

# Pre-Deployment Testing, Augmentation and Calibration of Cross-Sensitive Sensors

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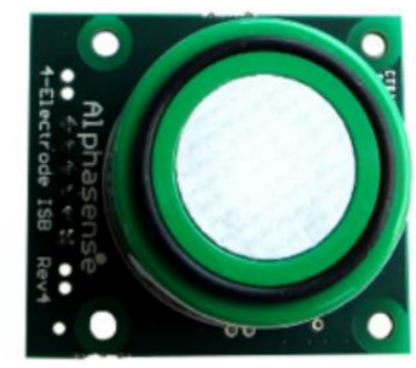
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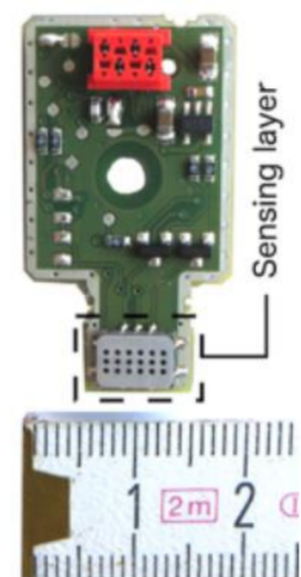


## Low-cost Gas Sensors

- Measure concentration of major pollutants: NO<sub>2</sub>, CO, O<sub>3</sub>, PM<sub>10</sub> etc.
- Cheap, small packaging, low-power consumption
- Challenges:
  - Affected by **environmental changes**, e.g. temperature
  - Low selectivity: **cross-sensitive** to multiple pollutants
  - Primarily **designed for higher concentrations** than in outdoor air, e.g. car industry



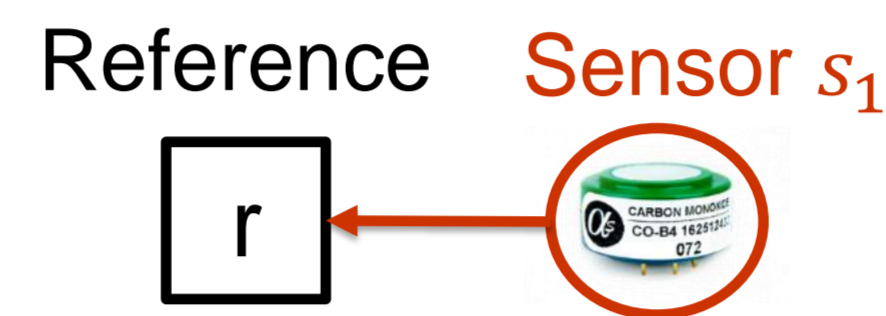
α-sense CO-B4



SGX Sensortech MiCS-OZ-47 O<sub>3</sub>

## Sensor Calibration

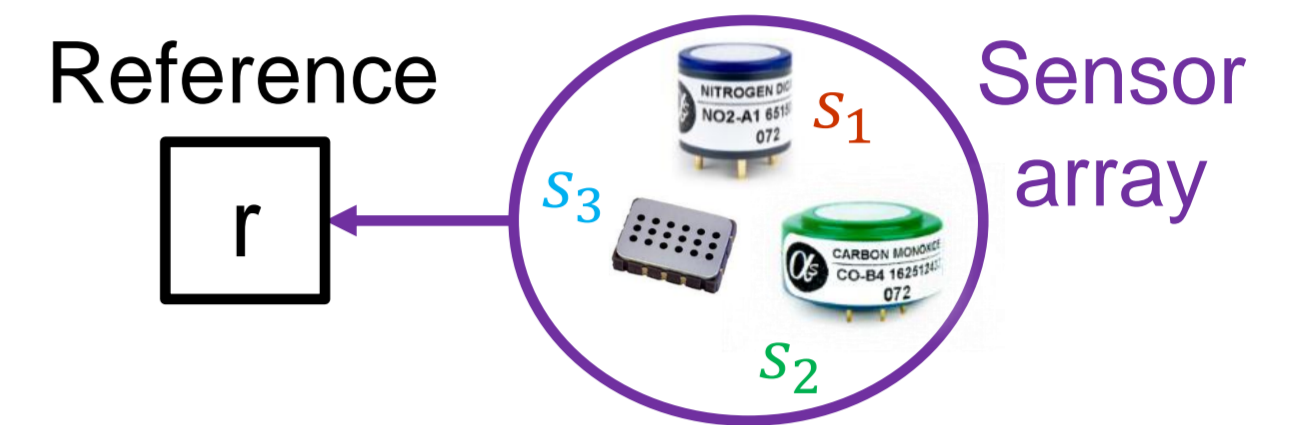
### Simple sensor calibration



Calibrate **single** sensor to **single** reference using **Ordinary Least-Squares (OLS)**:

