How accurate is my air quality monitor?

21st April 2024, Dr. Anika Krause

Concepts of accuracy and precision

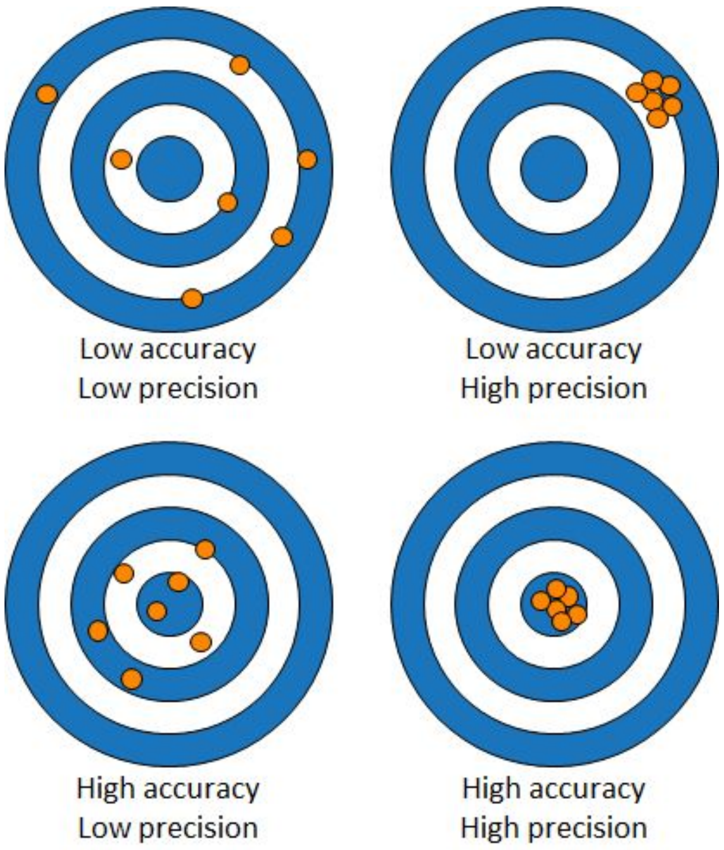
Experiments to determine sensor performance

How to quantify accuracy & precision

What’s an acceptable error?

Examples

Precision versus accuracy



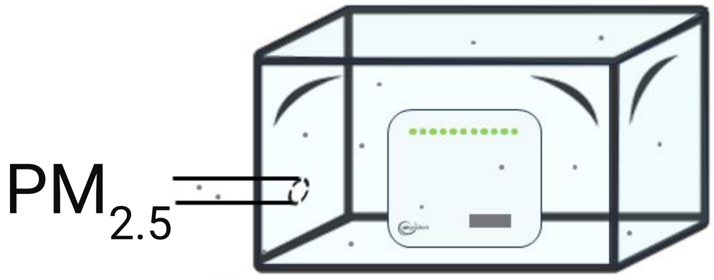
Precision refers to the consistency and repeatability of measurements, regardless of how far these are from the true value.

Accuracy, on the other hand, refers to how close a measurement is to the true or target value, regardless of whether it's consistently reproducible.

Precision versus accuracy of air quality sensors

Place sensor in an airtight box

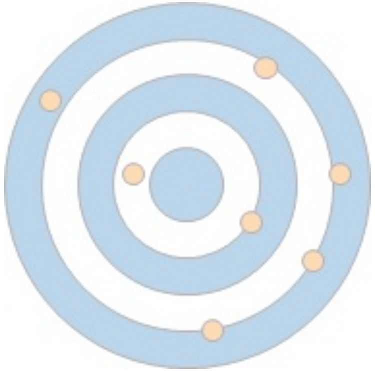
Precision versus accuracy of air quality sensors



Concentration = 20 μg/m^3

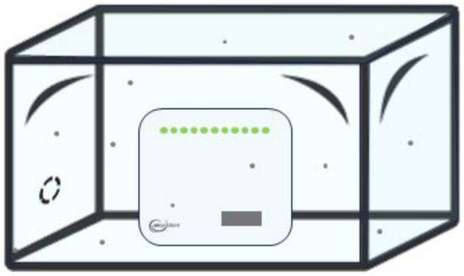
Fill box with a known pollution concentration.

Precision versus accuracy of air quality sensors



Low accuracy, low precision

Low accuracy, high precision



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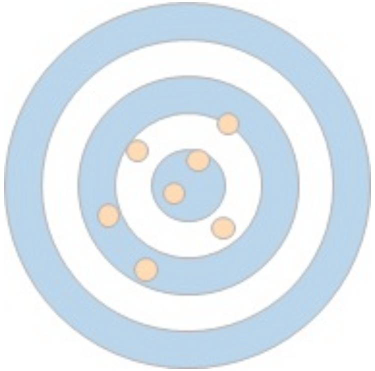

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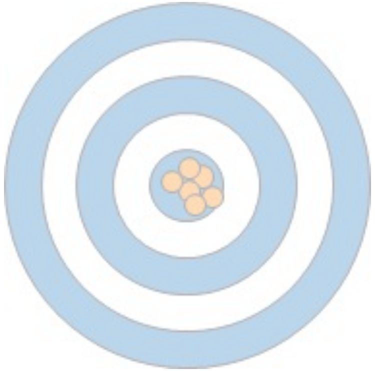

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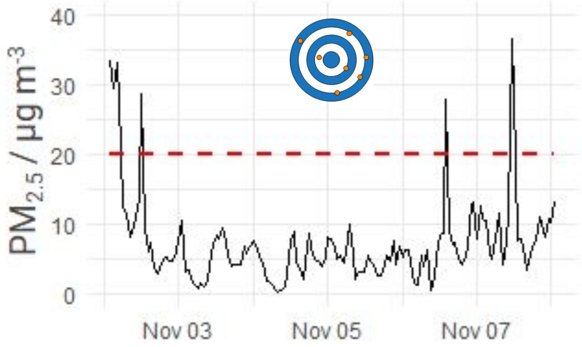
Precision versus accuracy of air quality sensors



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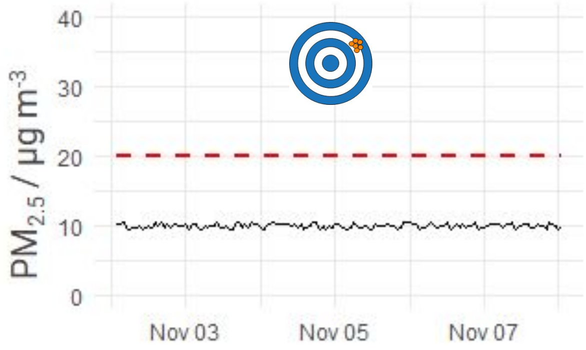

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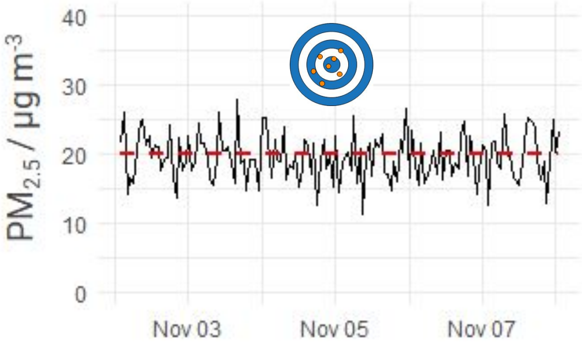

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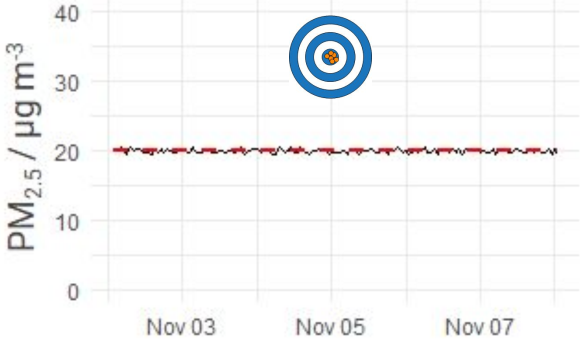
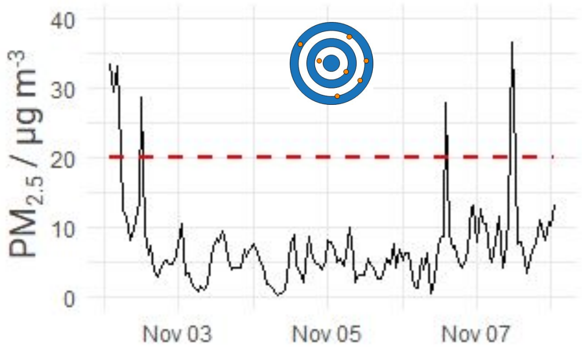


High accuracy, high precision

Precision versus accuracy of air quality sensors



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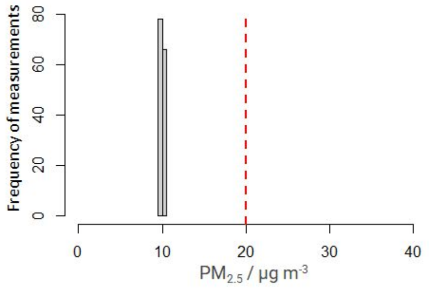

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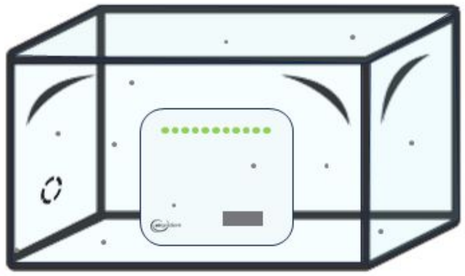

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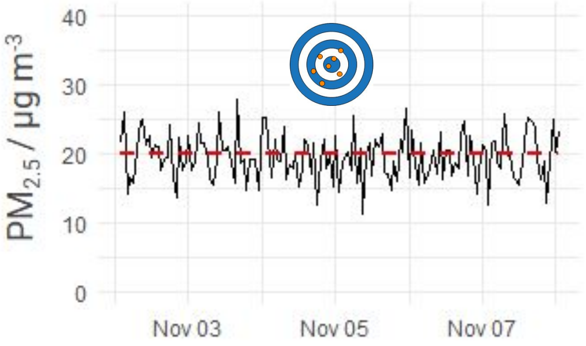

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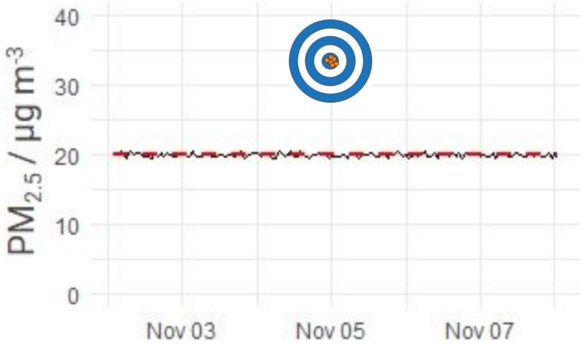


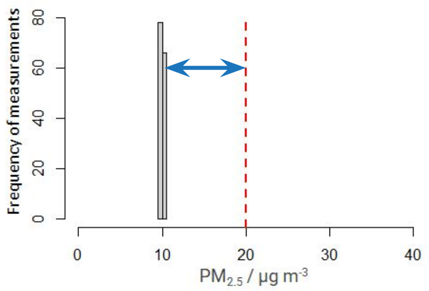
High accuracy, high precision

Precision versus accuracy of air quality sensors

Accuracy

(Average) difference between measurement and true value.

