Aerosol Science and Technology

ISSN: 0278-6826 (Print) 1521-7388 (Online) Journal homepage: https://www.tandfonline.com/loi/uast20

Performance evaluation of the cost-effective and lightweight Alphasense optical particle counter for use onboard unmanned aerial vehicles

Spyros Bezantakos, Fabian Schmidt-Ott & George Biskos

To cite this article: Spyros Bezantakos, Fabian Schmidt-Ott & George Biskos (2018) Performance evaluation of the cost-effective and lightweight Alphasense optical particle counter for use onboard unmanned aerial vehicles, Aerosol Science and Technology, 52:4, 385-392, DOI: 10.1080/02786826.2017.1412394

To link to this article: https://doi.org/10.1080/02786826.2017.1412394

AEROSOL SCIENCE AND TECHNOLOGY
2018, VOL. 52, NO. 4, 385–392
https://doi.org/10.1080/02786826.2017.1412394

Performance evaluation of the cost-effective and lightweight Alphasense optical particle counter for use onboard unmanned aerial vehicles

Spyros Bezantakos[a], Fabian Schmidt-Ott[b], and George Biskos[c,d]

[a]Maison de la Recherche en Environnement Industriel 2 (MREI2), Université du Littoral Côte d'Opale, Dunkerque, France; [b]Faculty of Humanities and Sciences, Maastricht University, Maastricht, The Netherlands; [c]Energy Environment and Water Research Center, The Cyprus Institute, Nicosia, Cyprus; [d]Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, The Netherlands

ABSTRACT

Air quality monitoring using airborne platforms is rapidly gaining ground as unmanned aerial vehicles (UAVs) are becoming easier, less expensive, and safer to operate on a routine basis. To facilitate measurements of key atmospheric properties, however, efforts are still required in developing/testing miniaturized instruments for use onboard UAVs. Here, we test two commercially available cost-effective/lightweight optical particle counters (OPCs; Alphasense Model N2) capable of measuring the size distributions of airborne particles having diameters from 380 nm to 17 μm. Tests were made against a reference and recently calibrated OPC (Grimm Model 1.109) using monodisperse polystyrene spheres. All instruments were placed in a chamber in which the temperature and pressure varied in the ranges of –5 to 23°C and 0.7 to 1.0 atm, respectively; conditions typically encountered during UAV flights. Agreement in the particle number concentrations measured by the Alphasense and the Grimm OPCs was within 40%, under all experimental conditions used in this work, when particles having sizes >1 μm were employed during the tests. Deviations higher than 50%, however, were observed when the instruments were tested with 1.0- and 0.8-μm polysterene spheres. The particle sizes reported by both Alphasense OPCs were within $\pm$ 5% with respect to the nominal polysterene spheres' size under all operating pressures and temperatures down to 5°C. At lower temperatures, the sizing accuracy of one of the two Alphasense OPCs degraded significantly. While our findings support that the Alphasense OPCs can be used at low temperature/pressure conditions, they should be carefully tested prior the measurements to ensure good performance.

ARTICLE HISTORY
Received 8 September 2017
Accepted 26 November 2017

EDITOR
Kihong Park

1. Introduction

Environmental monitoring using unmanned aerial vehicles (UAVs) is becoming more and more popular over the recent years mainly due to recent advances of the technology (Sørensen et al. 2017), and the fact that it is a cost-effective way for performing systematic Earth observations. Of particular interest is their application in the field of atmospheric sciences, where UAVs can provide excellent platforms for probing vertical distributions and obtaining three-dimensional mappings of key atmospheric parameters, as well as the capability to perform measurements at places that are not easily accessible (Villa et al. 2016). Considering that aerosol particles are very important constituents of the atmospheric environment—affecting human health, visibility, and climate—recent efforts have yielded vertical profiles of their properties using compact in-situ instruments onboard UAVs (Bates et al. 2013; Alvarado et al. 2015; Chilinski et al. 2016; Wilcox et al. 2016).

In view of the limitations in size and payload, several attempts have been made to develop miniaturized and lightweight systems for conducting atmospheric research flights with UAVs (Bezantakos et al. 2015; Barmpounis et al. 2016; Gao et al. 2016; Surawski et al. 2017; Yu et al. 2017). One commercially available and potentially promising tool for measuring the size distribution of aerosol particles onboard UAVs is the OPC produced by Alphasense Ltd. (Model OPC-N2), which has a volume of 190 cm^3 and weighs 105 g. The operating principle of this

CONTACT George Biskos G.Biskos@cyi.ac.cy; G.Biskos@tudelft.nl Energy Environment and Water Research Centre, The Cyprus Institute, Nicosia 2121, Cyprus, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft 2628 CN, The Netherlands.

Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/uast.

Supplemental data for this article can be accessed on the publisher's website.

OPC is similar to that of other commercial instruments that measure the light scattered by sampled particles when those are illuminated by a laser source (McMurry 2000).

A number of compromises have been made by Alphasense in order to keep the OPCs compact, lightweight, and inexpensive, the most important of which being the absence of a sheath flow to keep the aerosol sampled in a confined beam. Although this can reduce the particle sizing and counting capabilities of the instrument, using its signal to determine the size distributions of the sampled particles is still possible under certain assumptions made at the data inversion stage. The second most important compromise is the use of a fan (instead of a pump) to pull the sample flow through the system. Although this solution will not introduce any experimental artefacts when the instrument samples at still air, it can introduce significant errors due to flow fluctuations when the pressure drop along the flow path of the instrument is higher than that induced by the fan.

Sousan et al. (2016) have recently characterized the Alphasense OPC-N2, showing that it can provide number and mass concentrations similar to those reported by a Grimm OPC (Model PAS-1.108) for particles larger than 1μm, under laboratory conditions. Here, we build on this work and evaluate the sizing and counting performance of this OPC at low temperature and pressure conditions that can be typically encountered by the instruments during flights with UAVs that have no pressure and/or temperature controlled payload compartments. The operating conditions were simulated inside a laboratory chamber in which the temperature and pressure varied from –5 to 23°C and from 0.7 to 1.0 atm, respectively, corresponding to conditions at altitudes up to a few km above sea level (a.s.l.), depending on ground conditions.

2. Methods

2.1. Instrumentation

Two Alphasense OPC-N2 systems were used in the tests reported in this work. These OPCs employ a low-power micro fan that is sufficiently strong to draw an air flow through the device, with typical sample flow rates being around 220 ml/min, and distribute the particle number concentrations throughout 16 size bins, ranging from 0.38 to 17 μm. The instruments come calibrated by the manufacturer using polystyrene latex (PSL) spheres (i.e., refractive index of ca. $1.6 + i0$; Marx and Mulholland 1983), and against another commercially available OPC, namely the TSI Model 3300 OPC (personal communication with Alphasense). The commercially available software that accompanies the Alphasense OPC reports size distribution expressed either as particles/s (i.e., particle flux) or particles/ml (i.e., particle number concentration) for each size bin.

A recently calibrated OPC (Grimm Model 1.109) was used as reference for the measurements reported here. The Grimm OPC distributes the particle number concentration of the sampled aerosols into 31 size bins from 250 nm to 32 μm, and in contrast to the Alphasense OPC-N2 it employs a controlled pump for establishing a constant flow rate of ca. 1.2 lpm.

2.2. Experimental setup and procedure

Both the sizing and counting accuracy of the two Alphasense OPCs were determined using monodisperse polystyrene (PS) spheres (NIST Traceable PS Microspheres, Magsphere Inc.) of six different nominal sizes: 0.8, 1.0, 2.5, 5.1, 7.2, and 10.2 μm. Aqueous solutions containing the PS spheres were prepared by diluting some drops of the purchased PS stock solution with MilliQ pure water (conductivity of 0.055 μS/cm). All stock solutions contained 1% w/v PS solid spheres, except for those with a nominal size of 0.8 μm, whose content was 10% w/v. The amount of PS stock solution used varied from 5 to 30 drops per 100 ml of MilliQ pure water, depending on the desired concentrations during the tests (i.e., more droplets were used for the bigger particles to compensate for their lower number concentration and inertial losses along the experimental setup).

Figure 1 shows the experimental setup used for the measurements. A constant-output atomizer (TSI Model

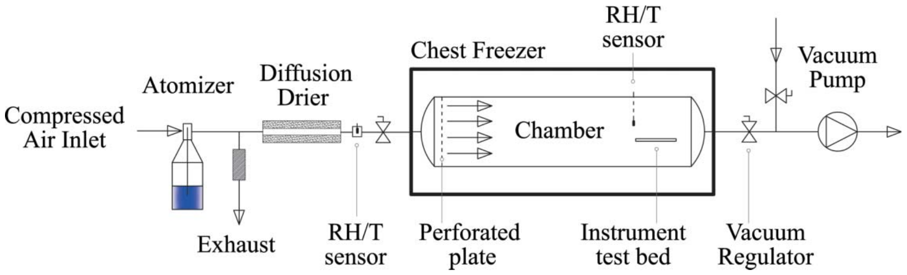

Figure 1. Schematic diagram of the experimental setup.

