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10.2. COMPARISON OF LOW-COST AND CONVENTIONAL PM SIZERS AND COUNTERS IN INDOOR AMBIENT ENVIRONMENT

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ABSTRACT

Low-cost particulate matter (PM) sensors can potentially bring PM level monitoring to a much wider audience, thus providing relevant information, at an affordable cost, to all interested stakeholders. However, there are a lot of unknowns about low-cost PM sensors and their performance compared to lab-grade equipment. The aim of this work was to explore the potential of several low-cost sensors as reliable PM monitors. The definition of term low-cost sensor itself can be somewhat ambiguous, and in this work, we opted for a more inclusive definition: we use the term for either commercially available low-cost instrument or for a prototype that includes bare-bones sensors and supporting electronics.

INTRODUCTION

While clean air can be considered as one of the most basic requirements and conditions for healthy life, the mean annual concentration of fine particles ($PM_{2,5}$), in many European cities according to the European environment agency reports [1], is two or three times higher than that recommended by the World health organization (WHO) [2]. Different individuals in the general population react differently after being exposed to similar levels of air pollution, ranging from almost no health issues to serious respiratory conditions from both short and long-term exposure. Regarding long-term exposure, the seriousness of air pollution can be seen through the fact that the International Agency for Cancer Research within the WHO - IARC frame [3], has classified the air pollution of the environment, as well as the particle pollution, in Group 1 of the carcinogenic substances. Air pollution is also, unfortunately, the highest environmental health risk in Europe [4].

All of the above facts point to the necessity of air pollution monitoring. As the level of air pollution can vary considerably from region to region as well as locally, traditional networks for monitoring cannot give the complete picture about pollution, primarily because of a small number of monitoring stations covering large area of interest. On the other hand, the monitoring of air pollution should not be restricted to outdoor ambient measurements, since people spend the majority of their time indoors. This increases the need for affordable air pollution monitoring, since, as air pollution awareness rises, many interested citizens want to know more about quality of the air that surrounds them.

Standard methods for measuring the main air pollutants (particulate matter and gaseous pollutants) are typically achieved using complex equipment that, despite its high accuracy, brings a number of drawbacks such as a high cost of maintenance (e.g. cleaning, periodic calibrations, parts replacement). This results in low spatial resolution, in both indoor and outdoor settings. Low data resolution, either temporal or spatial, makes realistic insight into the exposure and associated health risks more difficult. Low-cost sensors can potentially improve the situation, but their performance cannot be taken at face value from the data sheets of the manufacturers, instead they must be carefully studied and compared to the laboratory-grade instruments. This paper examines the potential of several low-cost sensors for real-time PM monitoring.

The outline of the paper is as follows. First, we provide a brief discussion on the importance of data quality, the established validation criteria that currently exist for low-cost sensors, and summarize the general types of particulate matter sensors that may be suitable for high resolution monitoring. Then we describe the method and experimental setup that was used in this study. The operating principle of the instruments used is described in detail along with some of the drawbacks of commercially available sensors. Finally, conclusions about the performance of the studied sensors are outlined.

DATA QUALITY, VALIDATION CRITERIA AND TYPES OF PARTICULATE MATTER SENSORS

Recent technological advancements, coupled with simplification and affordability of new measuring systems, give hope for the forward-looking prospects in upcoming air pollution monitoring networks. As well as advances such as an order of magnitude more nodes compared to the traditional regulatory networks, personalized exposure assessment, air pollution forecasts etc., it should be borne in mind that low-cost sensors, along with their advantages, bring a number of possible disadvantages, one being the looming question of data quality. Metrologically unreliable data originating from low-cost sensors, and the non-official networks which may utilize them, if uncritically provided to the general public and media, are very likely to result in unnecessary concerns and may raise questions about the validity of established governmental monitoring networks. While the involvement of the general public should always be encouraged and is welcome, (e.g. via citizen science projects about air pollution), validation of low-cost sensors should ensure that the results measured in this way will not provide spurious conflicts with the officially provided data. Therefore, the issue of metrological relevance is of utmost importance and data from low-cost sensors must be carefully processed and interpreted, sensors must be calibrated and compared to the lab-grade instruments and only then should data originating from low-cost sensors be made more widely available.

For a number of applications, the data quality of low-cost sensor data should be in accordance with legislation for indicative measurements (DQO - *Data Quality Objectives for indicative measurements*), where European legislation allows measurement uncertainty of up to 25%. Recommendations for validation criteria for measurements of air polluting substances via sensors, with respect to regulatory measurements, in European Union, China and USA are given in Table 1.