The smaller the difference (=error), the higher the accuracy.



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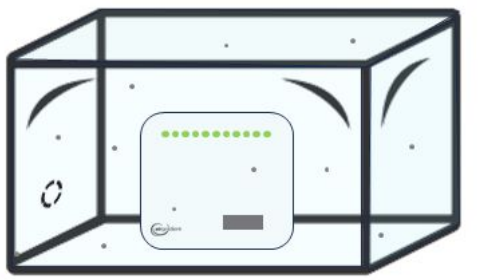
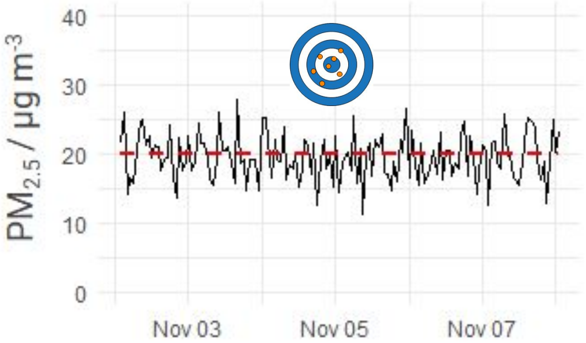


Concentration = 20 µg/m³



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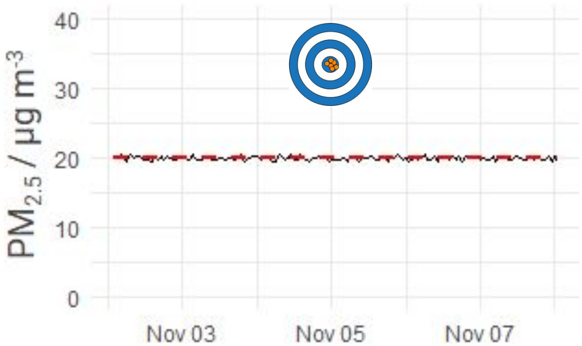

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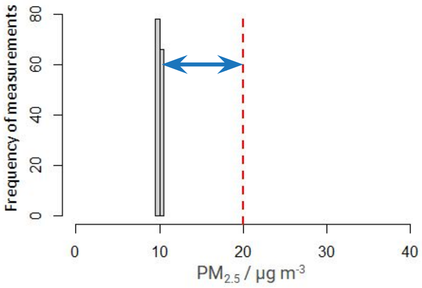

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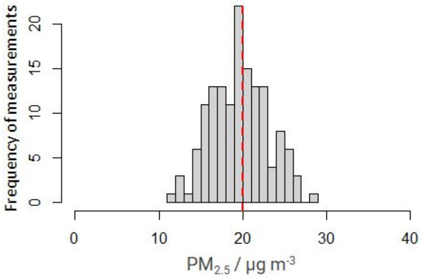

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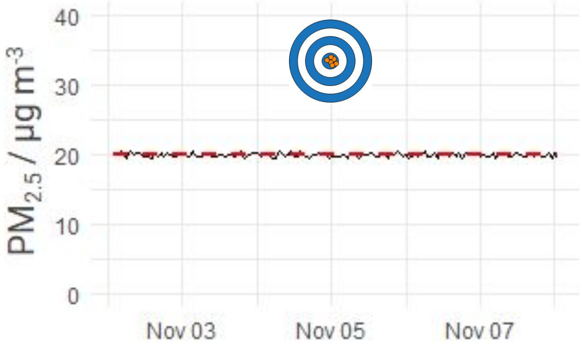

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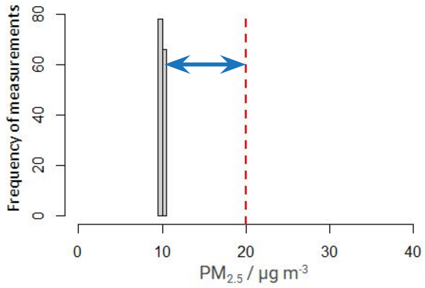

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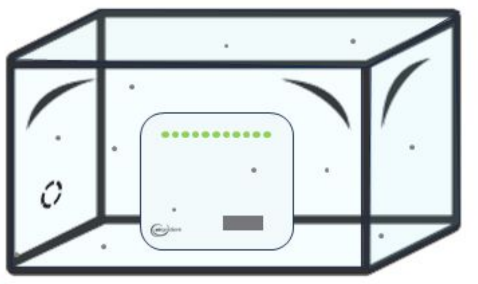

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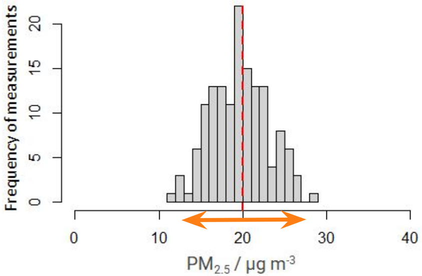
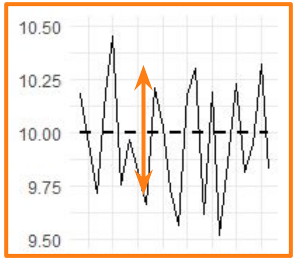


High accuracy, low precision

Precision

(Average) distance of the measurements from the average value.

The narrower the distribution, the higher the precision.



Practical considerations

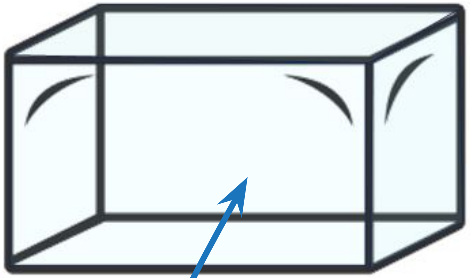
Clean air | **Known number of particles** | **Stable and known PM concentration**

Practical considerations

Clean air

Known number of particles

Stable ~~and known~~ PM concentration



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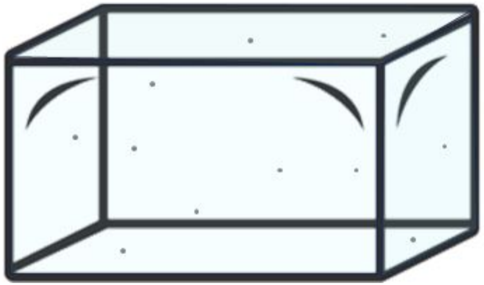


How to pre-clean the air?
- it's complicated...

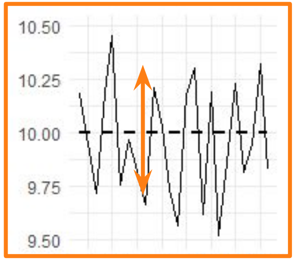
Where can I buy this?
- even more complicated...

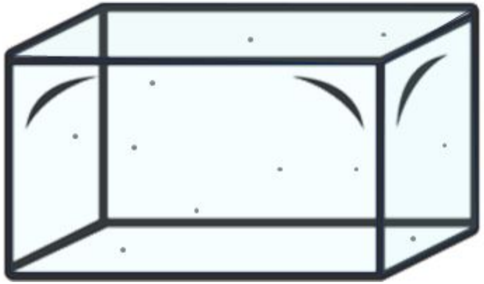
Practical considerations

Stable ~~and known~~
PM concentration

Could still measure precision?

For this, the concentration just needs to be stable

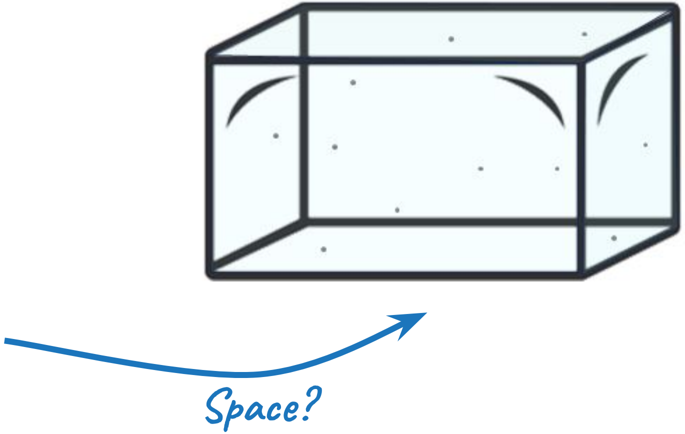




Practical considerations

Advantage of low-cost sensors: You can have many!

Stable ~~and known~~
PM concentration



Practical considerations

Advantage of low-cost sensors: You can have many!

~~Stable and known~~
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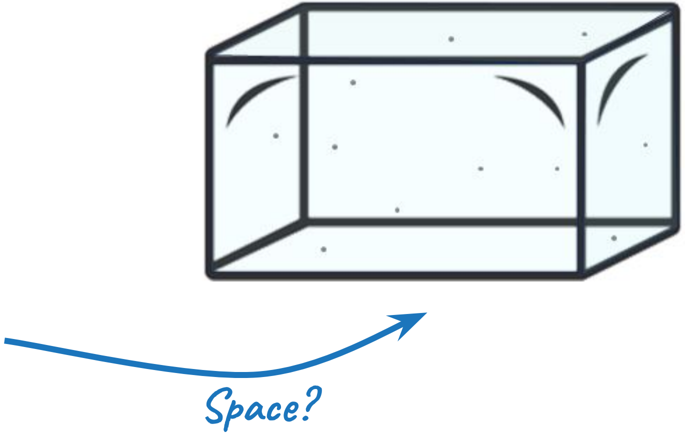
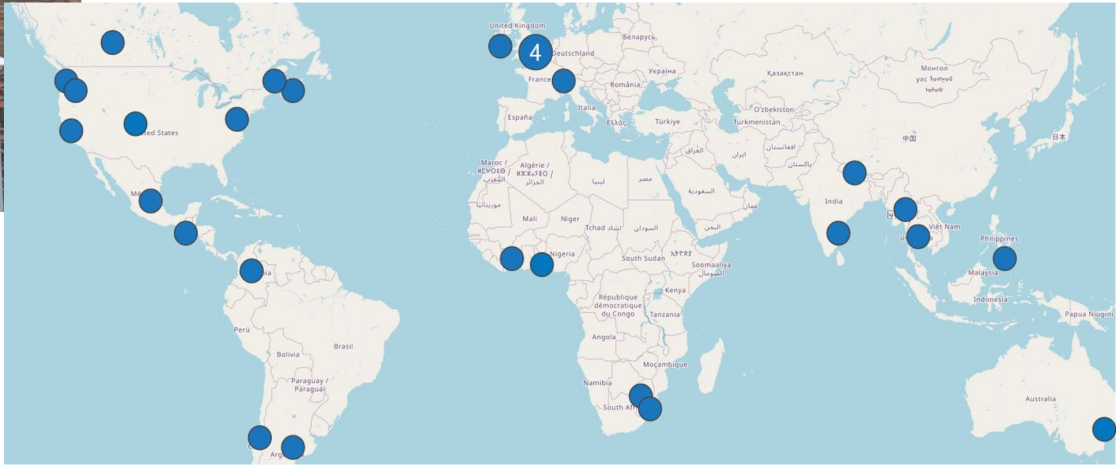
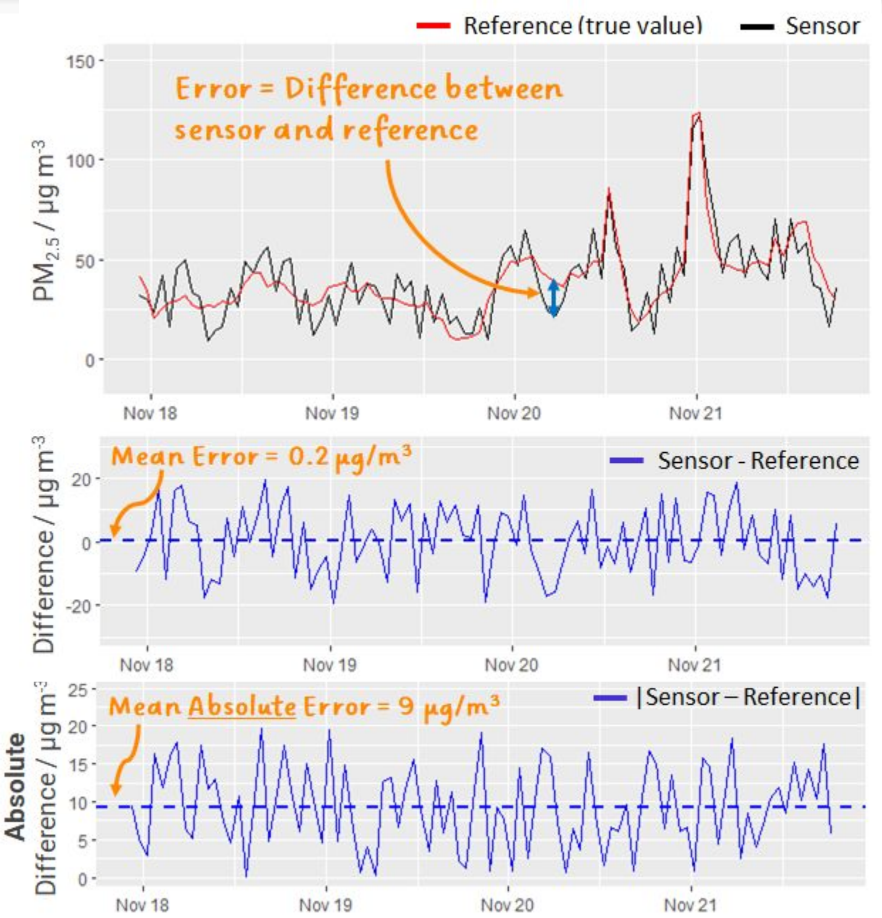