3076) was employed for atomizing the PS solutions, while a silica gel diffusion dryer was used downstream of the atomizer to dry the PS particles. Adequate drying of the atomized aerosol was ensured by measuring the relative humidity (RH) of the sample stream downstream the dryer using a temperature/relative humidity (T/RH) sensor (Rotronic HC2-05). The resulting dried aerosol (RH <35%) was then passed through a cylindrically stainless steel chamber, having diameter of 0.4 m and a length of 1.4 m, within which all three OPCs (i.e., the two Alphasense and the Grimm 1.109) were placed. It should be noted here that all the instruments, together with a second T/RH sensor for measuring the conditions inside the chamber, were placed close to each other near the chamber outlet, with their inlets facing the flow. A perforated plate was placed behind the chamber inlet to provide more homogenous airflow. To achieve temperatures down to –5°C, the entire chamber was placed inside a chest freezer that had internal dimensions 0.5, 2.1, and 0.7 (length, width, and height, respectively) m. A vacuum pump together with a vacuum pressure regulator and flow regulating valves was employed for maintaining the sample flow rate through the chamber at 3.0 lpm while regulating the pressure inside the chamber to 0.70, 0.85, and 1.00 atm for the different experiments. Potential deviations between the true and the measured RH caused by pressure variations were significantly lower (i.e., of the order of 0.1% at 0.70 atm; Luijten et al. 1998) than the T/RH sensor accuracy (i.e., of the order of 1.5%) and therefore not considered in this work.

2.3. Data processing

To acquire the data from the OPCs, we used the software provided by the manufacturers (Grimm 1.178 and Alphasense 1.0.5779.33206), setting the sampling time intervals at 6 s for all of them. All the recorded data were then averaged over 1 min. It should be noted here that the data recorded by the Alphasense OPC software include the particle flux expressed as particles/s for each size bin, and the flow rate through the instrument expressed in ml/s. The particle number concentrations (i.e., particles/ml) were then determined by dividing the two variables. For each particle size tested, we then compared the total number concentration, measured by each of the Alphasense OPCs with the one measured by the Grimm OPC, but using only the bins corresponding to particles larger than 0.4 μm. The main reasons for doing so were (1) to overcome potential differences associated with the lower boundary of the bin that includes the smallest particles (Grimm 1.109 has its lower detectable particles size at 0.25 μm, whereas Alphasense at 0.38 μm), and (2) to avoid counting particles formed by the residuals in the PS sphere solution that were usually observed as distinguished peaks at the low end of the size spectra recorded by the Grimm OPC.

The sizing accuracy of all OPCs was assessed by comparing the geometric mean diameters (GMDs) calculated by the measured size distributions with the nominal size of each monodisperse PS sphere sample. More specifically, the recorded measurements (i.e., particle number concentrations at each size bin) were first converted to normalized $dN/d\log d$ units and then fitted with a lognormal curve using a nonlinear least square fitting algorithm based on the interior-reflective Newton method (Coleman and Li 1994, 1996). Measurements using PS spheres of specific nominal sizes were recorded over several tens of minutes, and the median value of the GMDs obtained by the fitting procedure on every measurement was then used for assessing the sizing accuracy of each instrument. For smaller particles, the typical duration of the experiment was of the order of 30 min, but for the bigger particles (i.e., >5 μm in diameter) the experiments lasted ca. 10 min. The main reason for that was the lower number concentration of PS spheres in the initial stock solutions that forced us to use less solvent (i.e., pure water) for preparing the samples, resulting in small amount of solutions that depleted relatively fast during these experiments.

3. Results and discussion

3.1. Counting performance at room conditions

Figure 2 shows the correlation between the particle number concentrations measured at ambient conditions (i.e., ca. 23°C and 1 atm) by the two Alphasense and the Grimm OPCs for the six different PS sphere sizes used in this work. With the exception of particles smaller than 2.5 μm, agreement between the two Alphasense OPCs is within 20%. For particles having sizes of 0.8 and 1.0 μm, however, the discrepancy between them exceeds 100% in many cases, and are characterized by increased variability, compared to the measurements conducted with bigger particles (cf. also the recorded concentrations over time shown in the online supplementary information [Figure S1]). Compared to the reference instrument (i.e., the Grimm 1.109), both Alphasense OPCs overestimated the number concentrations by over 100% when tested with particles having nominal size of 0.8 μm. For all the other sizes (i.e., particles having nominal sizes above 1.0 μm), the differences between the number concentrations measured by the Alphasense and the Grimm OPCs did not exceed in most of the cases 40%. Best agreement (i.e., absolute difference <10%) between the two types of instruments was observed for particles having nominal size of 2.5 μm.

