Optical particulate matter sensors in $PM_{2.5}$ measurements in atmospheric air

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Abstract. Monitoring systems are needed to obtain information about particulate matter (PM) concentrations and to make such information accessible to the public. Small, low-cost, optical sensors could be used to improve the spatial and temporal resolution of PM data. The paper presents results of collocated comparison of four low-cost PM sensors and TEOM analyser, conducted from 20-08-2017 to 24-12-2017 in Wrocław, Poland. Plantower PMS7003 and Nova Fitness SDS011 sensors proved to be the best in terms of precision and were linearly correlated with TEOM data. Alphasense OPC-N2 sensors exhibited only moderate precision and linearity. Winsen ZH03A sensors had low repeatability between units and only one copy demonstrated good operation possibilities. All tested sensors had a bias in relation to $PM_{2.5}$ concentrations obtained from TEOM.

1 Introduction

The term particulate matter (PM) refers to very complex mixtures of small solid particles and liquid droplets suspended in the air [1]. Particulates vary in chemical composition (inorganic and organic substances), shape, size, surface area and also reactivity, solubility and origin [2]. Because of such complexity PM can be described by multiple terms. The most common refers to size or more precisely to aerodynamic diameter (d_a). According to EN 12341:2014, PM_x is particulate matter small enough to pass through a size-selective inlet with a 50% efficiency cut-off at x μm aerodynamic diameter [3].

Aerodynamic diameter of particulates has also implications for typical site of deposition when they are inhaled. Coarse PM (d_a in the range 2.5–10 μm) deposits mainly in the upper respiratory tract, but fine PM ($PM_{2.5}$) deposits throughout the respiratory tract and can penetrate to the lower parts and alveoli [2, 4]. Nowadays, the adverse health effects of PM are well documented. Both short term and long term exposures are related to respiratory and cardiovascular problems and even mortality from cardiovascular and respiratory diseases [2, 4–6]. What's more, the International Agency for Research on Cancer classified particulate matter as carcinogenic to humans [7].

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Despite the fact that PM could originate from natural sources, dominant emissions in Europe are linked with anthropogenic activities: transport, agriculture, industrial processes and residential sector. The latter includes emissions from commercial, institutional and households fuel combustion [8, 9]. The impact of residential heating is in particular important in Poland [9], especially in winter season when fuel burning (mainly fossil fuels, sometimes of poor quality) and specific atmospheric conditions result in the high pollution events [10].

In accordance with EU Directive 2008/50/EC emissions of harmful air pollutants should be avoided, prevented or reduced [11] and multi-sectorial approach is needed to help combat air pollution. First of all, networks of monitoring stations are needed to obtain information about air contaminants and to make such information available to the public. Standard method for the determination of mass concentration of suspended particulate matter is based on gravimetric measurements [3]. This method provides accurate results, however, only for relatively long periods of sampling (24 hours). Thus, it cannot deliver the real-time on-line data on PM concentration. Short-term temporal patterns and concentration peaks are masked in this way. Complement to this approach is based on automated measuring systems (AMS), applied in routine monitoring networks [12]. In Poland two types of continuous measuring instruments are used in those stations: β-ray attenuation monitors (BAMs) and tapered element oscillating microbalances (TEOMs). Such systems are capable of producing 1-hour average measurement values, that may be used for direct information of the public, e.g. through websites or mobile apps [13].

In spite of those possibilities, the complexity and price of typical AMS devices is high and there is a limited number of national measuring stations. It is known that spatial distribution of PM is quite non-uniform [14], because of many emission sources and secondary conversion processes. Thus, in case of poorly distributed measurement points, detection of "hot-spots" or execution of epidemiological studies is difficult to achieve. Improvement of the spatial and temporal resolution of PM data is possible by means of low-cost monitoring instruments [15, 16].