Chamber testing is not practicable.

Co-location with reference



How to measure the accuracy of a sensor?



Difference

Average (=mean) error

Accuracy

(Average) difference between measurement and true value.

Mean absolute error (MAE)

How to measure the accuracy of a sensor?

Mean Absolute Error

How far off
are the sensors
from the reference data
i.e. Error

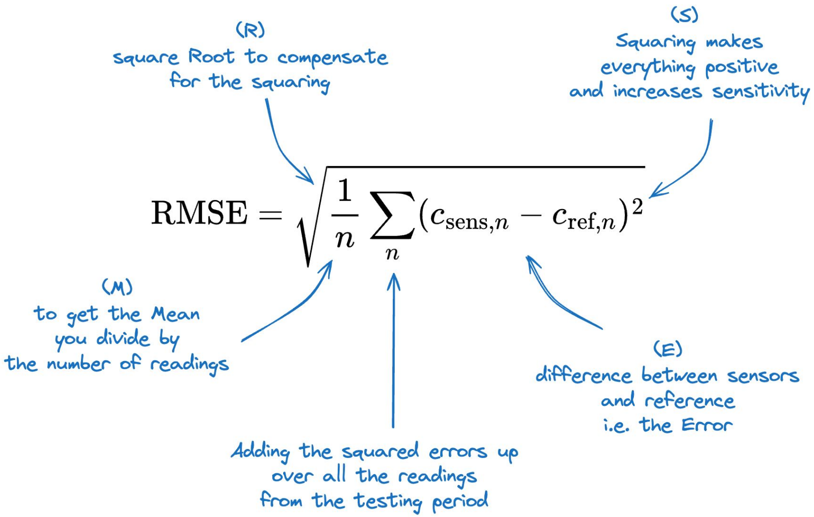
Adding the errors up
over all readings
from the testing period

Absolute value
so everything
is positive

$$\mathrm{MAE} = \frac{\sum_n |c_{\mathrm{sens},n} - c_{\mathrm{ref},n}|}{n}$$

To get the mean
you divide by the number
of readings

Alternative parameter: Root Mean Square Error



$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{n}(c_{\mathrm{sens},n} - c_{\mathrm{ref},n})^2}$$

- Measure of the average error of a sensor (like MAE)
- Always higher or equal to MAE → stricter criterion
- Recommended by US EPA

Examples of accuracy assessments

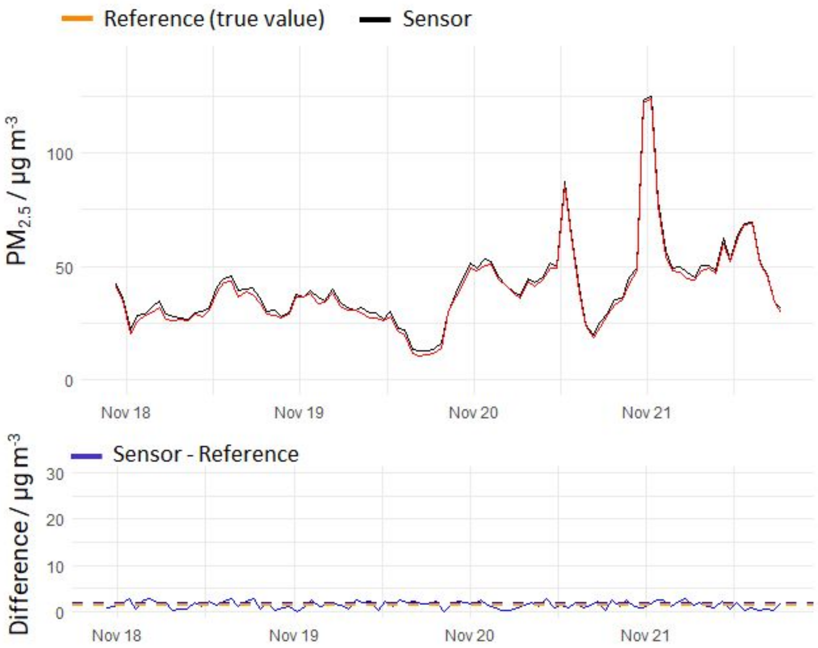
Good Sensor vs. Bad Sensor

From: The Lego Movie / https://hero.fandom.com

Clean vs. Polluted

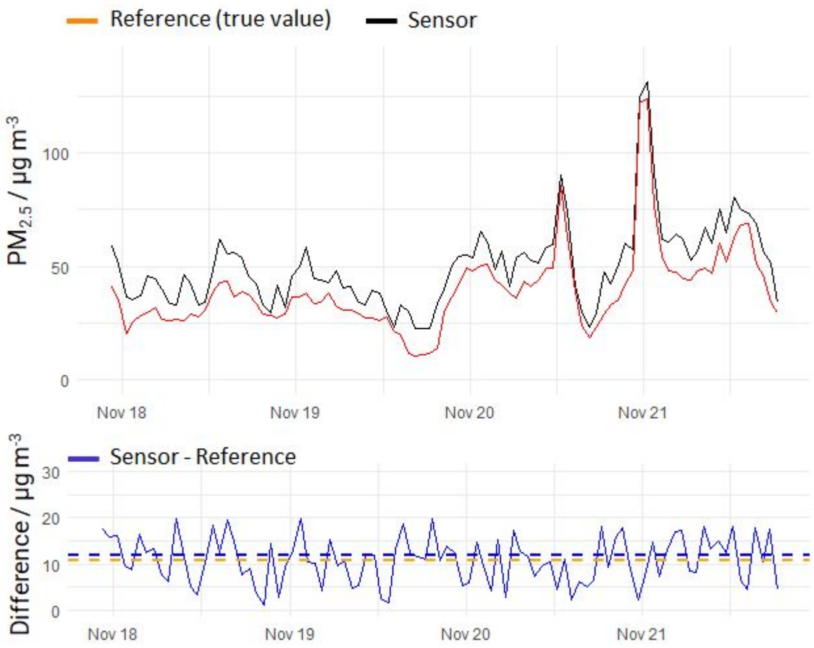
Example I: Good sensor vs. bad sensor

Good sensor



··· MAE = 1.5 µg/m³ ··· RMSE = 1.7 µg/m³

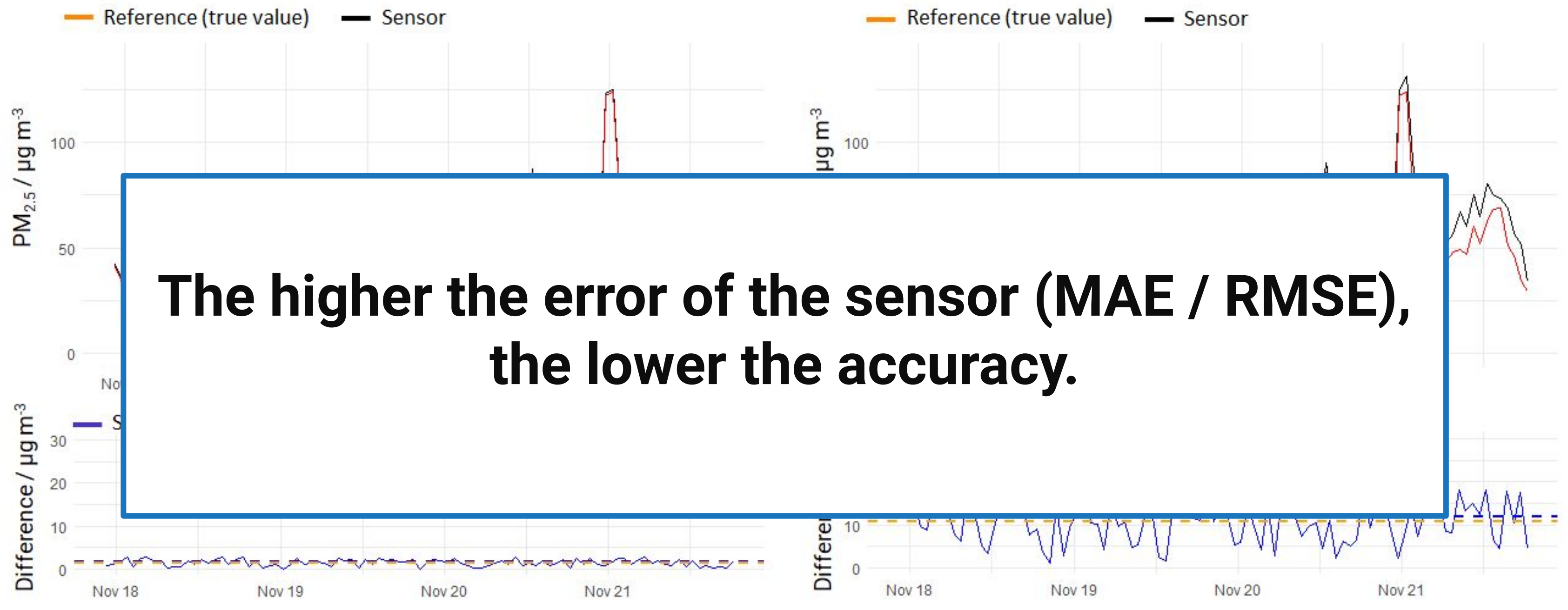
Bad sensor



··· MAE = 10.4 µg/m³ ··· RMSE = 12.0 µg/m³

Example I: Good sensor vs. bad sensor

Good sensor **Bad sensor**



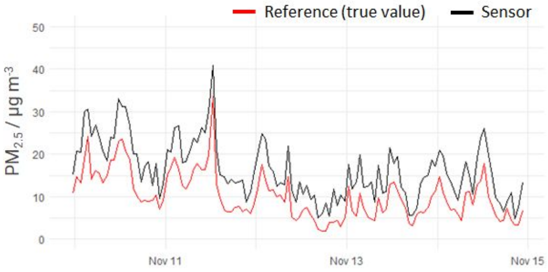
The higher the error of the sensor (MAE / RMSE), the lower the accuracy.

