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Technical note: Identifying a performance change in the Plantower PMS 5003 particulate matter sensor

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ABSTRACT

Communities, researchers, and citizen scientists have increasingly been deploying low-cost particulate matter (PM) sensors to understand pollution levels and personal pollution exposure. Currently, tens of thousands of these low-cost sensors have been deployed throughout the world. One of the most commonly used sensors is the Plantower PMS 5003. In 2021, PurpleAir (one of the largest sensor networks) noted a change in the performance of their PM sensors that could be identified by the ratio of PM counts in two size bins ($\geq$0.3 μm and $\geq$0.5 μm). This study confirmed that in June 2021, an updated version of the Plantower PMS 5003 (PMS-U) was deployed between approximately June 2021 and January 2022. Our laboratory study revealed that the PMS-Us $PM_{2.5}$ concentrations were biased low for raw concentrations (CF = 1) below 16 μg/m^3. Our field study also suggests that this bias translates into an approximately 3 μg/m^3 lower $PM_{2.5}$ concentrations (raw) over the long term, and between March to May 2023, more than 10% of outdoor sensors in the PurpleAir network are PMS-Us. This level of bias would not affect some uses of low-cost sensor networks, such as during wildfires. However, this bias could be important for health or environmental justice studies. This study also developed and evaluated a correction method for PMS-U sensors to reduce the observed bias in PMS-U sensors.

1. Introduction

Communities, researchers, and citizen scientists have increasingly been deploying low-cost particulate matter (PM) sensors to understand local outdoor pollution levels, indoor air quality, and personal pollution exposure (Do et al., 2021; Hegde et al., 2020; Kelly et al., 2021; Li et al., 2018, 2020; Liang et al., 2021). Currently, tens of thousands of these low-cost sensors have been deployed throughout the world. One of the most-commonly used sensors is the Plantower PMS 5003. It has been extensively evaluated and generally correlates well with atmospheric levels of PM_1 (particulate matter smaller than 1 μm in diameter) and $PM_{2.5}$ (particulate matter smaller than 2.5 μm in diameter) if they tend to be correlated with PM_1 (Ardon-Dryer et al., 2019; Barkjohn et al., 2021; Jaffe et al., 2023; Kaur & Kelly, 2022; Kuula et al., 2019; Malings et al., 2019, pp. 903–920; Molina Rueda et al., 2023; Ouimette et al., 2022; Sayahi, Butterfield, & Kelly, 2019; Kaur & Kelly, 2023; Tryner et al., 2020; Zheng et al., 2018, pp. 4823–4846). It is a key component of common commercially available air-quality sensing networks i.e., PurpleAir (PA) and Clarity.

In spite of their ubiquity, data quality still remains a concern with the use of low-cost PM sensors (Giordano et al., 2021). Some of the concerns for the Plantower series of sensors include the manufacturer's lack of transparency regarding signal processing or quality control (Ouimette et al., 2022). As one example of data quality challenges, PA has a network of more than 12,000 sensors (Barkjohn

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et al., 2022). In 2021, PA reported that changes in the Plantower PMS's 5003 circuit board caused differences in the reported particle size distributions and concentrations (PurpleAir, 2022). Specifically, Plantower's changes reduced the particle counts in the >0.3 μm bin size by a factor of three compared to the previous version of the Plantower PMS5003 (PurpleAir, 2022). The US EPA also noted the appearance of "new" PA sensors in a 2022 meeting. (Barkjohn, 2023).

This study aims to understand the timing of the Plantower change and the effect on $PM_{2.5}$ concentrations measurements in the laboratory and field, as well as to propose a method for addressing the bias in the Plantower PMS5003s.

2. Methods

This study aims to understand any differences in performance of the updated PMS5003 (PMS-U) compared to the original PMS5003 (PMS-O). Specifically, it addresses when PMS-Us began appearing in the field, whether the PMS-Us exhibit different performance in the field, and the concentration ranges where performance might differ. Additionally, we developed a correction factor to apply to PMS-U sensors to minimize the difference between their measurements and the measurements of PMS-O sensors.

2.1. Field data collection, quality control, and averaging

We examined two sample periods: June 2022 through August 2022 (P1) and March 2023 through May 2023 (P2) by gathering concentration and count measurements available through PA's application programming interface (API) for public, active PA sensors (Fig. 1). Sensors that were marked as indoors, without location data, or without PM nodes were removed from the evaluation. The sensors used in sample P1 were deployed between August 2016 and August 2022. A total of 16,620 sensors were accessible in sample P1. The sensors used in sample P2 were deployed between August 2016 and May 2023, and a total of 16,423 sensors were accessible in sample P2. The sensor's "first seen date" field provided by the API was used as the sensor deployment date.

Sensors with less than 75% $PM_{2.5}$ concentration measurement completion were removed from the analysis. An average $PM_{2.5}$ concentration between the two Plantower PMS5003 nodes present in each PA sensor was taken for each 6-h sample interval over each sample period. We followed the EPA's method for removing dual PMS sensors that did not agree with each other (Barkjohn et al., 2021). In addition, if one node was identified as downgraded by PA's API, it was removed from the analysis and only the second node's measurements were used. If both nodes were identified by downgraded by PA's API, the PMS sensor and its pair were removed from the analysis.

