Assessing Low-Cost Purple Air Particulate Matter Sensors

By

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Submitted to the Graduate Faculty of North Carolina State University in partial fulfillment of the requirements for the Degree of Master of Environmental Assessment

Raleigh, NC

2020

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April 27, 2020

Abstract

Wells, Heather. Masters of Environmental Assessment. Assessing Low-Cost Purple Air Particulate Matter Sensors

With technological advances, low-cost light scattering particulate matter (PM) sensors have come into more prevalent use. They operate by sensing laser light scattering by particles. The scattered light correlates to particle count, and then sensor algorithms can determine the size-selective PM concentration based on the intensity of the light and assumptions about average particle density. Low-cost sensors are not as accurate as Federal Reference Methods (FRMs), with concentrations having lower accuracy and precision. In order to be able to evaluate air quality using low-cost sensors, it is necessary to test reproducibility of the data. In this study, four PurpleAir low-cost sensors were collocated with a Federal Reference Method to measure PM in a chamber with a wood stove as the source. A data correction scheme for the PurpleAir sensors was developed. While the PurpleAir sensors had high correlations with the tapered element oscillating microbalance (TEOM) reference instrument, their concentrations were roughly 50% lower than those produced by the TEOM. A limitation of the study was that the sensors were only tested in a chamber environment with no varying environmental conditions. The chamber experiment should be repeated seasonally to account for any sensor drift or changes from environmental factors and for a number of sources and ambient conditions.

Acknowledgments

A special thanks to Dr. Jen Richmond-Bryant for advising on this project. Thanks to Dr. Neil Alexis (UNC) and Dr. Mary Katherine Sheats (NCSU) for funding the purchase of the four PurpleAir sensors. Thanks to Al Little (EPA) and Katherine Mills (UNC) for allowing the PA sensors to be placed in the wood smoke exposure chambers. Thanks to Jon Bernsten (TRC) for providing the TEOM data.

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Introduction

Particulate matter (PM) impacts visibility, human health, and the global climate (Wang et al., 2015). Ambient particulate matter can be emitted from many sources including motor vehicles, power plants, and industrial processes (Lehmann et al., 2019). By measuring the mass concentration of particles, PM can be quantified by size: nominal diameter smaller than 10 μm (PM_{10}), nominal diameter smaller than 2.5 μm ($PM_{2.5}$), and nominal diameter smaller than 1 μm (PM_1) (Wang et al., 2015). The size of the particle will determine the location of deposition within the human respiratory system (Wang et al., 2015). PM_{10} penetrates the nasal cavity, $PM_{2.5}$ penetrates the bronchi, and both $PM_{2.5}$ and PM_1 can deposit within the alveoli (Lehman et al., 2019). In addition, exposure to $PM_{2.5}$ has been found to cause cardiovascular disease, pulmonary disease, lung cancer, and mortality (Austin et al., 2015). A recent global assessment calculated that 3.3 million total deaths were caused by $PM_{2.5}$ (Evans et al., 2012). The World Health Organization (WHO) stated that particulate matter air pollution is the largest environmental cause of cancer deaths (IARC 2013). In a 2015 U.S. study, there were 123 counties that did not meet the 24-hour $PM_{2.5}$ National Ambient Air Quality Standard (U.S. EPA, 2015).

Air pollutant exposure is often characterized by estimating air pollution based on the nearest Federal Reference Method (FRM) and using modeling (Jerrett et al., 2017). However, a monitoring site may not accurately account for temporal or spatial PM variability (Wang et al., 2015), leading to error in exposure estimates (Zeger et al., 2000). Previous studies have shown that some air pollutants have high spatial variability, thus increasing exposure measurement errors due to uncharacterized differences between the true exposure concentration and that measured at the monitor (Suh et al., 2010). Currently, limitations exist in the density of monitoring sites in the US (Austin et al., 2015).

With advances in technology, low-cost light-scattering PM sensors have become more accessible. Because of their ease of use and availability, low-cost PM sensors are being placed both indoors and outdoors (Sayahi et al., 2019). These sensors use particle light scattering to measure particle counts, and algorithms associate the strength of the signal with the size of the particle (Castell et al., 2017). Since low cost sensors can operate with more spatial and temporal coverage, they are helpful for gaining insight on human exposures.

Unfortunately, data produced by low-cost sensors are considered to have "questionable quality" (Castell et al., 2017). Low-cost sensors are not as accurate as FRMs (Sayahi et al., 2019). Most users rely on manufacturer-provided calibration data; however, this does not factor in the conditions for which the sensor would be used or if there is any inter-sensor variability (Sayahi et al., 2019). Previous studies have shown that there can be both field and laboratory inter-sensor variability (Gao et al., 2015). Low cost PM sensors cannot truly be calibrated due to the different chemical characteristics, shapes, and densities of ambient PM (Hinds, 1999).

Concentration readings by low-cost sensors can be influenced by both environmental conditions and interference from chemicals (Aleixandre and Gerboles, 2012). Previous studies have shown that humidity can affect low-cost sensor readings (Wang et al., 2015). The reliability of low-cost sensors can also be impacted by varying temperatures (Gao et al., 2015). Thus far, there is insufficient information provided by low-cost sensor manufacturing regarding how well sensors perform over long-term deployment and under different environmental conditions (Castell et al., 2017). Low-cost sensors also have technical set-backs. The battery life tends to be low (Curto et al., 2018). Some low-cost sensors need to have filters exchanged regularly (Curto et al., 2018). Routine cleaning is required often on some low-cost sensors (Curto et al., 2018); whereas, some sensors cannot be cleaned at all and need replacement instead (PurpleAir). Low-cost sensor readings have also been shown to drift over time (Clements et al., 2017).

In order to use low-cost sensors for air quality evaluation, it is necessary to test reproducibility of the data to minimize uncertainties (Castell et al., 2017). One way to do this is to collocate the low-cost sensor with a Federal Reference Method to measure particulate matter in a chamber (Sayahi et al., 2019). Because calibration chambers have controlled conditions, they are useful for assessing low-cost sensors (Papapostolou et al., 2017). The advantages to using a chamber environment include the ability to generate aerosols and uniformity of the particle size distribution (Sayah et al., 2019). Since it would be difficult to collocate a large number of sensors with reference monitors for a long period of time, an environmental chamber that can accommodate a wide range of concentrations is advantageous (Sayah et al., 2019). It is important to note that each sensor must be calibrated individually, since previous studies have shown that there can be inter-sensor variability (Gao et al., 2015).

The objective of this study is to develop a data correction scheme for the PurpleAir sensors for application in a field study with the NCSU Veterinary School. A chamber study comparing the PurpleAir sensors with a tapered element oscillating microbalance (TEOM) was used to accomplish this goal. A time correction scheme for PurpleAir sensors was developed, because PurpleAir sensors and the TEOM do not report concentrations at exactly the same time. Regression models were then fit between the TEOM and PurpleAir data to correct inaccuracies in the PurpleAir data.

