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Atmospheric Measurement Techniques Discussions

# *Interactive comment on* "Laboratory evaluation of particle size-selectivity of optical low-cost particulate matter sensors" *by* J. Kuula et al.

**Anonymous Referee #1**

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In this work, Kuula et al. present an investigation of counting efficiency as a function of size for a series of low-cost light scattering devices. The research question that the authors seek to answer (whether low-cost sensors can correctly assign particles to the appropriate PM mass fractions) is an important one. The work appears well thought out and carefully conducted, although the manuscript is below average from an English language perspective. There are dozens of grammatical and stylistic mistakes that will need attention prior to publication. However, the authors present a novel experimental procedure and some interesting results, so I am supportive of publication if this and other concerns are addressed in a revised manuscript. Comments on how the presentation of the methods and the interpretation of the results could be improved are below.



Major Comments

One major drawback of this work is that the authors appear to have used a "forced flow" of 1 L/min through each sensor, which may not be in accordance with the manufacturer's intended use. The use of a non-standard flow rate (i.e., one that is different from the manufacturer's recommendation) could compromise a sensor in a number of ways. For example, it could lead to differential inertial losses of particles as they transmit through the sensor. Or, it could lead to variable pulse widths of particles during detection that deviate from the expected pulse widths during calibration. The authors need to verify that this method of testing under a forced flowrate did not affect sensor response. One way would be to repeat these tests at flow rates of 0.5 and 2 Lpm to see if the response factors change. If they do change, then the results presented here might lead to misinterpretation...I do not support publication of this manuscript until this issue is investigated further and/or resolved.

I think the VOAG method for generating a sequence of monodisperse particles of varying size is both novel and useful to the community. However, I would appreciate more detail on how the method is implemented so that others can properly reproduce this method. Such details could be enumerated as supplemental material.

Comments on the Methods section

The Methods section could be organized better and was missing key information needed to reproduce the work.

Comments on technical issues:

1. Table 1: The "number of size bins" column is problematic. It's not appropriate to compare the number of PM mass fractions reported by the low-cost sensors to the number of size bins that the GRIMM 1.108 classifies particle into. Perhaps the authors could remedy this problem by creating two columns: one labeled "number of mass fractions reported" and "number of particle size bins". For example, the SPS30 reports

data in 4 mass fractions and 5 particle size bins.

2. Line 76: Why did the authors remove the mechanism that drives sample flow through some of the sensors but not others? Specifically, why did they remove the air heating resistors from the PPD42 and B5W but not remove the fans from the PMS5003, SDS011, and SPS30? This discrepancy seems like it could lead to an unfair comparison between different sensors. A sensor's output is partially determined by how quickly and efficiently particles are drawn into the sensing zone. If the flow rate through the sensor is modified, the output of the modified sensor might differ from the output of the "as-purchased" sensor. For example, results presented by Tryner et al. (doi: 10.1039/C9EM00234K) indicate that varying the flow rate through a modified PMS5003 sensor changes the output. Since the authors modified some of the sensors used in this study, the results presented here might not be directly transferrable to unmodified sensors being used in the field.

3. Lines 85-89: The PMS5003 reports each mass fraction two ways: "CF=1, standard particle" and "under atmospheric environment". Which values were used in the data analyses presented here? 4. Lines 164-165: Please state the fraction of raw measurement points that were disregarded.

5. Line 170: Equation 3 is not clear. What is the maximum Sensor/APS ratio? Was this the maximum ratio measured during the entire 60-minute long test run?

6. Line 175: One issue is that the APS is known to have poor counting efficiency for liquid droplets above about 5 microns in diameter. Did the authors account for this artifact? See https://doi.org/10.1016/j.jaerosci.2005.03.009

7. Line 179-180: This definition of "valid detection ranges" is not clear. Do the authors mean that the valid detection range was the range of CMDs for which the normalized detection efficiency was greater than 50%? If so, please consider also rephrasing the text on lines 209-210 as something like "(the valid detection range was defined as the range of particle sizes for which normalized detection efficiency was > 50%)".