The PA sensors collect PM counts every second and report time-averaged concentrations at 2-min intervals. For both sample periods (P1 and P2), the $PM_{2.5}$ mass concentrations and PM counts (≥0.3 μm diameter and ≥0.5 μm diameter) for all the active sensors were averaged over 6-h time intervals. For some evaluations, we used the average of the 6-h averages for each sensor location over the entire time period (P1 or P2). These averages are referred to as the average over the sample period (P1 or P2). This study used $PM_{2.5}$

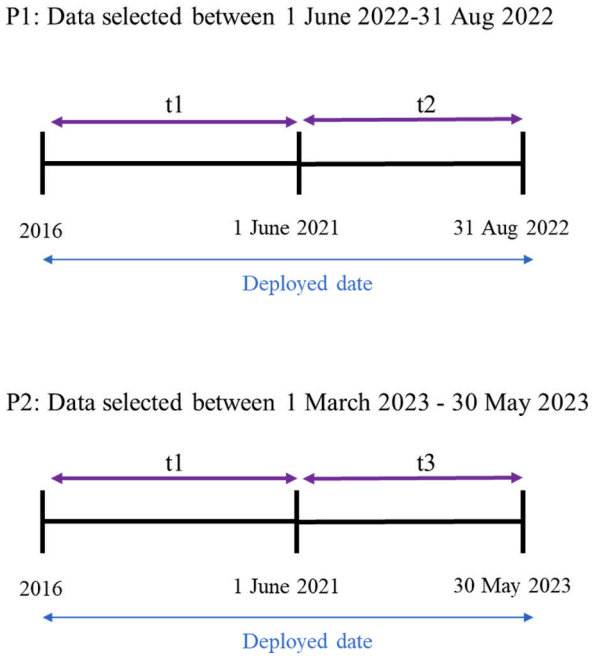

Fig. 1. Sample periods. Study period 1 (P1) lasts from June 2022 through August 2022 and includes sensors deployed between 2016 and May 2021 (t1) as well as sensors deployed between June 1, 2021 through August 31, 2022 (t2). Study period 2 (P2) lasts from March 2023 through May 2023 and includes sensors deployed between 2016 and May 2021 (t1) as well as sensors deployed between June 2021 through May 30, 2023 (t3).

concentrations corresponding to CF = 1, and no correction factors were applied to the $PM_{2.5}$ measurements.

2.2. Determining when PMS-U began appearing in the field and their prevalence

PA suggested a ratio of 0.4 (counts of ≥0.5 μm bin divided by counts of ≥0.3 μm bin) as a threshold for differentiating PMS-U from PMS-O (PurpleAir, 2022), and we applied this threshold of 0.4 to define sensors as PMS-U (ratio >0.4) or PMS-O (ratio ≤0.4). We calculated the average of the (≥0.5 to ≥0.3 count) ratio from each sensor over P1 and P2 and plotted this against the deployment date (Fig. 2 and Fig. S1). Fig. 2 suggests that the updated sensors began being deployed in June 2021. On approximately June 20, 2021, a clear increase in sensors with ratios above the 0.4 threshold can be observed. Only 53 of the 16,620 sensors (0.32%) had a ratio above the threshold and were deployed before June 2021. These 53 sensors were removed from further analysis in this study. Fig. 2 also suggests that PMS-Us began to be removed from the market in January 2022. However, the majority of PMS-Us deployed between June 2021 and January 2022 appear to remain in the field. For example, between June 2021 and May 2023, a total of 2117 of 16,423 sensors (12.9%) were PMS-Us.

Using the ratio of 0.4 to distinguish between PMS-O and PMS-U sensors, we determined the percentage of PMS-U sensors that were deployed between January 2021 and March 2023. Average ratios were calculated using the particle count measurements taken during sample P2. Fig. 3 displays the percentage of PMS-U sensors deployed every month between January 2021 and March 2023. The results suggest that PMS-U sensors first appeared during June 2021. The majority of sensors deployed between July 2021 and December 2021 were PMS-U sensors. In January 2022, the percentage of PMS-U sensors significantly decreased and remained below 20% through March 2023.

