Performance Evaluations of $PM_{2.5}$ Sensors in Research Triangle Park, NC

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Overview

- Introduction
  - Motivation for air sensor evaluation
  - Particulate matter measurement and evaluation methods
  - Evaluation site details
  - Sensors chosen for this study
- Performance Evaluation of Sensor Types
  - Data collection time period and uptime
  - Precision within a group of identical sensors
  - Performance against regulatory-grade instrument
- Conclusions
  - Summary of results
  - Future work

Motivation: Air Quality Monitoring

- Rapidly increasing number of air quality monitors entering the market
  - Provide users with real-time air quality measurement
- Often used for non-regulatory applications which do not necessarily require the same rigorous standards of accuracy and reliability
  - Evaluation of air quality sensor measurements against regulatory methods is critical to ensuring measurement accuracy and precision

Image source: https://clarity.io/solution; www.aeroqual.com/product/aqy-micro-air-quality-station; www.purpleair.com/

Sensor Evaluation: Contextualizing this Work

- Ongoing effort to evaluate sensor performance
- Evaluation covers a large number of sensor models and pollutants
  - These devices measure a varying number of pollutants including the following:*
    - $PM_{2.5}$
    - PM_{10}
    - O_3
    - NO_2, NO_x
    - SO_2
    - CO
  - Oftentimes devices also record meteorological data:*
    - Temperature
    - Relative Humidity

Particulate Matter (PM): $PM_{2.5}$ and PM_{10} represent particles of size < 2.5 µm and < 10 µm, respectively

Gases

Gases (O_3, NO_2, NO_x, SO_2, CO)

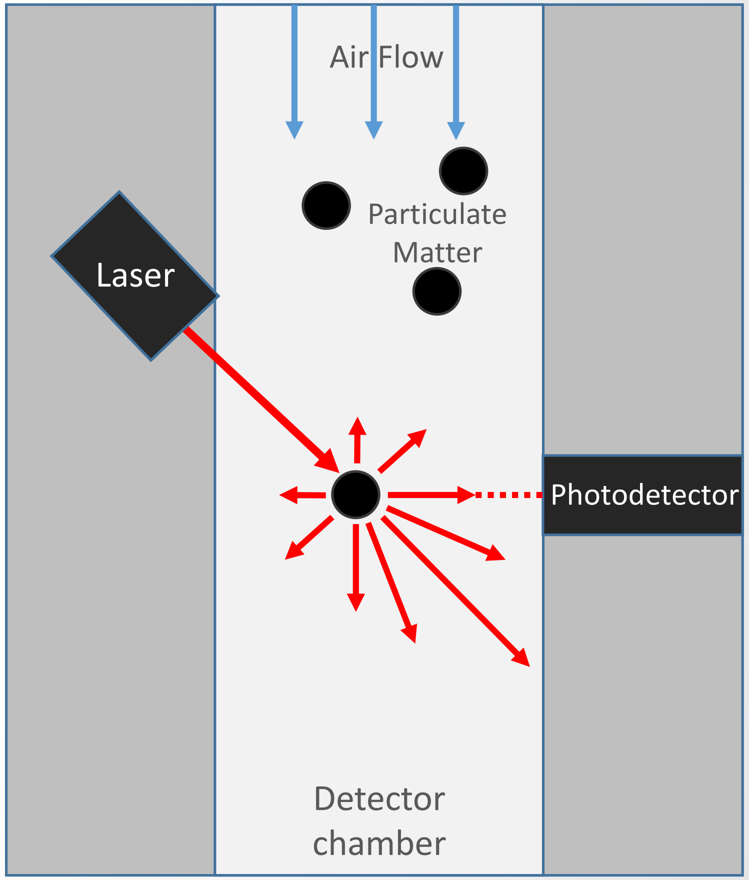
Particulate Matter ($PM_{2.5}$, PM_{10})

Particulate Matter ($PM_{2.5}$, PM_{10})

Not a comprehensive list of pollutants and meteorological values measured by air quality sensors

Particulate Matter Measurement

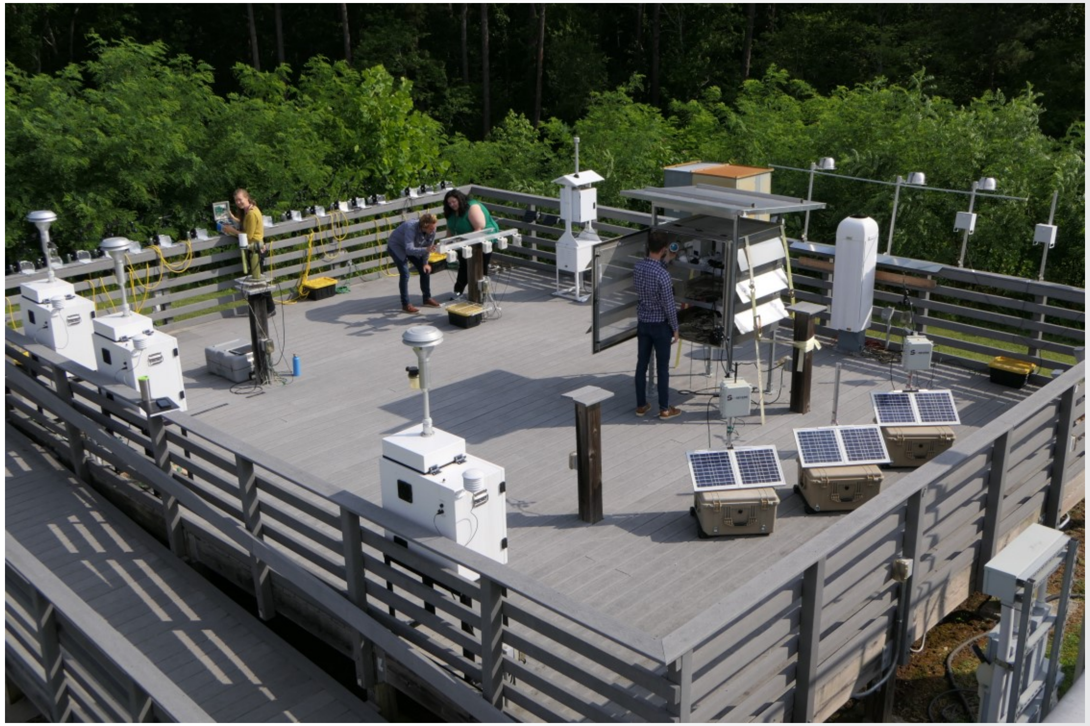
- Air quality sensors use optical scattering to measure PM. Despite cost effectiveness, this method presents limitations.
  - Optical scattered light proportional to the square of the **size of particles** for a fixed scattering angle
  - The size of volume of particles is converted to PM mass concentration often using a laboratory calibration
  - PM is often hygroscopic and can uptake water causing particles to grow in size
  - Increased particle size often results in an over-estimation of PM mass as compared to a dried sample resulting in a bias correlated to relative humidity (RH) and temperature
    - Regulatory-grade instruments are not as susceptible to this artifact because they are operated under controlled conditions: sample RH (30-40 %) and temperature (20 – 23 °C)



AIRS Evaluation Site

Air quality sensors collocated with regulatory-grade monitor

- Air sensors are tested in triplicate (or more)
  - Data recorded at ~1-min time resolution
  - Computed 1-hour averages for comparison
- Teledyne T640x PM Mass Monitor
  - Federal Equivalent Method (FEM) for $PM_{2.5}$
  - Scattered light spectrometry (heating element to reduce PM water content)
  - Default logging interval: 10-minute rolling averages (logged each minute)
  - Computed 1-hour averages for comparison



Goals of this Study

- **1-hour averaged $PM_{2.5}$ performance for six air quality sensor types**
  - Collocated sensors at AIRS evaluation site on RTP campus (Collocation period ≥ 30 days)
  - Determine precision within sensor types (≥ 3 sensors of the same type)
  - Evaluate performance against T640x FEM $PM_{2.5}$ measurements
  - Inform users regarding future sensor implementation both internal and external to EPA

Device Manufacturer	Device Name	Internal PM Sensor	Time Resolution
Vaisala	AQT420	OEM	1 minute
Aeroqual	AQY	NOVA SDS011	1 minute
Clarity	Node-S	Plantower PMS6003	3 minutes
SENS-IT	Ramp	Plantower PMS5003	15 seconds
APT	Maxima	Plantower PMSA003	30 seconds
PurpleAir	PA-II-SD	Plantower PMS5003	2 minutes

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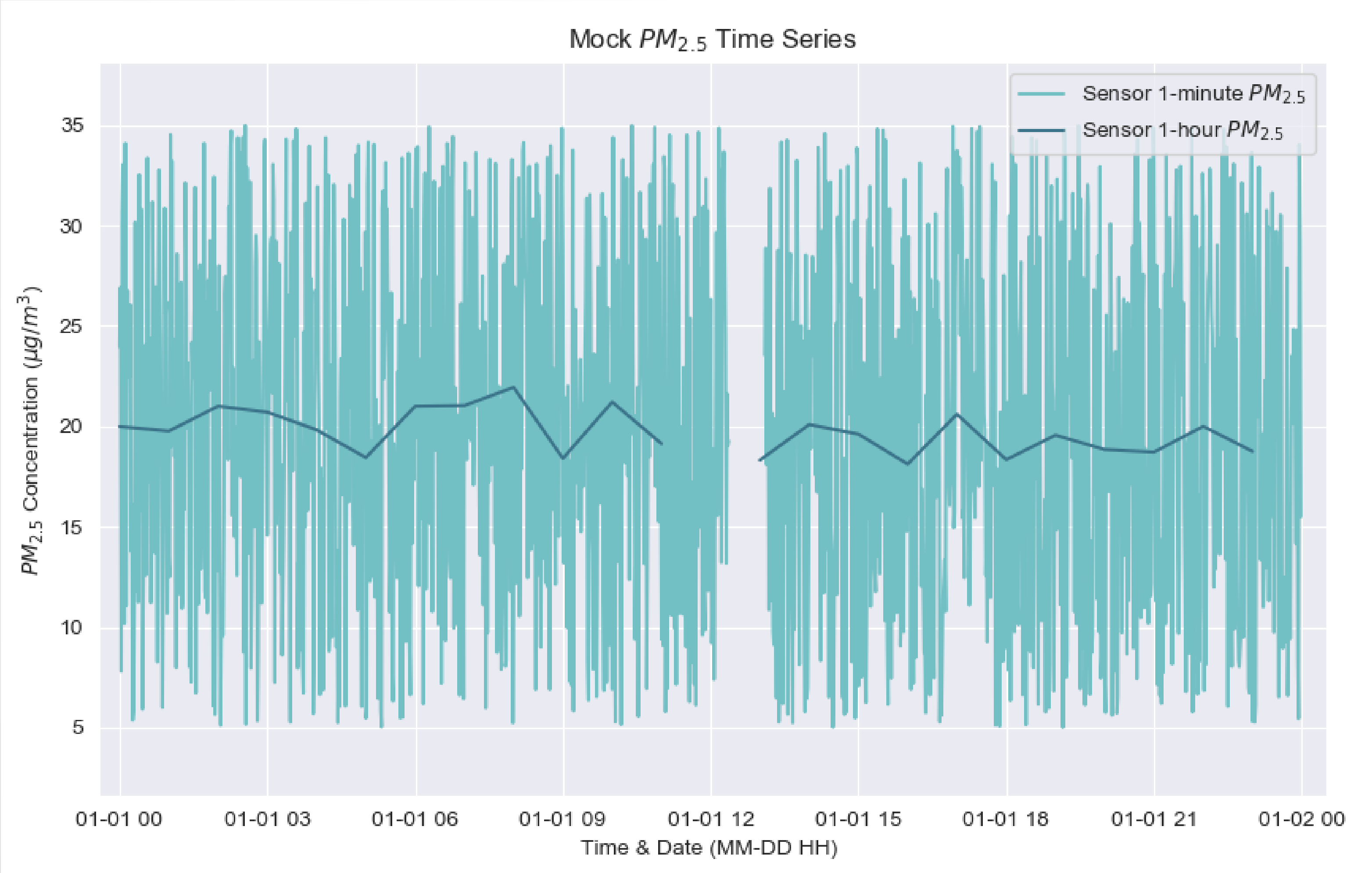
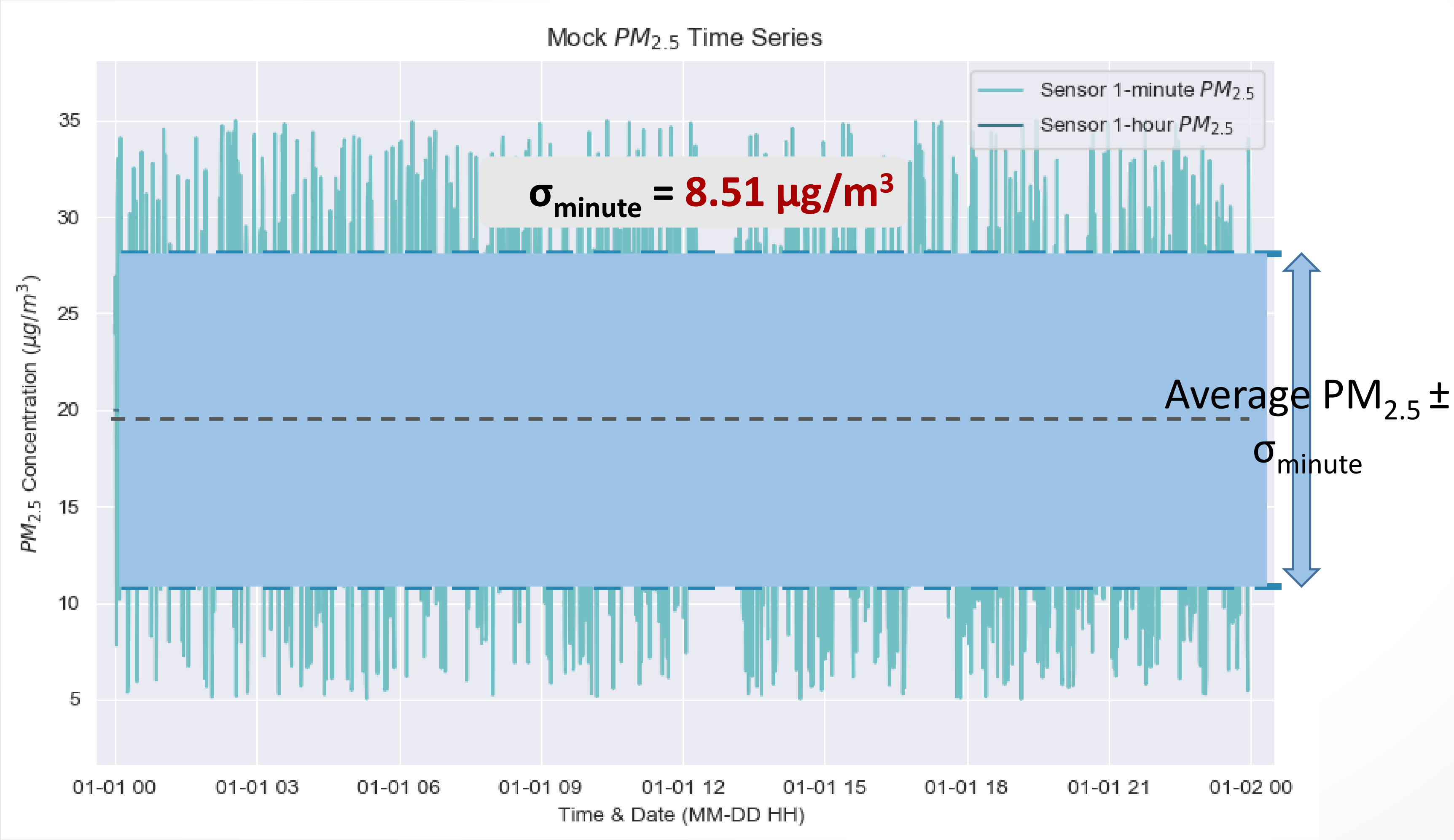
Imposed a 90% completeness criteria

Variation in Minute-Resolution Data



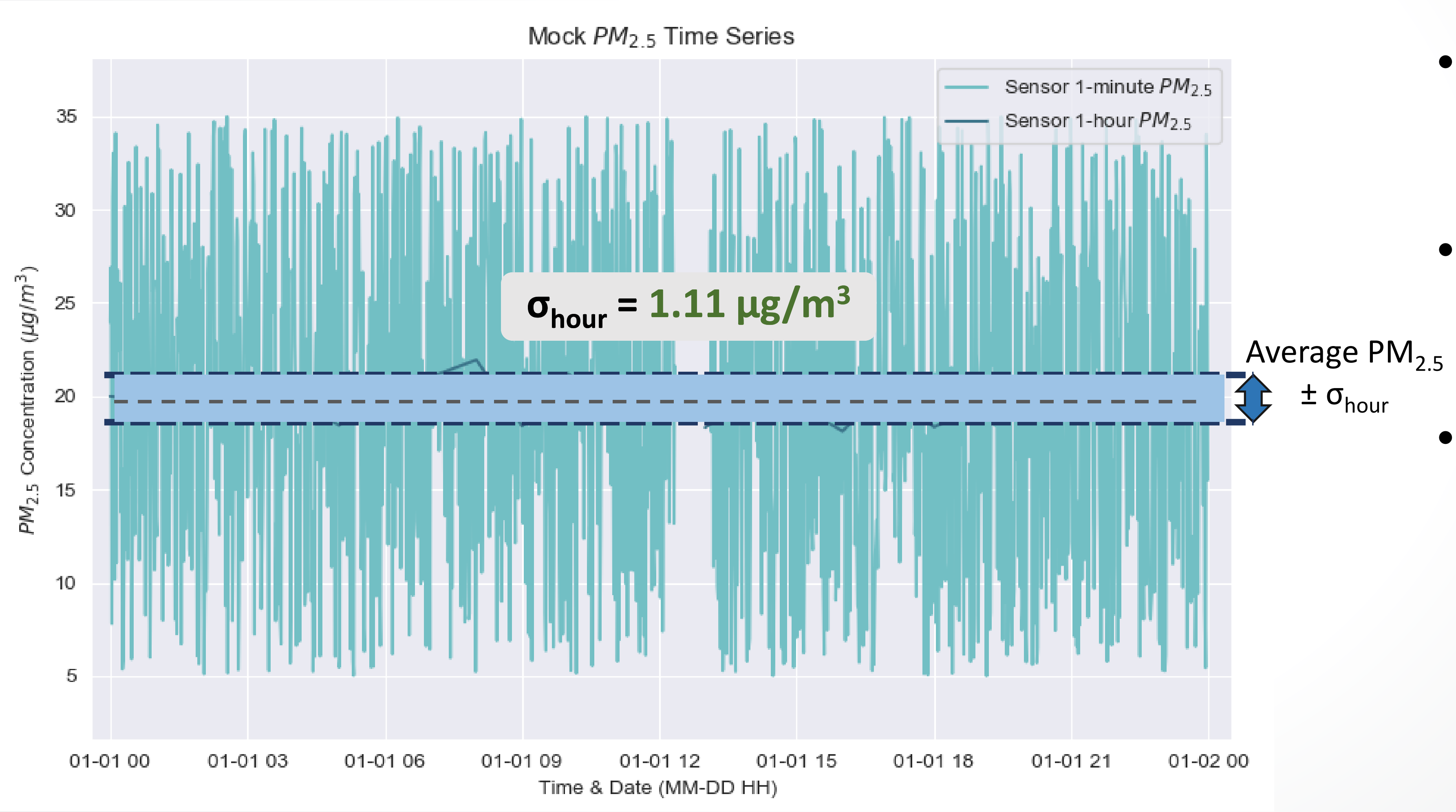
- **Data collected at minute intervals has a high degree of variation**

Variation in Minute-Resolution Data



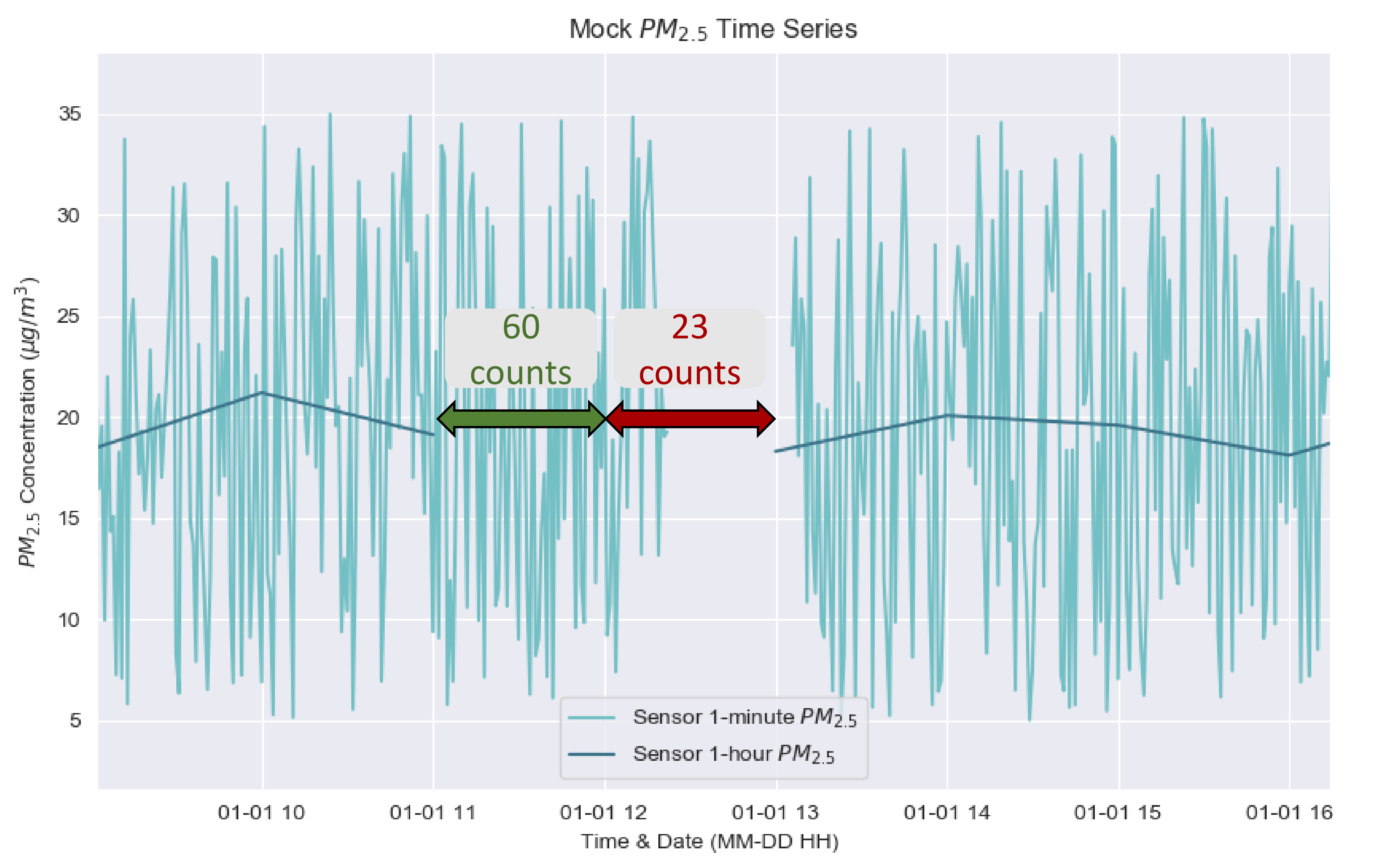
- Data collected at minute intervals has a high degree of variation
- **Standard deviation quantifies variation in the data**