Materials and Method

This study assessed the performance of PurpleAir sensors against a TEOM instrument within a chamber located within the U.S. Environmental Protection Agency Human Studies Facility in Chapel Hill, North Carolina in September, 2019. The samplers were exposed to controlled wood-smoke emissions.

Instrumentation

Four PurpleAir sensors were tested (https://www2.purpleair.com/collections/air-quality-sensors/products/purpleair-pa-ii-sd). The PurpleAir is a low-cost device (3.5 in x 3.5 in x

5 in) which uses two PMS5003 sensors (PurpleAir). Using Arduino firmware, the PurpleAir senses particles every second and then averages the concentrations over 20 second intervals. Data are stored on the installed SD card (PurpleAir). The PurpleAir sensor counts the number of particles by the following particle sizes: 0.3, 0.5, 1. 2.5, 5, and 10 um (PurpleAir). Using these count data, mass concentrations can be calculated for PM_1, $PM_{2.5}$, and PM_{10} (PurpleAir). To measure PM in real time, the laser counter uses a fan to pull an air sample past the laser beam (PurpleAir). The PurpleAir sensor detects the number and intensity of pulses based on the particle reflection (PurpleAir). Using an algorithm developed by Plantower, the PurpleAir converts the particle counts into mass concentrations of PM by assuming an average particle density (PurpleAir). While PurpleAir assumes an average particle density, they have not made concentration available to the public. In addition, this device measures temperature and relative humidity (PurpleAir).

The Tapered Element Oscillating Microbalance (TEOM) instrument has been designated by the U.S. Environmental Protection Agency as a Federal Equivalent Method (FEM) for $PM_{2.5}$ air quality monitoring (www.epa.gov). The TEOM has a size selective inlet that allows certain sized particles to flow through. A filter cartridge holds a filter on top of a hollow tube which allows the element to oscillate continually (www.thermofisher.com). When particles deposit on the filter, the oscillation frequency changes. The instrument can then measure the particle mass from the magnitude of the oscillation frequency change (Kulkarni et al., 2011).

Laboratory Set-up

Prior to running the chamber experiment, an ohmmeter was used to confirm that all connections to the sensors were grounded satisfactorily. Using zip cords, all four sensors were suspended inside the chamber. Chamber conditions of approximately 22 °C air temperature, 40 % relative humidity, and 500 $\mu g/m^3$ $PM_{2.5}$ concentration were maintained in the wood smoke chamber. The wood used for the exposure was white oak and was harvested in 2007 from trees in Cedar Grove, NC. An oak log smoldering on an electric heating unit in a Quadra-Fire wood stove produced the wood smoke. The wood smoke was delivered to the custom built chamber, which measured 6 ft X 6 ft X 8 ft.

Environmental staff was responsible for maintaining and operating the wood stove, exposure chamber, and TEOM instrument. During the experiment, if the $PM_{2.5}$ concentration measured by the TEOM exceeded 1200 $\mu g/m^3$ for a two-minute average measurement, the system automatically terminated the source. Sensors remained in the chamber for 2-hours.

Data Analysis

Mass concentration measurements from the four PurpleAir sensors were compared with the TEOM readings provided by TRC Environmental Corporation as follows. First, data for each sensor were reviewed for potential outliers. Because the data were normally distributed, a 3-σ statistical outlier test was used. By using this test, with a normal distribution, 99.7% of data

should fall within the calculated three sigma intervals (Pukelsheim, 1994). Next, all PurpleAir data were time matched with the corresponding TEOM values, using a linear interpolation function at each time step, because the reporting times for the TEOM and PurpleAir sensors did not match. The linear interpolation function was then used to estimate the concentration of the PurpleAir at each time when concentration was recorded for the TEOM. Next, a linear regression was applied. The slope and R^2 parameters were obtained to ascertain the quality of comparison for the TEOM and PurpleAir. A correlation analyses was performed. Descriptive statistics were calculated to compare $PM_{2.5}$ measurements of the PurpleAir and TEOM.

Results

Descriptive statistics were calculated for all four PurpleAir sensors (Table 1). The mean ranged between 561-630 $\mu g/m^3$ for all four sensors. The median ranged between 777-871 $\mu g/m^3$. The standard deviation for all sensors ranged between 518-585 $\mu g/m^3$. The kurtosis was negative, meaning the data had a somewhat flat top. The skewness was positive but very close to zero, meaning that the data were slightly skewed to the right. One-hundred fifty-six data points were generated for this comparison. Additional descriptive statistics can be found in the Appendix in Table A1.

Table 1: Purple Air Descriptive Statistics for each sensor measuring $PM_{2.5}$.

	Sensor 1 Channel A	Sensor 2 Channel A	Sensor 3 Channel A	Sensor 4 Channel A
Mean	630	593	595	561
Median	871	777	856	781
St Dev	585	548	547	518
Q1	0.00	0.06	0.01	0.12
Q3	1182	1109	1103	1040

The 3-σ outlier test eliminated one data point from each of the four sensors. The comparison among the PurpleAir sensors and the TEOM's mass concentration time series showed good agreement with time variation, but the Purple Air reported concentrations that were on average 49% lower than those reported by the TEOM. Figure 1 shows the concentration of both PurpleAir Sensor 1 and the TEOM. Peak concentrations were recorded for both instruments at 8:58 am. Additional sensor comparisons are presented in the Appendix in Figures A1-A3. The figures show that the comparison is similar for each of the $PM_{2.5}$ channels. The average differences between all four sensors and the TEOM are similar. In addition, the correlation between all four sensors is similar.