2.3. Do the PMS-Us have different field performance than the PMS-Os?

The $PM_{2.5}$ concentrations were compared between PMS nearest neighbors to understand whether PMS-Us could affect estimates of $PM_{2.5}$ concentrations. Each PMS-U sensor was paired with the absolute nearest PMS-O neighbor (within 1 mile and 500 feet elevation of each other using the geographic coordinate data provided by the API). PMS-U sensors that did not have a PMS-O pair that met these criteria were removed from the analysis. PMS-O sensors that were not selected as the absolute nearest sensor for any PMS-U sensor were also removed from the analysis. We compared PMS $PM_{2.5}$ concentrations under two different scenarios. First, we compared the $PM_{2.5}$ concentrations of PMS-U sensors (ratio >0.4) with their nearest-neighbor PMS-O paired sensors (ratio ≤0.4). This scenario included 498 nearest-neighbor pairs during P1 and 369 sensor pairs during P2. Figs. S2 and S3 display the valid sensor pairs' average ratio over P1 and P2, respectively. Second, we compared the $PM_{2.5}$ concentration of PMS-O sensors during the following intervals: 1) PMS-O deployed before June 1, 2021 (PMS-O-t1) and PMS-O sensors deployed between June 1, 2021 and August 2022 (PMS-O-t2) for P1, 2) PMS-O deployed before June 1, 2021 (PMS-O-t1) and PMS-O sensors deployed between June 1, 2021 and May 2023 (PMS-O-t3) for P2. This evaluation was performed to identify any difference in the performance of PMS-O sensors before the introduction of PMS-U sensors. This scenario included 291 sensor pairs in P1 and 620 sensor pairs in P2.

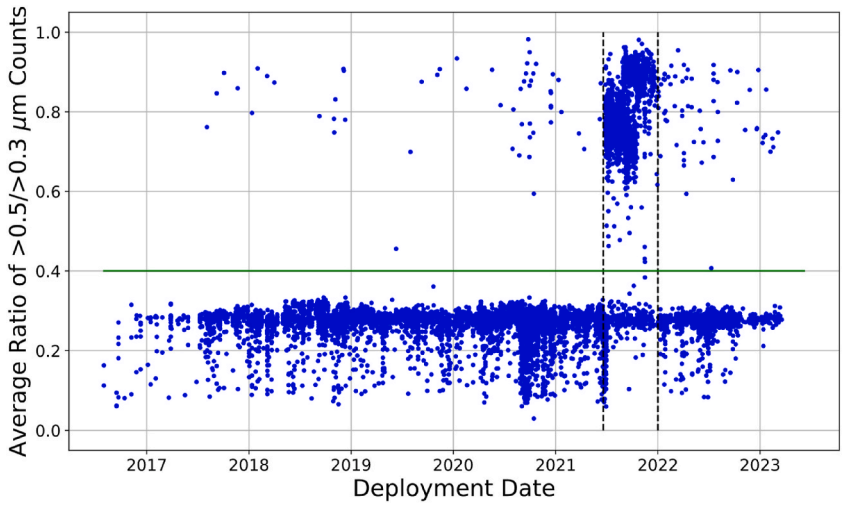

Fig. 2. Ratio of PM counts in size bins ≥0.5 μm and ≥0.3 μm during P2 (March 2023 through May 2023) vs. sensor deployment date for PA sensors deployed between August 2016 and May 2023. Each dot indicates a PMS sensor's average ratio taken over sample P2. The vertical dashed black lines indicate June 1, 2021 (the beginning of the month when PMS-Us started appearing) and January 1, 2022 (the date at which the deployment of PMS-Us began decreasing). The green line indicates the ratio threshold of 0.4. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

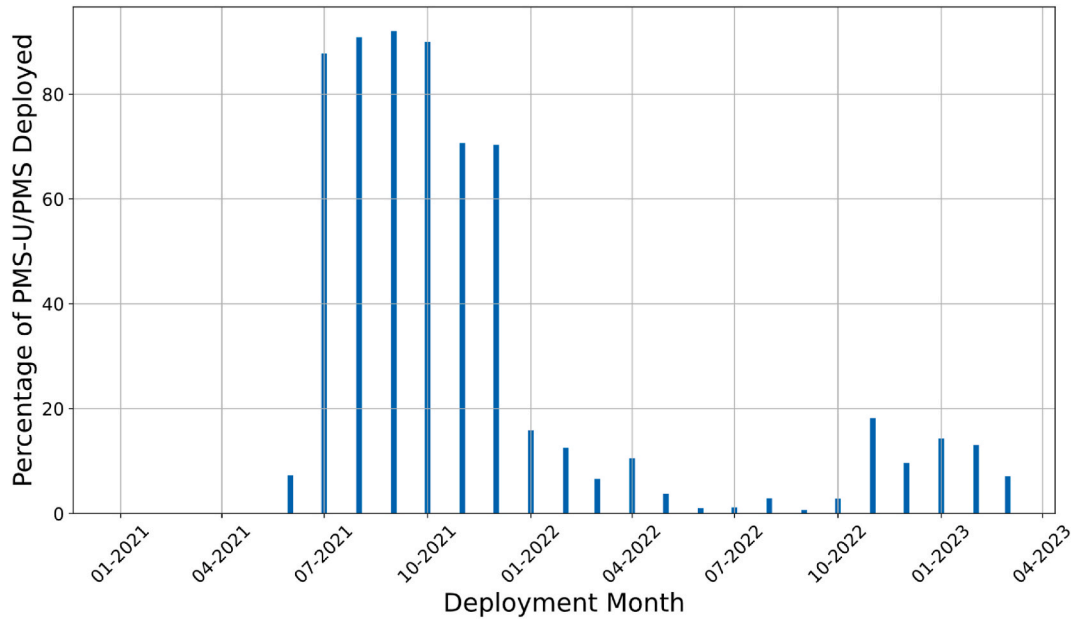

Fig. 3. Percentage of PMS sensors deployed that were PMS-U (average ratio >0.4) by month from January 2021 to March 2023. Average ratios were calculated over sample P2.

