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

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# Air Pollution

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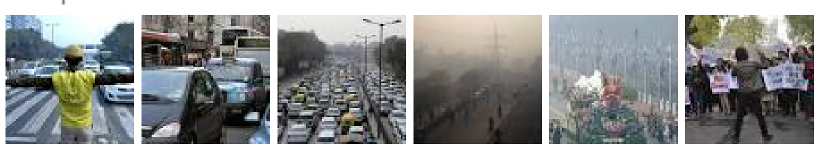

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# Active Research and Development

- Numerous research projects and start-ups

OpenSENSE

common sense

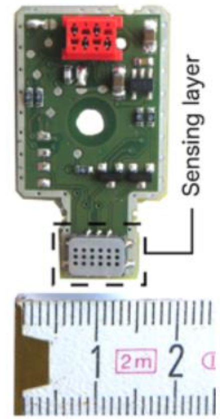
aclima


Air Quality Egg

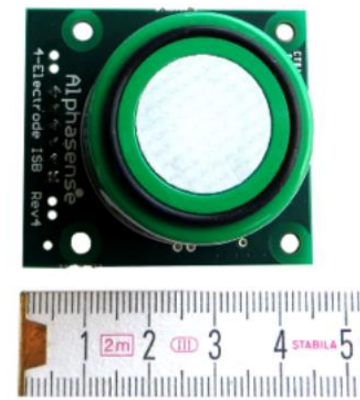
- Similar approach
  - Small and low-cost air quality monitoring systems

# Low-cost Air Quality Sensors

- Pro's:
  - Small
  - Cheap (1$ - 100$)
  - Low power consumption




SGX Sensortech MiCS-OZ-47 $O_3$



AlphaSense CO-B4

- Con's:
  - Low target pollutant concentrations, often at sensitivity boundaries
  - Environmental conditions affect sensor output
  - Low selectivity, i.e. sensors are cross-sensitive to multiple substances
  - Need frequent re-calibration

# Limiting Effects

- Datasheet information
  - Sparse or not provided at all
  - Laboratory results do not cover deployment conditions

**ENVIRONMENTAL**

| | | | |
|---|---|---|---|
| | Sensitivity @ -20°C | (% output @ -20°C/output @ 20°C) @ 2ppm $NO_2$ | 40 to 70 |
| | Sensitivity @ 50°C | (% output @ 50°C/output @ 20°C) @ 2ppm $NO_2$ | 120 to 135 |
| | Zero @ -20°C | nA change from 20°C | ±10 |
| | Zero @ 50°C | nA change from 20°C | 60 to 380 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **CROSS SENSITIVITY** | $H_2S$ | sensitivity | % measured gas | @ | 5ppm | $H_2S$ | < -130 |
| | NO | sensitivity | % measured gas | @ | 5ppm | NO | < 4 |
| | $Cl_2$ | sensitivity | % measured gas | @ | 5ppm | $Cl_2$ | < 100 |
| | $SO_2$ | sensitivity | % measured gas | @ | 5ppm | $SO_2$ | < -20 |
| | CO | sensitivity | % measured gas | @ | 5ppm | CO | < 0.1 |
| | $H_2$ | sensitivity | % measured gas | @ | 100ppm | $H_2$ | < 0.1 |
| | $C_2H_4$ | sensitivity | % measured gas | @ | 100ppm | $C_2H_4$ | < 0.1 |
| | $NH_3$ | sensitivity | % measured gas | @ | 20ppm | $NH_3$ | < 0.1 |
| | $CO_2$ | sensitivity | % measured gas | @ | 5% Vol | $CO_2$ | < 0.1 |
| | $O_3$ | sensitivity | % measured gas | @ | 100ppb | $O_3$ | 30 to 65 |
| | Halothane | sensitivity | % measured gas | @ | 100ppm | Halothane | < 0.1 |

