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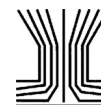
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Qualification of the Alphasense optical particle counter for inline air quality monitoring

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ABSTRACT

The Alphasense optical particle counter (OPC) provides a low-cost and lightweight solution for measurements of the size and number concentration of airborne particulate matter (PM). The micro fan with which it is originally equipped cannot, however, achieve a high enough pressure differential for maintaining an adequate flow rate when connected to sampling/pretreatment aerosol lines, limiting its use for air quality monitoring. Here, we propose a simple modification on the sample flow system that enables the connection of the Alphasense OPC with sampling/pretreatment lines (e.g., dryers) commonly employed on ground observational sites, as well as its use onboard Unmanned Aerial Systems (UASs). Tests of the modified OPC using monodisperse polystyrene spherical (PS) particles having sizes between 0.8 and 2.5 μm show that both the sizing and counting performance of the modified instrument is in agreement with that of a calibrated reference OPC at concentrations from ca. 50 to 800 #/ml, which are typically encountered in the atmosphere in that size range. For particle number concentrations below or above this range, we observed a concentration-dependent counting efficiency, which can be corrected using a polynomial function derived from our measurements. Tests conducted under reduced pressure and temperature conditions demonstrate the capability of the modified OPC for accurately (i.e., within 13% deviation from the reference measurements) determining the size and number concentration of the sampled particles. The tests reported in this work show that the proposed modification can qualify the Alphasense OPC for use in both ground and aerial observations without affecting its performance, and at the same time maintaining its strongly desired characteristics (i.e., cost effectiveness and high portability).

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1. Introduction


Particulate matter (PM) in the atmospheric environment affects directly the planetary radiative balance by absorbing and/or scattering the incoming solar radiation (IPCC 2013), and indirectly by acting as cloud condensation nuclei (CCN) that consequently change the albedo and structure of clouds while affecting precipitation and the overall water cycle (Seinfeld et al. 2016). At the same time, high concentrations of PM in the atmosphere affect visibility (Charlson 1969) and human health as they can cause cardiovascular and respiratory diseases (Anderson, Thundiyil, and Stolbach 2012).

Recent efforts in aerosol instrumentation have resulted in a number of low-cost and lightweight tools that can measure the concentration and in some cases the size of atmospheric particles (Morawska et al. 2018).

Numerous PM low-cost monitors (defined as those having price less than 2000 USD according to the Air Quality Sensor Performance Evaluation Center; AQ-SPEC 2020), are already available in the market. Such monitors can fulfill the needs for high temporal/spatial resolution measurements in complex and highly variable environments, such as cities (Kumar et al. 2015), for personal exposure assessment (Koehler and Peters 2015) and for indoor air quality monitoring (Kumar et al. 2016a, 2016b). Besides their low cost, they typically have compact size and thus high portability, making them also excellent candidates for use onboard Unmanned Aerial Systems (UASs; Villa et al. 2016).

The majority of these low-cost PM monitors employ optical techniques (i.e., light scattering) for

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the detection of the sampled particles. Some of these instruments measure only the intensity of the light scattered by all the particles passing through a detection volume, directly relating it to the PM mass concentration using calibration functions determined through tests against reference instruments. Other monitors have also the ability to analyze the pulses produced by the scattered light of a small fraction or of even individual particles, providing means to classify them according to their size in different classes/bins (Morawska et al. 2018). Low-cost PM monitors residing at the lower end of the price spectrum are mainly passive (i.e., they do not have any system for creating a stream flow through their detectors), and do not typically provide information on the size of particles, or if they do, they split the total concentration in 2–3 wide size bins. More expensive PM monitors are most commonly active (i.e., they have a system for pulling a flow through their detectors), and have the ability to classify sampled particles according to their size. In most cases, the means of providing an air flow through the detectors of these devices is carried out by a small fan in order to achieve maximum cost effectiveness, energy efficiency, and portability.

A number of low-cost PM monitors have been evaluated against reference instruments under laboratory and/or field conditions (Manikonda et al. 2016; Sousan et al. 2017; Borghi et al. 2017; Mukherjee et al. 2017; Badura et al. 2018; Bulot et al. 2019; Karagulian et al. 2019). It should be noted here that in most of these studies the performance of the sensors is evaluated in terms of the reported particle mass concentrations using $PM_{2.5}$ and PM_{10} (i.e., particles having sizes lower than 2.5 and 10 μm , respectively) metrics that are in line with global (WHO 2006) or regional (e.g., 2008/50/EC) guidelines and/or directives. As a result, the number concentrations reported by low-cost optical particle counters (OPCs) have to be converted to mass concentrations assuming a particle density and size (if the latter is not measured). Interestingly, the agreement between PM mass concentrations determined by cost effective PM sensors and reference instruments vary substantially. Some of these discrepancies can be related to the design characteristics of the low-cost systems (e.g., light source wavelength, orientation between the light source and the detector, flow rate, mode of particle transfer to the detector, etc.; Manikonda et al. 2016), while others have been related to drifts in their performance over time (e.g., Mukherjee et al. 2017), and over a wider concentration range (e.g., Badura et al. 2018; Zheng et al. 2018).

