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Potential and Limitations of the Low-Cost SDS011 Particle Sensor for Monitoring Urban Air Quality

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Abstract

In Particulate Matter (PM) monitoring, current laser scattering low-cost sensor generations exhibit better stability than early sensor generations and feature internal digital processing to achieve more accurate results. As a representative of this class of sensors, we examine the popular SDS011 PM sensor. Previous work about co-location measurements between SDS011 sensors indicates that the sensor delivers adequate correlation under "typical" conditions, but performs less well under other ambient conditions, especially high humidity. To further explore the sensor's data quality in-depth, we conducted a series of controlled experiments with high precision reference devices and different aerosols, both polydisperse (ambient air, ammonium sulfate, soot) and monodisperse (polystyrene particles of different sizes). We also present results from a longer-term comparison (days) of multiple sensors, as well as the key influencing factors on uncertainty and assess the sensor's potential and limitations. Our findings show that a single sensor generally does not capture PM_{10} satisfactorily and we discuss under which conditions $PM_{2.5}$ readings reflect the ambient air quality adequately.

Keywords: Low-Cost Sensors, PM, Environmental Sensing, Air Quality, Aerosol Monitoring, Evaluation

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1. Introduction

In Particulate Matter (PM) monitoring, developments towards incorporating distributed sensing approaches using low-cost sensors are being made (Snyder et al., 2013). Research on early generations of low-cost particle sensors compares them with official measurement stations, showing that they can in principle capture the dynamics of ambient PM levels (Budde et al., 2013; Holstius et al., 2014), but may suffer from low calibration stability, are unable to differentiate size classes, and may be susceptible to other sources of error (Budde et al., 2015). Current low-cost laser scattering sensors claim to exhibit better stability and more accurate readings. While they are mostly designated as $PM_{2.5}$ sensors, some also output PM_{10} and/or PM_1 values. As a representative of this class of sensors, we examine the SDS011 sensor (Nova Fitness, 2015). It is already widely being used in deployments around the world, ranging from sensor networks to grassroots citizen science projects, in which volunteers have deployed hundreds of these sensors in urban areas.

In related work, co-location measurements between the SDS011 have been performed (LUBW, 2017), indicating that the sensor signal exhibits adequate correlation under some conditions (relative humidity of 20-50 % and PM_{10} mass concentrations < 20 µg/m³) but performs less well under others, especially high humidity. To further explore the sensor's quality in-depth, we present the key influencing factors on measurement uncertainty, along with a series of experiments to appropriately assess its potential and limitations.

2. Experiments

We conducted lab experiments exposing the sensor(s) to increasing concentration levels of monodisperse and polydisperse particles, both artificially created and using ambient air.

2.1 Monodisperse Particulates

In order to assess the influence of concentration and particle size on the sensor readings, a series of experiments was carried out measuring inert monodisperse polystyrene particles with SDS011 sensors in a lab setting, with a *Palas PROMO 2000* device with *welas 2100* sensor as reference. An aerosol generator made specifically for fine control of the conditions under which particles are dispersed was used in all experiments (see Fig. 1, right).

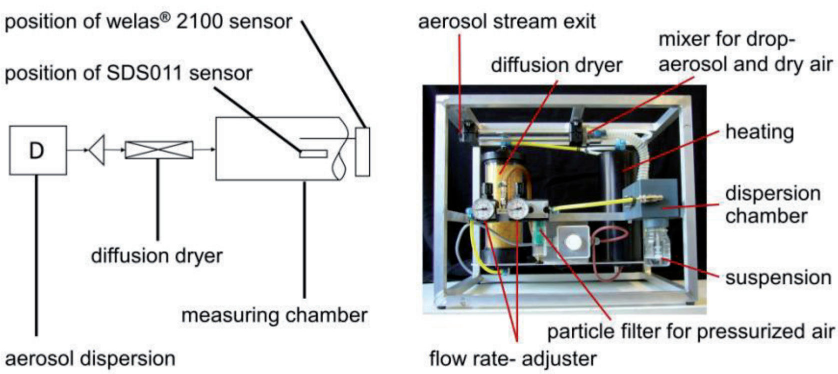


Fig. 1. Experimental setup of our tests with monodisperse polystyrene particles

Homogeneous watery suspensions containing the target particles are dispersed through a venturi nozzle. The small droplets containing single particles then enter a chamber, where they are mixed with a heated stream of dry, particle-free air, which dries the droplets and dictates the temperature during the experiment. The air stream entering the suspension is used to control the exiting concentration of the generator. The temperature and flow rate of the hot air stream are used to control temperature and humidity during the experiment. The stream exiting the generator contains the dispersed monodisperse particles that were originally in the suspension. This stream passes through a diffusion dryer before entering the measuring chamber, which was left open at the end, allowing to place SDS011 sensors horizontally (with the fan facing towards the ceiling) and the reference sensor in the chamber on the same height (Fig. 1, left). The particles used in these experiments were inert, non-hygroscopic, monodisperse polystyrene particles with a density of 1.055 g/cm³.