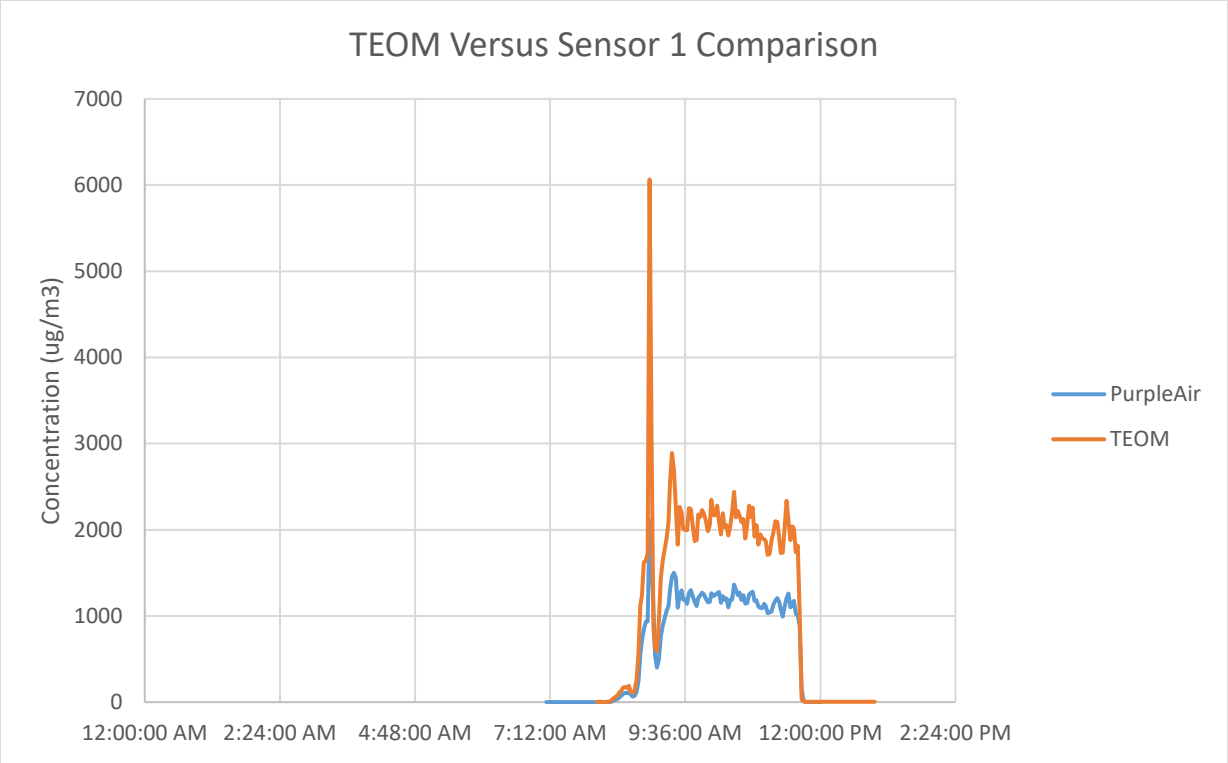

Figure 1: TEOM versus Sensor 1 Time Stamp versus Concentration Comparison

All four sensors were compared with one another to test for inter-sensor variability. Outliers were removed using a 3-σ outlier test. The inter-sensor variability test showed good agreement with PM_1, $PM_{2.5}$, and PM_{10} and can be seen in the Appendix Figures A4-A6.

For Sensor 1, Sensor 2, and Sensor 3, one outlier was removed for PM_1. Sensor 4 had no outliers removed for PM_1. All four sensors each had one outlier removed for $PM_{2.5}$. There were no outliers for any of the four sensors with PM_{10}.

After the time adjustment, a fitted linear regression model was used between the PurpleAir (independent) using the TEOM as the benchmark (dependent). All four PurpleAir Sensors and TEOM have a linear response. The comparison for PurpleAir Sensor 1 and TEOM is shown in Figure 2, while other sensors are shown in Appendix Figures A7-A9. The observations were from the two-minute averages of raw sensor data. All four sensors had an $R^2 \geqq 0.84$. While all four sensors compared well with the TEOM temporally, the reference (TEOM) concentration was underestimated by almost 50%. The slope is considered the relative error; whereas, the intercept indicates the zero offset. The sensors showed good precision but poor accuracy. With good precision, the sensors can still be deployed using a calculated correction factor.

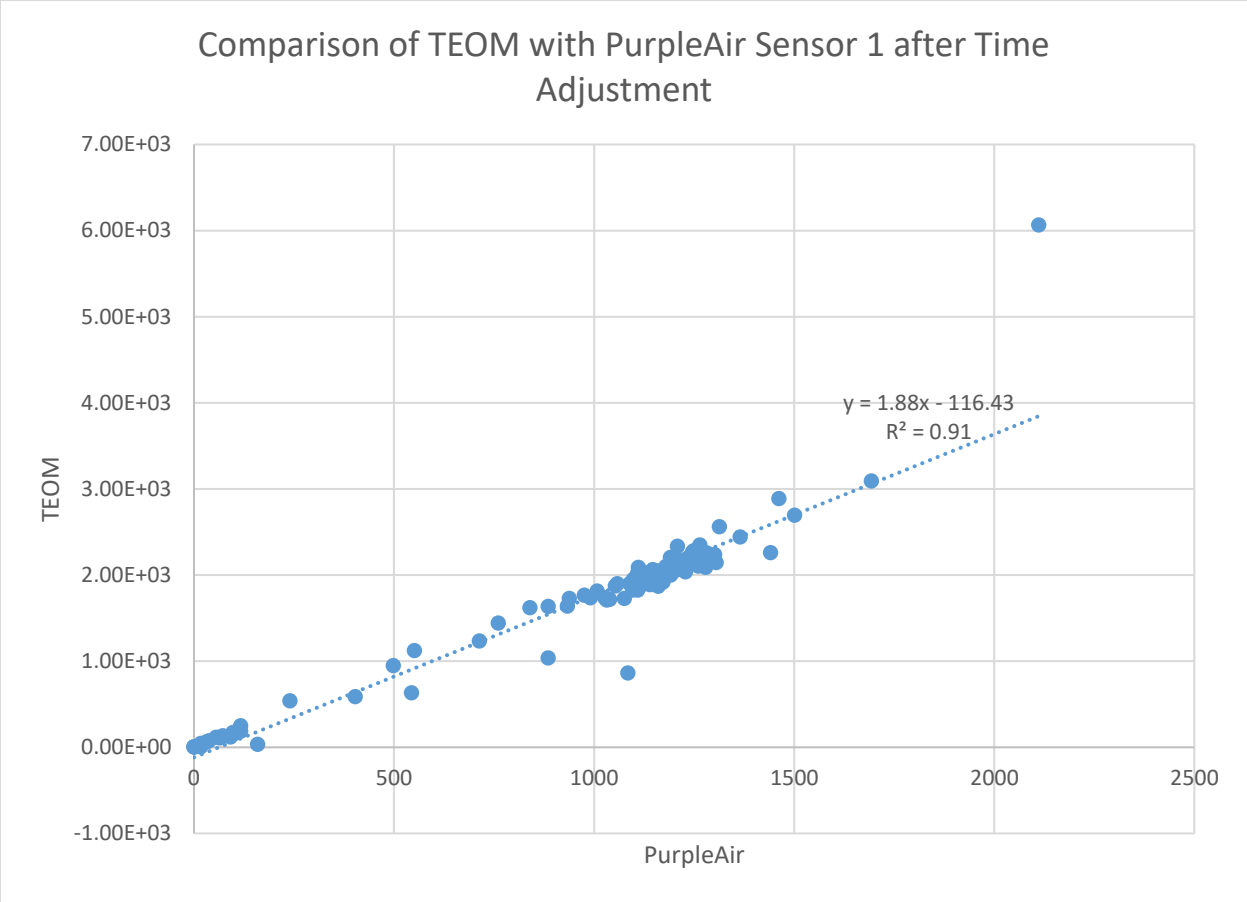

Figure 2: Comparison of TEOM with Purple Air Sensor 1 after Time Adjustment

Table 2: Slope and R^2 values for each TEOM (x) when compared with the PurpleAir (y).

	Sensor 1	Sensor 2	Sensor 3	Sensor 4
Slope	y=1.88x-116.43	y=1.94x-66.48	y=2.02x-140.79	y=2.17x-172.03
R^2	0.91	0.84	0.90	0.94

Discussion

PurpleAir sensors count airborne particles drawing the particles past a laser. The particles will reflect the laser light as they pass through the beam. PM composition and phase can vary. Because PurpleAir sensors assume an average particle density, uncertainty related to uncharacterized variation in particle density and size (PurpleAir), presents uncertainty in reported concentrations (Hinds, 1999).