Datasheet, NO2-B4 Nitrogen Dioxide Sensor, Alphasense

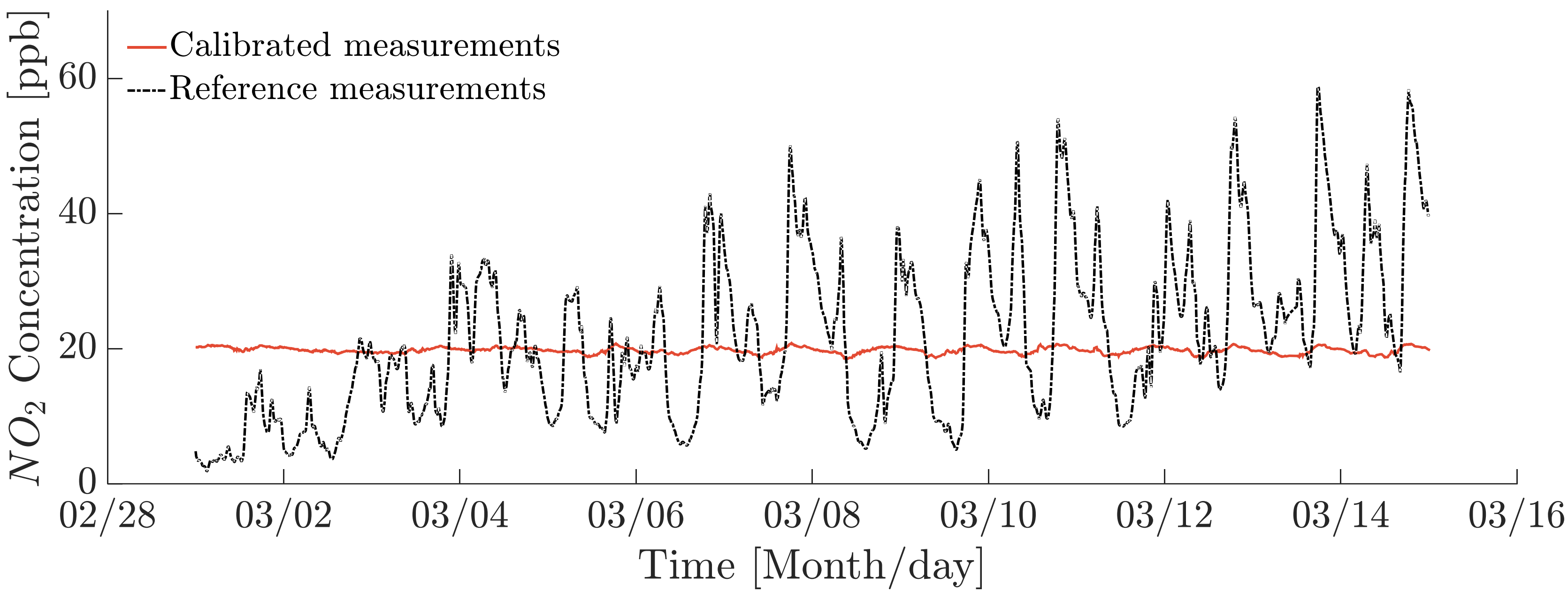
secondhand smoke, smoke generated from burning of wood and paper, volatiles of wine (alcohol) and cosmetics, ammonia, hydrogen sulfide, hydrogen, carbon monoxide, propane, methane, styrene, propylene glycol, phenol, acetone, thinner, insecticide, correction fluid, benzene, formaldehyde and so on.

Datasheet, TP401-A Indoor Air Quality Sensor, Shenzen Dovelet Sensors Technology CO., LTD

- Ignoring these effects limits performance
- **Goal**: Understand sensor characteristics under deployment-related conditions

# Example: Alphasense $NO_2$-B4 Sensor

- Deployed at high-quality monitoring station
- Ordinary Least-Squares (OLS) calibration to nitrogen dioxide ($NO_2$) reference measurements




- Root-Mean-Square-Error (RMSE) = 12.4 ppb (50%)

Sensor is highly cross-sensitive to ozone ($O_3$), temperature and humidity

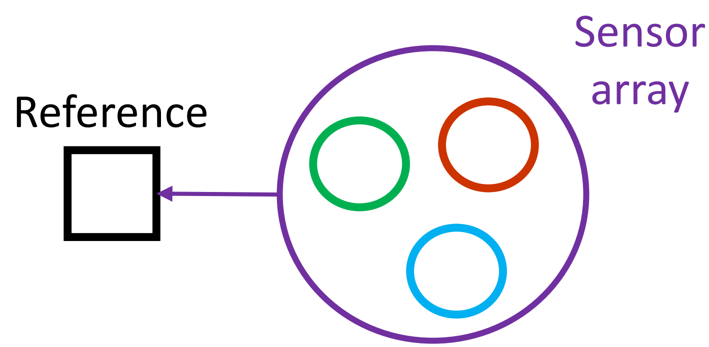
# Sensor Calibration

## Simple sensor calibration


Ordinary Least-Squares (OLS):

