Performance Comparison of Three Low-Cost Particulate Matter Sensors in an Ambient Environment

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Office of Research and Development

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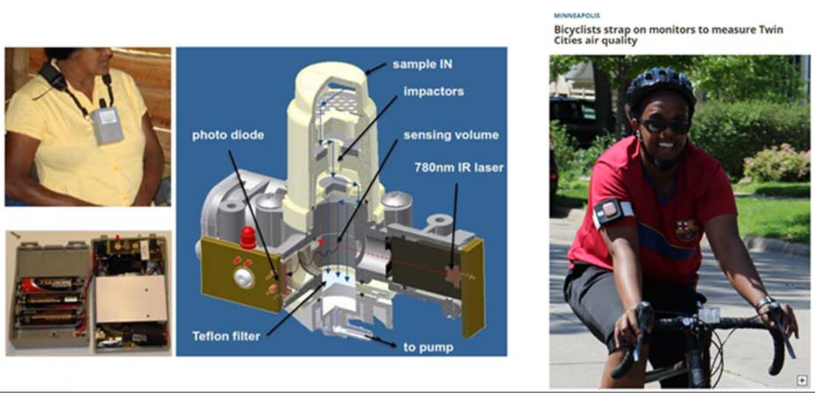
Current State of Air Sensors

Consumer-oriented turnkey devices:

Researcher- or developer-oriented, OEM sensors:

Portable devices for research, advocacy, and screening:



Large-scale air monitoring networks

EPA Air Sensor Research

- Rapid development has led to an increase use, despite not fully understanding performance specifications

- Low-cost advantage offers capability to collect measurements at higher spatial and time resolution

- Numerous low-cost sensors can be deployed as network or packaged as multi-pollutant sensor pods to supplement existing air quality measurements

Ambient Air Innovation Research Site (AIRS)

- Each low-cost sensor model was deployed in triplicates

- Deployed for at least 30 days between October 2017 to July 2018 at the Ambient Air Innovation Research Site (AIRS) in Research Triangle Park, NC.

- Low-cost sensors were collocated with two different federal reference monitors (T640x and Grimm)

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TES 5322 Air Quality Monitor

Price: $359.99 (with data logging)

Measures:

- $PM_{2.5}$ (0 – 500 µg/m^3)
- VOCs (0 – 50 PPM)
- Humidity (1- 99%)
- Temperature (-20 – 60°C)

Stores data to 4GB microSD Card

Plug-in or battery power (~8 hours)

Plantower PMS7003

Price: ~$20.00

Measures:

- PM_1 (0 – 999 µg/m^3)
- $PM_{2.5}$ (0 – 999 µg/m^3)
- PM_{10} (0 – 999 µg/m^3)

Design: Original Equipment Manufacturer (OEM)

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Aeroqual Portable Particulate Monitor

Price: $1,640 (base unit + sensor head)

Measures:

- $PM_{2.5}$ (0 – 500 µg/m^3)
- PM_{10} (0 – 500 µg/m^3)

On-board storage (~ 3 days of 1-minute data)

Plug-in or battery power (~24 hours)

Built-in relative humidity compensation

Statistical Analysis

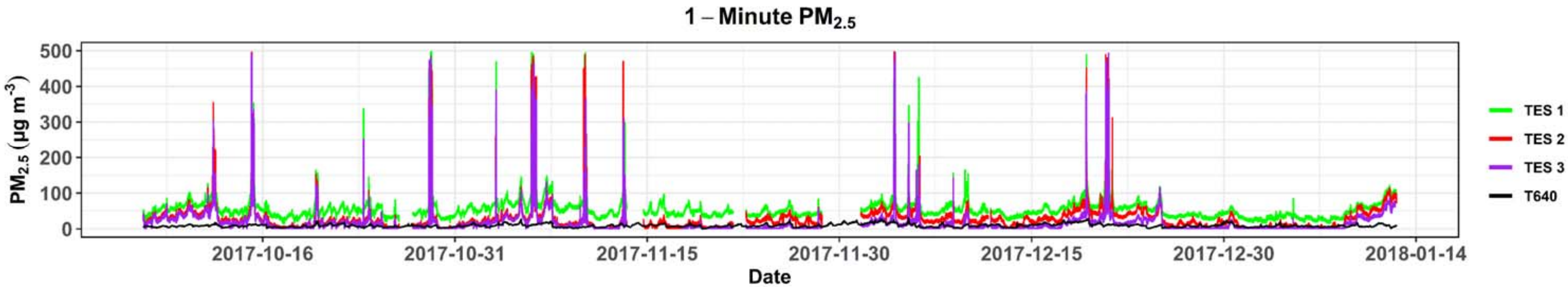
Coefficient of variation (CV) = $\frac{\sigma}{\mu} \times 100$

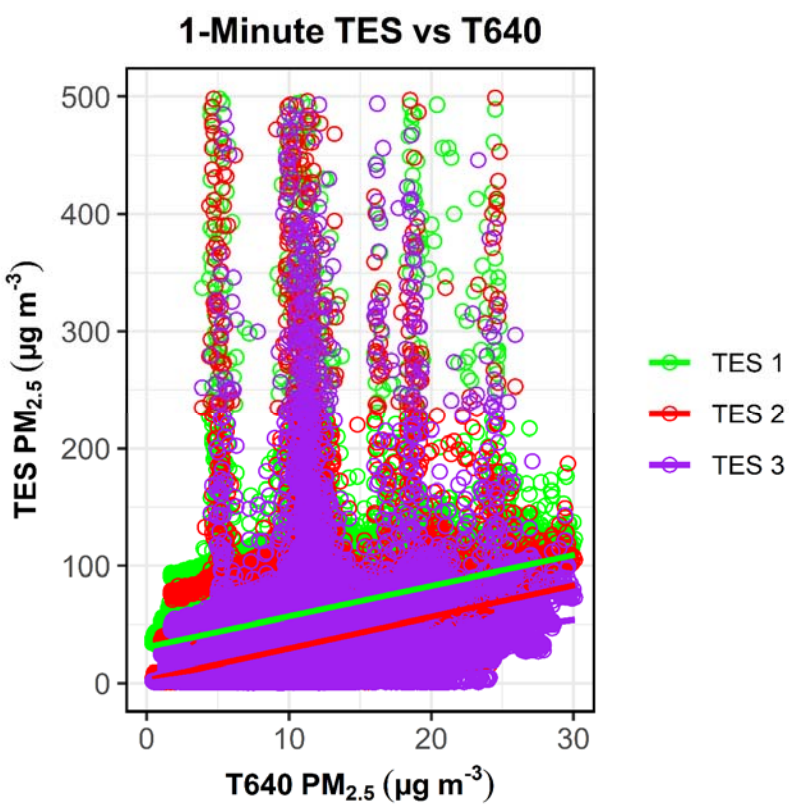
Root Mean Square Error (RMSE) = $\sqrt{\frac{\sum_{n=1}^{N}\left(y_n - y_{ref,n}\right)^2}{N}}$

Percent Error (PE) = $\frac{|Low-cost\ sensor - reference\ monitor|}{Reference\ monitor} * 100$

Coefficent of determination (R^2) = $\frac{Variation\ of\ reference\ monitor}{Variation\ of\ low-cost\ sensor}$