$$r = \beta_0 + \beta_1 s_1 + \epsilon$$

### Sensor array calibration



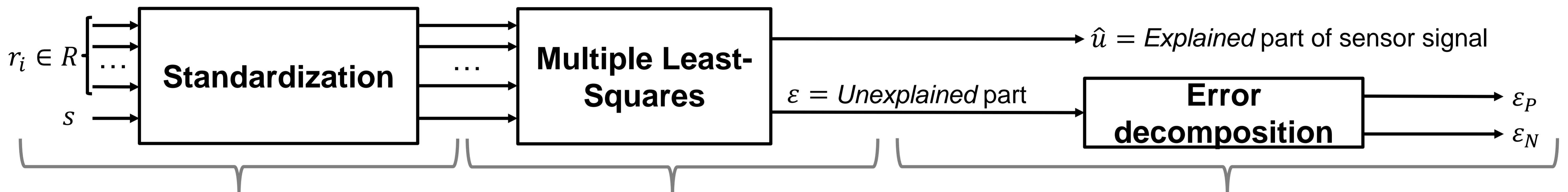
Calibrate **multiple** sensors to **single** reference using **Multiple Least-Squares (MLS)**:

$$r = \beta_0 + \beta_1 s_1 + \beta_2 s_2 + \beta_3 s_3 + \epsilon$$

Used to compensate for cross-sensitivities

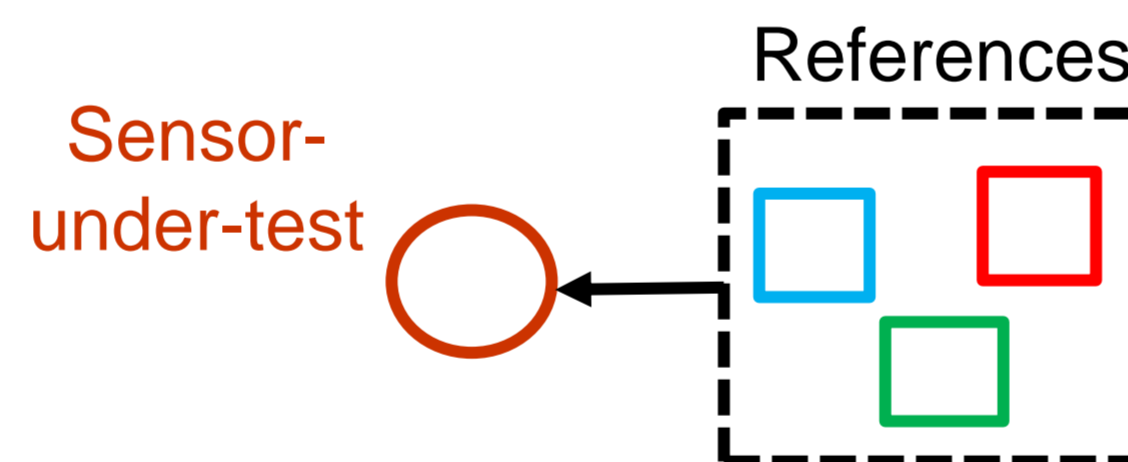
## Pre-deployment Testing

How can we uncover all cross-sensitivities and environmental dependencies of a low-cost sensor?



- In-field measurements, e.g. next to high quality monitoring station
- Sensor-under-test:  $s$
- Various reference signals:  $r_i \in R$
- Standardization (zero-mean & unit-variance) for scale-invariant results