2.4. How do PMS-U sensors respond to $PM_{2.5}$ concentrations?

This portion of the study was performed in the laboratory and aimed to understand any differences between the response of the PMS-O and PMS-U sensors in estimating $PM_{2.5}$ concentrations. PA suggested that the PMS-U sensor response differs from that of the PMS-O response only for $PM_{2.5}$ concentrations less than approximately 16 μg/m^3 (PurpleAir, 2022). For the laboratory analysis, we exposed 4 PMS-Os and 4 PMS-Us to different concentrations of ammonium nitrate aerosol. Ammonium nitrate aerosol has a mobility diameter between 14 and 2000 nm with mean mobility diameter at 137 nm (Sayahi, Kaufman, et al., 2019), which indicates that it should be captured by $PM_{2.5}$ or PM_1 measurements. Note, several studies have reported that the PMS5003 is most responsive to PM_1 (Kuula et al., 2019; Ouimette et al., 2022) although it also tends to correlate well with $PM_{2.5}$ (Ardon-Dryer et al., 2019; Barkjohn et al., 2021, 2022; Sayahi, Butterfield, & Kelly, 2019; Zheng et al., 2018, pp. 4823–4846). The $PM_{2.5}$ evaluation took place in a PM sensor calibration chamber, described by Sayahi et al. (2019). Fig. S4 shows the arrangement of the sensors, and Fig. S5 shows a simplified experimental setup (Supplementary Material).

Ammonium nitrate aerosols were generated using an atomizer (TSI model 9302). The concentration of ammonium nitrate solutions (in DI water) was adjusted (100–1000 μg/mL) to obtain the target $PM_{2.5}$ concentrations of 0, 5, 10, 15, 20, 30, 45, 60, ~250, ~460, and ~900 μg/m^3 (uncorrected), as measured by a DustTrak II (TSI 8530) nephelometer equipped with a $PM_{2.5}$ impactor. This research-grade instrument collected measurements at an interval of 15 s. The DustTrak mass concentration estimate for ammonium nitrate was corrected by dividing the DustTrak reported concentrations by a calibration factor of 1.85, developed using DustTrak's collocated gravimetric filter measurement. The corrected concentration set points were 0, 2.7, 5.41, 8.11, 10.8, 16.2, 24.3, 32.4, ~125, ~250, and ~500 μg/m^3. The pressure at the atomizer was set to 7–10 psig, leading to an outlet aerosol flow rate of ~3 LPM. The atomized aerosols flowed through a diffusion dryer. The dried aerosol was diluted with 12 LPM of particle-free air, which subsequently flowed into the chamber (Fig. S5). The aerosol concentrations were allowed to stabilize before taking any PMS measurements.

All the sensors were placed in the chamber at the same time (Fig. S4), but we had more PMS sensors than PA boards, so only 2 PMS-U and 2 PMS-O were evaluated at a time. All the eight sensors (4 PMS-U and 4 PMS-O) remained inside the chamber for the whole testing duration. At a target $PM_{2.5}$ concentration, PMSU1A, PMSU1B, PMSO1A, and PMSO1B were evaluated first for 20 min, then the sensor-board connections were disconnected, and other 4 sensors including PMSU2A, PMSU2B, PMSO2A, and PMSO2B were connected to the board and evaluated for 20 min using the same stable aerosol concentrations. The PMS-O and PMS-U measurements were stored in the cloud, and the sample averaging period was 2 min. For each concentration setpoint, measurements were taken for 20 min, i.e., 10 readings. The PMS measurements corresponding to CF = 1 were used in this laboratory study. For concentrations between 0 and 32 μg/m^3, the PMS sensor measurements were plotted against corrected DustTrak $PM_{2.5}$ measurements, and the results were evaluated using a linear regression. PMS sensors exhibited non-linear behavior at high $PM_{2.5}$ concentrations (>120 μg/m^3), and therefore linear regression analysis were limited to concentrations less than 120 μg/m^3, which in this study was 32 μg/m^3.

2.5. Can the PMS-U $PM_{2.5}$ measurements be corrected to reduce bias between the PMS-O and PMS-U sensors?

Both the PMS-U and PMS-O sensors used the DustTrak for laboratory comparison, and using this property we developed a

correction factor for PMS-U sensors. This factor adjusts raw (CF = 1) $PM_{2.5}$ concentrations below 16 μg/m^3 and can be used to reduce the bias between PMS-U and PMS-O sensors. The supplementary material contains the derivation of the correction factor, which is given by: PMS-U corrected = 1.348 × PMS-U – 2.797. This correction factor was then evaluated for its ability to reduce bias in the laboratory and field results (nearest neighbor pairs).