Variation in 1-Hour Averaged Data



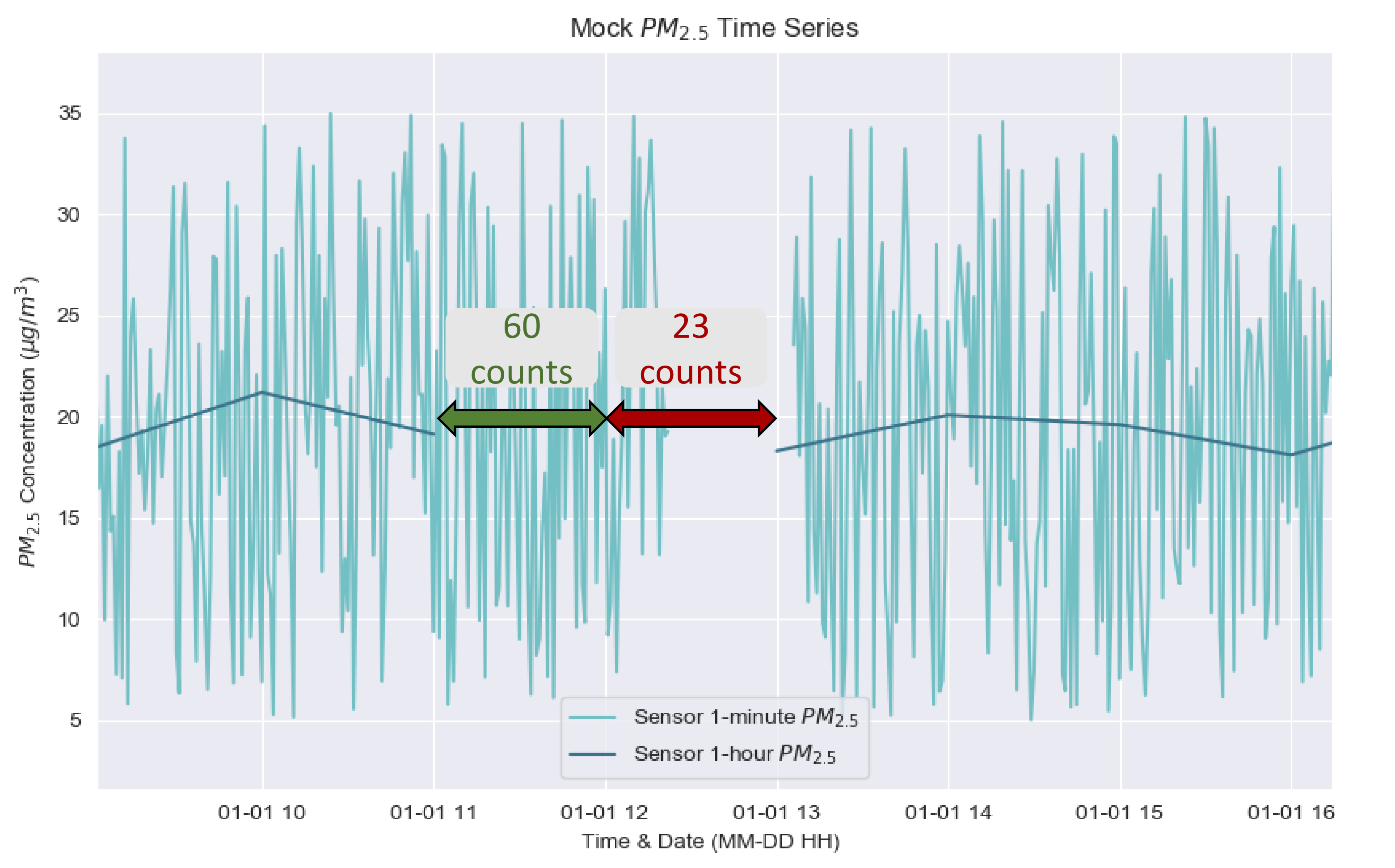
- Data collected at minute intervals has a high degree of variation
- Standard deviation quantifies variation in the data
- **Computing 1-hour averages significantly reduces this variation.**

Computing 1-Hour Averaged Data



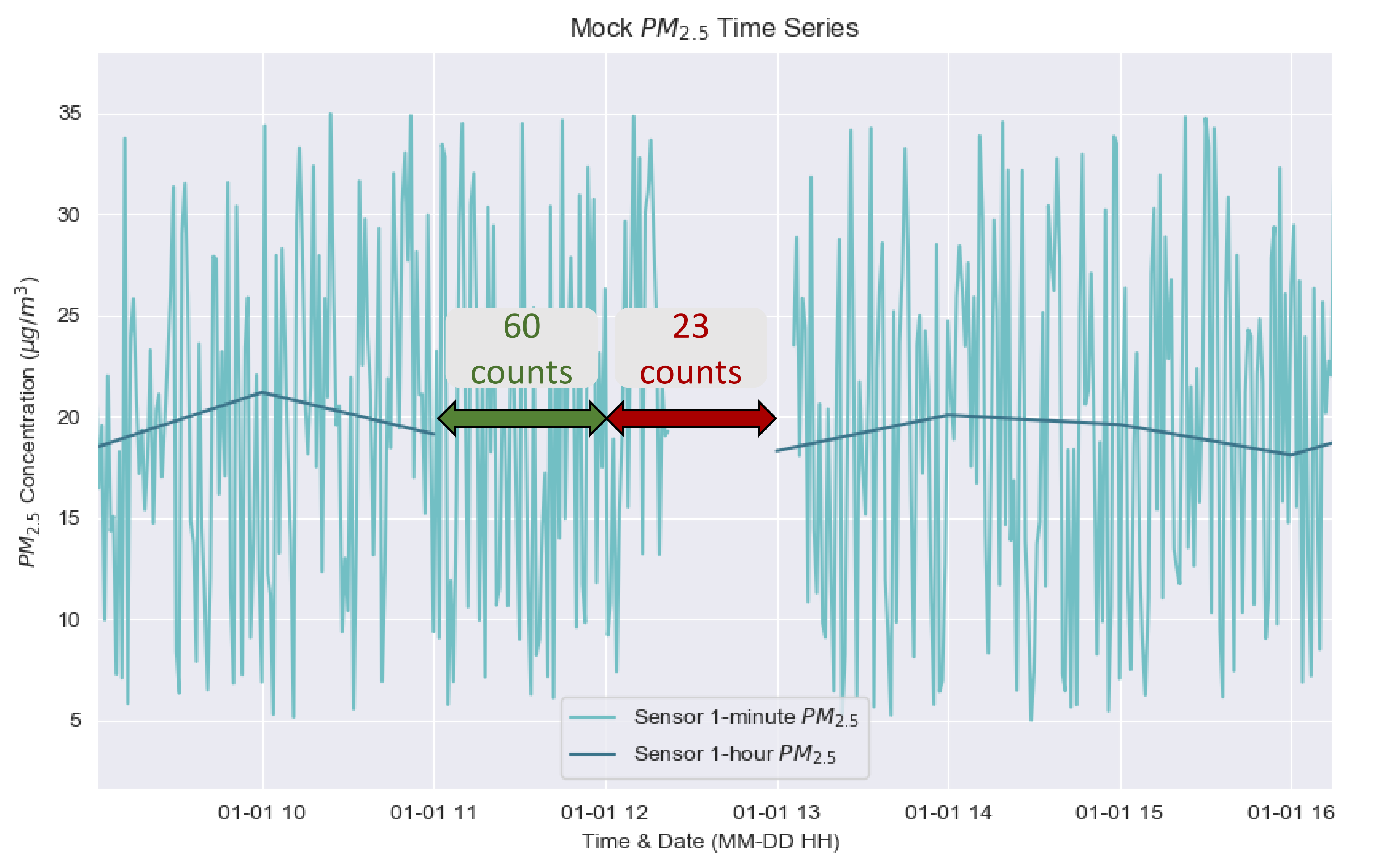
- Data may be incomplete for a given hour due to technical fault at the sensor level (e.g. loss of connection) or site level (e.g. loss of power, meteorological events)
- We want the 1-hour average to be representative of the 1-hour time period so we impose a completeness criteria requiring most of the data to be present before compute a 1-hour average

Computing 1-Hour Averaged Data



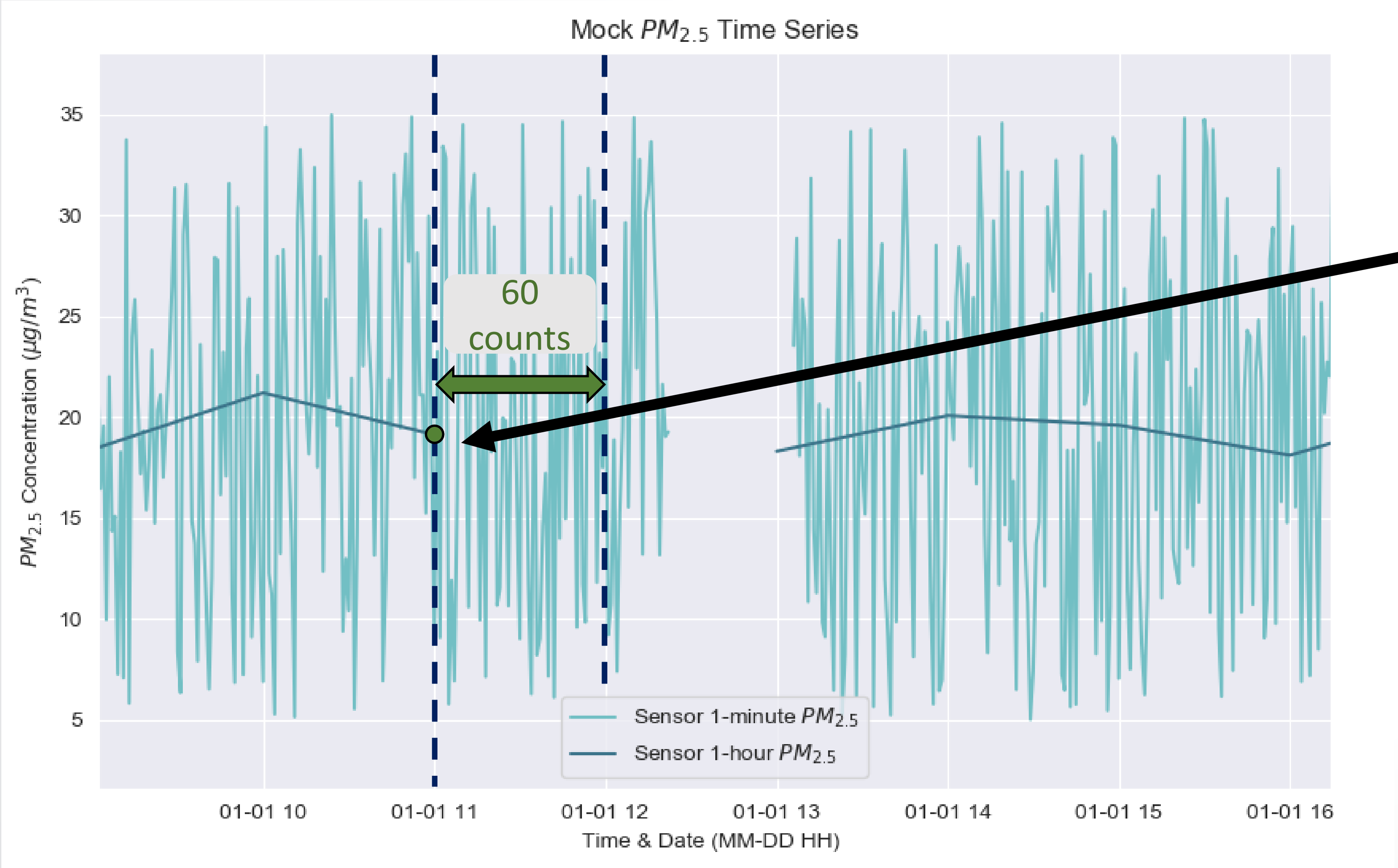
- Data may be incomplete for a given hour due to technical fault at the sensor level (e.g. loss of connection) or site level (e.g. loss of power, meteorological events)
- Requires enough data exist for a given hour to compute a 1-hour average
- **For this work, we required data recorded within a given hour to be ≥90% complete in order to compute 1-hour averages**

Computing 1-Hour Averaged Data



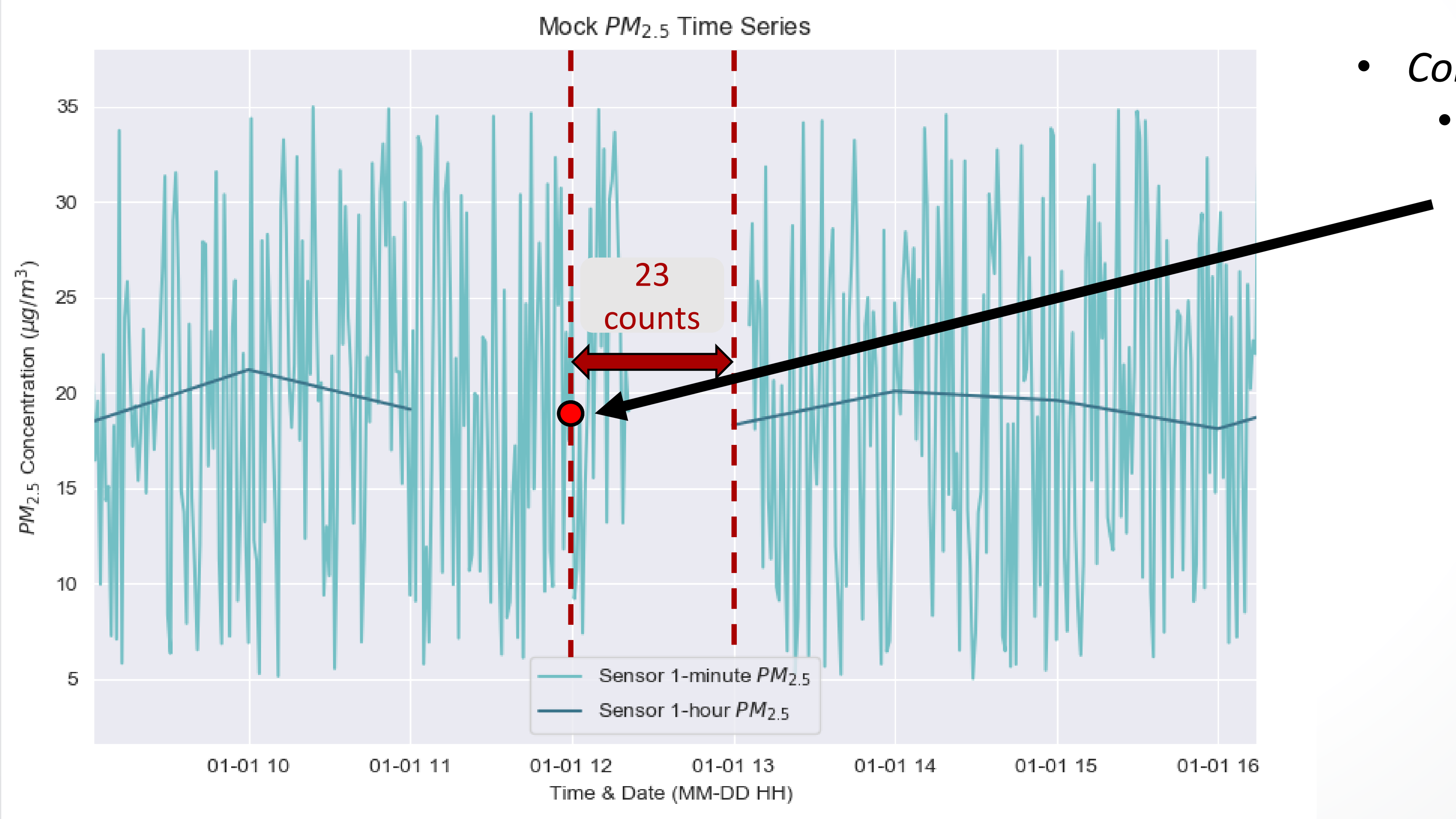
- *Completeness Example*
  - For 1-minute data, 60 data points are generated each hour.
  - 90% completeness requires ≥ 54 data points per hour to compute 1-hour average

Computing 1-Hour Averaged Data



- *Completeness Example*
  - For 1-minute data, this 1-hour average is computed from data collected between 11:00 – 11:59 and is assigned to 11:00 average.

Computing 1-Hour Averaged Data



- *Completeness Example*
  - Hourly periods with an insufficient number of data points are not averaged to 1-hour values

Sensor Performance Methods: Precision

Quantify agreement between sensors of the same type

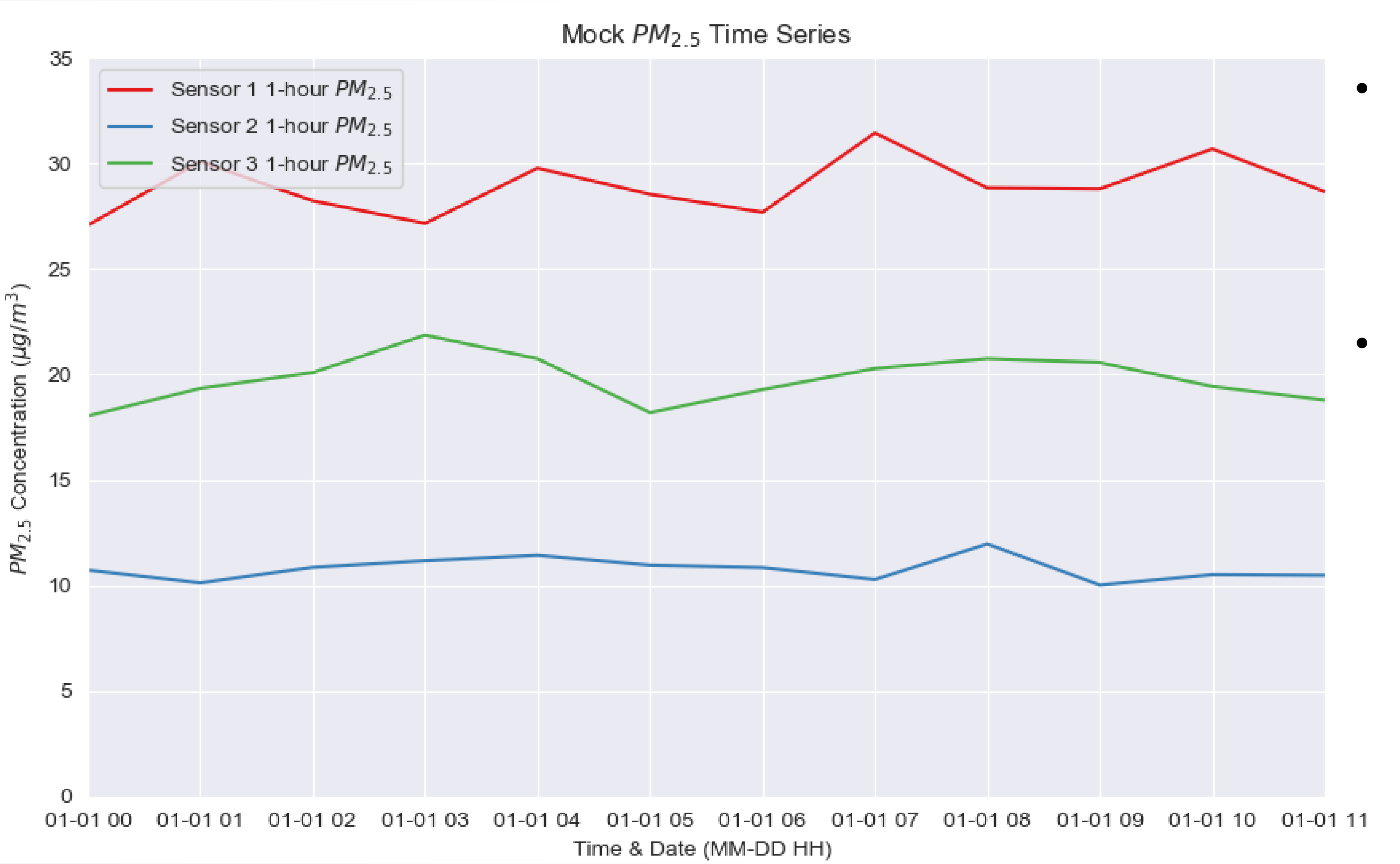
- Standard Deviation ($\sigma_{sensor\ type}$)

  Measure of the total variation in $PM_{2.5}$ measurements calculated for all sensors of the same type

- Coefficient of Variation ($CV_{sensor\ type}$)

