Article

Calibration of PurpleAir PA-I and PA-II monitors using daily mean $PM_{2.5}$ concentrations measured in California, Washington, and Oregon from 2017 to 2021

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Abstract: Large quantities of real-time particle data are becoming available from low-cost particle monitors. However, it is crucial to determine the quality of these measurements. The largest network of monitors in the United States is maintained by the PurpleAir company, which offers two monitors: PA-I and PA-II. PA-I monitors have a single sensor (PMS1003) and PA-II monitors employ two independent PMS5003 sensors. We determine a new calibration factor for the PA-I monitor and revise a previously published calibration algorithm for PA-II monitors (ALT-CF3). From the PurpleAir API site, we downloaded 83 million hourly average $PM_{2.5}$ values in the PurpleAir database from Washington, Oregon, and California between January 1, 2017 and September 8, 2021. Daily outdoor $PM_{2.5}$ means from 194 PA-II monitors were compared to daily means from 47 nearby Federal regulatory sites using gravimetric Federal Reference Methods (FRM). We find a revised calibration factor of 3.4 for the PA-II monitors. For the PA-I monitors, we determined a new calibration factor (also 3.4) by comparing 26 outdoor PA-I sites to 117 nearby outdoor PA-II sites. These results show that PurpleAir $PM_{2.5}$ measurements can agree well with regulatory monitors when an optimum calibration factor is found.

Keywords:sensors; low-cost particle monitors; calibration factor; PurpleAir; particles; $PM_{2.5}$; ALT-CF3; algorithm; PMS1003; PMS5003

1. Introduction

Recently a revolution has occurred with the development of low-cost particle sensors [1]. Many of these monitors operate continuously, often silently, and often data are transmitted in real time to cloud databases that can be accessed through Application Programmer Interfaces (APIs).

One example of this development is the large-scale community of users of PurpleAir monitors (https://www2.purpleair.com/). More than 20,000 PurpleAir monitors have been monitoring both outdoor and indoor fine particles at some time since 2017, although numbers were small before 2018. Two monitor types (PA-I and PA-II) are sold by PurpleAir. The PA-I monitor is recommended for indoor use. It contains a single sensor (PMS 1003) manufactured by Plantower (http://www.plantower.com/en/). The PurpleAir PA-II monitor is recommended for outdoor use. It contains two Plantower PMS 5003 sensors. The two sensors are independent and can be compared to determine the level of agreement. Except for sites designated as private by users, data on sites, access keys, and the latest sensor readings are publicly accessible using an API provided by the PurpleAir company (https://api.purpleair.com/), with complete real-time data available via the Mathworks Thingspeak API (https://www.mathworks.com/help/thingspeak/rest-api.html).

Multiple studies have examined the PMS 5003 sensor, either alone or as contained in the PA-II monitor[2,3]. The 1003 and 5003 sensors have been compared in several studies [4-6]. These studies have raised questions about how accurately PurpleAir (Plantower) sensors respond to particles of known size [7]. Laboratory studies of multiple common indoor sources of fine particles found widely varying responses of all low-cost sensors measured, including the Plantower sensors [8,9]. The AQ-SPEC program (http://www.aqmd.gov/aq-spec) found that the PA-II monitor has good precision but $PM_{2.5}$ readings read high by approximately 40%.. One California study applied geographic regression to compare 54 PurpleAir outdoor sites with 26 regulatory monitors providing 128,777 paired $PM_{2.5}$ measurements [10]. This study also found an overestimation of $PM_{2.5}$ concentrations using the CF1 algorithm provided by Plantower. A USEPA study of several US locations derived a model for estimated $PM_{2.5}$ including the effect of relative humidity; the model multiplies the CF1 estimate by about 0.54 [11]. Another study found that the CF1 algorithm required a calibration factor of 0.53, indicating nearly 100% overestimation [12].