Previous research has suggested that PurpleAir raw concentrations are almost double regulatory monitor values (PurpleAir). During ambient tests, PurpleAir sensors overestimate the particulate matter concentration (Kelly et. al, 2017). A University of Utah study published in early 2020 also noted the overestimation of PurpleAir monitors and developed a correction

factor (Tryner et. al, 2020). Since the University of Utah study has been published, the PurpleAir website has allowed users to apply that correction factor to their data (PurpleAir). These studies contradict the findings of the four PurpleAir sensors used in the chamber study, which underestimated PM concentrations. Because this correction factor was derived in Salt Lake City, Utah, during a certain time of the year, it is possibly not applicable to other locations and during different seasons, which could be a possible explanation as to why the chamber study indicated different results.

In this study, the four PurpleAir sensors correlated well with the TEOM. In a 2017 study, Clements et al. (2017) advised that, when compared with a FEM R^2>0.4, low-cost sensors can be used in conjunction with monitoring networks.

While the sensors performed well in the controlled chamber environment, there are uncertainties with sensor performance once deployed. Because sensor parameters might change under different environmental conditions, it is necessary to evaluate sensor performance seasonally. In addition, because sensors have a short lifespan, it is recommended to place more than one sensor at each deployed location. While the data obtained do not meet FEM standards, the data are still sufficient for making judgments about air quality (Castell et al., 2017) after some data adjustment. As long as the PurpleAir sensors correlate well with the FRM or FEM, data correction can be performed to make the data usable. Evaluation of the sensors in a chamber with concentrations much higher than ambient levels also creates uncertainties for how the PurpleAir sensors would perform at ambient concentrations.

There are many limitations with using low-cost sensors. Most manufactures do not provide information regarding how well their sensors perform (Castell et al., 2017). There is often not enough information regarding how to test low-cost sensors prior to deployment (Castell et al., 2017). In addition, data obtained from long-term usage have not been assessed (Castell et al., 2017). Low-cost sensors also have not been tested under varying environmental conditions (Curto et al., 2018).

Because there is not information regarding PurpleAir performance, it is necessary to compare each sensor to a FRM or FEM prior to being deployed. All four PurpleAir sensors had never been used, so any aberrant values would not likely be due to instrument drift. Because the chamber environment is controlled, the sensors were not tested for varying humidity, temperature, or weather. In addition, the sensors have not been tested for long-term performance (Austin et al., 2015). Because the wood-smoke combustion exposure requires continuously monitoring the wood-stove fire, the sensors could not be evaluated for longer periods of time in this manner. Over time, depending on the concentrations to which the sensors are exposed, deposits can form on the optical sensor, causing sensor drift (Austin et al., 2015). Therefore, the sensor comparison should be repeated within the chamber environment after every season, to account for drift.

Conclusions

To evaluate air quality in the field using the PurpleAir sensors, it was necessary to first perform a chamber study with a reference instrument. Four PurpleAir sensors were collocated with a TEOM reference instrument in a controlled wood-smoke chamber environment, and then a data correction scheme was applied. Because the TEOM and PurpleAir sensors did not collect measurements at exactly the same time points, an interpolation function was used to time match the values. After the data adjustment, a regression analysis was performed, which showed that the PurpleAir sensors correlated well with the TEOM.

A strength of this study was that all four sensors' inter-sensor variability showed good agreement with each other. A limitation of this experiment was that it was performed in a wood-smoke environment where the concentration is much higher than ambient levels. This study may not indicate performance of the PurpleAir sensors for measuring traffic-related PM, for which they will be deployed.

Based on the findings of this limited study, the following recommendations can be made regarding the use of PurpleAir sensors:

- PurpleAir sensors should be compared with a FRM or FEM instrument prior to being deployed.
- Prior to using data, there must be some data adjustment with PurpleAir sensors and the reference sampler

Because this was a limited study, the following recommendations were not evaluated but can be made based on low cost sensor literature (Austin et al., 2015):

- Since sensors have a short lifespan and can drift, it is recommended to have more than one sensor deployed at any single location.
- Sensor comparison should be repeated seasonally to account for any environmental changes.

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Appendix:

Table A1: Purple Air Descriptive Statistics for all four sensors measuring $PM_{2.5}$.

	Sensor 1 Channel A pm2_5_atm	Sensor 2 Channel A pm2_5_atm	Sensor 3 Channel A pm2_5_atm	Sensor 4 Channel A pm2_5_atm
Mean	630	593	595	561
Std Error	46.8	43.9	43.8	41.4
Median	871	777	856	781
Mode	0	0	0	0
St Dev	585	548	547	518
Kurtosis	-1.60	-1.65	-1.68	-1.41
Skewness	0.0597	0.0462	0.0258	0.0930
Min	0	0	0	0
Max	2241	2049	2002	2157
Count	156	156	156	156
Q1	0	0.06	0.0075	0.12
Q3	1182	1109	1103	1040
IQR	1182	1109	1103	1040
COV	92.8	92.4	92.0	92.3

