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Editor's Choice

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Abstract: Low-cost particulate matter sensors have seen increased use for monitoring at personal and local levels due to their affordability, ease of operation, and high time resolution. However, the quality of data reported by these sensors can be questionable, and a thorough evaluation of their performance is necessary. This study evaluated the particle sizing accuracy of several commonly used optical sensors, including the Alphasense optical particle counter (OPC), TSI DustTrak DRX aerosol monitor, Plantower PMS5003 sensor, and Sensirion SPS30 sensor, using laboratory-generated monodisperse particles. The OPC and DRX agreed partially with reference instruments and showed promise in detecting coarse-size particles. However, the PMS5003 and SPS30 did not correctly size fine and coarse particles. Furthermore, their reported mass distributions do not directly correspond to their number distribution. Despite these limitations, field measurements involving a dust storm period showed that the SPS30 correlated reasonably well with reference instruments for both PM_{2.5} and PM₁₀, though the regression slopes differed significantly. These findings underscore the need for caution when interpreting data from low-cost optical sensors, particularly for coarse particles. Recommendations for improving the performance of these sensors are also provided.

Keywords: fine particle; coarse particle; optical particle counter; low-cost sensors; particle size; OPC-N3; DustTrak DRX; PMS5003; SPS30



Academic Editor: Dean Venables

Received: 26 March 2025

Revised: 20 April 2025

Accepted: 23 April 2025

Published: 26 April 2025

Citation: Gautam, P.; Ramirez, A.; Bair, S.; Arnott, W.P.; Chow, J.C.; Watson, J.G.; Moosmüller, H.; Wang, X. Sizing Accuracy of Low-Cost Optical Particle Sensors Under Controlled Laboratory Conditions. *Atmosphere* **2025**, *16*, 502. <https://doi.org/10.3390/atmos16050502>

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1. Introduction

Airborne particulate matter (PM) is ubiquitous in the Earth's atmosphere, significantly impacting the climate, air pollution, weather, visibility, and human health [1–3]. Particle size is an important parameter that is related to the source, transport, transformation, removal, and impacts of particles. The U.S. Environmental Protection Agency (U.S. EPA) regulates particles with an aerodynamic diameter $\leq 2.5 \mu\text{m}$ (PM_{2.5}) and $10 \mu\text{m}$ (PM₁₀) as criteria pollutants [4,5]. Other size fractions, such as ultrafine particles ($\leq 0.1 \mu\text{m}$) and coarse particles (PM_{2.5–10}; $2.5–10 \mu\text{m}$), are also of interest.

The regulatory monitoring of PM_{2.5} and PM₁₀ uses integrated filter sampling (typically over 24 h) and gravimetric analyses, or continuous measurements by the beta-attenuation, tapered element oscillating microbalance, or light-scattering techniques [6,7]. These monitors, which use federal reference or equivalent methods (FRM/FEM), are costly and require shelters and line power [8]. Most samplers are located in population centers with limited spatial and temporal coverage.

Portable low-cost air quality sensors are changing the air pollution monitoring paradigm [9]. Many of these sensors can provide high-time-resolution data in near real time. Their low-cost, easy-to-operate, and small-footprint features allow air quality professionals and citizen scientists to enhance personal and community-based fine spatial resolution monitoring. However, the sensor data quality has become an increasing concern for deriving meaningful information, as many sensors have been deployed before their performances have been characterized or understood [7,10,11].

Most low-cost PM sensors are based on light scattering to infer PM concentrations, with two common types being nephelometers (also called aerosol photometers) and optical particle counters (OPCs) [12,13]. Nephelometers measure the total light scattering by an ensemble of particles in the sensing volume (i.e., the portion of aerosol flow illuminated by the laser beam). While they can cover a wide range of PM concentrations, they commonly do not resolve particles sizes. Furthermore, because the particle mass scattering efficiency is higher for particles with a geometric diameter (D_g) close to the wavelength (λ) of the light source, nephelometers are more sensitive to particle diameters close to λ . The scattering per unit PM mass drops sharply with differences between the D_g and λ . For the red (~650 nm) lasers used in most sensors, coarse particle ($\geq 5 \lambda$) concentrations are often underestimated [14]. OPCs measure the light scattered by individual particles and convert these signals to an optical-equivalent diameter (D_{opt}) based on predefined calibration curves. The measured optical size distributions are then converted to mass distributions by assuming that particles are spherical with a known density [15]. OPCs can measure optical diameters from ~0.1 μm to ~10 μm . However, OPCs suffer from coincidence errors at higher concentrations when multiple particles enter the sensing volume [16]. In addition to the optical diameter and density, a particle's refractive index, shape, and hygroscopicity affect the mass accuracy. Despite the limitations of relating light scattering to mass, Grimm, Palas, Teledyne, and Ambilabs have achieved FEM status for regulatory monitoring [8,17].

After appropriate calibration and relative humidity corrections, the PM_{10} or $\text{PM}_{2.5}$ concentrations by low-cost sensors often correlate with reference instruments [18], while the PM_{10} correlations are lower, as evidenced during dust storms [19–21]. Because low-cost sensors do not discriminate particle sizes accurately, Molina Reuda et al. [22] caution their use for estimating the $\text{PM}_{2.5-10}$ and PM_{10} levels.

Several factors could have led to the poor sizing accuracy of low-cost PM sensors. Sensirion [23] states that, since only a small fraction (3–5%) of the aerosol flow is illuminated by the laser beam, the SPS30 (Sensirion AG, Stäfa, Switzerland) counting statistics for coarse particles are too low to obtain accurate results. Instead of using directly measured data, the SPS30 PM_4 and PM_{10} outputs are estimated from the smaller sizes (i.e., $\text{PM}_{0.5}$, PM_1 , and $\text{PM}_{2.5}$), assuming a typical size distribution. Similarly, Ouimette et al. [24] found that 99% of 10 μm particles would miss the laser focal point and be sized smaller than 10 μm by the Plantower PMS5003 sensor. Gravitational settling and impaction losses also lower the number of coarse particles that reach the sensing volume.

Few studies have directly measured the sizing accuracy of low-cost PM sensors. He et al. [25] sampled monodisperse 0.1, 0.3, 0.5, and 0.7 μm particles with the Plantower PM5003 sensor, but this limited calibration size range did not address the larger particles. Kuula et al. [26] used monodisperse particles with diameters of 0.55–8.4 μm to challenge six low-cost sensors, finding that none of them adhered to the detection ranges specified by manufacturers. Kaur and Kelly [27] evaluated the sizing accuracy of the OPC-N3 (Alphasense, Essex, UK), PMS5003 (Plantower Technology, Beijing, China), and PMS6003 (Plantower Technology, Beijing, China) sensors for particle diameters in the 2–10 μm range, but they did not address the <2 μm sizes that are important for PM_1 and $\text{PM}_{2.5}$.

This study evaluated the sizing accuracy of the Alphasense OPC-N3, Plantower PMS5003, and Sensirion SPS30 sensors that are common in low-cost PM monitors. Their outputs were compared with research-grade instruments: a DustTrak DRX (DRX; Model 8534; TSI Inc., Shoreview, MN, USA), an optical particle sizer (OPS; Model 3330; TSI Inc., Shoreview, MN, USA), and an Aerodynamic Particle Sizer (APS; Model 3321; TSI Inc., Shoreview, MN, USA). The calibration aerosols consisted of laboratory-generated monodisperse dioctyl sebacate (DOS) particles in the size range of 0.4–7 μm . This study aimed to assess the data quality of commonly used optical sensors under laboratory conditions and provide recommendations for improving the performance of these sensors. Additionally, data from a short period of ambient measurement using the SPS30 were analyzed to offer insights into its data-processing algorithms.