Pretreatment of the sampled aerosol upstream an OPC or other optical detection instrument, is recommended according to the WMO/GAW guidelines (GAW report No. 227, 2016). While following these guidelines is rather easy with most of the commercially available laboratory-grade OPCs, it is impossible with cost-effective systems that employ fans (and not pumps) that cannot achieve adequate pressure differentials for maintaining a desired flow rate when connected with particle pretreatment systems (e.g., dryers). In fact, this is the reason why cost-effective PM sensors can only sample particles directly from the atmosphere, without any pretreatment, and therefore their performance is strongly affected by the Relative Humidity (RH) of the sampled air (Manikonda et al. 2016; Sousan et al. 2017; Rai et al. 2017; Badura et al. 2018; Jayaratne et al. 2018; Zheng et al. 2018; Bulot et al. 2019; Karagulian et al. 2019).

A number of correction models have been proposed to account for uncertainties associated to variable RH conditions in measurements with low-cost OPCs. These correction models employ functions that account for the hygroscopic growth of the sampled particles (Di Antonio et al. 2018; Crilley et al. 2018), for possible deviations from reference instruments determined during testing (e.g., Zheng et al. 2018; Zamora et al. 2019), or a combination of both (e.g., Malings et al. 2020). While the proposed correction methods can significantly increase the accuracy of cost-effective PM sensors, they come with their own complexities. To account for aerosol hygroscopicity, knowledge of the chemical composition of the sampled aerosol particles, preferably at different sizes, and accurate measurements of RH, are required. In addition to that, potential changes in the optical properties of the particles, which are associated with water uptake (i.e., lensing effect and change of refractive index), should also be considered. What is more, correction methods which are site specific, or include both particle hygroscopicity and site specific correction factors, require long term in-situ comparisons between the low-cost PM monitors with reference instruments in order to have adequate statistics and thus provide effectively accurate results.

In this work, we propose and test a simple modification that qualifies the compact and low-cost Alphasense OPC (Model N2) to an instrument that can be connected with aerosol pretreatment sample lines (e.g., dryers and sampling inlets), thereby enabling it for measurements at ground stations and mobile platforms (e.g., onboard UASs). More specifically, we modified the sampling flow system of the

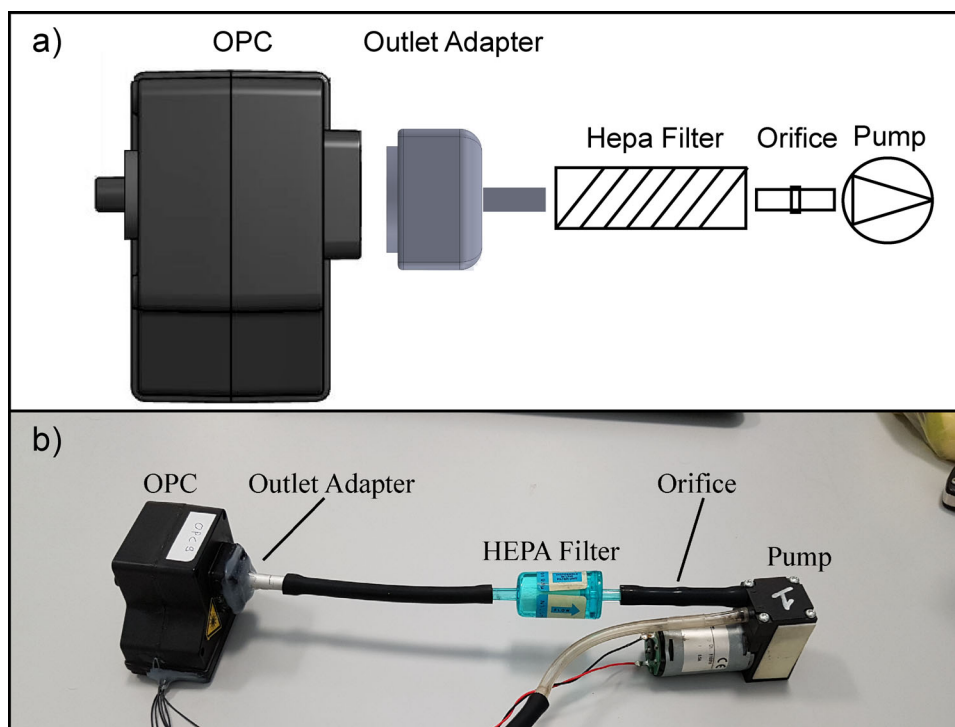


Figure 1. Schematic diagram (a) and photograph (b) of the modified Alphasense OPC.

OPC by replacing its micro fan with an external miniature pump, and test the system at different environmental conditions (i.e., temperatures and pressures varying from 5 to 20 °C and from 0.7 to 1.0 atm, respectively). This work builds on our previous study (Bezantakos, Schmidt-Ott, and Biskos 2018) where we tested the performance of the unmodified version of these OPCs.

