# EURAMET Project 1027

# Comparison of nanoparticle number concentration and size distribution

*report of results, V2.0*

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# Description and goal

The experimental work for EURAMET Project 1027 "Comparison of nanoparticle number concentration and size distribution" was hosted on 27 and 28 November 2008 at the Federal Office of Metrology METAS, Switzerland.

The particle number concentration and size distribution in a neutral combustion aerosol were measured with two types of instruments. First, the number concentration was measured with particle counters that do not evaluate the particle size (e.g. CPC = condensation particle counter). Second, the particle size distribution was measured through the combination of a particle size classifier and a particle counter (e.g. SMPS = scanning mobility particle sizer, ELPI = electrical low pressure impactor).

Particle size distributions can be characterized by the (total) particle number concentration and the geometric mean size. However, this analysis depends on instrumental parameters as well as on algorithms incorporated in the manufacturer's software. Thus, the separate comparison of simple number concentration allows the participants a direct comparison of their particle counters.

The comparison used continuously generated combustion aerosol in the size range 50 to 170 nanometres (nm), with number concentrations in the range 1 000 to 1 000 000 particles per millilitre of air ($cm^{-3}$). A typical measurement with constant aerosol generation lasted 30 minutes.

The reported measurements of the comparison were:

Average particle number concentrations at several points between $10^3$ and $10^6$ $cm^{-3}$. The results are referred to actual ambient conditions (22 °C and 950 hPa).

Average particle size at several points between 50 nm and 170 nm. The size is defined separately as the geometric mean or mode of the size distribution, and corresponds to the diameter of a sphere having the equivalent electrical mobility diameter.

Degrees of equivalence (DoE) were calculated for these quantities.

# Participants

Participation in this comparison was open to metrology institutes and designated institutes in this field (according to CIPM MRA – Appendix A).

There were three categories of instruments involved in the comparison: those measuring particle size distributions (particle sizers); those measuring particle number concentration without any size information (particle counters); and imaging instruments providing supplementary size information.

Table 1 Participating institutes and instrumentation grouped in following categories: particle sizers (first group), particle counters (second group), and imaging instruments (third group)

| Institute | Person during experiment | Instrument | Measurand |
|---|---|---|---|
| FORCE Technology, DK | Karsten Fuglsang | ELPI | aerodynamic diameter distribution |
| METAS, CH | Jürg Schlatter | SMPS | electrical mobility diameter distribution |
| NPL, UK | Jordan Tompkins, Richard Gilham | SMPS | electrical mobility diameter distribution |
| UBA, DE | Klaus Wirtz | SMPS | electrical mobility diameter distribution |
| AIST, JP | Hiromu Sakurai | CPC | number concentration |
| METAS, CH | Jürg Schlatter | Diluter and CPC | number concentration |
| METAS, CH | Jürg Schlatter | CPC | number concentration |
| NPL, UK | Jordan Tompkins, Richard Gilham | CPC | number concentration |
| UBA, DE | Klaus Wirtz | CPC | number concentration |
| DFM, DK | (Kai Dirscherl) | Atomic Force Microscope | geometric size |

SMPS: Scanning mobility particle sizer
CPC: Condensation particle counter (as independent instrument or an element of SMPS)
ELPI: Electrical low pressure impactor

# Measurement procedure

## Schedule

### *Setup with testing: Wednesday 26 November 2008*

The instruments were installed and tested. A test combustion aerosol was provided by METAS. The necessary calibrations and adjustments of the components were executed.

### *Comparison Measurements: Thursday and Friday 27 and 28 November 2008*

The measurements consisted of a series of 14 measuring points with a “natural” particle size distribution ($\sigma_g$ ≈ 1.6) and a series of 6 measuring points with a “monodisperse” particle size distribution ($\sigma_g$ ≈ 1.1). The aerosol was prepared and fed to the instruments for 30 minutes for each size/concentration combination. All the relevant concentrations at a specific particle size distribution were supplied before changing the size distribution. The general schedule is shown in Figure 1, with the full schedule shown in Table 2.

### *Dismantling: Friday 28 November 2008*

The Instruments were dismantled at the second day just after the final measurements.

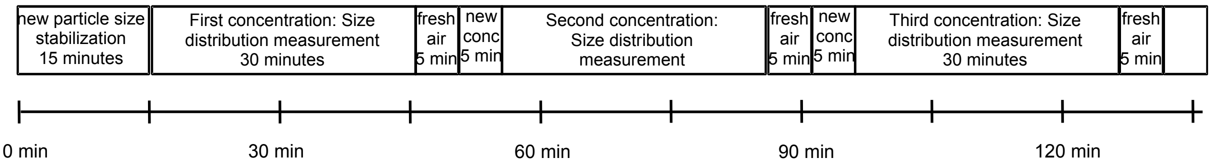



Figure 1 Measurement schedule for one particle size with three number concentrations.

