Anonymous Referee #2

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General Comments:

"This manuscript describes the development of a system to provide a flow of monodisperse particles, and the authors then use this system to evaluate several common low-cost sensors. The description and evaluation of the new system (VOAG-GP50) are clearly described. Although their conclusion that low-cost sensors mis-classify particle sizes is not new, the systematic evaluation of size selectivity in low-cost sensors is a valuable contribution to the field. However, the paper would be stronger if the authors improved the clarity of the data-processing section, address a few questions regarding sample flow rate, and polish the language."

We thank you for your feedback. Several improvements have been made to the manuscript according to the more detailed comments.

Specific comments:

"The data processing section needs some clarification. The authors discuss dividing the data into 30 size bins, but in line 146 they discuss 10 steps to produce different particle sizes. The authors need to clarify how 10 steps can yield 30 different size bins."

The 10-step program (or method) refers to the dispensing of liquids and is related to neither data processing nor the amount of different particle sizes produced. The number of used steps and the parameters assigned to them simply define the minimum and maximum particle size and the rate at which the particle size gradient evolves from the minimum size to maximum size. The word "gradient" is used to underline that a step from e.g. 2 to 3 µm does not in fact lead to a discontinuous and sudden step from one particle size to another.

The 30 bin sizes (or sections) refer to data processing in which the raw 10-second resolution data (typically ~ 300 data points altogether) was divided into 30 "sections" according to the measured CMDs. For each section, an average detection efficiency and CMD was calculated.

To make this clearer, details and a step-by-step example (with figures) of how the data was processed was added to the supplementary material.

Added to manuscript section 2.3 "Data processing": "A detailed example how the data was processed and how the valid detection ranges were calculated is shown in the supplementary material."

Added to manuscript section 2.2.2 "Sampling configuration": "It is worth underlining that the number of steps used in the GP50 dispensing program does not dictate the number of different particle sizes produced. The number of steps and the parameters assigned to them simply define the minimum (blending ratio of the first step) and maximum (blending ratio of the last step) particle size and the rate (step duration) at which the particle size gradient evolves from the minimum size to maximum size. The word "gradient" is used to note that a step from 2 to 3 µm, for instance, does not lead to a discontinuous and sudden step from one particle size to another."

"In Lines 175 to 180, the authors base their discussion of valid detection ranges on a detection efficiency curve, but I could not find a discussion of how they define a detection efficiency curve. I would suggest providing an example in the supplementary material and illustrating how the upper half of this curve is defined."

The normalized detection efficiency curve is defined in Eq. 3 and the respective curves are shown in Figure 4a-f. A demonstration how the valid detection ranges were calculated has been added to the supplementary material.

"I have some concerns regarding the effect of sample flowrate on the low-cost sensors. In the experimental setup, a pump draws the monodisperse particles into the sensor housing at a flow rate of 1 lpm. Figure S2 shows the sensor housing and placement of the low-cost sensors with the flow directed at the sensor inlet (mostly). The authors should consider whether this setup may be skewing their results. This is particularly important for sensors with fans that are designed to operate at a specific flowrate. It is possible that pushing a flowrate that differs from the design flow rate could alter the results. For example, the PMS sensor has a volumetric flowrate of approximately 0.1lpm (which is 10x lower than the volumetric flowrate into the sensor housing). Granted not all of the 1 lpm would flow into the sensor, but this is worth considering."

There is no clear theoretical basis as to why a different flow rate would change the way the sensor discriminates different particle sizes. Assuming the sensors function as spectrometers (which the results of this study suggest they do, at least partly), the size discrimination of such devices is predicated on the analysis of pulse height caused by the scattering light of particle (Mie-theory). Change in the flow rate would change the frequency (i.e. number concentration) and duration of pulses but not their height. Whether the measured absolute concentrations were higher than expected is trivial as the data analysis of this study was based on normalized concentrations. Although possible, the effect of particle-size dependent sampling losses was originally estimated to be negligible, and as all the tested sensors seemed to exhibit similar size discrimination characteristics as what previous studies had shown, the effect of ancillary flow rate was not addressed in any way.

However, to ensure that the ancillary flow rate did not affect the results, additional tests were conducted with flow rates of 0.5 and 2 L min^{-1}. Instead of testing all the three sensor units of the six different sensor models, only a single unit (unit #3) for each sensor model was evaluated. The results (Fig. 1, attachment) indicate that different flow rates had no meaningful effect on the responses. The SDS011 shows slightly stronger response for particles larger than ~2 – 3 µm, but this is probably resulting from operator inconsistency (or randomness) because the change is similar for both 0.5 and 2 L min^{-1} flow rates. The B5W sensor has weaker response for particle sizes larger than ~4 – 5 µm with 2 L min^{-1} flow rate which suggests that the sampling losses may have increased. However, the response is similar for 0.5 and 1 L min^{-1} flow rates (B5W was originally designed to be used with a heater resistor-induced flow which is most probably closer to 0.5 than 2 L min^{-1}). The difference in PPD42NS responses, which imply that the losses may have increased for smaller and not higher flow rates, is attributed to randomness.