Table 1. *Recommendations for validation criteria for measurements of air polluting substances by sensors*

Air pollutant	**Validation criteria**	**European Union**	**USA**	**China**
PM_{10}	Accuracy	/	$R^2 \geq 0,9409$	$R^2 \geq 0,9025$
	Measuring range	0-1000 µg m^{-3*} 0-10 000 µg m^{-3}**	0-300 µg m^{-3}	0-1000 µg m^{-3}
$PM_{2,5}$	Accuracy	/	R^2: 0,7225-0,9025	$R^2 \geq 0,8649$
	Measuring range	0-1000 µg m^{-3*} 0-10 000 µg m^{-3}**	3-200 µg m^{-3}	0-1000 µg m^{-3}
* average value for 24h long measurement ** average value for 1h long measurement				

The quality of data that originate from low-cost sensors is influenced by many factors, some of which are related to the technology choice (stability, selectivity, speed of response, homogeneity of response within the same batch of sensors), while others are related to exploitation cost (power demand of the sensors, manufacturing costs, calibration cost). A very important aspect of low-cost sensor usage is their calibration, which can be done either in laboratory conditions [5] or in the field. Despite the fact that laboratory testing is more repeatable if conducted in controlled atmosphere, field testing (either indoor or outdoor) and calibration is preferred for low-cost sensors since it gives more realistic insight into their performance.

Regarding the current and emerging standards covering the topic of sensors for air pollution monitoring, it is worth mentioning that within the *European Committee for Standardization* - CEN a work group CEN/TC 264 WG42 is developing a standard regarding technical specifications for sensors for gaseous pollutants. It is being proposed that they be divided into three classes. The first two fulfill specifications given in the *Directives 2004/107/EZ and 2008/50/EZ* while the third class does not fulfill a data quality objective but can be used for research purposes and citizen science. Regarding particulate matter monitors, MCERTS (The UK environment agency's monitoring certification scheme), a standard published by UK Environment Agency provides detailed instructions for the certification of PM monitors, albeit more oriented toward in-the-field calibration.

Table 2. *Advantages and possible drawbacks of sensors for PM measurements*

Type of Sensor	**Advantages**	**Possible drawbacks**
Sensor based on light scattering	Small dimensions Relatively cheap	Without additional aerosol conditioning they can't measure fine particles (due to size of particle compared to light wavelength). Limit of operation is about few hundred nanometers for the particle diameter

Type of Sensor	Advantages	Possible drawbacks
		Sensors measure number concentration which can only approximately be converted to mass concentration
Sensor based on light absorption	Higher cost and bigger dimensions Direct link to the climate change aspect of the PM air pollution Continuous measurements	Conversion of light intensity to mass concentration Filter or filter tape is required, and maintenance of filter tape Filter loading effects
Quartz crystal microbalance - QCM based sensor and thin-film bulk acoustic resonator-based sensor (TFBAR)	Direct mass measurement	Highly sensitive to meteorological parameters, which may require input aerosol conditioning