Table 2 Full measurement schedule.

| Date | Run | Nominal geo. Mean $d_g$ [nm] | $\sigma_g$ | Ambient pressure [hPa] | Time frame for the measuring point with $10^3$ $cm^{-3}$ | Time frame for the measuring point with $10^4$ $cm^{-3}$ | Time frame for the measuring point with $10^5$ $cm^{-3}$ | Time frame for the measuring point with $10^6$ $cm^{-3}$ |
|---|---|---|---|---|---|---|---|---|
| 27.11.2008 | A | 100 | 1.6 | 959 | 9:00 to 9:30 | 9:40 to 10:10 | 10:20 to 10:50 | 11:00 to 11:30 |
| 27.11.2008 | B | 140 | 1.6 | 957 | 13:00 to 13:30 | 13:41 to 14:11 | 14:20 to 14:50 | - |
| 27.11.2008 | C | 170 | 1.6 | 955 | 15:37 to 16:08 | 16:49 to 17:20 | 17:30 to 18:00 | - |
| 28.11.2008 | D | 70 | 1.6 | 943 | 8:15 to 8:45 | 8:55 to 9:25 | 9:35 to 10:05 | 10:15 to 10:45 |
| 28.11.2008 | E | 70 | 1.1 | 940 | 11:40 to 12:10 | 12:15 to 12:45 | - | - |
| 28.11.2008 | F | 50 | 1.1 | 937 | 13:45 to 14:16 | 14:20 to 14:50 | - | - |
| 28.11.2008 | G | 180 | 1.1 | 936 | 15:15 to 15:45 | 15:50 to 16:20 | - | - |

## Technical infrastructure

For the generation of “natural” and “monodisperse” particle distributions two types of setup were necessary (Figure 2). The "monodisperse" particle size distribution is not actually monodisperse, it contains also larger particles. When particles of a certain electrical mobility are selected by a DMA, the selection also contains double charged particles with larger diameter (Figure 3).

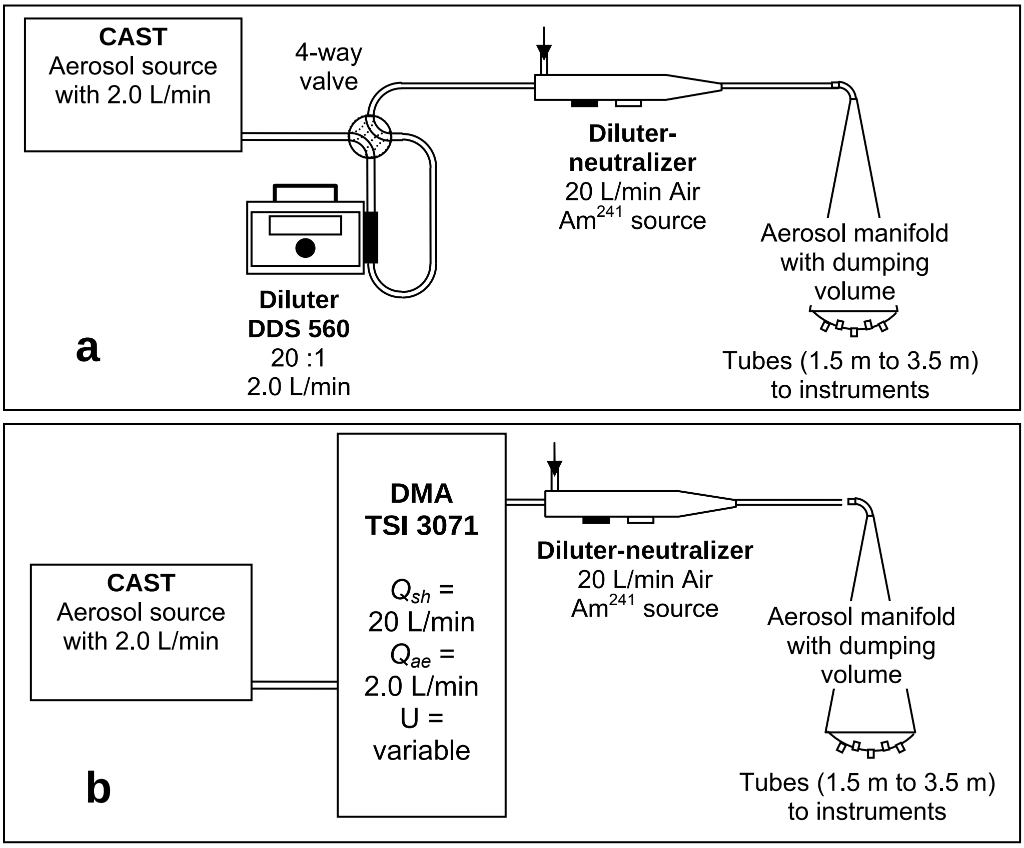



Figure 2 a: Setup for the combustion aerosol with a "natural" size distribution ($\sigma_g \approx 1.6$).
b: Setup for the combustion aerosol with a “monodisperse” size distribution ($\sigma_g \approx 1.1$)
DMA – differential mobility analyser.