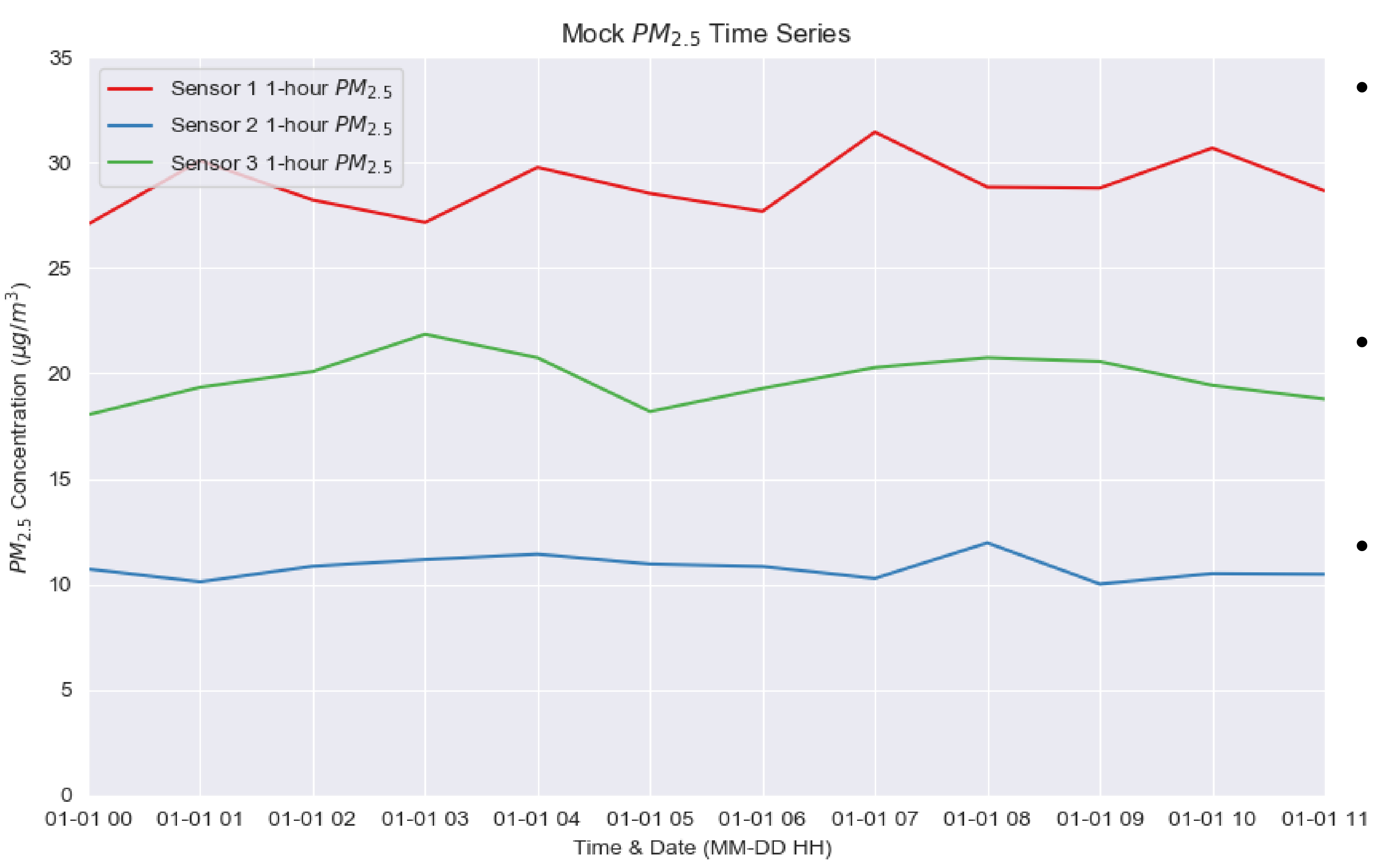
  Defined as ($\sigma_{sensor\ type}$) / (Mean $PM_{2.5}$ concentration for sensor type), measure of sensor measurement variation relative to mean concentration value

Measuring Sensor Precision



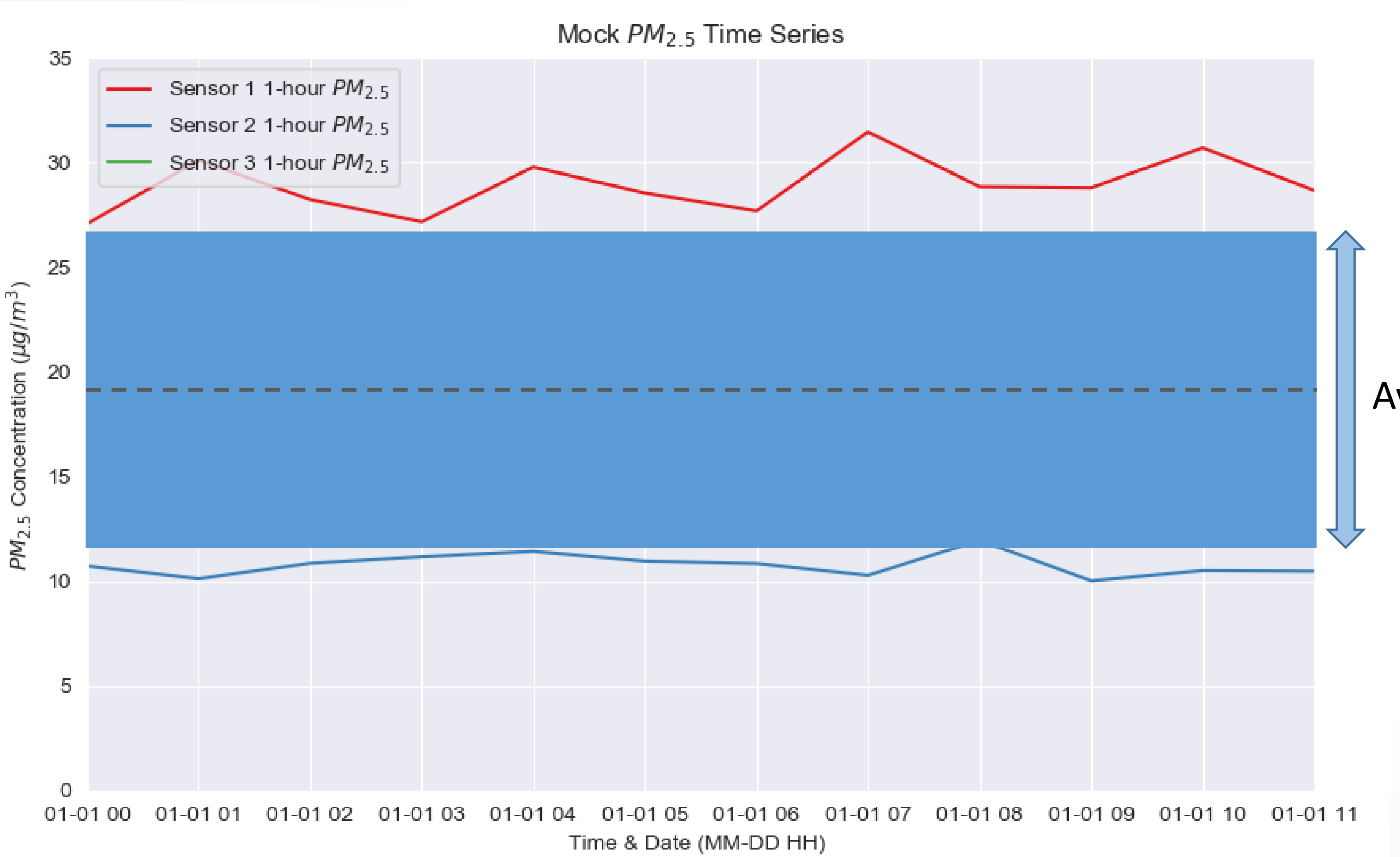
- An individual sensor's standard deviation doesn't inform how sensor measurements compare against other devices of the same type
- We compute the standard deviation of 1-hour measurements *across the entire set* of data for a given sensor type
  - $\sigma_{\textit{sensor type}}$

Measuring Sensor Precision



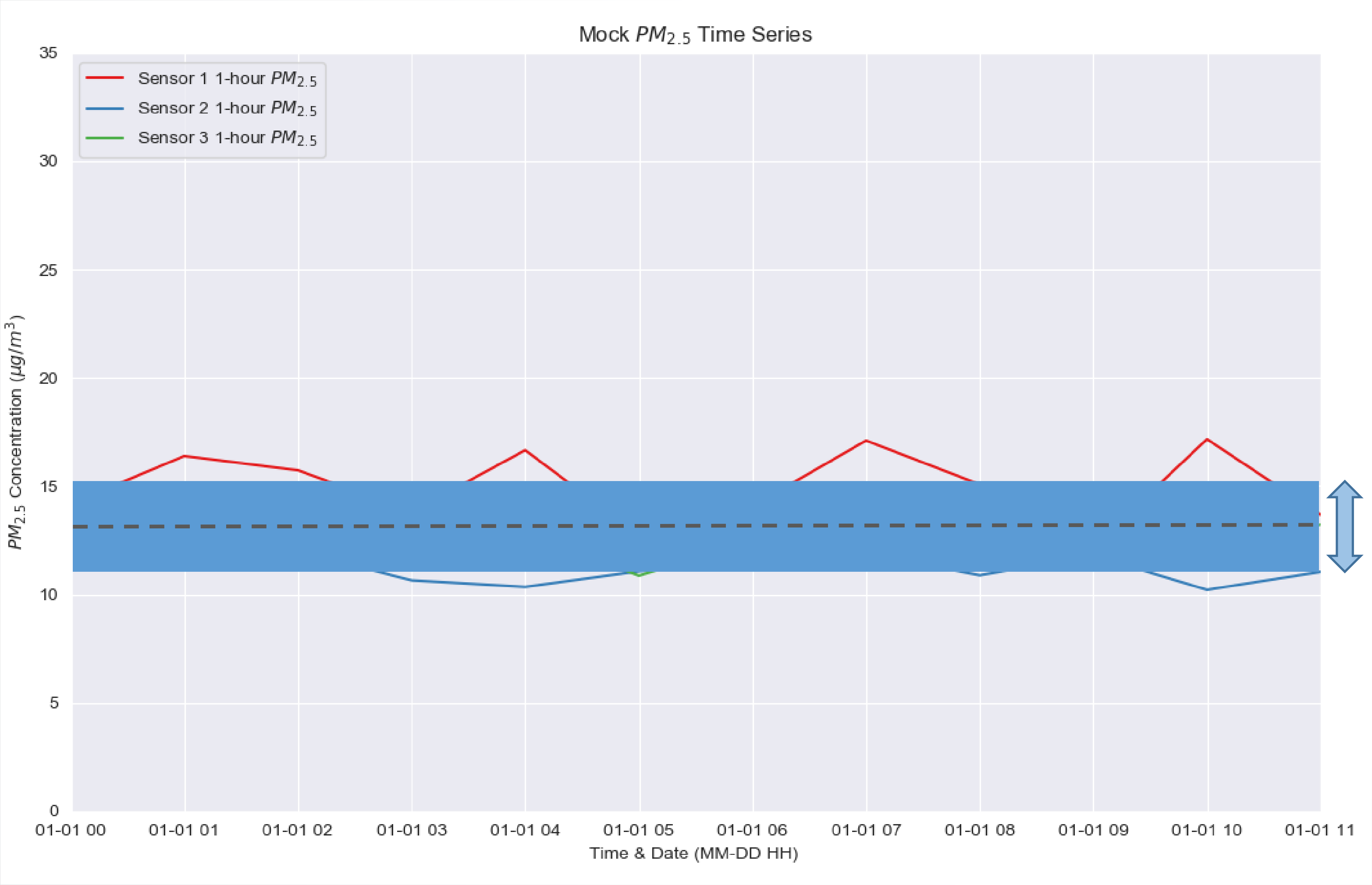
- An individual sensor's standard deviation doesn't inform how sensor measurements compare against other devices of the same type
- We compute the standard deviation of 1-hour measurements *across the entire set* of data for a given sensor type
  - $\sigma_{sensor\ type}$
- Because the measurements made by the individual sensors range in offset bias and sensitivity, $\sigma_{sensor\ type}$ is normalized by the average concentration value for all sensors in a given type.
  - $CV_{sensor\ type} = \dfrac{\sigma_{sensor\ type}}{\text{Mean } PM_{2.5} \text{ concentration}}$

Measuring Sensor Precision: Low Precision



- $\sigma_{sensor\ type}$ = **7.35 μg/m³**
- Average $PM_{2.5}$ = 19.79 μg/m³
- $CV = \frac{7.35\ \mu g/m^3}{19.79\ \mu g/m^3} \times 100 =$ **37.14%**

Measuring Sensor Precision: High Precision

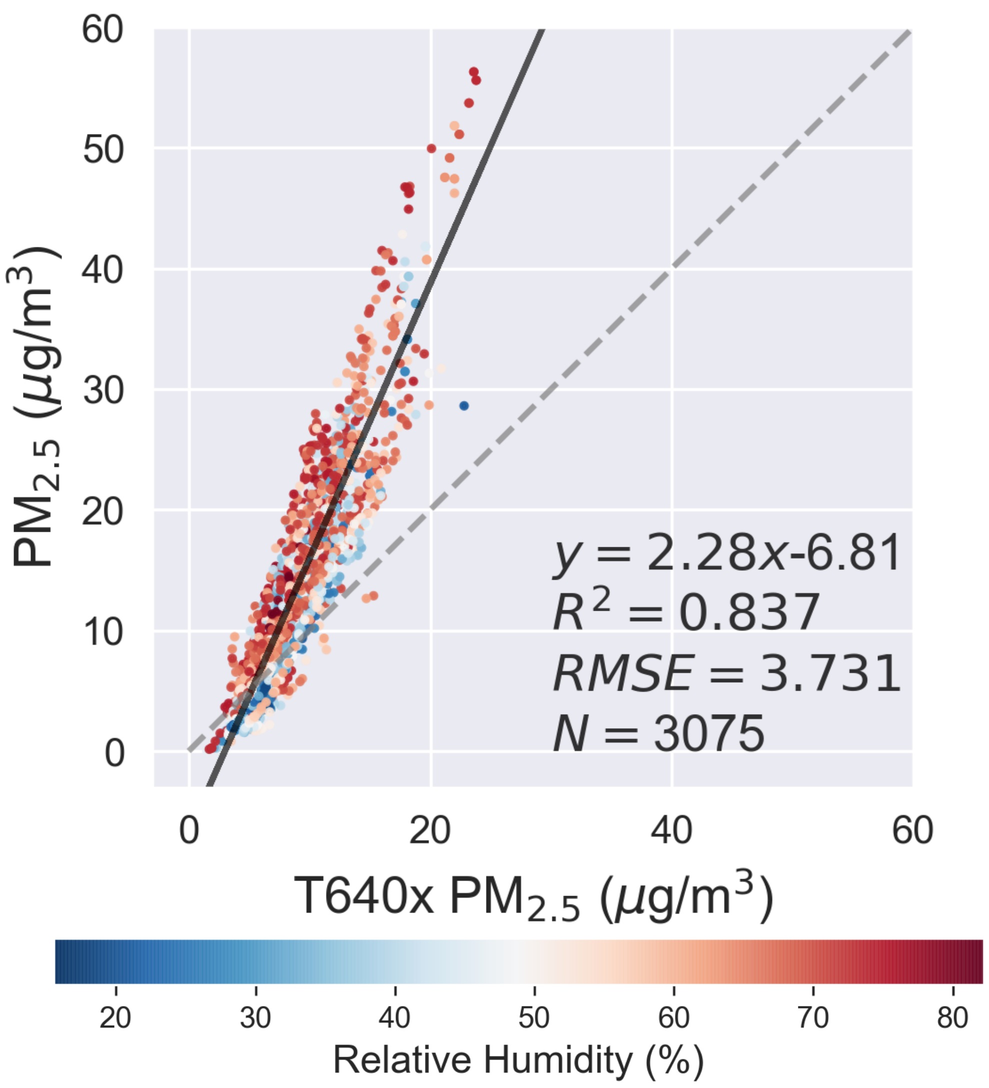


Average $PM_{2.5} \pm \sigma_{sensor\ type}$

- $\sigma_{sensor\ type}$ = **1.95 µg/m³**
- Average $PM_{2.5}$ = 13.04 µg/m³
- $CV = \frac{1.95\ \mu g/m^3}{13.04\ \mu g/m^3} \times 100 =$ **14.97%**

Sensor Performance Methods: Accuracy

Quantify how sensors perform against T640x regulatory monitor and monitor relative humidity influence

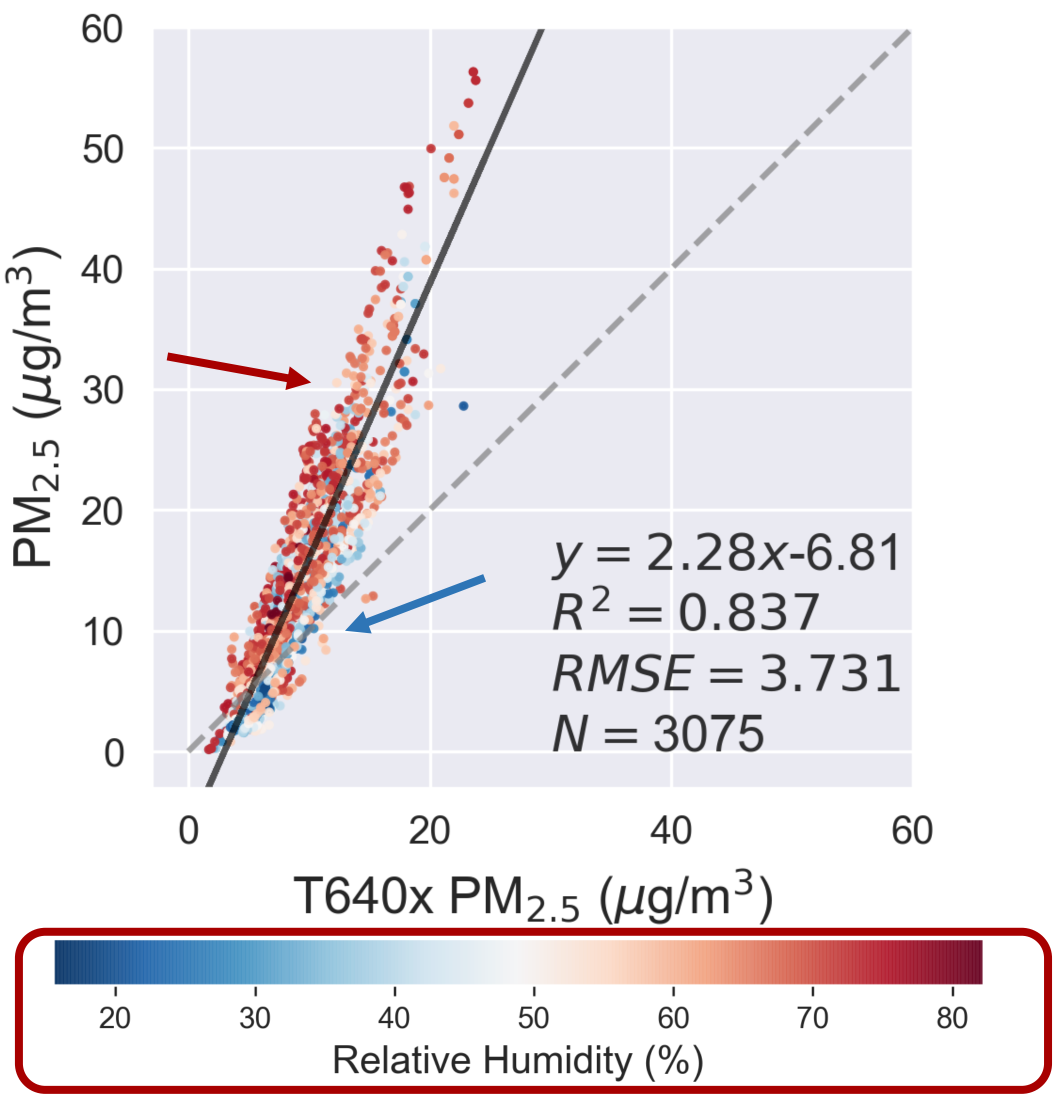


Sensor Performance Methods: Accuracy

Quantify how sensors perform against T640x regulatory monitor and monitor relative humidity influence

- Influence of relative humidity

  1-hour averages are colored based on the average relative humidity experienced that hour. A strong separation of red and blue dots indicate a strong influence of humidity on the sensor measurement.



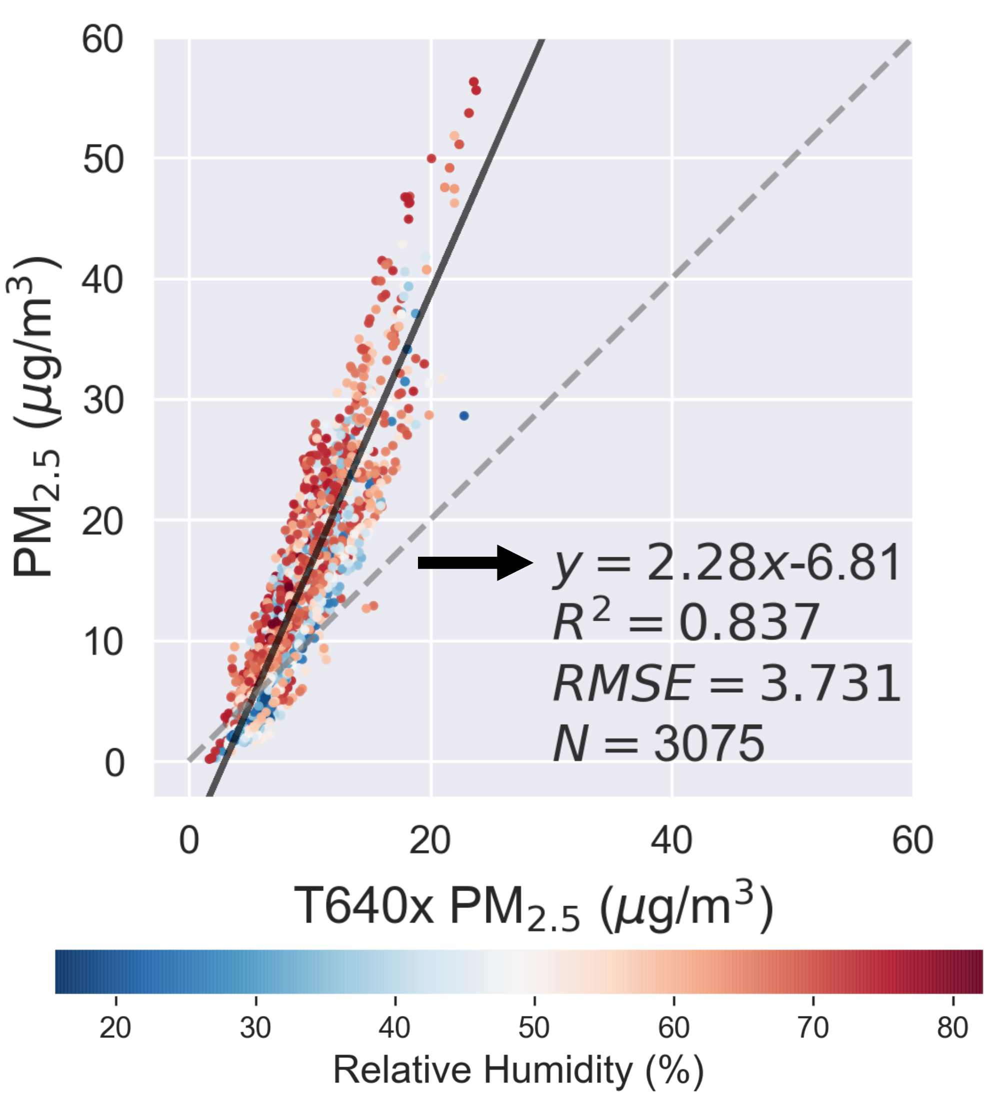
Sensor Performance Methods: Accuracy

Quantify how sensors perform against T640x regulatory monitor and monitor relative humidity influence

- Linear Regression (y = ax+ b)

  Slope tells us whether the sensor is under-reporting or over-reporting the monitor, intercept gives us a measure of the bias relative to the monitor

  Slopes (a) near 1 and intercepts (b) near 0 are desired.