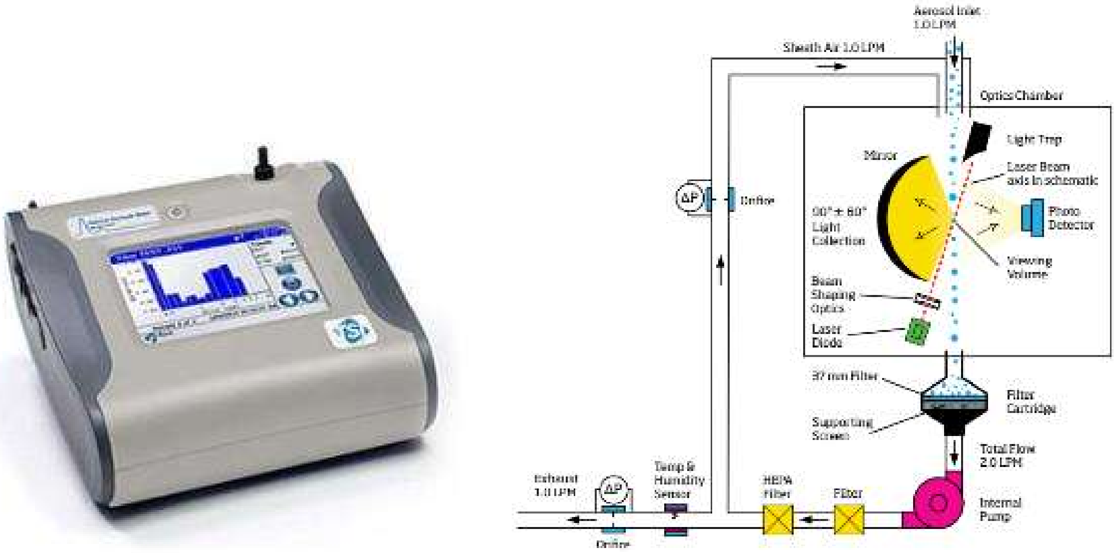
METHOD AND EXPERIMENTAL SETUP

Several low-cost sensors and laboratory-grade instruments were collocated in laboratory office space in Institute Vinca for several weeks from the end of November to the beginning of December 2016. Low-cost instruments included two Sharp GP2Y1010AU0F compact optical dust sensors connected to an Arduino platform, Alphasense CompactOPC sensor and Dylos DC1700 PM unit. Lab-grade instruments included TSI NanoScan SMPS Model 3910 and TSI Optical particle sizer 3330 (17 channels from 0.3um to 10um). However, in this work only the data from the TSI Optical particle sizer were used in order to simplify analysis. All instruments and sensors, except for the Arduino-connected optical dust sensor, sampled aerosol via an internal pump, while the Arduino dust sensor used internal thermal resistor to increase aerosol flow. All instruments that were used in this experiment are based on the scattering of laser light, which enables high temporal resolution. The time resolution of the instruments was set to 1 minute, which for Arduino dust sensor required averaging of about 40 samples per minute.

Both laboratory quality instruments and low-cost instruments, share a lot of similarities: the main differences being in the sophistication of the implementation of the basic operating principle. Therefore, descriptions of the instruments will start with detailed explanations of laboratory-grade instruments, and then will underline the differences for the low-cost instruments. Furthermore, for each analysed sensor/instrument, we will state its potential to be a node in a larger network of devices, and, if appropriate, state data rates needed to enable near-real-time monitoring.

TSI Optical particle sizer OPS 3330

Fig. 1 depicts schematic representation of a measurement system of TSI OPS 3330. The sampled air enters the aerosol inlet at a rate of 1 litre per minute. Suspended particles reach the optical cavity surrounded by clean filtered air (*sheath air),* which directs the sampled air to the laser beam, and additionally protects the optics of the instrument. In this way the necessity for cleaning the instrument is significantly reduced. The sampled air, which contains suspended particulate matter, is irradiated by a laser beam in the cavity, and scattered light is measured using a spherical mirror and a photodetector. In this way, under the assumption of Mie scattering (plane wave scattered by a spherical particle), the particle size and the concentration of particles is determined. Suspended particles may be collected, if necessary, on a gravimetric filter which can then be later used for calibration of the device (by measuring the differential mass of the filters), and chemical analysis of the collected particles or analysis under a microscope.



(a) (b)

Figure 1. *(a) Instrument TSI OPS 3330 and (b) schematics of the main parts of the measurement system. Figures were taken from manufacturer datasheets*

Note that the principle of operation of the instrument has some inherent flaws. For example, the mass concentration of the suspended particles is obtained from the number concentration under rather tight assumptions for particle shape (spherical), particle refraction index and density. If the particle is not spherical (e.g. particle originating from NaCl) or the assumed refractive index is incorrect, an error occurs. However, this is a general drawback of all devices based on light scattering.

This instrument is suitable for controlling air quality in indoor and outdoor environments, for monitoring workplace environments, industrial measurements, as well as, for controlling and monitoring harmful emissions. Using this device, it is possible to test filters (for example, by the ASHRAE 52.2 method), but because of its overall rather sophisticated functionality and cost, this device is not of direct interest for use in a larger sensor network.

This instrument can measure suspended particles of different sizes with diameters in a range of 0.3 to 10 μm, and this range can be divided into 16 channels. The device can measure up to 3000 particles per cubic centimetre. For each measured aerosol sample, the device records both the temperature and the pressure of the inlet air. The device is fully compliant with ISO 21501-01/04 standard (Determination of particle size distribution -- Single particle light interaction methods -- Part 1: Light scattering aerosol spectrometer).

Temporal resolution of the device can be very high, it can even go up to 1 s and the device can be connected to a data acquisition PC using a USB or Ethernet port. With a single battery, the device operates for 10 hours andthe charging time is 4 hours. With two batteries, both the operating time and charging time are doubled.

