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# Characterizing the performance of two optical particle counters (Grimm OPC1.108 and OPC1.109) under urban aerosol conditions

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ABSTRACT

The performance of Grimm optical particle counters (OPC, models 1.108 and 1.109) was characterized under urban aerosol conditions. Number concentrations were well correlated. The different lower cut-off diameters (0.25 and 0.3 μm) give an average difference of 23.5%. Both detect less than 10% of the total particle concentration (0.01–1 μm; Differential Mobility Analyzer), but in the respective size ranges, differences are $<10\%$. OPC number size distributions were converted to mass concentrations using instrument-specific factors given by the manufacturer. Mass concentrations for OPC1.108 were 60% higher than for OPC1.109 and (in case of OPC1.109) much lower than those measured with an impactor in the relevant size range or a TSP filter. Using the C-factor correction suggested by the manufacturer, OPC1.109 underestimated mass concentrations by 21% (impactor) and by about 36% (TSP filter), which is in the range of comparability of co-located different mass concentration methods (Hitzenberger, Berner, Maenhaut, Cafmeyer, Schwarz, & Mueller et al., 2004).



## 1. Introduction

Adverse health effects of aerosol particles have been recognized for several decades (see the review by Anderson, 2009; or e.g. Samoli, Analitis, Touloumi, Schwartz, Anderson, & Sunyer et al., 2005; Dockery & Pope, 1994; Schwartz & Marcus, 1990). In order to protect public health, standards were introduced, which are set in terms of mass concentration. In the EU, current standards are for PM10 (total mass concentration of particles smaller than 10 μm) and PM2.5 (total mass concentration of particles smaller than 2.5 μm) (Air Quality Directives 1999/30/EC and 2008/50/EC). Real-time PM data are needed, but as the standard methods rely on filter samples (reference method EN12341), on-line instruments are used for PM monitoring, and data are later validated with the reference method.

Monitoring networks often use online instruments such as Tapered Element Oscillating Microbalances (TEOMs; Patashnick & Rupprecht, 1980) or $\beta$-attenuation monitors (e.g. Willeke & Baron, 1993). In both cases, however, calibration, temperature and humidity issues have to be taken into account (e.g. Allen, Sioutas, Koutrakis, Reiss, Lurmann, & Roberts, 1997; Hauck, Berner, Gomiscek, Stopper, Puxbaum, & Kundi et al., 2004).

Although PM10 or PM2.5 is the current standard, alternative metrics have been proposed for health protection issues. Studies indicate that "ultrafine" particles (with sizes below 1 μm or 100 nm, depending on the definition) cause most of the observed health effects (e.g. Pope & Dockery, 2006; Brugge, Durant, & Rioux, 2007, or the review by Davidson, Phalen, & Solomon, 2005). As the number size distributions of urban aerosols typically peak in the size range around or below

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100 nm, one such metric could be the total number concentration, the particle size distribution or, more easily measured, PM1 (i.e. mass concentration of particles with sizes below 1 μm). The instruments currently available for measuring total number concentration (condensation particle counters (CPC)) or number size distribution in the relevant size range (10 nm–1 μm; Differential Mobility Analyzers, DMA), however, require rather frequent maintenance by specialized personnel, and are therefore not yet suited for long-term stand-alone monitoring.

Optical particle counters (OPCs) seem to be an attractive alternative. They are easy to use and can be run without supervision for long time spans. The lower size cut, however, is limited to $>100$ nm optical equivalent diameter, so they can access only part of the relevant size range for ultrafine particles, and their calibration depends on the refractive index, particle shape and mixing type of the sampled aerosol. If a relation between the number concentration in the size range of an OPC and the total number concentration at a certain site could be found, OPCs might also provide a rough (order-of-magnitude) estimate of the total number concentration. As most of the total mass concentration, however, is due to particles $>100$ nm, OPCs could be used to measure PM (10, 2.5 or 1, depending on the size cuts of the OPC's channels), if the average aerosol bulk density is known. An example of calibrating an OPC for a specific test dust and using this OPC to measure PM mass concentrations is given by Binnig, Meyer, & Kasper (2007).

The two Grimm OPCs (models 1.108 and 1.109) used in our study were developed originally for indoor air quality monitoring, filter efficiency tests, inhalation studies and the measurement of oil droplets, but especially model 1.109 is suggested also for use as an aerosol monitor for general application, and has been extended to the Grimm Environmental Dust Monitor EDM180, which is certified for continuous PM (2.5 and 10) measurements and is used in monitoring networks.