Currently, many PM sensor models are available on the market. Their price is quite low and they have relatively small power consumption. They all work on the principle of light scattering and it should be noted that particle parameters (size, shape, density and refractive index) strongly influence the output signal [17]. Therefore, before any monitoring, PM sensors should be calibrated under conditions close to the final ones [18]. One of possible ways of low-cost sensors calibration is the use of collocated data from higher class instruments [19].

The article presents the results of collocated comparison of four models of low-cost optical particulate matter sensors and TEOM analyser. Measurements of $PM_{2.5}$ were performed in ambient air of the city of Wrocław. The study focused on some sensor performance characteristics: precision of sensors (intra-model variability), bias and linearity between sensors signals and TEOM data. The novelty of this work includes the long-term comparison campaign (4 months) in the ambient air of Polish city. That kind of comparison takes into account real properties of ambient particulates and could be performed to calibrate any low-cost sensor for air monitoring.

2 Experimental

2.1 Site description

Comparison was carried out in the period of 18 weeks, from 20-08-2017 to 24-12-2017, at the Meteorological Observatory of Department of Climatology and Atmosphere Protection

of University of Wrocław. This measurement point is situated at Kosiby Street in Wrocław, in area of detached houses, allotments and city park. Sources of PM emission are related mainly to individual heating systems in households and to a lesser extent to city road transport.

2.2 $PM_{2.5}$ measurements

2.2.1 Tapered element oscillating microbalance (TEOM)

The measurement station is equipped with TEOM 1400a analyser (Rupprecht & Pataschnick, Co., USA) with size-selective $PM_{2.5}$ inlet and heated flow tube.

This device utilizes a filter cartridge on the end of the hollow tapered tube. This tube is maintained in oscillation by electronic feedback system. When air is passed through the filter, particulate matter deposits and the filter mass change is detected as a frequency change in oscillation of the tube. Mass concentration is obtained by dividing the determined mass by flow rate through the system [20]. The measurement range is very wide: from around 0 $\mu g/m^3$ to 5 g/m^3. The accuracy of mass measurement is at the level of ±0.75%. 1-minute averaged data were logged in database and used in this research.

2.2.2 PM sensors measurement setup

Four sensor models for particulate matter determination were used in this research. The following devices were examined: SDS011 (Nova Fitness Co., Ltd., China), ZH03A (Zhengzhou Winsen Electronics Technology Co., Ltd, China), PMS7003 (Beijing Plantower Co., Ltd, China), OPC-N2 (Alphasense, UK).

Those optical sensors measure light scattered by particles carried in an air stream through a light beam. All sensors compose of light source (light emitting diode), light receptor (photodiode detector), a set of focusing lenses and a fan – all enclosed in a small housing. The output signals (number of particles per unit volume or mass concentration) were determined on the basis of light scattering intensity by algorithms implemented in sensors. A short characteristic of sensors was shown in Table 1.

Table 1. Characteristic of optical particulate matter sensors used in the research.

Sensor model	SDS011 (Nova Fitness)	ZH03A (Winsen)	PMS7003 (Plantower)	OPC-N2 (Alphasense)
Price, $	~20	~20	~20	~500
Dimensions, mm	71×70×23	50×32.4×21	48×37×12	75×63.5×60
Weight, g	~50	~30	~30	105
Detectable size range, μm	0.3 – 10	0.3 – 10	0.3 – 10	0.38 – 17
Size bins	not available	not available	6 size bins	16 size bins
Estimated concentrations	$PM_{2.5}$, PM_{10}	PM_1, $PM_{2.5}$, PM_{10}	PM_1, $PM_{2.5}$, PM_{10}	PM_1, $PM_{2.5}$, PM_{10}

Three copies of each model were placed inside the housing made of foamed PVC sheets, covered with a rainproof lid. The enclosure dimensions were approximately 56×50×26 cm. Two rectangular air inlets (13×10 cm), secured with mesh filters, were located at one side of this box. A fan, which allowed the airflow through the box, was mounted at the opposite site.

PM sensors were connected to Raspberry Pi microcomputer via USB hubs. Sensors signals were read with a 1- or 2-second resolution and averaged in 1-minute intervals. Data

of this type was sent to database for further analysis. 5 V power supply was used as a voltage source for the microcomputer and 12 V were used to power the fan.