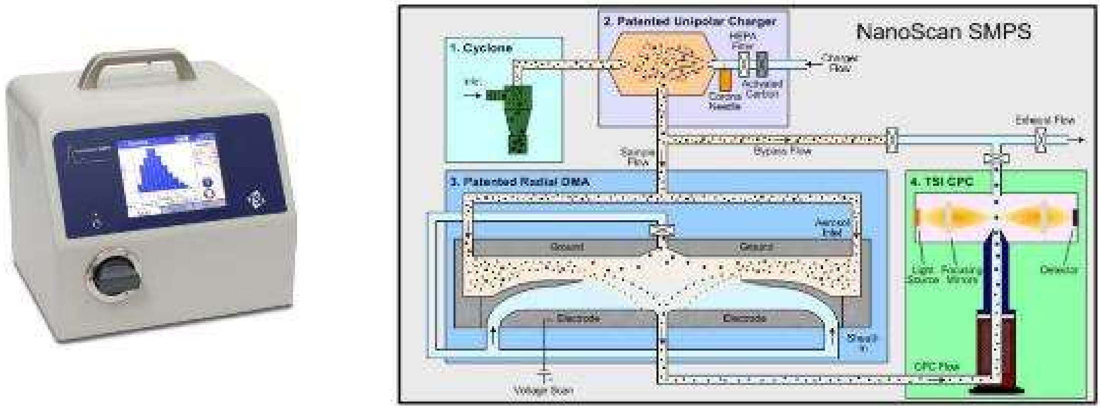
For the estimation of the necessary data flow from the instrument, when used in a larger network of nodes, we can use an estimate based on capacity of the internal memory of the device (internal capacity is about 5 MB and it can be used to store 30,000 measurements). This roughly corresponds to the amount of data of around 40 floating point numbers (4 bytes for a floating-point number is assumed) per measurement, where one measurement includes data from 16 channels (channel boundaries and numerical value of the concentration in the channel), temperature, pressure, sampling duration and sample timestamp.

TSI NanoScan 3910

As stated earlier, devices based on the principle of light scattering from suspended particles have a limit regarding the particle size that they can measure. Smaller particles, with the diameter below the lower range of instruments such as TSI OPS 3330, (i.e. around a few hundred nanometers), cannot be directly detected by the system which only includes an optical cavity, laser and a photodetector.

The estimation of the particle size for devices that use a particle magnification fluid is not carried out in the optical cavity, as was the case with, for example, TSI OPS 3330 (where counting and particle size determination is performed simultaneously). Particles are first classified using, for example, a DMA (differential mobility analyzer) classifier. The DMA classifier is a separate device, or a part of a larger device, that has a polydisperse aerosol as its input (an aerosol having particles of different sizes), and provides a monodisperse aerosol (ideally only particles of a particular diameter) at its output.

A schematic diagram of the principle of operation of the NanoScan 3910 is given in Figure 3b.



(a) (b)

Figure 2. *(a) Instrument TSI NanoScan 3910, (b) schematics of the main parts of the measurement system. Figures were taken from manufacturer datasheets*

As can be seen from the schematic, although the main principles of operation are similar for all instruments based on light scattering, the NanoScan 3910 has a much more complicated measuring system compared to the previously described OPS 3330. This is due to the above-mentioned fact that particles of diameter below 300 nm cannot be detected by purely optical methods. Therefore, the classification of particles is more complicated, and is not based on the analysis of the intensity of the scattered waves (as is for the OPS 3330), but is based on the DMA classifier.

The aerosol first passes through the cyclone (point 1 in Fig. 2), which, because of the particle inertia, prevents larger particles from proceeding further through the measuring system. The aerosol is then further treated (point 2 in Fig. 2) in order to produce the known distribution of aerosol charge, this is a necessary step since the newly-created aerosol does not have known and stable charge distribution. In the model of the instrument being described, this is done by exposing the aerosol to charged ions created from clean air using the needle corona.