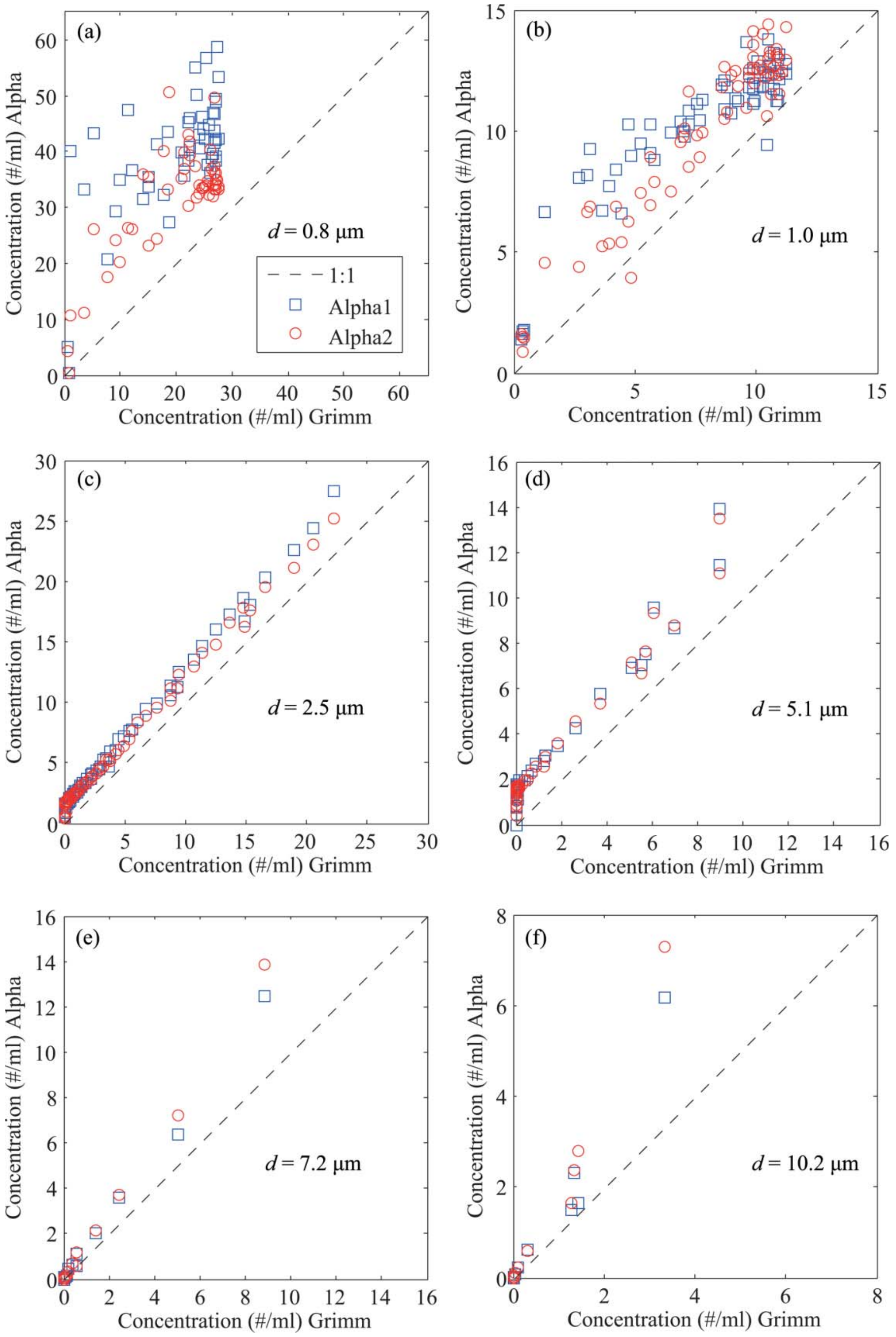

Figure 2. Comparison of particle number concentrations measured by the two Alphasense OPCs, denoted as Alpha1 and Alpha2, and the Grimm 1.109 OPC that was used as a reference. The measurements were carried out with PS spheres having sizes of 0.8 (a), 1.0 (b), 2.5 (c), 5.1 (d), 7.2 (e) and 10.2 (f) μm.

The observed overestimations in the reported particle number concentrations of 0.8 μm is in contrast to what is reported by Sousan et al. (2016), who found that the counting efficiency of the Alphasense OPC is similar to that of the Grimm 1.108, which in turn has a very similar performance with the Grimm 1.109 model (Heim et al. 2008; Burkart et al. 2010) for this size of particles. Excluding potential experimental artefacts such as coincidental counts (since the concentration of particles was always less than 100 #/cm^3) and concentration nonuniformities within the test chamber, the most plausible explanation for this disagreement is the updated firmware used by the Alphasense OPCs (version 18 and above), which, since the work reported by Sousan et al. (2016) (that used version 17b), includes an additional weighing for taking care of the underestimation of particle concentrations for the smaller size bins (Alphasense 2015).