The performance of the OPCs characterized in our study was already evaluated before for specific test aerosols (Peters, Ott, & O'Shaughnessy, 2006; Heim, Mullins, Umhauer, & Kasper, 2008) and another OPC (model 1.107 which is identical to the monitor EDM170) by Grimm and Eatough (2009) also under urban aerosol conditions. Peters et al. (2006) compared the performance of OPC1.108 and OPC1.109 to an aerodynamic particle sizer (TSI, Inc.,St. Paul, MN, USA) when measuring number and mass concentration of monodisperse (polystyrene latex spheres) and polydisperse (Arizona test dust) aerosols. In the study by Heim et al. (2008), the sizing accuracy and the counting efficiency of OPC1.109 was tested with a specific "multimodal" calibration method, using a polydisperse oil aerosol (di-ethyl-hexyl-sebacate particles) in comparison to the usual polystyrene latex calibration method.

So far our study is the first to carefully examine the performance and the comparability of OPC1.108 and OPC1.109 under urban aerosol conditions, as only OPC1.107 was tested for ambient aerosols (Grimm & Eatough, 2009). OPC1.107 is similar to OPC1.109, but adapted for US PM standards and has a laser wavelength of 675 nm (instead of 655 nm). In their study, the results of OPC1.107 were compared to the results of standard methods for mass concentration measurements such as a TEOM and a Rupprecht and Patashnick Co. filter dynamic measurement system (FMDS) in two cities in California, US. The "Grimm protocols" as used with OPC1.107 in this study for the conversion of the particle size distribution to a mass distribution are based on several comparisons between the data obtained by Grimm monitors and the data obtained by the official US monitoring network. The data compared by Grimm and Eatough (2009) showed good agreement, e.g. linear regression of the Grimm vs. the FDMS data in Rubidoux yielded a slope of $1.10 \pm 0.05$ with an intercept of $-3.9 \pm 4.2$ μg/m$^3$. The uncertainty was 9.9%.

The goal of our present study was to test the two commercially available OPCs, manufactured by Grimm Aerosol Technik GmbH (models 1.108 and 1.109), for suitability as ambient PM monitors, both in terms of particle number concentration and PM mass concentration. The instruments were tested for inter-comparability, the accuracy of the number concentration in their respective size ranges and their suitability to measure PM mass concentrations. A comparison of the number concentrations obtained by the OPCs to the total number concentration is also given.

## 2. Experimental section

### 2.1. Site description and instrument set-up

The measurements were performed at the urban aerosol measurement station of the University of Vienna in two periods. The comparability of the two OPCs was tested in the first period (November 30, 2008–January 7, 2009). During that time, aerosol number size distributions and total particle number concentrations were also measured. In the second period (November 24, 2009–January 26, 2010), PM concentrations obtained with OPC1.109 were compared to mass concentrations measured with a Berner 7-stage low-pressure impactor and an open-face filter sampler measuring total suspended particles (TSP)

The station is situated in downtown Vienna (population 1.8 million) in the roof laboratory of the Physics building, approximately 35 m above ground level. Direct influence from traffic emissions can be excluded as the site is separated from the nearest road (distance approximately 100 m) by interconnected buildings and courtyards. As the surrounding buildings are heated with district heating or natural gas, there are no other single large aerosol sources close to the station. The sampled aerosol is well mixed and can be classified as urban background aerosol. The weather situation in both periods was characterized by typical late autumn and winter conditions. Temperatures and relative humidities ranged $-7.1$ to 11.9 °C and 48–97%, respectively, during the first period and $-12.2$ to 15.8 °C and 49–99% during the second

period. The meteorological data were kindly provided by the Austrian Central Institute for Meteorology and Geodynamics, ZAMG.

During the first period, the OPCs were placed inside the laboratory close to a window and were connected with a *Y*-piece to a common sampling tube drawing in atmospheric aerosol with a flow rate of 1.2 L/min. They were set to record one data set every minute. In addition a Vienna-type DMA linked to TSI condensation nuclei counter (CPC; model 3760A) performed a scan of the number size distribution of the atmospheric aerosol every 10 min.