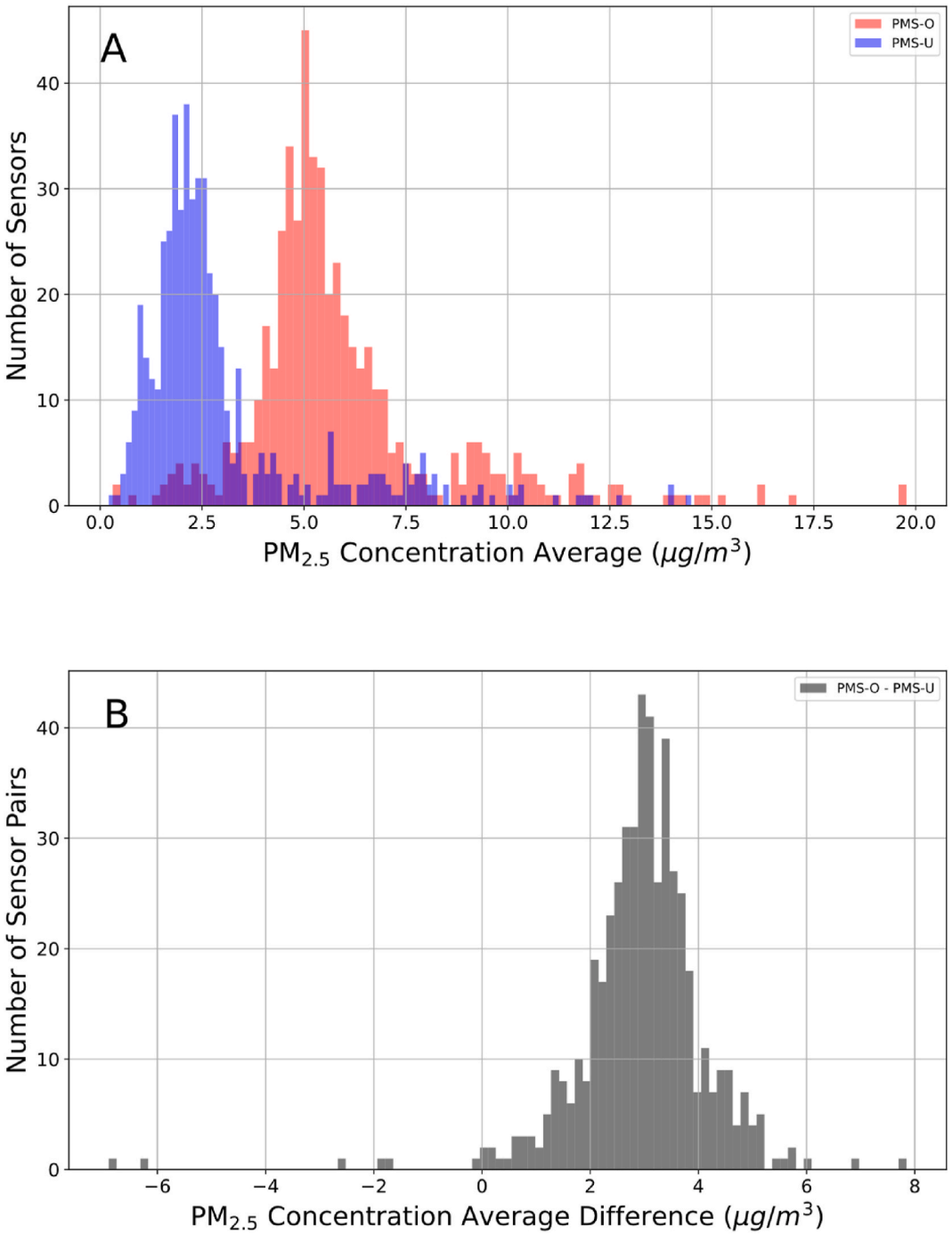

Fig. 4. (a) Average $PM_{2.5}$ concentrations of PMS-O (red) and PMS-U (blue) nearest neighbor paired sensors over sample P1, and (b) average $PM_{2.5}$ concentration differences over sample P1 (PMS-O minus PMS-U). The x-axis range excludes one sensor pair with a mean value that exceeds 20 μg/m^3. Similar analysis for sample period P2 can be found in Fig. S6. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2.6. Statistical analysis

We determined whether the sensor's $PM_{2.5}$ measurements were normally distributed using the Shapiro-Wilk test for normality and the Kolmogorov-Smirnov test for goodness of fit by comparing samples to the normal distribution. Because none of the sensors' measurements were normally distributed, we compared the mean difference between nearest-neighbor pairs for 6-h averages using Wilcoxon signed rank tests with the Bonferroni correction for multiple paired tests. Each of these tests were run in Python using the scipy.stats library. First order linear regression parameters were calculated via the numpy.polyfit library. We compared the difference in laboratory sensor response using one-way ANOVA Bonferroni test using astatsa.com.