2. Methods

2.1. Instrumentation and modification

The Alphasense OPC-N2 determines the number and size of the sampled particles by measuring the intensity of light they can scatter when illuminated by a laser source. The OPC employs a low-power micro fan that is sufficiently strong to draw an air flow through the device, with a nominal total flow rate of 1.2 lpm and a typical flow rate of around 0.22 lpm through its detection volume (i.e., accounting for 1/5 of the total flow rate), as claimed by the manufacturer. The instruments are calibrated by the manufacturer using particle size standards (i.e., polystyrene latex spheres), and against another reference OPC, namely the TSI Model 3300 (personal communication with Alphasense). Particle counts reported by the Alphasense OPC are distributed among 16 size bins, ranging from 0.38 to 17 μm .

The micro fan of the original instrument (Sunon MF25100V2-1000U-A99) can achieve the nominal flow rate provided that no tubing or device is connected to the system upstream (User Manual; Alphasense LTD, 2015), since it can achieve a maximum pressure differential of only 45 Pa (0.18 in H_2O) at zero flow rate (cf. Figure S1 in the online supplementary information [SI] for the complete performance curve of the fan). Here, we modified the original flow system of the OPC in order to withstand the pressure drop caused by sampling lines upstream the instrument (providing for example the ability of employing aerosol dryers), and to improve its flow stability upon sudden changes of airspeeds (common during operation onboard UASs) while allowing its use with isokinetic inlets.

The modification involved the replacement of the micro fan with a custom-made outlet adaptor coupled with an orifice and a miniature pump (KNF, Model NMP830KNDC), as shown in Figure 1. The outlet adaptor (cf. Figure S2 in the SI) was 3D printed and firmly attached to the back of the instrument where the fan was originally located, and downstream the outlet aperture of the OPC (cf. Figure S3 in the SI). A cylindrical metallic tube with similar inner diameter to that of the outlet aperture of the unmodified OPC extends to the other side of the outlet adaptor in order to allow connection to the orifice and the pump using flexible tubing. Proper sealing of the outlet

adaptor was achieved by applying a two-compound epoxy resin (Bison Epoxy 5 Minutes) on its main body, while its anchoring and further sealing was achieved by applying the same material between the outlet adaptor and the main body of the OPC. Further sealing of the modified OPC was achieved by applying the epoxy resin at the joints of the two main plastic covers of the OPC, and at the crevices located at the cables exit; something that is not a hard requirement when the micro fan is employed. A miniature HEPA grade filter (ETA, Model HC01U-4N-B) was included right after the outlet adapter in order to prevent coarse particles from clogging the rest of the flow system; i.e., the orifice and the miniature pump. The former was a disk-shaped custom-made orifice with an opening of ca. $450\ \mu\text{m}$, yielding a total flow rate of 1.26 lpm when combined with the miniature pump operated at constant speed. The selection of all parts/materials was made with the criterion of maintaining the high portability and cost effectiveness of the OPC, which is also critical for mobile applications (e.g., use onboard UASs and for exposure monitoring).

A calibrated OPC (Grimm Model 1.109) was used as reference for the particle number concentration measurements reported here. The reference OPC employs a pump for establishing a constant flow rate of 1.2 lpm.

2.2. Experimental setup and procedure

Both counting and sizing performance of the modified Alphasense OPC were determined using monodisperse polystyrene (PS) spheres (Magsphere INC.; NIST Traceable PS Microspheres). Tests were conducted at 1 atm pressure and $20\ ^\circ\text{C}$ with PS particles having nominal sizes of 0.8, 1.0 and $2.5\ \mu\text{m}$, over a wide concentration range, reaching up to a few thousand $\#/\text{ml}$. Although such high concentrations are not typically encountered in the atmosphere for particles in the micron-size range, they can occur under extreme conditions such as those during dust storms (Middleton 2017), or in the proximity of strong PM sources, including several industrial processes (Ding et al. 2017). It should be noted here that high particle number concentrations increase the coincidence error of OPCs; i.e., error introduced when more than one particles are simultaneously passing through the detector and counted as one bigger particle. The concentration threshold beyond which coincidence starts to have a significant effect on the performance of an OPC depends on its design characteristics, and thus is different for each

instrument. For example, the coincidence error for the Grimm 1.109 is 20% at a concentration of $2 \times 10^3\ \#/\text{ml}$ (Heim et al. 2008), whereas for the Alphasense N2 OPC the coincidence probability is reported at 0.84% at $10^3\ \#/\text{ml}$ (Alphasense User Manual).

Additional experiments with 0.8 and $1.0\ \mu\text{m}$ PS particles were carried out by placing the OPC in an environmental chamber operated at low pressures/temperatures, simulating conditions in flights of UASs at higher altitudes. The particle number concentrations in these experiments were kept below $10^2\ \#/\text{ml}$, similarly to the work of Bezantakos, Schmidt-Ott, and Biskos (2018), in order to avoid any coincidence errors. The experimental setup used in the tests was the same with that described in Bezantakos, Schmidt-Ott, and Biskos (2018). In brief, a constant-output atomizer (TSI Model 3076) was employed for atomizing the solutions with the PS particles, while a silica gel diffusion dryer was used downstream of the atomizer to dry the produced aerosol. The resulting dried aerosol was then passed through a cylindrical stainless steel temperature- and pressure-controlled chamber, having a diameter of 0.4 m and a length of 1.4 m, within which both the modified and the reference OPCs were placed. All PS stock solutions used for atomization contained 1% w/v PS solid spheres, except for those with a nominal size of $0.8\ \mu\text{m}$ (whose content was 10% w/v) and were further diluted with laboratory grade ultrapure water (having electrical resistivity $>18\ \text{M}\Omega/\text{cm}$) for achieving the desired particle number concentration levels.