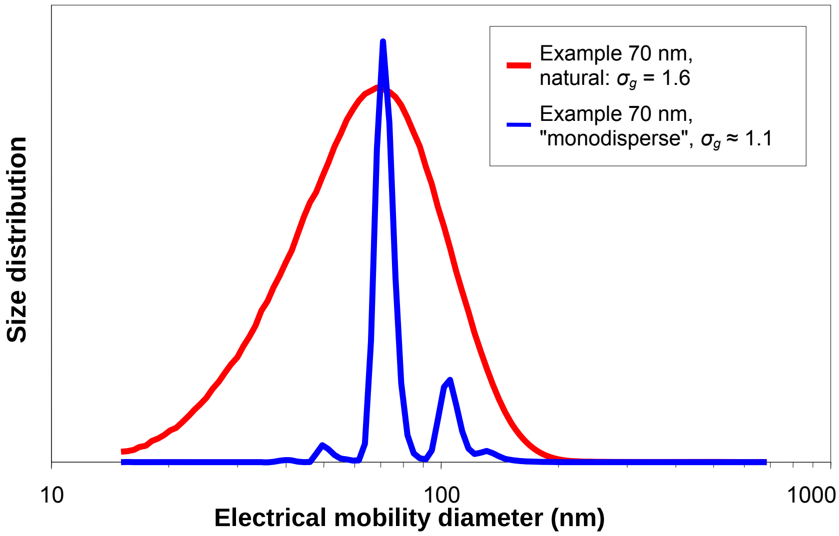



Figure 3 Examples of “natural” and the “monodisperse” size distributions.

The distance between the generator and the measuring instruments was minimized (Figure 4). Nevertheless, connection with long tubes was necessary. Diffusion losses mean that tube lengths were adapted to the flow rate as shown in Annex A.

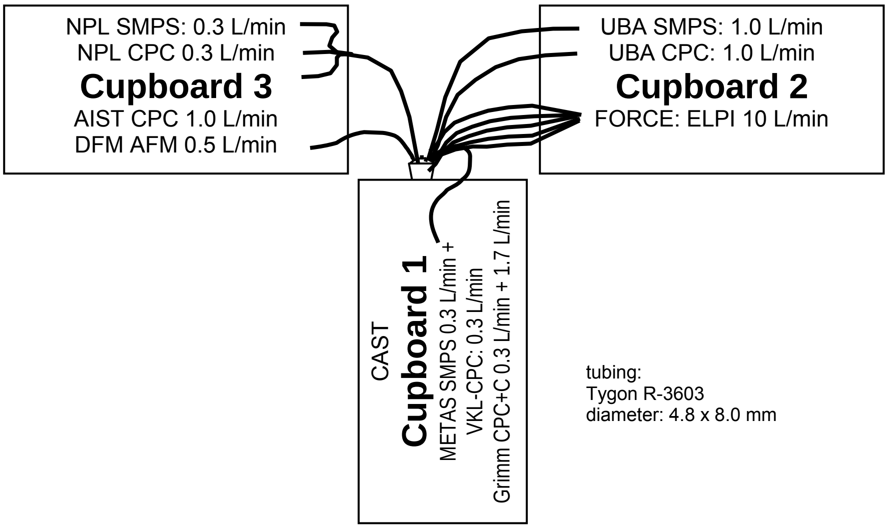



Figure 4 Arrangement of the measuring instruments.

# Data analysis and reporting

## Particle Size Distribution Parameter

The size distribution from the instruments' software consists of a table of values. Particle measurements are normally given with logarithmic spaced size bins $d_1, d_2, d_3 \ldots d_n$ normally with constant $d_{i+1} / d_i$. For the particle number concentration for each bin *i,* two measures are used: the first is the average *differential number concentration density* $c_i$ (also indicated as $\frac{dN}{d\log(d)}$ or $\frac{dc}{d\log(d)}$ or $\frac{dc}{d\ln(d)}$ and second is the *number concentration* $C_i$ in the size bin (also indicated as d*W*).