TES 5322 Air Quality Monitor





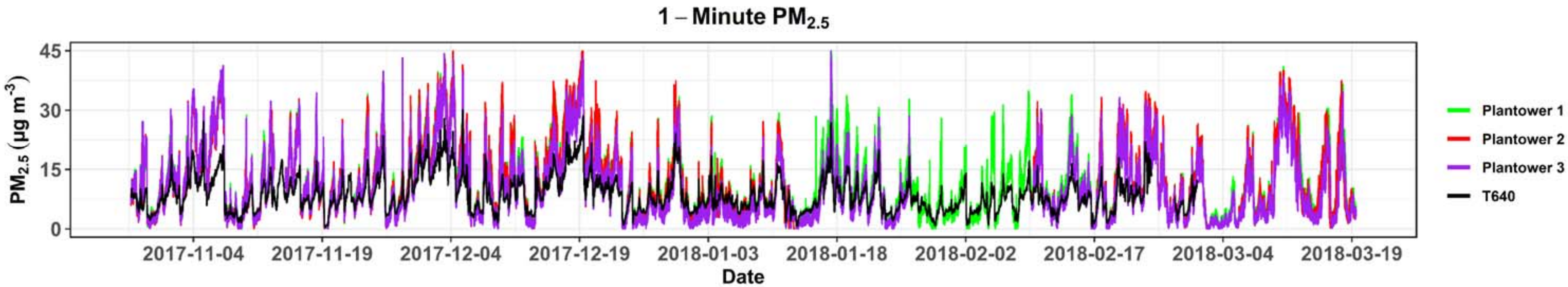
CV = 74.0%

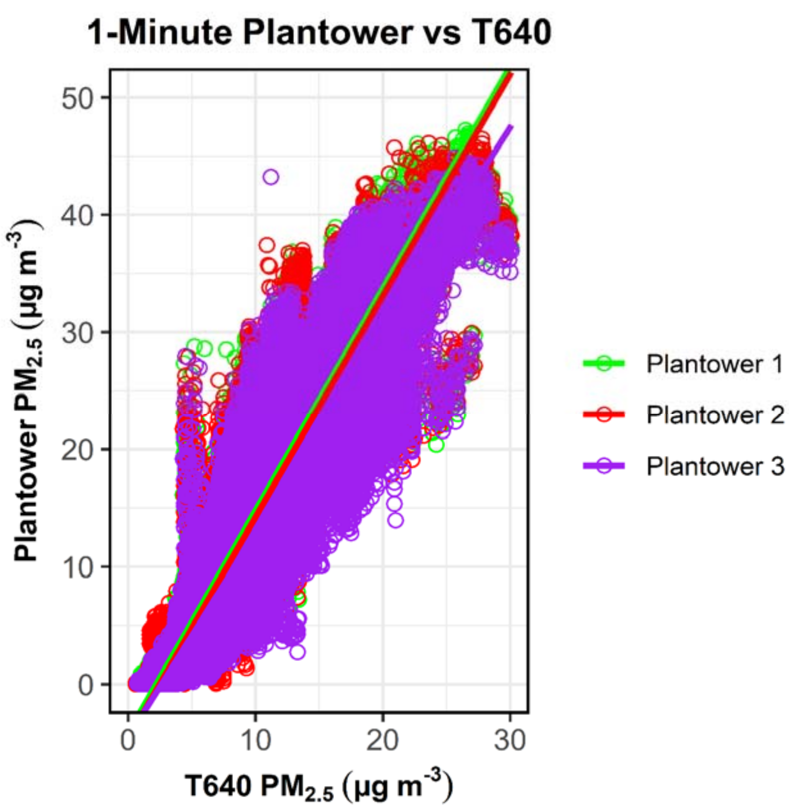
RMSE (Grimm) = 27.8 – 51.0 μg/m^3
RMSE (T640x) = 28.3 – 51.3 μg/m^3

PE(Grimm) = 185.1 – 749.1%
PE(T640x) = 250.9 – 628.9%

R^2(Grimm) = 0.09 – 0.22
R^2(T640x) = 0.06 – 0.19

Plantower PMS7003





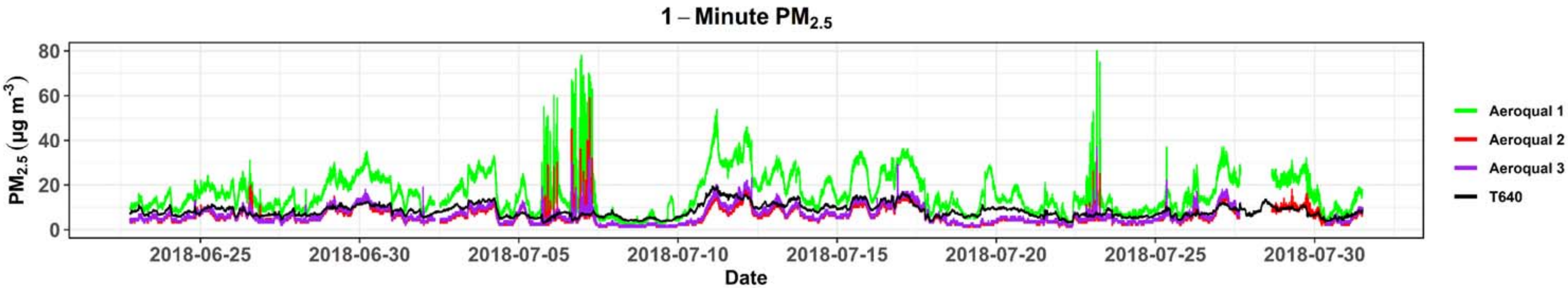
CV = 16.8%

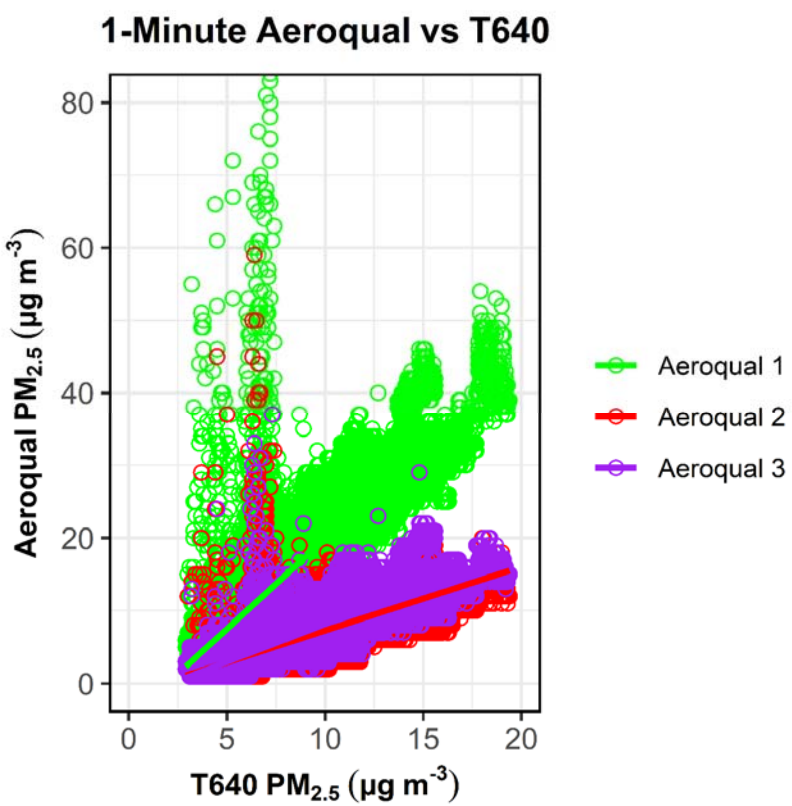
RMSE (Grimm) = 4.4 – 5.6 µg/m^3
RMSE (T640x) = 4.9 – 6.4 µg/m^3