2. Materials and Methods

2.1. Evaluated Low-Cost Sensors and Research-Grade Instruments

Table 1 compares the characteristics and costs of the tested sensors. The OPC-N3 has a higher size resolution (24 channels) than the other low-cost PM sensors (typically ≤ 6 channels), and it uses an elliptical mirror and a dual-element photodetector. Mie theory with a purely real part of the refractive index of 1.5 and a particle density of 1.65 g cm^{-3} was used to convert the measured scattering intensities into particle sizes, which were further summed to $\text{PM}_{1.0}$, $\text{PM}_{2.5}$, and PM_{10} mass concentrations [27].

Table 1. Key features of low-cost PM sensors and research-grade instruments.

Sensor/Instruments	Scattering Angle	Wavelength	Output	Price (USD)
OPC-N3	32–88°	658 nm	PM_1 , $\text{PM}_{2.5}$, PM_{10} , and number concentrations for 0.35–40 μm in 24 channels	~500
Plantower PMS5003	90 $\pm$ 37°	657 nm	PM_1 , $\text{PM}_{2.5}$, PM_{10} , and number concentrations for >0.3, >0.5, >1, >2.5, >5, and >10 μm	~20
Sensirion SPS30	Data not available	660 nm	PM_1 , $\text{PM}_{2.5}$, PM_4 , PM_{10} , and number concentrations for 0.3–0.5, 0.3–1, 0.3–2.5, 0.3–4, and 0.3–10 μm	~50
TSI DRX 8534	90 $\pm$ 62°	655 nm	PM_1 , $\text{PM}_{2.5}$, PM_4 , PM_{10} , and total PM	~11,000
TSI OPS 3330	90 $\pm$ 60°	660 nm	Number, surface area, and mass distributions for 0.3–10 μm in up to 16 channels	~19,000
TSI APS 3321	Aerodynamic particle sizing		Aerodynamic size distribution for 0.5–20 μm in 52 channels	~57,000

While the detailed PMS5003 or SPS30 signal-processing algorithms (i.e., nephelometry or OPC) are not published, Ouimette et al. [24] found that the PMS5003 counts individual pulses and classifies them into six size bins: >0.3, 0.5, 1.0, 2.5, 5.0, and 10 μm , from which $\text{PM}_{1.0}$, $\text{PM}_{2.5}$, and PM_{10} are calculated. The PMS5003 is widely used in low-cost PM monitoring systems, including the PurpleAir Air Quality Sensor (PurpleAir, Inc., Draper, Utah, USA) [28–30]. The SPS30 classifies particle numbers into five size ranges, 0.3–0.5, 0.3–1.0, 0.3–2.5, 0.3–4.0, and 0.3–10 μm , from which $\text{PM}_{1.0}$, $\text{PM}_{2.5}$, and PM_{10} are calculated.

The DRX is a research-grade instrument that combines optical particle counting with nephelometry in one device [12]. Single-particle counting for larger particles better represents supermicron particles, while nephelometry enables the DRX to measure submicron particles at high concentrations (up to 400 mg m^{-3}) that would otherwise have high coincidence errors. The DRX reports PM mass concentrations calibrated with Arizona road dust

(ARD) and permits custom calibrations when particles have different optical properties or densities from ARD. This instrument has been widely used as a reference for evaluating low-cost PM sensors, including the factory calibration of the SPS30 [23,31,32].

The TSI OPS 3330 is claimed to be in compliance with ISO 21501-1 [33] by the manufacturer [34]. Vasilatou et al. [35] found that a well-maintained OPS 3330 has high counting efficiencies (>85%) over the size range of 0.3–10 μm with a size resolution better than 15% (sizing uncertainty related to the specified particle size).

The TSI APS 3321 measures aerodynamic diameters based on time-of-flight [36,37]. This high-size-resolution aerodynamic diameter measurement has led to its widespread use as a reference instrument in calibrating aerosol inlets, classifiers, and sizers, including the evaluation of low-cost PM sensors [7,24,26,38].

2.2. Experimental Setup

Figure 1 describes the experimental setup. DOS was selected as the test aerosol, as the particles are nearly spherical liquid droplets with a low evaporation rate for diameters > 0.2 μm [39,40]. DOS has a density of 0.91 g cm^{-3} at room temperature and a real refractive index of 1.45 at 589 nm. The DOS refractive index was input into the OPS data-processing software (TSI AIM Software v10.1) so that the geometric diameter (D_g), rather than the optical diameter (D_{opt}), was reported. Similarly, the aerodynamic diameter (D_{ae}) reported by the APS was divided by $\sqrt{0.91}$ to convert to the D_g , assuming similar slip correction factors for the D_{ae} and D_g [41]. Monodisperse test aerosols were generated by atomization followed by electrostatic classification for the 0.4–1 μm sizes. A flow-focusing monodisperse aerosol generator (FMAG 1520, TSI Inc., Shoreview, MN, USA) generated 1.5–7 μm size particles.

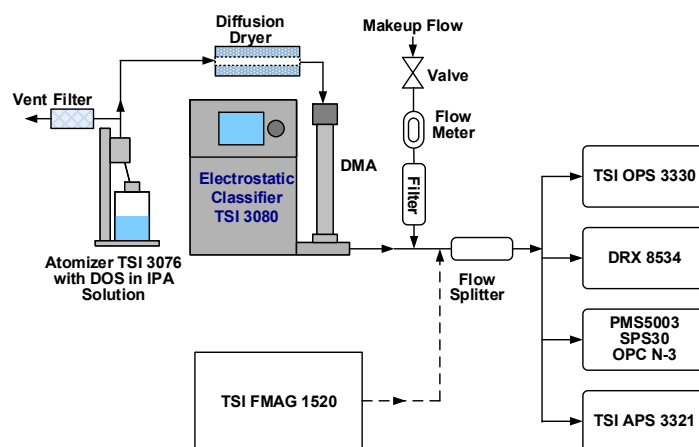


Figure 1. A schematic diagram of the experimental setup for evaluating the particle sizing accuracy of low-cost sensors. (DMA: differential mobility analyzer; DOS: dioctyl sebacate; FMAG: flow-focusing monodisperse aerosol generator; IPA: isopropanol alcohol).

As shown in Figure 1, polydisperse DOS particles were generated with a constant output atomizer (Model 3076, TSI Inc.) using a 1% DOS solution (by volume, in isopropanol alcohol). The particles were dried with a diffusion dryer to remove isopropanol alcohol vapor. An electrostatic classifier (Model 3080, TSI Inc.) with a long differential mobility analyzer (DMA; Model 3081, TSI Inc.) selected the sizes of monodisperse particles for testing. The DMA voltage and sheath flow rate were adjusted to select the particle size, while the sheath-to-aerosol flow ratio was set to 10:1 to achieve a high DMA resolution [42]. Make-up flow was added downstream of the DMA monodisperse particle outlet to meet the flow requirement of the test instruments. It was recognized that some multiply charged particles with larger sizes co-exit the DMA. However, as the mode diameter of the polydisperse

particles from the atomizer was $<0.1\ \mu\text{m}$ and all the selected monodisperse sizes were much larger than $0.1\ \mu\text{m}$, the contamination by multiply charged particles was low [43].