The *precision* of the PA-II monitors is a crucial input in judging their accuracy. Precision is defined here as the absolute difference between the A and B sensors in a single PA-II monitor divided by their sum: precision = abs(A-B)/(A+B). For two sensors, this corresponds to the relative standard deviation (RSD)/√2. The mean precision of 350,000 indoor and outdoor measured $PM_{2.5}$ concentrations from PA-II monitors was 6% [13]. The median or geometric mean precision was 4-5%. The independence of the two PMS 5003 sensors makes it possible to identify observations with poor precision. This allows investigators to filter data by selecting a cutoff precision. For this quality-assured data, a single adjustment (the calibration factor, or CF) can remove much of the bias and bring the readings close to the measured concentrations of a regulatory or research-grade instrument.

A basic limitation is our dependence on the Plantower PMS 1003 and PMS 5003 sensors. Studies referenced above document serious limitations in the response of these sensors to particles in the three smallest size categories that we use in the present research to calculate $PM_{2.5}$ concentrations using the ALT-CF3 method. Nevertheless, when we compare the sensors to these research-grade instruments we find the correlations to be high. This is largely due to the good precision of the sensors (mean values of 4-6%), with more than 90% of values showing a precision better than 20% [13]. In practice, we can correct for bias by finding the proper calibration factor. Of course, the bias may vary unpredictably due to variation in particle composition. If this is the case, then it would be impossible to achieve good agreement with research-grade instruments or regulatory monitors. However, applying the single correction factor of 3 to all data, we find quite high R^2 values (median 0.92 within a narrow IQR of 0.89 to 0.94) when compared to 95 regulatory monitors over typical periods of hundreds of days [13,14]. This is evidence that even though the bias may be large, the dependability and repeatability of the response are high. Therefore we hypothesize that a simple correction to the bias (the CF estimate) can produce good agreement with research-grade instruments.

The PurpleAir API site offers several calibration-factor algorithms for adjusting downloaded data. Two of these are proprietary algorithms offered by the manufacturer (Plantower) of the PMS 1003 and PMS 5003 sensors used in the PurpleAir PA-I and PA-II monitors, respectively. The two algorithms are called CF1 and CF_ATM and are recommended for indoor and outdoor use respectively [15]. These algorithms act as "black boxes" since Plantower does not reveal the composition or density of the aerosol used to calibrate the monitors, nor the operations employed to translate from the estimated particle numbers to a mass concentration. Since their methods are hidden, the company could theoretically change their methods at any time and users might not be able to detect the change. In fact, in March 2022, Plantower made a change that seemed to cut the total number of particles by about a factor of 3. The change resulted in causing about a 95% drop in the number of particles in the smallest size category 0.3-0.5 µm. Whereas formerly this category typically produced about 17% or 1/6 of the total $PM_{2.5}$ mass, it produced less

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than 1% of the mass in the new monitors (unpublished data). At this writing (early May, 2022) it is not known whether the change will be permanent.

An alternative approach was developed to provide a transparent algorithm to replace the proprietary algorithms provided by Plantower (Wallace et al., 2021[13]). This approach (ALT-CF3) uses the particle numbers reported by Plantower in the three size categories 0.3-0.5 μm, 0.5-1 μm, and 1-2.5 μm. Selecting an average particle size in each category and calculating the particle volume, followed by multiplying by an assumed density (in this case, the density of water), provides an alternative estimate of $PM_{2.5}$. This estimate for 33 outdoor PurpleAir monitors was then compared to 27 nearby regulatory monitors over a 20-month period from November 2018 to Jun 30, 2020 to provide a final calibration factor. Four different approaches to determining the CF resulted in estimates ranging from 2.93 to 3.14, with a final estimate of 3.05 (SE 0.05).

The ALT-CF3 algorithm performs better than the Plantower algorithm (smaller bias, better precision, higher accuracy, lower limit of detection, improved distribution characteristics), and has been made available for download as an alternative to the Plantower algorithms on the PurpleAir API site. On this API site, the ALT-CF3 algorithm is given the name "PM2.5 alt". Of various alternatives offered by PurpleAir, the ALT-CF3 algorithm is the only one that does not incorporate the proprietary Plantower algorithms. We use and evaluate the ALT-CF3 algorithm in the present study.

In this paper, we determine a revised calibration factor for PA-II monitors using all PurpleAir monitors located near regulatory $PM_{2.5}$ Air Quality System (AQS) monitors using Federal Reference Methods (FRM) in the West Coast states of Washington, Oregon, and California between the dates of Jan 1, 2017 through Sept. 8, 2021. We also determine a new calibration factor for PA-I monitors by comparing to nearby outdoor PA-II monitors.