PE(Grimm) = 31.3 – 39.0%
PE(T640x) = 38.1 – 44.3%

R^2(Grimm) = 0.83 – 0.86
R^2(T640x) = 0.86 – 0.89

Aeroqual Portable Particulate Monitor





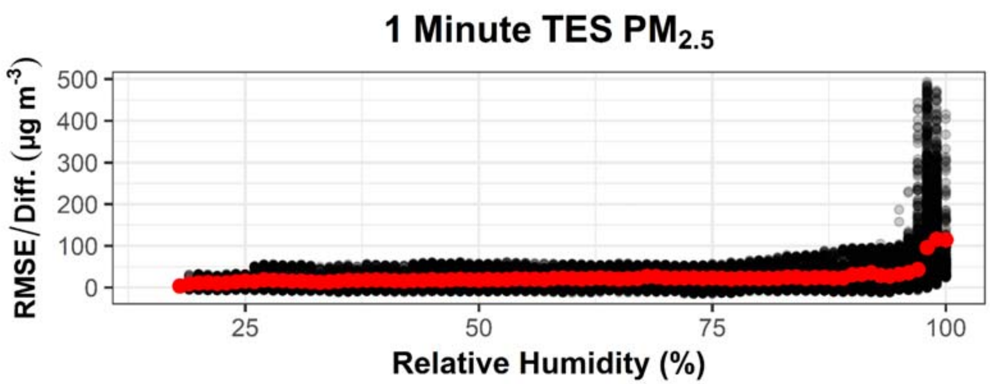
CV = 59.9%

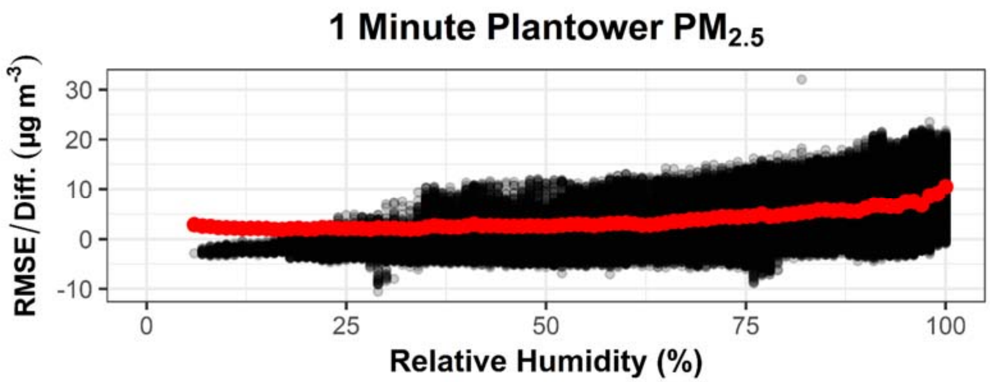
RMSE (Grimm) = 2.6 – 9.8 μg/m^3
RMSE (T640x) = 2.8 – 9.7 μg/m^3

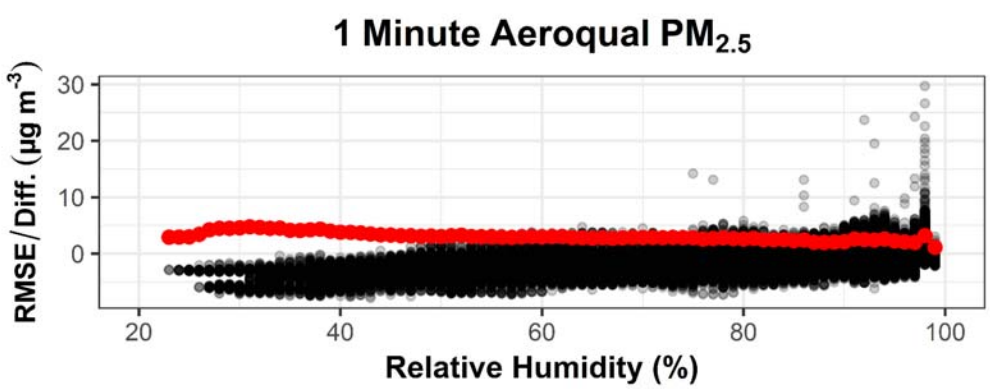
PE(Grimm) = 28.5 – 96.0%
PE(T640x) = 31.8 – 84.8%

R^2(Grimm) = 0.62 – 0.71
R^2(T640x) = 0.56 – 0.72

Variation of RMSE Across Relative Humidity

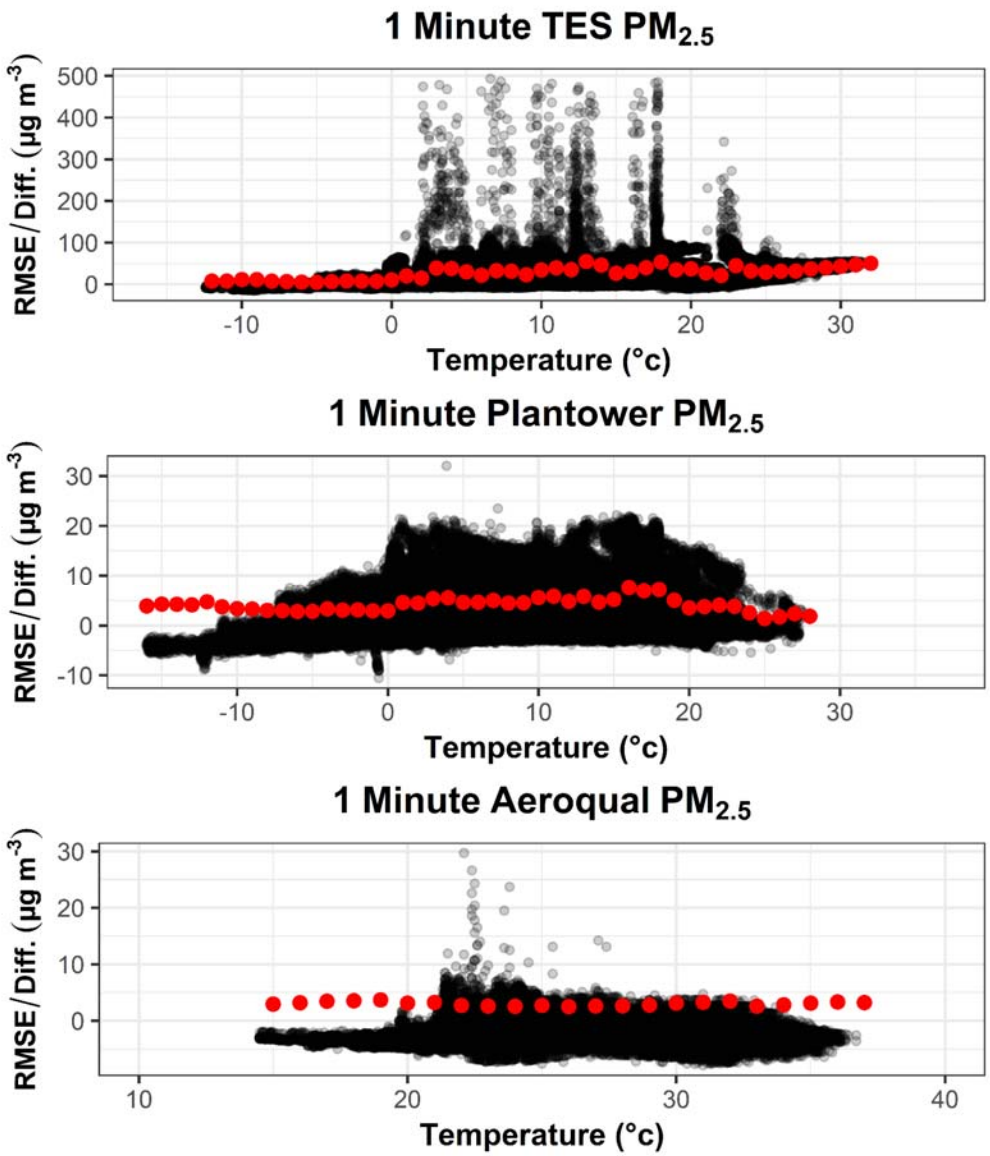






- RMSE *increases* with relative humidity for the **TES** and **Plantower** sensors and *decreases* with the **Aeroqual** sensors
- Difference between reference instruments and low-cost sensors increase with relative humidity
- Plantower and Aeroqual underpredict concentrations at low relative humidity

Variation of RMSE Across Temperature



- Outliers occur across a wide range of temperatures
- RMSE does not show a strong correlation with temperature
- Difference between reference instruments and low-cost sensors is minimized at low and high temperatures