The FMAG can generate monodisperse aerosol particles [44]. The DOS solution (in isopropanol alcohol) passed through a $100\ \mu\text{m}$ nozzle and formed a thin jet constrained by a focusing flow. A piezo-ceramic actuator applied a periodic mechanical perturbation to the liquid jet and broke the jet into monodisperse droplets. The droplets were then dried in an air-drying column and neutralized by an electrical neutralizer. Different sizes were generated by adjusting the DOS solution concentrations, liquid feed pressure and flow rate, and vibration frequency.

The low-cost sensors were enclosed inside an enclosure with slightly positive pressure caused by the feeding aerosol. A mixing fan homogenized the particles inside the chamber. Particle losses due to gravitational deposition and impaction, as well as non-uniform mixing, may cause differences in the concentrations measured by the test instruments. Therefore, this study focused on the particle sizing accuracy, while the accuracy of the concentration was not assessed.

3. Results

3.1. Monodisperse Particles Measured by Reference Instruments

The particle size and monodispersity were verified using OPS (Figure 2a) and APS (Figure 2b–d). The results are presented as the percentage of the total measured particle number or mass in each size bin, normalized by the width of the bin. The area of each histogram bar represents the percentage in that size bin. For $0.4\ \mu\text{m}$ diameter particles, Figure 2a shows that most of the particles measured by the OPS were in the $0.305\text{--}0.384\ \mu\text{m}$ size bin, with a geometric standard deviation (σ_g) of 1.16. For 1.5 , 3 , and $7\ \mu\text{m}$ particles, Figure 2b–d show that the APS-measured mode diameters were close to the set diameters, with σ_g being 1.16, 1.27, and 1.24, respectively. Similar size accuracies were also observed for other results, as shown in Figure S1.

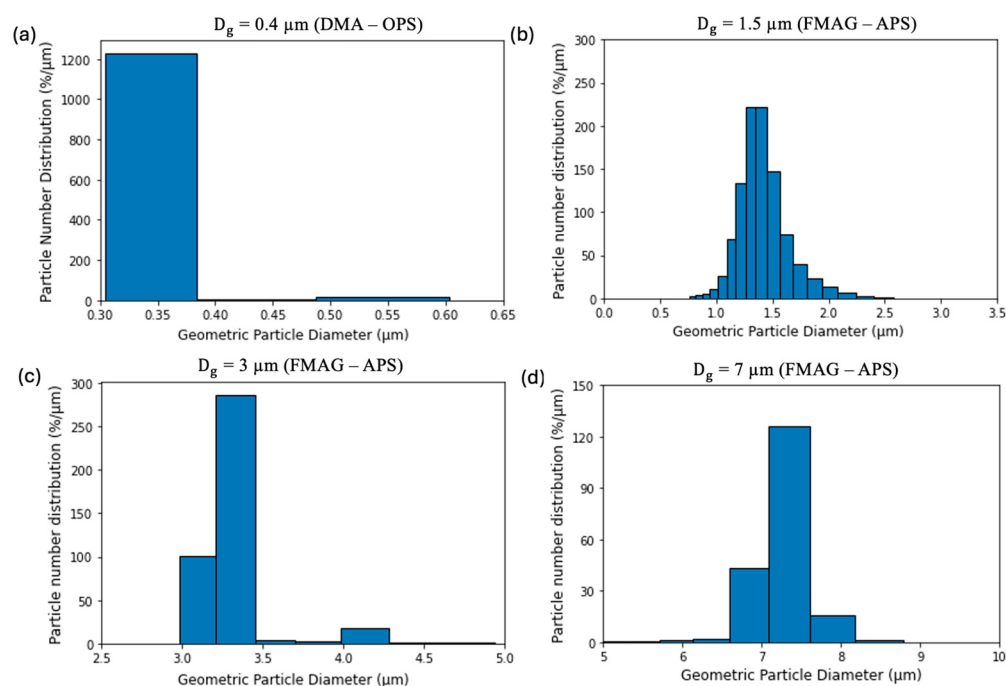


Figure 2. Particle size distributions of dioctyl sebacate (DOS) measured with the reference instruments for four geometric particle diameters (D_g): (a) DMA-generated $0.4\ \mu\text{m}$ particles measured with OPS and FMAG-generated (b) $1.5\ \mu\text{m}$, (c) $3\ \mu\text{m}$, and (d) $7\ \mu\text{m}$ particles measured with APS. Additional particle size distribution measurements can be found in Figure S1.

3.2. Sizing Accuracy of OPC-N3 and DRX

Figure 3 shows that the mode D_{opt} values measured by the OPC-N3 were close (differing by $\leq$ one size channel) to the set D_g values of 1, 2, 3, and 6 μm , indicating that the OPC-N3 can properly size particles, although the measured distributions were much wider than those quantified by the OPS or APS, as shown in Figure 2. The APS has a monotonic relationship between the aerodynamic diameter and time-of-flight, resulting in a finer size resolution. In contrast, the OPC-N3 scattering intensity vs. diameter response curve is not monotonic [13], resulting in lower size resolutions. Kaur and Kelly [27] also observed wider distributions for the OPC-N3 than for the APS. They showed that the OPC-N3 consistently reported a larger D_{opt} than the D_g by the APS, which was only observed for 1 and 2 μm particle diameters in this study. Some small particles were measured by the OPC-N3's lower-size channels (~ 0.35 –1 μm). These underestimated sizes were likely caused by particles not passing through the focused portion of the laser beam, generating smaller pulses, as the OPC-N3 does not have sheath air to confine particles to the laser focal point.

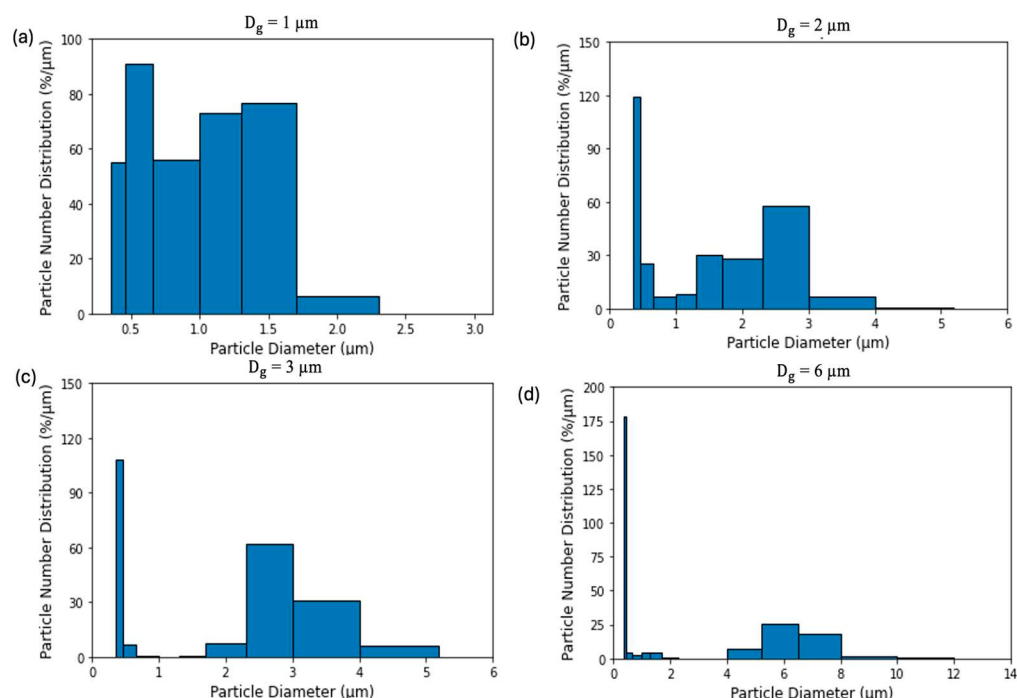


Figure 3. Number distributions of DOS particles measured with the OPC-N3 for four particle diameters (D_g): (a) 1 μm , (b) 2 μm , (c) 3 μm , and (d) 6 μm .