Despite the discrepancies in the measured number concentrations of sub-1-μm particles, which need to be investigated further, the overall good agreement between the two Alphasense and the Grimm OPCs when sampling larger particles builds trust toward employing them for measuring the concentrations of particles in the coarse mode. Considering, however, that the counting performance of OPCs depends strongly on the stability of the flow pulled through the instrument, a more robust sample flow system (i.e., replacing the fan with an external pump) should be used to compensate for potential flow fluctuations due to sudden air speed changes; something that is quite common in UAV flights.

3.2. Sizing performance at room conditions

Figure 3 shows the median GMDs obtained from all the OPC measurements (cf. Section 2.3 for details) as a function of the nominal size of the monodisperse PS spheres.

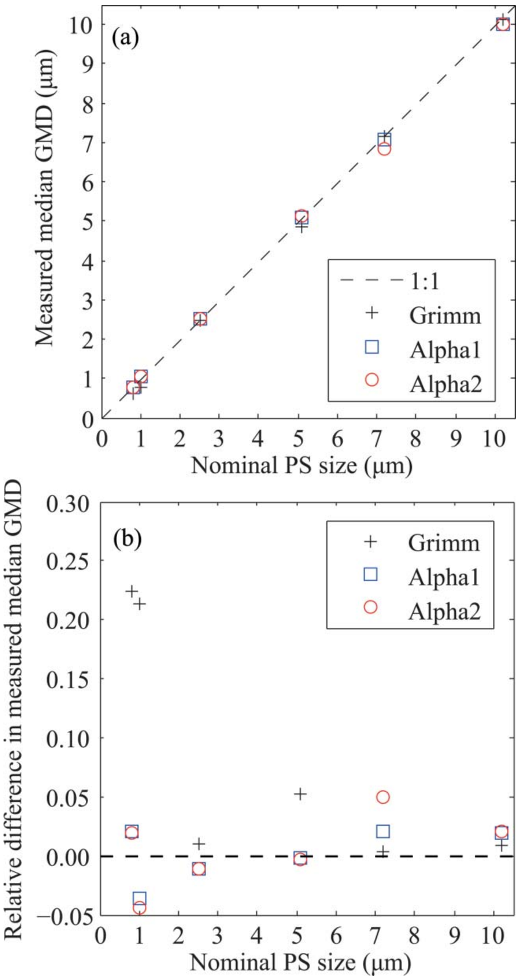

Figure 3. Geometric mean diameter (GMD) of PS spheres determined from the size distributions measured by the Alphasense and the Grimm OPCs (a), together with the relative differences from the nominal PS particle size (b), for each test.

In general, all instruments provided GMD values close to the 1:1 line (Figure 3a), exhibiting a ±5% uncertainty in determining the size of the PS spheres (Figure 3b). The only exception was an underestimation of the order of 20% reported by the Grimm 1.109 OPC when PS spheres having sizes of 0.8 and 1.0 μm were used in the tests (Figure 3b). Similar observations have also been reported by Peters et al. (2006) who compared the performance of that OPC with an Aerodynamic Particle Sizer (APS; TSI Model 3321), and later by Heim et al. (2008), during a comparison of three different OPCs, who attributed them to undulations in its response resulting from the use of monochromatic light and the higher number of size bins (31) compared to other similar instruments. Considering that the Alphasense OPCs also employ a monochromatic light source (cf. table 1 in Sousan et al. 2016) but have fewer sizing bins (16), sizing accuracy is not affected in the sub-2-μm range.

3.3. Overall performance at low temperature conditions and sea level pressure

Figure 4 shows the measured number concentrations and estimated GMDs by the two Alphasense and the Grimm 1.109 OPCs when sampling 0.8-μm PS spheres at atmospheric pressure as the temperature in the chamber decreased gradually. The chamber, which was placed in the chest freezer for this set of experiments as described in section 2.2, was gradually cooled from ambient temperature to –5°C over 5 h. Temperature and RH in the vicinity of the instruments within the chamber were constantly monitored, with the RH never exceeding 75%. The counting performance of all OPCs at low temperatures was comparable in the sense that all instruments exhibited similar trends, capturing the decrease in particle concentration during the course of the measurements (Figure 4a). This decrease was caused by PS spheres gradually adhering to the glass reservoir of the atomizer when the excess liquid was recirculated back to the solution.