During the second measurement period, only OPC1.109 was available, which was set to record one data set every 5 min. The Berner low-pressure impactor was mounted outside the laboratory with its inlet right beside the inlet tube for the OPC and the TSP filter, which was placed upside down. Twenty 24-hr impactor and filter samples were collected. Aluminium foils were used as sampling substrates in the impactor, and quartz fibre filters (Pallflex tissue quartz 2500QAT-UP, 47 mm) were used as TSP filters. All sampling substrates were weighed before and after loading on a Mettler ME3 microbalance (precision $\pm 0.5$, reproducibility $\pm 3$ μg) after at least 24 h of acclimatisation to laboratory conditions (typical temperature: 22 °C, typical relative humidity: 20%)

### 2.2. Instruments

Both OPCs used in this study were produced by Grimm Aerosol Technik GmbH & Co. KG, Ainring, Germany. Both models (1.108 and 1.109) detect scattered laser-light at a mean scattering angle of 90° with a parabolic mirror (120°) on one side and another one (18°) on the opposing side (for further information, see Heim et al., 2008) and classify electronic pulse heights to obtain a size spectrum (for more information on OPCs, see e.g. Szymanski, Nagy, & Czitrovszky, 2009). The main differences between the two instruments are the numbers of size channels and the laser wavelengths. Model 1.108 has 15 size channels in the range 0.3–20 μm, while model 1.109 has 31 size channels in the range 0.25–32 μm (all sizes given as optical equivalent diameters). The laser wavelength is 780 nm for OPC1.108 and 655 nm for OPC1.109.

The Vienna-type differential mobility analyzer (DMA, Winklmayr, Reischl, Lindner, & Berner, 1991) classifies particles according to their mobility equivalent diameter and was operated in a closed-loop arrangement (e.g. Jokinen & Mäkelä, 1997). The DMA used in this study is equivalent to the one described in detail by Giebl, Berner, Reischl, Puxbaum, Kasper-Giebl, & Hitzenberger (2002) with differences only in the specific settings: the sheath air flow rate was set to 7.5 L/min and the aerosol flow rate to 1.5 L/min. The aerosol size distribution was scanned in 87 logarithmically equidistant steps from 10.12 to 925.84 nm within 10 min.

The impactor was a 7-stage Berner low-pressure impactor operated at a flow rate of 70 L/min with stage lower cut sizes (aerodynamic equivalent diameter) of 0.1, 0.212, 0.464, 1, 2.12, 4.64 and 10 μm. The last stage serves only as a pre-precipitator for large particles and is not analyzed. For the comparison with the OPC, however, only the appropriate size range (0.212–10 μm) was considered.

## 3. Results and discussion

### 3.1. Comparison of the measured particle concentrations

The particle concentrations measured by OPC1.109 and OPC1.108 were compared for two cases. First, simply the particle concentration reported by OPC1.108 and OPC1.109 in the respective size ranges was considered regardless of the differences in the cut-off diameters of the OPCs.

In Fig. 1, the particle concentration measured by OPC1.108 is plotted versus the concentration measured by OPC1.109. It can be seen clearly that the particle concentration obtained by OPC1.108 is 23.5% lower than the one measured by OPC1.109. This result is not surprising when considering that OPC1.109 detects particles over a much larger size range than OPC1.108 (0.25–32 μm for OPC1.109 and 0.3–20 μm for OPC1.108).

The differences between the OPCs in terms of size range and response curves depend strongly on the characteristics of the aerosol (e.g. size distribution and refractive index). Some indication of this dependence is seen in Fig. 1, where the data points are not arranged completely randomly, but fall along distinct lines. These lines contain consecutively sampled data from time periods spanning from several hours to several days with fairly stable meteorological and aerosol conditions.

Fig. 2 shows examples of typical number size distributions measured with the DMA during the measurement period. The solid black line indicates the lower cut-off diameter of OPC1.108, while the dashed line represents the lower cut-off diameter of OPC1.109. There is a considerable negative slope of the number size distribution between the cut sizes of OPC1.109 and OPC1.108, which explains the differences in the particle concentrations measured by the OPCs. In all cases, the maximum of the number size distribution (in terms of the count mean diameter) is well below 250 nm and the particle concentration decreases rapidly with increasing particle size. The OPCs can therefore detect only a fraction of the total particle concentration. The difference in the OPCs' upper cut-off diameters can be neglected as hardly any particles larger than 20 μm can be found at our sampling site (35 m above ground).