All the experiments were conducted with the modified Alphasense OPC (Model N2) operated at a total flow rate of 1.26 lpm, which is similar to that of the unmodified version of the instrument as reported by the manufacturer. This was verified by a bubble meter (Sensidyne, Model Gilian Gilibrator 2) at room conditions (i.e., 1.00 atm pressure), or by a mass flow meter (TSI Model 4143) upstream the modified OPC at low pressures achieved inside the temperature- and pressure-controlled chamber. During the low pressure tests the standard flow rate reported by the mass flow meter was converted to volumetric flow, taking into account the pressure/temperature conditions set in the environmental chamber (cf. Application note Flow-004; TSI, 2001).

2.3. Data acquisition and processing

Data from the modified Alphasense OPC were acquired with a time interval set at 1 s using a miniaturized single-board Raspberry Pi 3 (Rpi3) computer

through its Serial Peripheral Interface (SPI), and a custom python script implementing the Alphasense OPC library (Hagan 2015). This data acquisition-storage/software interface was preferred to the solution provided by the manufacturer (which requires a USB-SPI adaptor and an MS® Windows equipped PC) due to its small dimensions, which attributes high portability required for a number of applications (e.g., in personal exposure monitoring, and aerial measurements using UASs). Tests were also conducted using the SPI-USB interface and the software (Alphasense 1.0.5779.33206) provided by the manufacturer at a 1-s time resolution for comparison. These tests showed that the two acquisition-storage/software interfaces had identical performance, after taking into considerations small discrepancies (i.e., of the order of 0.1 s) associated to the sampling time, which are accounted for in our results. To acquire the data from the reference OPC we used the software provided by the manufacturer (Grimm 1.178), setting the sampling time interval at 6 s.

The data collected by both instruments were averaged over 1 min before using them to assess the counting and sizing efficiency of the modified Alphasense OPC. It should be noted here that the data recorded by the modified OPC included the particle flux, expressed as particles per sampling period for each size bin, and the sample flow rate (SFR) that is a fraction of the total flow rate through the system. The particle number concentration is obtained by dividing the particle flux by the SFR. The total number concentration, determined by the modified OPC as described above, was compared with the one measured by the reference OPC, but using only the bins corresponding to particles larger than $0.4\ \mu\text{m}$. This was done in order to count only the particles residing in the common detection range of both instruments (i.e., Grimm 1.109 has its lower detectable particle size at $0.25\ \mu\text{m}$, whereas the modified OPC at $0.38\ \mu\text{m}$), and for avoiding the detection of particles that form by residuals in the PS particle solution. The later were usually observed as distinguished peaks at the low end of the size spectra recorded by the reference OPC.

In order to assess the sizing accuracy of the modified OPC we compared the geometric mean diameters (GMDs) calculated by the recorded size distributions, with the nominal sizes of standard particles (i.e., the PS spheres) used in our experiments. More specifically, a lognormal curve was fitted to the recorded normalized size distributions (i.e., $dN/d\log d_p$) using a non-linear least square fitting algorithm based on the

interior-reflective Newton method (Coleman and Li 1994, 1996).

3. Results and discussion

3.1. Sizing and counting performance of the modified OPC

Figure 2 shows the sizing performance of the modified Alphasense OPC when sampling monodisperse PS particles having diameters of 0.8, 1.0, and $2.5\ \mu\text{m}$ at room conditions (i.e., 1.00 atm and ca. 20°C). The total particle number concentration in these measurements was varied from ca. 10 to a few $10^3\ \text{#/ml}$ as measured by the reference OPC (N_{ref}). While the median GMD values measured by the modified OPC deviated within $\pm 5\%$ from the nominal size of PS particles, variations of more than 20% were observed for individual measurements as indicated by the error bars in Figure 2a. These variations can be explained by the fact that the sizing ability of the Alphasense OPC exhibits a clear dependency on the total particle concentrations as demonstrated by the experiments using particles of all the tested sizes (cf. Figures 2b–d). For instance, the GMD of the $0.8\text{-}\mu\text{m}$ PS spheres was determined as 0.66 and $1.07\ \mu\text{m}$ at concentrations of 10 and $2.3 \times 10^3\ \text{#/ml}$, respectively. In a similar manner, the size of $1.0\text{-}\mu\text{m}$ PS spheres determined by the modified OPC increases from $0.92\ \mu\text{m}$ at concentrations around $10\ \text{#/ml}$ to almost $1.4\ \mu\text{m}$ at $5 \times 10^3\ \text{#/ml}$. For the $2.5\text{-}\mu\text{m}$ PS particles the GMDs determined by the measurements with the modified OPC were considerably lower (i.e., ca. $2.1\ \mu\text{m}$) than the nominal size even at number concentrations of a few hundreds #/ml . Considering, however, that the reference OPC was reporting similar sizes, we attribute this behavior to the potential deterioration of the solution containing the $2.5\text{-}\mu\text{m}$ PS particles. The corresponding measurements recorded by the reference OPC, showing that the size of the sample particles remains unchanged, are also provided in Figures 2b–d for comparison.