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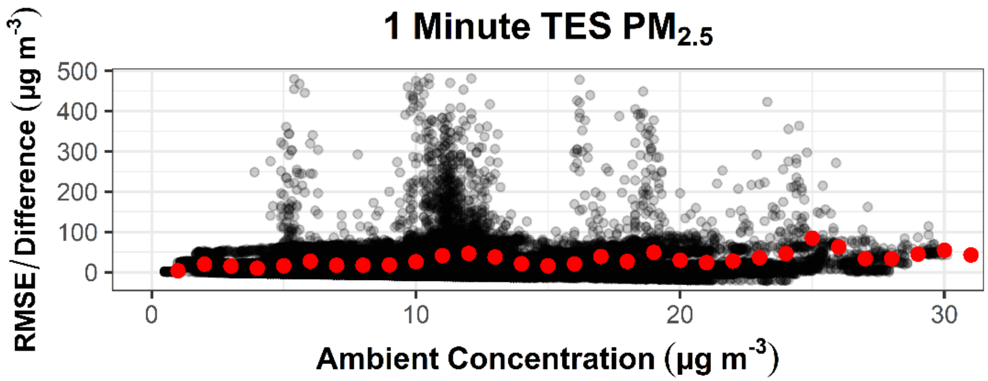
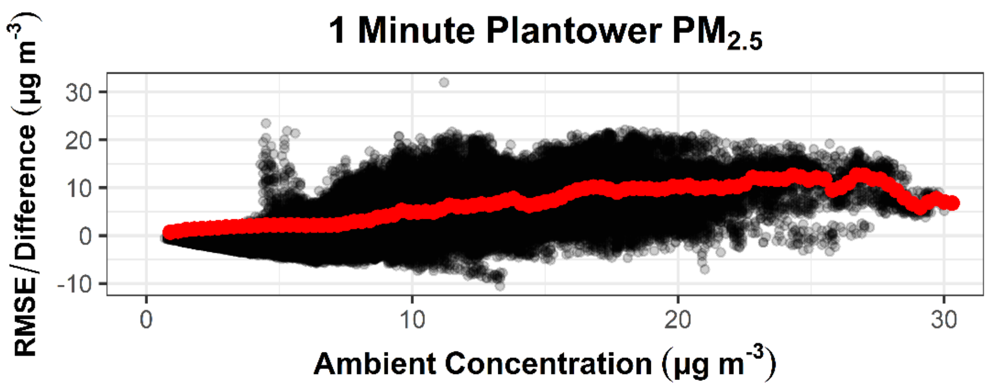
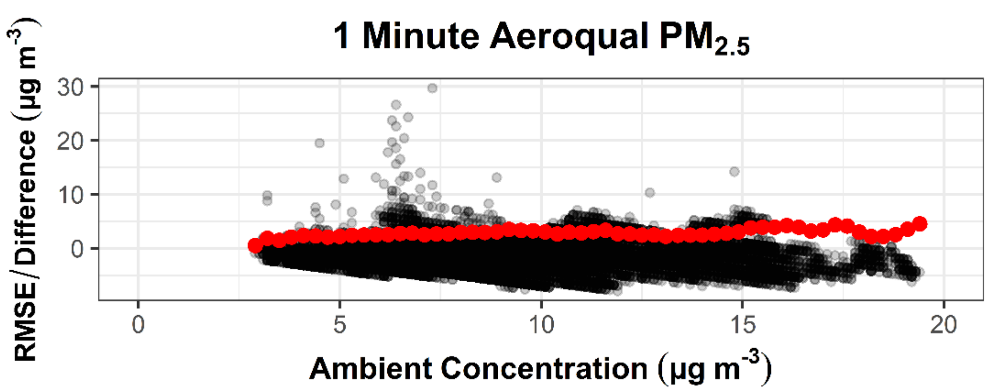
Variation of RMSE Across Ambient Concentration







- TES outliers occur across a wide range of ambient concentrations
- Plantower error gradually increases with ambient concentrations
- Aeroqual error gradually decreases with ambient concentrations

Impact of Parsing Data as a Function of Relative Humidity

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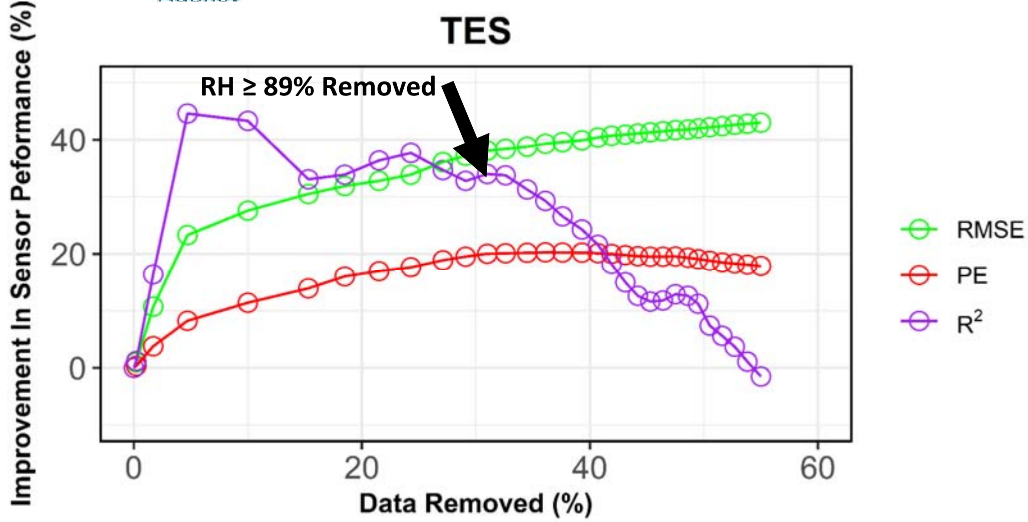
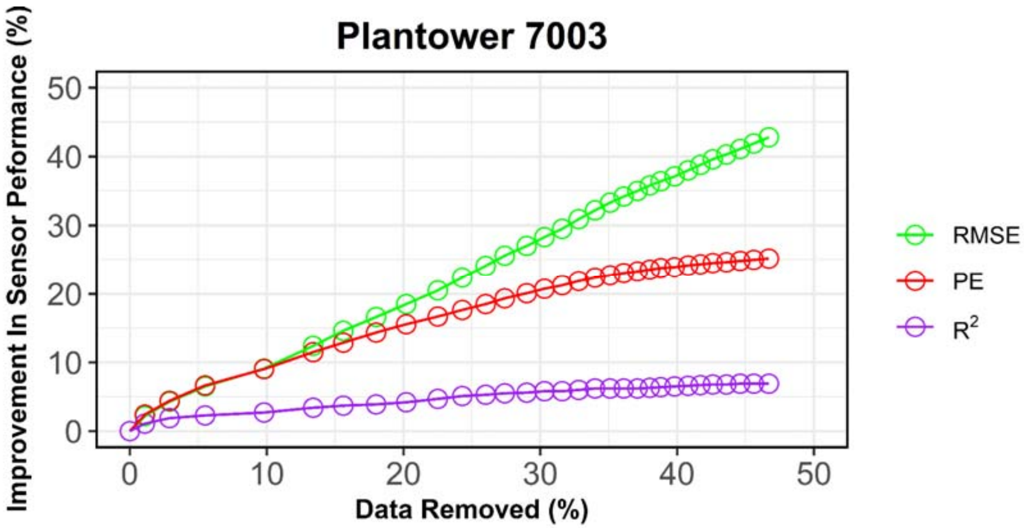
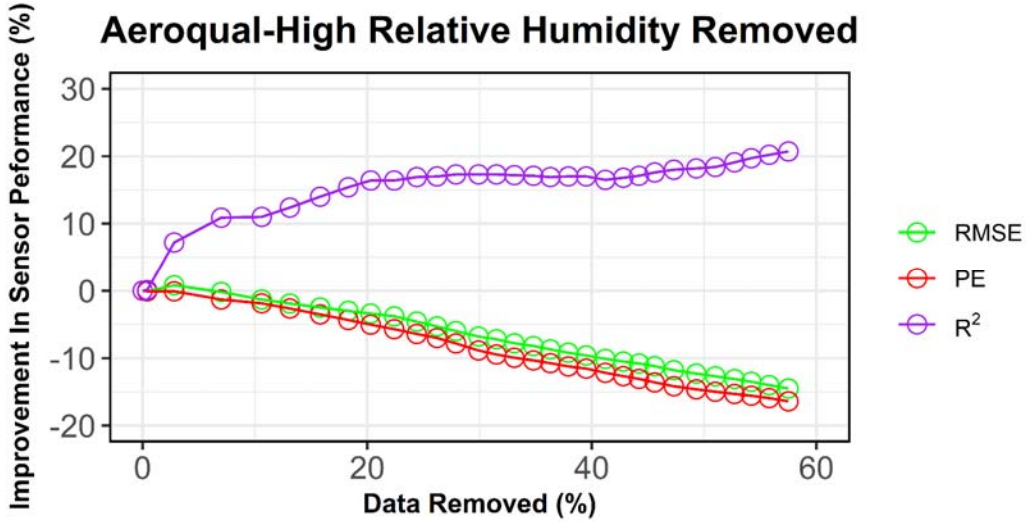
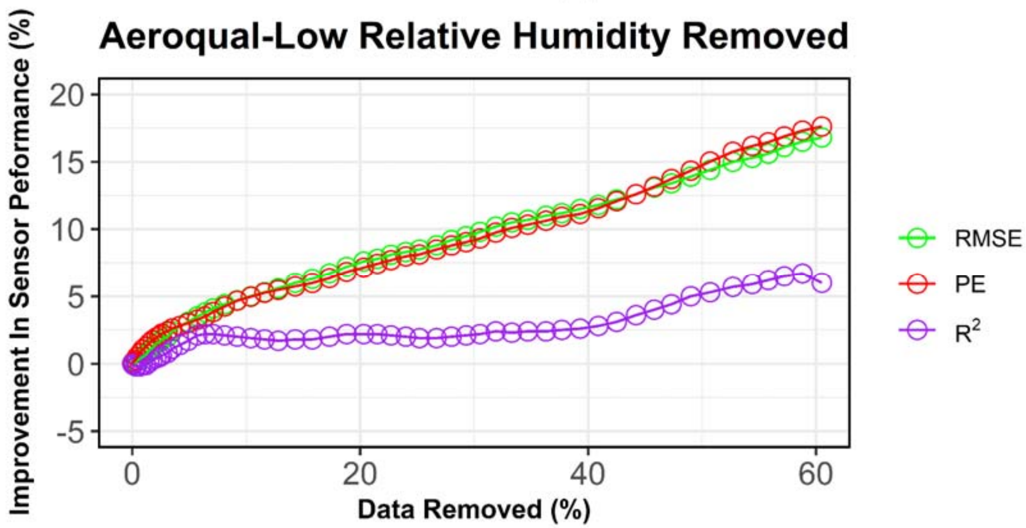