MAE = 1.5 µg/m³ RMSE = 1.7 µg/m³

MAE = 10.4 µg/m³ RMSE = 12.0 µg/m³

Example II: Polluted vs. “Clean”

Less polluted



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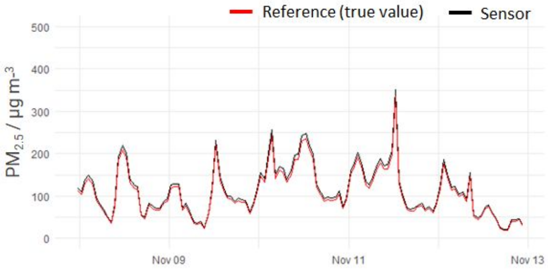

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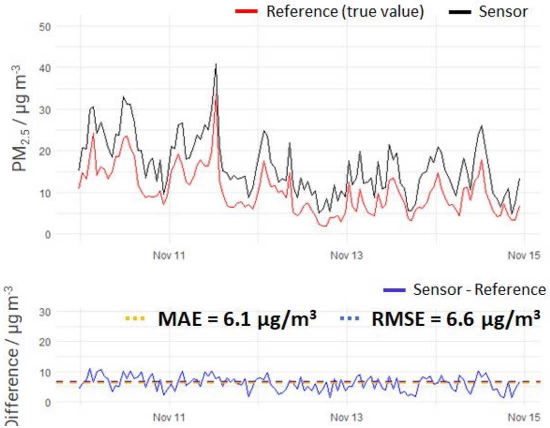

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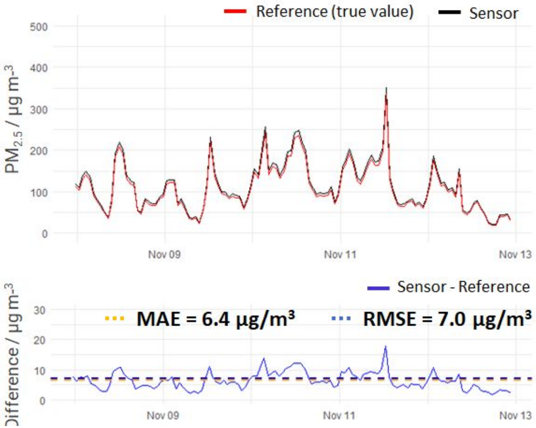

Same error = same performance?

Example II: Polluted vs. "Clean"

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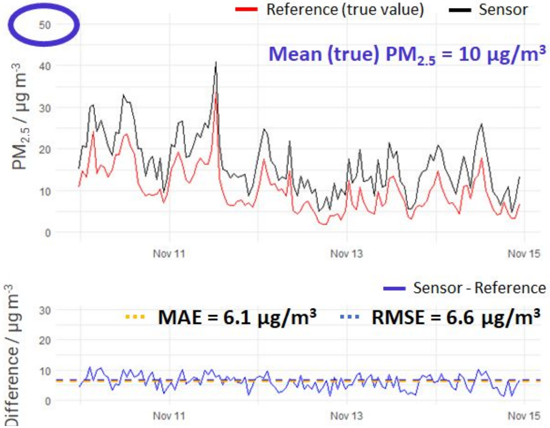

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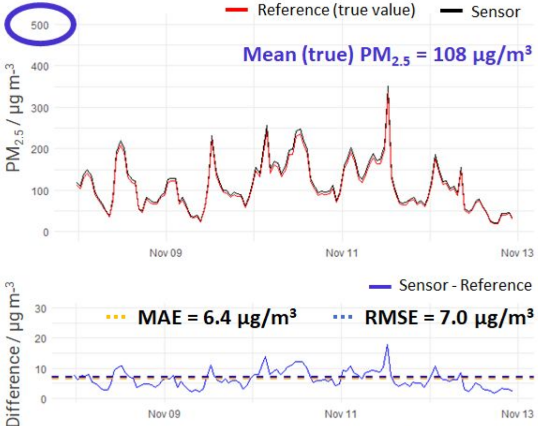
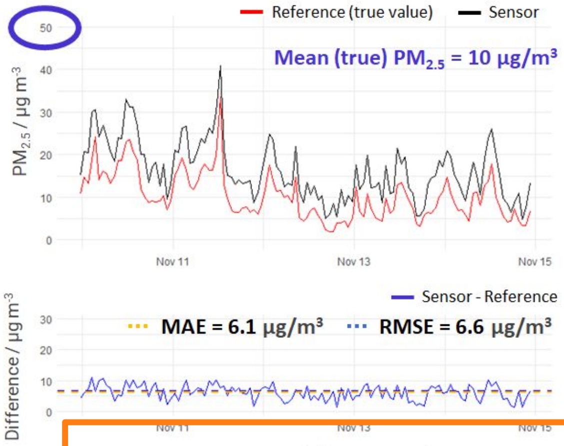


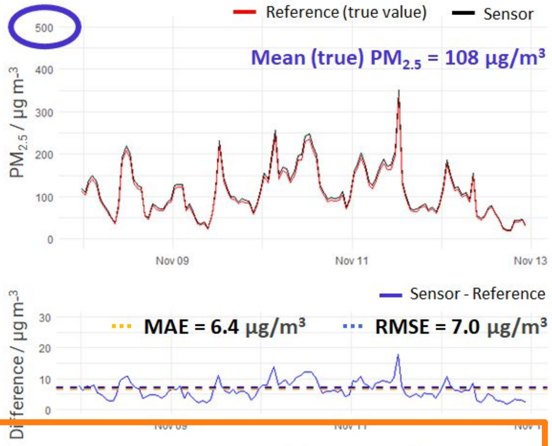
Error has relatively high impact in cleaner environment

Example II: Polluted vs. “Clean”

Less polluted

More polluted





nRMSE = 6.6 µg m^{-3} / 10 µg m^{-3} = 66 %

nRMSE = 7.0 µg m^{-3} / 108 µg m^{-3} = 6.5 %

Normalised RMSE

= RMSE / average concentration

→ helps to compare sensors across different environments

Recap Accuracy

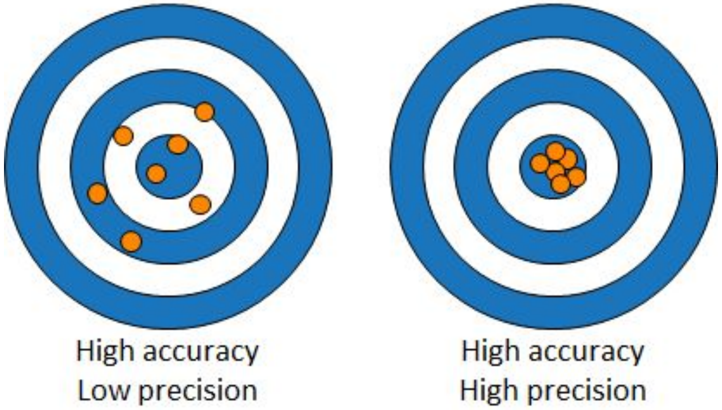
How far is a sensor from true value?

Determined via co-location with reference.

Quantification via the mean error (MAE / RMSE).

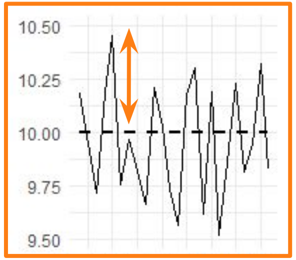
Normalise to compare across different locations.

How to measure the **precision** of a sensor?

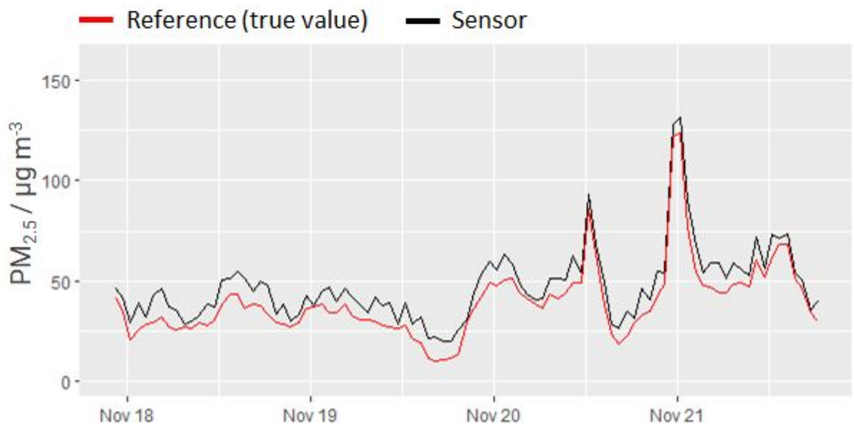


How to measure the precision of a sensor?

Precision:
Distance of the measurements from the average value



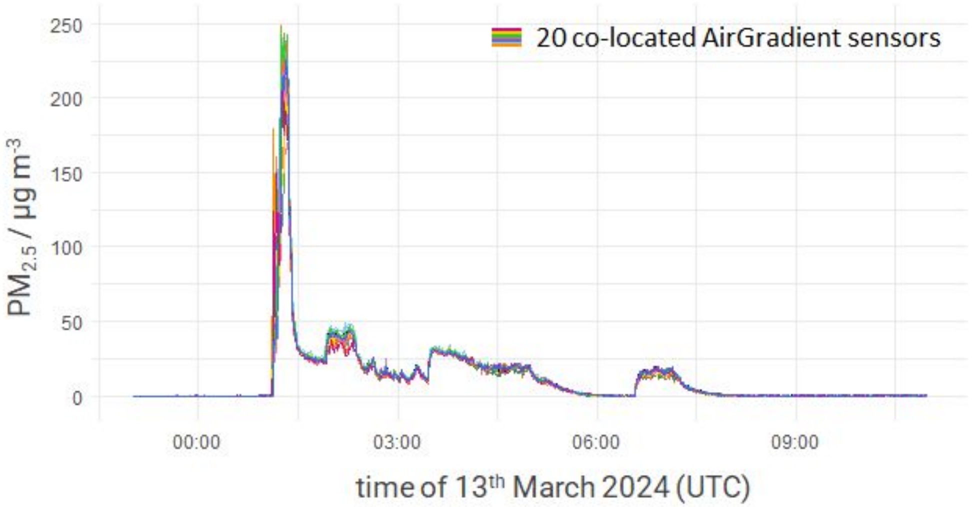
Repeated measurements @ stable concentration

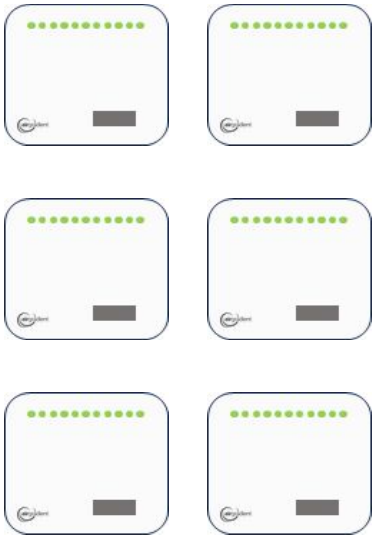


No stable concentration!