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

## Sensor array calibration



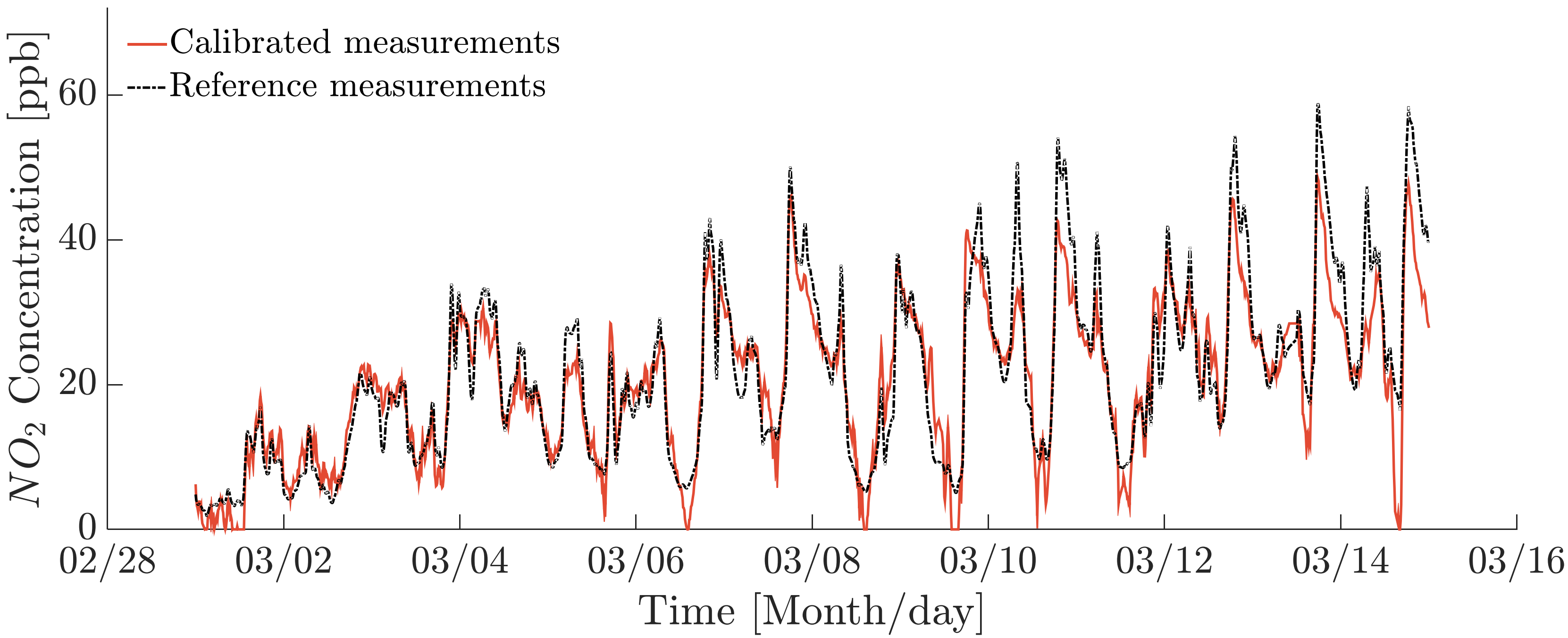

Multiple Least-Squares (MLS):

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

*Used to compensate for cross-sensitivities*

# Example: Alphasense $NO_2$-B4 Sensor revised

- Multiple Least-Squares (MLS) sensor array calibration
  - $NO_2$-B4, SGX $O_3$, humidity and temperature




- RMSE = 4.6 ppb (18%)

# Challenges

## Testing

Identify ALL

1. cross-sensitivities and
2. environmental dependencies
3. under deployment-related conditions.

## Augmentation

Select low-cost sensors and augment to optimal sensor array

## Calibration

Sensor array calibration for

1. accurate measurements
2. with long-term stability

# Challenges

**Testing** → **Augmentation** → **Calibration**

### Testing

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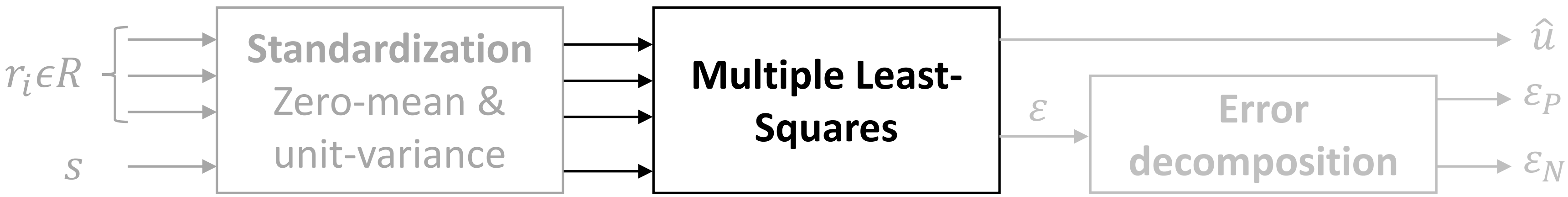
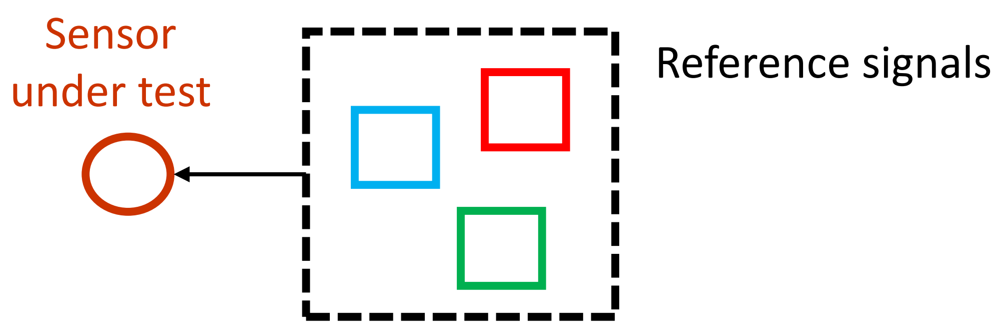
# Sensor Testing: Signals


- In-field measurements
  - Measurements next to high-quality monitoring stations, e.g. run by governmental authorities
- Sensor-under-test $s$
- Various reference signals $r_i \epsilon R$ , e.g. pollutants, temperature, humidity…
- Standardization for scale-invariant results