- RMSE continuously improves for both TES and Plantower as the impact of relative humidity is minimized
- PE initially improves for both TES and Plantower but then becomes less accurate as the removal of data results in a reduced sample size
- 2/3 TES R^2 peaks when relative humidity ≥ 89% is removed
- Plantower R^2 continuously increases

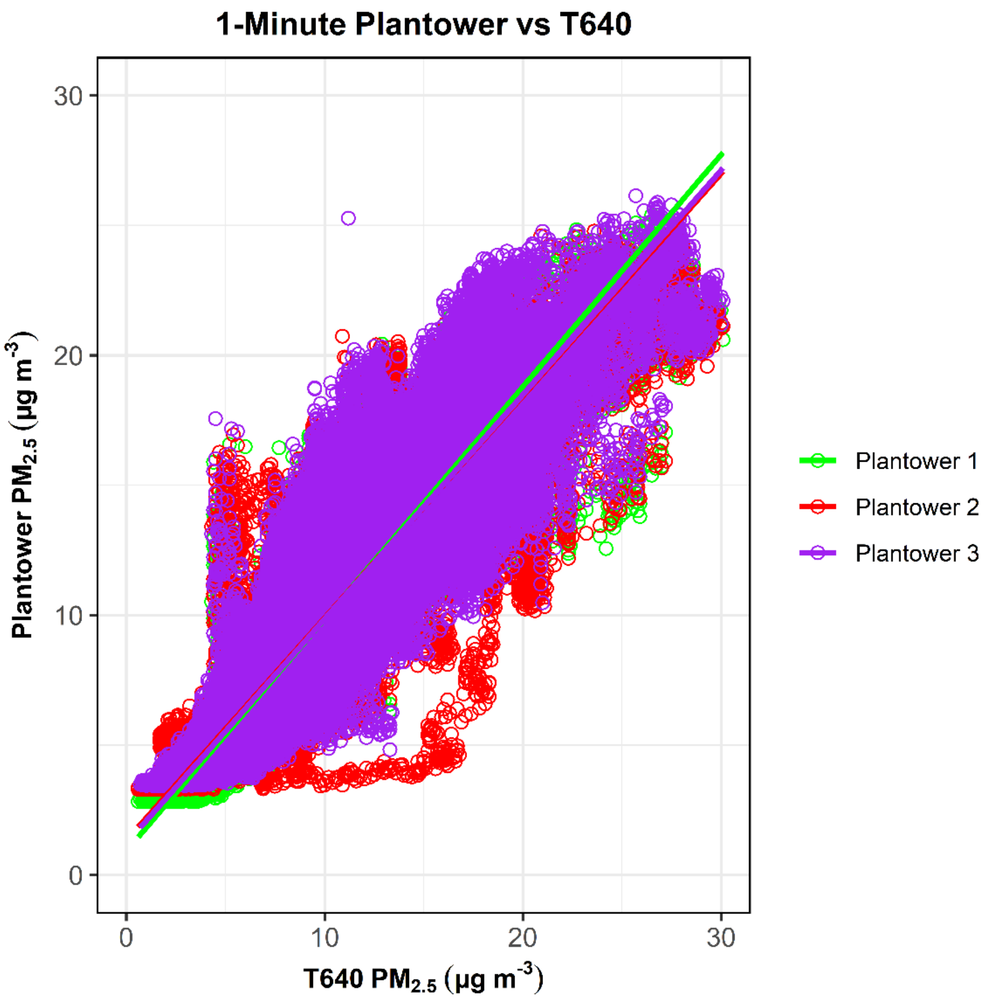
Impact of Parsing Data as a Function of Relative Humidity





- The accuracy (RMSE and PE) of the Aeroqual sensor decreases as data at high relative humidity is removed
- The accuracy (RMSE and PE) improves as data at low relative humidity is removed due to less under predicted values
- Aeroqual variance (R^2) increases more rapidly with the removal of data at high relative humidity compared to data at low relative humidity due to the removal of outliers