How to measure the ~~precision~~ **reproducibility** of a sensor?

Reproducibility:
The consistency of measurements obtained from multiple sensors placed in the same location





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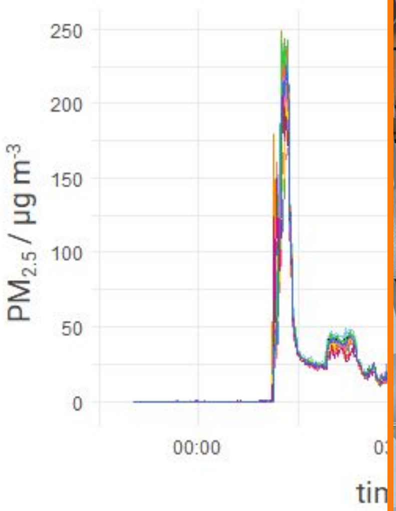

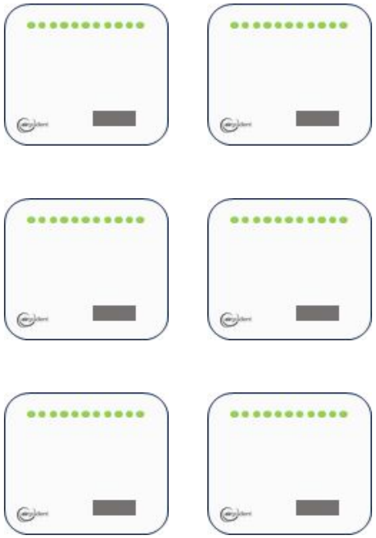

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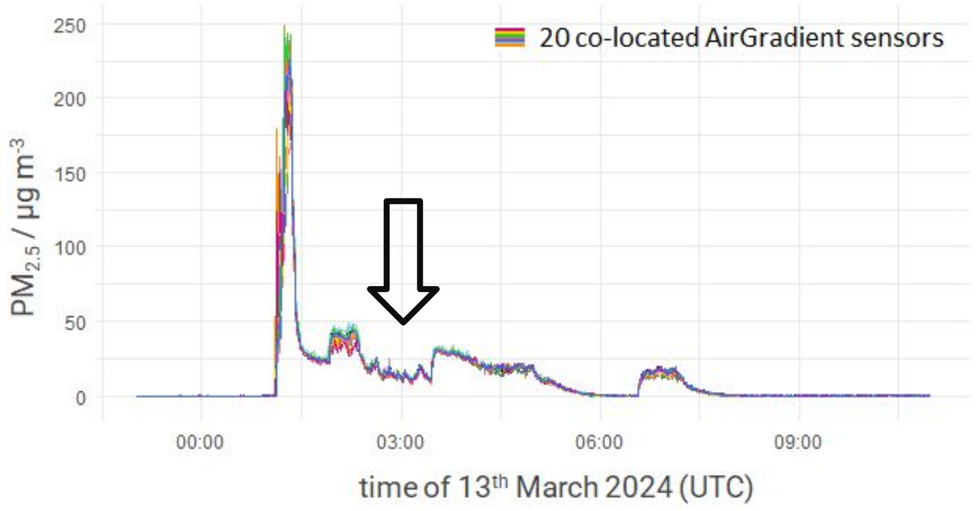
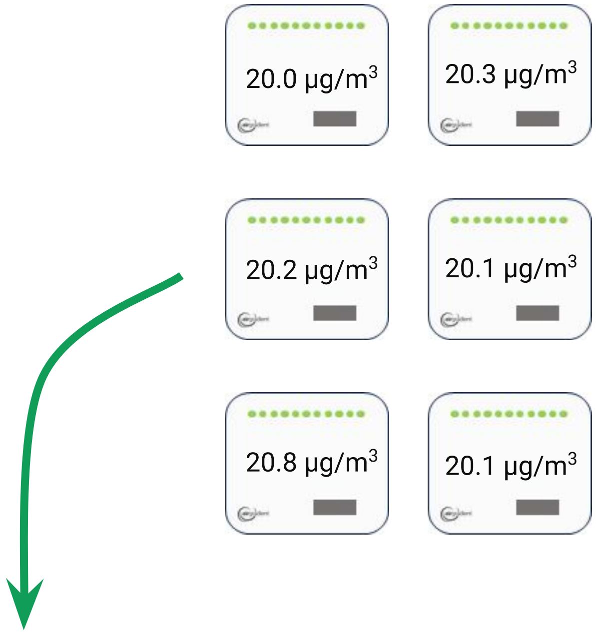
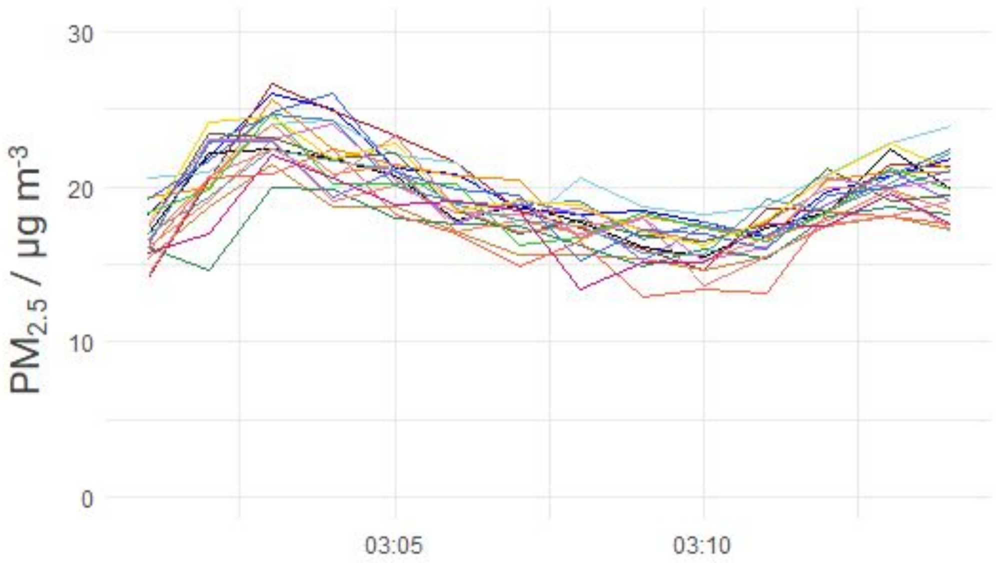




Spread of multiple sensors around their average value

Precision:
Spread of a sensor's measurements around a constant value.

How to measure the reproducibility of a sensor?



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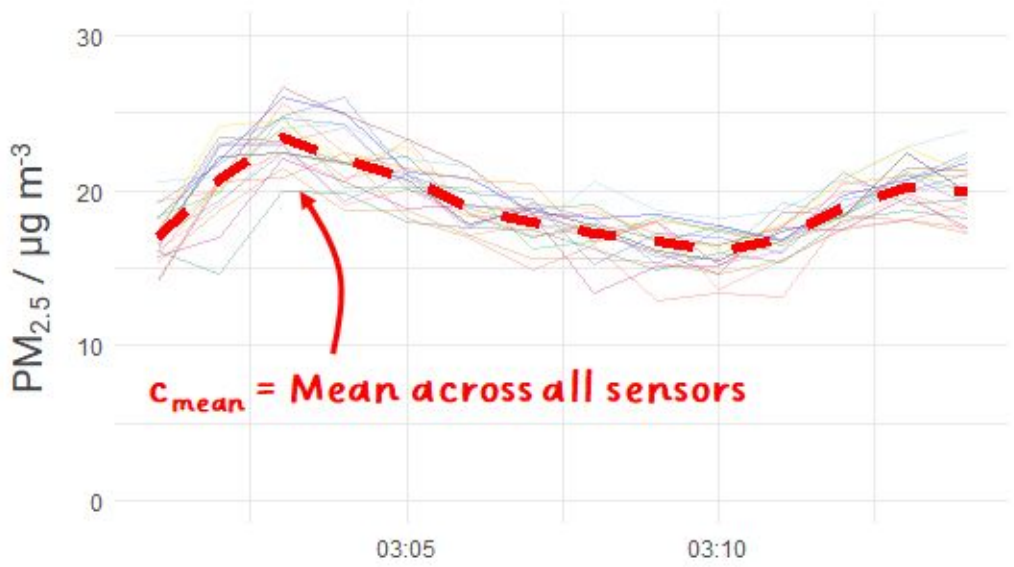

$$c_{mean} = \frac{1}{x} \sum_{x} c_{sensor\,x}$$

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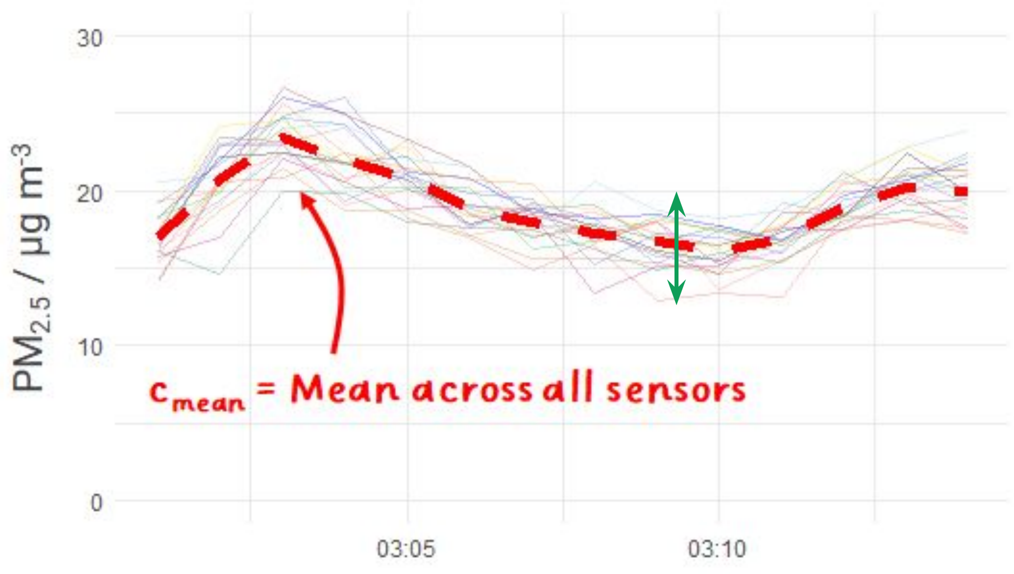
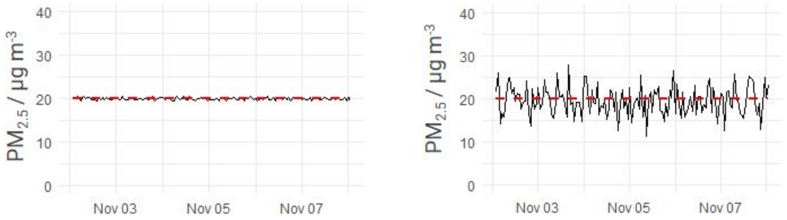


$$c_{mean} = \frac{1}{x}\sum_{x} c_{sensor\,x}$$

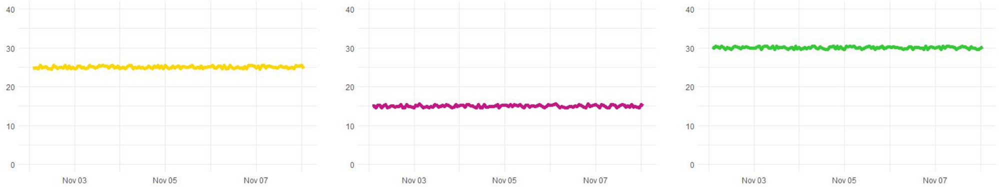
The narrower the spread around the mean, the bigger the reproducibility.

