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FNSNF

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

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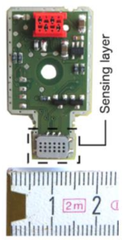
## *Low-cost Gas Sensors*

- Measure concentration of major pollutants: $NO_2$, CO, $O_3$, $PM_{10}$ 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

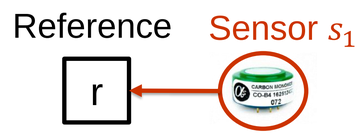
α-sense CO-B4




SGX Sensortech MiCS-OZ-47 $O_3$

## *Sensor Calibration*

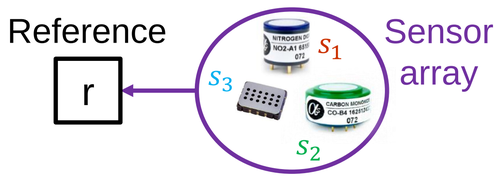
***Simple sensor calibration***




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

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

***Sensor array calibration***



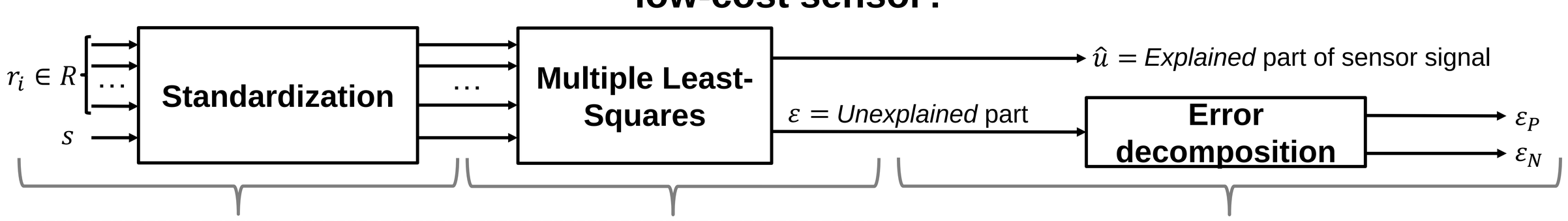

Calibrate **multiple** sensors to **single** reference using *Multiple Least-Squares* (MLS):

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

*Used to compensate for cross-sensitivities*

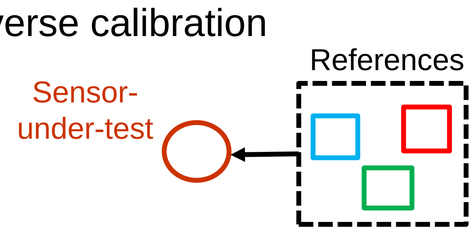
## *Pre-deployment Testing*

### 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

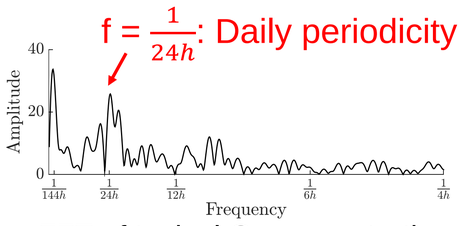
- Inverse calibration




- Multiple Least-squares

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

- Reason for substantial error can be two-fold



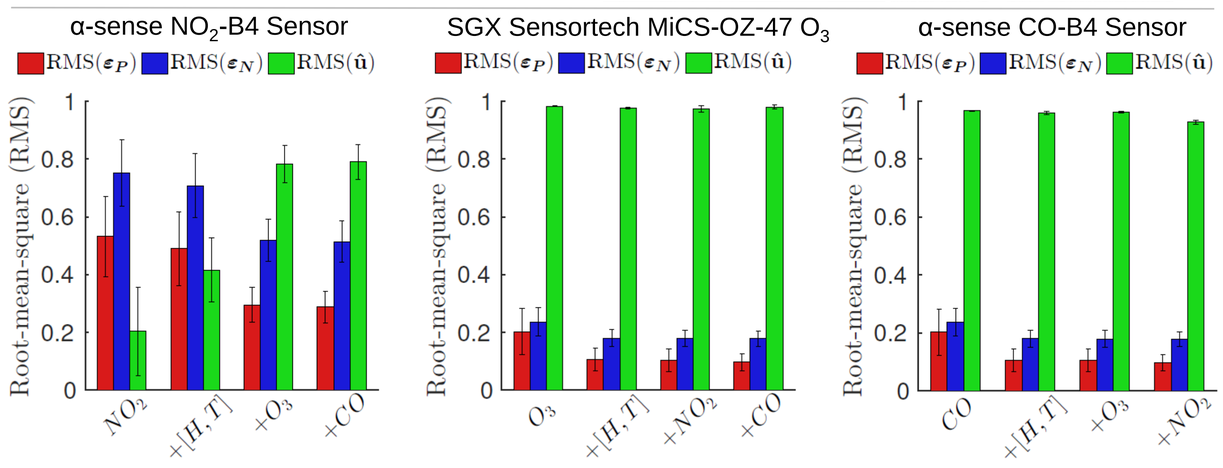

FFT of typical $O_3$ concentration

- Low-frequent part $\varepsilon_P$ : Uncaptured cross-sensitivities
- High-frequent part $\varepsilon_N$ : 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

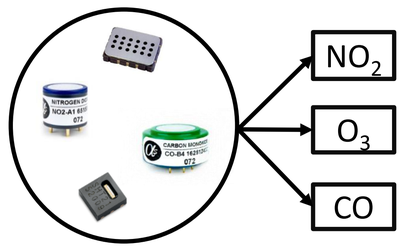



- Quantify captured ($\hat{u}$) & uncaptured ($\varepsilon_P$) cross-sensitivities and sensor noise ($\varepsilon_N$) using root-mean-square value (RMS)
- Gradually extend references to highlight individual effects
- $NO_2$-B4 is highly cross-sensitive to $O_3$ and environmental effects
- CO-B4 and SGX $O_3$ both depend on environmental effects

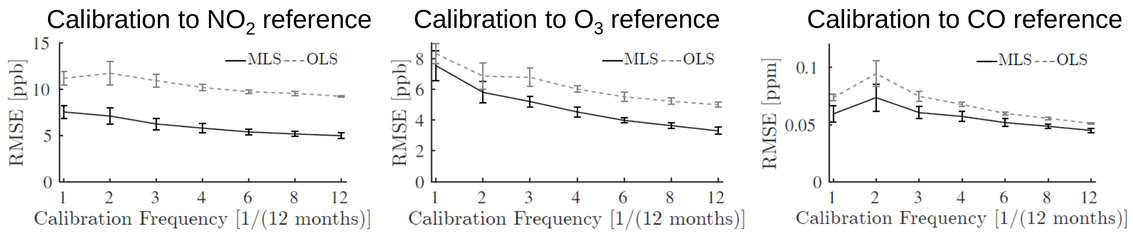
## *Optimized Sensor Array*

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

- Augmented sensor array
  - SGX Sensortech MiCS-OZ-47 $O_3$
  - α-sense $NO_2$-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

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