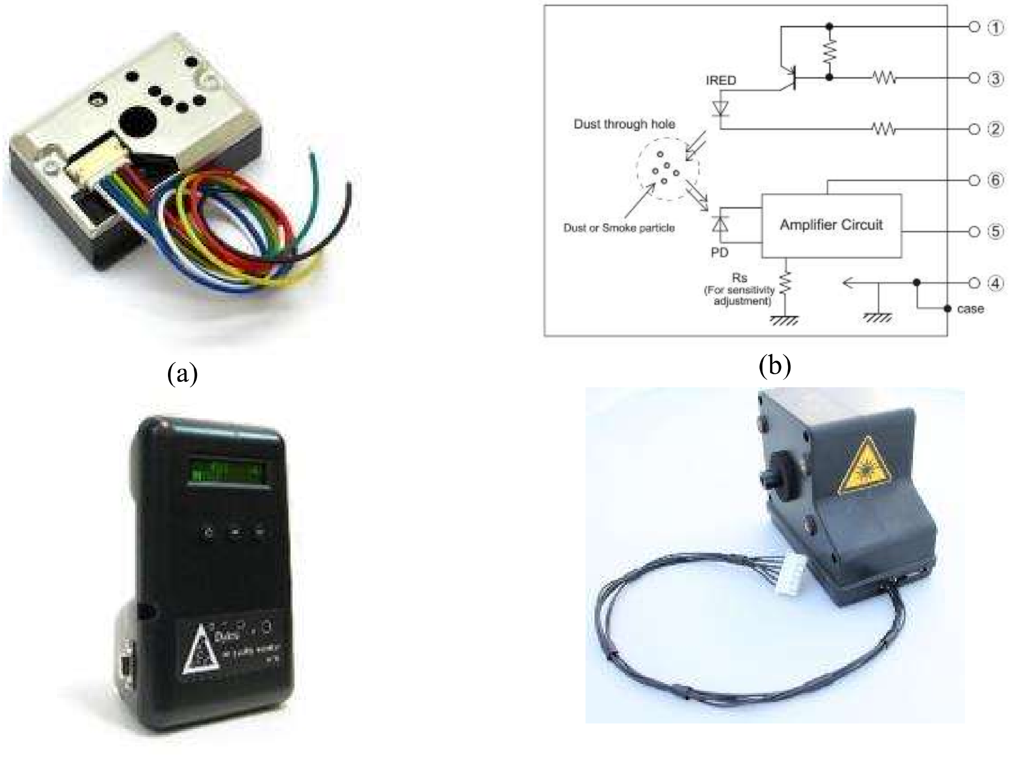
This is closely related to the classification method using the DMA classifier (point 3 in Fig. 2), which was mentioned above. In this embodiment, the DMA classifier is a capacitor, in which a DC electric field with a controllable intensity is established, one of the electrodes is modified, it has an opening through which the desired aerosols can go further into measurement system. There is a flow of aerosol surrounded by clean air through the electrodes of the capacitor. The DMA classifier extracts the aerosol particles of certain electrical mobility by establishing a field of appropriate intensity which guides a certain particle size through a hole in the modified electrode. It is clear that the DMA only classifies the particles by size, more accurately by electrical mobility, guiding only the part of the particles that are suitably charged (for example, only a portion of positively charged particles, if the central electrode is negative). Determining the total aerosol concentration is possible only if the particle charge distribution is known, which is not always the case. This is why, before classification and counting of the particles, the aerosol is conditioned to establish a precisely-known charge distribution in the aerosol sample.

As previously mentioned, small particles with diameters below a few hundred nanometres cannot be directly detected by the optical chamber-laser-photodetector system. Therefore, for particles of a diameter from a few nanometres to several hundred nanometres, a physical "magnification" is required to make particles detectable. This magnification is carried out by passing an aerosol sample through a saturated vapour of the working fluid (such as isopropanol, n-butanol or even water), see point 4 in right part of the Fig 2. and then by applying a suitable temperature gradient so that the condensation of the working fluid vapour on the aerosol particles occurs. The particles with the condensed vapour of the working fluid on them are now enlarged and can be detected in the optical chamber.

Low-cost PM monitors

The focus of the previous sections was on laboratory quality instruments. Now we will also briefly describe the low-cost sensors that were used in this experiment, note that some of them are not stand-alone devices, but must be, connected to a microcontroller platform.

In Fig. 3 (top left), a Sharp GP2Y1010AU0F sensor is displayed. The infrared light emitting diode (IRED) is used in a detector system, and the sensor output somewhat follows the level of particles in the air. Wavelength data using the sensor are not specified in the manufacturer's specification, but it is known that IRED diodes usually have wavelengths of 770 nm, 870 nm, 880 nm, 940 nm, and 950 nm. In preliminary tests of this sensor, as we will see, it turned out that its output can correlate with some of the channels of laboratory instruments. Sensor performance could be potentially improved by introducing an additional air sampling system (aerosol input, pump flow), because in the basic form, the air flow is made in a rather uncontrollable manner, by using only one heating resistor which stimulates the diffusion of air.