Reproducibility = Precision + Consistency

Precision
"Stability" of measurements over time; Absence of noise.



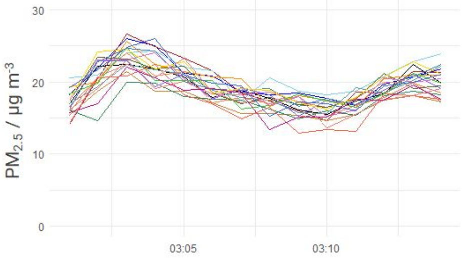
Consistency:
Different sensors measure the same values.



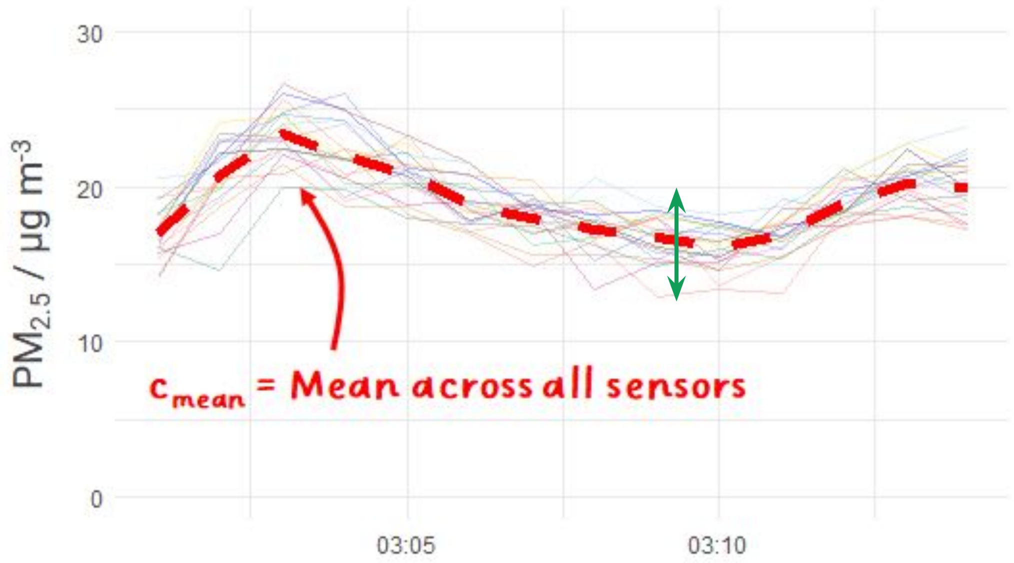
Reproducibility:
Co-located sensors measure the same.

→ **Requires precision and consistency.**

(Hence, the EPA refers to it as precision.)



How to measure the reproducibility of a sensor?



$$c_{mean} = \frac{1}{x}\sum_{x} c_{sensor\,x}$$

The narrower the spread around the mean, the bigger the reproducibility.

Standard Deviation (SD)

= Measure for width of spread

“Error across sensors”

Standard Deviation

Standard Deviation of the sensor x

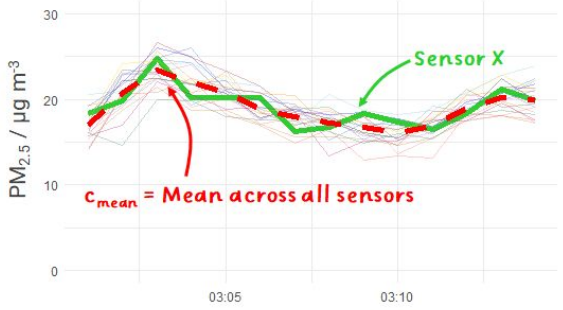
Root to compensate for the squaring

Squaring makes everything positive

$$\mathrm{SD}(\mathrm{sensor}_x) = \sqrt{\frac{1}{n}\sum_n \left(\mathrm{c}_{\mathrm{sensor}_{x,n}} - \mathrm{c}_{\mathrm{mean},n}\right)^2}$$

Taking the mean

Difference between sensor x and the average



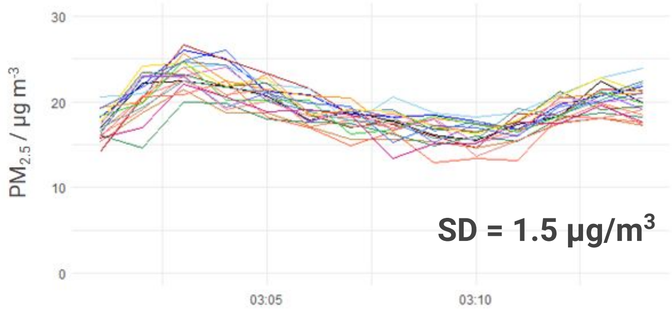
The lower the SD, the higher the precision.

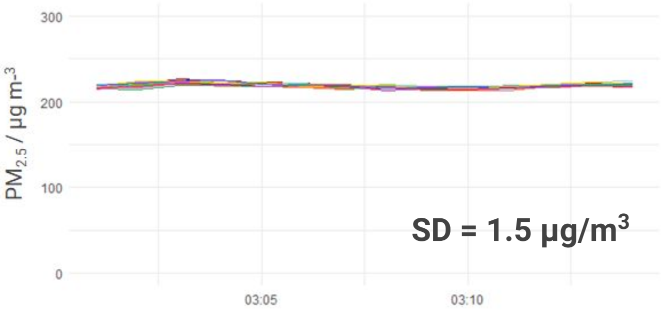
Math "fun fact": The calculation is the same as for the RMSE, but you use the mean concentration instead of the reference concentration.

Polluted vs. "clean"

Less polluted

More polluted





Normalised SD

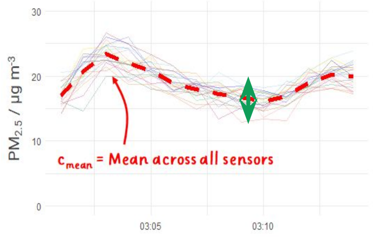
= SD / average concentration

= "Coefficient of variation" (CV)

CV = 1.5 µg/m^3 / 19 µg/m^3 = 7.9%

CV = 1.5 µg/m^3 / 219 µg/m^3 = 0.7%

Recap precision

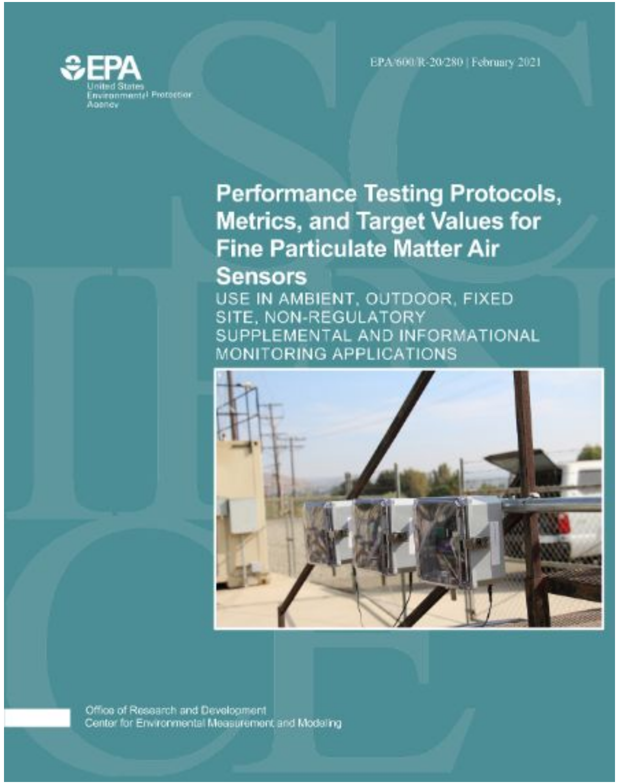


What's the spread of the measurements

Determined via co-location of multiple sensors

Quantification via Standard Deviation

Normalise to compare across different locations



EPA target values

Precision	Standard Deviation (SD) -OR- Coefficient of Variation (CV)	$\leq 5\ \mu g/m^3$ $\leq 30\%$
Error	Root Mean Square Error (RMSE) or Normalized Root Mean Square Error (NRMSE)	RMSE $\leq 7\ \mu g/m^3$ or NRMSE $\leq 30\%^{\dagger}$

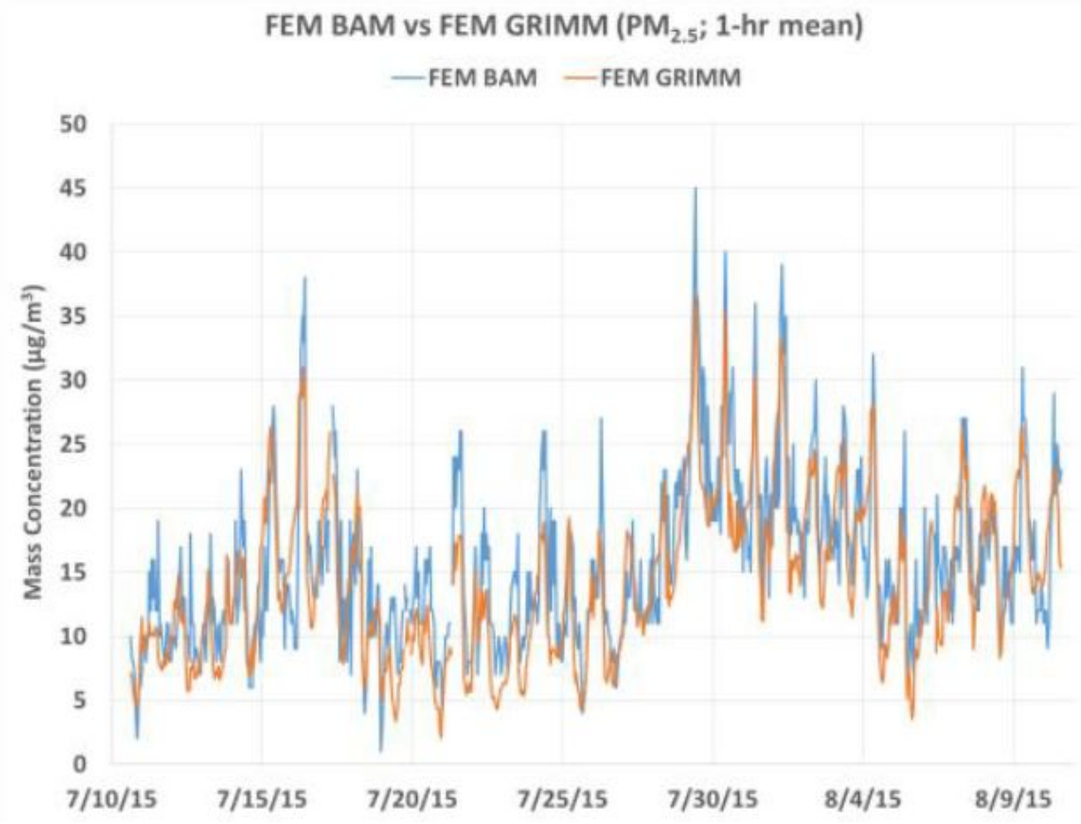
From Table 4-2: Recommended Performance Metrics and Target Values for PM2.5 Air Sensors Used in Ambient, Outdoor, Fixed Site, NSIM Applications. ***All values for 24h averaged data.***