In a second step, as illustrated in Fig. 3, only the size channels of OPC1.109 with sizes above 0.3 μm were considered so that both OPCs had the same nominal lower cut-off diameter. We observed that under these conditions, OPC1.108 detects a higher particle concentration than OPC1.109. This is true especially during times with high particle concentrations. On an

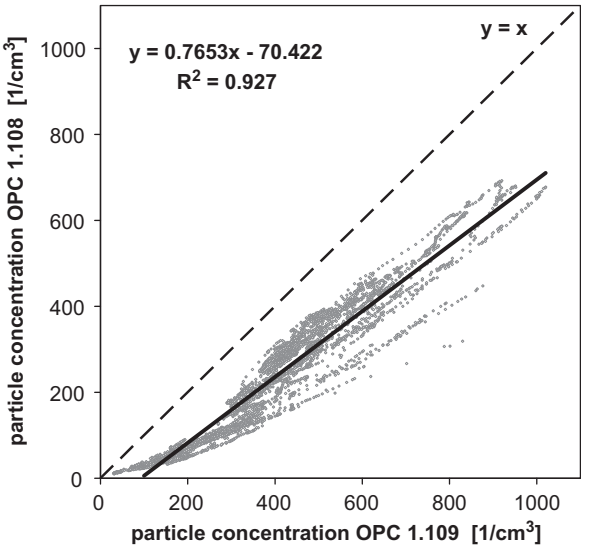


**Fig. 1.** Particle concentration measured by OPC1.108 ( $>0.3$ μm) vs. particle concentration measured by OPC1.109 ( $>0.25$ μm). The difference in the lower cut-off diameters is disregarded and leads to a considerable difference ($\sim$23%) in detected particle concentrations.

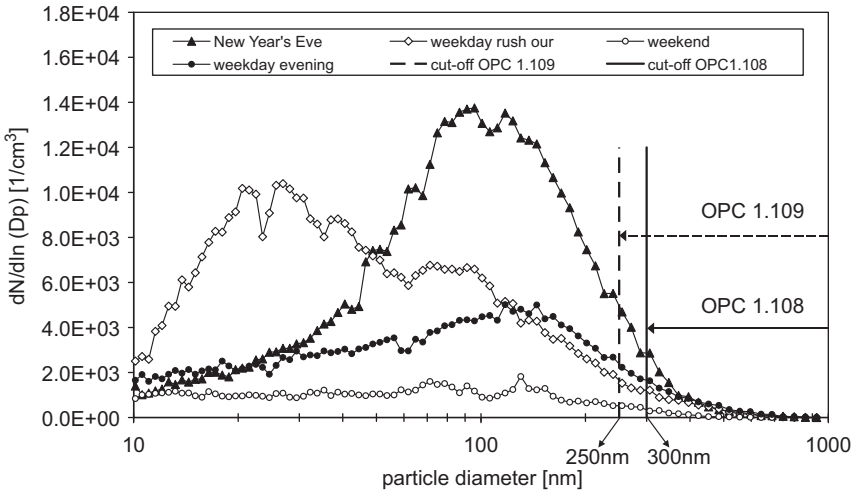


**Fig. 2.** Typical number size distributions on characteristic days and times, obtained by the DMA, during the first measurement period. The New Year's Eve size distribution is very unusual and found only during the hours of the fireworks. The maximum of all the size distributions is well below both lower detection limits of the OPCs (dashed and solid vertical lines).

average, OPC1.108 detects 18% more particles larger than 0.3 μm than OPC1.109. This discrepancy between the instruments might be due to the variable aerosol composition (resulting e.g. in a variable refractive index) and the consequently different response of the instruments as they operate at different laser wavelengths as well as to possible coincidence errors at high particle concentrations. Fig. 4 shows the ratio of concentrations measured by OPC1.109 to those measured by OPC1.108 for particles larger than 0.3 μm versus the concentrations measured by OPC1.109 for its entire size range. At low concentrations, this ratio is $>1$, but at concentrations around 300/cm$^3$ OPC1.109 measures fewer particles $>0.3$ μm than OPC1.108, although the manufacturer's specification indicates that coincidence errors should not occur if concentrations are $<2000$/cm$^3$.

The number concentrations obtained with the OPCs were also compared to total number concentrations and number concentrations measured with the DMA in the size range of the OPCs. The size distribution obtained by the DMA was integrated starting from 250 nm upwards (size range of OPC1.109) and from 300 nm upwards (OPC1.108) and compared to the concentrations measured with the OPCs (see Figs. 5 and 6). The particle concentrations measured by OPC1.108 are 9% higher than those obtained by the DMA, while the particle concentrations detected by OPC1.109 are 8% lower than those obtained by an integration of the DMA size distribution in the respective size ranges. A conversion between electrical