2. Materials and Methods

2.1. Obtaining the Data

We created a custom R package containing scripts to automate downloads of hourly data using the API for the Mathworks ThingSpeak cloud database for PurpleAir data and compute hourly $PM_{2.5}$ concentrations from size-specific particle counts. The R package was also used to compute daily mean $PM_{2.5}$ concentrations from the downloaded hourly data, using the ALT-CF3 algorithm. We required at least 18 valid hourly measurements for a given daily mean to be accepted into the final database. We removed negative numbers, zeros, "NA" notations, and duplicates. We also removed readings for the PA-II indoor and outdoor measurements if the two independent "A" and "B" PMS-5003 sensors did not agree within a precision of 20%. Also, individual sites were required to have at least 30 daily $PM_{2.5}$ averages. Our present dataset runs over a 56-month period from January 2017 to September 8, 2021 in three U.S. states-- Oregon, Washington, and California. We used the ALT-CF3 algorithm, as described above, to adjust $PM_{2.5}$ for all downloaded data.

There is a direct relationship between the number of particles per deciliter in the three smallest size categories (N1, N2, N3) and the ALT-CF3 $PM_{2.5}$ estimate. This relationship is

$$PM_{2.5} = 3(0.00030418*N1 + 0.0018512*N2 + 0.02069706*N3) \quad (1)$$

The number of particles per deciliter N1 in the smallest size category is found by subtracting the Plantower-provided number ">= 0.5-1 um" from the number ">=0.3-0.5 um". N2 and N3 are found by similar subtractions from the next-higher sets of size categories. The factor of 3 shown is the CF; any change in the CF would only affect that factor and not the other coefficients.

No computation is required to download the "PM2.5 alt" variable in the PurpleAir API site; PurpleAir staff have already performed the operation using the equivalent of equation (1). Also, the "ALT-CF3" algorithm, available as an alternative "conversion factor" in the PurpleAir mapping page has also had the above computation performed by the PurpleAir staff.

2.2. Federal and State Agency data

The US EPA Air Quality System (AQS) supports monitoring stations around the country. These sites operate two main types of monitors. The Federal Reference Method (FRM) collects a single sample over 24 hours on a filter that is weighed under strict conditions of relative humidity (RH) and temperature. The Federal Equivalent Method (FEM) measures hourly $PM_{2.5}$ concentrations. Daily average $PM_{2.5}$ concentrations are accessible at https://aqs.epa.gov/aqsweb/airdata/download_files.html.

For the years 2017 through 2020, the FRM and FEM data were downloaded from that site. For the year 2021 (up to Sept. 8), the data were obtained from various State and Regional Agencies.

2.3. Recalibration of PA-II monitors with PMS-5003 sensors

We re-examined the estimated calibration factor of 3.0 for PA-II monitors using a larger sample of PurpleAir monitors over a longer period (>4 years) than previously used [13].

Our general approach to determining the revised calibration factor for outdoor PA-II monitors is outlined here:

1. Identify all PurpleAir sites within a specified distance of the target site (e.g., an FRM site)
2. Download the hourly average $PM_{2.5}$ data calculated using the published calibration factor of 3 in the ALT-CF3 or "PM2.5 alt" algorithms
3. Regress the $PM_{2.5}$ daily measurements at these sites on the target (regulatory) site $PM_{2.5}$ measurements
4. Find the best-fitting (revised) calibration factor by minimizing the mean absolute error (MAE) or the root mean squared error (RMSE) for all pairs of sites

2.5. New calibration of PA-I monitor with PMS-1003 sensor

Because the PurpleAir company offers its PA-I monitor specifically for use indoors, there are many more PA-I monitors used indoors than PA-II monitors (3191 compared to 981) over our 4.7 year period. To our knowledge, the PA-I monitors do not have a recognized calibration factor. Therefore we developed a CF specifically for this sensor. Since indoor sites have no expected similarity to nearby indoor sites, we were limited to comparing ***outdoor*** PA-I sites to nearby outdoor PA-II sites. We required (1) at least 30 days of joint measurements and monitor operation greater than or equal to 18 hours each day and (2) that the two sensors in the PA-II monitors have a precision better than 20%.