Additionally, temperature and relative humidity were measured inside the box by means of AR235 datalogger (APAR, Poland). A scheme of measurement setup is shown in Fig. 1. The measurement box was located at a distance of about 1.5 m from air inlet to TEOM instrument.

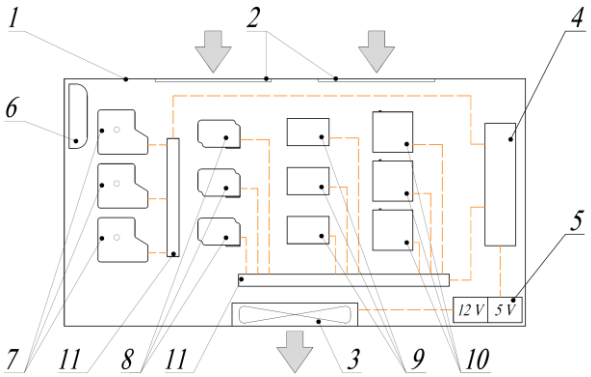

Fig. 1. Scheme of optical sensors measurement box: *1* – PVC enclosure; *2* – air inlets with mesh filters; *3* – air outlet with fan; *4* – microcomputer; *5* – power suppliers; *6* – temperature and humidity datalogger; *7* – OPC-N2 sensors (Alphasense); *8* – ZH03A sensors (Winsen); *9* – PMS7003 sensors (Plantower); *10* – SDS011 sensors (Nova Fitness); *11* – USB hubs

3 Data analysis

3.1 Types of data

For the purpose of this study only data related to $PM_{2.5}$ mass concentration was utilized. In case of Plantower sensors $PM_{2.5}$ outputs without and with so-called "atmospheric environment" correction factor ("AE") were taken into account. The details of that calibration factor were not provided by manufacturer.

In case of OPC-N2 sensors, the mass concentration was calculated on the basis of particle size histogram and number concentration data, with assumption of particles density (1.65 g/cm^3 by default) and refractive index (1.5 by default). OPC-N2 sensors were calibrated by manufacturer using Polystyrene Spherical Latex Particles of a known diameter and known refractive index. Factory calibration procedures were not specified for other sensors.

Relationships between sensors signals and TEOM signals were considered in the following time scales: 1) 1-minute averaged data, 2) 15-minute averaged data, 3) 1-hour averaged data, 4) 24-hour averaged data.

Data sets with at least 75% completeness were used for averaging.

3.2 Precision of sensors

Precision of sensors was assessed in terms of variability of output signals from copies of the same sensor model. The coefficient of variation (CV) was used for this purpose. Temporary coefficient of variation was calculated as:

$$CV_{(t)} = 100 \cdot \sigma / \mu, \%, \quad (1)$$

where σ was the standard deviation and μ was the mean of 1-minute averaged data from copies of the same sensor model. The final CV value for each sensor model was determined as average value of all temporary CV values.

3.3 Bias of sensors

Bias of sensors was calculated to assess whether the sensors overestimate or underestimate TEOM data. Percentage bias for 1-minute data was calculated as:

$$bias_{(t)} = 100 \cdot (\text{Sensor}_{(t)} - \text{TEOM}_{(t)}) / \text{TEOM}_{(t)}, \%, \quad (2)$$

where $\text{Sensor}_{(t)}$ was the 1-minute averaged sensor signal and $\text{TEOM}_{(t)}$ was the 1-minute data from TEOM analyser. Temporary biases were averaged for whole measurement period to receive the final bias for each instrument.

3.4 Linearity of sensors

Pearson correlation coefficient (r) was used to determine linear correlations between outputs of measurement devices. Linearity between sensors and TEOM responses was also assessed on the basis of coefficient of determination (R^2) from ordinary least-squares regression fitting.

Calculations were made for all considered time scales and with pairwise matched data. Data analysis was performed in MATLAB environment.