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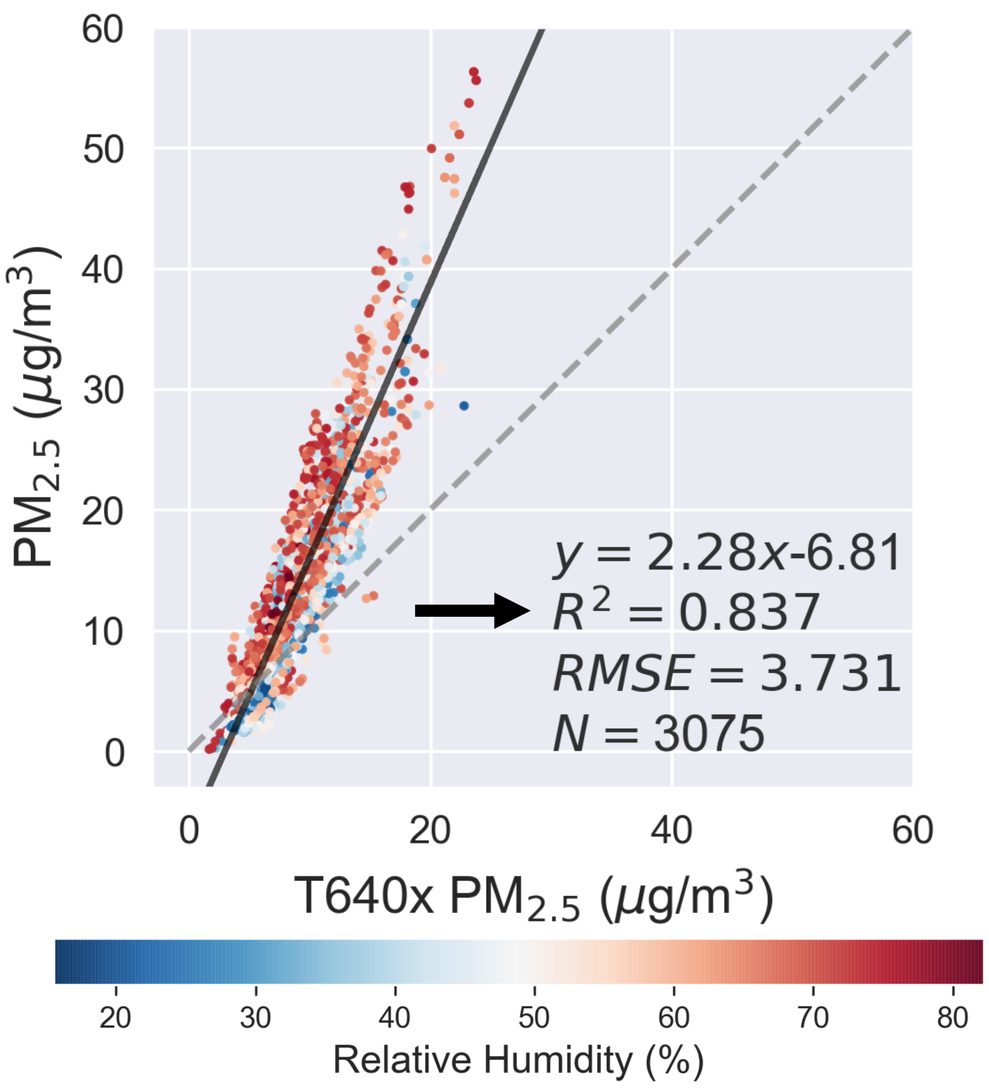
- Coefficient of determination (R^2)

  Measure of linear correlation between sensor PM values and regulatory monitor values

  R^2 values range between 0 and 1. Values near 1 indicate strong linear relationships.



Sensor Performance Methods: Accuracy

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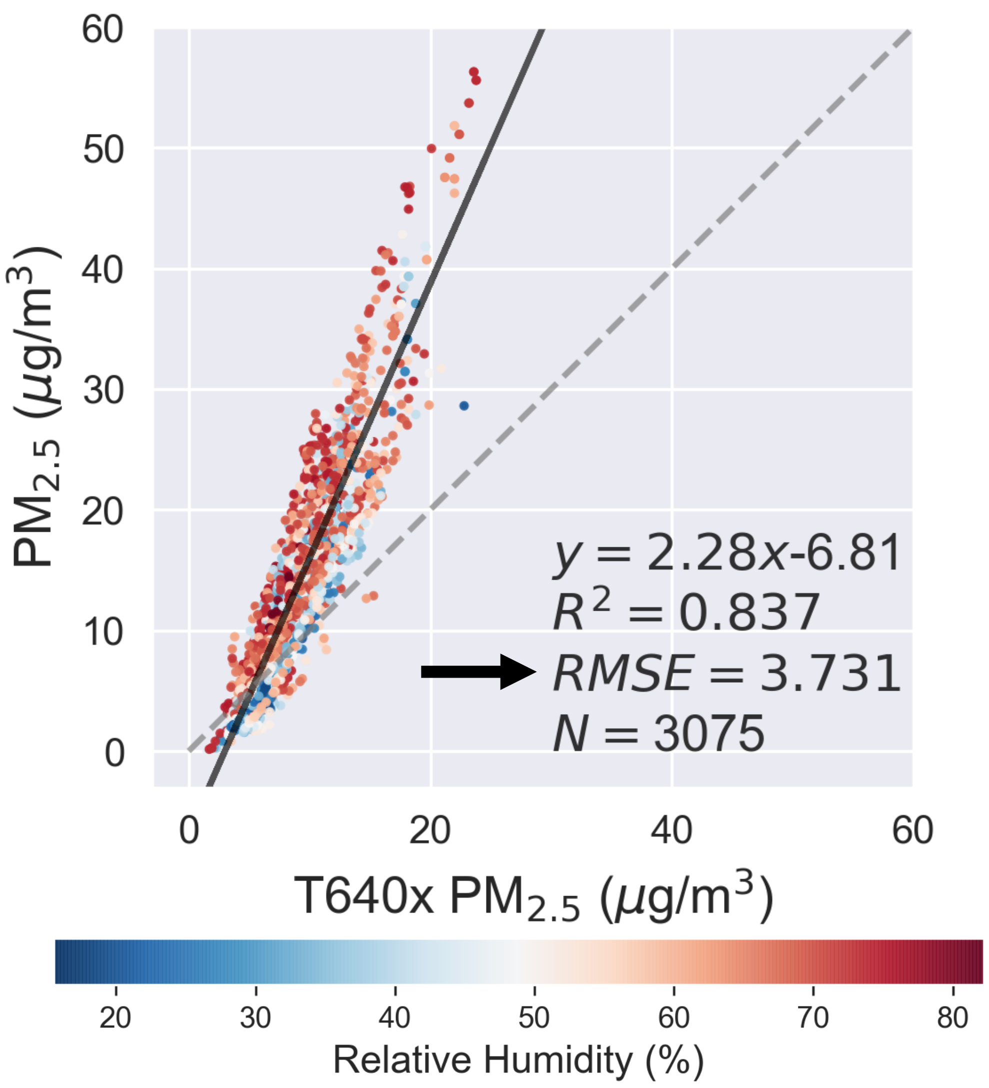
- Coefficient of determination (R^2)

  Measure of linear correlation between sensor PM values and regulatory monitor values
- Root Mean Square Error (RMSE)

  Measure of the spread of sensor PM data, squaring penalizes outliers

  Lower RMSE is desirable.



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- Root Mean Square Error (RMSE)

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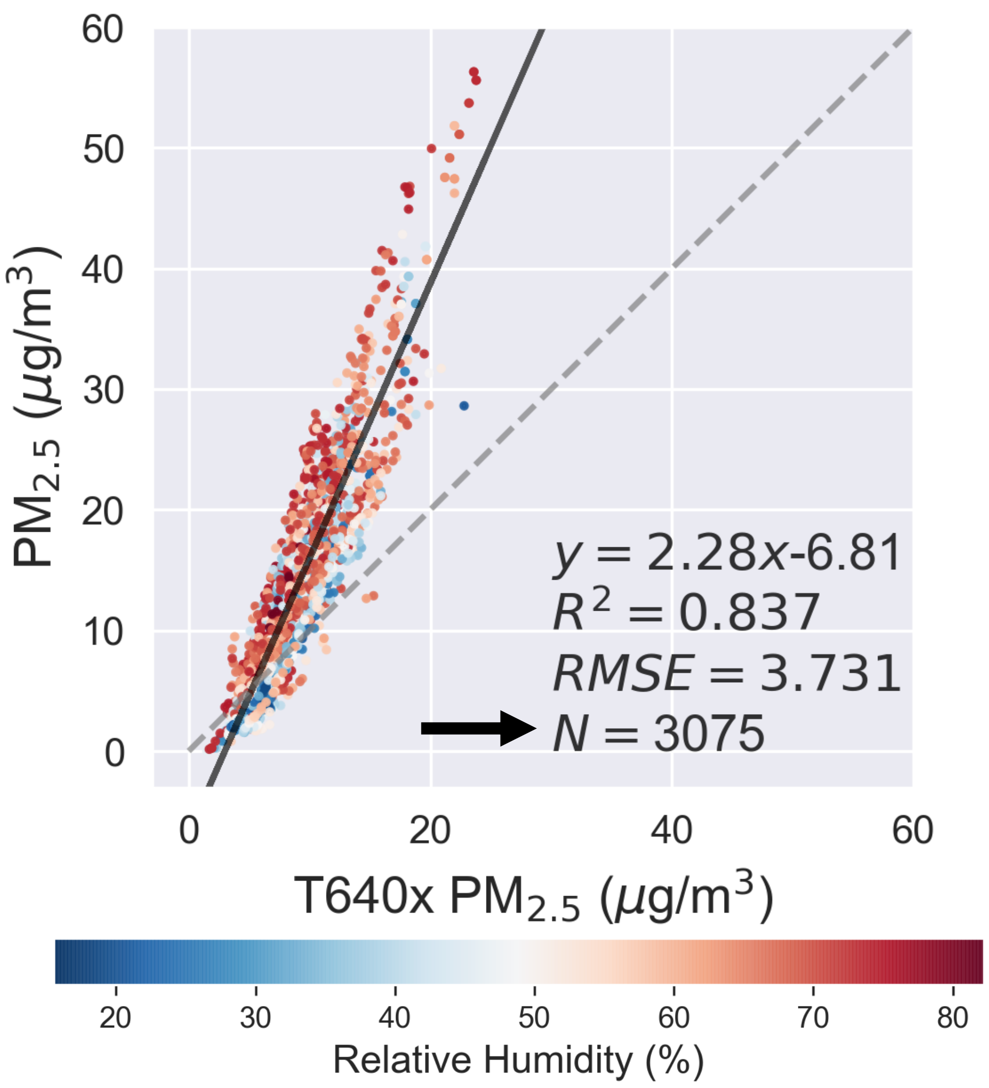
- Total Number of Datapoints (N)

  The number of 1-hour averaged data points that satisfy the 90% completeness criteria for computing 1-hour averages



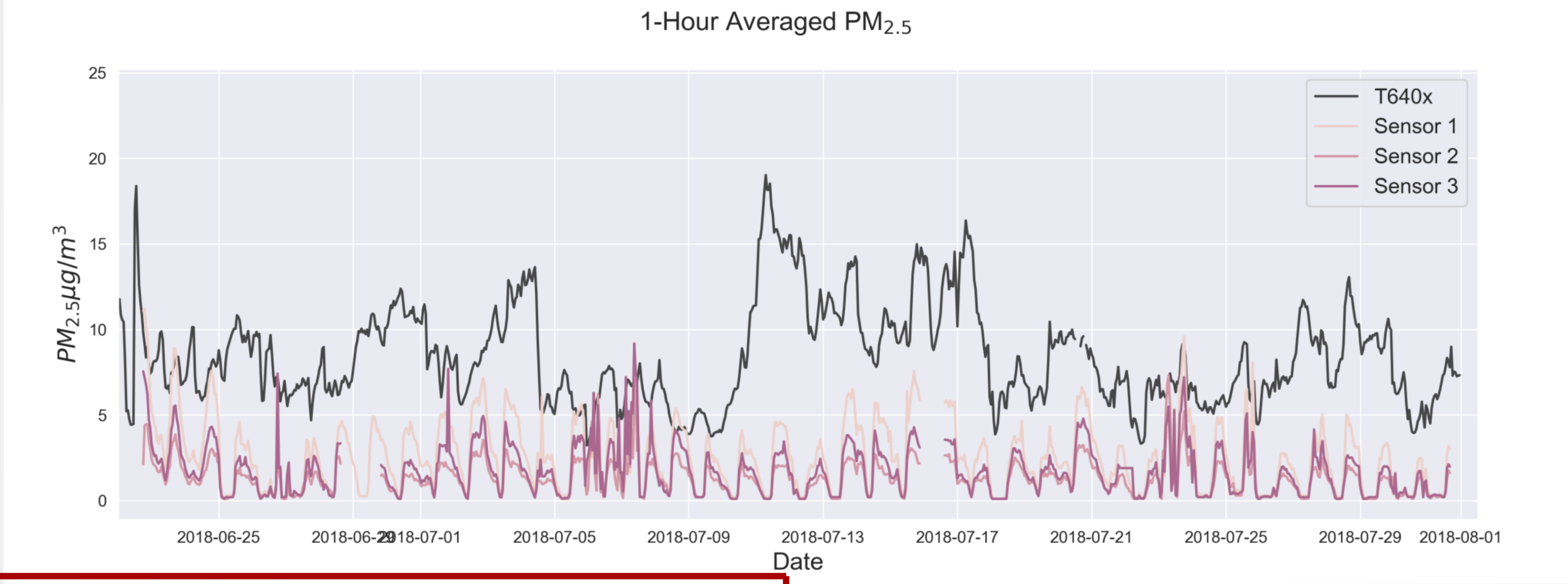
Evaluated Sensors: Vaisala AQT420

Sensor Number	Data Collection Period
1	2018/06/22 – 2018/07/31
2	2018/06/15 – 2018/07/31
3	2018/06/22 – 2018/07/31

- Pollutants Measured:
  $PM_{2.5}$, PM_{10}, O_3, NO_2, SO_2, CO
- Cost:
  ~$5200
- Time Resolution:
  1-minute

AQT420 - Vaisala

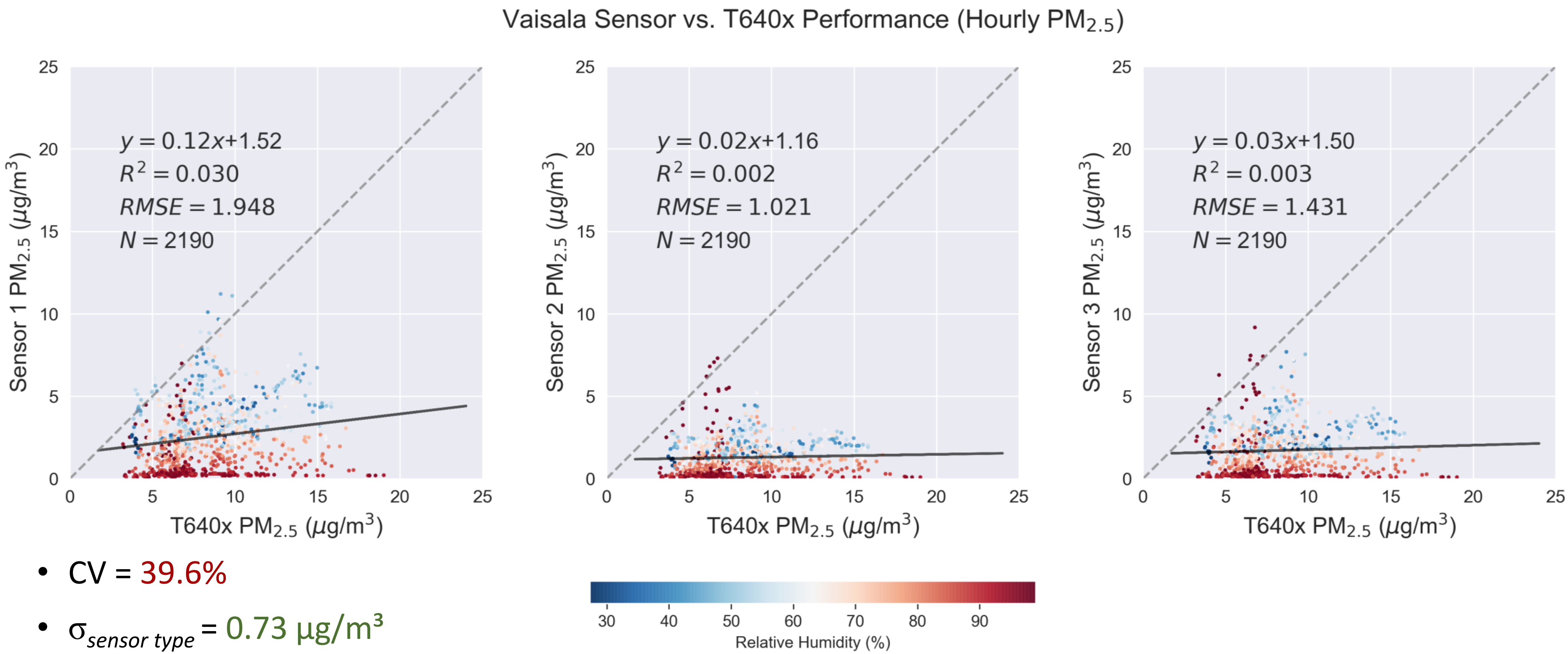
AQT420: Time Series and Uptime



Uptime= (Hours meeting 90% completeness averaging threshold) / (Total number of hours sensor in field)

Sensor	Uptime (%)	Data Points (Hours)
1	98.2%	918
2	80.8%	891
3	95.2%	890

AQT420 : Performance against Regulatory Monitor



- CV = 39.6%
- $\sigma_{sensor\ type}$ = 0.73 µg/m³

Vaisala AQT420: Takeaways

- Precision:
  - CV (39.6%) and $\sigma_{sensor\ type}$ (0.73 µg/m^3) indicate poor agreement between individual AQT420 devices
- Accuracy:
  - Correlation between AQT420 and T640x $PM_{2.5}$ measurements indistinguishable ($R^2 \leq 0.03$)
- The AQT420 under-reports $PM_{2.5}$ concentrations relative to T640x by >90%
- Observations for users:
  - Strong correlation between AQT420 $PM_{2.5}$ values and temperature and relative humidity

Evaluated Sensors: Aeroqual AQY

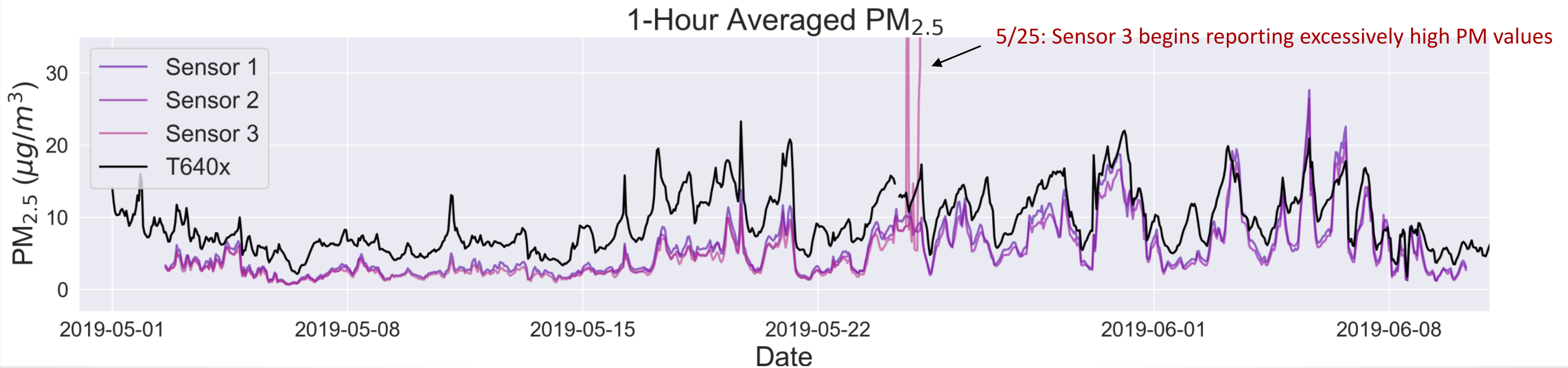
Sensor Number	Data Collection Period
1	2019/05/02 – 2019/06/10
2	2019/05/02 – 2019/06/10
3	2019/05/02 – 2019/05/25

- Pollutants Measured
  $PM_{2.5}$, O_3, NO_2
- Cost
  ~$3000
- Time Resolution:
  1-minute