To investigate the influence of particle size and concentration, monodisperse particles of different sizes (0.3, 1, 2, 5 and 10 µm respectively) were used in separate experiments. Various concentrations of up to approximately 2500 µg/m³ were used for each particle size. The experiments were conducted at ambient pressure and a relative humidity of approximately 45 %. Temperatures during the experiment were kept between 20 and 22 °C. All sensors measured the concentration constantly for at least 20 minutes each to ensure stable concentration conditions. The data presented in this paper shows the results of one SDS011 sensor only. Other SDS011 sensors (four tested in total) showed the same trends.

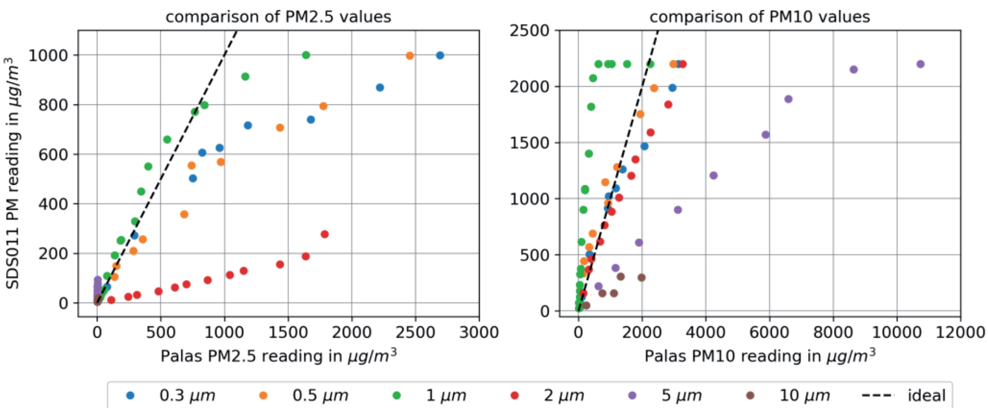


Fig. 2. SDS011 readings vs. reference for different monodisperse particle sizes for $PM_{2.5}$ (left) and PM_{10} (right)

$PM_{2.5}$ and PM_{10} readings of the SDS011 sensor deviate from the reference, depending on particle size and concentration (see Fig. 2). For 0.3 µm particles, $PM_{2.5}$ readings (Fig. 2, left) are similar to those of the reference up to a reference concentration of 300 µg/m³. For concentrations above this value, the SDS011 reports lower values for 0.3 µm than the welas 2100. For 1 µm particles, too high $PM_{2.5}$ values are reported by the SDS011 for $PM_{2.5}$ concentrations between 300 µg/m³ and 800 µg/m³. Below they fit well to the reference, above $PM_{2.5}$ concentrations are underestimated. 2 µm particles are strongly underestimated by the SDS011 in the $PM_{2.5}$ value. The $PM_{2.5}$ results for 5 µm and 10 µm particles must be treated with caution. For them, the reference device reported impurities in the size channels between 0.2 µm and 0.5 µm, which lead to $PM_{2.5}$ values below 10 µg/m³. The SDS011 shows much higher $PM_{2.5}$ values (up to ~100 µg/m³), but it remains unclear if it reacts stronger to the impurities or if it wrongly includes the 5 µm and 10 µm particles.

In the SDS011's PM_{10} readings (Fig. 2, right), particles of 5 µm and 10 µm are severely underestimated. PM_{10} readings for 0.3 µm particles are similar for both the SDS011 and the reference. 1 µm particles are overestimated in the SDS011 PM_{10} value above concentrations of 300 µg/m³. When we look at the PM10 values for 2 µm particles, we can see a peculiar behavior. As we presented before, the SDS011 sensor underestimates the mass for 2 µm particles in its $PM_{2.5}$ values, indicating that it either does not follow the same $PM_{2.5}$ curve as our reference or assumes a too low density for the particles. However, for PM_{10}, the SDS011 and the welas 2100 report similar values for 2 µm particles.