4 Results and discussion

4.1 Precision of sensors

Table 2 presents coefficients of variation for tested sensor models. Plantower PMS7003 and Nova Fitness SDS011 sensors proved to be the most precise in terms of intra-model variability – the mean CV values were below 7%. In case of Plantower PMS7003, the signals obtained with "AE" correction factor reached the lowest CV value (6.23%).

Table 2. Coefficients of variation (CV, %) for tested PM sensors.

Sensor model	SDS011	ZH03A	PMS7003	PMS7003 "AE"	OPC-N2
CV, %	6.99	54.5	6.98	6.23	17.6

The lowest repeatability between copies of the same sensor was observed for Winsen ZH03A sensors. A malfunction of unit No. 1 was detected, so that further analysis was based on the other units. The mean CV value was at the level of 55%, but only one copy (No. 3) was observed to be stable during the whole measurement period.

The most expensive of examined sensors – Alphasense OPC-N2 – have surprisingly moderate precision. The average CV value reached 17.6%.

4.2 Bias of sensors

Fig. 2 presents measurement results (1-min averages) for an example period of one-week. The trend of $PM_{2.5}$ concentration changes was generally similar for TEOM device and PM sensors, but bias was observed for all tested sensor models (Table 3). Taking into account the entire measurement period all sensors generally overestimated the TEOM responses

(positive average bias was noticed). The lowest overestimation was observed for Nova Fitness (SDS011) sensors and the highest for Plantower (PMS7003) units.

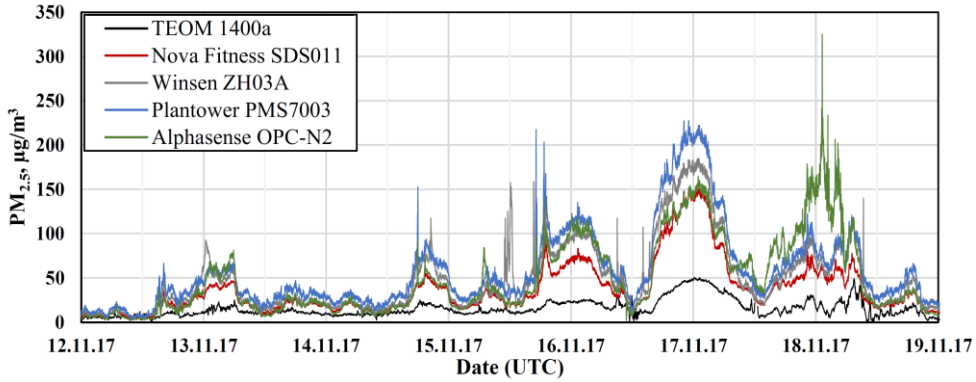

Fig. 2. Example of $PM_{2.5}$ measurement data from TEOM analyser and optical sensors

In case of Winsen ZH03A sensors, unit No. 1 was excluded from analyses due to a failure. Unit No. 2 was characterized with relatively small bias, but its operation cannot be described as stable for the entire measurement campaign and correlation with TEOM was worse in comparison to other sensors (as described in section 4.3).

Table 3. Bias (%) for tested PM sensors.

Sensor model	SDS011			ZH03A			PMS7003			PMS7003 "AE"			OPC-N2		
Unit	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Bias, %	80	61	66	-	7	139	177	169	162	146	141	139	101	78	165

4.3 Linearity of sensors

4.3.1 Linear correlations between PM sensors and TEOM

Moderate to high linear correlations to TEOM were noticed for all tested sensor models. For Nova Fitness SDS011 and Plantower PMS7003 correlation coefficients were at the level of about 0.8 for short-time data (1- and 15-minute averages) and reached 0.85–0.87 in case of 1-hour averaging for Plantower devices. For 24-hour averaged concentrations Pearson's r values were equal 0.90–0.92 for PMS7003 sensors and 0.88 for SDS011.