In terms of sizing, all OPCs exhibited fluctuations (Figure 4b) as temperature decreased in the chamber, with the difference between the Alphasense and the Grimm OPCs being consistent with the measurements at ambient conditions (cf. Section 4.2). One of the Alphasense OPCs and the Grimm OPC showed fluctuations within less than 5%, which can be attributed to instrument uncertainties. The other Alphasense OPC, however, exhibited a sudden decrease in the GMD calculated by the measurements below 5°C, although the number concentration of particles reported by the same instrument was not affected (cf. Figure 4a). This behavior (for the specific Alphasense OPC) was repeatable, with the

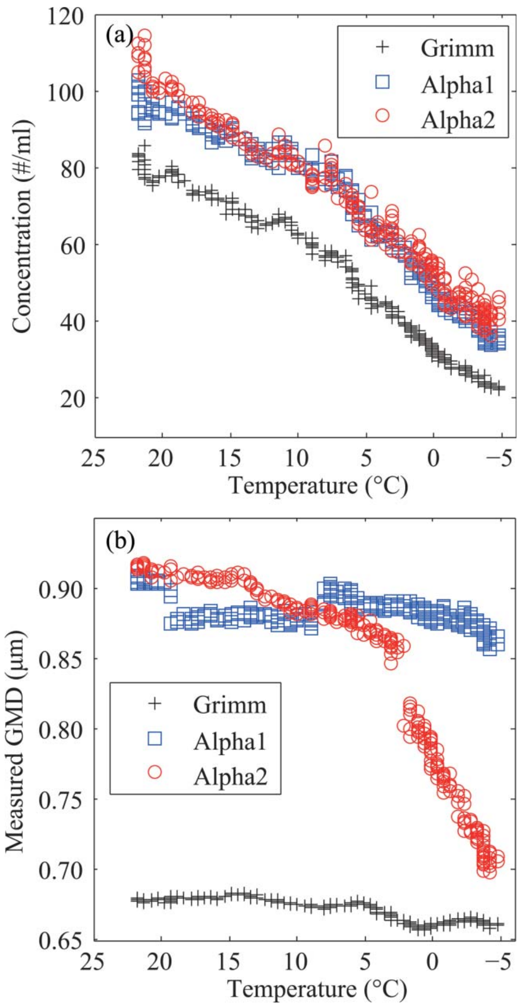

Figure 4. Number concentrations (a) and GMDs (b) determined by all the OPCs when sampling 0.8-μm PS spheres at 1 atm and temperature that decreased from 23 to –5°C. Note that the concentration of particles in the chamber was decreasing during the course of the experiment that lasted ca. 5 h.

signal recovering again at temperatures higher than 5°C. A possible reason for this behavior could be the condensation of water vapor on impurities on the optics of the specific OPC, as the temperature inside the chamber decreased. Considering that the Alphasense OPCs do not use a sheath flow, as compared to the Grimm and other commercially available OPCs, the possibility of contaminating the optical system of the instrument, which can very well affect its overall performance since impurities can serve as sites for water condensation at lower temperatures and/or higher humidity, is increased. It is therefore absolutely necessary to run calibration tests in order to identify potential similar behaviors before deploying these systems in UAV missions, especially when the operating temperature is expected to be significantly lower than 10°C. Adequate drying of the sampled aerosol (i.e., maintaining its RH as low as possible and ideally below 40%) is therefore essential for avoiding condensation of water on impurities in the measuring volume of the instrument. Doing so will also prevent aerosol particle growth due to water uptake, thereby yielding measurements of their size distributions according to the WMO/GAW guidelines and recommendations (GAW report No. 227, 2016).

3.4. Overall performance at low pressure and low temperature conditions

Summarized results of the sizing performance of all the OPCs when sampling 0.8-μm PS particles at reduced pressures and ambient temperature, as well as at a combination of the lowest pressure (i.e., 0.7 atm) and 5 °C temperature, are provided in Table 1. PS particles having sizes of 0.8 μm were selected for these tests as with those we observed the largest difference between the Alphasense and the Grimm OPC during the tests conducted at 1.0 atm pressure and at room or reduced temperatures (cf. Sections 4.1 and 4.3). The counting efficiency (data not shown) of all the OPCs was not affected by exposing them to lower than sea level pressures (i.e., down to 0.70 atm.) and temperatures down to 5°C, exhibiting similar performance in tests conducted with particles of the same size at room conditions (cf. Section 4.1). The sizing results of the tests performed at 1.00 atm were very similar to our initial measurements (cf. Section 4.2) demonstrating the good repeatability of the experiments and of the performance of all the OPCs used in this work. When reducing the pressure to 0.85 and 0.70 atm, the sizing performance of both the OPCs (cf. Table 1) remained fairly constant (i.e., standard deviation of the estimated GMDs from all the measurements was lower than 2.5×10^{-3} μm) and within experimental uncertainty. The sizing performance of the instruments remained unaffected also when both the temperature and pressure were reduced to 5°C and 0.70 atm, respectively, as shown in Table 1. A minimum temperature of 5°C was selected in these tests, since below this threshold the sizing accuracy of one of the two Alphasense OPCs was degraded as discussed above.