### Inverse calibration

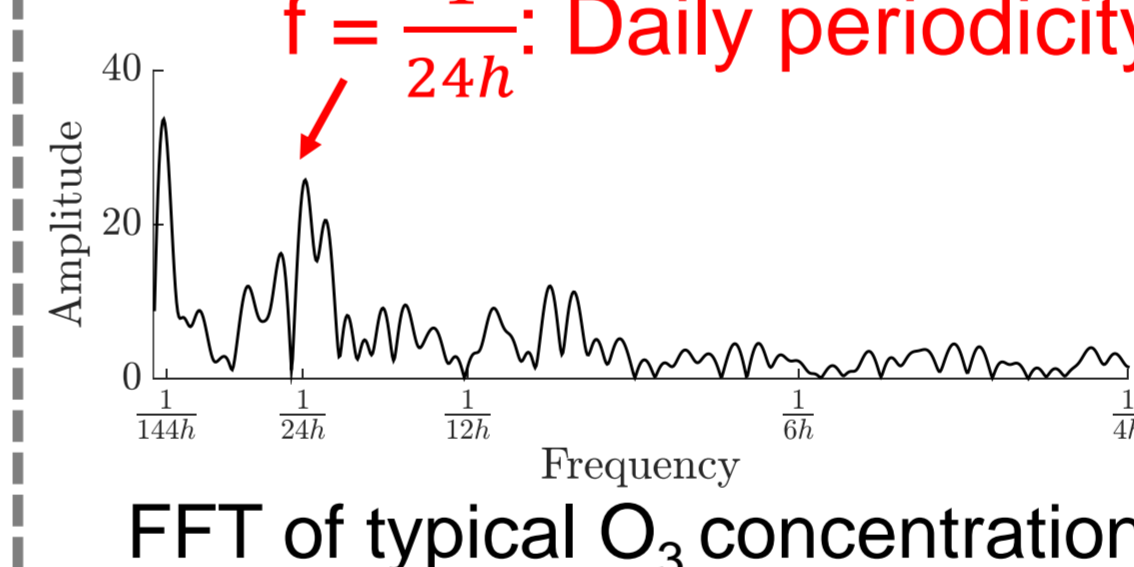


### Multiple Least-squares

$$s = \beta_0 + \beta_1 r_1 + \beta_2 r_2 + \beta_3 r_3 + \epsilon$$

### Reason for substantial error can be two-fold

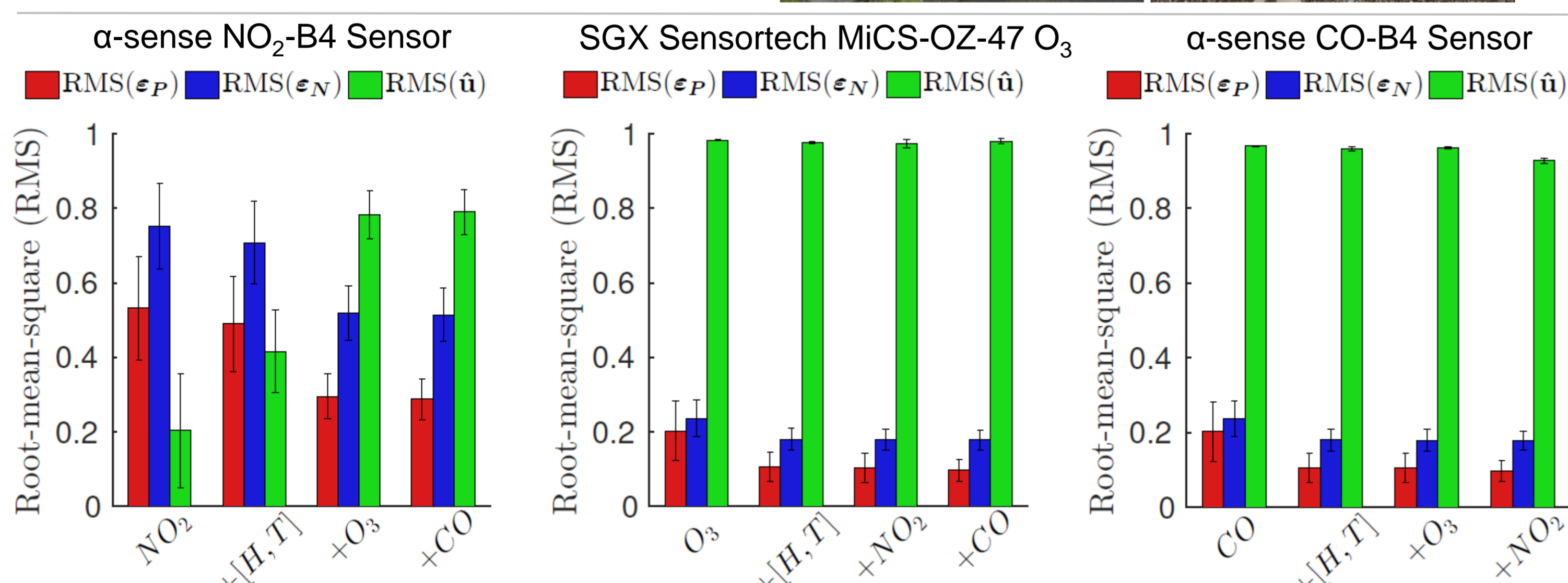
- $f = \frac{1}{24h}$ : Daily periodicity  $\Rightarrow$  Low-pass filter (cut-off:  $\frac{1}{24h}$ )
- Low-frequent part  $\epsilon_P$ : Uncaptured cross-sensitivities
- High-frequent part  $\epsilon_N$ : Sensor noise



Find combination of references that best explains the sensor-under-test by quantifying the amount of captured/uncaptured cross-sensitivities and sensor noise

## Experimental Evaluation

Testing of various low-cost sensors at a governmental high-quality station (NABEL) in Dübendorf, Switzerland