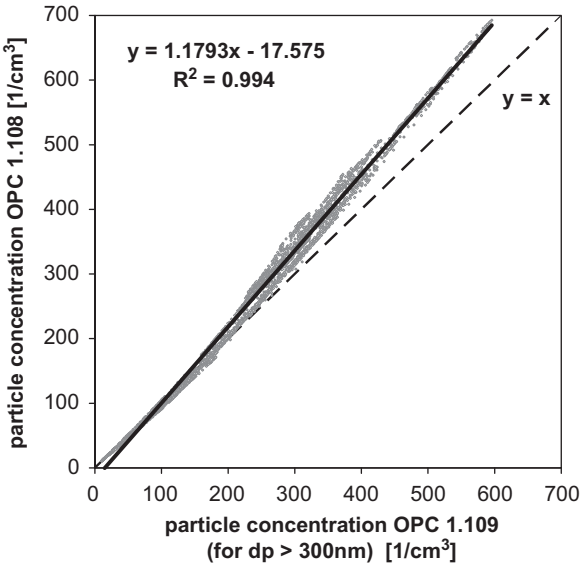


**Fig. 3.** Comparison of the particle concentrations measured by OPC1.108 and OPC1.109 (for $d_p > 0.3$ μm). Only particles larger than 0.3 μm are considered so that the nominal lower cut-off limits are the same.

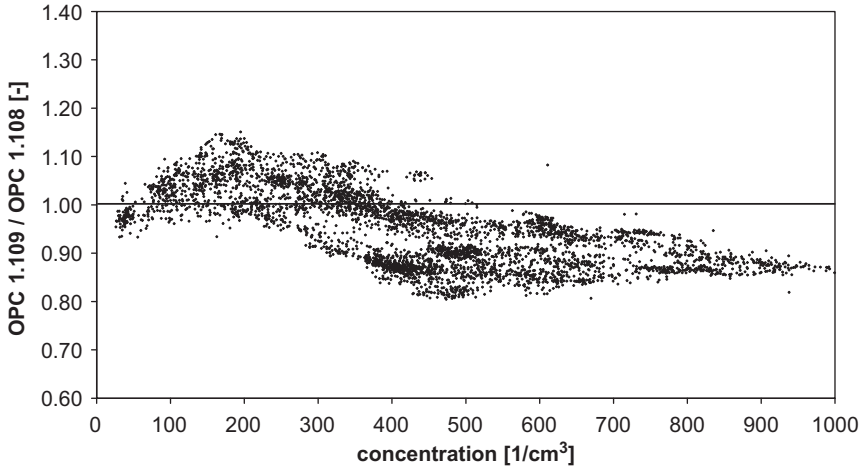


**Fig. 4.** Ratio of number concentrations measured by OPC1.109 and 1.108 (for $d_p > 300$ nm) vs. concentration measured by OPC1.109 over its entire size range.

mobility diameters and optical equivalent diameters was not performed as the necessary background information was not available (e.g. form factor, refractive index of the aerosol).

We also integrated the size distributions measured by the DMA over the entire size range to obtain total particle concentrations and compared them to the concentrations provided by the OPCs. Fig. 7 shows the results for OPC1.109. As expected from the number size distributions, both OPCs measure only a small fraction of the total particle concentration. For OPC1.109, the fraction is $(5.7 \pm 1.9)$%, and the variation is quite high (around 30%). OPC1.108 detects only $(3.6 \pm 1.5)$% of the total particle concentration and the variation is even higher (40%). Because of the large variation, OPCs should not be used to determine even a rough estimate of total particle number concentrations.

### 3.2. Comparison of the mass concentrations

The Grimm OPCs can be either run in the particle count mode or in the mass concentration mode. In this mode, the instrument reading should be equivalent to the total particle mass concentration for particles with diameters in the respective size ranges. In the mass concentration mode, conversion of number to mass concentration is performed using instrument-specific factors by the internal software of the instrument (see below). The instruments, however, are also equipped with a small filter in their exhaust line. If needed, the filter can be weighed before and after sampling to adjust

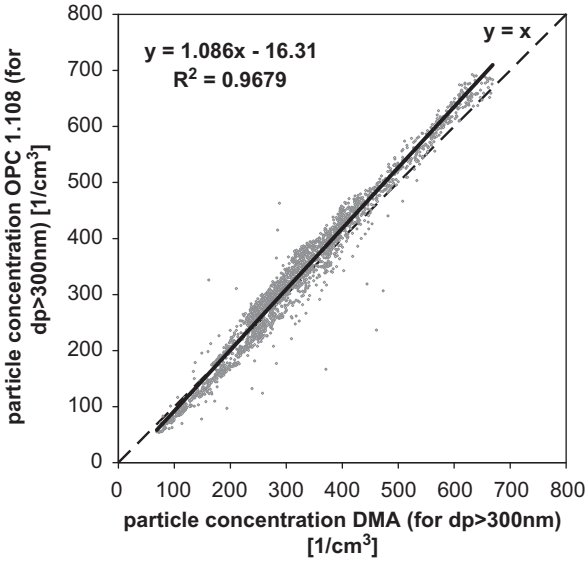


**Fig. 5.** Comparison of the particle concentrations measured by OPC1.108 and the DMA. Only particles larger than 0.3 μm are considered so that the nominal lower cut-off limits are the same.