AQY - Aeroqual

Image source: www.aeroqual.com/product/aqy-micro-air-quality-station

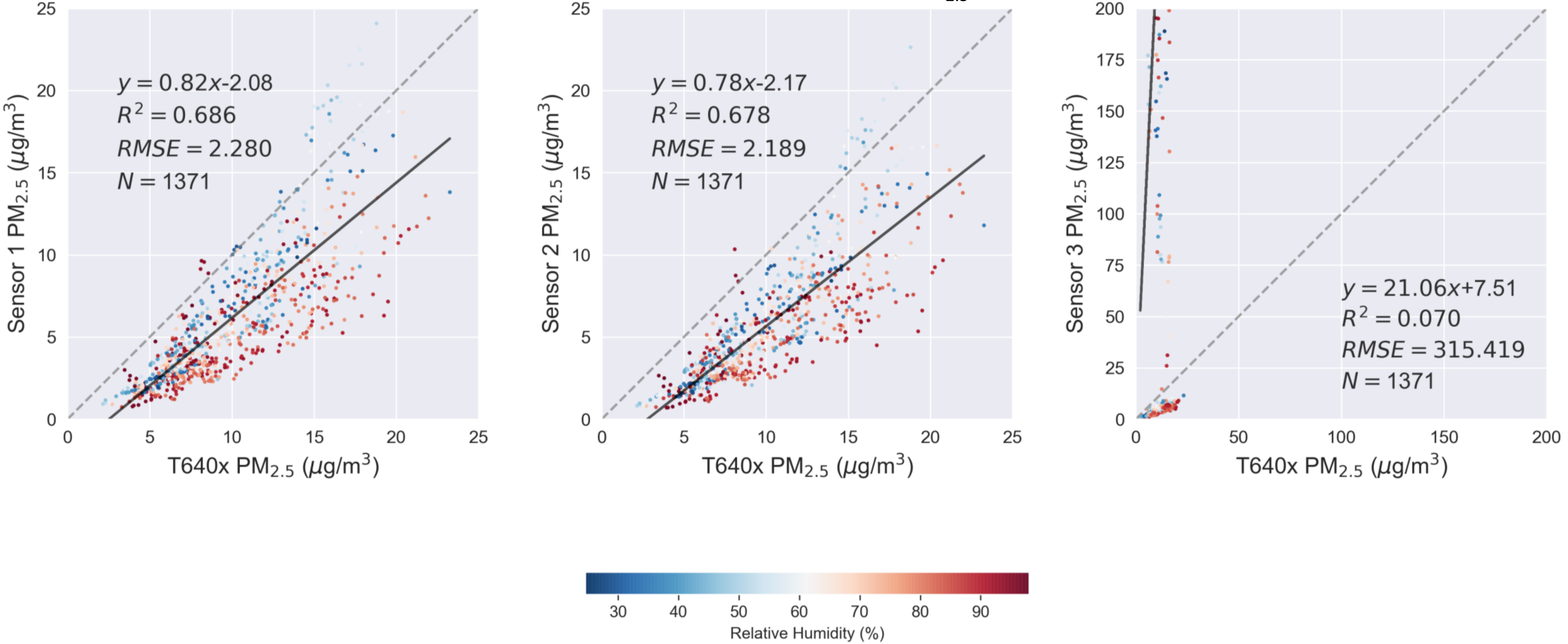
AQY: Time Series and Uptime



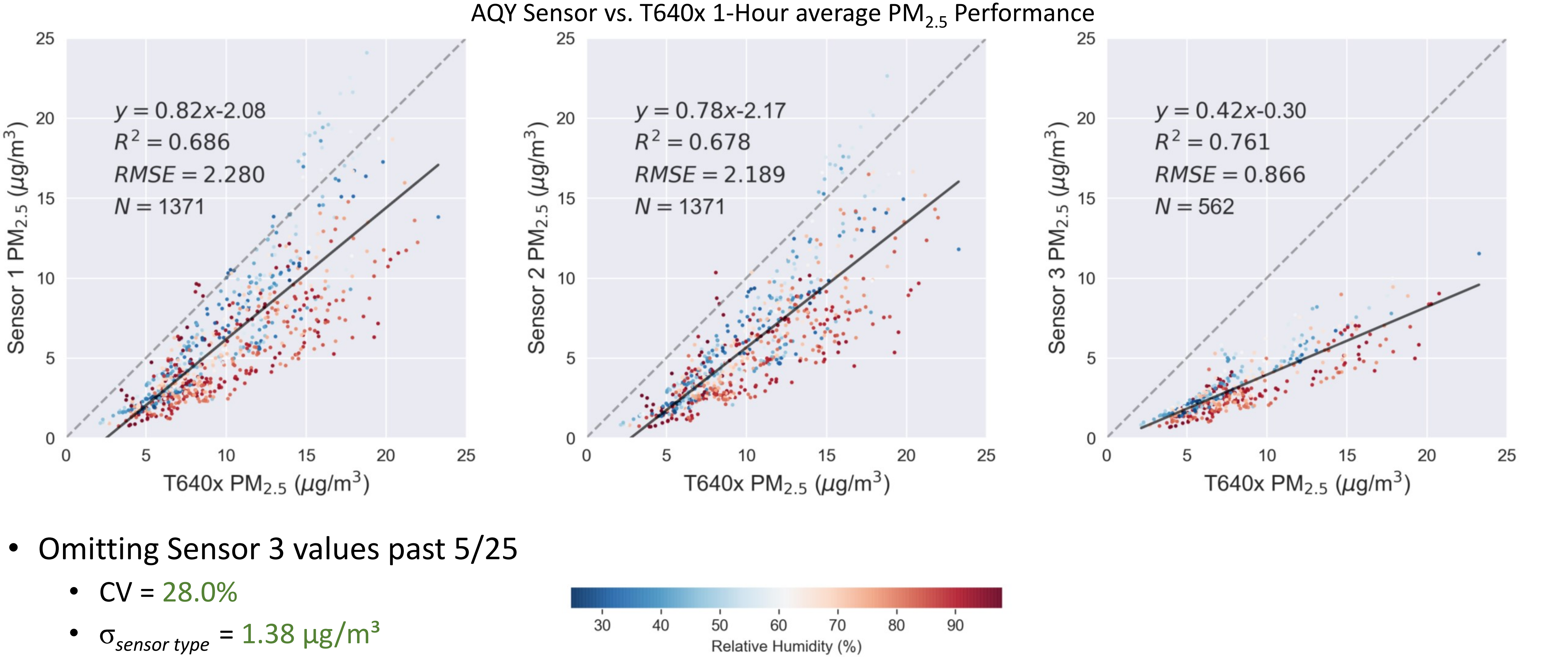
Sensor	Uptime (%)	Data Points (Hours)
1	99.9%	933
2	85.9%	802
3	58.1%	543

AQY: Performance against Regulatory Monitor

AQY Sensor vs. T640x 1-Hour average $PM_{2.5}$ Performance



AQY: Performance against Regulatory Monitor



- Omitting Sensor 3 values past 5/25
  - CV = 28.0%
  - $\sigma_{sensor\ type}$ = 1.38 μg/m³

Aeroqual AQY: Takeaways

- Precision:
  - CV (28.0%) and $\sigma_{sensor\ type}$ (1.38 µg/m³) indicate moderate agreement between individual AQY devices
- Accuracy:
  - Moderate Correlation (R^2~0.68-0.76) between AQY and T640x $PM_{2.5}$ measurements
  - The AQY under-reports $PM_{2.5}$ concentrations relative to T640x by ~(20-60%)
- Observations for users:
  - High RH (> ~70%) causes increased underreporting of AQY
  - Dramatic over-reporting of $PM_{2.5}$ values observed for sensor #3 after 5/25, investigating potential causes

Evaluated Sensors: Clarity Node-S

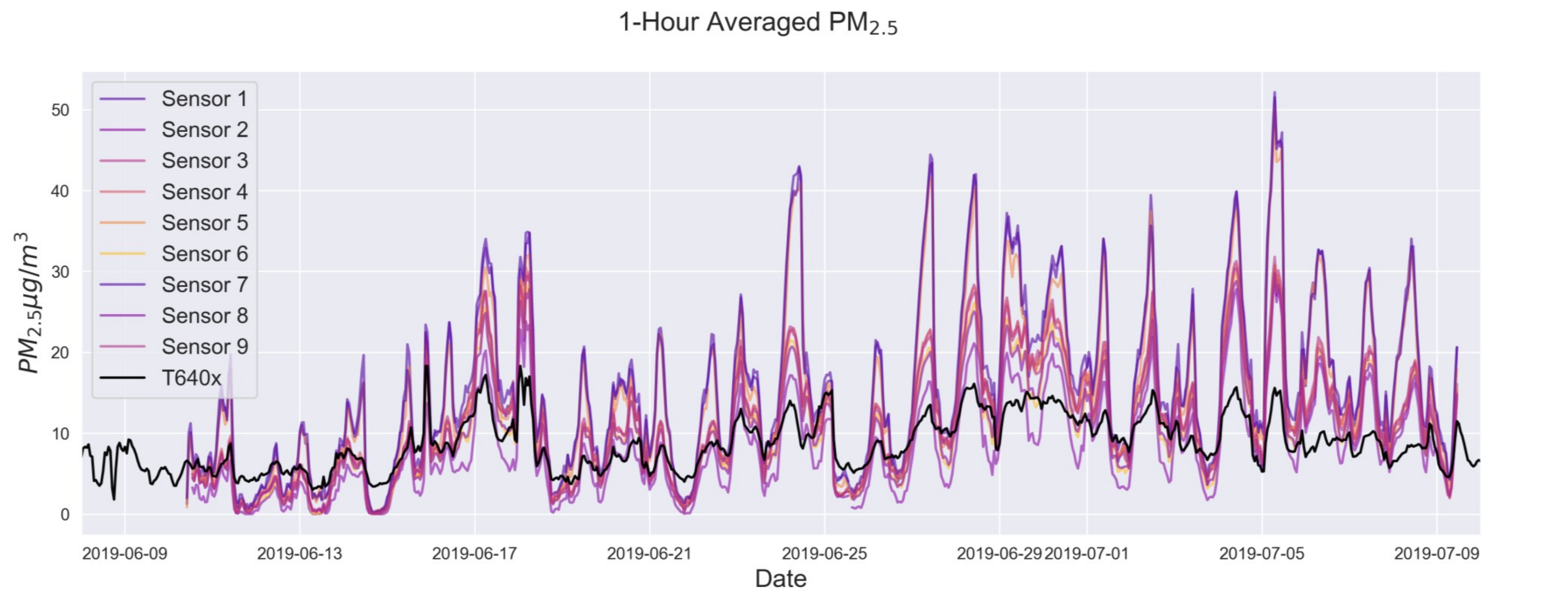
Sensor Number	Data Collection Period
1-9	2019/06/10 – 2019/07/09

- Pollutants Measured:
  PM_1, $PM_{2.5}$, PM_{10}, NO_2
- Cost:
  $1000 annual subscription
- Time Resolution:
  3 minutes

Clarity Node-S –
Clarity Movement Co.

Image source: https://clarity.io/solution

Clarity Node-S: Time Series and Uptime



Sensor	Uptime (%)	Data Points (Hours)
1	99.8%	696
2	99.7%	694
3	99.7%	695

Sensor	Uptime (%)	Data Points (Hours)
4	99.6%	693
5	99.8%	696
6	99.4%	693

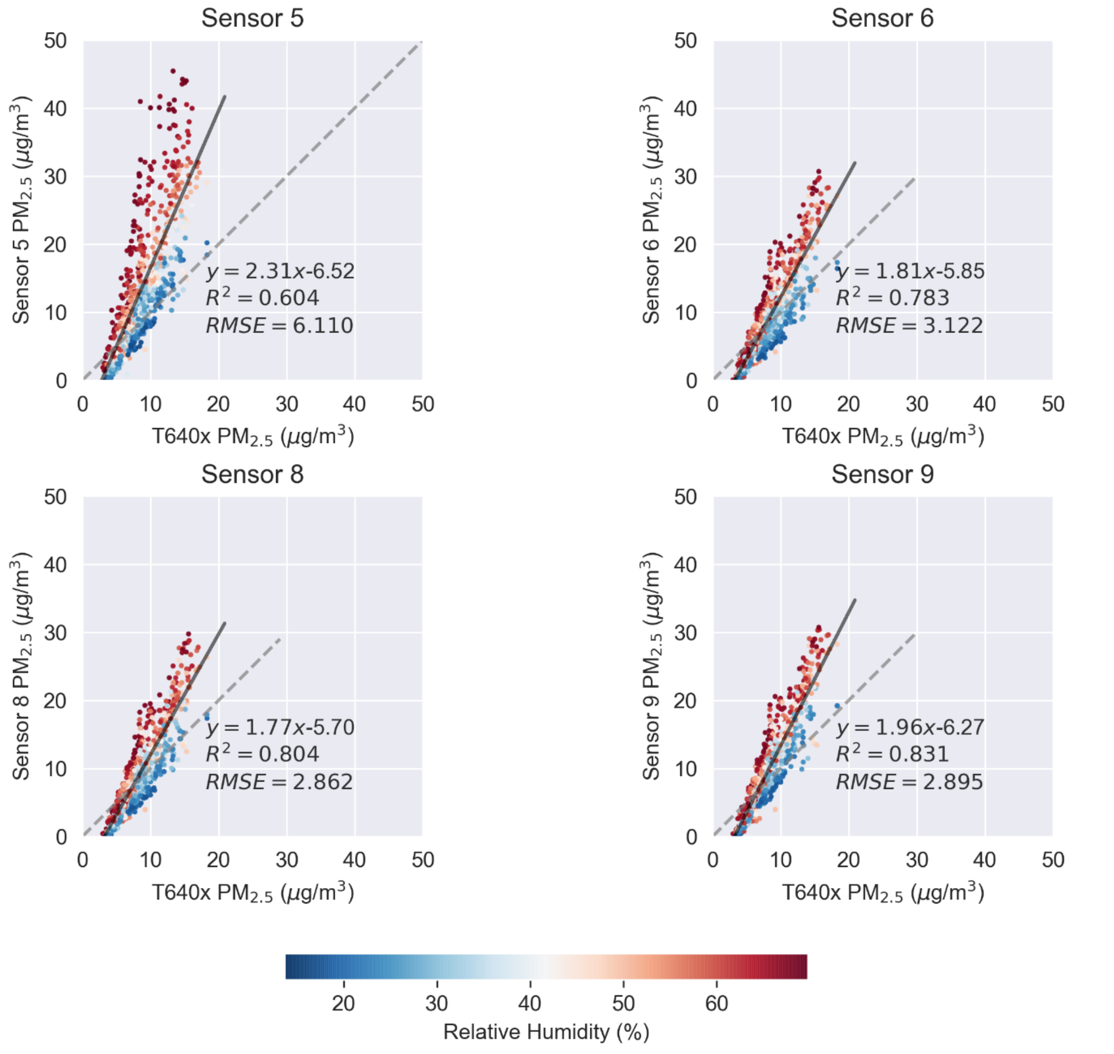
Sensor	Uptime (%)	Data Points (Hours)
7	99.7%	696
8	99.6%	694
9	99.6%	694

Clarity Node-S: Performance against Regulatory Monitor

Sensor Number	R^2 (1-hour $PM_{2.5}$)	RMSE (1-hour $PM_{2.5}$)
1	0.603	6.413
2	0.69	3.31
3	0.838	2.932
4	0.842	2.811
5	0.604	6.11
6	0.783	3.122
7	0.657	5.868
8	0.804	2.862
9	0.831	2.895

- Coefficient of Variation =26.5%
- Standard Deviation = 3.15 µg/m³

Selection of Clarity Node-S Sensor vs. T640x 1-Hour $PM_{2.5}$



Clarity Node-S: Takeaways

- Precision:
  - CV (26.5%) and $\sigma_{sensor\ type}$ (3.15 µg/m³) indicate moderate agreement between individual Node-S devices
- Accuracy:
  - Varying Correlation (R^2 ~0.60-0.84) between Node-S and T640x $PM_{2.5}$ measurements, some devices indicated moderate correlation ($R^2 \gtrsim 0.70$)
  - The Node-S generally over-reports $PM_{2.5}$ concentrations relative to T640x but is highly variable (~80 – 150%)
- Observations for users:
  - Distinct relative humidity bias, increasing RH causes increased overreporting by Node-S

Evaluated Sensors: SENSIT RAMP

Sensor Number	Data Collection Period
1-6	2019/02/14 – 2019/04/10
7-9	2019/04/10 – 2019/05/30

- Pollutants Measured:

  PM_1, $PM_{2.5}$, PM_{10}, O_3, NO_2, SO_2, CO, CO_2

- Cost:

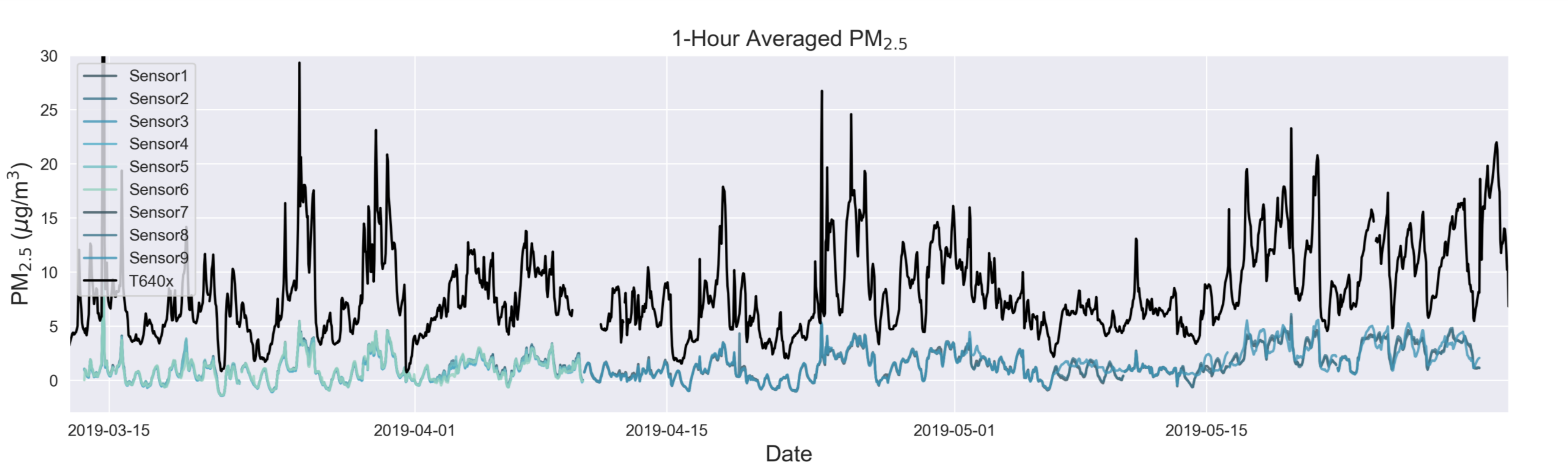
  ~$3000

- Time Resolution:

  15 seconds

Ramp – SENSIT
Above, sensors 1-6 deployed at AIRS

RAMP: Time Series and Uptime



Sensor	Uptime (%)	Data Points (Hours)
1	98.8%	660
2	98.8%	660
3	98.8%	660

Sensor	Uptime (%)	Data Points (Hours)
4	98.8%	660
5	98.8%	660
6	98.8%	659

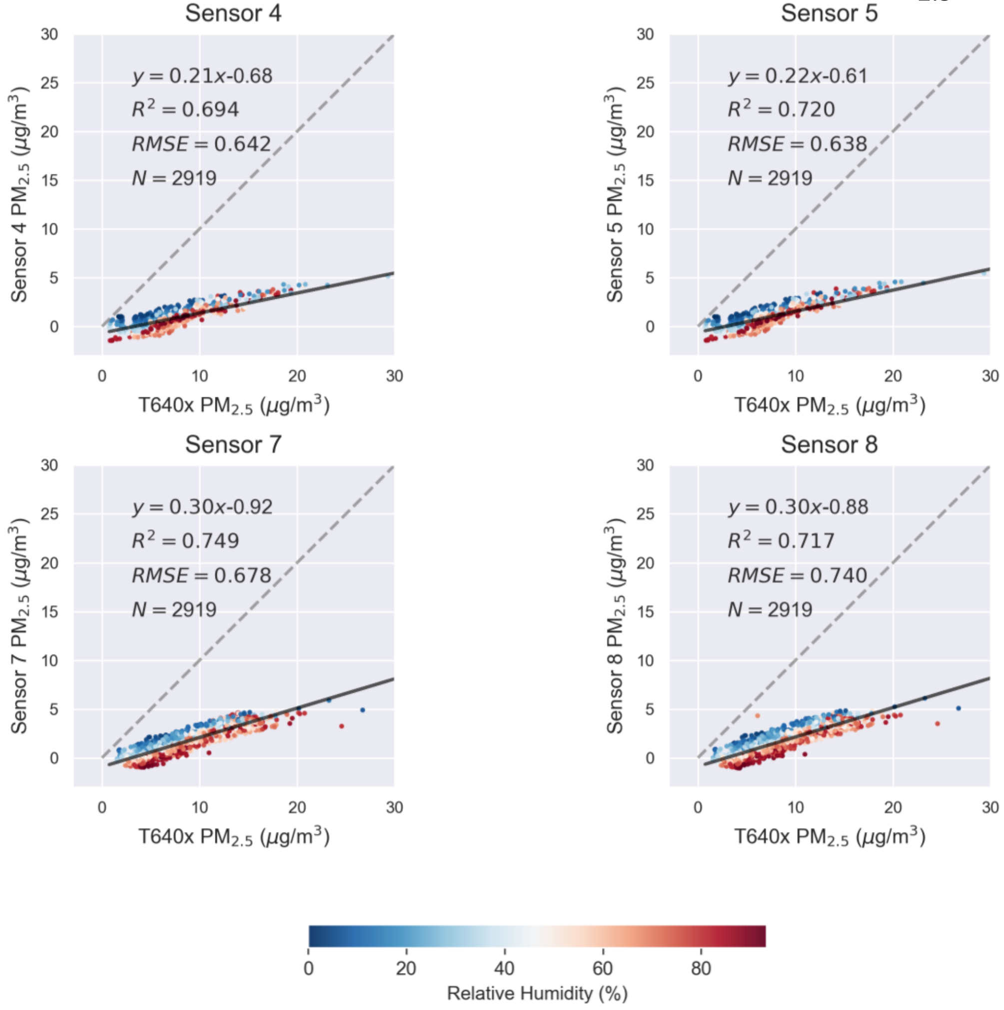
Sensor	Uptime (%)	Data Points (Hours)
7	99.2%	1188
8	99.2%	1183
9	99.2%	1188