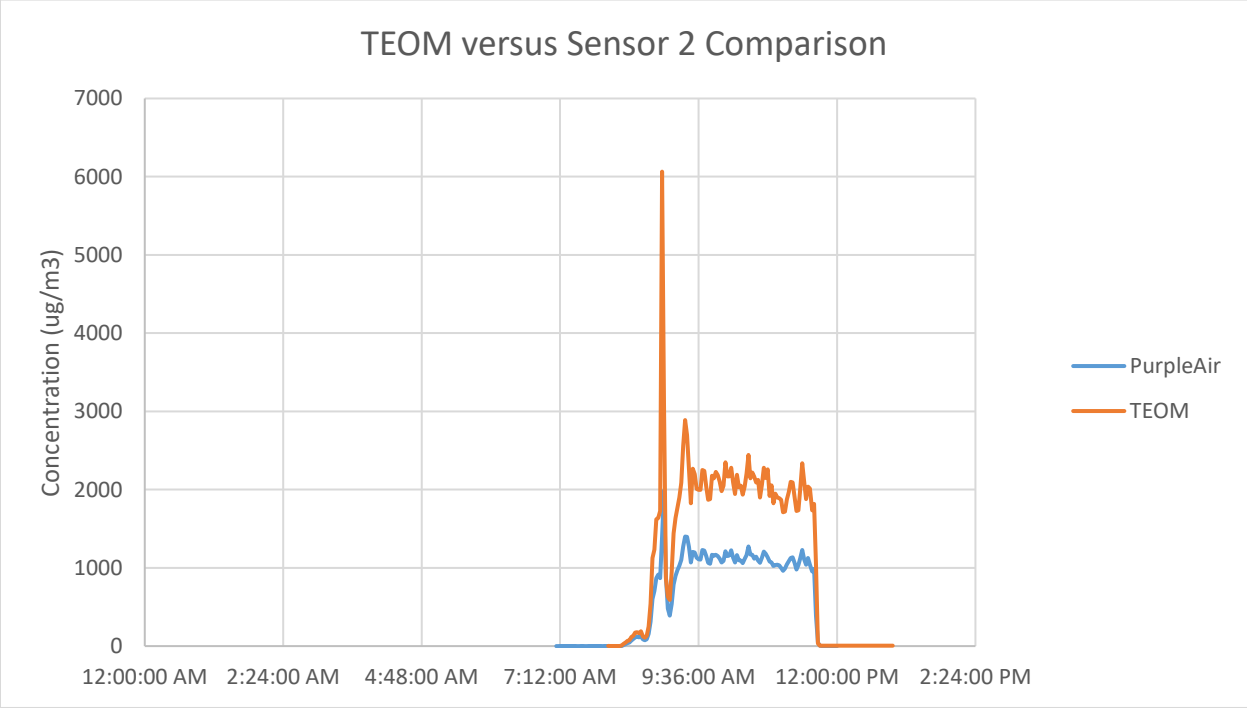

Figure A1: TEOM versus Sensor 2 Time Stamp versus Concentration Comparison

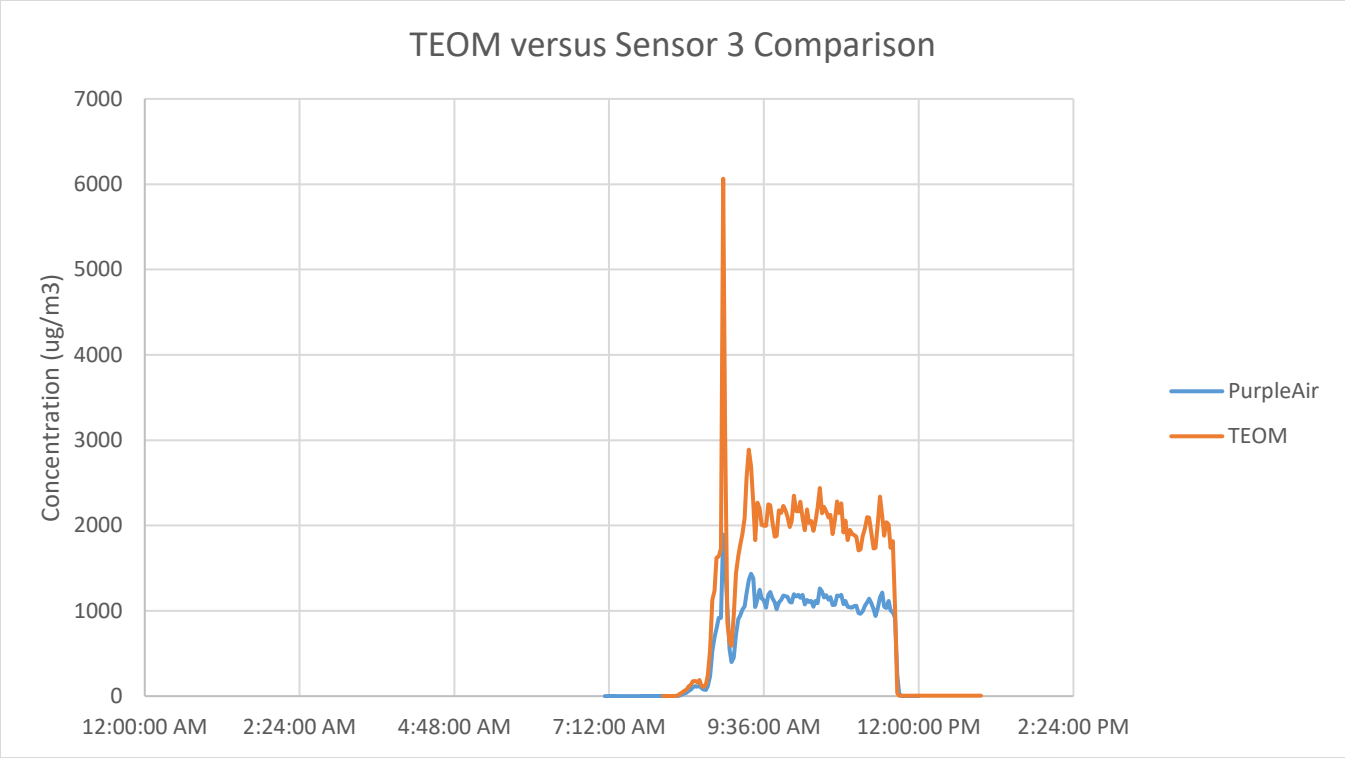

Figure A2: TEOM versus Sensor 3 Time Stamp versus Concentration Comparison

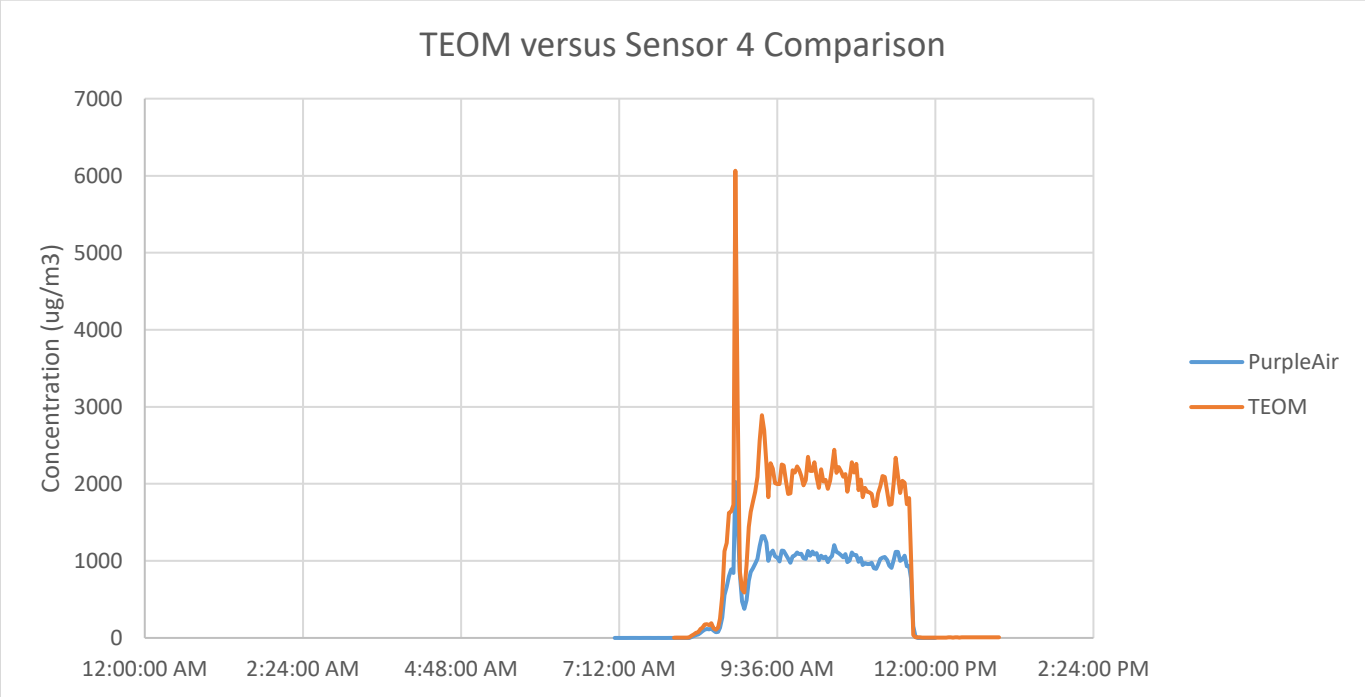