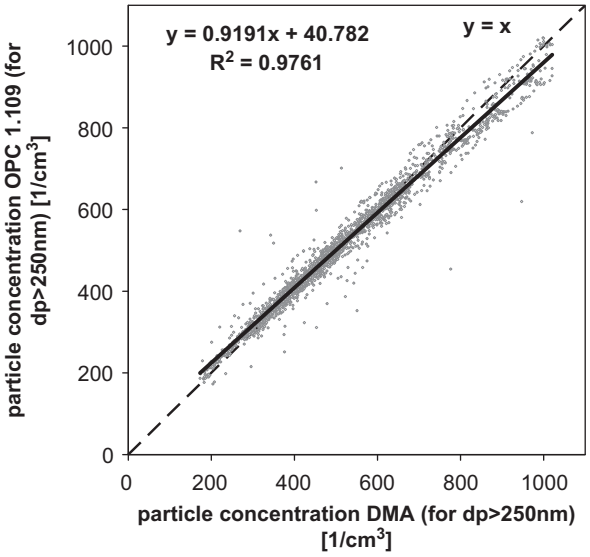


**Fig. 6.** Comparison of the particle concentrations measured by OPC1.109 and the DMA (for $d_p > 0.25$ μm). Only particles larger than 0.25 μm are considered so that the nominal lower cut-off limits are the same.

the instrument-specific factor for the actual bulk density of the aerosol at the sampling site via a correction factor, the "C-factor". For all our experiments, the particle count mode was used. Mass concentrations were calculated from the number size distributions using the instrument-specific factors (2.8 for OPC1.108 and 1.65 for OPC1.109 provided by Grimm GmbH; Schneider, personal communication), which have been obtained from earlier calibration measurements with polystyrene-latex aerosols and include particle density as well as a correction for the complex refractive index of other aerosols. Using the instrument-specific factors for the calculation of the mass concentrations, the results roughly correspond to those obtained when the instruments are run in the mass concentration mode with a C-factor of 1. The only difference is that when the instruments are run in the mass mode, an additional virtual size channel is added by extrapolation of the size distribution, so both instruments have a nominal lower size limit of 0.22 μm.

Fig. 8 gives the comparison of the mass concentrations obtained from OPC1.108 and OPC1.109, using the instrument-specific factors without considering the different cut-off diameters. Even though OPC1.109 detects higher particle number concentrations, it underestimates the mass concentrations by about 60% compared to OPC1.108, which is due to the different instrument-specific factors and possibly also to the different size resolutions of the instruments.

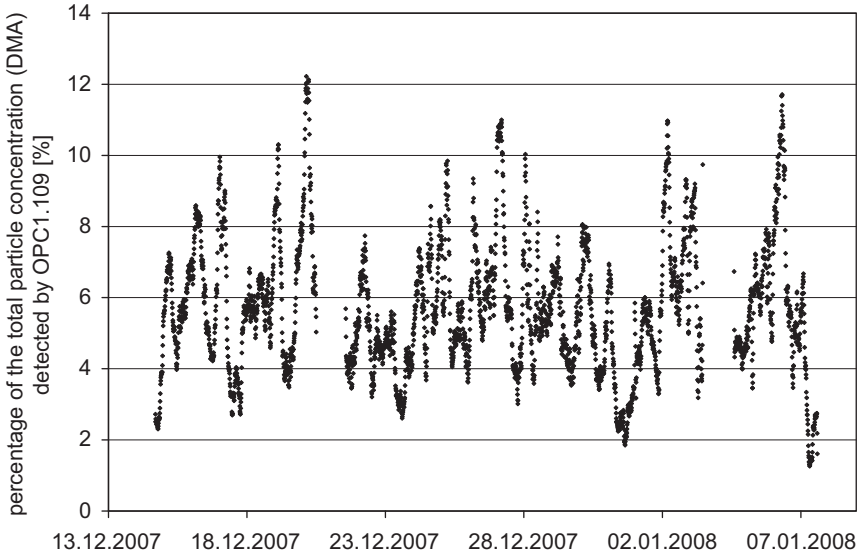


**Fig. 7.** Percentage of particles measured by OPC1.109 of the total particle concentration measured by the DMA. On an average OPC1.109 detects 5.7% of the total particle concentration obtained by the DMA. For OPC1.108 (not plotted here), values are even lower (3.6%).