It should be noted here that the Grimm 1.109 OPC underestimates the sizes of both the 0.8- and the $1.0\text{-}\mu\text{m}$ particles by ca. 25%, as has been previously reported in other studies (Peters, Ott, and O'shaughnessy 2006; Bezantakos, Schmidt-Ott, and Biskos 2018). This observation can be explained by undulations in the response of the Grimm OPC resulting from the use of monochromatic light and the higher number of size bins (i.e., 31 in total) compared to other similar instruments (Heim et al. 2008). Despite the underestimation in the size of the 0.8- and $1.0\text{-}\mu\text{m}$ PS particles, the Grimm OPC exhibits a

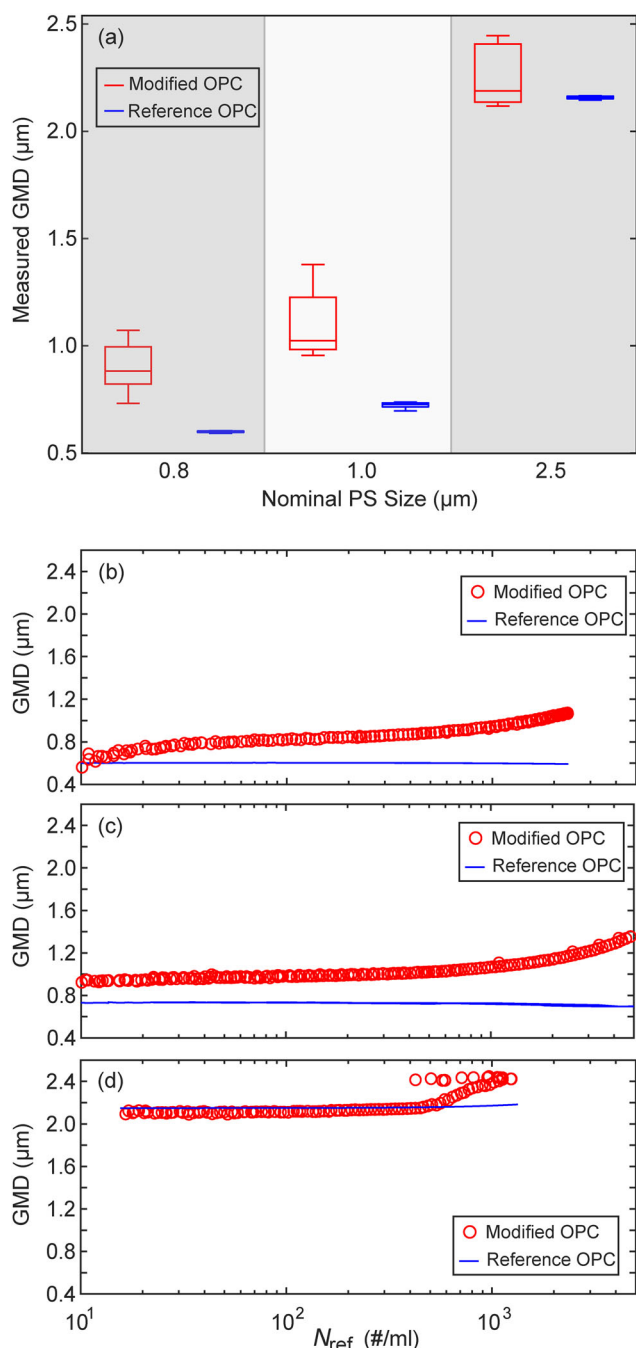


Figure 2. Median values (solid lines) with ± 2.7 standard deviation (whiskers) of the Geometric Mean Diameters (GMDs) reported by the modified and the reference OPCs when sampling PS spherical particles that were 0.8, 1.0, and 2.5 μm in diameter (a), and the reported GMDs by both OPCs when sampling 0.8 μm (b), 1.0 μm (c), and 2.5 μm (d) PS spherical particles as a function of the total particle number concentration reported by the reference OPC.

stable (i.e., within $\pm 5\%$ variability) counting performance throughout the whole spectrum of particle size concentrations tested, as shown in Figure 2, albeit that the upper concentration limit is slightly beyond the threshold where coincidence errors become important (i.e., $> 2 \times 10^3$ #/ml; cf. section 2.2).