# Sensor Testing: Inverse Calibration



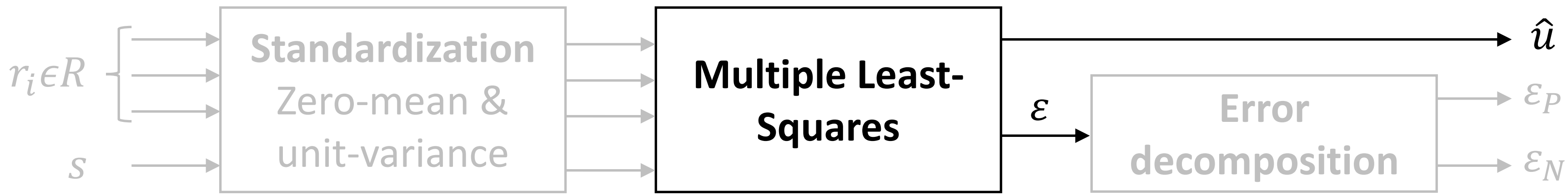

- Inverse calibration




- Multiple Least-Squares

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

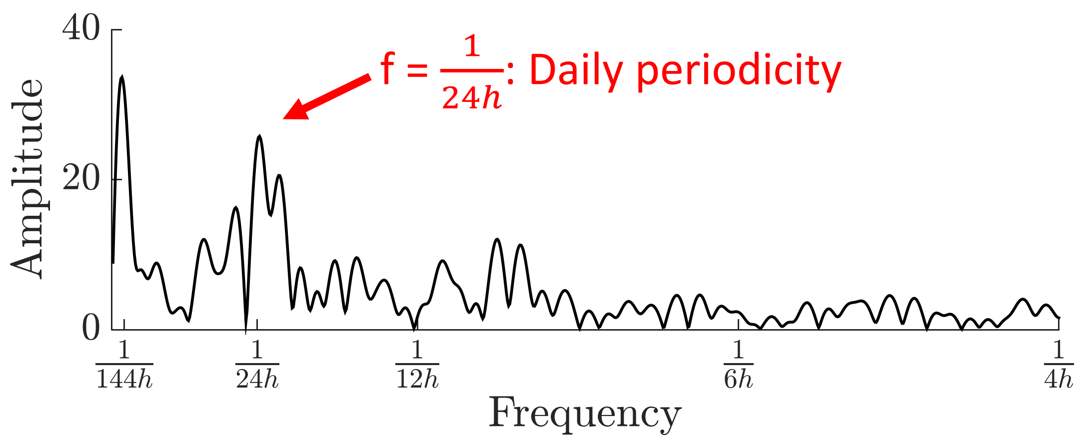
# Sensor Testing: Regression Error




- Regression estimation $\hat{u}$
  - *Explained* part of the sensor signal with given references
- Regression error $\varepsilon$
  - *Unexplained* part of the sensor signal
- Reason for substantial error can be two-fold
  - Uncaptured cross-sensitivities
  - Sensor noise

# Sensor Testing: Error Decomposition


- FFT of typical $O_3$ concentration



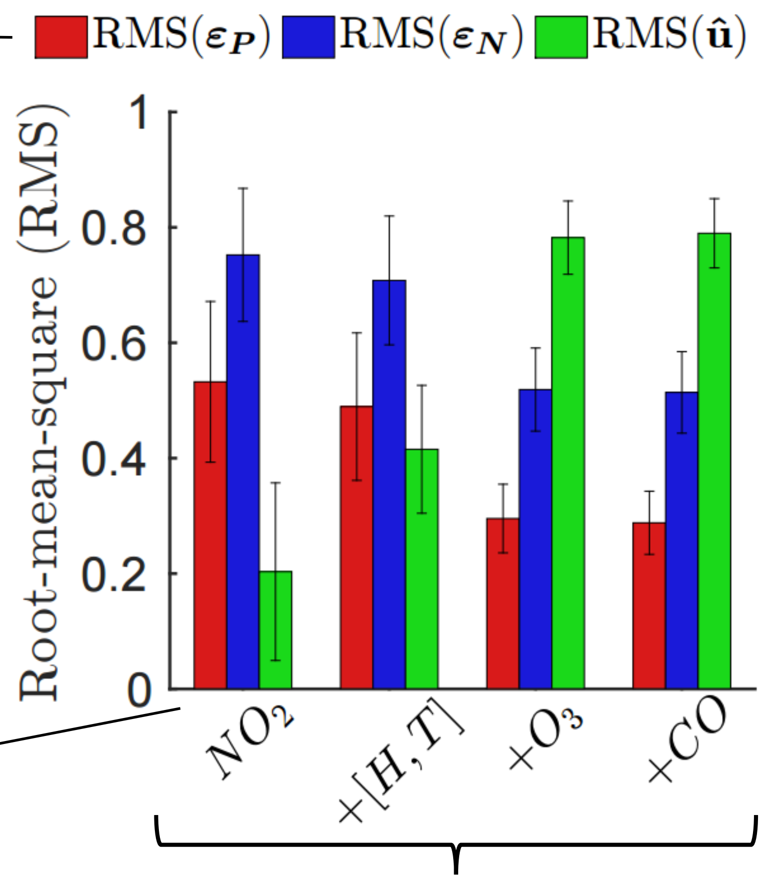

- Error decomposition: Low-pass filter (cut-off: $\frac{1}{24h}$)
  - Low-frequent part $\varepsilon_P$ : Uncaptured cross-sensitivities
  - High-frequent part $\varepsilon_N$ : Sensor noise