Table 1. Median values of the GMD determined from the particle size distributions measured by each instrument at different pressures and at room temperature, as well as at 0.70 atm and at 5°C using PS spheres with a nominal size of 0.8 μm. Note that the RH inside the chamber was <35% during the tests carried out at room temperature and under all pressures, while it did not exceed 75% during the 0.70 atm/5°C test.

Pressure	Grimm	Alpha1	Alpha2
1.00 atm	0.63	0.85	0.86
0.85 atm	0.60	0.83	0.85
0.70 atm	0.59	0.84	0.84
Pressure/Temperature			
0.70 atm/5°C	0.62	0.81	0.83

The results provide evidence that at least down to 0.70 atm and at 5°C the sizing accuracy of the Alphasense OPC is not compromised. Evidently, only the temperature and not the pressure was the only reason for degrading the sizing performance of one of the two Alphasense's OPC below 5°C.

4. Conclusions

In this work, we tested the performance of two Alphasense OPCs under a wide range of conditions, which can be encountered within the atmospheric column, in order to assess the possibility of employing them onboard UAVs. The tests were carried out using monodisperse NIST traceable PS spheres having diameters that ranged from 0.8 to 10.2 μm and by employing a Grimm 1.109 OPC as a reference instrument. The measured particle number concentrations of both Alphasense OPCs under room conditions was found to be comparable to that of the reference instrument for particles having sizes of 1 μm and above, exhibiting differences within less than 40%. When using PS particles having a nominal size of 0.8 μm, we observed larger differences (with the Alphasense OPCs overestimating the particle number concentrations by a factor of two or more) under the same conditions. Our results therefore build confidence toward using these lightweight OPCs for measuring the number concentration of coarse particles, but also suggest that the data corresponding to smaller particles should be treated with care. The sizing accuracy of the Alphasense OPCs under room conditions was within experimental uncertainty and within ±5% of the nominal size of the particles used in the tests. Both the counting and sizing performance of the Alphasense OPCs remained unaffected down to 5°C and 0.7 atm. However, one of the two available instruments suffered from a systematic degradation of its sizing accuracy at temperatures below 5°C, most likely due to impurities in its optics system. This highlights the need for testing these systems before any use. During flights where the instruments are expected to be directly influenced by sudden air speed changes, causing sample flow fluctuations, it is also advised to either record the flow rate through the system, or replace the fan driving the sample flow with a well-controlled flow system.

References

Alphasense. (2015). *Alphasense User Manual OPC-N2 Optical Particle Counter*. Chapter 4. Alphasense Ltd.

Alvarado, M., Gonzalez, F., Fletcher, A., and Doshi, A. (2015), Towards the Development of a Low Cost Airborne Sensing System to Monitor Dust Particles after Blasting at Open-Pit Mine Sites. *Sensors*, 15(8):19667–19687. doi:10.3390/s150819667.

Bates, T. S., Quinn, P. K., Johnson, J. E., Corless, A., Brechtel, F. J., Stalin, S. E., Meinig, C., and Burkhart, J. (2013), Measurements of Atmospheric Aerosol Vertical Distributions above Svalbard, Norway, Using Unmanned Aerial Systems (UAS). *Atmos. Meas. Tech.*, 6:2115–2120. doi:10.5194/amt-6-2115-2013.

Barmpounis, K., Maisser, A., Schmidt-Ott, A., and G. Biskos, G. (2016), Lightweight Differential Mobility Analyzers: Towards New and Inexpensive Manufacturing Methods. *Aerosol Sci. Technol.*, 50:ii–v. doi:10.1080/02786826.2015.1130216.

Bezantakos, S., Huang, L., Barmpounis, K., Attoui, M., Schmidt-Ott, A., and Biskos, G. (2015), A Cost-Effective Electrostatic Precipitator for Aerosol Nanoparticle Classification. *Aerosol Sci. Technol.*, 49:iv–vi. doi:10.1080/02786826.2014.1002829.

Burkart, J., Steiner, G., Reischl, G., Moshammer, H., Neuberger, M., and Hitzenberger, R. (2010), Characterizing the Performance of Two Optical Particle Counters (Grimm OPC 1.108 and OPC 1.109) under Urban Aerosol Conditions. *J. Aerosol Sci.*, 41:953–962. doi:10.1016/j.jaerosci.2010.07.007.

Chilinski, M. T., Markowicz, K. M., and Markowicz, J. (2016), Observation of Vertical Variability of Black Carbon Concentration in Lower Troposphere on Campaigns in Poland. *Atmos. Environ.*, 137:155–170. doi:10.1016/j.atmosenv.2016.04.020.