Figure 4 shows the mass distributions measured by the DRX for 0.4, 1.5, 3, and 7 μm DOS particles. The distributions for additional sizes are shown in Figure S2. Figure 4a shows that particles were detected predominantly in the <1 μm channel for $D_g = 0.4$ μm . For $D_g = 1.5$ μm , 94% of the particles were classified as <1 μm , with 6% in the 1–2.5 μm channel. Although the particle sizes reported by the DRX were smaller than those reported by the APS (Figure 2b), all the particles were within the <2.5 μm range. For $D_g = 3$ μm (Figure 4c), the DRX showed 61% mass concentration below 1 μm , with particles reported as large being in the 4–10 μm range. To enable very high-concentration (up to 400 mg/m^3) measurements, the DRX estimated $\text{PM}_{2.5}$ concentrations from nephelometry. Single particle counting was then used to calculate masses in the size bins of 1–2.5, 2.5–4, and 4–10 μm , which were subtracted from or added to the $\text{PM}_{2.5}$ mass to obtain the PM_1 , PM_4 , and PM_{10} masses [12]. As particles larger than 2.5 μm would also contribute to the nephelometry signal, thereby generating a reading of $\text{PM}_{2.5}$, an empirical algorithm was used to correct

this artifact due to a compromise between high-concentration measurements and sizing accuracy. However, when this correction does not function perfectly, larger particles may cause readings in PM_1 and/or $PM_{2.5}$ channels. Additionally, $3\ \mu\text{m}$ particles are close to the Mie oscillation size range of the DRX, leading to less accurate sizing [12]. For $D_g = 7\ \mu\text{m}$, the highest mass concentration (75%) was correctly observed within the $4\text{--}10\ \mu\text{m}$ size range. Again, 23% of the particle mass was reported as below $1\ \mu\text{m}$, due to an inaccurate correction of the contributions of $7\ \mu\text{m}$ particles to the nephelometry signal.

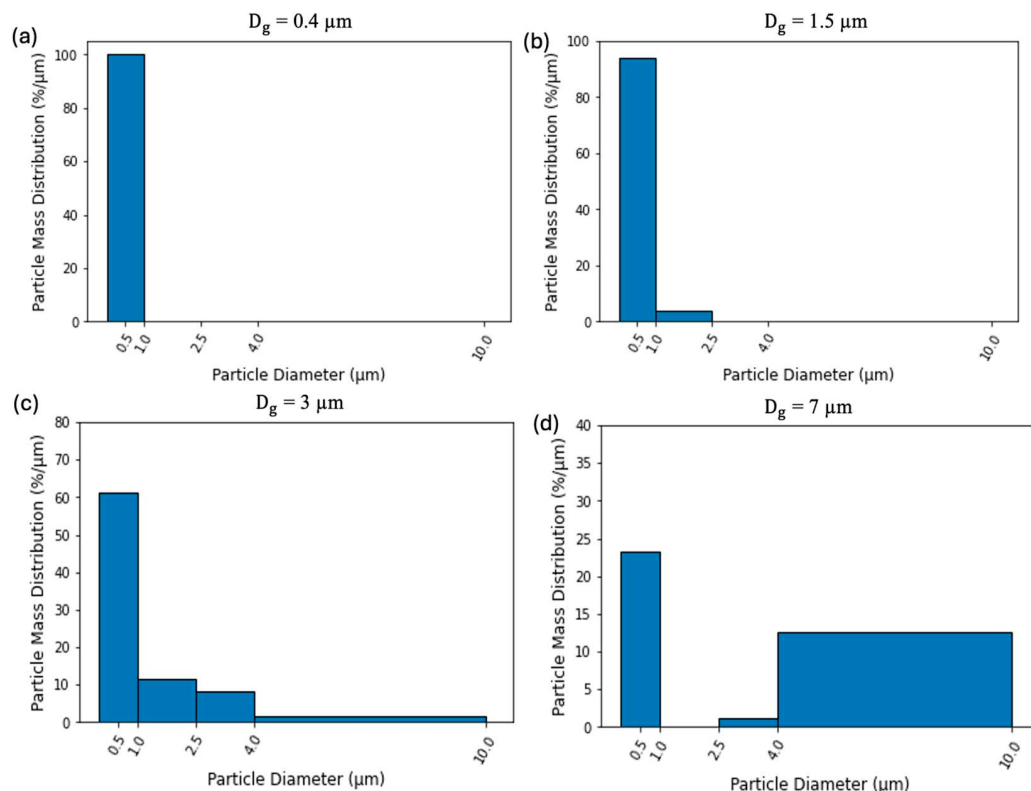


Figure 4. Mass concentrations of DOS particles measured with DRX for four particle diameters (D_g): (a) $0.4\ \mu\text{m}$, (b) $1.5\ \mu\text{m}$, (c) $3\ \mu\text{m}$, and (d) $7\ \mu\text{m}$. Additional particle size distribution measurements can be found in Figure S2.

3.3. Sizing Accuracy of PMS5003 and SPS30

Figures 5 and 6 show the particle size distributions measured by the PMS5003 and SPS30 for D_g values of 0.4 , 1.5 , 3 , and $7\ \mu\text{m}$. The distributions for additional sizes are shown in Figures S3 and S4. Figure 5 shows that the highest particle concentrations reported by the PMS5003 were always in the $0.3\text{--}0.5\ \mu\text{m}$ channel, regardless of the test particle sizes. This was the case even for large particles (i.e., 3 and $7\ \mu\text{m}$), confirming that the PMS5003 does not correctly measure particle size. A similar performance was observed in laboratory evaluations [24,26,27,38] and field measurements [19–22]. Ouimette et al. [24] reasoned that most large particles would miss the laser focal point and be sized as smaller particles by the PMS5003 sensor. However, these low counting statistics cannot explain the fact that none of the $7\ \mu\text{m}$ particles (Figure 5d) were sized correctly when monodisperse $7\ \mu\text{m}$ particles were injected. It is likely that additional factors contribute to the inability of the PMS5003 sensor to correctly size particles. As the signal-processing and data-reporting algorithms are undisclosed [29], the exact cause could not be determined.