The counting performance of the modified OPC at room conditions, expressed as the ratio between the measured total particle number concentrations by the modified and the reference OPC (i.e., N_{mod}/N_{ref}), exhibited variabilities depending primarily on the total particle number concentration and on their nominal size. Especially for the 1- μm particles sampled at concentrations in the range from 1 to 10^4 #/ml, there is a strong dependence of the modified OPC counting efficiency when the total concentration gets below ca. 50 #/ml or above ca. 800 #/ml. This observation is in agreement with the results reported in our previous study where we tested the unmodified Alphasense OPC at room conditions (i.e., 1.00 atm and 23 °C) with PS spheres of the same size (i.e., 1.0 μm in diameter) and at number concentrations lower than a few tens #/ml (cf. Figure 2 in Bezantakos, Schmidt-Ott, and Biskos 2018). We should note that comparison with the results reported in our previous study using the unmodified version of the Alphasense OPC is only possible in the lower end of the concentrations range (i.e., up to a few tens #/ml) due to lack of measurements with that system at higher concentrations.

Similarly to the 1.0- μm particles, the counting performance of the modified OPC exhibited a concentration-dependent response for the 0.8- μm and the 2.5- μm PS particles, underestimating their number concentration above 800 #/ml. In addition, for the 2.5- μm PS particles the number concentration was overestimated below ca. 500 #/ml, exhibiting a 35% deviation from the reference measurement at ca. 10 #/ml. The actual measured total particle number concentrations of the modified and the reference OPCs are shown in Figure S4 in the SI.

Additional tests with the modified OPC were conducted at low temperature/pressure conditions, corresponding to those encountered at higher altitudes when the instruments fly onboard UASs. In these tests the particle number concentration was kept almost constant and below 10^2 #/ml for a duration of ca. 20 min in order to avoid coincidence errors (cf. section 2.2). The results of these tests are provided in Tables 1 and 2. The sizing performance of the modified OPC exhibited a slight dependence with temperature when sampling 0.8- μm PS spheres, exhibiting the highest overestimation of their size by 13% at 5 °C. This temperature dependence was not observed for the 1.0- μm PS particles (cf. Table 1). A slight dependence of the sizing performance (i.e., exhibiting a maximum deviation of 8% from the nominal size of the PS spherical particles) of the modified OPC with pressure was also observed for both the 0.8- and 1.0- μm

Table 1. Average geometric mean diameter (GMD) and $N_{\text{mod}}/N_{\text{ref}}$ ratio (with ± 1 standard deviation) determined when the modified OPC samples 0.8- and 1.0- μm PS particles at a pressure of 1.00 atm and temperatures varying from 20 to 5 °C.

	Nominal PS Size	20 °C	15 °C	10 °C	5 °C
GMD	0.8 μm	0.82 \pm 0.01	0.85 \pm 0.03	0.88 \pm 0.01	0.92 \pm 0.02
	1.0 μm	0.97 \pm 0.01	1.00 \pm 0.00	1.01 \pm 0.01	1.02 \pm 0.01
$N_{\text{mod}}/N_{\text{ref}}$	0.8 μm	0.97 \pm 0.02	0.95 \pm 0.02	0.90 \pm 0.03	0.99 \pm 0.02
	1.0 μm	0.90 \pm 0.02	0.95 \pm 0.02	0.95 \pm 0.02	0.95 \pm 0.02

Table 2. Average geometric mean diameter (GMD) and $N_{\text{mod}}/N_{\text{ref}}$ ratio (with ± 1 standard deviation) determined when the modified OPC samples 0.8 and 1.0 μm PS particles, at a temperature of 20 °C and pressures varying from 0.7 to 1.0 atm.

	Nominal PS Size	1.00 atm.	0.85 atm.	0.70 atm.
GMD	0.8 μm	0.82 \pm 0.01	0.78 \pm 0.01	0.77 \pm 0.02
	1.0 μm	0.97 \pm 0.01	0.93 \pm 0.01	0.92 \pm 0.01
$N_{\text{mod}}/N_{\text{ref}}$	0.8 μm	0.97 \pm 0.02	0.97 \pm 0.02	0.95 \pm 0.01
	1.0 μm	0.88 \pm 0.02	0.95 \pm 0.01	0.99 \pm 0.03

PS particles sampled at low pressure conditions ranging from 1.0 down to 0.7 atm at 20 °C (cf. Table 2).

The counting performance of the modified OPC (i.e., expressed by the $N_{\text{mod}}/N_{\text{ref}}$ ratio) when sampling 0.8- and 1.0- μm PS spheres, remained close to unity during all these tests. Small deviations in the counting efficiency of the modified OPC from unity (i.e., within less than 12%) when measuring particles of the same size at different conditions (cf. Tables 1 and 2) can be attributed only to the dependence of its detection efficiency on the absolute total particle number concentrations.

3.2. Testing of the modified OPC and data correction

The main modification of the Alphasense OPC described in this work was on its flow system. The flow rate of the instrument was measured at room conditions using a bubble flow meter, and at different pressure conditions, ranging from 0.7 to 1.0 atm, using a mass flow meter (cf. sections 2.2). The volumetric flow of the modified OPC was found to be stable within 5% under all tested pressure conditions (i.e., from 0.7 to 1.0 atm; cf. Table 3).