Overall, the SDS011 shows good results for particles smaller than 5 µm for the PM_{10} value, as long as these are measured under dry, stable conditions, but does not sufficiently consider particles with the sizes 5 µm and 10 µm. The sensor appears to deliver good $PM_{2.5}$ readings for particle sizes 1 µm and 0.3 µm and good PM_{10} readings for particle sizes 0.3 µm and 2 µm for the material used in these experiments. It remains unclear how the sensor's internal processing estimates the particle sizes.

2.2 Polydisperse Particulates

We compared several SDS011 sensors with reference measurements in a lab setting at the *World Calibration Center for Aerosol Physics (WCCAP)* at the *Leibnitz Institute for Tropospheric Research (TROPOS)* that is operated in cooperation with the *German Federal Environmental Agency (UBA)* and the *World Meteorological Organization (WMO)*. We exposed a set of 17 SDS011 sensors to different aerosols (ammonium sulfate, ambient air, soot from a Jing Ltd. miniCAST propane gas burner, and zero air) in an airtight aluminum chamber, depicted in Figure 3. The air outlet was connected to two reference devices: An aerodynamic particle sizer (TSI APS model 3321) and a Scanning Mobility Particle Sizer (SMPS) custom made at the WCCAP (Wiedensohler et al., 2012). This combination enabled the measurement of 92 aerodynamic size channels between 10 nm and 20 µm. Time resolution was one reading every 4.5 minutes. The SMPS samples the different channels in a time multiplex fashion, i.e. one after another over a time of 4.5 minutes. This is how long it takes to scan through all size channels. From these individual size channels, we calculated the three size classes PM_{10}, $PM_{2.5}$ and PM_1 as reference. Aerodynamic particle diameters were converted to a geometric diameter assuming spherical particles and using a particles density of 1.7 g/cm³.

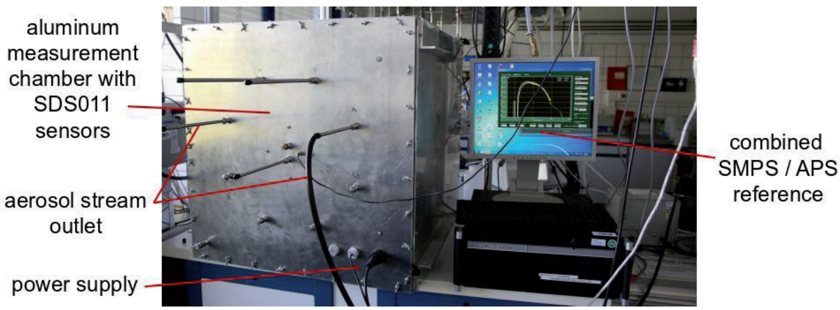


Fig. 3. SDS011 sensors were placed inside an airtight aluminum measurement chamber (left), into which a varying concentration of polydisperse particles was injected. An SMPS and a TSI APS were used as referencev

Figure 4 shows the time series of our experiments. Three individual sensors were disregarded, as was the complete ambient air 2 session, due to technical errors. We can see that the SDS011 generally captures dynamics well, but also that the readings have an offset to the reference and that this offset differs for the individual sensors. This variance can also be seen in the scatterplot in Figure 5.

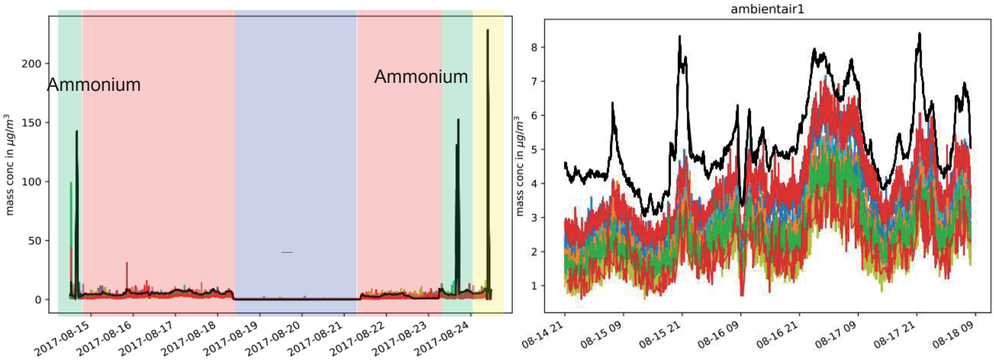


Fig. 4. Time series of experiments with different polydisperse aerosols (left) and zoomed in for $PM_{2.5}$ mass for the first session of ambient air measurements (right). The reference is the solid black line