Plantower PMS7003 Linear Regression



Raw data

Linear regression applied

CV = 16.8%

CV = 6.4%

RMSE (T640x) = 4.9 – 6.4 µg/m^3

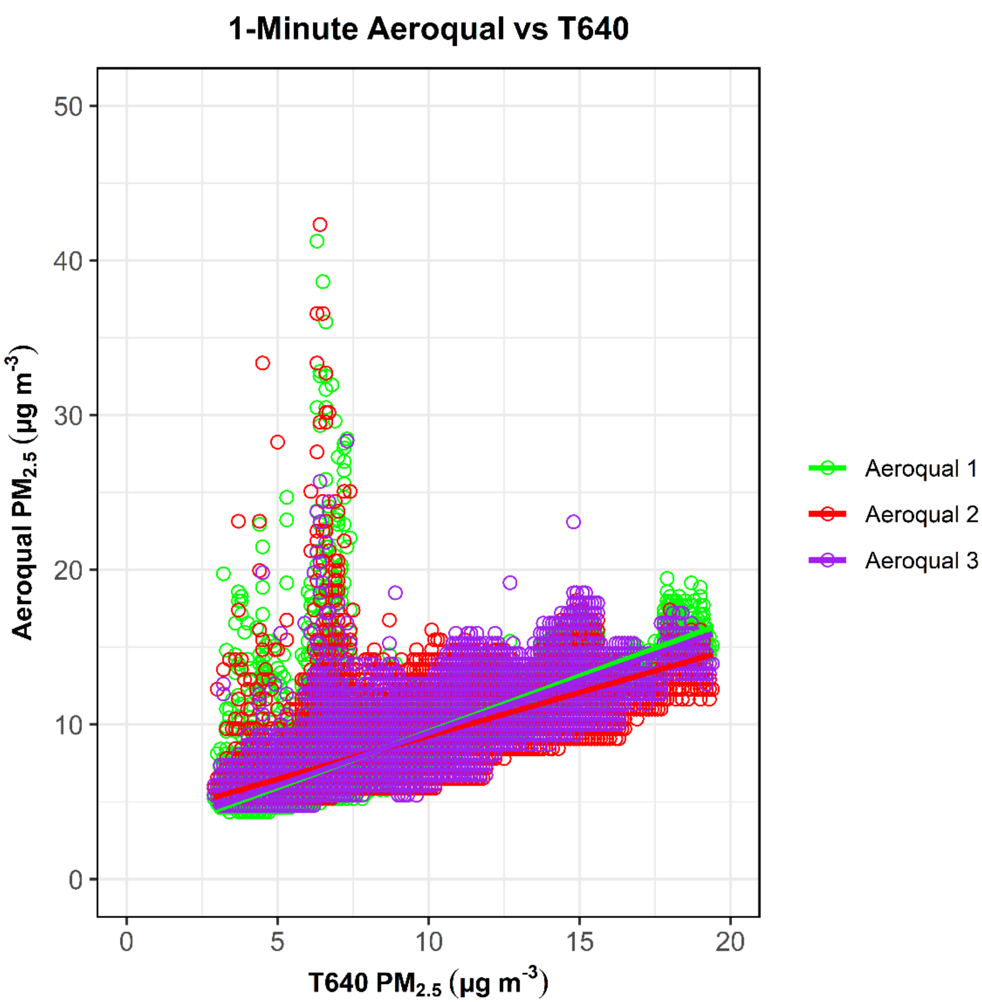
RMSE (T640x) = 1.5 – 1.8 µg/m^3

PE(T640x) = 38.1 – 44.3%

PE(T640x) = 13.2 – 15.6%

R^2(T640x) = 0.86 – 0.89

Aeroqual Linear Regression



Raw data

Linear regression applied

CV = 59.9%

CV = 6.0%

RMSE (T640x) = 2.8 – 9.7 µg/m^3

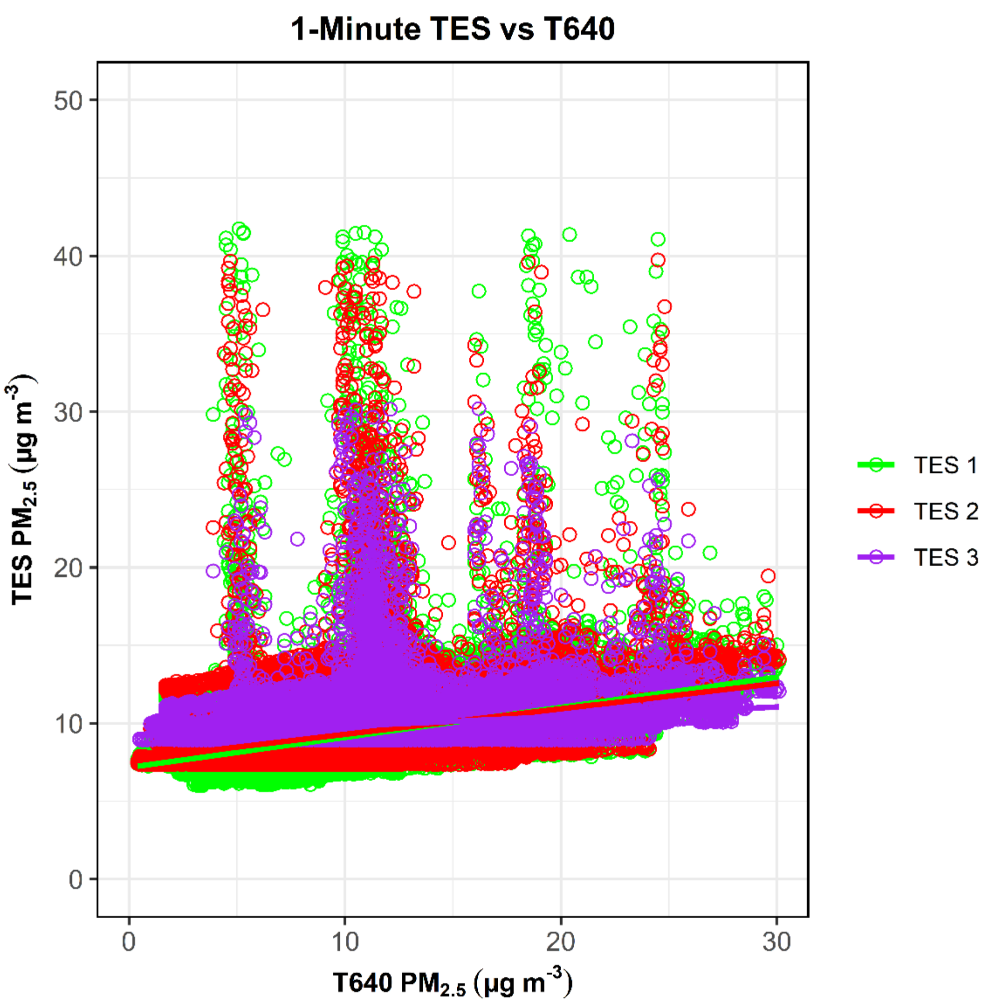
RMSE (T640x) = 1.5 – 1.9 µg/m^3

PE(T640x) = 31.8 – 84.8%

PE(T640x) = 13.9 – 18.4%

R^2(T640x) = 0.56 – 0.72

TES 5322 Linear Regression



Raw data

Linear regression applied

CV = 74.0%

CV = 5.6%

RMSE (T640x) = 28.3 – 51.3 µg/m^3

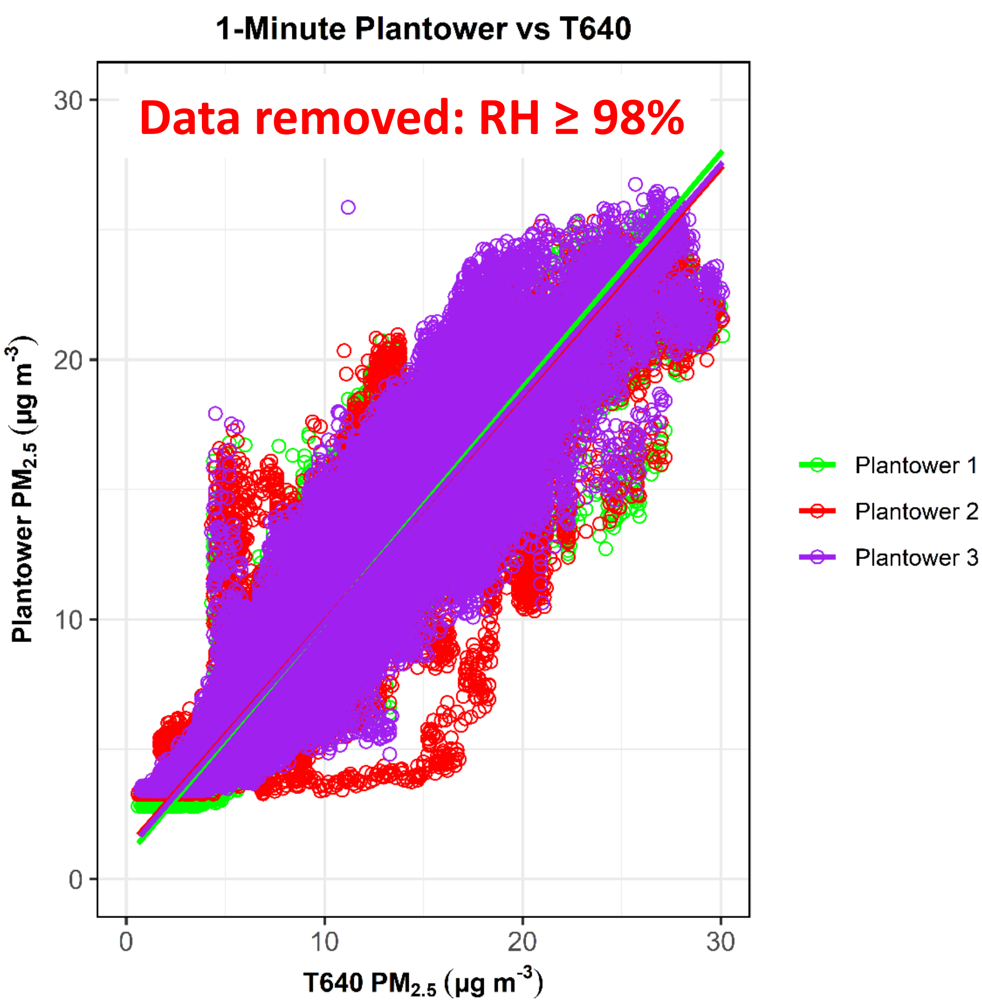
RMSE (T640x) = 4.0 – 4.5 µg/m^3