Despite that the total flow rate through the modified OPC was almost the same to that of the unmodified version (as claimed by the manufacturer), the SFR value reported by the former (i.e., the modified OPC) was different than the nominal value of ca. 1/5 of the total flow rate, reported for the unmodified version. More specifically, in all the measurements with the modified OPC operated at room conditions the reported SFR had an average value of 1.99 ± 0.07 ml/s (i.e., ca. 0.12 lpm) which is 1/10.5 of the total flow

Table 3. Average values and standard deviation of the volumetric flow rate of the modified OPC, at a temperature of ca. 20 °C and pressures varying from 0.7 to 1.0 atm.

Pressure (atm.)	1.00	0.85	0.70
Flow (lpm)	1.26 \pm 0.06	1.33 \pm 0.04	1.33 \pm 0.04

rate (i.e., 1.26 lpm) and not 1/5 as reported by the unmodified version.

It should be noted here that the instrument reports the SFR based on measurements of the time needed by particles to cover a specific distance within the optical detection volume reported as mean time of flight (MTOF). MTOF values obtained by the modified OPC were ca. 2.2 times lower than those reported by its unmodified counterpart (Bezantakos, Schmidt-Ott, and Biskos 2018) when sampling 1.0- μm PS particles, further corroborating the lower SFR reported by the former (cf. Figure S5 and Table S1 in the SI for more details). Since, however, the SFR is rather stable, leading to an almost constant factor used to convert the particle flux to particle number concentration, it affects only the magnitude of the reported number concentration and not its dependence on the actual number concentration.

Considering that the modification proposed in this work only affects the SFR despite that the flow rate through the system remains unchanged compared to the value reported by the manufacturer for the unmodified version, the size-dependent counting performance of the modified OPC at particle number concentrations higher than 10^3 #/ml can be explained by coincidence errors. It should be noted here that the saturation limit of the Alphasense OPC detector is reached at concentrations higher than 10^4 #/s, as claimed by the manufacturer; a threshold which was never reached in our experiments. We should also highlight that the coincidence probability of the unmodified OPC is 0.84% at 10^3 #/ml (cf. section 2.2) according to the manufacturer, which is far lower than the reduction in the counting efficiency we observed with the modified version. This is not surprising considering that the Alphasense OPC does not use any means (e.g., focusing nozzle, sheath flow) to align the particles in a narrow beam before they pass through its detection volume, as other laboratory-grade OPCs do. As a result, it is more prone than the reference OPC to coincidence error, as the larger the particle stream volume to the optical detection volume ratio is, the lower the threshold of this error becomes. The reduction of the counting efficiency coincides with an increase in the geometric standard deviation of the fitted distributions to the measurements (cf. Figure S6) and the reported mean particle size (cf.

Figure 2), both of which indicate coincidence counting (Jaenicke 1972).

To adjust the counting efficiency of the modified OPC to within a narrow range around unity over the entire particle concentration range investigated here, we further provide a correction function determined by correlating concentrations measured by the instrument with those reported by the reference OPC (Grimm 1.109), given by:

$$N_c = \exp\left(a + \sum_i b_i \ln(N_m)^i\right) \quad (1)$$

where N_c and N_m are respectively the corrected and measured total particle number concentrations, whereas a and b_i (with $i = 1-6$) are fitted parameters. The values of the fitted parameters corresponding to the best fit ($R^2 = 0.9962$; root mean square error of 14%) through the recorded data are: $a = 1.460003552$, $b_1 = -4.50543750$, $b_2 = 4.940621628$, $b_3 = -1.96977068$, $b_4 = 0.398044684$, $b_5 = -0.03989559$, $b_6 = 0.001578195$. It should be noted that in order to obtain the fitting values of Equation (1) we used all the recorded data (i.e., data corresponding to all the PS particle sizes employed in this work) with total particle number concentrations ranging from ca. 10 to a few thousands #/ml, depending on the size. Figure 3 shows the corrected, in comparison to the measured, results of the modified OPC expressed as counting efficiency (i.e., $N_{\text{mod}}/N_{\text{ref}}$ ratio) for all the measured PS particle sizes. Evidently, the corrected counting performance of the modified OPC is within $\pm 30\%$ over a broad range of total particle number concentrations (i.e., from 10 to 10^4 #/ml), which is a significant improvement compared to that determined when using the uncorrected data.

We should highlight here that the above correction function was obtained using the combined measurements of monodisperse PS particles having sizes from 0.8 to 2.5 μm . Although one can in principle determine calibration curves using monodisperse particles of different sizes for correcting the concentration reported by the Alphasense OPC or the combination of these measurements as a proxy to polydisperse aerosols, this method should be employed with caution. The main reason is that the optical properties of the particles used (i.e., standard size PS particles) have a fixed refractive index, which does not necessarily match that of real-life particles, which can exhibit different optical properties. Another reason is associated with potential interferences among the different size bins of the instrument when sampling polydisperse aerosols having wide size distributions, that can affect the recorded signals in ways that are not present when using monodisperse aerosols and consequently not