Comments on organization:

1. Lines 75-84: This information should be moved to the "Sampling configuration" section. These methods are difficult to understand or justify without additional knowledge of the system used to pass monodisperse aerosol through the sensor.

2. Lines 85-82: This information should be moved to the "Data processing" section.

3. Lines 89-90: Please move the sentence that starts "Three units of each sensor. . ." to the end of the first paragraph in Section 2.1.

4. Lines 90-93: Please start a new paragraph here that contains the information on the GRIMM 1.108.

5. Line 95: Section 2.2.1 should start with a sentence that says, "The aerosol sampled by the low-cost sensors was generated using a Vibrating Orifice Aerosol Generator 3450 (VOAG, TSI Inc., USA)." That way readers will know why the information contained in this section is relevant.

6. Lines 101-102, "This aerosol generation method. . .": This sentence is neither relevant nor helpful. Please delete it.

7. Lines 121-125: The second sentence in this paragraph is more helpful than the first. I suggest rephrasing as "The novelty of the aerosol generation method used in this research is based on the observation that the particle size of the monodisperse and constant number concentration reference aerosol can be controlled by feeding solutions with different non-volatile concentrations to the VOAG, one after each other."

8. Lines 161-162: Please show at least one example panel from Figure S2 in the main text.

9. Lines 176-177, "The decision to divide the data into 30 bins. . .": This sentence is not necessary. Please consider deleting it.

10. Lines 186-187: The sentence that begins "The previously-described data process-

ing technique. . .” should be moved to the “Data processing” section.

Comments on the Results section

Comments on technical issues:

1. Overall, the authors interpretation of their experimental results seems to be based on the tenuous assumption that the low-cost particulate matter sensors all function as aerosol spectrometers rather than as nephelometers. In the GRIMM 1.108 aerosol spectrometer, sample air is aerodynamically focused and passes through a narrowly-focused laser beam so that the detector sees the light scattered by just one particle at a time. Thus, the GRIM1.108 can count and size individual particles. The low-cost sensors evaluated in this study do not aerodynamically focus the sample air and, as a result, it is unlikely that the detectors in these sensors see light scattered by individual particles. Instead, the mass concentrations reported by the low-cost sensors are most likely determined by the intensity of light scattered by a group of particles, and not from a measured particle count and size distribution. Results presented by Kelly et al. in 2017 (doi: 10.1016/j.envpol.2016.12.039) suggested that, for Plantower sensors, “the allocation of light scattering to PM1, PM2.5, and PM10 is based on a theoretical model rather than a measurement” (pp. 495-496) and “the size distribution provided by the PMS is based on a theoretical model rather than a measurement” (pp. 497). Claims in the literature that sensors such as the PMS5003 do function as optical particle counters are dubious.

2. Lines 207: I would not say that “the particle sizing of the different bins is not working properly.” See the comment above for justification. I think it would be appropriate to say “it is apparent that the PMS5003 does not accurately distinguish between the PM1, PM2.5, and PM10 size fractions.” Do the ratios of the masses in the PM1, PM2.5, and PM10 change as the sensor are exposed to different particle sizes?

3. Line 223: Levy Zamora et al. evaluated the PMSA003 sensor, so results from that study might not be directly comparable to results from this study.



4. Lines 231-235: The authors state that they expect the SDS011 to measure PM2.5 more accurately than the PMS5003 based on differences in 2.5 – 10 um mass fractions reported by the two sensors. I don’t see how differences in the 2.5 – 10 um mass fractions would affect the reported 0.3 – 2.5 um mass fractions. The two sensors have similar detection efficiencies for the 0.3 – 2.5 um mass fraction. How does the accuracy of PM2.5 measurements reported by the SDS011 (as reported by Badura et al. and Liu et al.) compare to the accuracy of PM2.5 measurements reported by the PMS5003 (see, for example, Malings et al., doi: 10.1080/02786826.2019.1623863)?