RAMP: Performance against Regulatory Monitor

Sensor Number	R_2 (1-hour $PM_{2.5}$)	RMSE (1-hour $PM_{2.5}$)
1	0.729	0.633
2	0.722	0.646
3	0.703	0.642
4	0.694	0.642
5	0.720	0.638
6	0.665	0.695
7	0.749	0.678
8	0.717	0.740
9	0.771	0.657

- Sensor Precision: Devices 1-6
  - Coefficient of Variation = 12.06%
  - Standard Deviation = 0.12 µg/m³
- Sensor Precision: Devices 7-9
  - Coefficient of Variation =15.3%
  - Standard Deviation = 0.25 µg/m³

Selection of RAMP Sensor vs. T640x 1-Hour $PM_{2.5}$



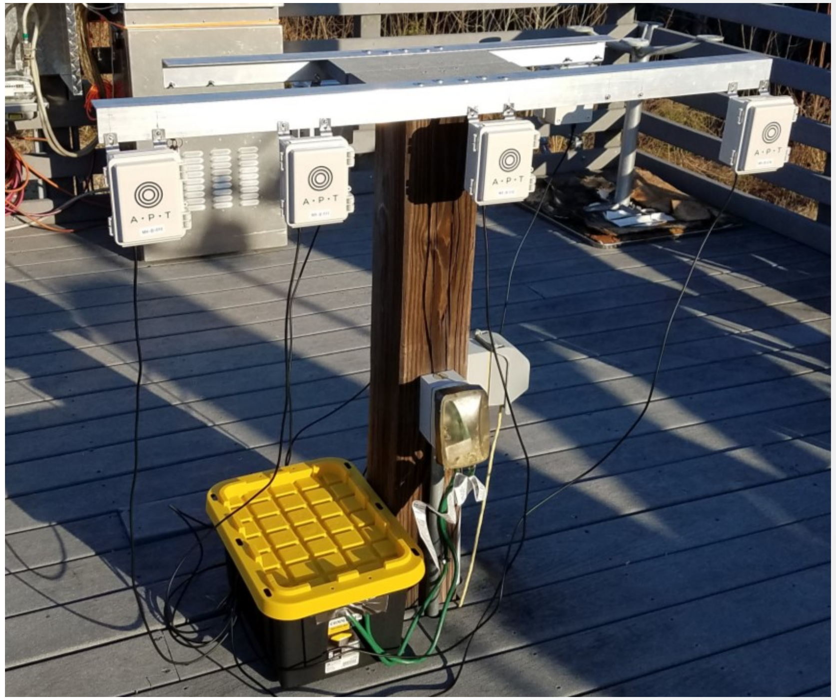
SENSIT RAMP: Takeaways

- Precision:
  - CV (12.06%, 15.3%) and $\sigma_{sensor\ type}$ (0.12, 0.25 µg/m³) indicate good agreement between individual Ramp devices
- Accuracy:
  - Moderate Correlation (R^2 ~0.66-0.77) between RAMP and T640x $PM_{2.5}$ measurements
  - The RAMP under-reports $PM_{2.5}$ concentrations relative to T640x by ~70-80%
- Observations for users:
  - Distinct relative humidity bias, increasing RH causes increased underreporting by RAMP

Evaluated Sensors: APT Maxima

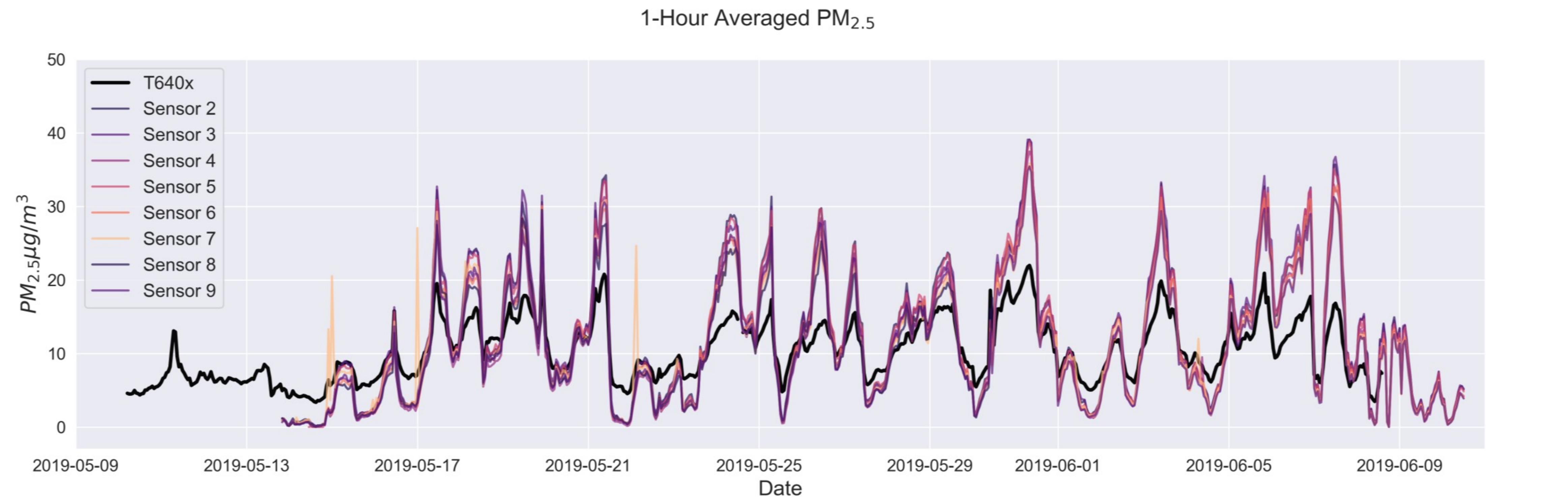
Sensor Number	Data Collection Period
2-7, 9	2019/05/13 – 2019/06/10
8	2019/05/13 – 2019/05/30

- Pollutants Measured
  PM_1, $PM_{2.5}$, PM_{10}
- Cost
  ~$350
- Time Resolution
  30 seconds



Maxima – Applied Particle Technology
Above, Maxima devices 4-7 deployed at AIRS

Maxima: Time Series and Uptime



Sensor	Uptime (%)	Data Points (Hours)
2	88.8%	665
3	88.8%	665
4	88.8%	665

Sensor	Uptime (%)	Data Points (Hours)
5	86.9%	651
6	88.8%	665
7	88.8%	665

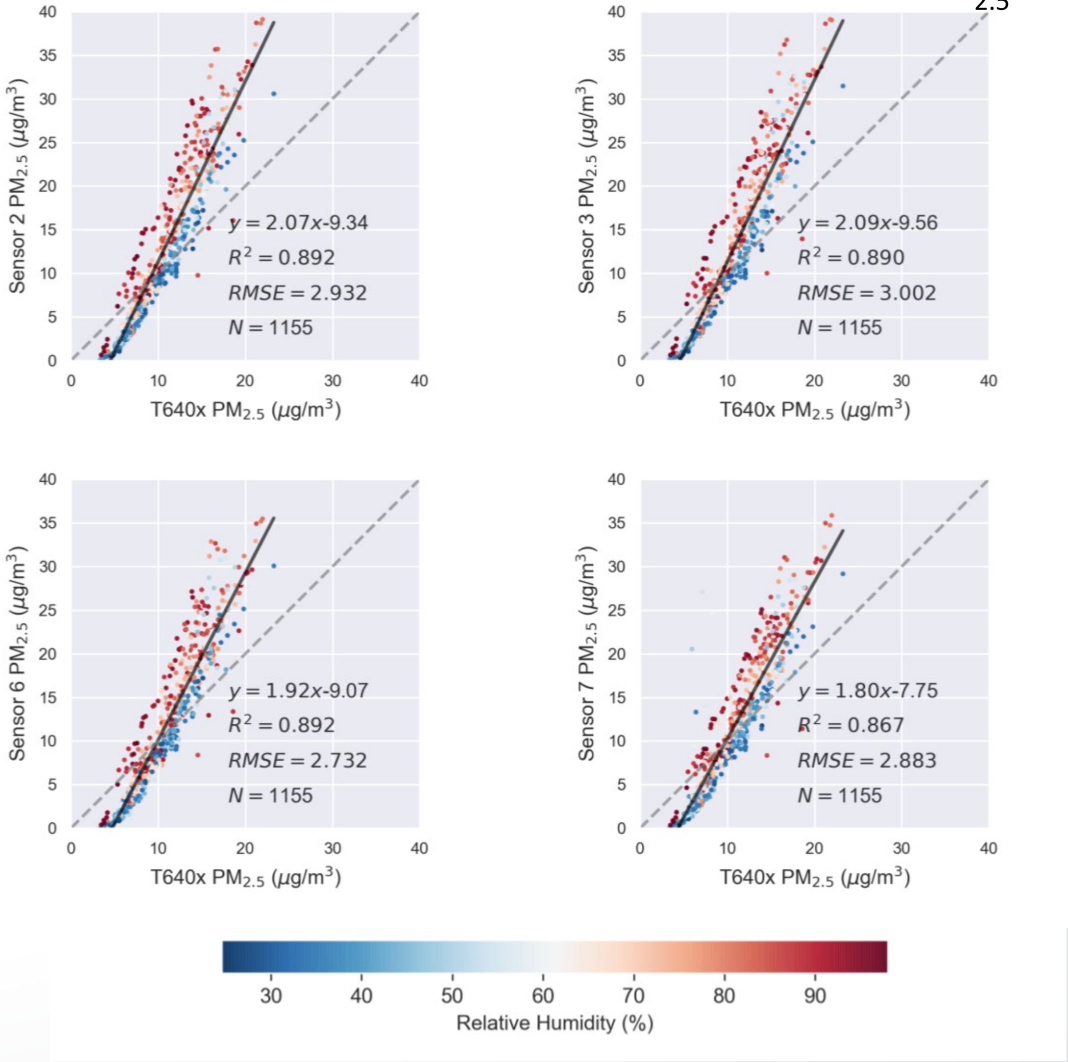
Sensor	Uptime (%)	Data Points (Hours)
7	88.8%	665
8	84.6%	400
9	88.8%	665

Maxima: Performance against Regulatory Monitor

Sensor Number	R^2 (1-hour $PM_{2.5}$)	RMSE (1-hour $PM_{2.5}$)
2	0.892	2.932
3	0.890	3.002
4	0.886	2.835
5	0.888	2.933
6	0.892	2.732
7	0.867	2.883
8	0.913	2.112
9	0.894	2.645

- Coefficient of Variation = 9.22%
- Standard Deviation = 1.07 µg/m³

Selection of Maxima Sensor vs. T640x 1-Hour $PM_{2.5}$



APT Maxima: Takeaways

- Precision:
  - CV (9.22%) and $\sigma_{sensor\ type}$ (1.07 µg/m³) indicate good agreement between individual Maxima devices
- Accuracy:
  - Good Correlation (R^2 ~0.89) between Maxima and T640x $PM_{2.5}$ measurements
  - The Maxima has a large-magnitude intercept leading to an underestimation of $PM_{2.5}$ below ~10 µg/m³ and a large slope leading to over-reporting of $PM_{2.5}$ concentrations relative to T640x by ~90-110% above 10 µg/m³
- Observations for users:
  - Distinct relative humidity bias, increasing RH causes increased overreporting by Maxima

Evaluated Sensors: PurpleAir PA-II-SD

Sensor Number	Data Collection Period
1	2019/08/01 – 2019/11/19
2	2019/08/01 – 2019/11/19
3	2019/08/01 – 2019/11/19

- Pollutants Measured

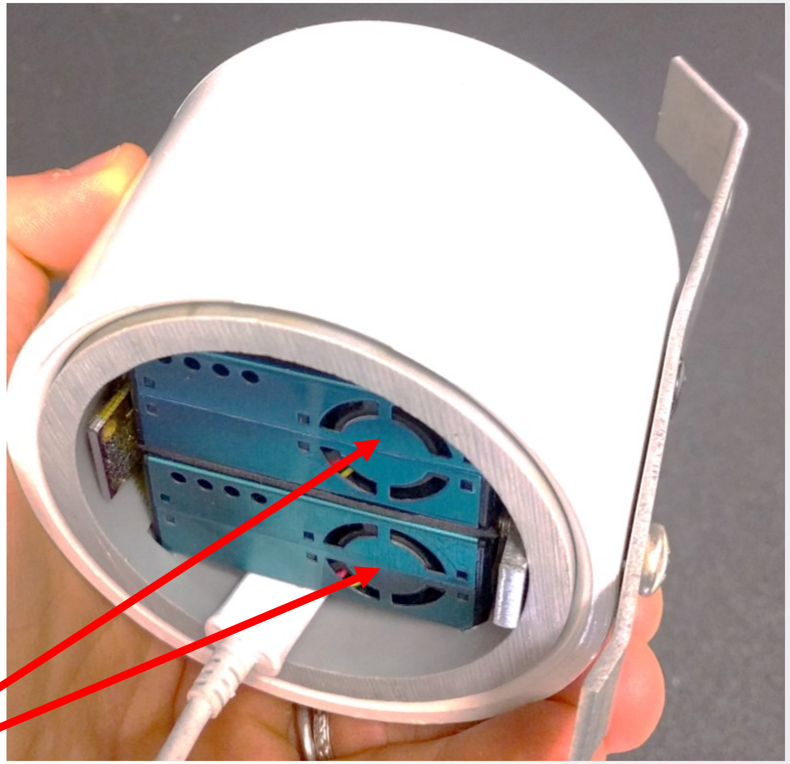
  $PM_{2.5}$, PM_{10}

- Cost

  ~$250

- Time Resolution

  2 minutes

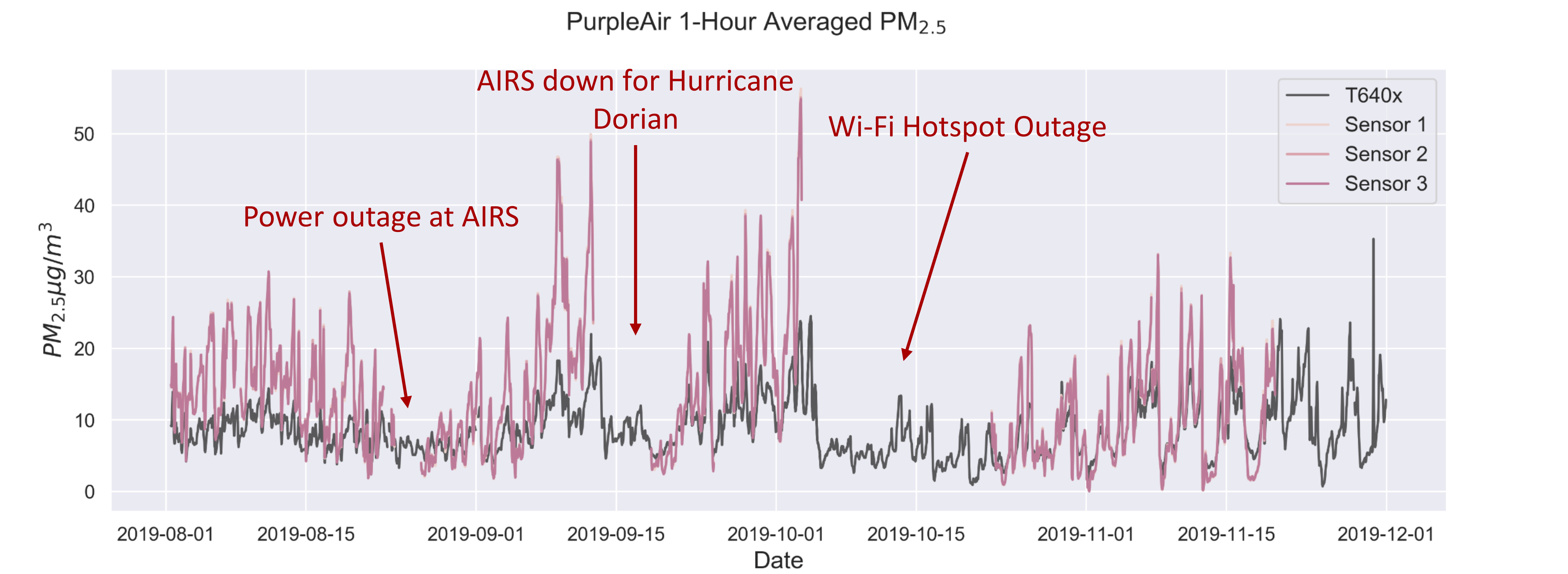


Sensor channels A & B

PA-II SD - PurpleAir

Image source: www.purpleair.com/

PurpleAir: Time Series and Uptime



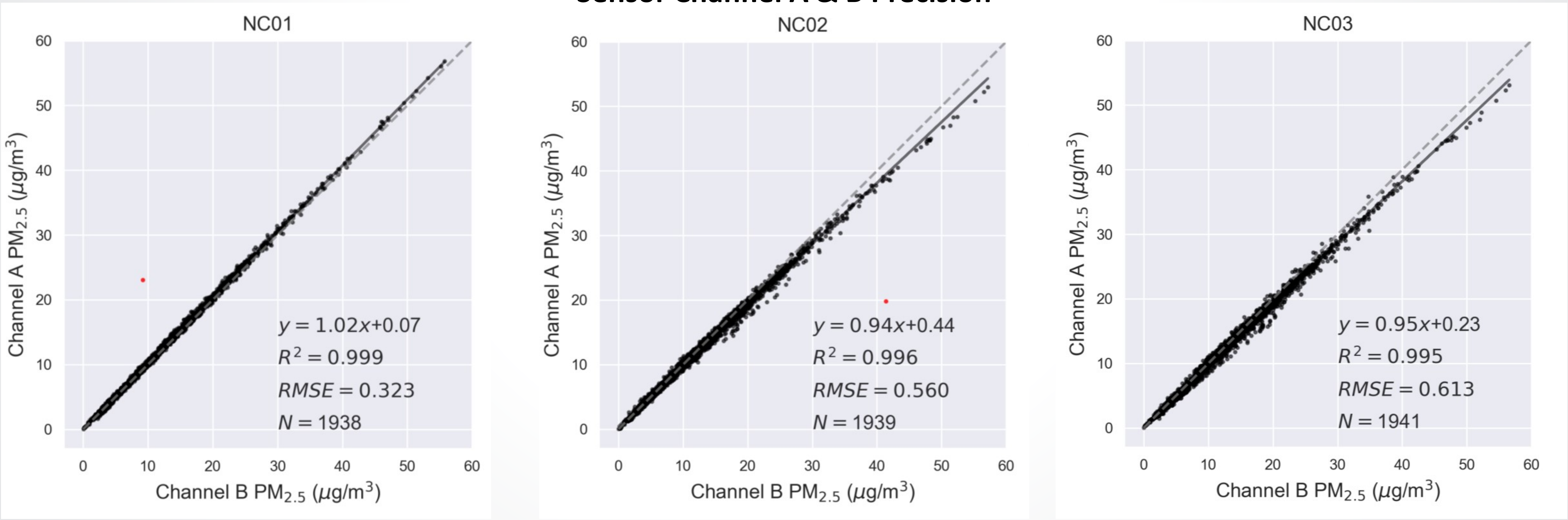
Uptime is artificially low based on site management decisions.

Sensor	Uptime (%)	Data Points (Hours)
1	73.16%	1938
2	73.17%	1939
3	73.22%	1941

PurpleAir: Sensor-Channel Precision

- **We determine the precision between sensor channels A and B to verify whether it is justified to average $PM_{2.5}$ concentration values computed at two-minute intervals for both channels**
- Ideal agreement between channels A and B would result in a linear one-to-one correlation. Plotting $PM_{2.5}$ concentrations for channel A vs. channel B, we find good agreement between sensor channels.

