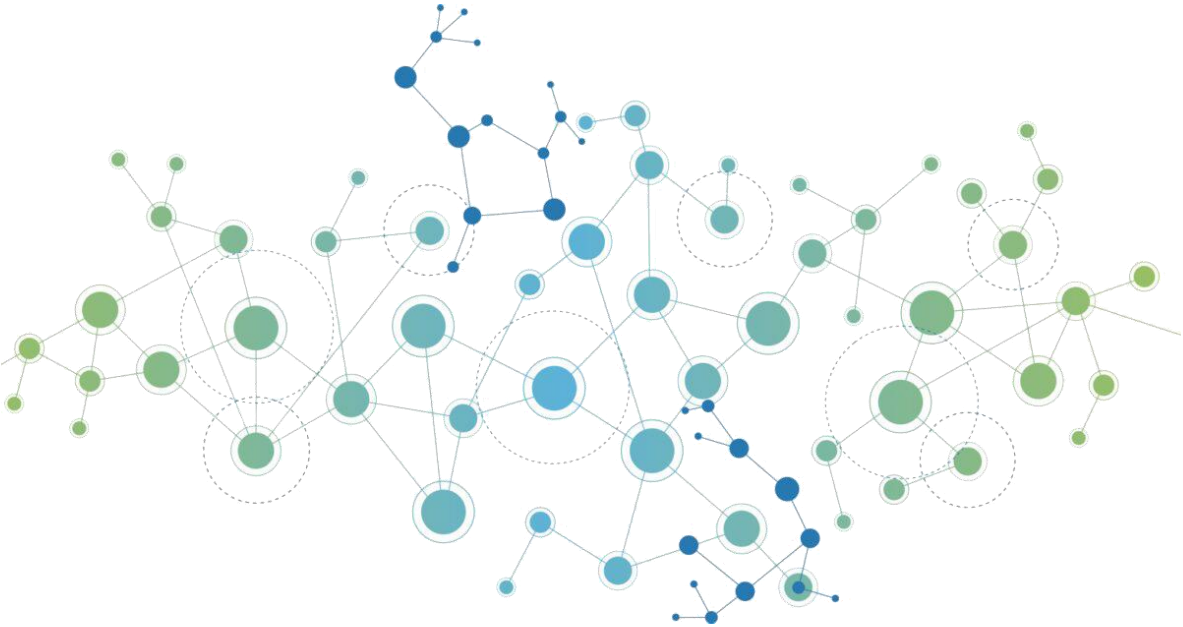
Funding Projects

SmartAQM

ΚΡΗΠΙΣ
ΠΟΙΟΤΗΤΑ ΖΩΗΣ ΙΙ
MIS 5002464

PyroTRACH

FORCeS



FORTH
INSTITUTE OF CHEMICAL ENGINEERING SCIENCES

C-STACC
Center for the Study of Air Quality & Climate Change

IoT Air Quality Monitoring

Thank You!

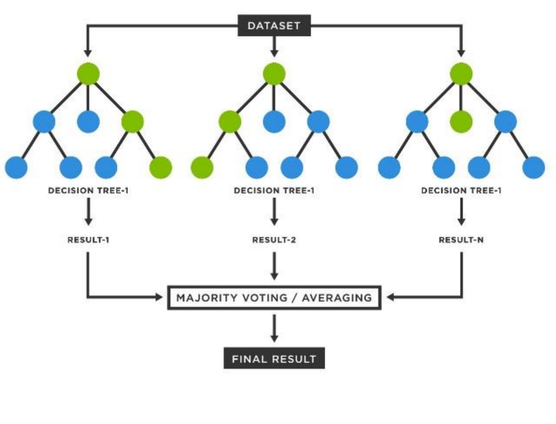
Random Forest application example (Ozone)