# Experimental Evaluation

- Various low-cost sensors
- Governmental high-quality station (NABEL) in Duebendorf, Switzerland
  - 20 different reference signals
- 15 months of data

# Alphasense $NO_2$-B4 Sensor

Root-Mean-Square
$RMS(\cdot) \epsilon [0,1]$

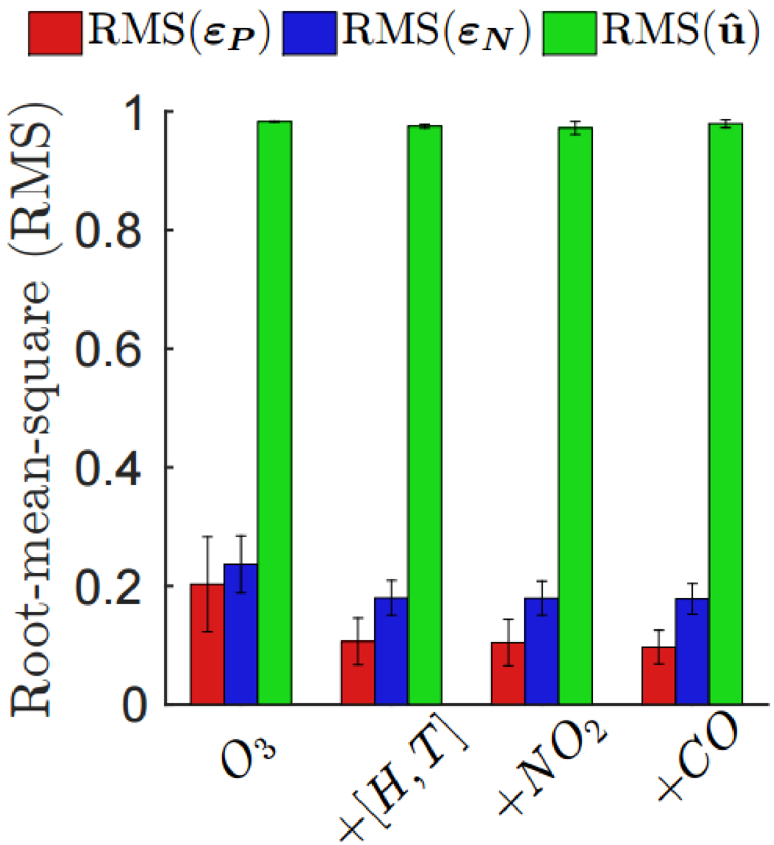



Decreased error and increased explained signal components when adding $O_3$, temperature and humidity

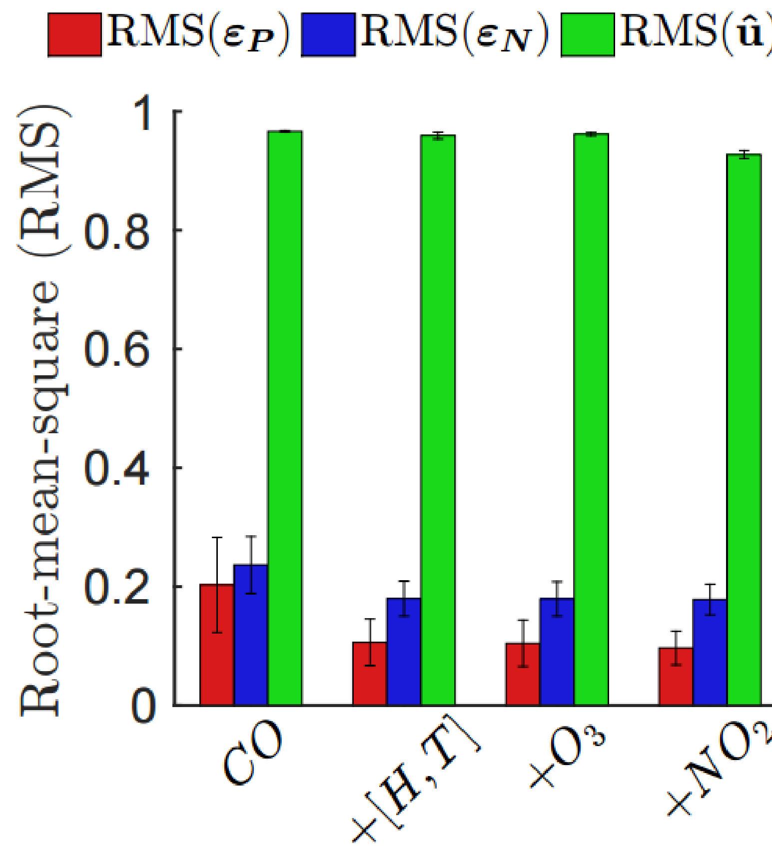
High error components when using only $NO_2$ reference