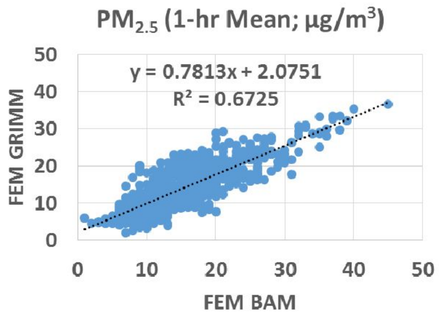
Further aspects of sensing performance:

Linearity (R^2), Bias (Slope, intercept)

NSIM - non-regulatory supplemental and informational monitoring

Is an 30% error to much?





Comparison of two reference instruments.

AQ-SPEC; South Coast Air Quality Management District, USA

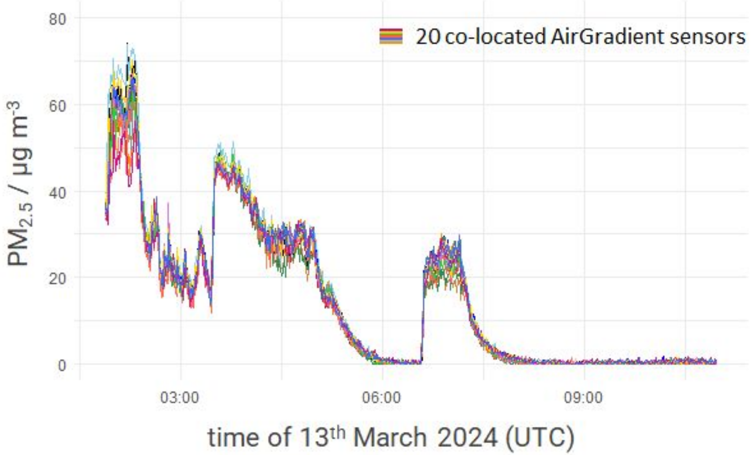
→ They can differ a lot!

Let’s dive into that later…

FEM - Federal Equivalent Method

Real world examples of sensor performance assessment

Precision of AirGradient indoor monitors in testing chamber

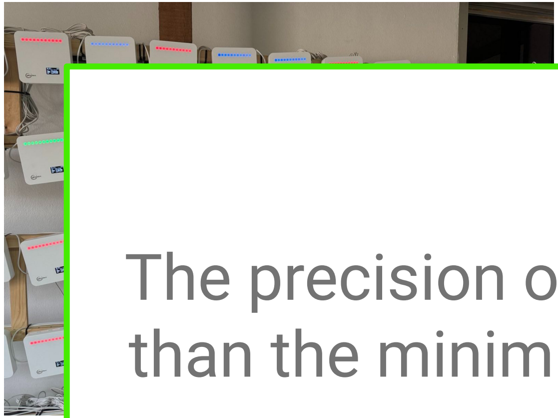


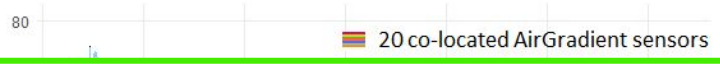
SD across all sensors: ± **1.6 µg/m³** **< 5 µg/m³ → within EPA guidelines**

Average concentration of test run: 14.8 µg/m³

CV = 1.6 µg/m³ / 14.8 µg/m³ = ± **10.8%** **< 30% → within EPA guidelines**

Precision of AirGradient indoor monitors in testing chamber





Conclusion

The precision of AirGradient $PM_{2.5}$ sensors is higher than the minimum precision recommended by EPA.

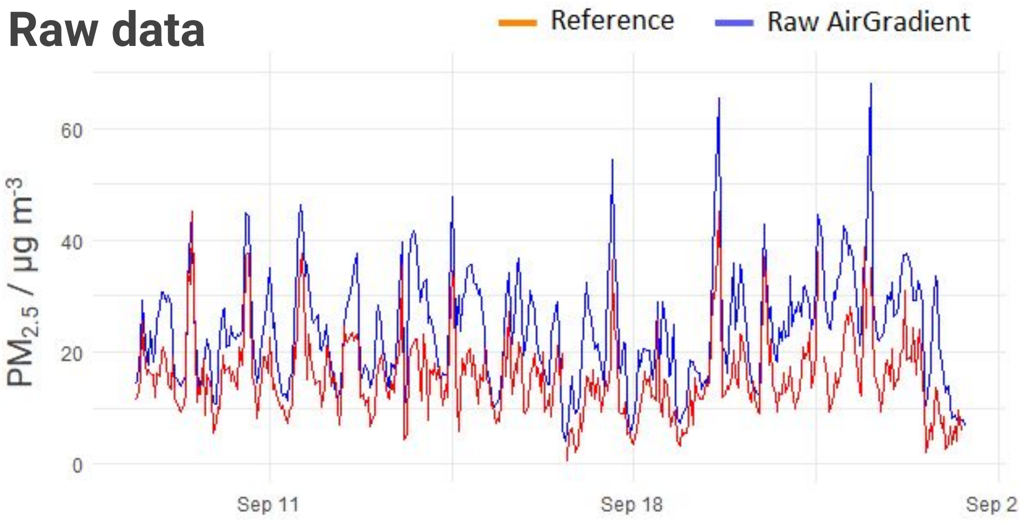
SD acr ... es

Average concentration of test run: 14.8 µg/m^3

CV = 1.6 µg/m^3 / 14.8 µg/m^3 = ± **10.8%** **< 30%** → **within EPA guidelines**

Accuracy of AirGradient outdoor monitor in Chennai

Raw data



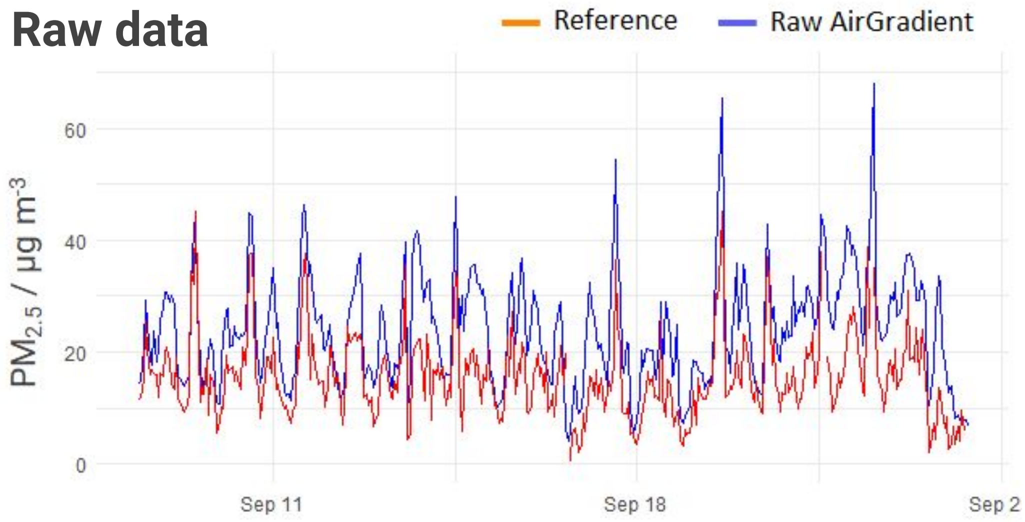
RMSE = ± **10.0 µg/m³** **> 7 µg/m³ → not within EPA guidelines**

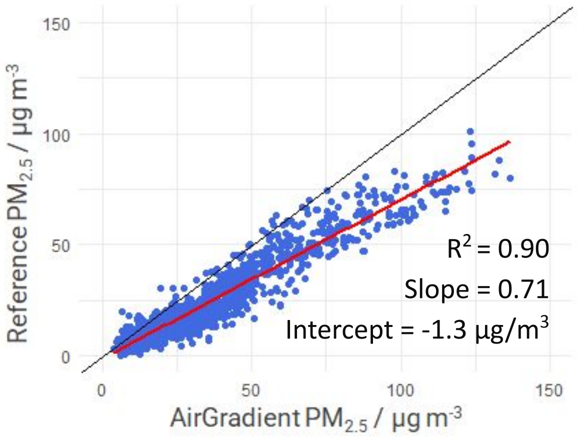
Average concentration of test run: 15.6 µg/m³

nRMSE = 10.0 µg/m³ / 15.6 µg/m³ = ± **64.5%** **> 30% → not within EPA guidelines**

Accuracy of AirGradient outdoor monitor in Chennai

Raw data

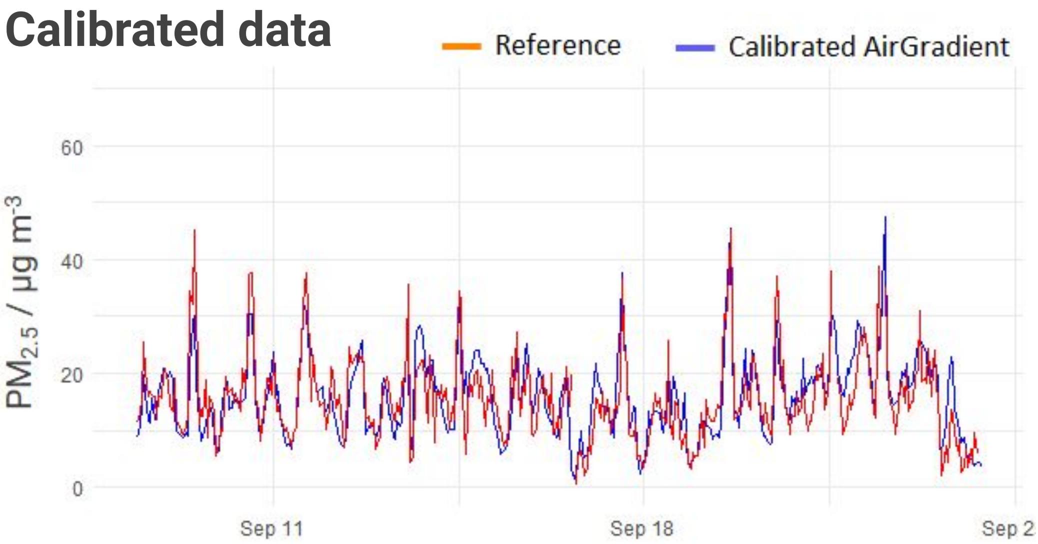


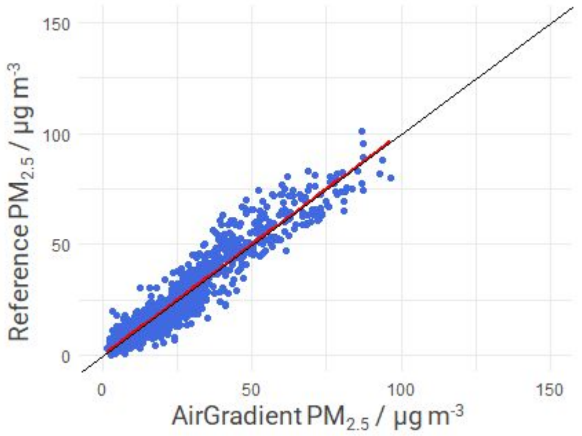


More information about linearity and sensor calibration:
https://youtu.be/b5mSJSS9i_A?feature=shared
https://youtu.be/CXueV0Am80Y?feature=shared