For this case, there are too few PA-I outdoor sites to be able to compare with nearby regulatory sites. Instead, we compare with nearby PA-II outdoor sites using step 3 above, except that the "target" site is now a PA-II outdoor site. Step 4 above will now give us a calibration factor for the PA-I monitors *that is related to the calibration factor* of the PA-II monitors. That is, we may find that the PA-I monitors are reading about 10% higher than the PA-II monitors. In that case, the relative calibration factor of 1.1 times the CF (=3) of the PA-II monitors, would be 3.3.

3. Results and Discussion

3.1. Recalibration of PA-II monitors by comparison with regulatory monitors

Following the quality control measures described above, the PurpleAir PA-II outdoor data consisted of 83,304,477 million hourly observations at 10,235 sites. Requiring the precision to be better than 20% reduced the total number to 77,277,831 hourly observations at

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9,347 sites, a loss of 7.2% of all observations. These were averaged to provide 3,529,229 daily observations (Figure S1 in the Supplementary Information). Daily mean measurements from 95 Federal and State regulatory monitors in the three-state region were also obtained (Figure S2). The outdoor mean $PM_{2.5}$ concentrations and related statistics from these two fundamental datasets are provided (Table S1 and Table S2).

From these PA-II sites, we selected all those within a distance of 0.5 km from a regulatory monitor to match our previous choice [13]. 182 PA-II outdoor monitors and 47 regulatory monitors in three states provided 39,494 pairs of sites averaging about 300 days of joint measurements. About 12 million daily averages were recorded. We regressed the PurpleAir PA-II estimates of $PM_{2.5}$ on those of the regulatory monitors, using the published value of 3.0 as the calibration factor for the ALT-CF3 algorithm. The minimum root mean squared error (RMSE) of 2.14 μg/m^3 occurred at a CF of 1.11 times the old CF of 3 and the minimum mean absolute error (MAE) of 1.46 μg/m^3 occurred at a CF of 1.13 times the old CF. These values would support an upward revision of 11%-13% applied to our previous CF of 3.0, or a new estimated CF in the range of 3.33 to 3.39, or about 3.4. The new CF (3.4) and old CF (3.0) $PM_{2.5}$ values are compared to the regulatory $PM_{2.5}$ values (Table 1).

Table 1. Comparison of old and new calibration factors for PA-II monitors with regulatory monitor measurements of $PM_{2.5}$ (μg/m^3)

	N	Mean	Std. Err.	min	Z=−1*	median	Z=1*	max
PM2.5	39474	11.5	0.076	0.042	3.9	8.5	17	577
PM2.5 CF3.4	39474	11.0	0.090	0.164	2.6	6.2	18	464
PM2.5 CF3	39474	9.9	0.080	0.146	2.3	5.5	16	414

*one normal probability standard deviation below or above the median

In Figure 1, we have applied an upward correction of 12% (new CF 3.4) to the PurpleAir PA-II outdoor monitors. Figure 1 displays selected percentiles for all 39,474 daily mean outdoor $PM_{2.5}$ measurements from the PurpleAir data using the new CF of 3.4 matched with the AQS (regulatory monitors) data. The data are displayed in terms of standard deviations of the normal probability curve (the Z-score). That is, the median daily average value is plotted at 0, the 16th and 84th percentiles at -1 standard deviation and +1 standard deviation, etc. The maximum outdoor PurpleAir daily average was 464 ug/m3 and the minimum daily average was <0.1 μg/m^3. Reasonable agreement with the regulatory monitors is evident throughout the entire range of concentrations from <0.1 μg/m^3 to 464 μg/m^3. On this log-normal probability graph, a log-normal distribution would appear as a straight line. Although not perfectly straight, there is a fair approximation to a log-normal distribution. A physical explanation of why many environmental datasets display a nearly log-normal distribution has been provided [16].