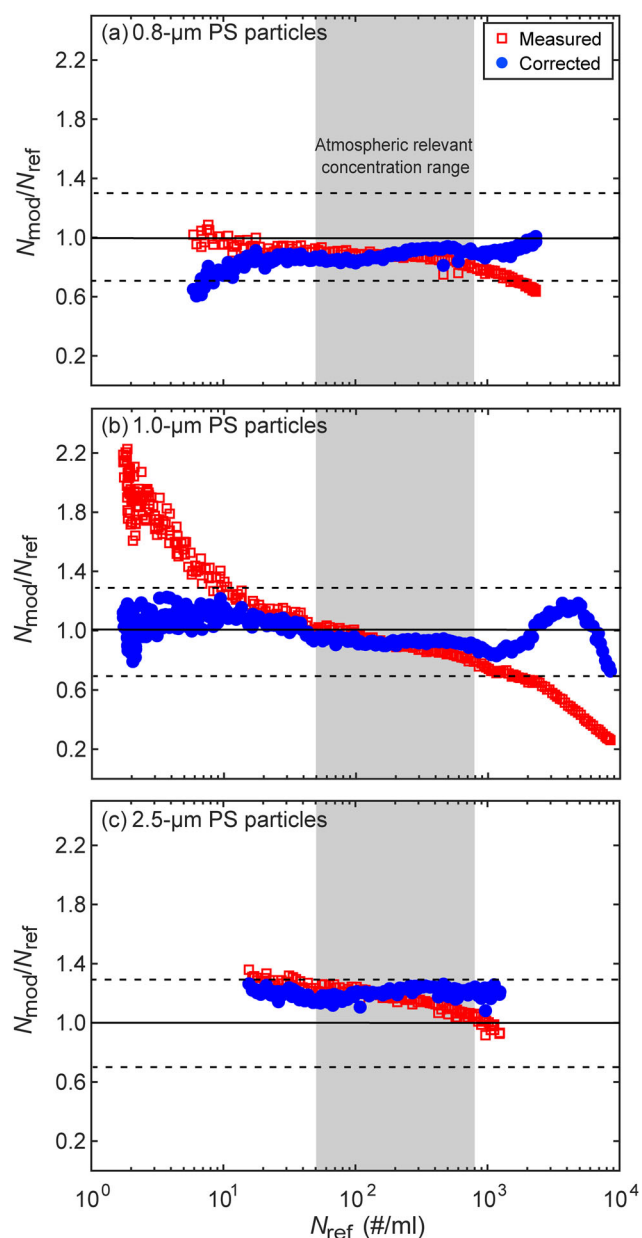


Figure 3. Counting efficiency of the modified OPC when sampling 0.8 μm (a), 1.0- μm (b), and 2.5 μm (c) PS spherical particles before (red squares) and after (blue circles) applying the correction function. Dashed-dotted lines depict a $\pm 30\%$ deviation from the 1:1 ratio (solid line).

captured by the correction function provided here. For these reasons, determining correction functions using polydisperse particles on site may provide a better strategy for providing site-specific calibrations.

Despite the limitations discussed in the previous paragraph, the measurements reported here show that for the most atmospheric relevant conditions, where the total number concentration range resides within 50 to ca. 800 #/ml, the modified instrument can be safely employed for accurately (i.e., within 20%) determining the concentration and the size of these particles, without requiring any post-corrections.

4. Conclusions

In this work we modified the flow system of the widely used, cost-effective and lightweight Alphasense OPC (Model OPC-N2) by replacing its micro fan with an orifice and a miniature pump. The scope of this modification was to expand the capabilities of the instrument by allowing its connection with sampling lines and/or other aerosol pretreatment equipment, required for air quality monitoring in stationary or mobile platforms.

The performance of the modified OPC was tested using monodisperse PS spherical particles over a wide range of number concentrations at room conditions (i.e., 1.0 atm pressure and 20 °C temperature). The sizing performance of the modified OPC deviated within 10% from the nominal size of the PS particles when the total particle number concentrations was below ca. 800 #/ml. At higher concentrations (and especially above 2000 #/ml) its sizing accuracy decreased, resulting in overestimation of the size of the sampled particle by more than 20% from the nominal size of the PS spheres. The counting efficiency of the modified OPC was found to depend on the actual total particle number concentration, being accurate (i.e., within $\pm 20\%$) in the range from ca. 50 to 800 #/ml. This behavior is attributed to the design characteristics and the operating principle of the OPC itself, and not to the modification proposed and tested in this work.

To account for the size-dependent counting efficiency of the Alphasense OPC we introduce an empirical function to correct the reported number concentrations when the instrument samples highly diluted or concentrated aerosols (i.e., aerosols having particle number concentrations < 50 or > 800 #/ml). This correction function limits the reported number concentration to within $\pm 30\%$ uncertainty over a broad range (i.e., from 10 to almost 10^4 #/ml). It should be noted that the suggested correction scheme is based on a combination of measurements using monodisperse particles having specific optical properties, and should therefore be used with caution and only at very low or high particle number concentration conditions.




Tests conducted under reduced pressure/temperature conditions (down to 0.7 atm and 5 °C), resembling conditions encountered by instruments operated at higher altitudes, demonstrated that the modified OPC can be safely used onboard UASs for measuring the concentration and size of aerosol particles without significantly sacrificing of its performance.

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