*Differential number concentration density* is $c_i(d_i) = c_i^{(\log)}(d_i) = \frac{d\,c(d_i)}{d\log(d)} \neq \frac{d\,c(d_i)}{d\ln(d)} = c_i^{(\ln)}(d_i)$. Here the base chosen for the logarithm affects the result, but the concentration density can be transformed as $d_i^{(\log)} = d_i^{(\ln)} \times \ln(10)$

The bin particle *number concentration* is $C_i = \frac{c_i^{(\log)}}{2}\log\left(\frac{d_{i+1}}{d_{i-1}}\right) = \frac{c_i^{(\ln)}}{2}\ln\left(\frac{d_{i+1}}{d_{i-1}}\right)$. As the bin particle number concentration depends on the size bins, the number of bins per size range is important for any comparison (e.g. in SMPS instruments there are often 64 channels per decade, whereas in ELPIs there are 8).

The table of values $\left(d_i, c_i^{(\log)}\right)$ or $\left(d_i, c_i^{(\ln)}\right)$ or $(d_i, C_i)$ is used to calculate the size distribution coefficients as number concentration, mode, geometric mean, median, and geometric standard deviation. As indicated in the participants' reporting template the number concentration was indicated as concentration density with base 10 logarithms i.e. $\frac{dc}{d\log(d)}$

### *Number concentration from Size Distribution*

The (total) number concentration is the number of particles per unit volume (cm$^{-3}$), as given by:

$$C = \sum_{i=1}^{n} \frac{c_i^{(\log)}}{2}\log\left(\frac{d_{i+1}}{d_{i-1}}\right) = \sum_{i=1}^{n} \frac{c_i^{(\ln)}}{2}\ln\left(\frac{d_{i+1}}{d_{i-1}}\right) = \sum_{i=1}^{n} C_i$$

### *Count Mode Diameter*

The mode is the diameter of the highest point on the size distribution curve. The mode $\hat{d}^{(\log)}$ for a size distribution with a logarithmic diameter scale is much larger than the mode $\hat{d}^{(\mathrm{lin})}$ for a size distribution with linear diameter scale. Here we use the mode with a logarithmic size scale.

$$\hat{d} = \hat{d}^{(\ln)} = \hat{d}^{(\log)} = d_m > \hat{d}^{(lin)} \quad \text{with} \quad m: \quad c_m = \max(c_i)$$

### *Geometric Mean Diameter*

The geometric mean is defined as the *n*th root of the product of *n* values. For particle distributions this measurand is equivalent to the mean calculated with logarithmic diameters.

### *Count Mean Diameter (not used in EURAMET 1027)*

The count Mean is defined as the arithmetic mean of the particle diameter in the system.

$$\bar{d} = \frac{1}{C}\sum_{i=1}^{n} C_i \times d_i$$

### *Count Median Diameter (not used in EURAMET 1027)*

The median is defined as the diameter for which one-half the total number of particles are smaller and one-half are larger.

$$d_{50} = d_m \quad \text{with} \quad m: \quad \sum_{i=1}^{m-1} \frac{c_i}{2} \log\left(\frac{d_{i+1}}{d_{i-1}}\right) \approx \sum_{i=m+1}^{n} \frac{c_i}{2} \log\left(\frac{d_{i+1}}{d_{i-1}}\right)$$

Higher accuracy for $d_{50}$ can be obtained with the assumption of a constant $c_i$ within size bin $m$ and interpolation of the diameter within the boundaries of the size bin.

### *Geometric Standard Deviation $\sigma_g$*

The Geometric Standard Deviation $\sigma_g$ is the standard deviation of the distribution with a logarithmic size scale.

$$\sigma_g = exp\left(\sqrt{\frac{1}{C}\sum_{i=1}^{n} C_i \times \left(\ln\left(\frac{d_i}{d_g}\right)\right)^2}\right)$$

## Data cropping for the evaluation of distribution parameters

Measured particle size distributions are always limited by either the size range of the instrument or a selection of the size range by the user. This must be considered during comparisons. The size range of the data is important for calculating the mean or geometric mean diameter, the total number concentration, and for the fitting of a theoretical curve to the data (Figure 5).