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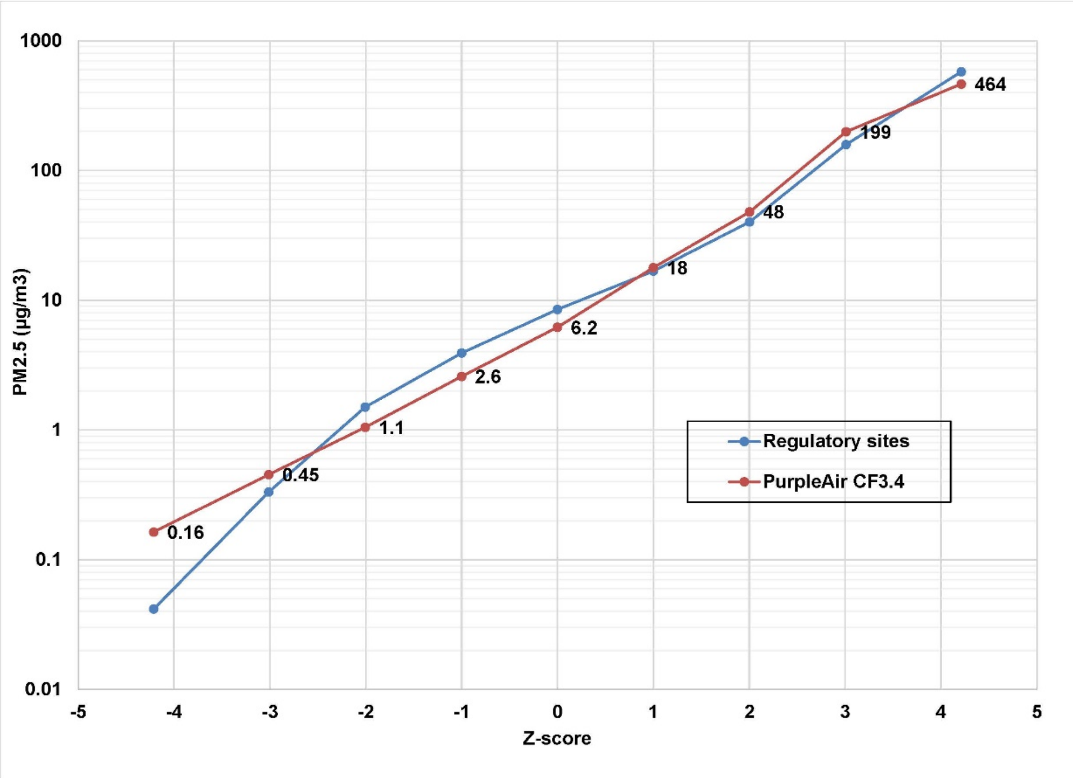

Figure 1. Comparison (using revised CF of 3.4) of 39,474 daily average $PM_{2.5}$ measurements by 182 PurpleAir PA-II outdoor monitors within 0.5 km of 47 Federal and State Agency regulatory monitors in three states. Data labels are shown for the PurpleAir sites. The associated regulatory monitor values are not displayed but can be read from the graph. The x-axis shows the normal probability standard deviations (Z-score). A Z-score of zero corresponds to the median value.

3.2. New calibration of the outdoor PA-I monitor with PMS 1003 sensor vs. outdoor PA-II monitors

We located 194 outdoor PA-II sites within 1 km of 43 outdoor PA-I sites. 117 pairs of sites including 26 unique PA-I outdoor sites met our quality assurance requirements. The PA-II monitors were required to have a precision better than 20%. The paired sites produced 24,924 matched pairs of outdoor PA-I and Pa-II monitors with each pair having from 33 to 365 days of valid data.. Since the PA-I monitors do not have a second sensor, we minimized possible PA-I outliers by requiring that PA-I values differ by no more than a factor of 3 from the associated PA-II values. This resulted in a final dataset of 23,120 pairs. Mean (standard error) values of $PM_{2.5}$ for the 23,120 days were 5.81 (0.07) µg/m^3 for the PA-I monitors and 6.04 (0.07) µg/m^3 for the PA-II monitors

We regressed the PA-I monitor on the PA-II monitor for all 117 joint pairs. All slopes were significantly different from zero. The median (IQR) slope was 0.98 (0.90-0.99) and the median (IQR) R^2 estimate was 0.96 (0.81-0.98) (Table 2).