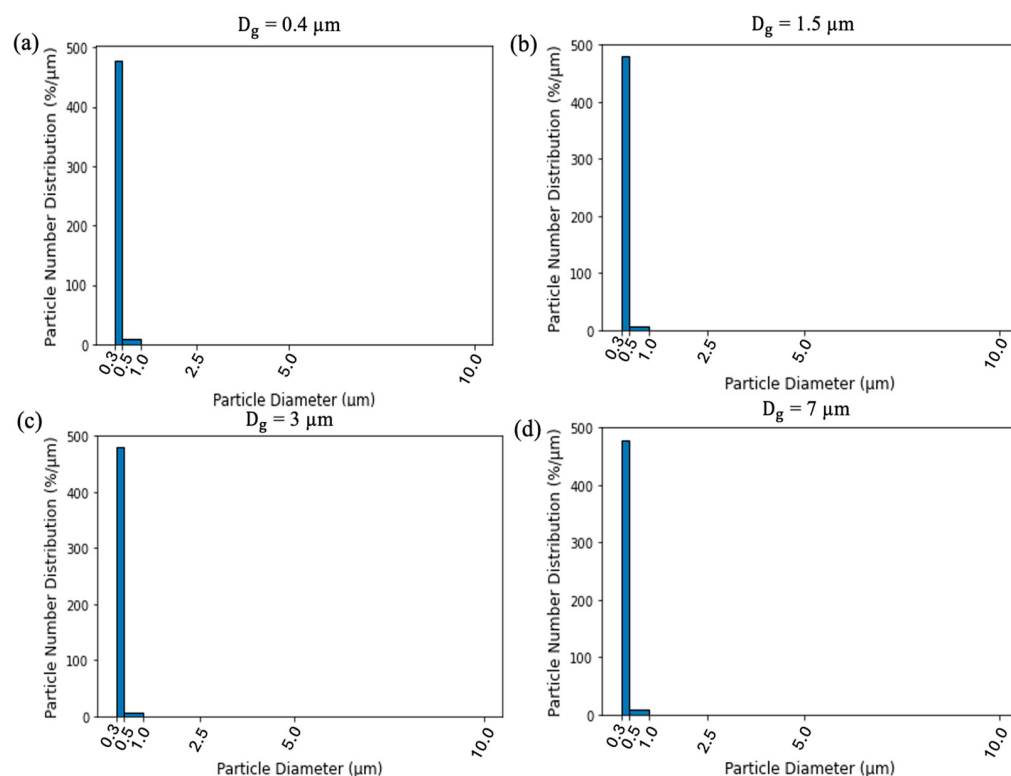


Figure 5. The particle number size distributions measured with the PMS5003 for four particle diameters (D_g): (a) $0.4 \mu\text{m}$, (b) $1.5 \mu\text{m}$, (c) $3 \mu\text{m}$, and (d) $7 \mu\text{m}$. Additional particle size distribution measurements can be found in Figure S3.

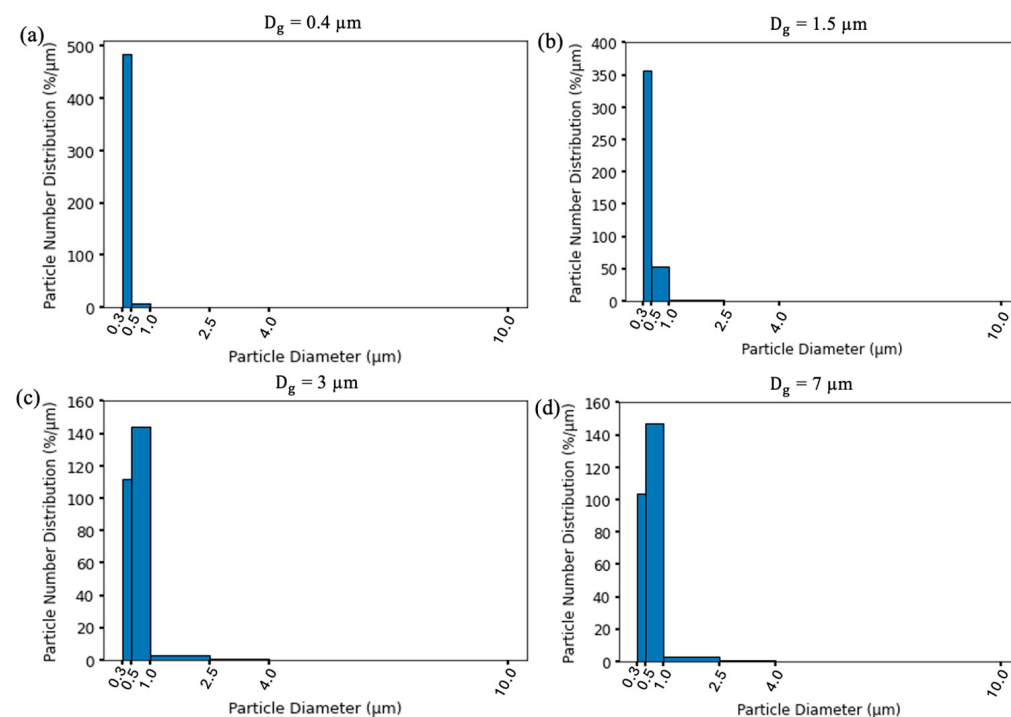


Figure 6. Particle number size distributions measured with the SPS30 for four particle diameters (D_g): (a) $0.4 \mu\text{m}$, (b) $1.5 \mu\text{m}$, (c) $3 \mu\text{m}$, and (d) $7 \mu\text{m}$. Additional particle size distribution measurements can be found in Figure S4.

Sensirion [23] acknowledged that the SPS30 does not reasonably count coarse particles due to low counting statistics in the sensing volume, and therefore, the SPS30 estimates

PM₄ and PM₁₀ from smaller sizes, assuming a typical size distribution. Figure 6 shows differences in the measured distributions for 0.4 and 1.5 μm particles; however, similar to the PMS5003, it assigned almost all 3 and 7 μm particles to the PM₁ size range, with <1% particles between 1 and 2.5 μm .

These results show that the PMS5003 or SPS30 will generally underestimate coarse particle concentrations. Unless these sensors are calibrated with the aerosol to be measured and the aerosol properties (size distribution and density) are stable, the coarse particle concentration will not be measured accurately. Because coarse particles will be counted as smaller particles, the PM_{2.5} concentration will be overestimated. However, under typical ambient conditions, where fine particles are more numerous than coarse particles, this overestimation may be negligible, which allows these low-cost PM sensors to report PM_{2.5} concentrations that are reasonably correlated with reference instruments.

3.4. Mass Distribution of PM₁, PM_{1–2.5}, and PM_{2.5–10} Measured with SPS30, PMS5003, and DRX

As most current air quality standards for PM regulate mass concentrations, it is informative to compare the size-segregated mass concentrations reported by the sensors. Figure 7 shows the fraction of the PM₁₀ mass (in percent) measured in PM₁, PM_{1–2.5}, and PM_{2.5–10} channels by the DRX, PMS5003, and SPS30 for particle D_g values of 0.4, 1.5, 3, and 7 μm . Data for additional diameters are shown in Figure S5. The DRX reported the highest PM₁ mass concentrations for particle D_g values of 0.4, 1.5, and 3 μm . As the particle size increased, higher PM mass concentrations were observed in the PM_{1–2.5} and PM_{2.5–10} ranges. For a particle diameter of 7 μm , the DRX showed the highest (75%) mass concentration in the PM_{2.5–10} range, with 23% also observed in the PM₁ range, but none in the PM_{1–2.5} range. This indicates that the PM₁ by DRX may have artifacts from larger sizes.