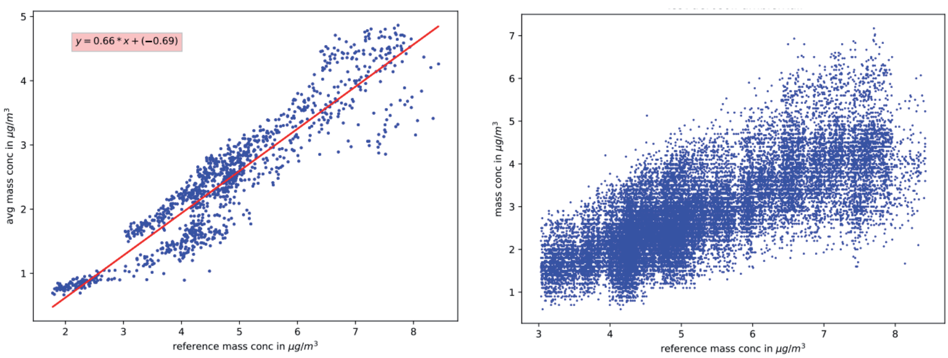


Fig. 5. Scatterplots: mean $PM_{2.5}$ mass against the reference (left) and for all individual 14 valid sensors for the test aerosol ambient air (right).

We see that the sensor exhibits overall good linearity, but also systematic misestimation of the true concentration. On average, the SDS011 showed only 66 % of the $PM_{2.5}$ in ambient air. Individually, the readings ranged from 45 % to 85 %. For ammonium sulfate, the SDS011s on average show only 48 % of the reference's $PM_{2.5}$. For pure soot, no usable readings could be obtained, as was expected due strong absorption and low light scattering. This is a general issue of optical measurements and not specific to the SDS011. It should be mentioned that soot in ambient air is coated with other materials, e.g. organics and sulfates, and scatters light. A general conversion factor how much soot is seen by the SDS011 cannot be given. For zero air, the sensors showed minimum $PM_{2.5}$ values of ~0.3 μg/m³, which seems acceptable for ambient air measurements. All results are presented in Table 1.

2.3 Other Factors

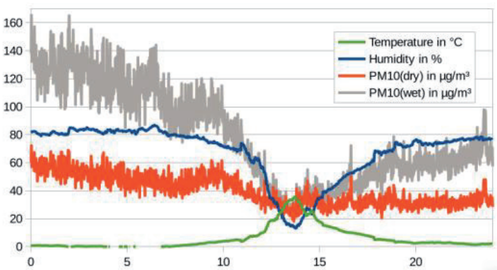
The other most noteworthy aspect that affects the SDS011 sensor is humidity. Generally, the sensors are only specified to operate up to a relative humidity of 70% (Nova Fitness, 2015). Above these values, large deviations must be expected. Figure 6a shows one

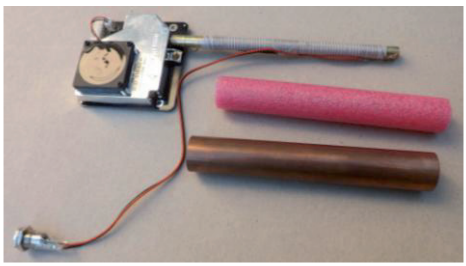
Table 1. Measurement results for the individual sensors ($PM_{2.5}$ / PM_{10}).