ENSENSIA
AIR QUALITY MONITORING STATION BY FORTH / ICE-HT

O_3 reading

NO, CO, NO_2, $PM_{2.5}$, T

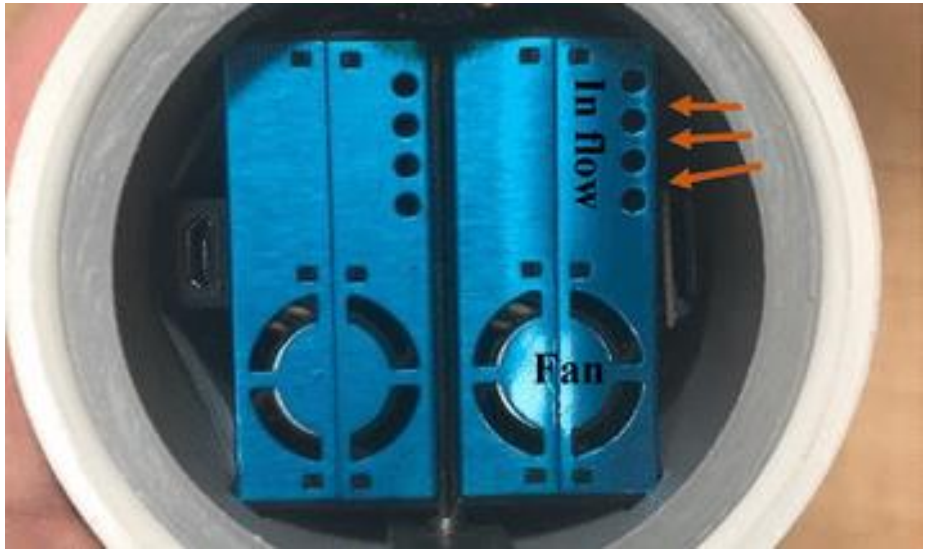
Trained RF

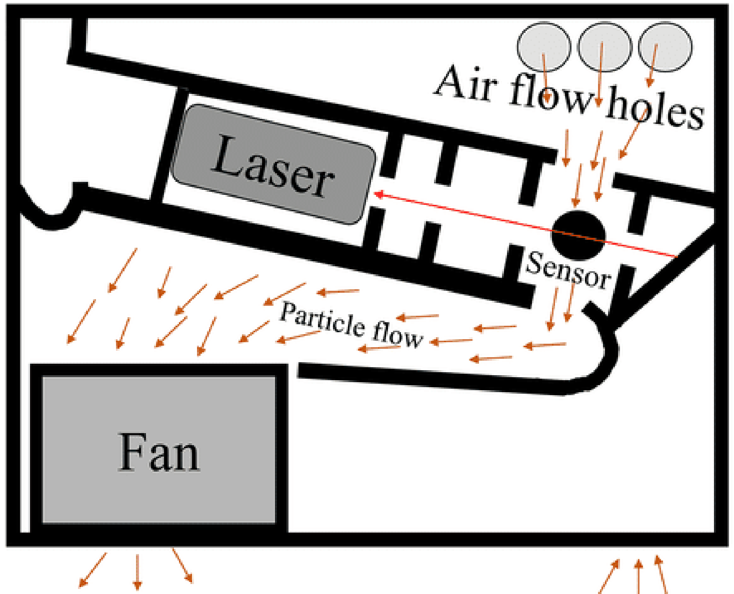


Corrected O_3

Fundamental principles of laser sensors

Particle Matter ($PM_{2.5}$) sensor





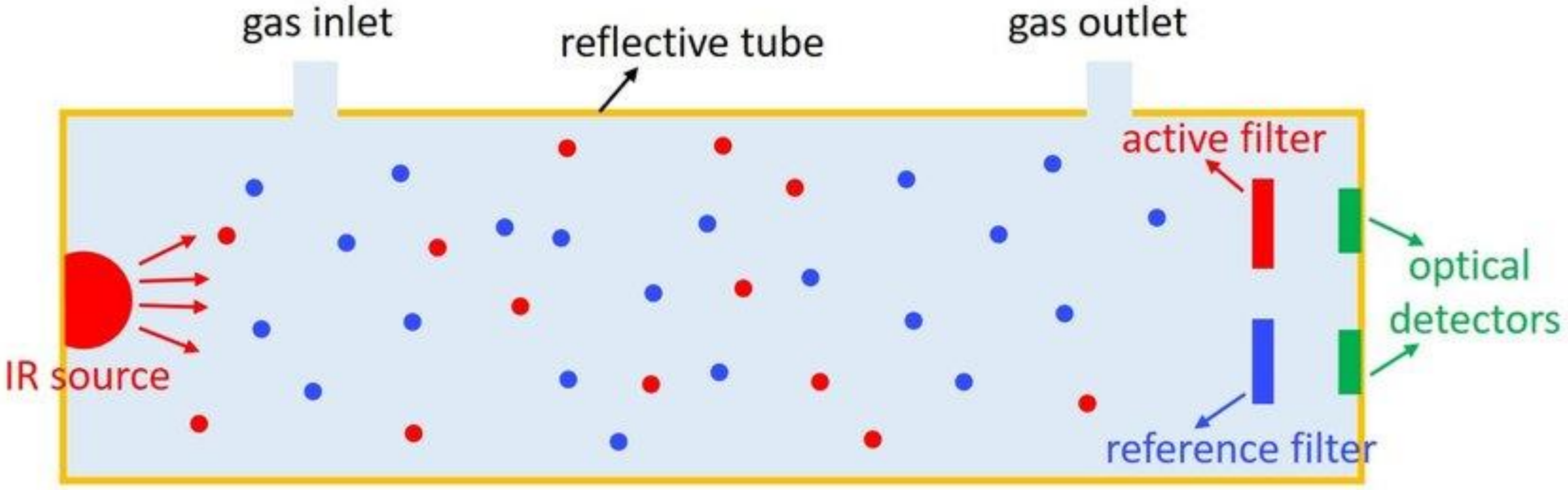
Ardon-Dryer, K., Dryer, Y., Williams, J. N., and Moghimi, N.: Measurements of PM2.5 with PurpleAir under atmospheric conditions, Atmos. Meas. Tech., 13, 5441–5458, https://doi.org/10.5194/amt-13-5441-2020, 2020