Coleman, T. F., and Li, Y. (1994), On the Convergence of Reflective Newton Methods for Large-Scale Nonlinear Minimization Subject to Bounds. *Math. Program.*, 67:189–224. doi:10.1007/BF01582221.

Coleman, T. F., and Li, Y. (1996), An Interior, Trust Region Approach for Nonlinear Minimization Subject to Bounds. *SIAM J. Optimiz.*, 6:418–445. doi:10.1137/0806023.

Gao, R. S., Telg, H., McLaughlin, R. J., Ciciora, S. J., Watts, L. A., Richardson, M. S., Schwarz, J. P., Perring, A. E., Thornberry, T. D., Rollins, A. W., Markovic, M. Z., Bates, T. S., Johnson, J. E. and Fahey, D. W. (2016), A Light-Weight, High-Sensitivity particle Spectrometer for PM 2.5 Aerosol Measurements. *Aerosol Sci. Tech.*, 50:88–99. doi:10.1080/02786826.2015.1131809.

Heim, M., Mullins, B. J., Umhauer, H., and Kasper, G. (2008), Performance Evaluation of Three Optical Particle Counters with an Efficient "Multimodal" Calibration Method. *J. Aerosol Sci.*, 39:1019–1031. doi:10.1016/j.jaerosci.2008.07.006.

Luijten, C. C. M., van Dongen, M. E. H., and Stormbom, L. E. (1998), Pressure Influence in Capacitive Humidity Measurement. *Sens. Actuators, B.*, 49:279–282. doi:10.1016/S0925-4005(98)00148-8.

Marx, E., and Mulholland, G. (1983), Size and Refractive Index Determination of Single Polystyrene Spheres. *J. Res. Nat. Bur. Stand.*, 88(5):321–338. doi:10.6028/jres.088.016.

McMurry, P. H. (2000), A Review of Atmospheric Aerosol Measurements. *Atmos. Environ.*, 34:1959–1999. doi:10.1016/S1352-2310(99)00455-0.

NIST traceable size standards, Magsphere INC. Accessed July 2017. http://www.magsphere.com/Products/Size-and-Count-Standards/Size-Standards/size-standards.html

Peters, T. M., Ott, D., and O'shaughnessy, P. T. (2006), Comparison of the Grimm 1.108 and 1.109 Portable Aerosol

Spectrometer to the TSI 3321 Aerodynamic Particle Sizer for Dry Particles. *Ann. Occup. Hyg.*, 50(8):843–850.

Sousan, S., Koehler, K., Hallett, L., and Peters, M. T. (2016), Evaluation of the Alphasense Optical Particle Counter (OPC-N2) and the Grimm Portable Aerosol Spectrometer (PAS-1.108). *Aerosol Sci. Tech.*, 50(12):1352–1365. doi:10.1080/02786826.2016.1232859.

Sørensen, L. Y., Jacobsen, L. T., and Hansen, J. P. (2017), Low Cost and Flexible UAV Deployment of Sensors. *Sensors*, 17 (1):154. doi:10.3390/s17010154.

Surawski, N. C., Bezantakos, S., Barmpounis, K., Dallaston, M. C., Schmidt-Ott, A., and Biskos, G. (2017), A Tunable High-Pass Filter for Simple and Inexpensive Size-Segregation of sub-10-nm Nanoparticles. *Sci Rep.*, 7:45678. doi:10.1038/srep45678.

Villa, T. F., Gonzalez, F., Miljievic, B., Ristovski, Z. D., and Morawska, L. (2016). An Overview of Small Unmanned Aerial Vehicles for Air Quality Measurements: Present Applications and Future Prospectives. *Sensors*, 16(7):1072. doi:10.3390/s16071072.

WMO/GAW Aerosol Measurement Procedures, Guidelines and Recommendations. (2016), 2nd Edition, Chapter 2, Chairperson, Publications Board World Meteorological Organization (WMO), Geneva, Switzerland.

Wilcox, E. M., Thomas, R. M., Praveen, P. S., Pistone, K., Bender, F. A. M., and Ramanathan, V. (2016), Black Carbon Solar Absorption Suppresses Turbulence in the Atmospheric Boundary Layer. *Proc. Natl Acad. Sci.*, 113 (42):11794–11799. doi:10.1073/pnas.1525746113.

Yu, F., Liu, Y., Fan, L., Li, L., Han, Y., and Chen, G. (2017), Design and Implementation of Atmospheric Multi-Parameter Sensor for UAV-based Aerosol Distribution Detection. *Sensor Rev.*, 37(2):196–210 doi:10.1108/SR-09-2016-0199.