(a) (b)

(c) (d)

Figure 3. *a) Sharp GP2Y1010AU0F sensor, b) schematics of Sharp sensor, c) Dylos DC1700, d) Alphasense OPC N1. Figures were taken from manufacturer datasheets*

The DC1700, shown in Fig. 3c, is a laser particle counter, which measures particles in two size fractions, particles of diameter above 0.5 µm and particles of diameter above 2.5 µm. It has temporal resolution of 1 minute, and an internal memory of the instrument can store up to 7 days of continuous measurement. The input aerosol flow is 1 l/min. The manufacturer proposes several typical usages for the instrument. One typical scenario is for the monitoring of workplace air quality. Also, it is possible to gain insight into the effectiveness, or to determine optimal placing, of the air filtration systems. Finally, some users were able to correlate some health issues with the increased level of air pollution, which was tracked using the Dylos monitor.

The Alphasense OPC (*optical particle counter*), is shown in Fig. 3d, and it measures scattered light on individual particles in the air stream which is directed into a specially designed optical chamber (laser wavelength is 658 nm). As was the case for the laboratory-grade instrument, TSI OPS 3330, the particle size is determined from measurement of the intensity of the scattered light (under the assumptions of Mie scattering) and also particle concentration. As stated earlier, in order to convert the number concentration into mass concentration, a significant number of assumptions must be made, such as particle density and refractive index, with default values being 1.65 g/ml for the density, and $R_i = 1.5 + i0$ for the refractive index. Additionally, for all particles, disregarding their true physical shape, equivalent size is assigned assuming spherical shape (for homogenous spherical particle there is an exact analytical solution of Maxwell equations, known as Mie solution or Mie scattering). The instrument has 16 channels which cover the range from 0.38 to 17 µm.

Most conventional optical counters and sizers have a narrow aerosol inlet in order to precisely guide particles to pass through optical chamber and intersect the laser beam, in that way enhancing accuracy and repeatability of the measurements (see for example Fig. 1 illustrating working principle of TSI OPS330). The disadvantage of this approach is that it requires a stronger pump in order to force the air to flow through narrow aerosol inlet, and filters which help avoid pump contamination and produce clean sheath air to protect the sensitive optics. This increases maintenance and use costs through more frequent filter changes and cleaning of the instrument and more frequent pump replacement. Energy demand of the instrument is increased, which can be a drawback when instrument is battery operated. The Alphasense OPC uses a different approach: pump and air filtration are removed, and by using system of elliptical mirrors and photodetectors the "virtual working volume" is produced in the centre of open optical chamber.

RESULTS

Initial comparisons of the low-cost Alphasense OPC sensor and the laboratory-grade TSI OPS 3330 revealed surprising results. Table (Fig. 4a) summarizes channel cut-off points for the two instruments. A cross-correlation matrix was calculated between all channels of the two instruments, and it is shown in Fig. 4b. By observing the trend of the correlations for the low-cost Alphasense OPC sensor, it can be observed that within one instrument, neighbouring channels are correlated, and that the amount of correlation diminishes relatively quickly when moving away from the observed channel. When comparing channels between the instruments (rectangular region in upper triangular matrix) we can observe very high levels of correlation between (approximately) corresponding channels, with the exception of a few end channels of the Alphasense OPC, which are outside of the range of TSI OPS 3330. Note that correlations between thechannels of the different instruments are somewhat approximate due to different channel boundaries that are setup in the Alphasense OPC firmware. For the (approximately corresponding) channels, cross correlation was about ~ 0.90m, normalized timeseries plots would be in very good alignment, almost indistinguishable. Remaining comparisons will only use the TSI OPS 3330, since the Alphasense OPC would show very similar correlations.