Table 2. Statistics for matched outdoor PA-I and PA-II monitors, including calculations of the slopes, R^2 estimates, standard error of the estimate (µg/m^3), and the number of days monitored for each pair.

Statistic (N=117 sites)	Mean	Std. Err.	Lower quartile	Median	Upper quartile	90th Percentile	Max
slope (centered)	0.93	0.0094	0.90	0.98	0.99	0.99	0.999

Adjusted R^2	0.87	0.016	0.81	0.96	0.98	0.99	0.998
Std. Err. of Estimate	1.7	0.10	0.81	1.5	2.3	2.8	7.4
Number of days	197	10.4	92	178	303	344	497

A formal analysis minimizing either the absolute error or the sum of squared errors resulted in an estimated PA-II/PA-I ratio of 1.04 (MAE=1.21 μg/m³) or 0.96 (RMSE = 2.82 μg/m³). That is, the PA-I monitor measurements agreed to within ±4 % of the PA-II monitor measurements, and therefore we assign the same calibration factor of 3.4 to the PA-I monitors. The mean $PM_{2.5}$ values for the 117 PA-I monitors are regressed against the mean $PM_{2.5}$ values of the matched PA-II monitors (Figure 2). The slope was 1.01 with an R^2 of 94%.

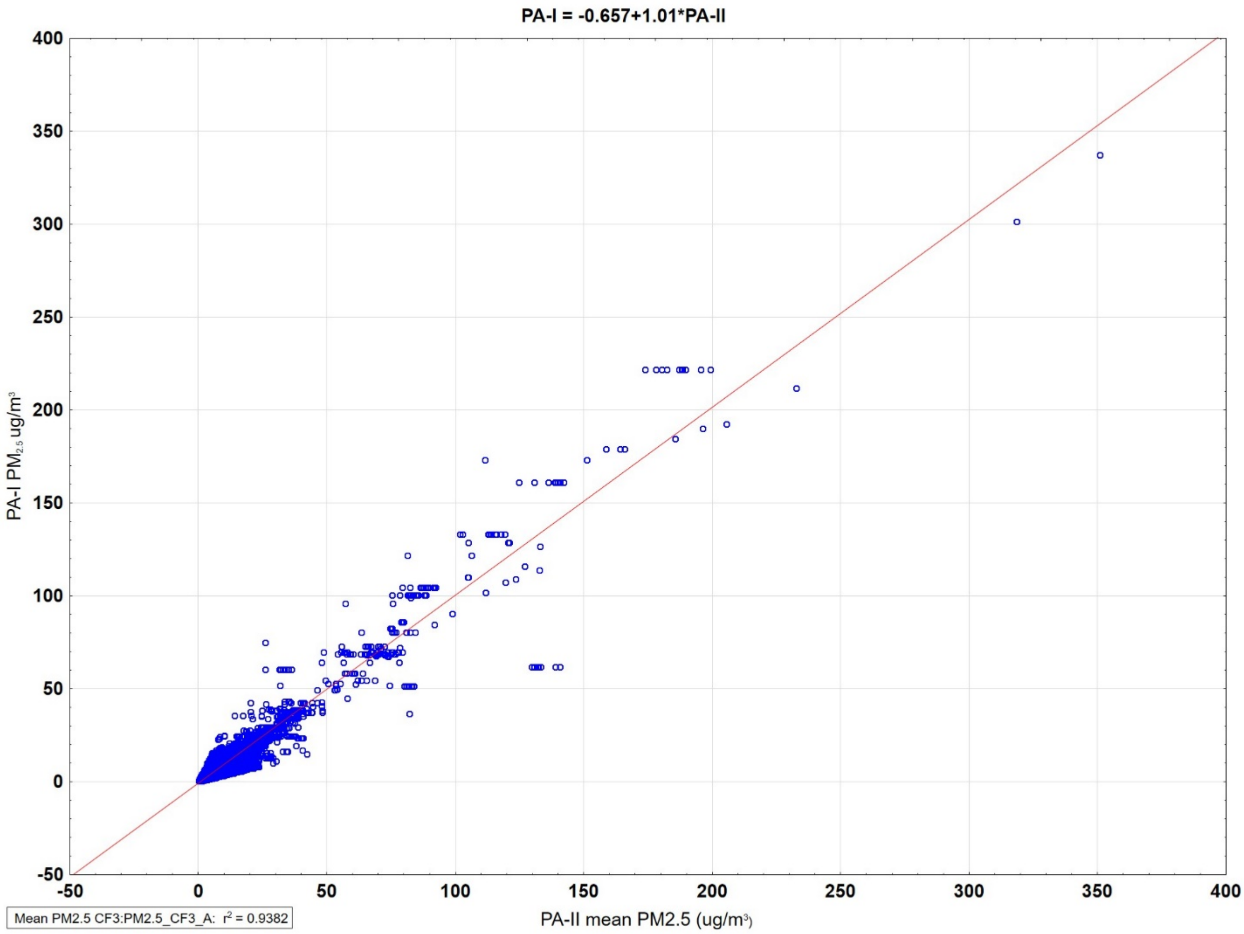

Figure 2. PA-I outdoor $PM_{2.5}$ **averages are regressed against matched mean PA-II outdoor averages at 117 sites less than 1 km distance apart.**

3.3. Comparison with other algorithms and effect on the AQI

Published calibration factors based on the Plantower CF_1 algorithm, such as the value of 0.53 [12] and the EPA value of 0.54 [11], indicate that the CF_1 algorithm overestimates PM2.5 concentrations, perhaps by nearly a factor of 2. This is also true for the ALT-CF3 algorithm, which is not based on CF_1 but results in $PM_{2.5}$ estimates similar to [11,12]. The EPA Air Quality Index (AQI) is a useful way of gauging the outdoor air quality. Community information systems use color shadings to indicate the air quality on a real-time basis. The PurpleAir maps show the Plantower CF_1 PM2.5 concentrations with the appropriate color shadings as a default. However, the evidence is that these concentrations are overestimates and that therefore many people are seeing air quality estimates that are worse than the reality. PurpleAir offers the other algorithms as alternatives, but it may be that most people accept the default option. This could be a topic for discussion in the future.

4. Limitations