Figure A3: TEOM versus Sensor 4 Time Stamp versus Concentration Comparison

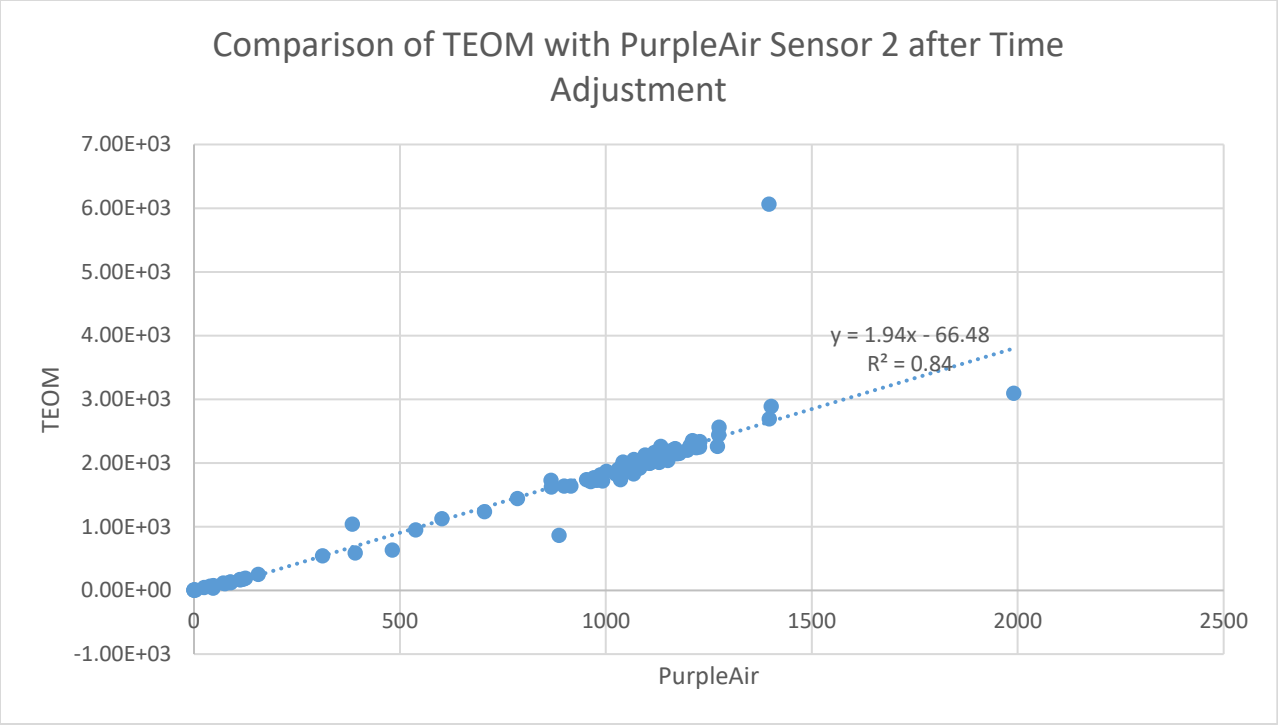

Figure A4: Comparison of TEOM with Purple Air Sensor 2 after Time Adjustment

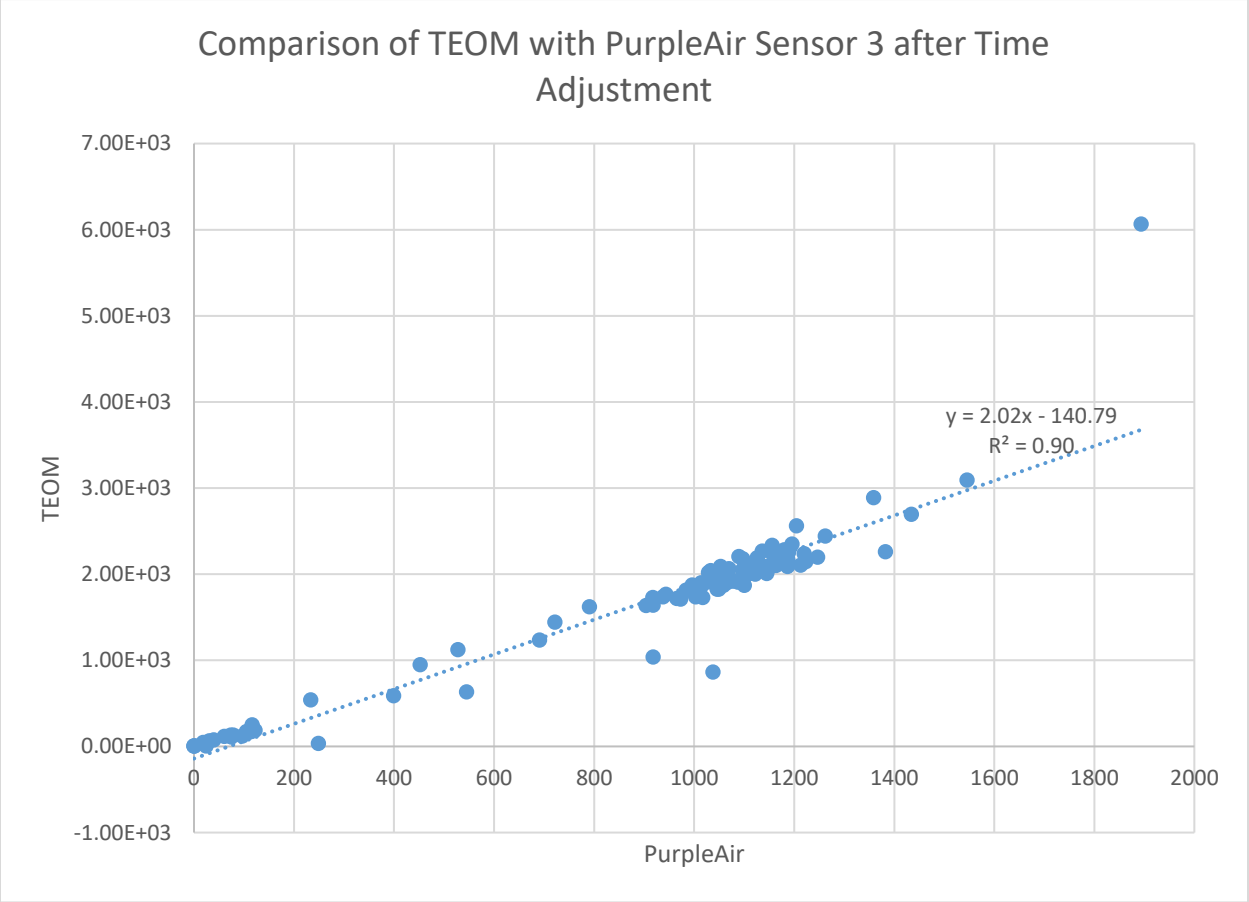