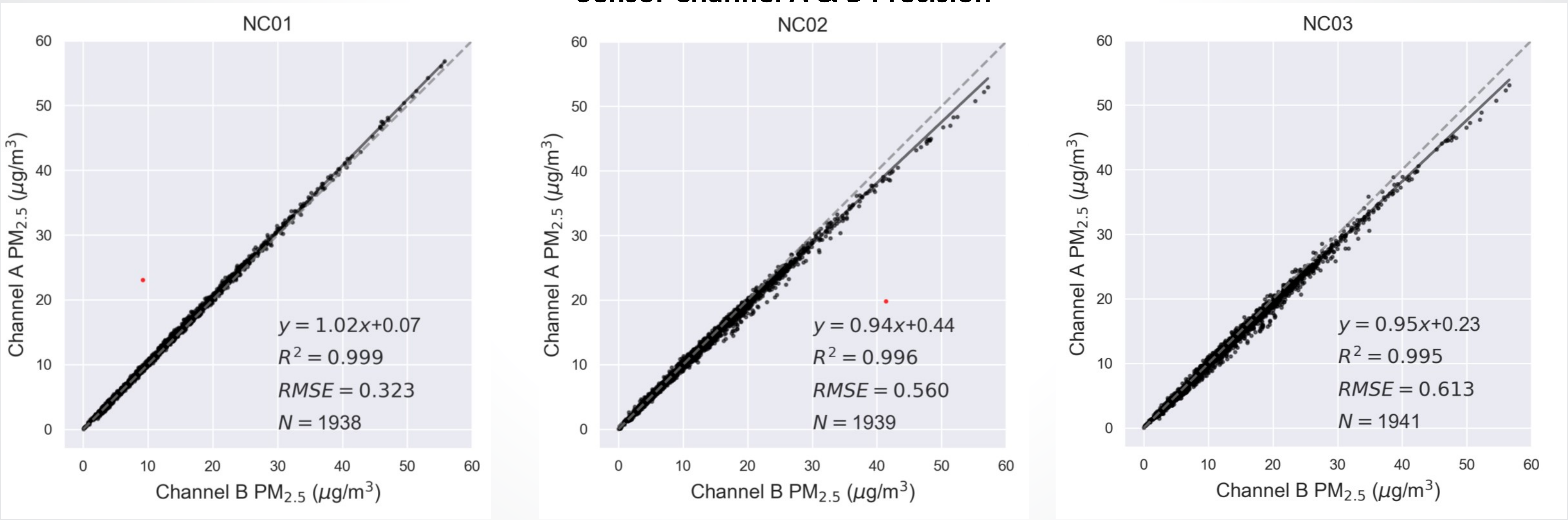
Sensor Channel A & B Precision



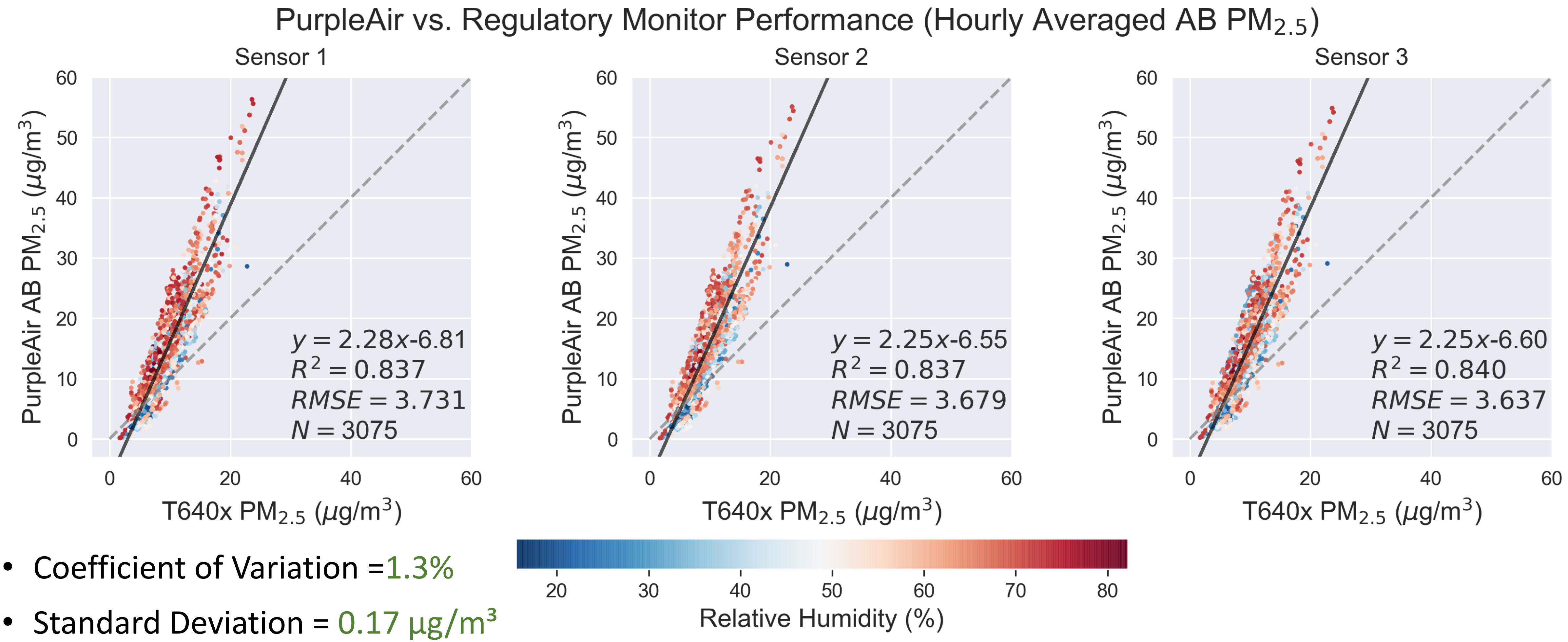
PurpleAir: Sensor-Channel Precision

- We determine the precision between sensor channels A and B to verify whether it is justified to average $PM_{2.5}$ concentration values computed at two-minute intervals for both channels
- **Ideal agreement between channels A and B would result in a linear one-to-one correlation. Plotting $PM_{2.5}$ concentrations for channel A vs. channel B, we find good agreement between sensor channels.**

Sensor Channel A & B Precision



PurpleAir : A & B Averaged Performance against Regulatory Monitor

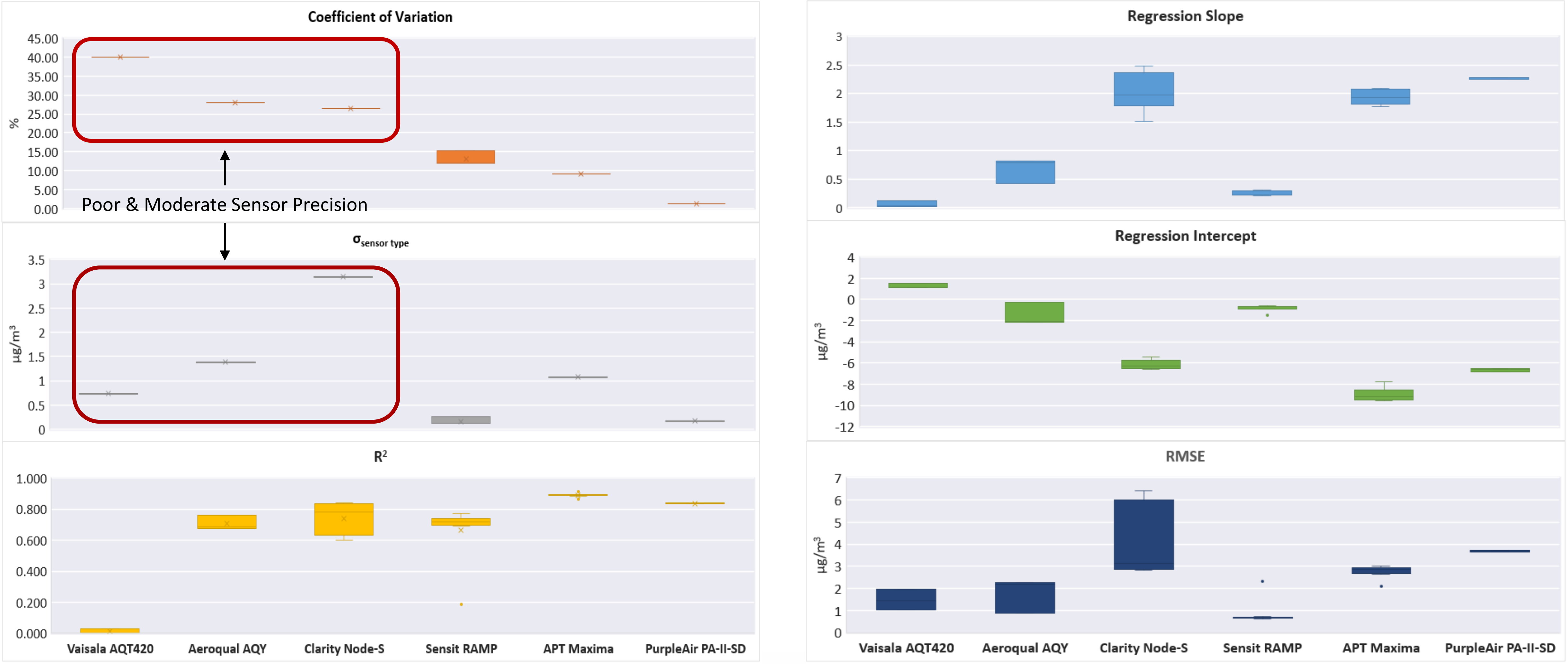


- Coefficient of Variation =1.3%
- Standard Deviation = 0.17 μg/m³

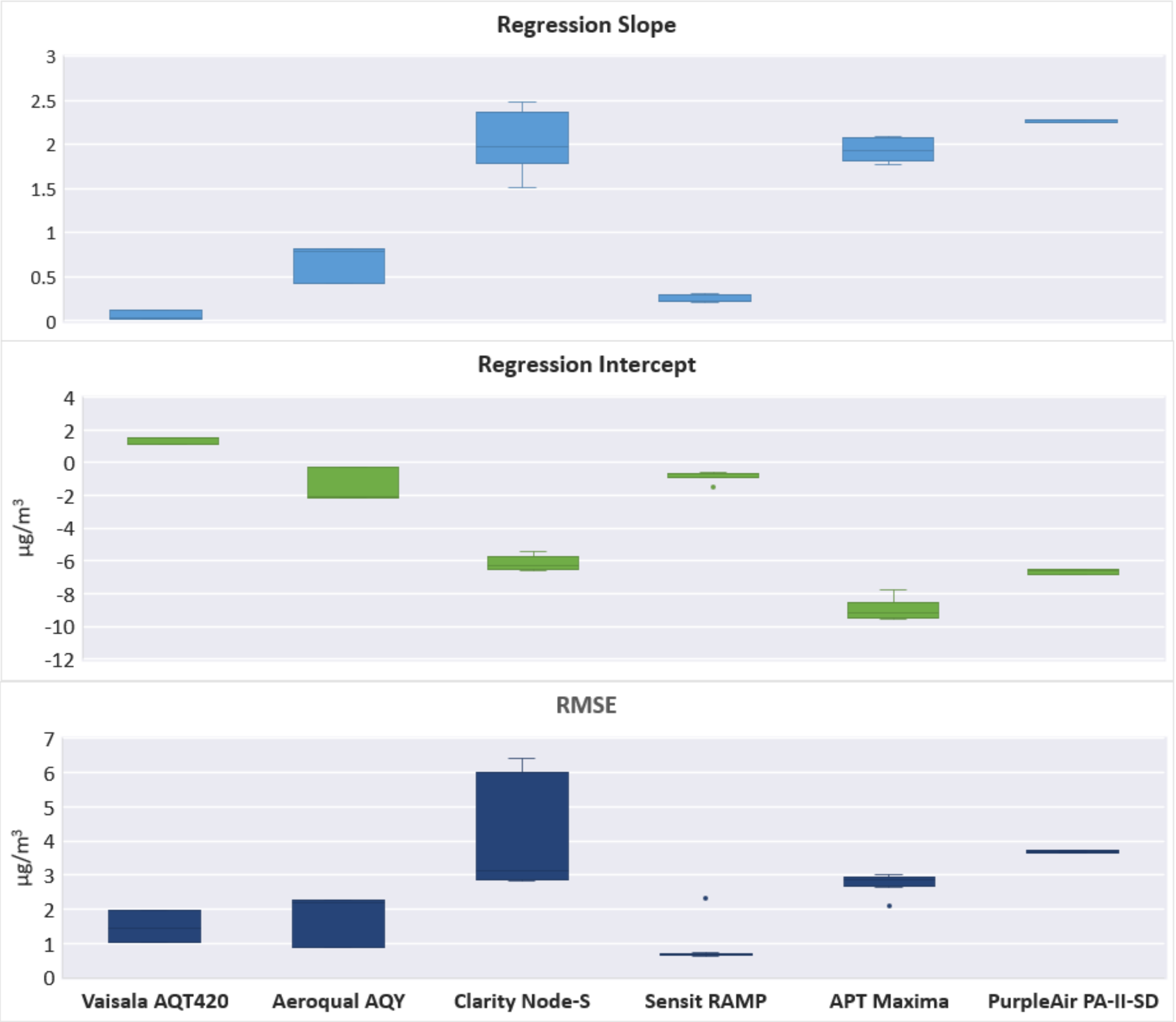
PurpleAir PA-II-SD: Takeaways

- Precision:
  - CV (1.3%) and $\sigma_{sensor\ type}$ (0.17 µg/m³) indicate good agreement between individual PA-II-SD devices
- Accuracy:
  - Good Correlation (R^2 ~0.84) between PA-II-SD and T640x $PM_{2.5}$ measurements
  - The PA-II-SD over-reports $PM_{2.5}$ concentrations relative to T640x by ~125%
- Observations for users:
  - Relative humidity influence is less pronounced