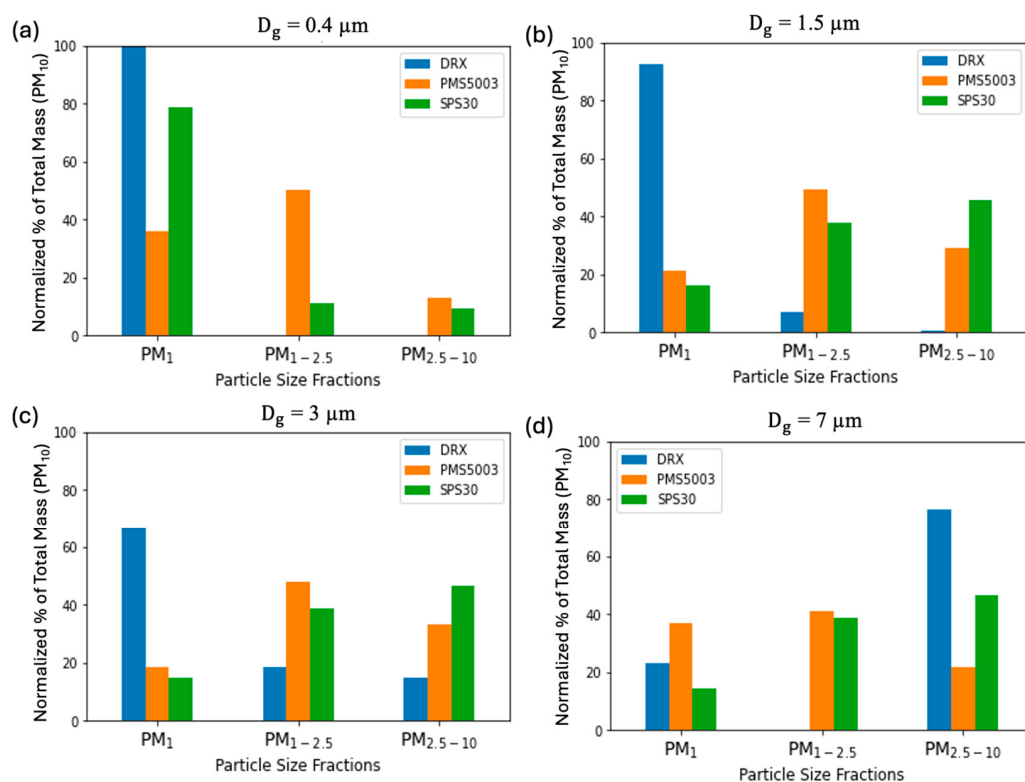


Figure 7. PM₁, PM_{1–2.5}, and PM_{2.5–10} fractional mass concentrations measured with DRX, PMS5003, and SPS30 for geometric diameters (D_g): (a) 0.4 μm , (b) 1.5 μm , (c) 3 μm , and (d) 7 μm . Fractional mass concentrations for additional diameters are in Figure S5.

Even though few particles were detected in the 2.5–10 μm size range by the PMS5003 (Figure 5), it still reported the mass across all size intervals, which did not agree with the volume distribution calculated from the number distribution, assuming the particles are spherical. The highest concentrations were observed in the $\text{PM}_{1-2.5}$ range, regardless of the actual particle size. These observations indicate that the mass concentrations were not directly derived from particle counting and sizing.

The SPS30 measurements show that the particle mass was mainly detected in the PM_1 range for $D_g = 0.4 \mu\text{m}$ (and $D_g = 0.6 \mu\text{m}$, Figure S5), with smaller amounts in the $\text{PM}_{1-2.5}$ and $\text{PM}_{2.5-10}$ ranges. For larger diameters ($D_g = 1.5, 3$, and $7 \mu\text{m}$), the particle mass was primarily observed in the following order: $\text{PM}_{2.5-10} > \text{PM}_{1-2.5} > \text{PM}_1$.

Table 2 lists the $\text{PM}_{2.5}/\text{PM}_1$, $\text{PM}_{10}/\text{PM}_{2.5}$, and $\text{PM}_{10}/\text{PM}_1$ mass ratios reported by the PMS5003 and SPS30 for monodisperse particles. For smaller particles ($D_g = 0.4$ and $0.6 \mu\text{m}$), the expected $\text{PM}_{2.5}/\text{PM}_{1.0}$ and $\text{PM}_{10}/\text{PM}_1$ should be close to 1 because all particles are in the PM_1 size fraction. This was the case for the SPS30, while the PMS5003 had ratios > 2 . The ratios were significantly greater for $D_g \geq 1 \mu\text{m}$ than those for the submicron particles, and the ratios remained similar regardless of the actual particle size. These observations further indicate that some of the PM mass fractions may be estimated from measured values for other PM size fractions rather than from direct measurements of the larger particles.

Table 2. $\text{PM}_{2.5}/\text{PM}_{1.0}$ and $\text{PM}_{10}/\text{PM}_{2.5}$ mass ratios reported by PMS5003 and SPS30 for monodisperse particles.

Sizes (μm)	$\text{PM}_{2.5}/\text{PM}_1$ Mass Ratio		$\text{PM}_{10}/\text{PM}_{2.5}$ Mass Ratio		$\text{PM}_{10}/\text{PM}_1$ Mass Ratio	
	PMS5003	SPS30	PMS5003	SPS30	PMS5003	SPS30
0.4	2.39	1.14	1.15	1.10	2.75	1.25
0.6	2.26	1.26	1.36	1.21	3.07	1.52
1	3.17	3.10	1.37	1.80	4.34	5.58
1.5	3.30	3.31	1.40	1.84	4.62	6.09
2	3.50	3.55	1.47	1.86	5.15	6.60
3	3.56	3.61	1.50	1.87	5.34	6.75
6	3.25	3.53	1.35	1.84	4.39	6.50
7	2.12	3.68	1.28	1.88	2.71	6.92

3.5. Ambient $\text{PM}_{2.5}$ and PM_{10} Measured with SPS30 and Beta-Attenuation Monitors

Similar limits for the PM ratios were also observed in ambient measurements. Figure 8 presents the ambient PM data collected at the University of Nevada Reno Department of Physics over several days in February 2020. A dust storm occurred in the afternoon of 8 February 2020, as indicated by the high peaks in Figure 8a. Figure 8b,c show that the $\text{PM}_{2.5}/\text{PM}_1$ and $\text{PM}_{10}/\text{PM}_1$ mass ratios reported by the SPS30 had upper limits of 2.4 and 3.9, respectively, corresponding to the dust storm event. During the non-dust storm periods, the ratios ranged between these upper limits and the lower limit of 1. These upper limits were lower than those shown in Table 2.

To gain insights into the SPS30 data-processing algorithms, mass concentrations were computed from number concentrations by assuming spherical particles with a density of 1 g/cm^3 . These values were compared to the mass concentrations directly reported by the SPS30. Figure 9a,b show that, during the non-dust storm periods, the ratios of the reported and calculated $\text{PM}_{2.5}$ values ranged from 0.46 to 1.1, while those for PM_{10} ranged from 0.23 to 1.0. In contrast, during the dust storm periods (Figure 9c,d), the reported and calculated $\text{PM}_{2.5}$ and PM_{10} had a ratio of 0.34 and 0.18, respectively. These results indicate that the SPS30 generally reports lower mass concentrations than those calculated

from number concentrations, with the scaling factor varying depending on the particle size and concentration.