Sensor	Ambient air		Ammonium sulfate		Soot		Zero air	
	slope	intercept	slope	intercept	slope	intercept	baseline	stdev
1188476	**0.85 / 0.85**	-0.88 / -0.74	**0.63 / 0.67**	0.01 / 0.26	0 / 0	1.55 / 1.84	0.247 / 0.454	0.0020 / 0.0018
1190049	0.67 / 0.66	-0.66 / -0.50	0.50 / 0.53	0.19 / 0.40	0 / 0	1.21 / 1.39	0.303 / 0.400	0.0009 / 0.0002
1197947	0.61 / 0.60	-0.68 / -0.59	0.46 / 0.49	0.23 / 0.63	0 / 0	1.09 / 1.37	**0.200 / 0.300**	0.0007 / 0.0004
1200580	0.84 / 0.84	-0.60 / -0.59	0.62 / 0.66	0.24 / 0.41	-0.01 / -0.01	1.95 / 2.09	**0.415** / 0.413	0.0017 / 0.0024
132097	0.65 / 0.64	-0.79 / -0.57	0.47 / 0.50	0.17 / 0.72	0 / 0	1.11 / 1.38	0.200 / 0.402	0.0003 / 0.0024
1547350	0.60 / 0.59	-0.80 / -0.76	0.47 / 0.51	-0.06 / 0.55	0 / 0	1.09 / 1.24	0.301 / 0.400	0.0004 / 0.0002
1547430	0.69 / 0.65	-0.98 / -0.67	0.48 / 0.53	0.03 / 0.94	0 / 0	1.26 / 1.68	0.300 / **0.800**	0.0000 / 0.0003
1547436	0.64 / 0.60	-0.80 / -0.44	0.51 / 0.56	-0.12 / 0.34	0 / 0	1.27 / 1.70	0.393 / 0.700	0.0014 / 0.0000
1548172	**0.48 / 0.45**	-0.53 / 0.12	0.42 / **0.45**	0.04 / 1.44	0 / 0	0.97 / 1.82	0.300 / 0.600	0.0002 / 0.0005
1548187	0.65 / 0.71	-0.52 / -0.48	0.47 / 0.53	0.36 / 1.08	0 / 0	1.28 / 1.84	0.407 / 0.601	0.0010 / 0.0008
1548303	0.66 / 0.69	-0.59 / -0.69	0.50 / 0.55	0.11 / 0.55	0 / 0	1.26 / 1.49	0.391 / 0.500	0.0012 / 0.0002
1581752	0.64 / 0.62	-0.62 / -0.41					0.396 / 0.699	0.0017 / 0.0013
158693	0.63 / 0.62	-0.76 / -0.62	0.46 / 0.49	0.21 / 0.53	0 / 0	1.08 / 1.37	0.200 / 0.401	0.0002 / 0.0004
1590613	0.52 / 0.52	-0.73 / -0.52	**0.41 / 0.45**	-0.13 / 0.65	0 / 0	0.94 / 1.15	0.300 / 0.400	0.0000 / 0.0004
Average	*0.65 / 0.65*	*-0.71 / -0.53*	*0.49 / 0.53*	*0.10 / 0.65*				

day of data collected in-the-wild on a humid day. The graph shows that the sensor drastically overestimates the particle concentration in the morning and evening hours when humidity is high. There are two sources of error caused by humidity: Hygroscopic growth of saline particles and condensed fog droplets of similar size as PM-relevant particles. We observed that the overestimation is much stronger in fog, and less extreme in otherwise high humidity or rain. These findings are in line with results published in parallel with this work (Jayaratne et al., 2018). Both effects can be reduced significantly by drying the air. Therefore, in future work, we intend to investigate using a sensor augmentation with a simple low-cost heated air inlet to compensate (Fig. 6b).

Besides humidity effects, we expect age related deviations in long-term use due to the design of the sensor (e.g. due to residual dust in the sensor and aging of the fan). We are currently investigating this in a long-term real-world deployment. Finally, with non-expert users, an often overlooked source of error is the human operator (Budde et al., 2017b).





(a) (b)

Fig. 6. The SDS011 is very susceptible to humidity. In fog, e.g., readings overestimate the actual particle concentration drastically (a). In future work, we intend to investigate drying the air using a low-cost do-it-yourself (DIY) sensor augmentation with a heated air inlet (b) to compensate this effect

3. Conclusions

In summary, our experiments show that:

- The SDS011 can capture **dynamics** of fine dust with **high temporal resolution.**
- There is a notable **variance** between individual sensors.
- **$PM_{2.5}$** readings seem **promising**, esp. for background PM sensing.
- **PM_{10} estimates may be wrong**, esp. if distribution shifts towards larger particles.
- **Humidity dependence** is a problem, esp. in fog.
- **Without further measures,** the sensor is only appropriate for **qualitative** not quantitative data.
- The SDS011 is **less sensitive to ambient soot.**

That being said, the sensor shows remarkable stability for its cost and has the potential to enable novel applications. In future work, we will explore humidity compensation methods, e.g. sensor augmentation, sensor data fusion, and networked sensing scenarios of low-cost sensors combined with big data analytics approaches (Budde et al. 2017). We will also report on the long-term stability of the sensors in a real-world deployment.

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