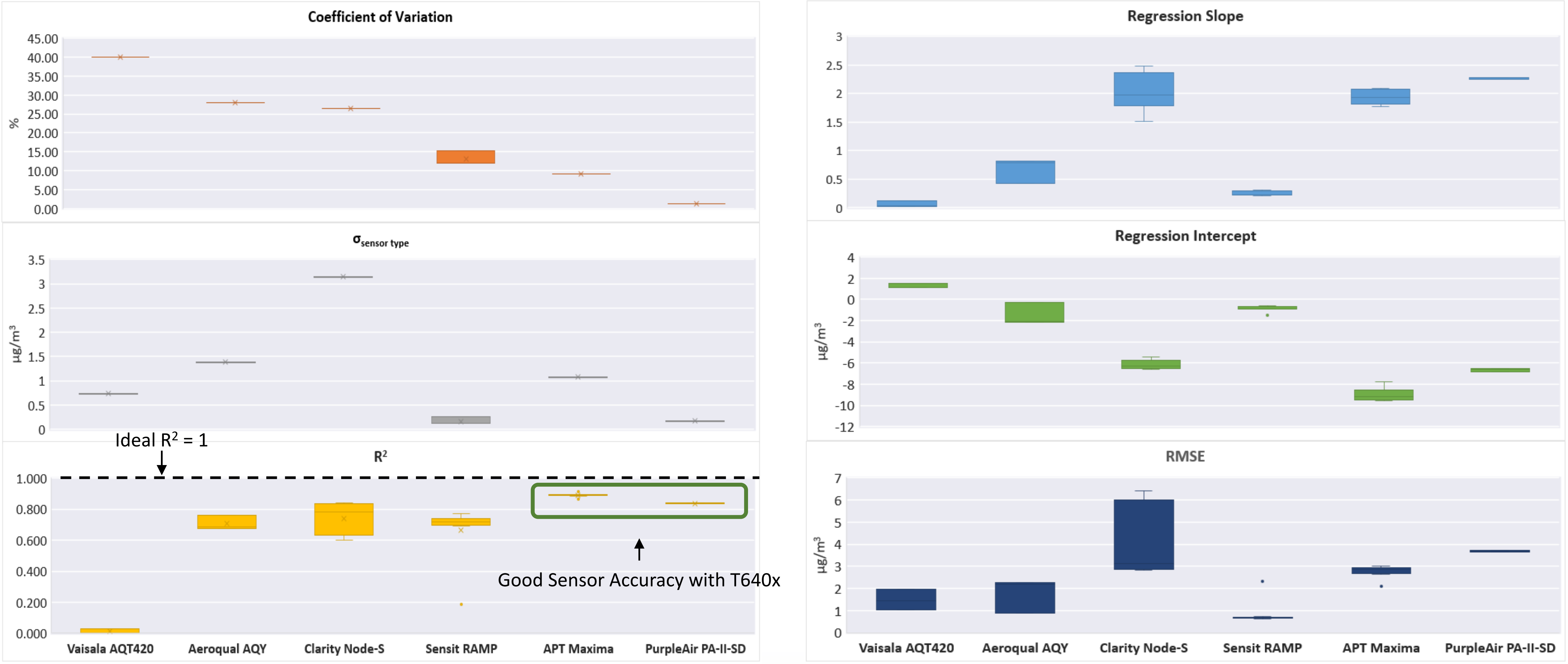
Summary of Results



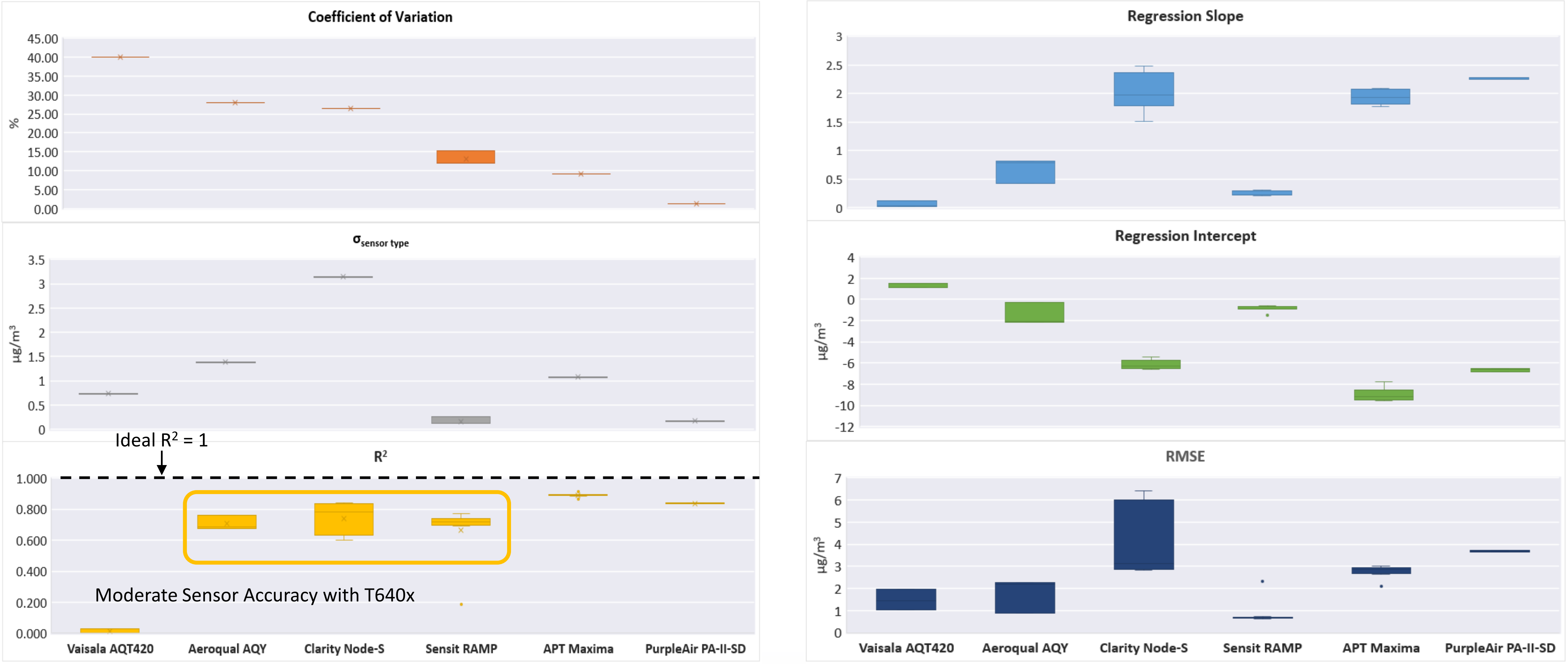
Summary of Results



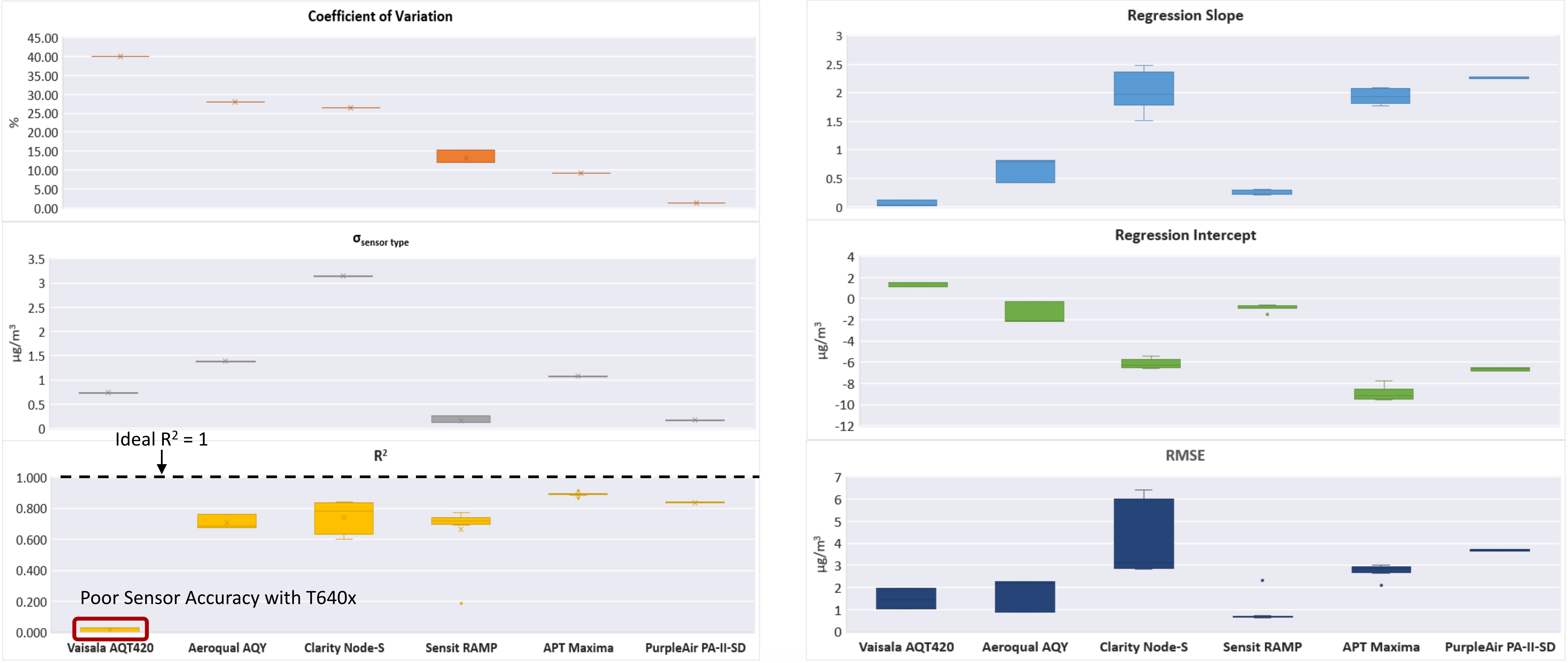
Summary of Results



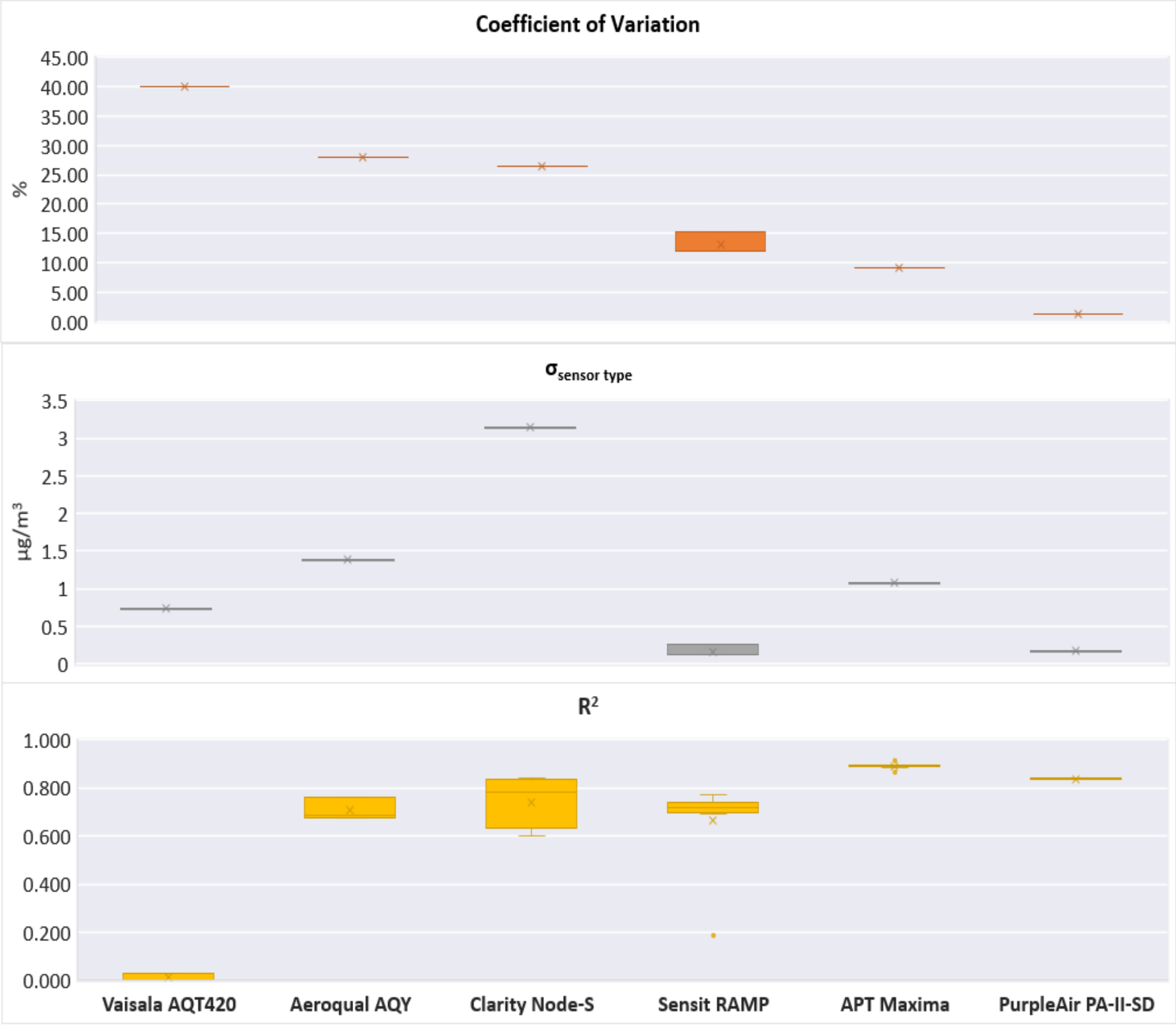
Summary of Results



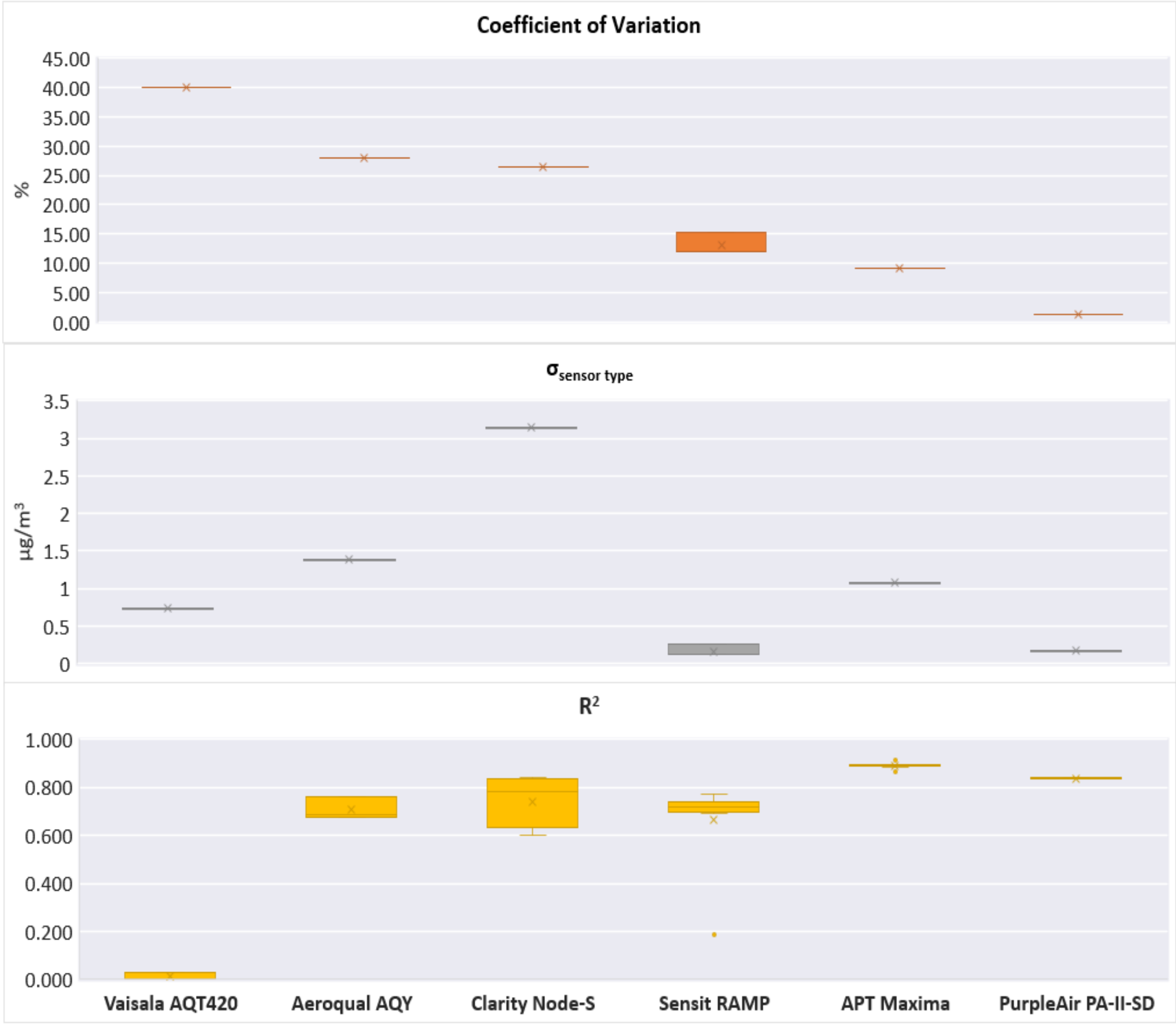
Summary of Results

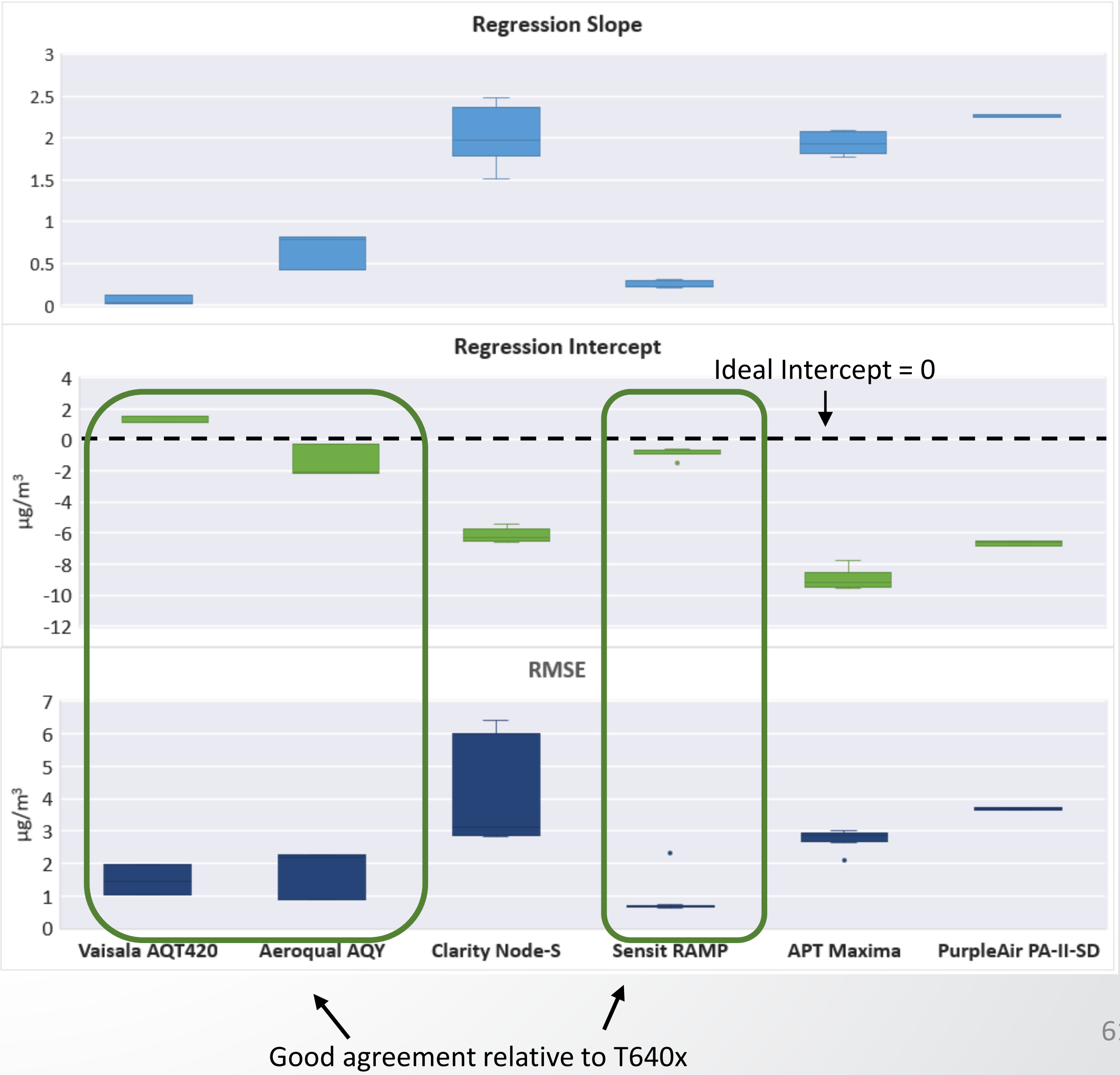


Summary of Results

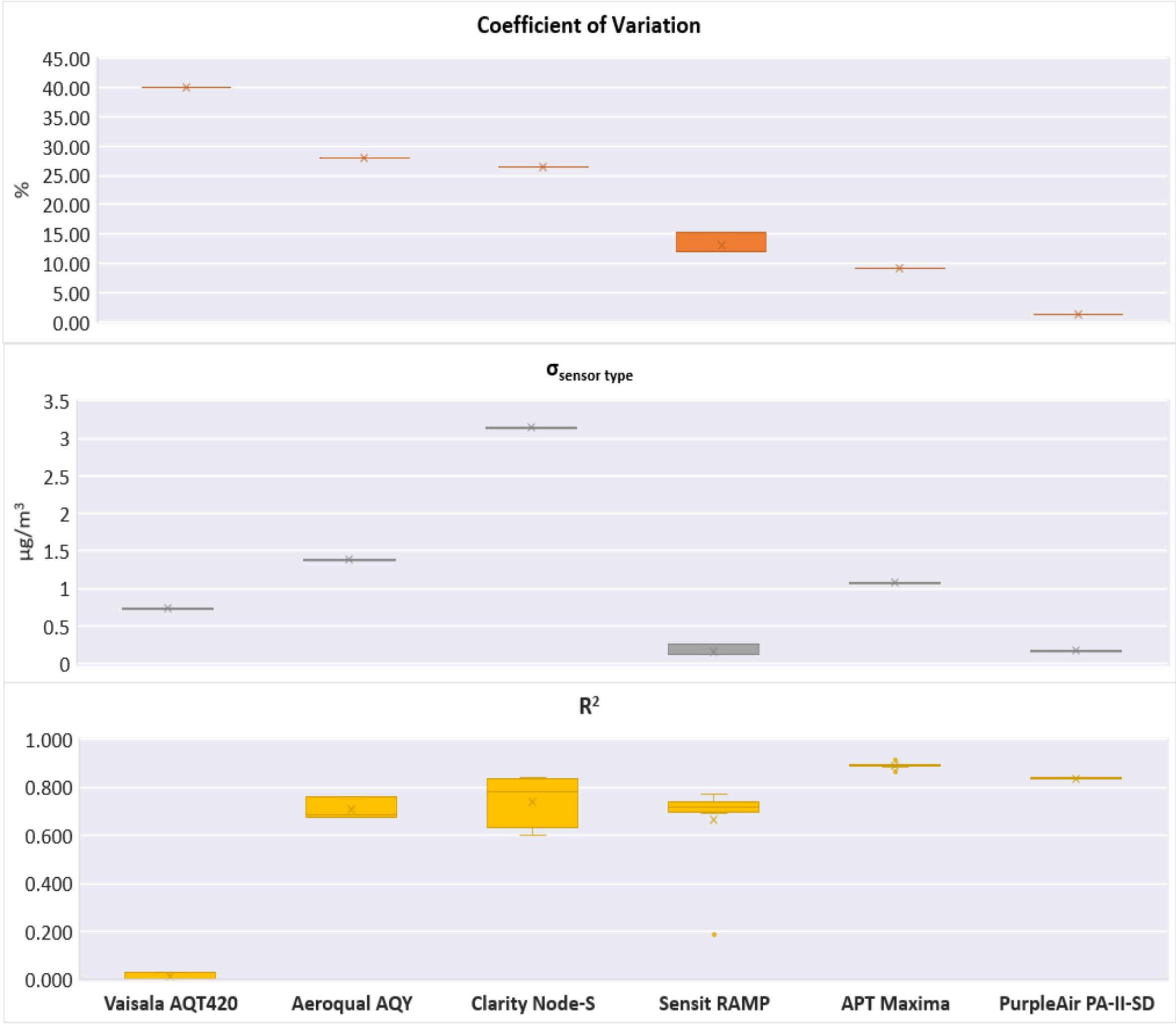


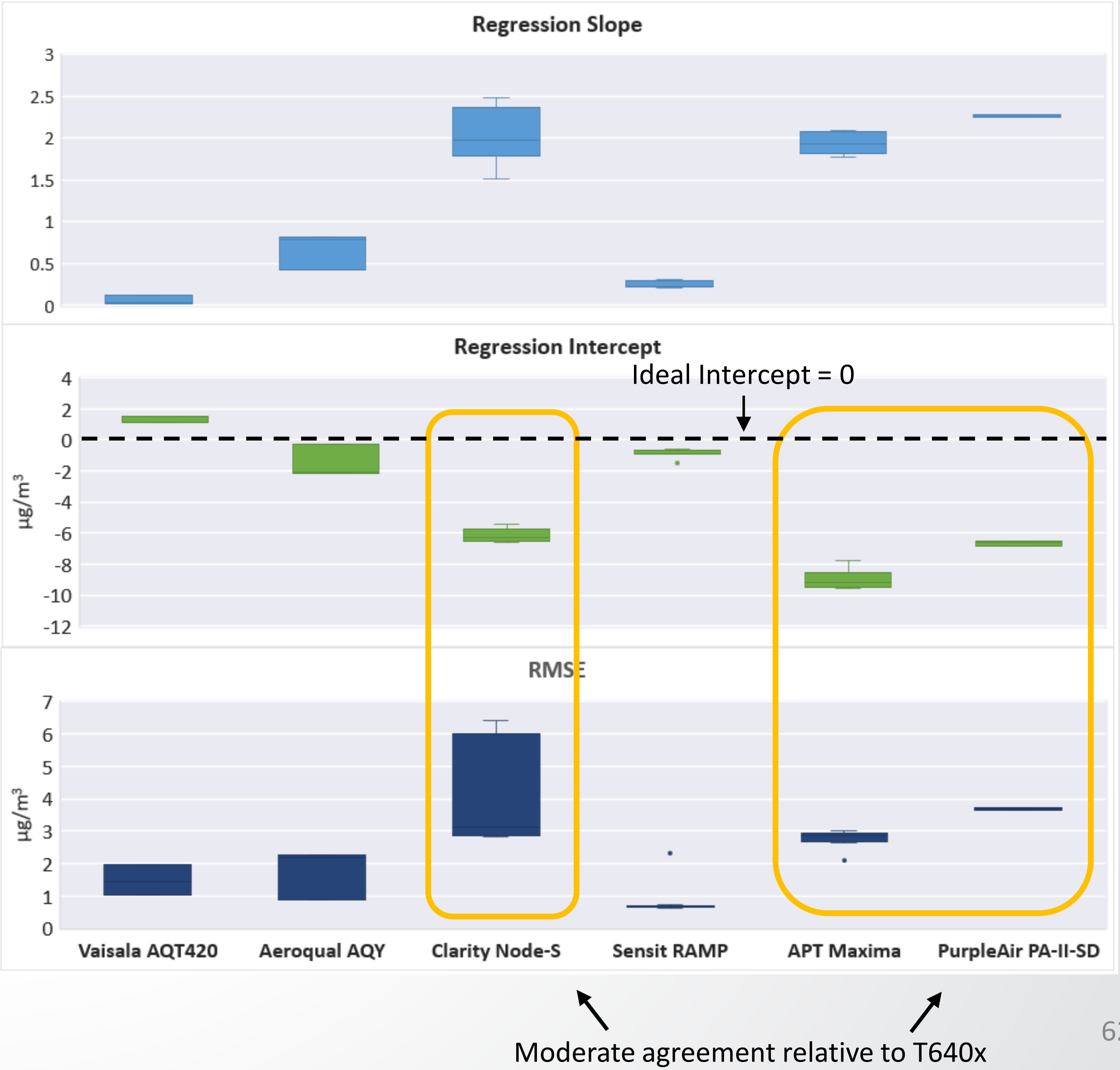
Summary of Results





Summary of Results





Future Work

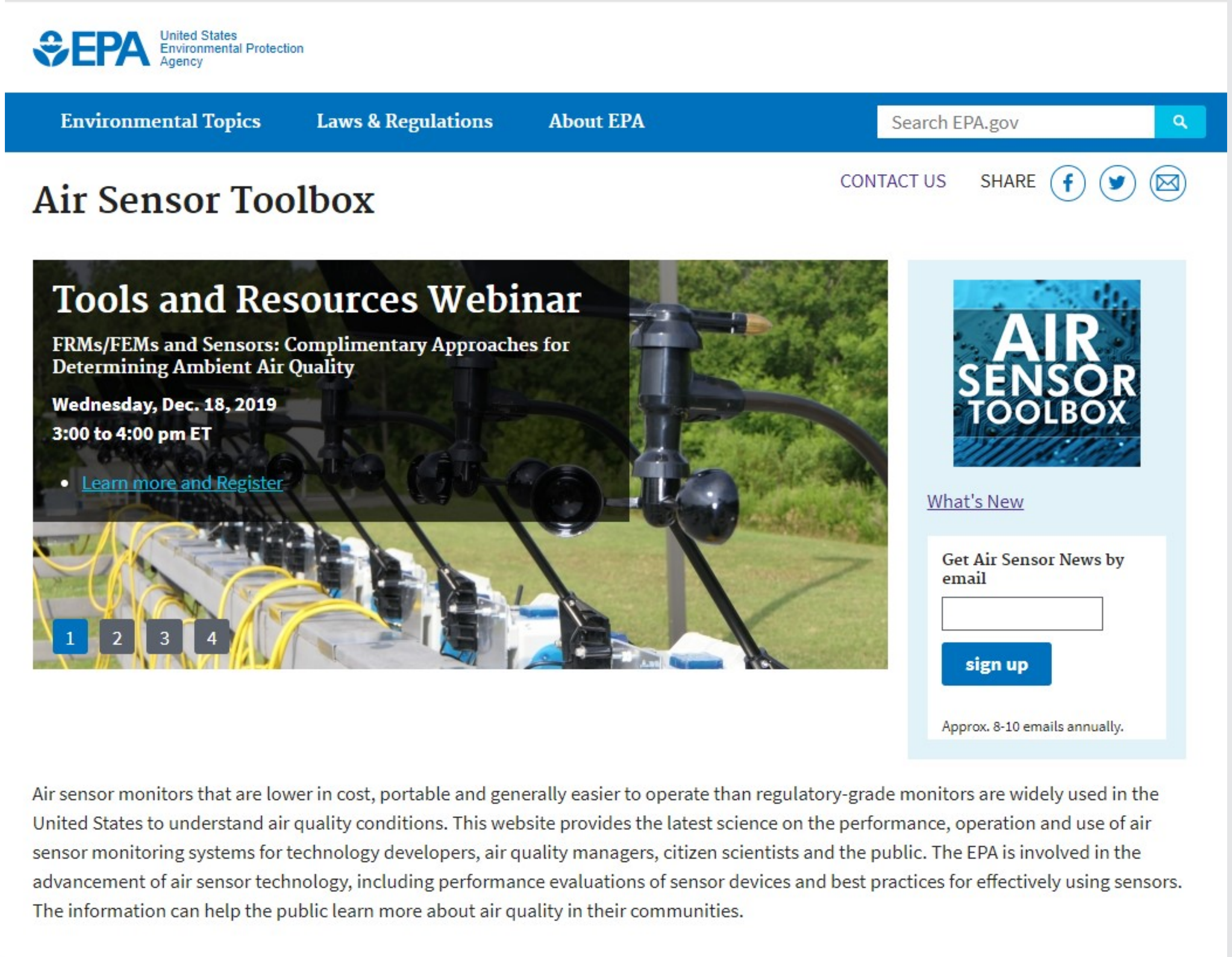
- Evaluate additional pollutants measured by each sensor type (PM_{10}, O_3, NO_2 etc.)
- Further explore the influence of relative humidity and temperature on each sensor type
- Explore correction methods for $PM_{2.5}$ sensor data appropriate for each sensor type
  - Is one correction equation appropriate for all sensors in a given type or does poor precision suggest a sensor-specific correction will be needed?
  - Is a linear correction method appropriate or is another regression method more suitable for the data?
- Ongoing sensor performance evaluations for additional sensors types

Application of this Work: Long-Term Performance

- Some of the sensors in this study are part of an ongoing project to determine the long-term performance of air quality sensors
  - Deployment at 7 air monitoring stations across the U.S. (North Carolina (NC), Georgia (GA), Delaware (DE), Arizona (AZ), Colorado (CO), Oklahoma (OK), Wisconsin (WI))
- The results of this study inform evaluation of sensor performance in the Long-Term Performance Project (LTPP)
  - ➢ ***Project Lead: Andrea Clements***

Resources

- [EPA's Air Sensor Toolbox]
  - Interpreting sensor readings and FAQs
  - Documentation for choosing and operating air sensors
  - Performance evaluations for air sensors
  - Tools to analyze air sensor data
  - **Update coming this spring** to improve navigation and will include new performance evaluations



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