Extending the used references

# SGX $O_3$ and Alphasense CO-B4



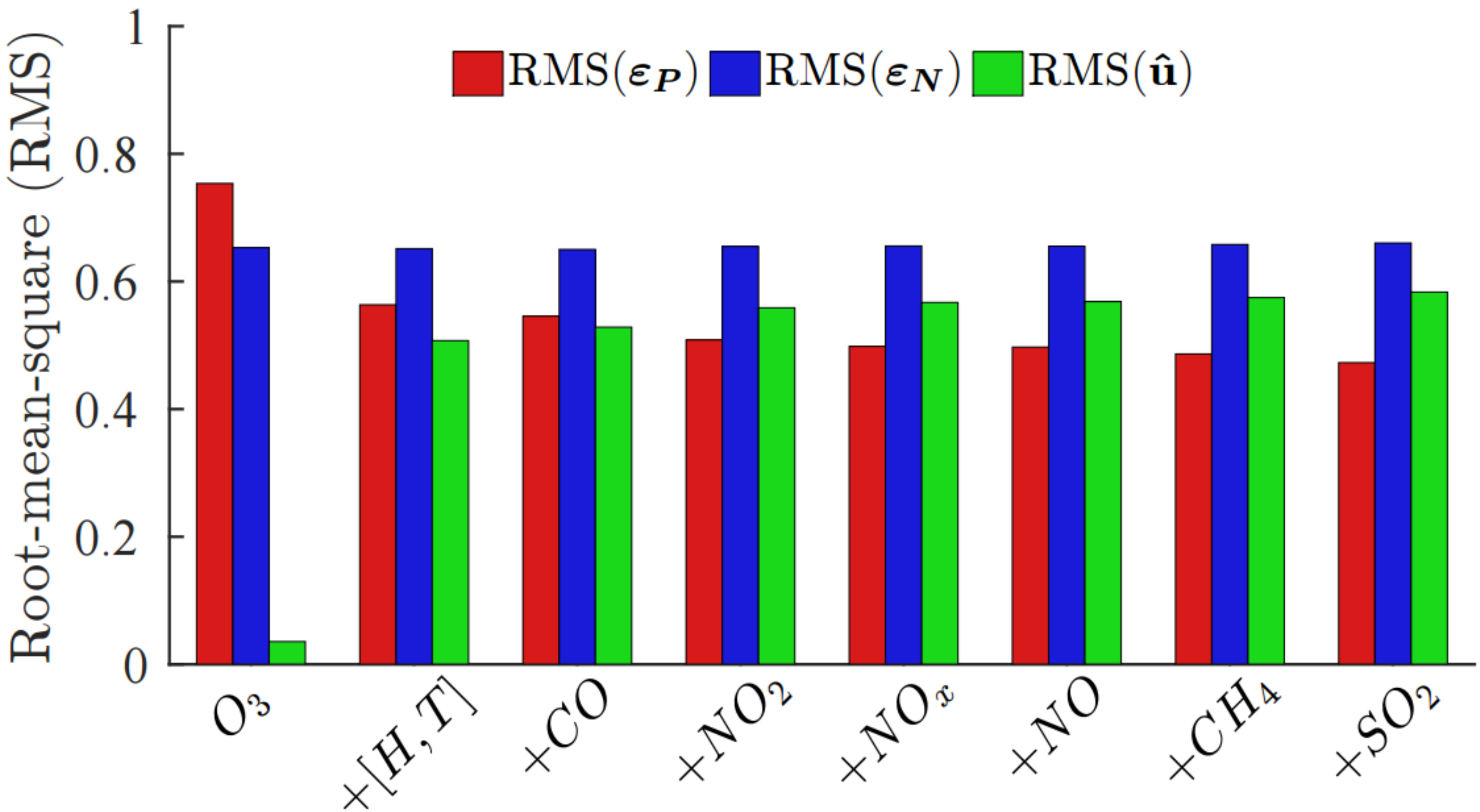

SGX $O_3$ Sensor




Alphasense CO-B4

Similar results: Highly sensitive to target gas.
Adding T & H reduces error components.

# Dovelet Air Quality Sensor




Not sensitive to any pollutants.
Unqualified sensor for outdoor air quality measurements.

# Testing Conclusion

1. Need $O_3$, humidity and temperature measurements to compensate for cross-sensitivities of the $NO_2$ sensor
2. $O_3$ and CO sensor depend on humidity and temperature

## Testing

Identify ALL

1. cross-sensitivities and
2. environmental dependencies
3. under deployment-related conditions.

Deployment goal: Monitor pollutants O3, CO and NO2

## Augmentation

Select low-cost sensors and augment to optimal sensor array

## Calibration

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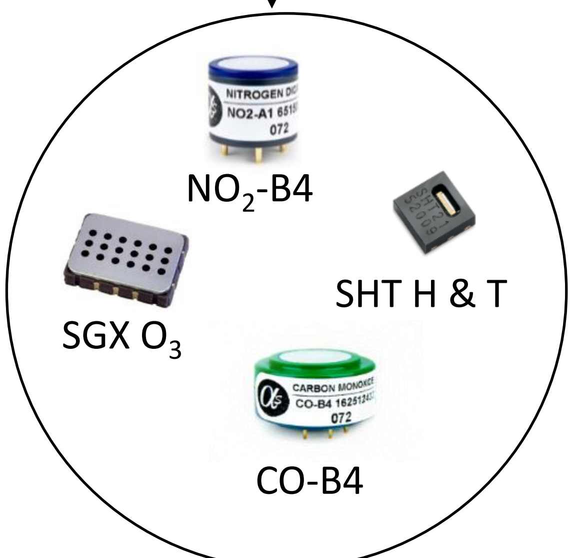