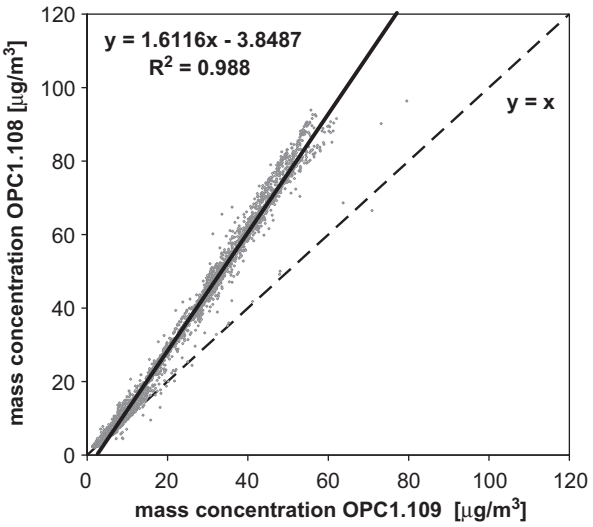


**Fig. 8.** Comparison of the mass concentrations measured by the OPCs, using the instrument-specific factors provided by the manufacturer. The discrepancy between the instruments is rather large (~60%) and cannot be explained by the difference in the lower and upper cut-off diameters.

As the assumed aerosol bulk density strongly influences calculations of mass concentrations from number concentrations, the density of the Vienna aerosol was calculated based on size segregated chemical composition measured in February and March 2004 (Hitzenberger, Tursic, Grgic, Berner, Ctyroky, & Podkrajsek, 2006) and found to be 1.38 g/cm$^3$ in the relevant size range. When calculating the mass concentrations based on this density, the mass concentrations detected by OPC1.109 are about 6% higher than the ones detected by OPC1.108, which reflects the difference in the measured number concentrations.

In the second part of the study, the mass concentrations obtained by OPC1.109 were compared to those obtained in the relevant size range (0.212–10 μm) of the Berner impactor (Fig. 9) and the TSP filter (Fig. 10). For these measurements, the C-factor correction was also performed (see above). The C-factor was found to be 1.22, which is similar to the ratio of the instrument-specific factor to the calculated bulk density. It can be seen that with the C-factor correction, the mass is underestimated by the OPC by 21% when compared to the impactor measurements ($r^2$=0.86). Part of this underestimation could be attributed to the slightly different lower size cuts of the OPC (0.25 μm) and the impactor (0.21 μm). An estimate based on the DMA data obtained during the first measurement period showed that this might account for about seven percentage points of the underestimation. As all these instruments, however, classify particles according to different

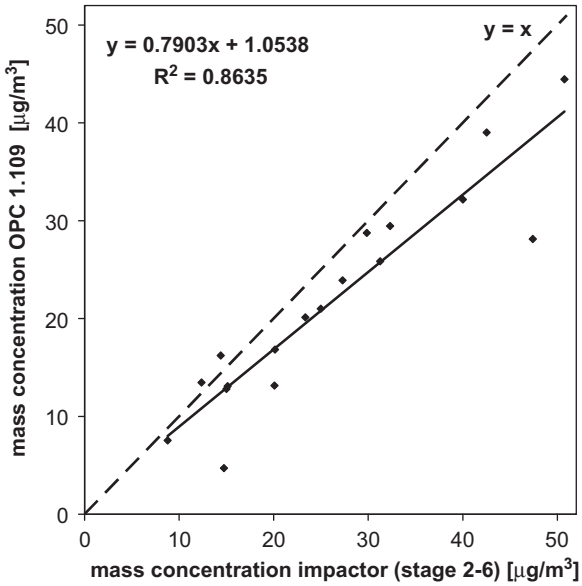


**Fig. 9.** Comparison of the mass concentrations measured by OPC1.109 (including C-factor correction) and the impactor in the relevant size range. The mass concentrations detected by the OPC1.109 are on an average about 21% lower than those obtained by the impactor.