ENSENSIA Properties

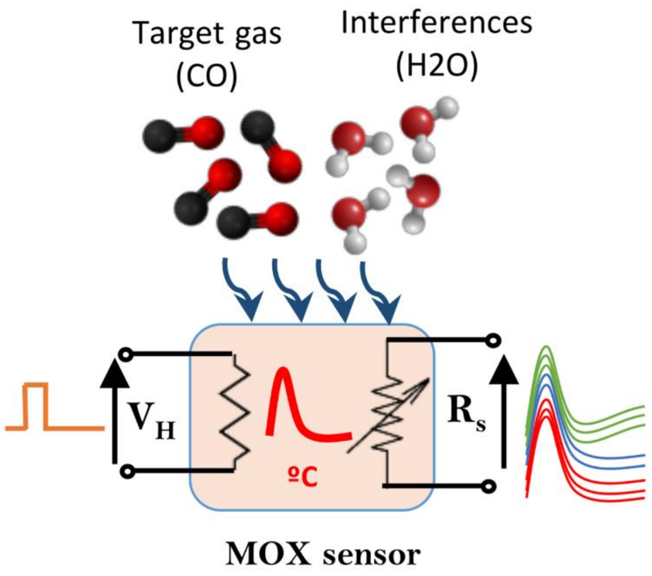
ENSENSIA
Environment Sensing Appliance
AIR QUALITY MONITORING STATION BY FORTH / ICE-HT

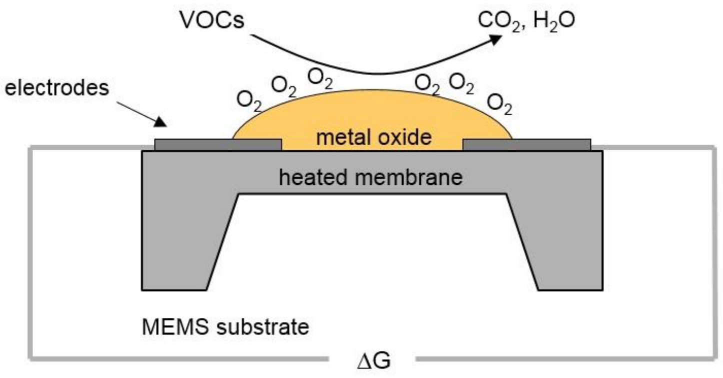
- Low-level info for each sensor estimate (electrodes voltage)
- Enough CPU power to process sophisticated dynamic calibration / correction algorithms (Edge computing)
- Fully remote managed appliance
- Improved precision of measurements based on Machine Learning
- Bundled with a friendly visualization web-based tool

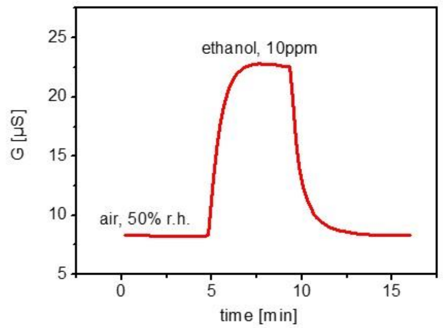
Fundamental principles of NDIR sensors



Fundamental principles of Mox sensors







VOC Sensor Operating Principle with Sensor Diagram and Example Response to VOC

- The gas-sensitive Metal Oxide Material [MOX] consists of a highly porous and granular semiconducting material.
- The grains form a resistor with distinct conductive paths between the electrodes
- Interaction of the VOC with the MOX (Combustion/chemical reaction driven by the heated membrane) results in predictable modulation of the measured electrical resistance

Sensor evaluation and calibration

Machine Learning

China,
UK,
USA

1^{st} evaluation

2^{nd} evaluation

3^{rd} evaluation

Sensors

Factory Calibration

Chamber Calibration

Inter-unit consistency

Field Calibration

Sensor Integration

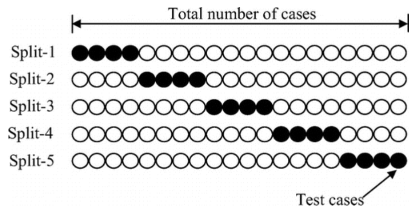
General calibration model

Data Clean

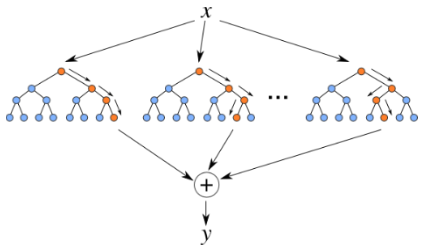
- Remove Zeros
- Remove Negatives
- Remove Outliers

Training Data
2021-2022
Drosopoulou Sq.

Training - Validation



Trained Model



Patra

2021 - 2022
Georgiou Sq.

1 month
Outside a school
in Kato Kastritsi

2023
Drosopoulou Sq.

Athens

10 months
In the National
Observatory