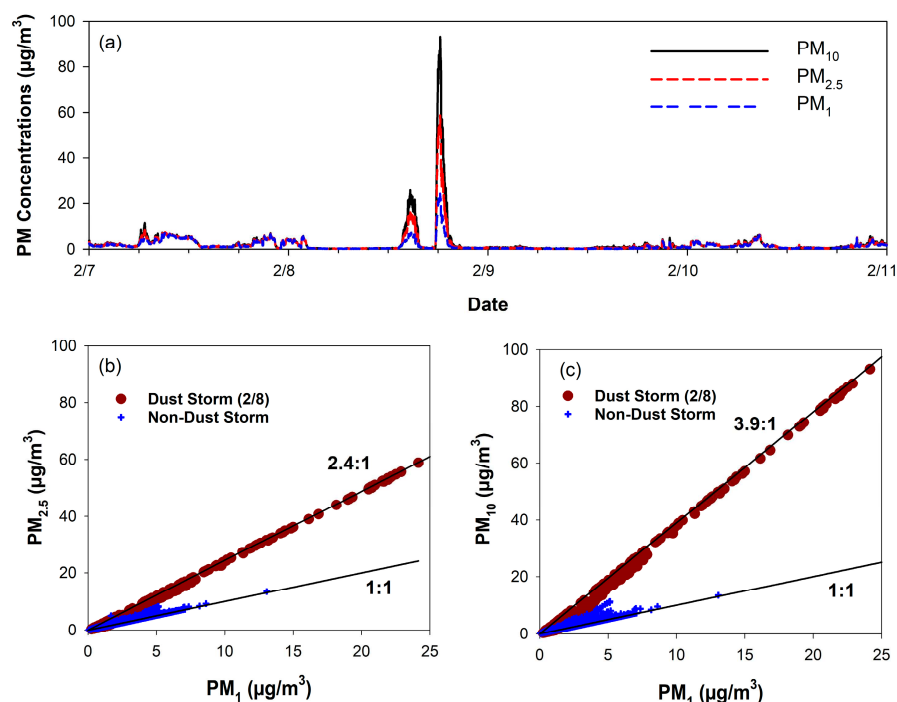


Figure 8. Minute-averaged PM concentrations measured by an SPS30 in Reno, Nevada, during 7–10 February 2020: (a) time series of PM_1 , $\text{PM}_{2.5}$, and PM_{10} concentrations reported by the SPS30; (b) $\text{PM}_{2.5}$ vs. PM_1 during dust storm and non-dust storm periods; and (c) PM_{10} vs. PM_1 during dust storm and non-dust storm periods.

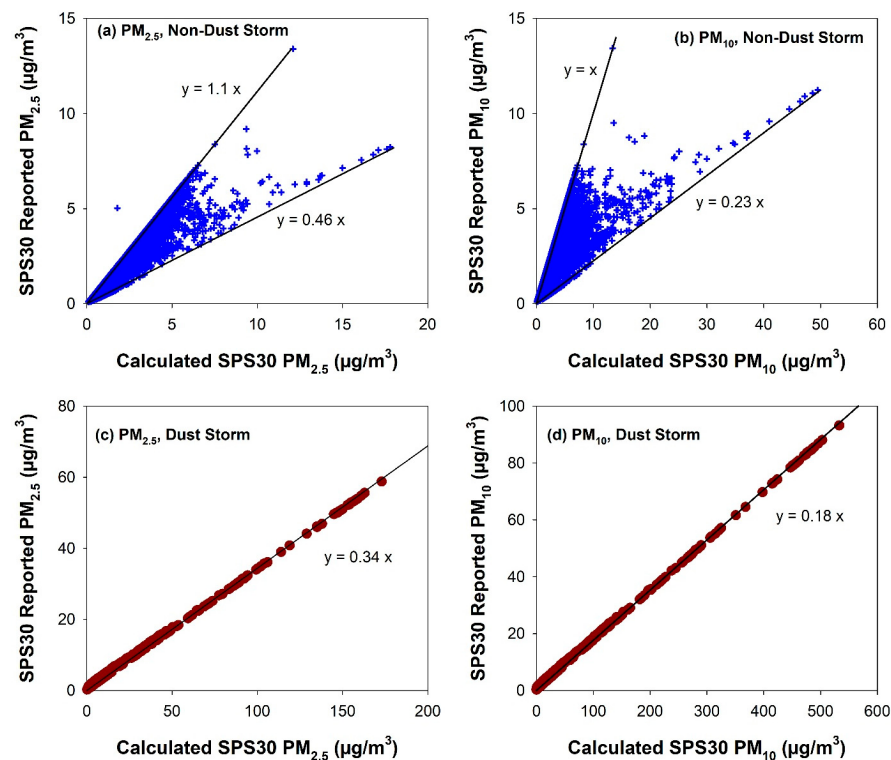


Figure 9. A comparison of minute-averaged PM mass concentrations reported by the SPS30 and those calculated from the SPS30 number distributions: (a) $\text{PM}_{2.5}$ during non-dust storm periods; (b) PM_{10} during non-dust storm periods; (c) $\text{PM}_{2.5}$ during dust storm periods; and (d) PM_{10} during dust storm periods.

Two beta-attenuation monitors (BAMs) were collocated with the SPS30 to measure the hourly average $PM_{2.5}$ and PM_{10} (Figure S6). During the dust storm period, the average $PM_{10}/PM_{2.5}$ mass ratio was 7.8 (ranging from 4 to 14), which is substantially higher than the SPS30 ratio of 1.6 shown in Figure 8. As shown in Figure 10a,b, the SPS30-reported $PM_{2.5}$ and PM_{10} mass concentrations were reasonably correlated with the BAM measurements across both dust storm and non-dust storm periods ($r^2 \geq 0.8$). The $PM_{2.5}$ concentrations measured by the SPS30 differed from the BAM by a factor < 2 , whereas the PM_{10} concentrations were underestimated by a factor of ~ 6 . Interestingly, the mass concentrations derived from the SPS30 number concentrations showed a reduced correlation with the BAM data, although the calculated PM_{10} values were closer in magnitude to those from the BAM. Despite its inaccuracy in the sizing of monodisperse particles under laboratory conditions, the SPS30 appears to employ internal algorithms that enhance its correlations with reference instruments across a broad concentration range. However, the proprietary and opaque nature of its signal- and data-processing algorithms limits the ability to derive physics-based interpretations or propose informed improvements [13].