Alphasense OPC-N2 sensors demonstrated only moderate linear correlation with TEOM. For 1-, 15- and 60-minutes time scales r values were at the level of 0.6 to 0.7. Correlation coefficients were equal to 0.72–0.77 for daily averages.

Winsen sensors had low repeatability between copies and only one unit (No. 3) had similar properties as Plantower instruments. Unit No. 1 was not correlated to TEOM at all ($r \approx 0$), because of the failure and correlation coefficients for unit No. 2 were similar to OPC-N2 sensors.

4.3.2 Results of linear regression fitting

Coefficients of determination from linear regression fittings were summarized in Table 4. The best results were obtained for Plantowers' sensors, for both with and without correction

factor. R^2 values were at the level of about 0.6–0.7 for 1-, 15- and 60-minutes data. In case of 24-hour averaging R^2 values exceeded 0.8.

Only slightly worse results were achieved for Nova Fitness units. R^2 values for short-time measurements were close to results from Plantower SDS011 and in case of diurnal averages R^2 values were around 0.77.

The quality of the linear fitting for OPC-N2 sensors was only moderate. R^2 values reached the level of 0.3–0.4 for shorter time scales and in case of 24-hour data R^2 values were around 0.5–0.6. Fittings for sensor No. 1 were slightly better than for other units.

As previously described, Winsen's units were not repeatable and unit No. 1 was excluded from calculations. The results obtained for copy No. 2 were modest and could be compared to results from OPC-N2 devices. Interestingly, R^2 values calculated for unit No. 3 were quite high and in case of 24-averaged concentrations they exceeded marginally coefficients obtained for Plantower PMS7003 sensors.

Table 4. Coefficients of determination (R^2) for tested PM sensors and different time scales: 1) 1-min averaged data, 2) 15-min averaged data, 3) 1-h averaged data, 4) 24-h averaged data.

Sensor /Time scale	SDS011			ZH03A			PMS7003			PMS7003 "AE"			OPC-N2		
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
1)	0.59	0.63	0.61	-	0.36	0.61	0.67	0.68	0.67	0.66	0.65	0.65	0.41	0.31	0.31
2)	0.62	0.66	0.64	-	0.39	0.66	0.71	0.71	0.71	0.69	0.68	0.68	0.42	0.32	0.32
3)	0.66	0.70	0.67	-	0.41	0.72	0.75	0.75	0.75	0.73	0.72	0.72	0.45	0.34	0.34
4)	0.77	0.78	0.77	-	0.48	0.86	0.83	0.84	0.85	0.81	0.80	0.82	0.60	0.53	0.54

4.4 Humidity influence

Strong diurnal variations of relative humidity and temperature were observed with elevated RH levels and lower temperatures at nights. Many elevated $PM_{2.5}$ concentration levels were also associated with night hours and household heating systems might contribute to that situation. This co-occurrence of elevated RH and PM levels may explain the moderate correlation coefficients between sensors outputs and RH values – $r \approx 0.4$ for short-term averaged data and $r \approx 0.5$ for 24-hour averages. Nevertheless, including the RH values to linear regression models did not bring significant improvement of fitting quality.

5 Conclusions

Nowadays, many types of small and inexpensive particulate matter sensors are available. However, their properties and possibilities of application are quite different.

The results of this study show that Plantower PMS7003 and Nova Fitness SDS011 sensors are characterized with good precision (CV < 7%) and relatively high linear relationship with TEOM device ($R^2 \approx 0.6$–0.7 for short-time averages and $R^2 \approx 0.8$ for 24-hour averages). Good repeatability of responses between sensor units is an important factor in the field of construction and calibration of measurement devices. High correlations with high class instrument show that PMS7003 and SDS011 sensors could be useful tools for detection of elevated PM concentration events or indication of PM "hot-spots". That kind of sensors could be also used in widely dispersed sensor networks to improve the spatio-temporal resolution of PM data.

It should be noted, that all tested off-the-shelf sensors were characterized by a bias in relation to TEOM responses, so the calibration of such devices is crucial before any measurement campaign.

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