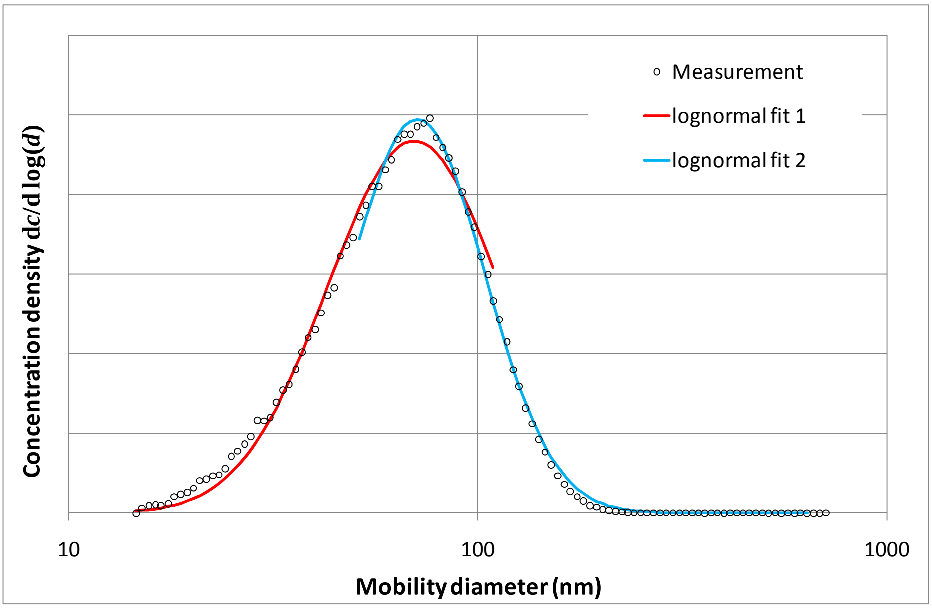



Figure 5 Total number concentration is represented as the area under the size distribution. Depending on the size range the results may bias. Shift of unimodal curve fit using different boundaries for cropping at almost unimodal size distribution.

## Curve fitting

When curve fitting, the size range, curve characteristics, and uncertainties of the data points can greatly affect the results. As an example, in Figure 6 a lognormal curve is fitted to a bimodal distribution. The mode and height of the fitted distribution is clearly affected by the data cropping. A similar but smaller effect was already seen in Figure 5.

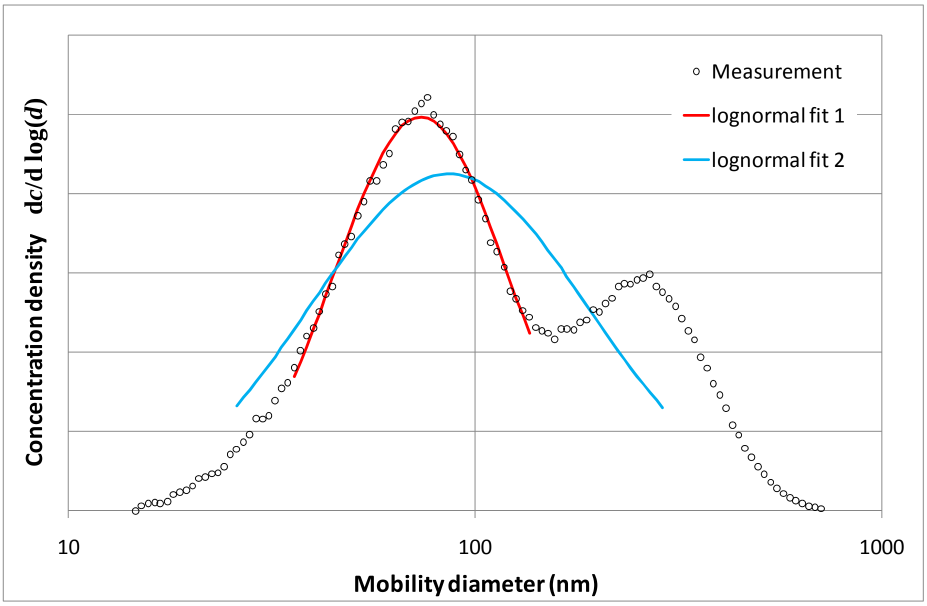



Figure 6 Shift of unimodal curve fit using different boundaries for cropping at bimodal size distribution.

## Data reporting

### *Protocol for number concentration measurements (see Annex B)*

The report contains the full information about instrument settings during the measurement, number concentration results, and any observations made during the measurement.

The number concentration and the associated uncertainty (in $cm^{-3}$) are reported for ambient conditions.

### *Protocol for particle size measurements (see Annex C)*

The report contains the full information about instrument settings during the measurement, and the results as an average for each run of the size distribution measurements.

Size distribution results are reported as a table of logarithmic spaced size bins and particle number concentration densities $c_i$ , averaged over the whole measurement run.

The following parameters and their uncertainties are reported using up to three analysis methods:

- Mode $\hat{d}^{(\log)}$
- Geometric Mean $d_g$
- Geometric Standard Deviation $\sigma_g$
- Total number concentration for the raw data $c_t$ over the full size range
- Total number concentration for the data with a cropped size range $c_c$ containing only the main peak

The three analysis methods are:

1. The "raw data" (as it is provided by the instrument and with the software given by the instrument manufacturer)
2. Using a lognormal distribution fit to the individual size bin data points
3. According to an individual method chosen by the participant, described in the reporting sheet

## Data comparison and degree of equivalence (DoE)

As a reference value $x_{ref}$ the average of the measured values $x_i$ without any weighting was taken. In some cases not all measurements $x_i$ are incorporated in this average. Using this reference value the Degree of Equivalence is calculated as follows:

$$DoE = \frac{x_i - x_{ref}}{x_{ref}}$$

# Results for particle number concentration

## Reference values

The number concentration was directly measured with five particle counters (CPCs) and also calculated from three size distribution instruments (two SMPS and one ELPI). As reference values[1] the results from all of the CPCs were averaged without any weighting, providing the concentration was within the calibrated range of the CPC. A valid comparison for $10^6$ $cm^{-3}$ could not therefore be performed, because only one particle counting system was calibrated for such high concentrations.