While conducting the additional flow rate tests, the Sharp sensors were found to exhibit completely different characteristics to what was previously measured. The underlying reason for this is still unknown, but it is possible that a prototyping breadboard, which was used to make the required connections for the external resistor and capacitor, had loose connections which resulted in misleading bias measurements. Nevertheless, all the Sharp sensors were re-evaluated with the original 1 L min^{-1} flow rate and the unit #3 was tested additionally with the 0.5 and 2 L min^{-1} flow rates. The new valid detection range was measured to be < 0.8 µm which is no longer in an obvious conflict with the results of the previously mentioned study of Wang et al. (2015). Considering the additional tests, it appears that the different flow rates may influence the sensor response in smallest particle sizes (< 0.55 µm), but the responses with 0.5 and 1 L min^{-1} flow rates are so similar that the stated valid detection range remains the same. Smaller flow rates are likely to better represent the original flow rate, which for the Sharp sensors, was based on plain diffusion.

Added to manuscript section 2.2.2 “Sampling configuration”: “Although there is no clear theoretical basis as to why a different flow rate would affect the way the sensor discriminates different particle sizes (apart from the different particle size-specific sampling losses), additional tests were conducted with flow rates of 0.5 and 2 L min-1 to ensure that this was indeed the case (see Supplemental Figure S2).”

Section regarding the results of Sharp GP2Y1010AU0F has been revised as: “The response function of the GP2Y1010AU0F is shown in Figure 4d, and its valid detection range appears to be approximately < 0.8 µm. Like the previously discussed sensors, the GP2Y1010AU0F can be used to measure small particles (e.g., PM1) but not coarse mode particles. Several laboratory evaluations have been previously conducted for the GP2Y1010AU0F, but none of these have assessed its detection range using monodisperse test aerosols (Li and Biswas, 2017; Manikonda et al., 2016; Sousan et al., 2016). Wang et al. (2015) used atomized polystyrene latex (PSL) particles to evaluate the effect of particle size on the GP2Y1010AU0F response, but no concluding remarks can be obtained from these results. The study method utilized only three different sized PSLs; moreover, it was not designed to investigate the complete detection range of the GP2Y1010AU0F. However, according to the authors, the results implied that the sensor was more sensitive to 300 nm particles than to 600 and 900 nm particles, which is in slight disagreement with the results of this study whereby the normalized detection efficiency curve shows the highest sensitivity peak for 0.6 µm sized particles as well as a decreasing trend for particles smaller than this. There is no obvious explanation for this discrepancy, but it is worth re-emphasizing the differences in the used evaluation approaches.”