3. Results and discussion

3.1. Field performance of the PMS-U and PMS-O sensors

Fig. 4a and b displays the average over P1 of $PM_{2.5}$ concentrations and $PM_{2.5}$ concentration differences, respectively, for PMS-U and PMS-O sensor pairs. Fig. 4a shows that PMS-O and PMS-U exhibit different mean concentrations, indicating a bias in PMS-U $PM_{2.5}$ concentration measurements. Fig. 4b shows that the distribution of the difference between PMS-U and PMS-O (PMS-O minus PMS-U) is not centered around zero, and PMS-U sensors measure 2.94 μg/m^3 less on average than PMS-Os. Comparing the sensor pairs also reveals that 97.0% of PMS-Us had significantly lower average readings than their paired PMS-Os during sample P1. This difference in sensor performance would likely not affect some uses of low-cost PM sensors, such as understanding the impacts from pollution events, like wildfire smoke (Barkjohn et al., 2022), but this difference could be important for researchers using these low-cost sensor networks to perform long-term health or environmental justice studies. For example, Yadzi et al. (2021) found that each 1 μg/m^3 increase in annual $PM_{2·5}$ concentrations increased the absolute annual risk of death by 0·073% (95% CI 0·071–0·076). (Yazdi et al., 2021).

In order to evaluate whether the selected time period might contribute to the observed differences between PMS-O and PMS-U, we also evaluated two PMS-O sensors deployed in different time ranges. Figs. S7a and S7b display the average over P1 of $PM_{2.5}$ concentrations and $PM_{2.5}$ concentration differences, respectively, of PMS-O-t1 (deployed prior to June 1, 2021) and PMS-O-t2 (deployed between June 2021 and August 2022) sensors. The lack of a difference in the histograms between PMS-O-t1 and PMS-O-t2 in Fig. S7b suggests that there is not a significant difference between PMS-Os $PM_{2.5}$ concentrations deployed during the two different time periods. Fig. S7b also shows that the difference between PMS-Os deployed during the two different time periods is much closer to being centered around zero than the distribution in Fig. 4b. Similarly, Figs. S8a and S8b display the average $PM_{2.5}$ concentration and $PM_{2.5}$ concentration difference over P2 between PMS-O-t1 and PMS-O-t3 sensors. The mean difference displayed in Fig. S8b is similarly centered much closer to zero than the PMS-U to PMS-O mean differences displayed in Fig. S6b. These findings suggest that the behavior observed in Fig. 4a and b is unique to the PMS-U sensors.

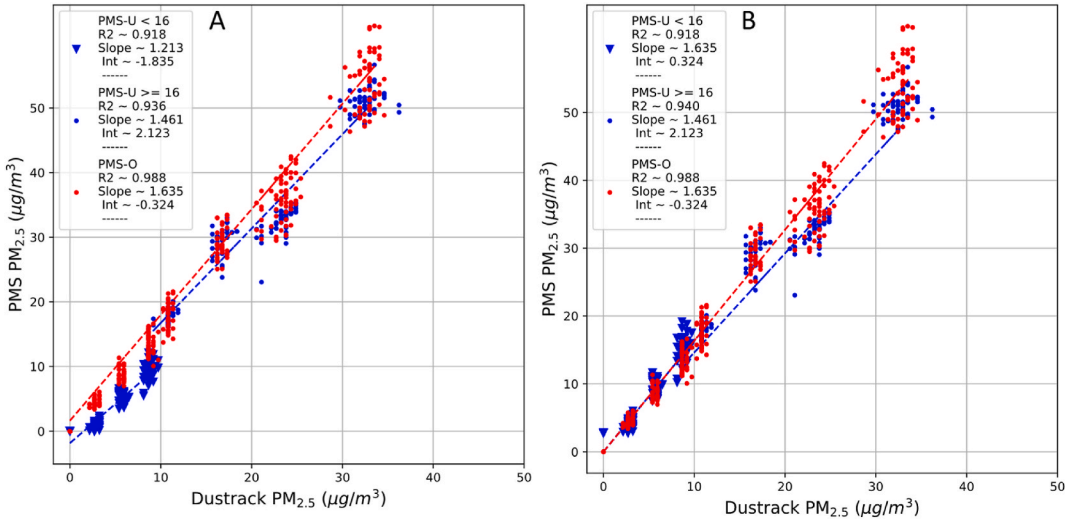

Fig. 5. (a) Raw PMS-U and PMS-O $PM_{2.5}$ concentrations vs. mass-corrected DustTrak $PM_{2.5}$ concentrations. Different behavior was observed for PMS-U sensor for concentrations <16 μg/m^3 and >16 μg/m^3, and therefore two linear regressions were performed. (b) Corrected $PM_{2.5}$ concentrations from PMS-U sensors vs. mass-corrected DustTrak concentrations. For both (a) and (b) PMS-U values < 16 μg/m^3 are marked with blue triangles, PMS-U values ≥ 16 μg/m^3 are marked with blue circles, and PMS-O values are marked with red circles. The linear regression model results are displayed with the corresponding dashed lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.2. Laboratory performance of the PMS-U and PMS-O sensors

Fig. 5a show the combined laboratory PMS-U and PMS-O sensor measurements versus the DustTrak $PM_{2.5}$ measurements of $PM_{2.5}$ concentrations as well as the regression model results. The individual PMS-O and PMS-U sensor linear regression model results are presented in Fig. S9 and Fig. S10. These figures show a high correlation ($R^2 > 0.9$) with the corrected DustTrak $PM_{2.5}$ concentrations in the laboratory. Numerous laboratory studies report high correlations ($R^2 > 0.9$) between the PMS sensors and optical-based, research-