Channels	TSI OPS 3330 [um]	Alphasense OPC [um]
1	0.300 - 0.374	0.38 - 0.52
2	0.374 - 0.465	0.52 - 0.75
3	0.465 - 0.500	0.75 - 1.00
4	0.500 - 0.721	1.00 - 1.25
5	0.721 - 0.897	1.25 - 1.49
6	0.897 - 1.097	1.49 - 2.00
7	1.097 - 1.391	2.00 - 2.99
8	1.391 - 1.732	2.99 - 4.00
9	1.732 - 2.156	4.00 - 5.00
10	2.156 - 2.500	5.00 - 6.50
11	2.500 - 3.343	6.50 - 8.00
12	3.343 - 4.162	8.00 - 10.00
13	4.162 - 5.182	10.0 - 12.00
14	5.182 - 6.451	12.0 - 14.00
15	6.451 - 8.031	14.0 - 16.00
16	8.031 - 10.00	16.0 - 17.23
17	>10.00	NA

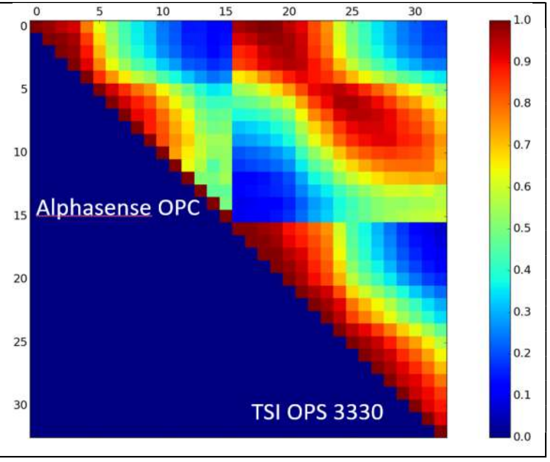


Figure 4. *Cut off points for particle diameter [um] for TSI OPS3330 and Alphasense OPC channels*

Fig. 5 shows comparisons between remaining low-cost sensors and the TSI OPS 3330. Sharp sensors were connected to the Arduino platform and functioned very reliably, both in terms of up time and consistent recording of measured values. Among themselves, Sharp low-cost sensors, had an extremely high correlation of about ~0.98. Compared to the laboratory-grade instrument, they correlated best with the first channel of the TSI OPS 3330 ~0.75 and the correlation coefficient steadily declined when compared to the remaining channels.

Low-cost Dylos instrument outputs data in two channels, small particles (above 0.5um) and larger particles (above 2.5um). Dylos small particles correlate best with the 4th TSI OPS 3330 channel (0.5-0.721um) with a correlation of approximately ~ 0.60 (partial time series of normalized signals is shown in Fig. 6a). Dylos large particles correlate best with 10th TSI OPS 3330 channel (2.156 - 2.500) with correlation of approximately ~ 0.978 with OPS 2.156um.

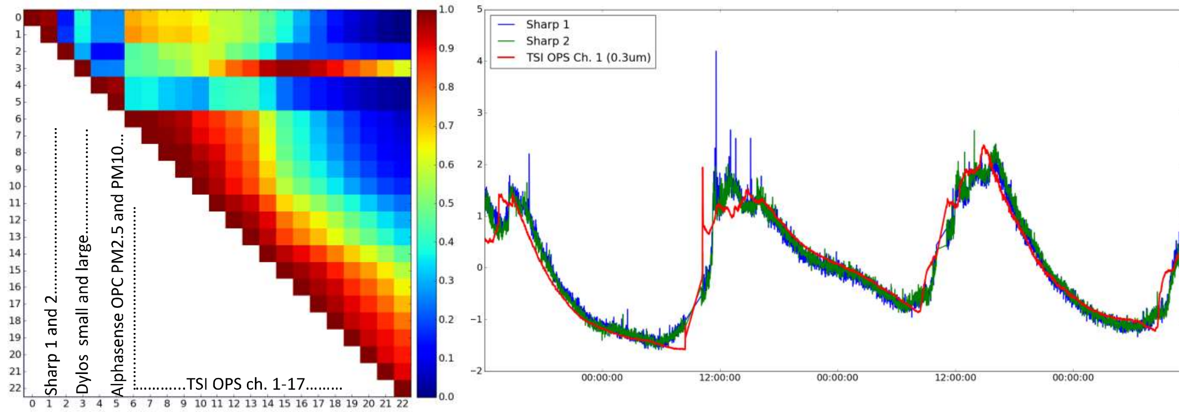


Figure 5. *(a) Cross-correlation matrix of normalized measurements: Sharp 1, Sharp 2, Dylos - small particles, Dylos - large particles, TSI OPS channels 1-17, total of 21 individual signals (b) Normalized Arduino and TSI OPS 3330 ch. 1, from 2016-11-29 12h to 12-02 11h.*