PE(T640x) = 250.9 – 628.9%

PE(T640x) = 46.8 – 51.0%

R^2(T640x) = 0.06 – 0.19

Plantower PMS7003 Linear Regression + Data Removal



Raw data
Linear regression applied
Data removal + linear regression

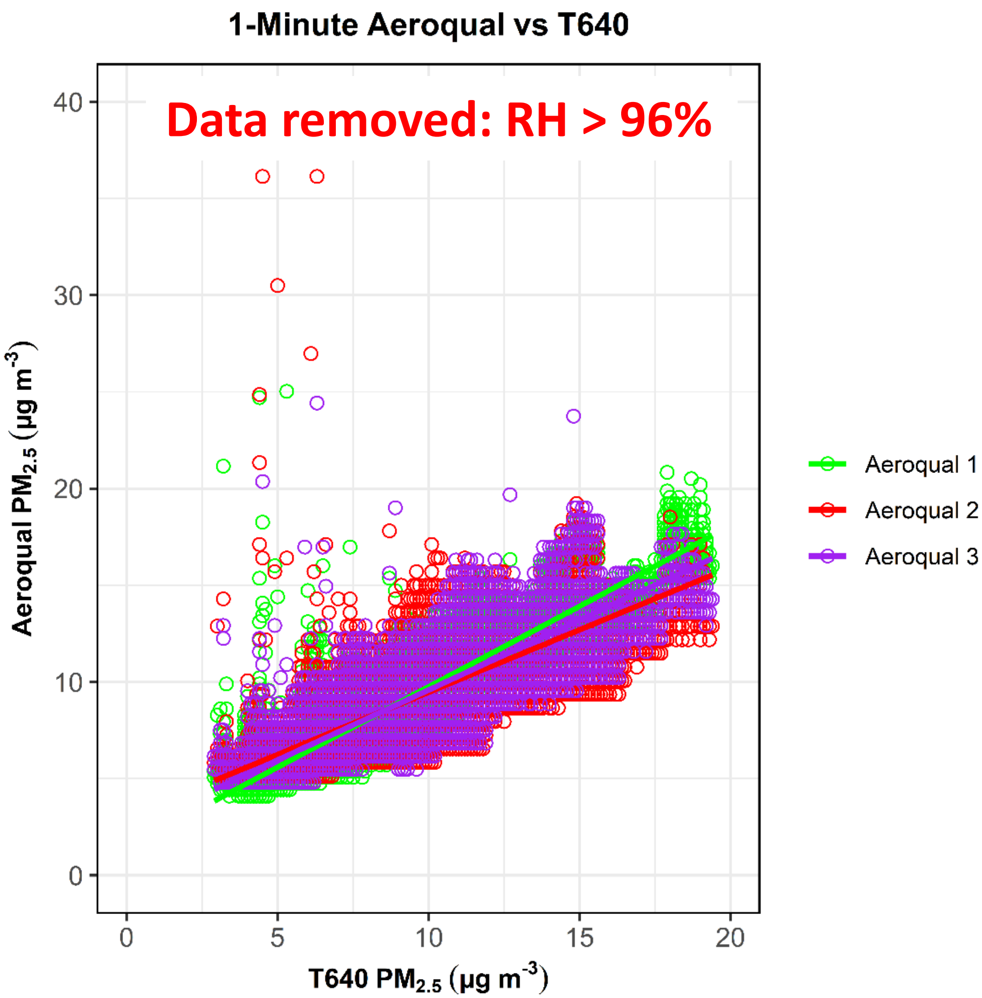
CV = 16.8/CV = 6.4/CV = 6.5%

RMSE (T640x) = 4.9 – 6.4 µg/m^3
RMSE (T640x) = 1.5 – 1.8 µg/m^3
RMSE (T640x) = 1.4 – 1.8 µg/m^3

PE(T640x) = 38.1 – 44.3%
PE(T640x) = 13.2 – 15.6%
PE(T640x) = 12.8 – 15.0%

R^2(T640x) = 0.86 – 0.89
R^2(T640x) = 0.87 – 0.90

Aeroqual Linear Regression + Data Removal



Raw data
Linear regression applied
Data removal + linear regression

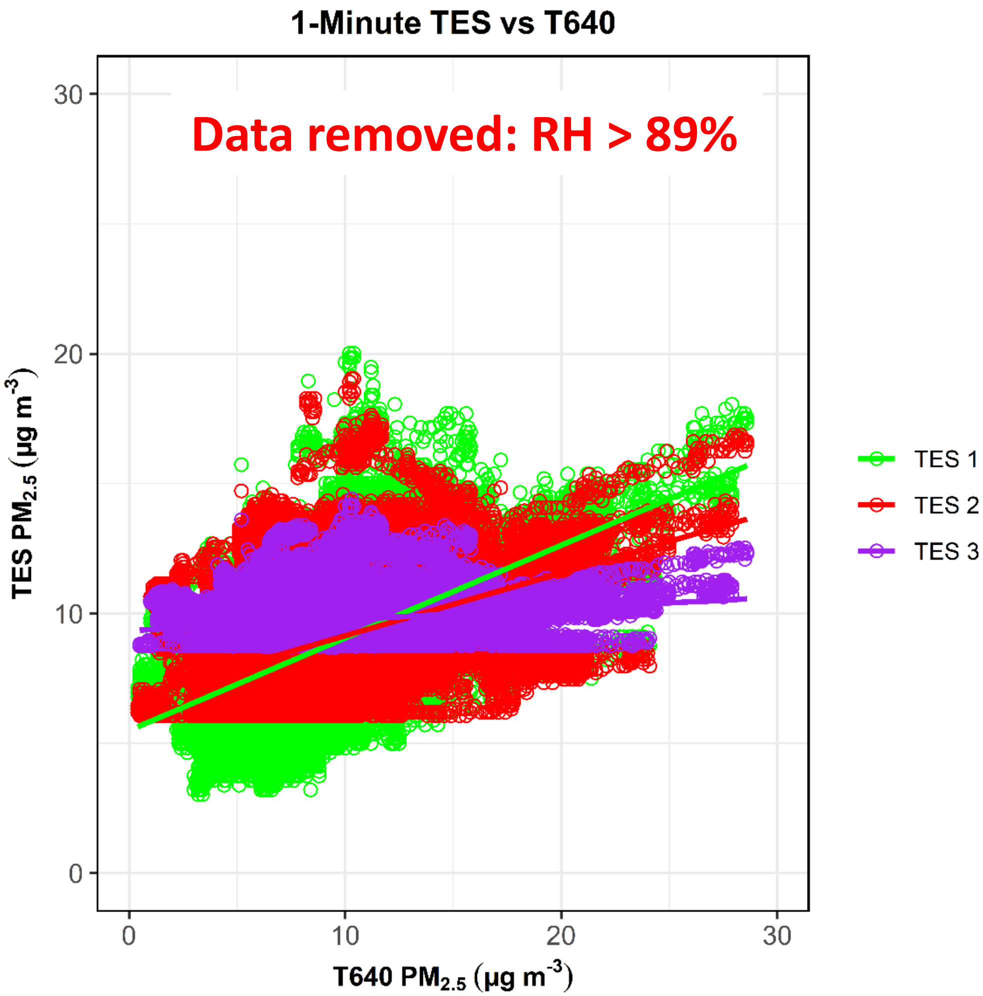
CV = 59.9/CV = 6.0/CV = 6.2%

RMSE (T640x) = 2.8 – 9.7 µg/m^3
RMSE (T640x) = 1.5 – 1.9 µg/m^3
RMSE (T640x) = 1.2 – 1.8 µg/m^3