Figure A5: Comparison of TEOM with Purple Air Sensor 3 after Time Adjustment

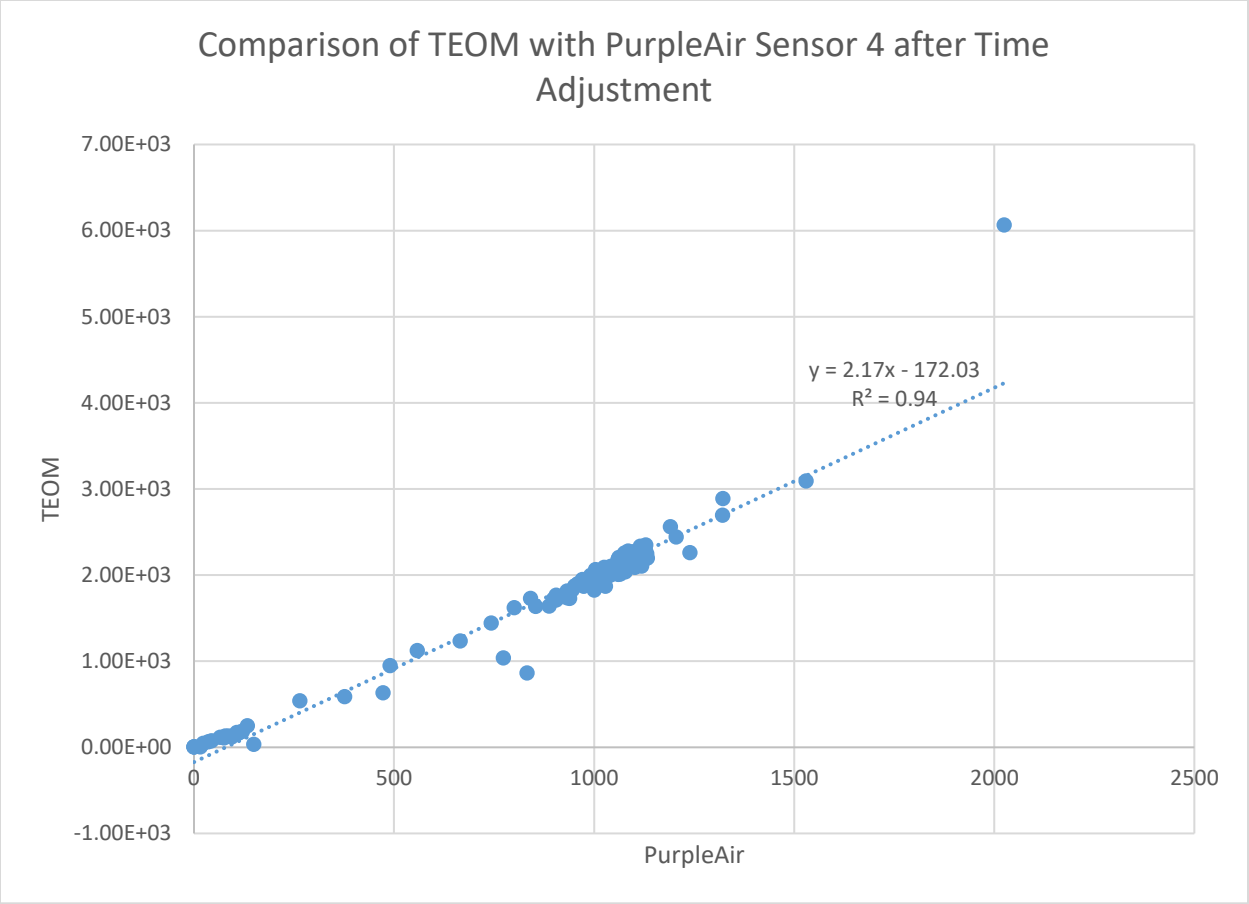

Figure A6: Comparison of TEOM with Purple Air Sensor 4 after Time Adjustment

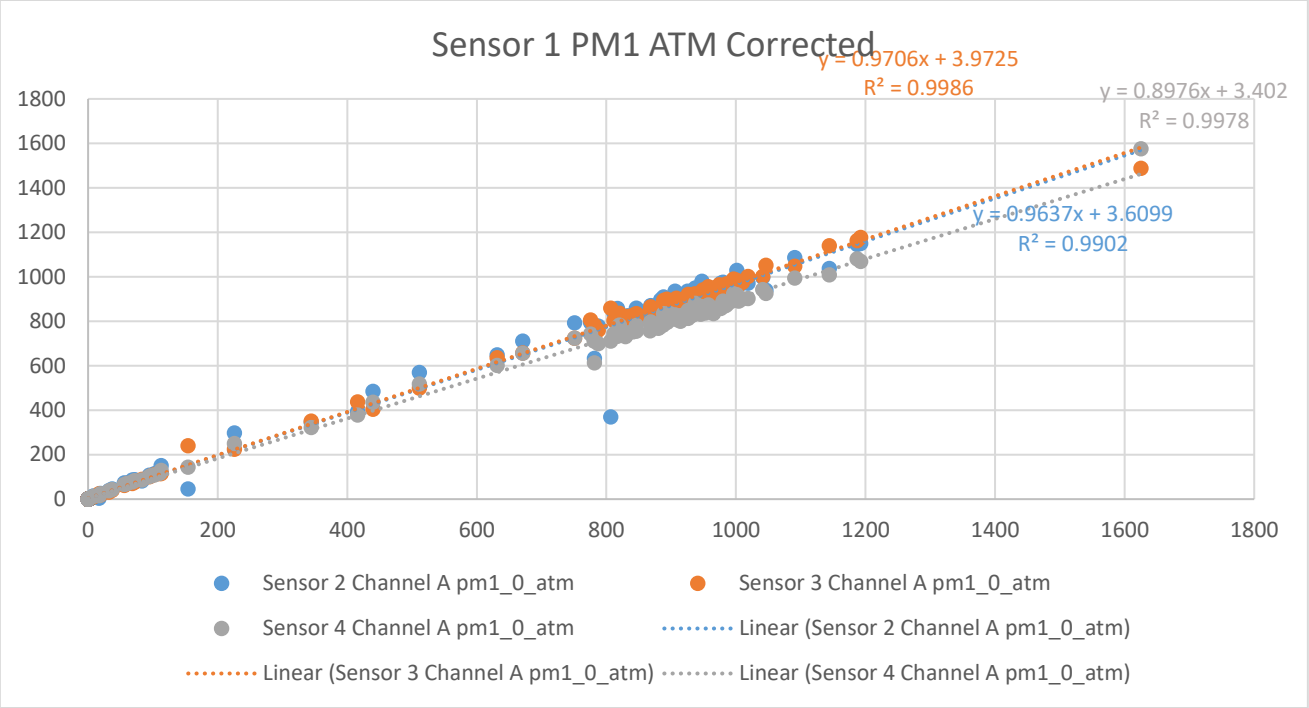

Figure A7: Sensor Comparison between Sensors 1-4 for PM1 ATM Corrected