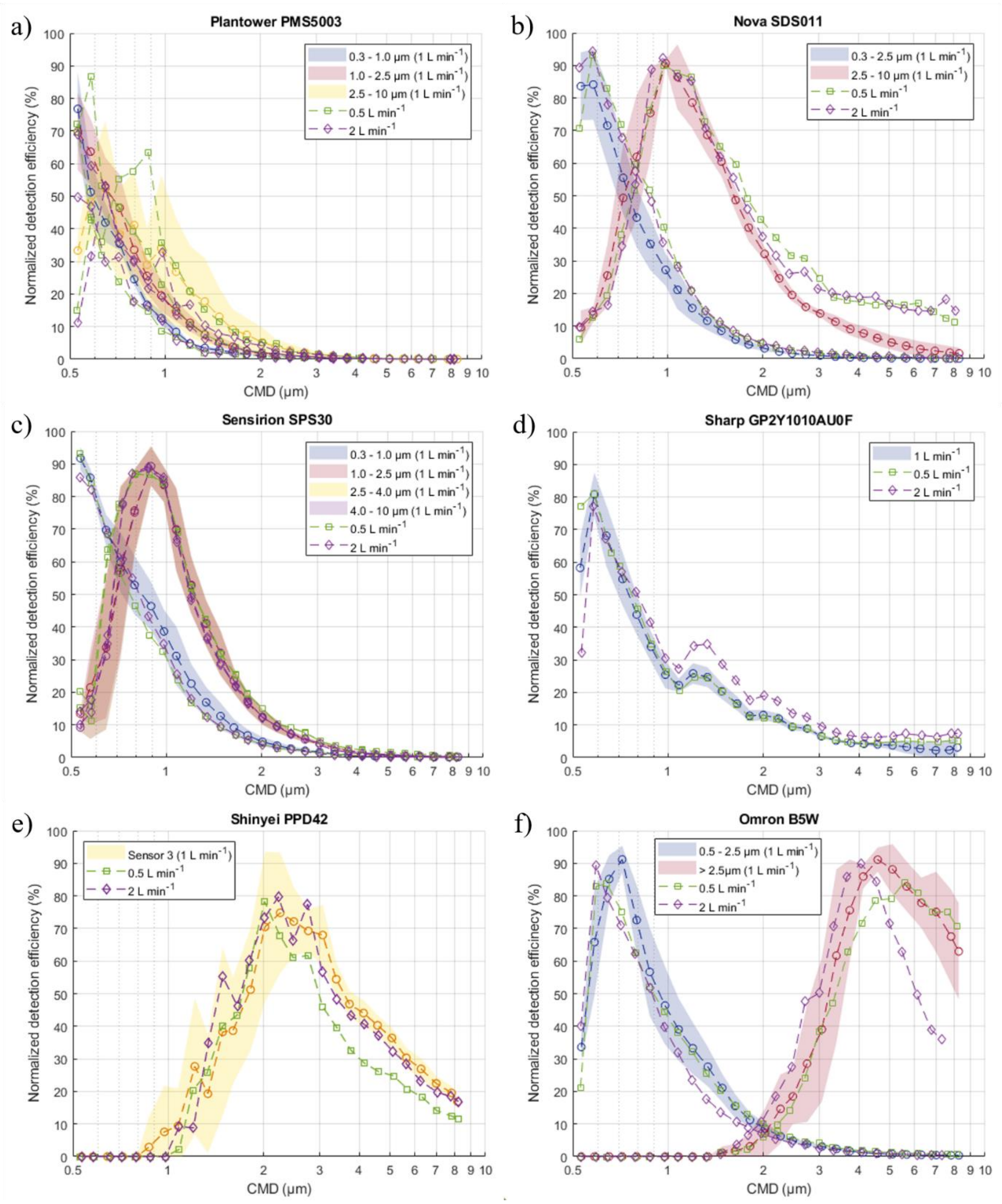

Fig 1. Results of the additional tests.

"The manuscript needs a thorough review and edit by a native English speaker. The language is awkward and sometimes confusing. I am including a few examples from the abstract, but this list is not comprehensive: - "due to their prospective nature regarding spatial extension of measurement coverage". Vague and awkward wording. - "sensors can be useful in achieving this goal". No goal is mentioned previously. - "it is often reminded that the risk of sensor misuse". Improper usage."

Commercial editing services were used to check and correct the language.

Technical corrections:

"Line 121. Do the authors mean stable particle size distribution rather than particle size gradient? If they mean particle size gradient, this needs to be explained."

This has been rephrased 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" (as suggested by Referee #1).

"Line 185. The authors should clarify what the response curves are for. The 10-step(30-bin) generation of monodisperse particle sizes?"

The GRIMM 1.108 was tested the same way as was all the low-cost sensors. The goal was to show how the particle size discrimination characteristics of the mid-cost, 15 bin spectrometer-type instrument differed from the ones of the low-cost sensors.

Following changes were made to the manuscript: "The response curves" replaced with "The normalized detection efficiencies of the 15 bin GRIMM 1.108…"

"Line 203. The authors should provide the standard deviations of the CMDs. In Figure2, the text says, "The GSD of the size distribution remains below 1.2, but line 113 says that the VOAG has relative standard deviation of less than 3 %.""

The reason not to provide standard deviations of CMDs is discussed in the added supplementary material. In short, they were insignificant.

The statement "… standard deviation of less than 3 %" refers to the standard deviation of the **number concentration** of the VOAG, which was stated in the original paper of Berglund and Liu (1973), and it is in no way related to **size distributions**.

Line 113 rephrased as: "According to Berglund and Liu (1973), the output aerosol number concentration of the VOAG has a relative standard deviation of less than 3 %, and the formed particle size distribution is monodisperse having a geometric standard deviation (GSD) less than 1.014".

"The authors mention the size limitation of the APS as being a limiting factor in the analysis (Figure 2), but in line 119 they mention that the VOAG cannot reliably generate particles smaller than 0.55 um. This limitation should be mentioned in Figure 2 in addition to the APS limitation. It would also be worth mentioning this important limitation in the abstract."

Added to line 19 (Abstract): "(from ~ 0.55 to 8.4 µm)"

Added to Figure 2 caption: "Along with the lower detection limit of the APS, another limiting factor of the study was the smallest producible particle size, which was approximately 0.55 µm."

"Figure 1 – The GRIMM is not shown. Where does the GRIMM draw its sample? How are the flows distributed symmetrically between the APS and GRIMM since the GRIMM's flow is 1.2 lpm whereas the GRIMM is 1 lpm?"

The GRIMM drew its sample from where the sensor enclosure is now shown. The isokinetic flow splitter was designed for equal (1 L min^{-1}) flow rates, but this was not considered problematic as there was never intention to evaluate the GRIMM other than cursorily. Furthermore, the Figure 3 shows that the unequal flow distribution probably had little to no effect on the response.

Figure 1 caption rephrased as: "Figure 1: Schematic of the sensor evaluation setup. The GRIMM 1.108 drew its sample from where the sensor enclosure is now shown."