PE(T640x) = 31.8 – 84.8%
PE(T640x) = 13.9 – 18.4%
PE(T640x) = 11.7 – 16.8%

R^2(T640x) = 0.56 – 0.72
R^2(T640x) = 0.64 – 0.83

TES 5322 Linear Regression + Data Removal



Raw data

Linear regression applied

Data removal + linear regression

CV = 74.0/CV = 5.6/CV = 8.8%

RMSE (T640x) = 28.3 – 51.3 μg/m³

RMSE (T640x) = 4.0 – 4.5 μg/m³

RMSE (T640x) = 3.3 – 4.3 μg/m³

PE(T640x) = 250.9 – 628.9%

PE(T640x) = 46.8 – 51.0%

PE(T640x) = 41.0 – 48.7%

R^2(T640x) = 0.06 – 0.19

R^2(T640x) = 0.04 – 0.36

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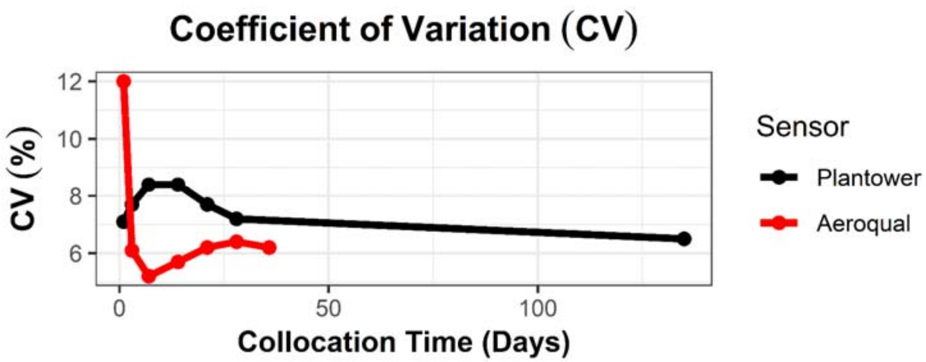
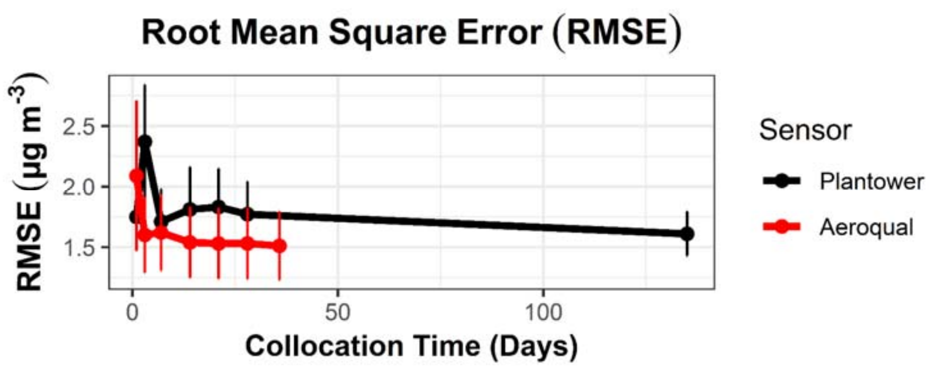
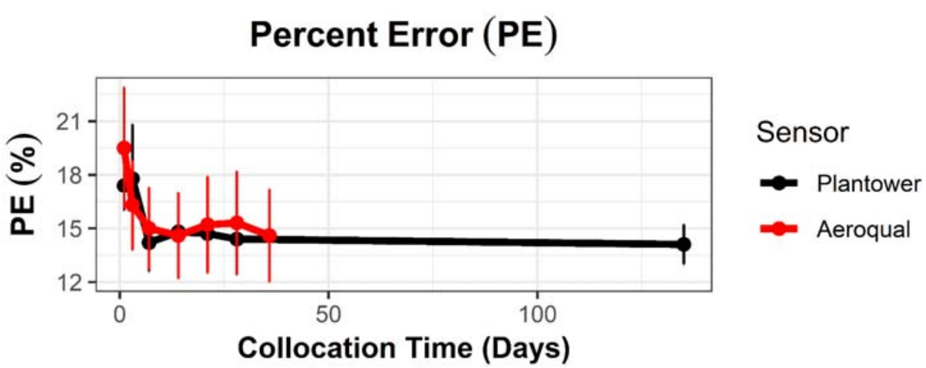
Variation In Performance With Increasing Collocation Period







- Duration of collocation period determines how well the linear regression will be able to characterize the performance of the low-cost sensor.
- Collocation period can be performed at the beginning and/or end of the deployment but must be representative of deployment conditions
- Performance of Plantower sensor begins to plateau at a collocation period of 28 days.
- Performance of the Aeroqual sensor begins to plateau at a collocation period of 14 days.

Conclusions

- Combination of linear regression and data removal is necessary to improve performance of low-cost sensor measurements
- Considerable variation in the performance between low-cost sensor replicates and manufacturers
- Low-cost ≠ FRM or FEM performance standards
- Low-cost ≠ low labor intensity
- Duration of collocation period is dependent on type of low-cost sensor

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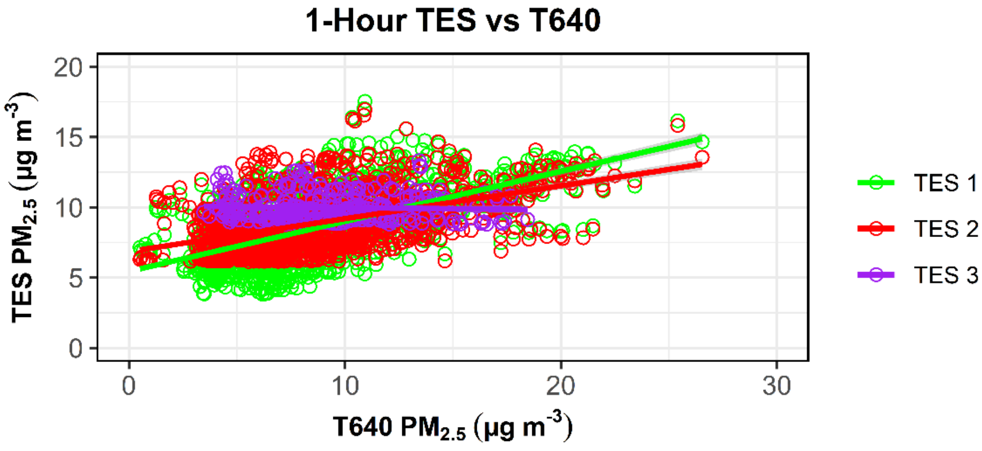
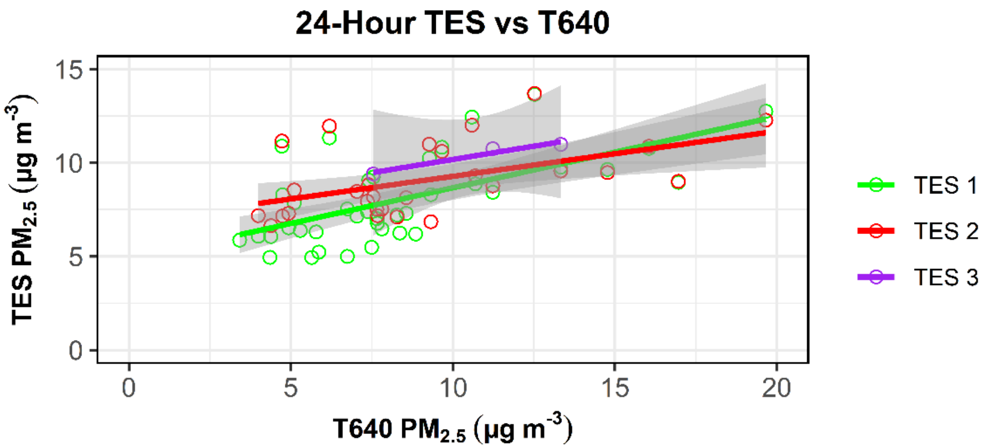
Questions?

TES 5322 1-Hour and 24-Hour Average





TES 1-Hour

CV = 8.0

RMSE (T640x) = 3.2 – 3.7 µg/m^3

PE(T640x) = 38.1– 44.9%

R^2(T640x) = 0.00 – 0.36

TES 24-Hour

CV = 5.5

RMSE (T640x) = 2.8 – 4.1 µg/m^3

PE(T640x) = 32.3– 44.0%

R^2(T640x) = 0.26 – 0.95

Change In Normalized RMSE With Relative Humidity