Where possible, the uncertainty of measurements is indicated ($k$ = 2). It was not possible to calculate the uncertainty of the reference values.

## Remarks for particle counters

All CPCs used butanol as the working fluid.

The inlet flow rate was calibrated individually. As an example, the METAS-CPC used external flow meters at the outlet of instruments during all measurements and corrected the concentration values numerically.

The CPCs had one of two flow configurations. In one version (AIST, NPL, METAS), the total flow from the inlet passes through the saturator, condenser and laser beam (for counting). In another version of the CPC (UBA) the inlet flow is internally split so that only 0.05 L/min carries particles to the detector. Only the flow through the detector is relevant for the calculation of number concentration.

The counting mode of most CPCs has an upper limit. Above this value the instruments either stopped their measurements (AIST-CPC, METAS2-CPC above $10^4$ $cm^{-3}$, UBA-CPC above $3{\cdot}10^5$ $cm^{-3}$) or changed to the photometric mode (NPL-CPC above $10^4$ $cm^{-3}$).

The instrument METAS1 was combined with an injection diluter (1:100) at the inlet in order to avoid the photometric mode of the CPC.

Instruments AIST, NPL and METAS1 apply calibration curves for the measured values of the instrument.

## Remarks for particle sizers

Although particle counters were the main focus of this part of the comparison, the number concentration results from the size analysers are also incorporated. Because the counters measure incoming particles across the whole size range covered by the particle sizers, the comparison was performed without any size cropping of the particle sizer data.

Total number concentration from SMPS instruments is known to depend on several parameters including the flow and scan settings, and is expected to be less reliable than number concentration from CPCs.

AFM was used to provide information on particle size and shape, and was not used to measure number concentrations.

[1] CCQM KCRV WG (19 March 2008) Data evaluation Principles for CCWM Key Comparisons

## Results

The results for the "natural" size distributions (Figure 7) and "monodisperse" particle distribution (Figure 8) show a clear difference between the particle counters and the sizers:

- The particle counters agreed within ± 5 % ($k$ = 2) for all particle diameters and all particle concentrations.

- Particle sizers in many cases indicated concentrations that deviated by around 20% from the particle counters.

- Relatively higher number concentrations were observed for smaller particles (70 nm) compared to larger particles (170 nm) in the particle sizing instruments. This may be due to the diffusion correction software within the SMPS instruments. All SMPS users applied the diffusion correction for the size distribution calculation that is provided by the instrument manufacturer (TSI). The algorithm for this correction is proprietary. Because the diffusion losses are higher for small particles, the application of the correction algorithm is more important for smaller particle diameters (e.g for particles with 70 nm and $\sigma_g$ = 1.6 the concentration increases by 35 % with the diffusion loss correction).

- The ELPI uses a different measuring principle and is designed for larger particles. The particle sizes within this comparison were not in the optimal measuring range of the ELPI, and so both size resolution and concentration measurements from the ELPI were not expected to be in good agreement with the SMPS measurements.