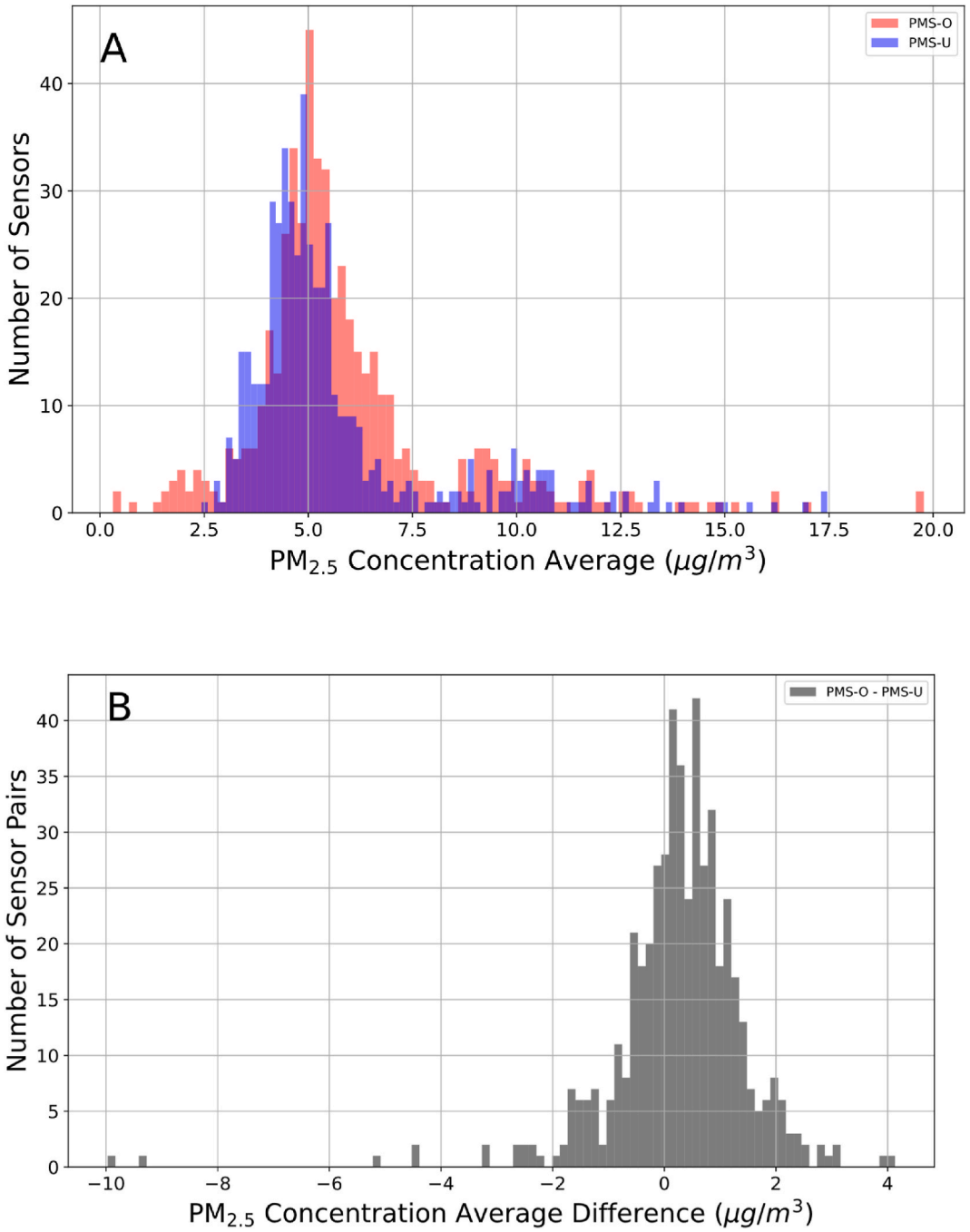

Fig. 6. (a) Average $PM_{2.5}$ concentrations of PMS-O (red) and PMS-U (blue) sensors during sample P1, and (b) average $PM_{2.5}$ concentration differences (PMS-O minus PMS-U) after applying the correction factor to PMS-U $PM_{2.5}$ concentrations below 16 μg/m^3. The x-axis range excludes one sensor pair with a mean value that exceeds 20 μg/m^3. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

grade monitors (Kelly et al., 2017; Kuula et al., 2019; Levy Zamora et al., 2019; Park et al., 2023; Sayahi, Butterfield, & Kelly, 2019). The PMS-O sensors showed a slope between 1.53 and 1.77 (Fig. S9). Some variation in the slope of the A and B pairs (Fig. S9, difference of ~11–14%) was observed, but they both showed similar trends.