All optical monitors will respond to the increase in aerosol diameter due to an increase in relative humidity (RH) [17]. The effect is expected to manifest itself strongly at RH in the 60%-80% range. However, PurpleAir PA-II monitors have been shown to maintain an internal temperature about 8 ^{o}C above ambient temperatures and a corresponding *decrease* of about 15 percentage points in RH [13]. The mean RH of 33 outdoor PA-II monitors in the cited study had a diurnal variation of 30%-56% RH, never reaching the level at which deliquescence is observed for common atmospheric salts such as KCl, Na2SO4 and (NH4)2SO4 [18]. Another study observed a rather small effect at RH levels below 50% [19]. For long-term studies such as this one, the variation of RH over the multiday monitoring periods will tend to dilute the effect of high RH for a few hours in a minority of days. Therefore we have not attempted to incorporate a correction for RH. Another recent study found the RH effect was too small to include in their model [12].

5. Summary and Conclusions

About 83 million hourly averages of outdoor PurpleAir $PM_{2.5}$ data in three states over a 4.7-year period were downloaded from the PurpleAir API site. 77 million observations (92.8%) met the requirement of precision better than 20%. These hourly values were further averaged to form about 3.5 million daily outdoor averages and compared to about 66,000 daily averages at nearby Federal and State Agency regulatory monitors.

A revised calibration factor (CF) of 3.4 based on comparisons of 182 PurpleAir PA-II monitors with 47 Federal and State agency regulatory monitors in three states and over the entire 4.7-year time period was developed. The revised CF of 3.4 represents about a 12% increase over the current CF of 3 used in the ALT-CF3 algorithm.

A new calibration factor for the PA-I monitors with a PMS1003 sensor was determined to be within ±4% of the CF for the PA-II monitors and therefore is also estimated at 3.4. This result suggests that the large amount of indoor $PM_{2.5}$ data collected by PA-I monitors may be considered on a par with the smaller amount of indoor data collected by PA-II monitors.

These results show that PurpleAir data can agree well with regulatory monitors when an optimum calibration factor is found.

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