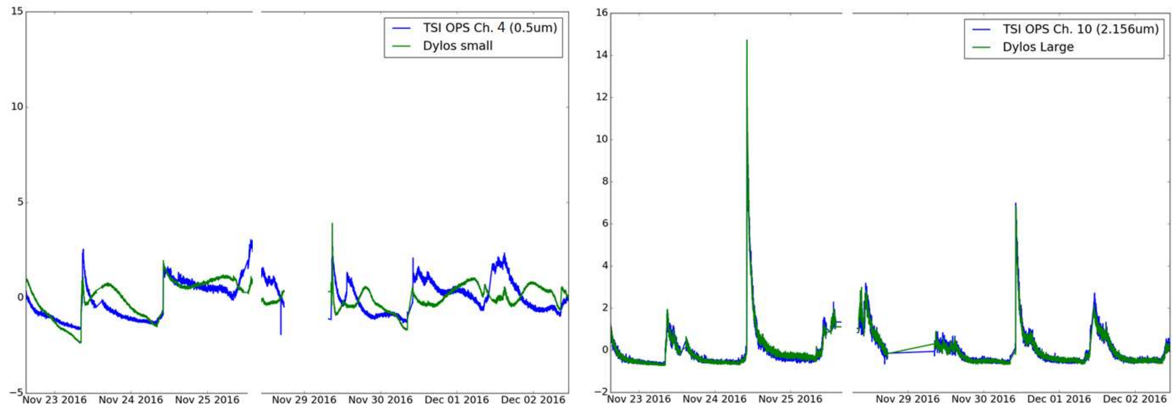


Figure 6. *Overlapped time series of normalized signals from TSI OPS 3330 and Dylos DC1700 (a) OPS Ch. 4 vs Dylos small (b) OPS Ch. 10 vs. Dylos large*

CONCLUSION

Low-cost sensors showed the potential to measure certain ranges of particle sizes with very high accuracy. Sharp dust sensors had high reliability and consistency among themselves and correlated to particle sizes measurements in 0.3um - 1.4um range. The Dylos low-cost sensor also showed decent results, in contrast to the Sharp sensors it measures two fractions, addressing larger particles with much greater accuracy compared to the lab-grade instrument. The Alphasene OPC was hands-down the most surprising of all sensors, with almost laboratory-grade results. Normalized values were compared and real word deployment would require separate calibration of each sensor, due to differences in absolute levels among signals.

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REFERENCES

1. Air quality in Europe - 2018 report, ISBN 978-92-9213-990-2, European Environment Agency, Copenhagen, Denmark, 2018.
2. World Health Organization. Air quality guidelines: global update 2005: particulate matter, ozone, nitrogen dioxide, and sulfur dioxide. World Health Organization, 2006.
3. IACR 2013. Air Pollution and Cancer. Eds. Straif K., Cohen A., Samet J. , IARC scientific publication no. 161. International agency for Research on Cancer, Lyon. ISBN 978-92-832-2166-1
4. Special report no 23/2018: Air pollution: Our health still insufficiently protected, European Court of Auditors
5. EU, 2008, Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe. Off. J. Eur. Union, L 152, 1-44.
6. United States Environmental Protection Agency, 2018. Peer Review and Supporting Literature Review of Air Sensor Technology Performance Targets, EPA 600/R-18/324
7. Papapostolou V., Zhang H., Feenstra B., Polidori A., 2017. Development of an environmental chamber for evaluating the performance of low-cost air quality sensors under controlled conditions, Atmospheric Environment, 171, 82-90
8. Jovašević-Stojanović, Milena, Alena Bartonova, Dušan Topalović, Ivan Lazović, Boris Pokrić, and Zoran Ristovski. “On the use of small and cheaper sensors and devices for indicative citizen-based monitoring of respirable particulate matter.” Environmental Pollution 206 (2015): 696-704.
9. Moltchanov S., Levy I., Etzion Y., Lerner U., Broday M.D., Fishbain B., 2015. On the feasibility of measuring urban air pollution by wireless distributed sensor networks. Science of the Total Environment, 502:537-547.
10. Sharp, GP2Y1010AU0F Compact Optical Dust Sensor, Sheet No.: E4-A01501EN Date Dec. 1. 2006, datasheet
11. TSI, Optical particle sizer spectrometer model 3330, operation and service manual p/n 6004403, revision f, October 2013
12. TSI, NanoScan SMPS nanoparticle sizer model 3910, operation and service manual
13. Alphasense User Manual OPC-N2 Optical Particle Counter Issue 3, 072-0300, Alphasense