**Testing** → **Augmentation** → **Calibration**

**Testing**

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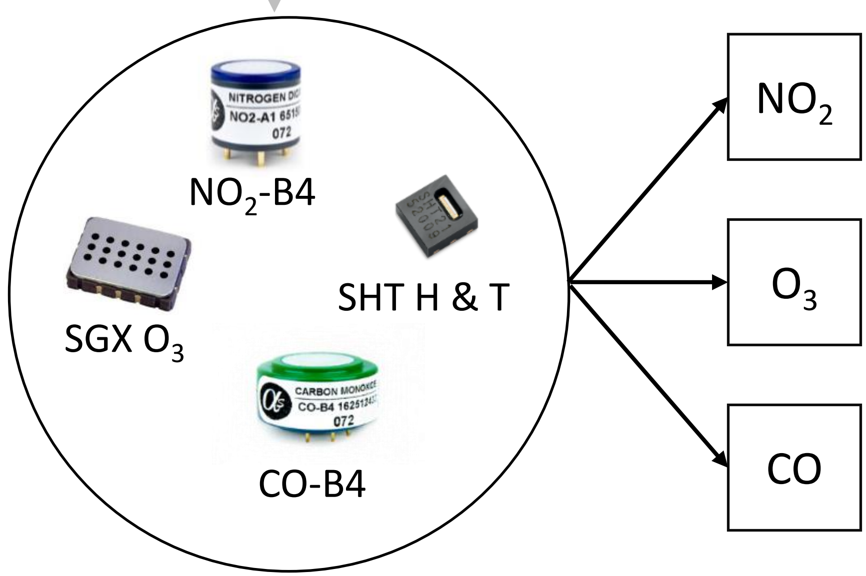
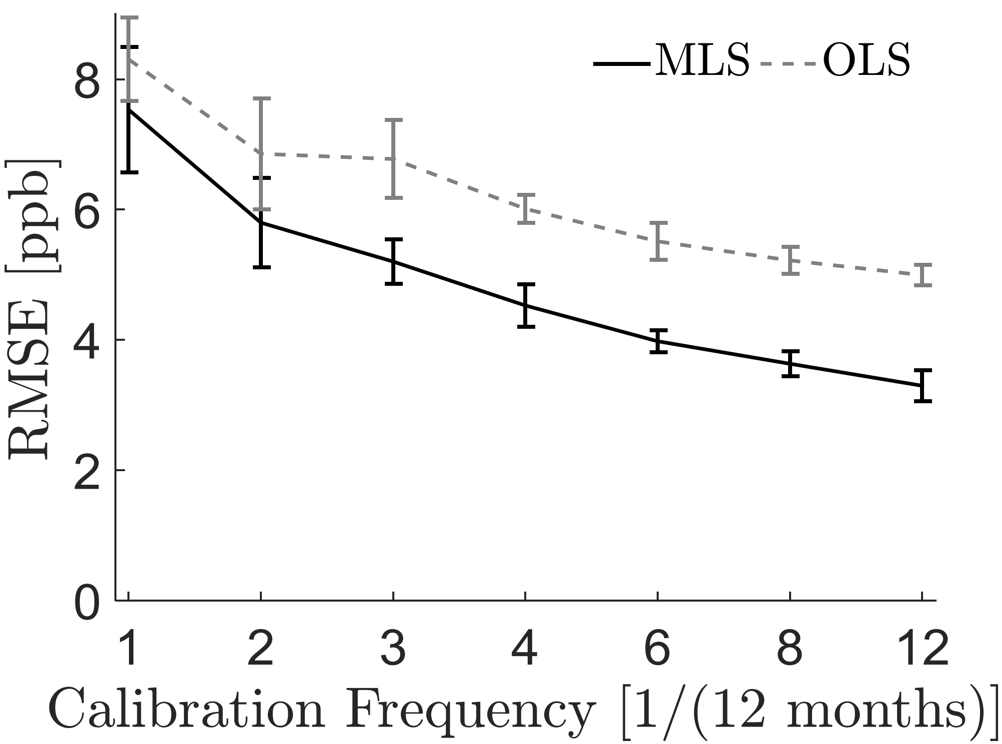