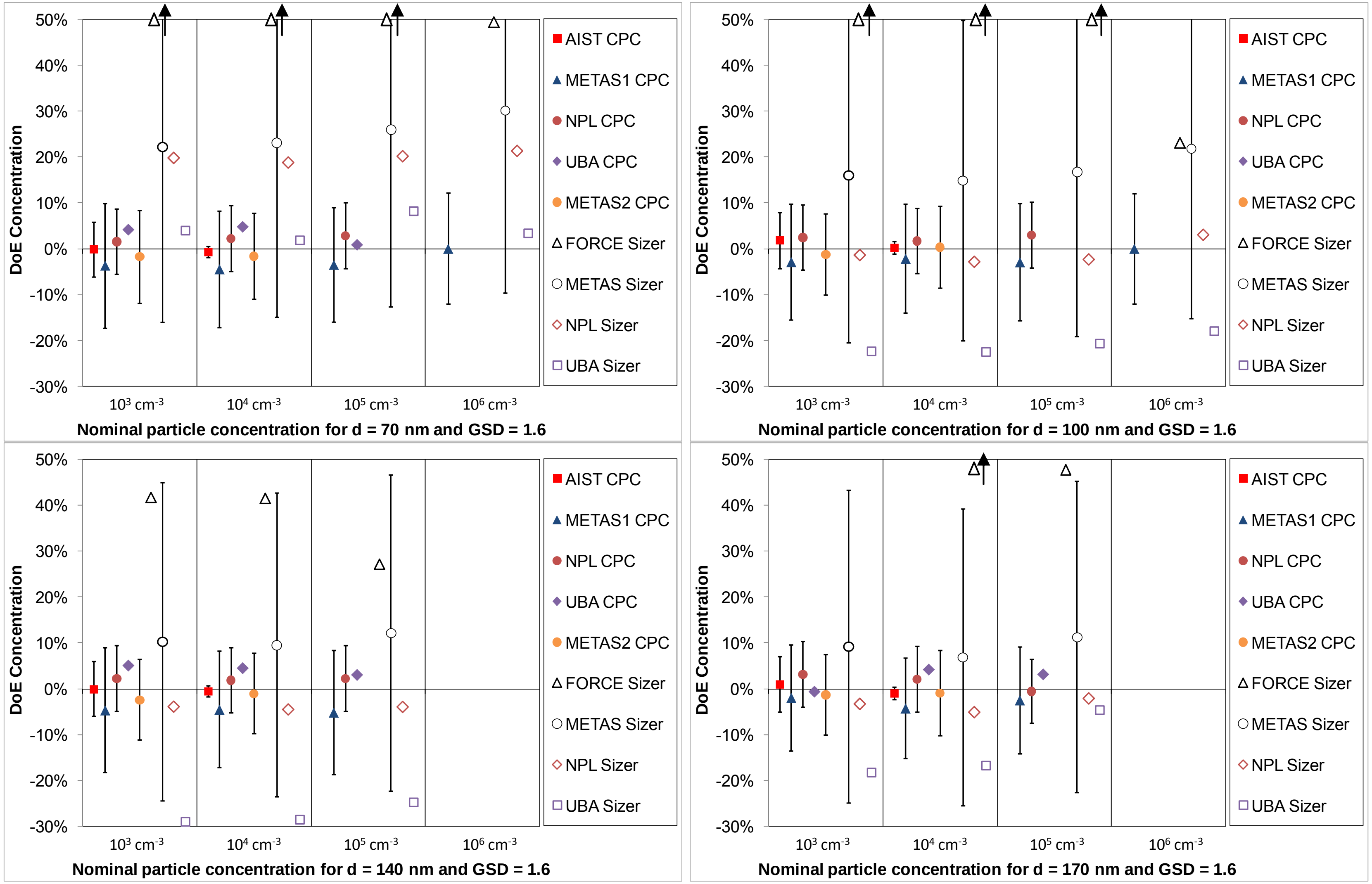



Figure 7 Comparison of concentration measurement for natural size distribution at diameter Mode 70 nm, 100 nm, 140 nm, and 170 nm and at various concentrations. The concentrations are normalised to average CPC results. The bars indicate the uncertainties ($k$ = 2). Remark: Not all participants have results for all concentrations. The graphs contain all data.