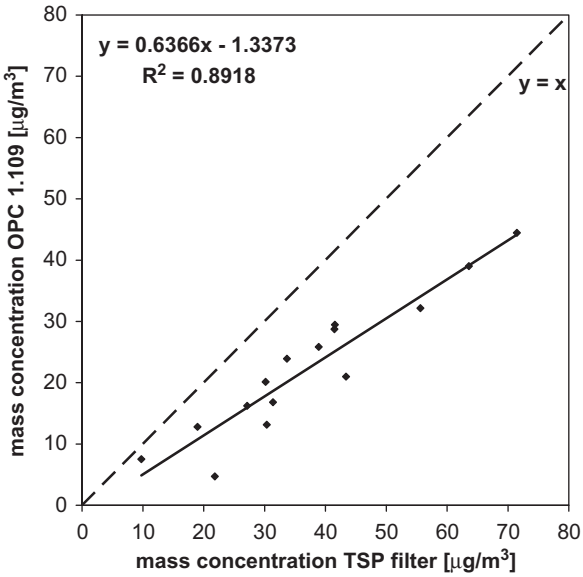


**Fig. 10.** Comparison of the mass concentrations measured by the OPC1.109 (including the C-factor correction) and the TSP filter. The mass concentrations is about 36% higher, which is not surprising as the filter collects total suspended particulate mass, while the OPC has lower and upper cut-off diameters (0.25 and 30 μm, respectively).

equivalent diameters, discrepancies in mass concentrations are to be expected. As no information is available on chemical composition and particle shape, no analysis of the differences between mass concentrations measured with the impactor and obtained from the OPC is possible.

Compared to the TSP filter measurements, which collect all particles without any size cut (Fig. 10), the mass concentration is underestimated by OPC1.109 by about 36% ($r^2$=0.89). It has to be pointed out though that this underestimation is much larger without the C-factor correction, when the OPC underestimates the mass concentration by 33% compared to the impactor measurements and by 46% compared to the TSP filter measurements. The differences between mass concentrations measured with the (C-factor corrected) OPC1.109 and the impactor are in the range found for co-located instruments at an earlier field study (Hitzenberger et al., 2004).

For non co-located measurements, differences can be much larger. As an example, a comparison of the mass concentrations measured at our background station were compared to PM10 concentrations obtained by the official

Viennese monitoring network during the second measurement period. These concentrations had been measured with a $\beta$-attenuation monitor (Eberline FH 62 I/R) according to EN12341 at the monitoring station (Währinger Gürtel) closest to our sampling site, which, however, is a kerbside station near an eight-lane road with high traffic density. The mass concentrations measured with the TSP filters at our roof sampling station (urban background) are highly correlated ($r^2$=0.95), but about 20% lower, and the mass concentrations detected by OPC1.109 (C-factor corrected) are about 47% lower ($r^2$=0.9), again reflecting the difference between both size cuts and station type.

## 4. Summary and conclusions

In this study, the performance of two optical particle counters, Grimm OPC1.108 and 1.109, was compared and characterized for urban background aerosols. The ability of the optical particle counters to estimate specific properties of the atmospheric aerosol, such as number and mass concentrations, was investigated. The data obtained by both OPCs were compared to the data obtained by other instruments, such as a Vienna-type DMA (particle concentration), a seven stage Berner impactor (mass concentrations in the relevant size range) and a TSP filter (total mass concentrations).

In terms of particle number concentration, the results obtained by the OPCs are fairly similar and compare favourably to the DMA data if the different lower cut-off diameters of the instruments are taken into account (OPC1.108 detects 9% higher, OPC1.109 8% lower particle concentrations than the DMA). If the total particle concentration is considered, however, we find that the OPCs detect on an average only 6% of the total particle concentration of the atmospheric aerosol. This is not surprising and due to the nature of the atmospheric aerosol number size distributions (maximum well below the detection limit of the OPCs). Because of the large variation of the data (30% for OPC1.109 and 40% for OPC1.108), the OPCs are not suitable for estimating the total number concentration of the atmospheric aerosol.

If the OPCs are used for PM measurements, the C-factor correction should certainly be performed for the specific type of aerosol at the site. When comparing mass concentrations, significant discrepancies between the OPCs emerge without the C-factor correction. In this case, OPC1.108 yields mass concentrations on an average about 60% higher than OPC1.109. Comparisons of OPC1.109 to an impactor and TSP filter measurements reveal that in both cases the mass is severely underestimated by the (uncorrected) OPC1.109. In case of the impactor, the underestimation in the relevant size range (0.212–10 μm) is 33%, in case of the TSP filter the underestimation is as high as 46%. If the C-factor correction is performed for OPC1.109, the underestimation is reduced to 36% in case of the TSP filter and to 21% in case of the impactor, which lies roughly in the range of differences expected for co-located mass concentrations measurements performed with instruments operating on both similar and different physical principles (Hitzenberger et al., 2004).

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