# Calibration Stability: $O_3$

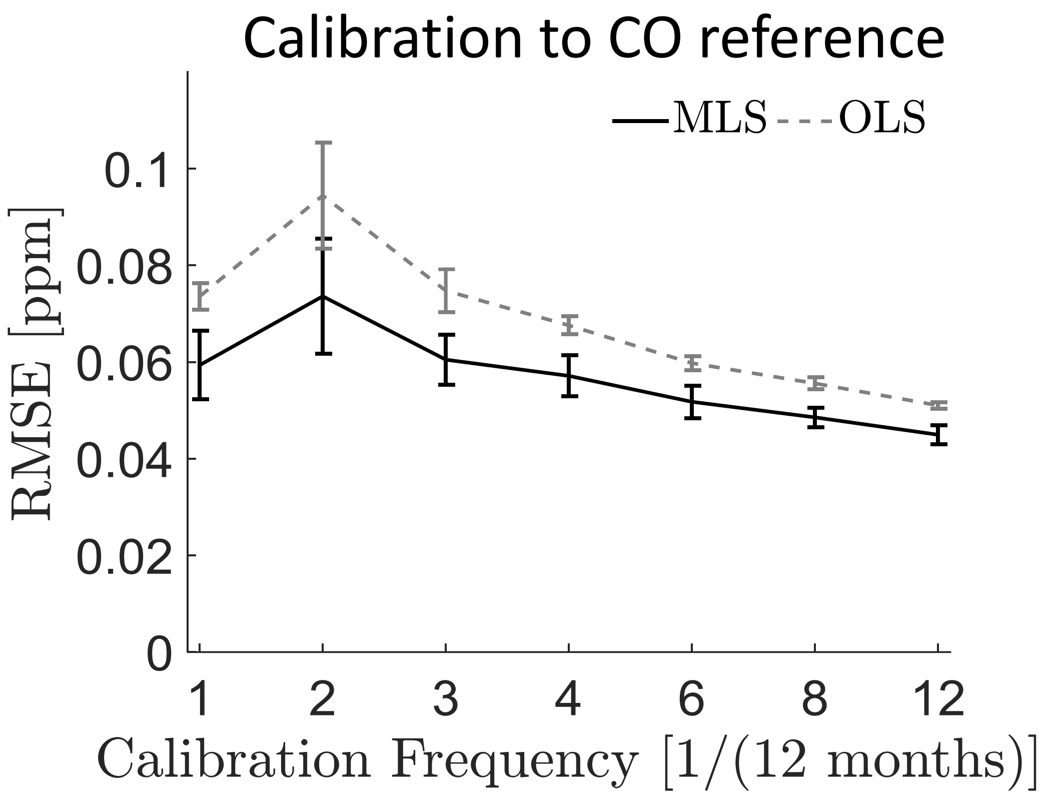
- Calibration error vs. different training frequencies over 12 months
- Training time: 4 weeks

Calibration to $O_3$ reference



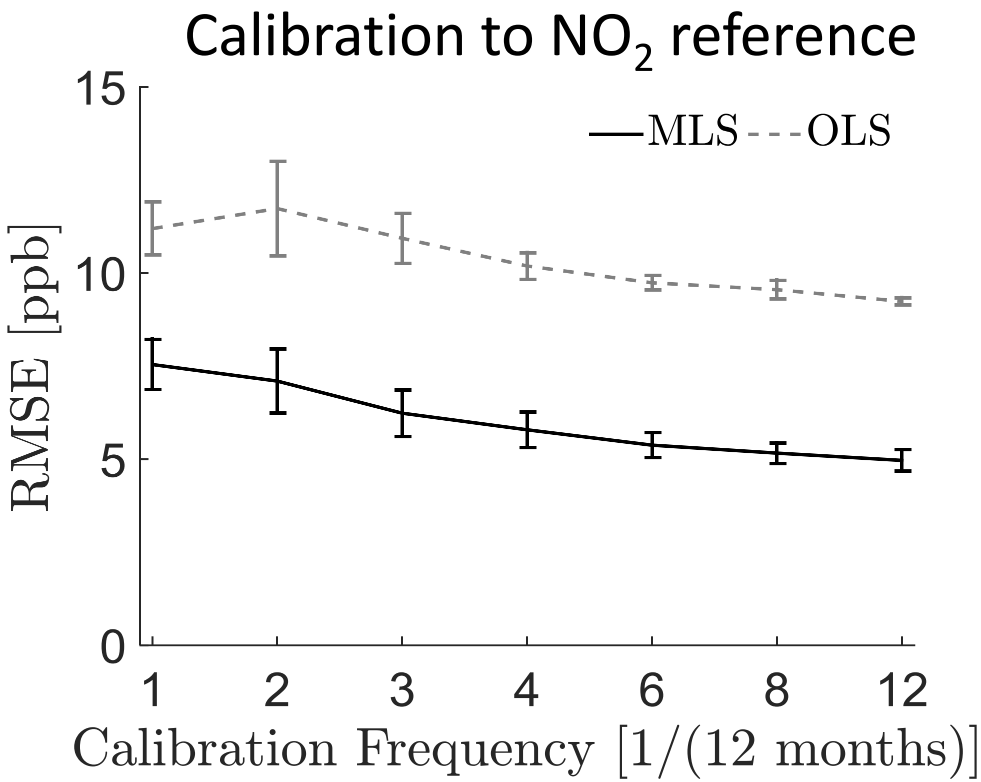

- Decreasing error with increasing calibration frequency
- OLS requires monthly recalibration to achieve same error when calibrating the array every 4 months

# Calibration Stability: CO




- Increasing error at f = 2: Unstable parameters during summer
- Sensor array calibration beneficial

# Calibration Stability: $NO_2$




- Decreasing error
- MLS outperforms OLS

# Conclusions

- Low-cost sensors suffer from **cross-sensitivities** and **meteorological dependencies**
- In-field testing using reference measurements to **explain sensor-under-test**
- **Quantify amount** of captured and uncaptured cross-sensitivities and sensor noise
- **Improved accuracy and stability** when calibrating an augmented sensor array

# Thank You!

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