RMSE = ± 10.0 µg/m³
Average concentration of test run: 15.6 µg/m³
nRMSE = 10.0 µg/m³ / 15.6 µg/m³ = ± **64.5%**

Accuracy of **calibrated** AirGradient outdoor monitors in Chennai

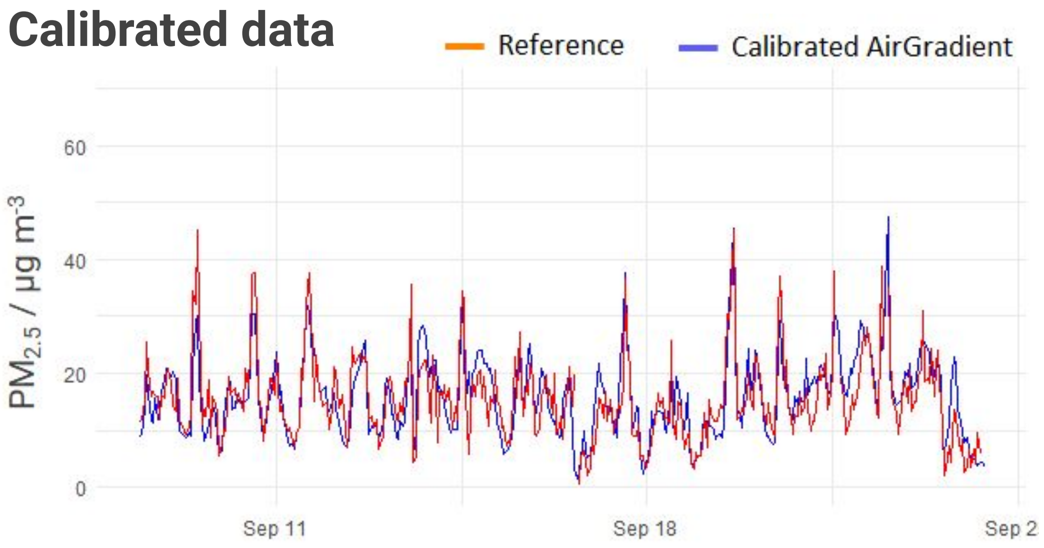


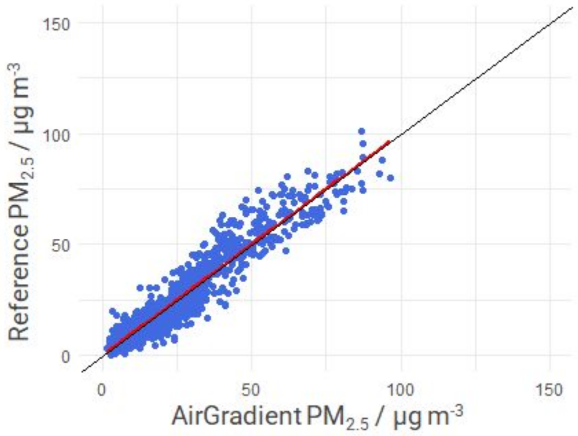


More information about linearity and sensor calibration:
https://youtu.be/b5mSJSS9i_A?feature=shared
https://youtu.be/CXueV0Am80Y?feature=shared

RMSE = ± **4.4 μg/m^3**
Average concentration of test run: 15.6 μg/m^3
nRMSE = 4.4 μg/m^3 / 15.6 μg/m^3 = ± **28.2 %**

Accuracy of **calibrated** AirGradient outdoor monitors in Chennai





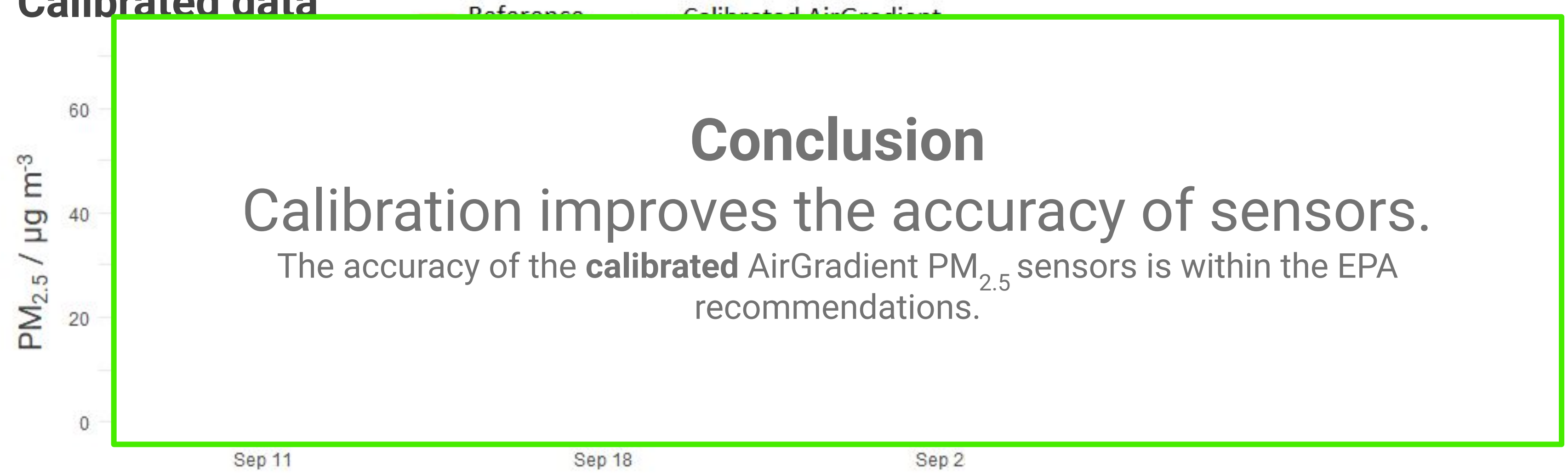
RMSE = ± **4.4 µg/m^3** — **< 7 µg/m^3 → within EPA guidelines**

Average concentration of test run: 15.6 µg/m^3

nRMSE = 4.4 µg/m^3 / 15.6 µg/m^3 = ± **28.2 %** — **< 30% → within EPA guidelines**

Accuracy of **calibrated** AirGradient outdoor monitors in Chennai

Calibrated data



Conclusion

Calibration improves the accuracy of sensors.

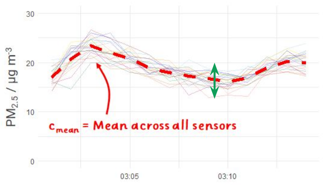
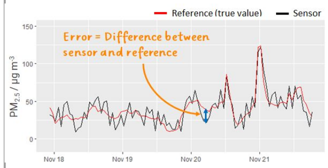
The accuracy of the **calibrated** AirGradient $PM_{2.5}$ sensors is within the EPA recommendations.

RMSE = ± **4.4 µg/m³** — < 7 µg/m³ → **within EPA guidelines**

Average concentration of test run: 15.6 µg/m³

nRMSE = 4.4 µg/m³ / 15.6 µg/m³ = ± **28.2 %** — < 30% → **within EPA guidelines**

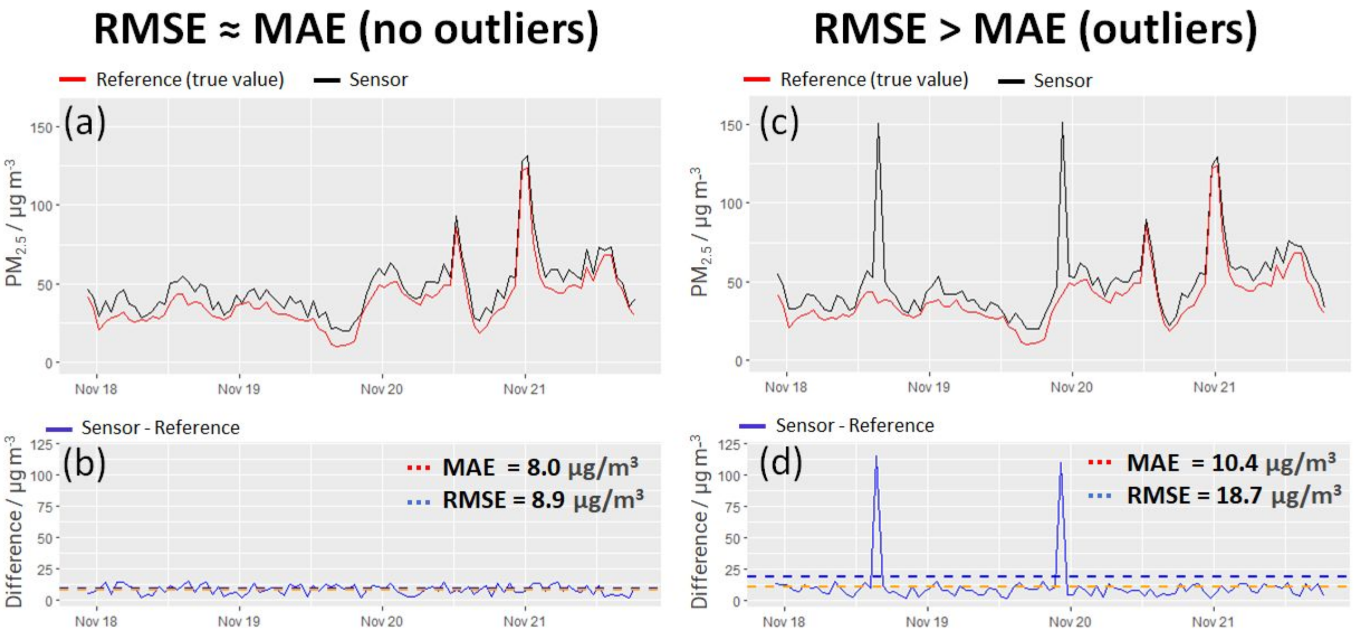
Summary

	Definition	Experiment	Performance parameter	EPA recom-mendation	Improve via
Precision 	Consistency of measurements.	Sensor - sensor co-location	SD, CV	≤ 5 µg/m³, ≤ 30%	Averaging
Accuracy 	Agreement of measurement with true value.	Reference - sensor co-location	RMSE, nRMSE, MAE	≤ 7 µg/m³, ≤ 30%	Calibration

Questions?

Appendix

Mean Absolute Error vs. Root Mean Square Error



Larger difference between RMSE and MAE when outliers occur.