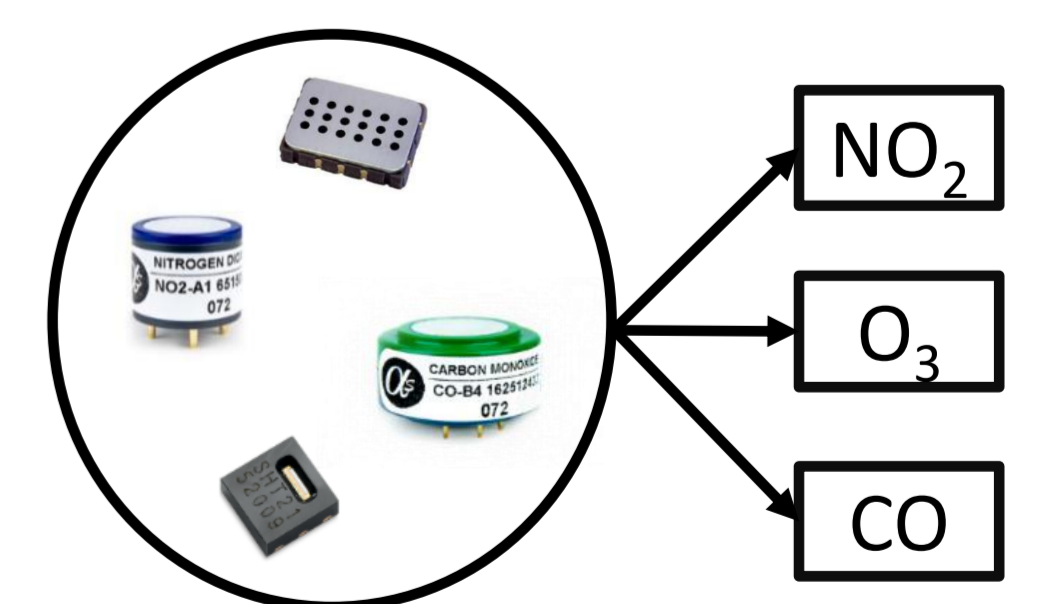


- Quantify captured ( $\hat{u}$ ) & uncaptured ( $\epsilon_P$ ) cross-sensitivities and sensor noise ( $\epsilon_N$ ) using root-mean-square value (RMS)
- Gradually extend references to highlight individual effects
- NO<sub>2</sub>-B4 is highly cross-sensitive to O<sub>3</sub> and environmental effects
- CO-B4 and SGX O<sub>3</sub> both depend on environmental effects

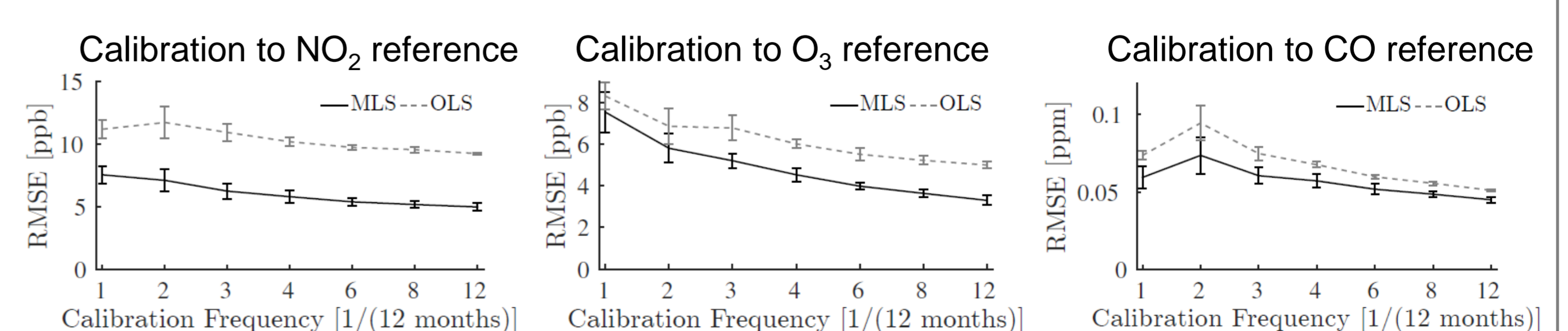
## Optimized Sensor Array

Compensating for cross-sensitivities and environmental dependencies improves calibration accuracy and stability of low-cost sensors

- Augmented sensor array
  - SGX Sensortech MiCS-OZ-47 O<sub>3</sub>
  - α-sense NO<sub>2</sub>-B4
  - α-sense CO-B4
  - Sensirion SHT H & T



### Calibration accuracy and stability



- Smaller average calibration error when calibrating sensor array (MLS) compared to simple sensor calibration (OLS)
- Longer stability of sensor array calibration parameters, i.e. MLS requires less re-calibration compared to OLS