5. Lines 240-241: The SPS30 product datasheet states that the SPS30 is calibrated using “a defined potassium chloride particle distribution” (www.sensirion.com/fileadmin/user_upload/customers/sensirion/Dokumente/0_Datasheets/F

6. Lines 246-247: The Rˆ2 values reported here provide no indication of sensor accuracy. Accuracy is related to the absolute difference between the concentration reported a low-cost sensor and a reference monitor. It’s possible for the mass concentrations reported by a low-cost sensor to be very different in magnitude from the concentrations reported by an FEM monitor but for the concentrations reported by the two to still be strongly correlated. Saying that the fraction of variance explained by a linear model is high doesn’t imply that the model has an intercept of zero and a slope of one.

7. Lines 281-288: Again, the Rˆ2 values reported here provide zero information on sensor accuracy. These values only imply whether or not a linear model explains the relationship between concentrations reported by a reference monitor and concentrations reported by the sensor. Measures of accuracy include mean error, mean absolute error, and mean percentage error.

8. Lines 309-317: See comment #1 on the results.

Comments on organization:

1. Figure 3: This figure could be improved to help readers interpret it. A title above

the legend that says “Particle size bins” would be nice. I also suggest revising the first sentence in the caption to something like “Normalized detection efficiency of the 15 particle size bins as a function of the count median diameter of the reference aerosol.” Finally, please also move the sentences from lines 185-186 (“For the sake of clarity. . .”) and line 187-188 (“Bins 14 and 15,. . .”) to the figure caption.

2. Figure 4: The caption for this figure should be more informative. I suggest “Normalized detection efficiency of discretized PM mass fractions reported by the low-cost sensors as a function of the count median diameter of the reference aerosol.” I also suggest moving the text on lines 201-204 (“The coloured circles represent. . ...ranges stated by the corresponding manufacturer.”) to the caption.

Editorial comments:

1. Line 13: The PM acronym should come before the word ’sensors’.

2. Lines 17-18: I disagree with the statement “This implies that there are underlying reasons yet to be characterized which are causing inaccuracies in sensor measurements.” The underlying reasons for why light-scattering sensors are inaccurate (regardless of cost) has been known among the aerosol research community for decades; there is a vast literature on the limitations and biases associated with this measurement method.

3. Line 29: “enabling” should be “enable” and “higher resolution” should be “higher-resolution”.

4. Lines 30-31: It might be helpful to refer readers to some more recent studies demonstrating applications of sensor networks. See, for example, Feinberg et al., 2019 (doi: 10.1016/j.atmosenv.2019.06.026) and Rickenbacker et al., 2019 (doi: 10.1016/j.scs.2019.101473).

5. Line 54: I would use a phrase like "size discrimination" instead of "size selectivity" in this context. The term “size selectivity” is most often used in the aerosol literature



to discuss inlet aspiration/transmission performance, such as that of a PM10 or PM2.5 inertial separator.

6. Line 59: “cursory” should be “cursorily” or “concurrently”, depending on what the authors mean by this sentence.

7. Line 82: Rephrase as “However, the more stable sample flow system (i.e., fan instead of convection) might help compensate for the sub-optimal layouts of these sensors.”

8. Line 85: “analogue” should be “analog”.

9. Line 86: For clarity, please change “sensor outputs shown” to “PM mass fractions listed”.

10. Line 92: Change “being” to “to be” and delete the word “other”. The GRIMM 1.108 does not measure PM mass directly. Also, please specify which metric reported by the GRIMM 1.108 (or derived from values reported by the GRIMM 1.108) has a comparable accuracy to the filter weighing method.

11. Line 126: Delete the word “produced”.

12. Lines 227-228: Consider replacing “two more clear different” with “two clearly different”.

13. Line 242: Revise as “and neither Web of Science nor Scopus literature research showed. . .”.

14. Line 249: Replace “align” with “alignment”.

15. Line 293: Replace “prominent” with “promising”.

16. Line 296: Add the word “Neither” before “Web of Science”.

17. Line 307: Replace “pertain” with “retain”.

18. Figure 2: The title for this graph is “Sample aerosol”, but the aerosol sampled by the

low-cost sensors is referred to as the “reference aerosol” throughout the manuscript. Please use consistent terminology.

References

GRIMM 1.108 manual: https://wmo-gaw-wcc-aerosol-physics.org/files/opc-grimm-model–1.108-and-1.109.pdf

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