PMS-U behavior differs from that of the PMS-O, and this difference appears to be concentration dependent. For corrected DustTrak $PM_{2.5}$ mass concentration less than 10.8 μg/m^3, the PMS-U sensors read lower than PMS-O sensors, whereas, for target concentrations greater than 10.8 μg/m^3, the PMS-Us show a response similar to that of the PMS-O sensors (Fig. 5a, Fig. S9 and Fig. S10). The PMS-U reported $PM_{2.5}$ (CF = 1) concentration of ~16 μg/m^3 corresponds to the mass-corrected DustTrak measurement of 10.8 μg/m^3, which agrees with the concentration threshold suggested by PA. To explore this further, two linear regressions were performed: one for raw PMS-U concentrations less than 16 μg/m^3 and one for concentrations greater than 16 μg/m^3 (Fig. 5a, Fig. S10). For PMS-U $PM_{2.5}$ concentrations below 16 μg/m^3, the slope varied between 1.02 and 1.37, and the R^2 varied between 0.899 and 0.933 (Fig. S10). The slope for PMS-U concentrations greater than 16 μg/m^3 was significantly greater (slope of 1.47–1.54, Fig. S10). The difference between the PMS-U slopes (greater or less than 16 μg/m^3) was statistically significant ($p < 0.05$). In addition, the difference in slopes between PMS-U (<16 μg/m^3) and PMS-O sensors was statistically significant ($p < 0.01$). Comparing the slopes for the PMS-U concentrations greater than 16 μg/m^3 to the slopes of the PMS-O sensors revealed that these slopes did not differ significantly ($p = 0.487$). These results suggest that the PMS-Us exhibit a different performance than the PMS-Os and that a new concentration-dependent correction factor may be necessary for PMS-U sensors for concentrations below 16 μg/m^3. The PMS-O and PMS-U sensors also behaved similarly for elevated $PM_{2.5}$ concentrations (~125–500 μg/m^3, Fig. S12), with no statistically significant difference between their slopes ($p > 0.8$) or intercepts ($p > 0.4$).

Fig. 5b displays the result of applying the correction factor (PMS-U corrected = 1.348 × PMS-U – 2.797) to the laboratory PMS-U sensor measurements below 16 μg/m^3. It also shows that the correction factor has changed the PMS-U concentrations below 16 μg/m^3 to follow the PMS-O trend better than in Fig. 5a.

3.3. Field evaluation of the correction factor

We also applied the same correction factor to the PMS-U field measurements below 16 μg/m^3 and reperformed the same Wilcoxon signed-rank test comparison of nearest neighbors. Fig. 6a and b shows the resulting average $PM_{2.5}$ concentration and mean difference histograms, respectively, after the correction was applied.

Fig. 6 shows a decrease in the difference between PMS-U and PMS-O sensors from an average of 2.94 μg/m^3 to an average of 0.26 μg/m^3. For the initial nearest-neighbor comparison (Fig. 4), only 1.0% of the mean differences were insignificant (mean difference equal to zero), and after applying the correction factor, 24.7% of the mean differences were insignificant. This is also more similar to the 13.4% of mean differences that were insignificant when comparing PMS-O-t1 and PMS-O-t2 sensors (Fig. S7), suggesting that the correction model developed could be a viable means of correcting the PMS-U values. Similar results may be seen in Figs. S11a and S11b for sample P2.

4. Limitations

This study does have some limitations. For example, PA users must enter their GPS coordinates manually, and it is possible that some of these coordinates were incorrect. In addition, some PA sensors may have been moved during the evaluation period, which would affect our field evaluation of nearest neighbors. Furthermore, a user could have replaced the PMS sensors in their PA unit, and this would not be apparent. It is possible that replacements could have accounted for 53 units that appeared to be PMS-Us but were deployed before June of 2021. However, these limitations would have a similar effect on both the results of the PMS-O vs. PMS-O evaluation and the PMS-U vs. PMS-O evaluation. It is also unknown whether the updates to the PMS 5003 affected other Plantower models, i.e., 1003, 3003, 6003, 7003.

5. Conclusions

This study systematically evaluated the identification and prevalence of PMS-U sensors using a threshold of 0.4 for the ratio of PM counts (≥0.5 to ≥0.3 μm). The results suggest that PMS-Us began appearing in the PA network in June of 2021, and their deployment declined after January 2022. Between June 2021–May 2023, we estimate that approximately 12.9% of the outdoor PA sensors were PMS-Us. Both our laboratory and field evaluations revealed that PMS-U sensors provided lower estimates of $PM_{2.5}$ concentrations compared to PMS-Os. The laboratory evaluation suggested that the performance of PMS-Us differed from those of PMS-Os for raw (CF = 1) $PM_{2.5}$ concentrations below 16 μg/m^3, and this difference was statistically significant. In the field, comparing nearest neighbors revealed that long-term $PM_{2.5}$ averages of PMS-Us were 2.94 μg/m^3 lower than PMS-Os. This could have an impact on community-level estimates of air quality, groups who purchased a batch of PMS-U sensors, and health studies of $PM_{2.5}$ concentrations that rely on these low-cost sensor networks. Consequently, individuals using PM measurements that rely on PMS5003s, should check the PM count ratios to determine if they have PMS-Us or PMS-Os and apply an appropriate correction factor, such as the one proposed here.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jaerosci.2023.106256.

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