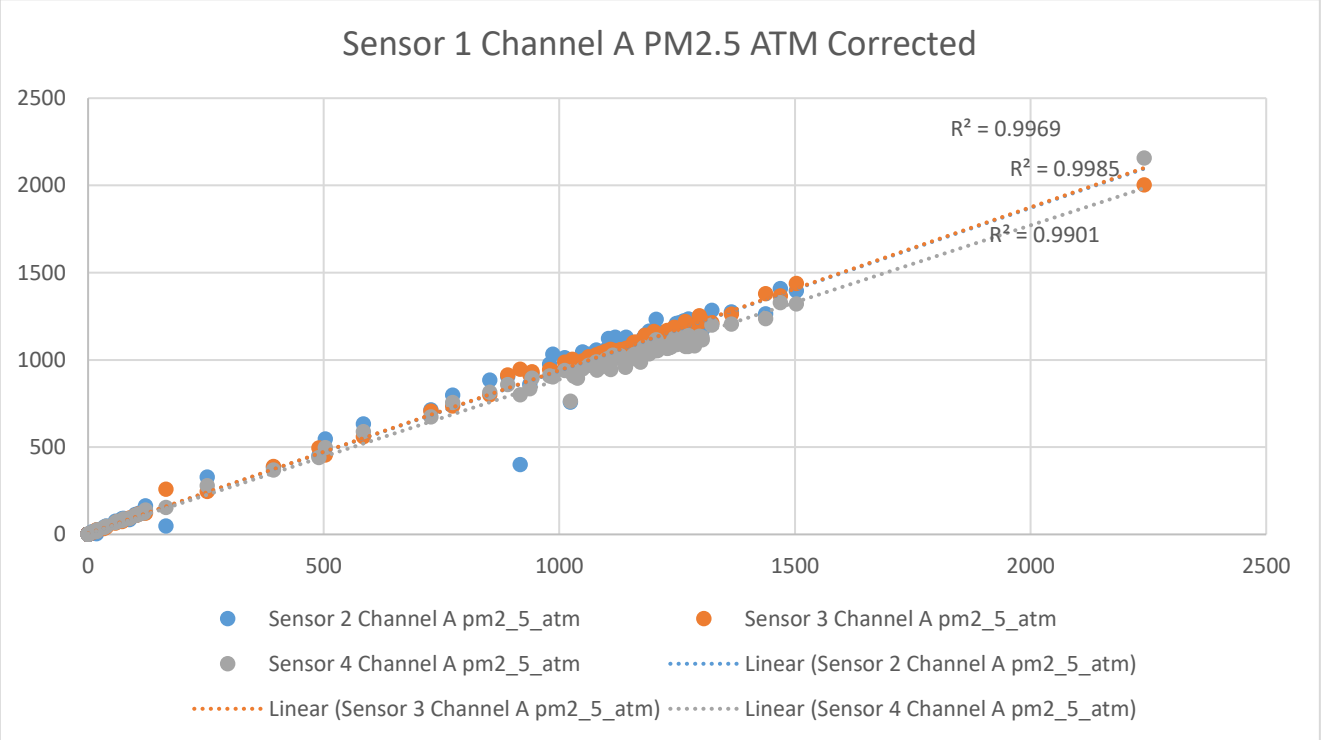

Figure A8: Sensor Comparison between Sensors 1-4 for PM2.5 ATM Corrected

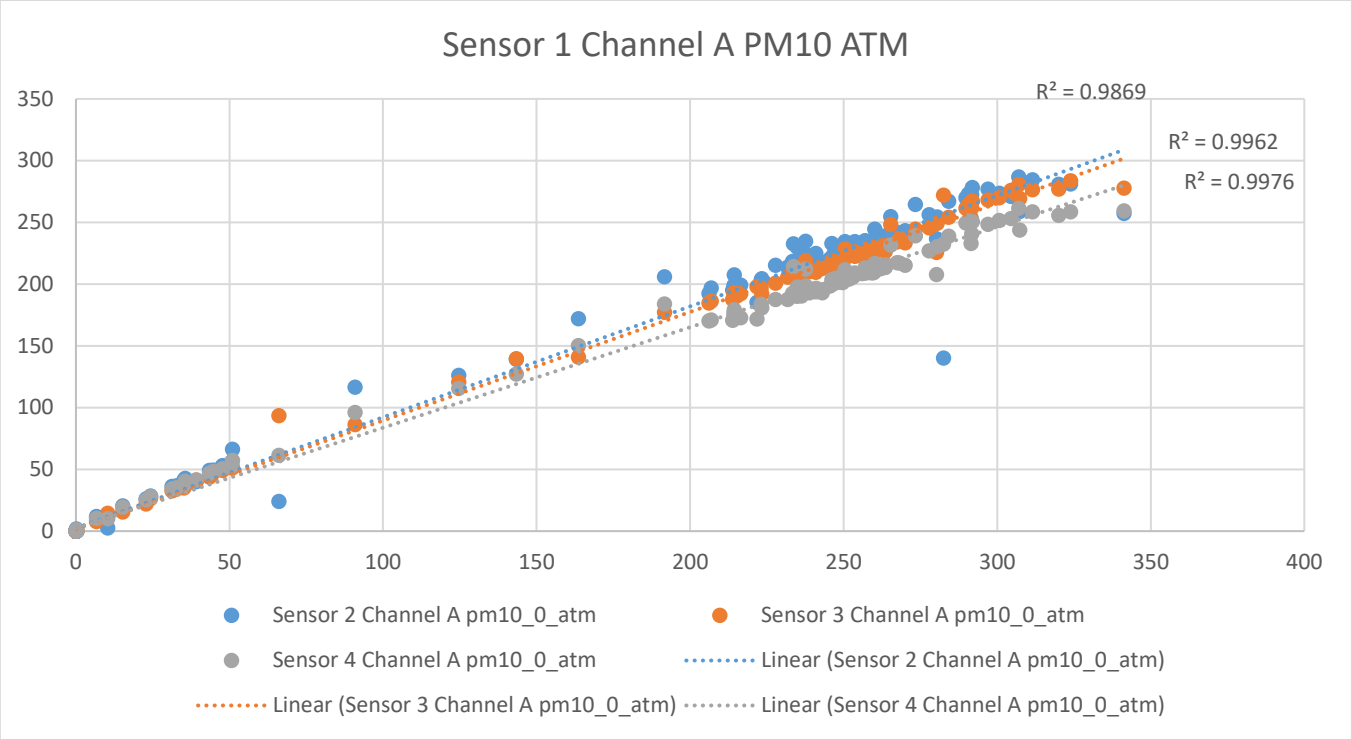

Figure A9: Sensor Comparison between Sensors 1-4 for PM10 ATM

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