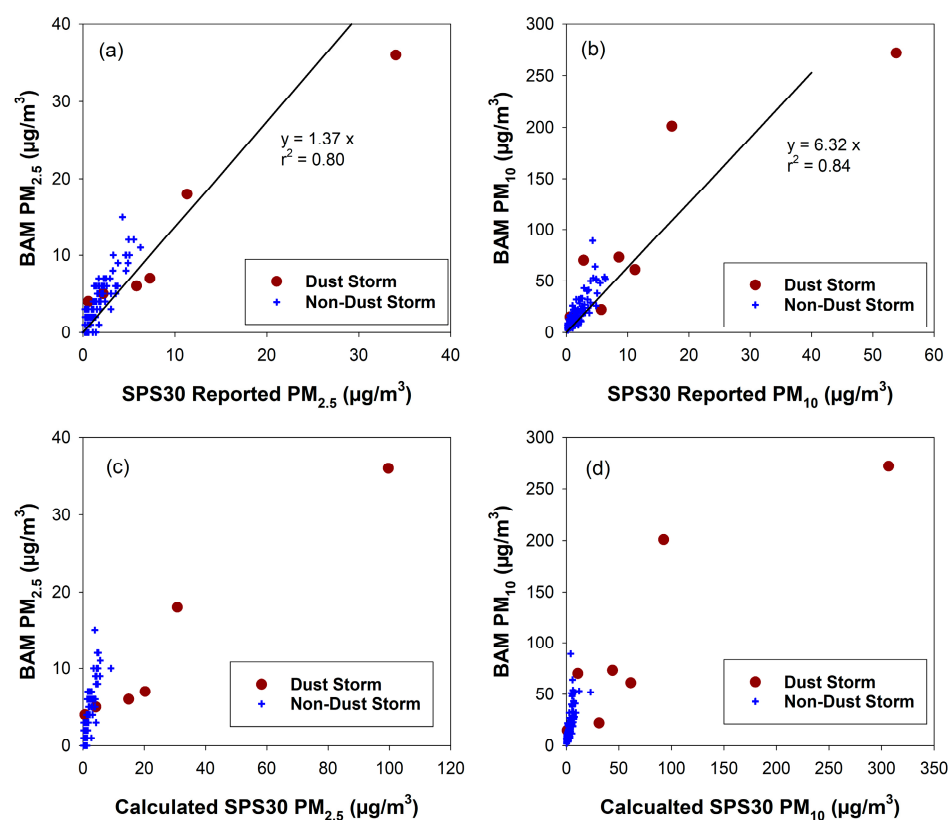


Figure 10. Hourly-averaged PM mass concentrations measured by a beta-attenuation monitor (BAM) collocated with the SPS30. Data were taken in Reno, Nevada, during 7–10 February 2020: (a) $PM_{2.5}$ by the BAM vs. that reported by the SPS30; (b) PM_{10} by the BAM vs. that reported by the SPS30; (c) $PM_{2.5}$ by the BAM vs. that calculated from the SPS30 number distributions; and (d) PM_{10} by the BAM vs. that calculated from the SPS30 number distributions.

4. Conclusions and Discussion

This study evaluated the particle-sizing accuracy of several widely used sensors, using laboratory-generated monodisperse particles. The OPC-N3 resolved particle sizes, although its reported size distributions were wider than those measured by reference instruments, and small particles were reported when measuring large-sized particles. The DRX was able to size small and large particles; however, the concentrations were reported in the PM_1 channel when measuring particles larger than $1 \mu m$, due to a compromise between

high-concentration measurements and the sizing accuracy. The PMS5003 and SPS30 did not accurately size either fine or coarse particles, and there was not a simple relationship between the number and mass distributions for coarse particles. Despite the inaccuracy in sizing monodisperse particles, a short period of ambient measurement, including a dust storm event, showed that the SPS30 had reasonable correlations with reference instruments for both $PM_{2.5}$ and PM_{10} . This study highlights the need for proper calibration and careful data analyses when using these sensors. The PMS5003 and SPS30 are suitable for estimating ambient PM_1 or $PM_{2.5}$ concentrations, but are not a substitute for dependable, high-quality air quality monitoring systems.

There are two main differences between the low-cost PM sensors (e.g., PMS5003 and SPS30) and higher-end OPCs (e.g., OPC-N3, DRX, and OPS). First, higher-end OPCs typically have a small inlet nozzle to create a collimated or focused particle beam that propagates through the most intense part of the laser beam. The particle beam width is smaller than the laser beam to reduce edge effects due to lower laser intensities near the edges. Some OPCs further use sheath flow to confine the particle beam and reduce recirculation inside the optical chamber. In contrast, the particle beams in low-cost sensors are often wider than the laser beam, resulting in only a small fraction of the particles propagating through the focused portion of the laser beam. Therefore, particles are sized incorrectly due to the varying laser intensity across the laser beam. The sizing accuracy of low-cost sensors could also be partly influenced by their electronic designs and signal-processing methods and algorithms. Second, most higher-end OPCs have a short, vertical, and straight flow path from the inlet through the optical chamber and outlet to reduce particle deposition. In contrast, low-cost sensors often do not have a well-organized flow path, causing size-dependent losses before the particles enter the sensing volume [24]. Therefore, two key modifications are needed to increase the accuracy of low-cost sensors: (1) focusing the particle beam to pass through a more uniform portion of the laser beam or making the laser beam intensity more uniform, and (2) making the flow path short, vertical, and straight. These modifications may increase the cost of these sensors, but more accurate measurements would increase the data's value and reduce the data analysis cost. Additionally, sensor manufacturers are strongly encouraged to share more information about their signal- and data-processing methods, while preserving proprietary details. This transparency would not only help users interpret the data more accurately, but it would also foster innovation to improve the technologies.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/atmos16050502/s1>, Figure S1. Particle size distributions of dioctyl sebacate (DOS) measured with the reference instruments for set geometric diameters (D_g): (a) 0.6 μm and (b) 1 μm , generated with DMA and measured with OPS; (c) 2 μm and (d) 6 μm , generated with FMAG and measured with APS. Figure S2. Mass concentrations of DOS particles measured with DRX for three geometric diameters (D_g): (a) 1 μm , (b) 2 μm , and (c) 6 μm . Figure S3. Particle number size distributions measured with PMS5003 for four geometric particle diameters (D_g): (a) 0.6 μm , (b) 1 μm , (c) 2 μm , and (d) 6 μm . Figure S4. Particle number size distributions measured with SPS30 for four geometric particle diameters (D_g): (a) 0.6 μm , (b) 1 μm , (c) 2 μm , and (d) 6 μm . Figure S5. PM_1 , $PM_{1-2.5}$, and $PM_{2.5-10}$ fractional mass concentrations measured with DRX, PMS5003, and SPS30 for geometric diameters (D_g): (a) 0.6 μm , (b) 1 μm , (c) 2 μm , and (d) 6 μm . Figure S6. Time series of hourly-averaged $PM_{2.5}$ and PM_{10} concentrations by two beta-attenuation monitors (BAMs) collocated with the SPS30. The data were taken in Reno, Nevada, during 7–10 February 2020.

Author Contributions: Conceptualization, P.G. and X.W.; methodology, P.G., A.R., S.B., W.P.A., and X.W.; software, P.G. and A.R.; validation, P.G. and X.W.; formal analysis, P.G. and X.W.; investigation, P.G., A.R., and S.B.; resources, X.W., J.C.C., and J.G.W.; data curation, P.G., A.R., and S.B.; writing—original draft preparation, P.G. and X.W.; writing—review and editing, P.G., X.W., J.C.C., J.G.W., W.P.A., and H.M.; visualization, P.G. and X.W.; supervision, X.W.; project administration, X.W.; funding acquisition, X.W. and W.P.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Department of Energy, grant award No. DE-SC0021214.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors upon request.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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