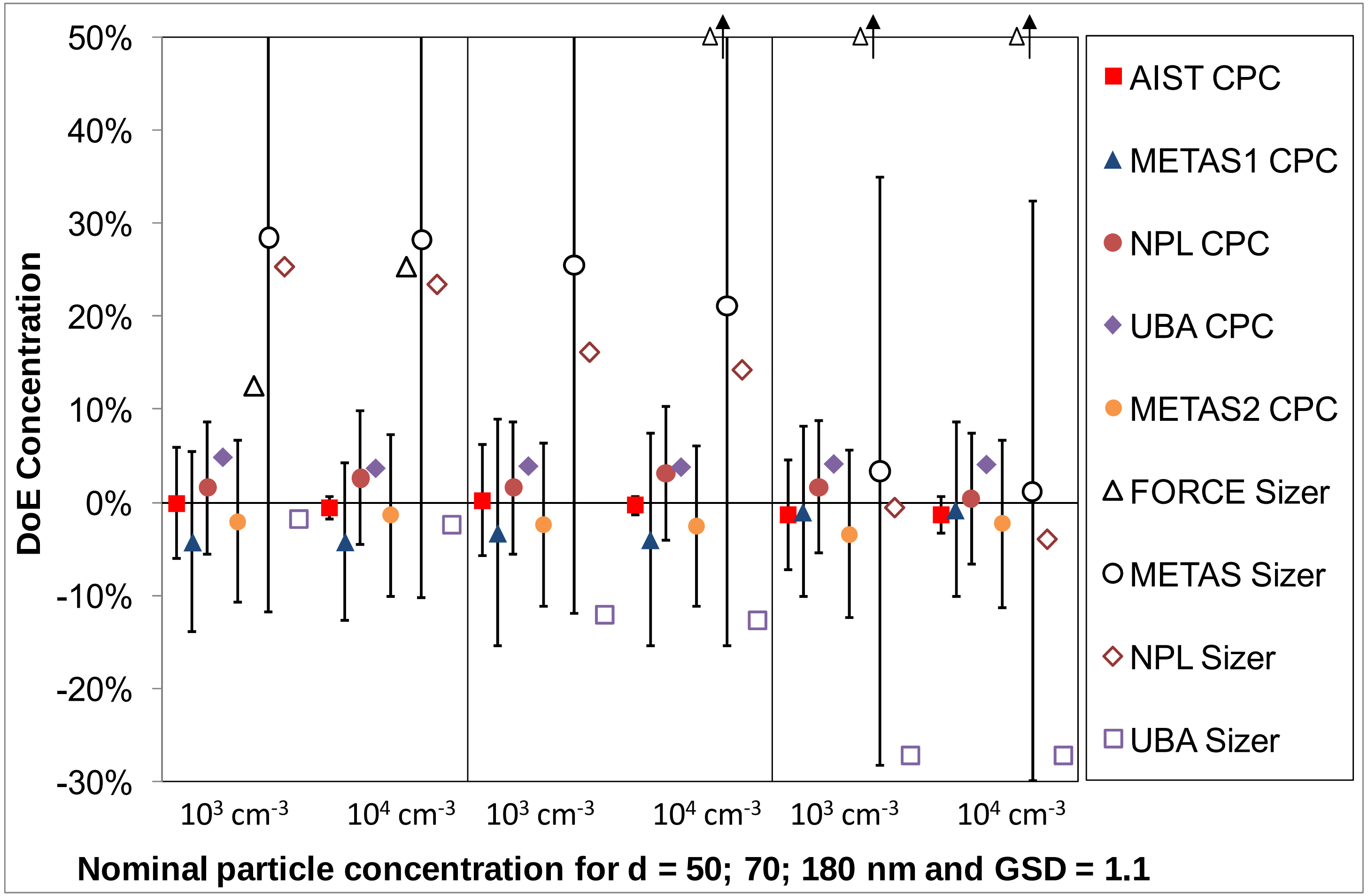



Figure 8 Comparison of concentration measurement for pseudo monodisperse size distribution (primary peak is accompanied with several further peaks) at diameter Mode 50 nm, 70 nm, and 180 nm, and at two concentrations each. The concentrations are normalised to average CPC results. The bars indicate the uncertainties ($k$ = 2). Remark: Not all participants have results for all concentrations. The graphs contain all data.

# Particle size distribution measurement

## General remarks

The particle size distribution was measured using three measurement principles giving different size information for the particles: a) SMPS measuring the electrical mobility diameter of the particle; b) ELPI measuring the aerodynamic (Stokes) diameter; c) AFM giving an image based on physical dimensions and allowing the calculation of the particle height and volume.

Deviations between measurements based on different principles are expected. The most important difference between mobility diameter and aerodynamic diameter is that the aerodynamic diameter is affected by the mass of the particle.

The particle size was compared via the mode and the geometric mean of the measured size distributions. Three different procedures were used to calculate these:

- Calculation with the software from the instrument (method 1),
- calculation by fitting a lognormal curve to the size bin data (method 2)
- individual analysis methods specified by the participants (method 3).

The uncertainty ($k$ = 2) was provided by some participants. Uncertainty calculation according to GUM is complicated in this case. More detailed work is in progress and will be an important element of future comparisons.

Uncertainty estimation for differential mobility analysers in static (not scanning) mode was evaluated by NIST[1, 2] and was about 1%. Significantly higher uncertainties are expected in scanning mode.

## Graphical results – a qualitative view

The particle size distributions in Figure 9 show the main difference between ELPI and SMPS measurements: the number of size divisions in the ELPI is much smaller than in SMPSs and therefore the resolution of the size measurements is poor in the size ranges used.

Both instrument types achieve smoother size distributions at higher concentrations through better sampling statistics. The width (geometric standard deviation) and peak (mode) of the curve stay almost the same at all concentrations (Figure 10).

For the “monodisperse” size distribution, the method of particle generation leads to the main peak being joined by smaller peaks of multiply charged particles with larger diameters. The size resolution of the ELPI is not adequate to show this (Figure 11).

[1] Michelle K. Donnelly and George W. Mulholland (2003) Particle Size Measurements for Spheres With Diameters of 50 nm to 400 nm, NISTIR 6935

[2] George W. Mulholland, Nelson P. Bryner, and Caroll Croarkin (1999) Measurement of the 100 nm NIST SRM 1963 by Differntial Mobility Analysis, Aerosol Sci. and Techn 31:39-55

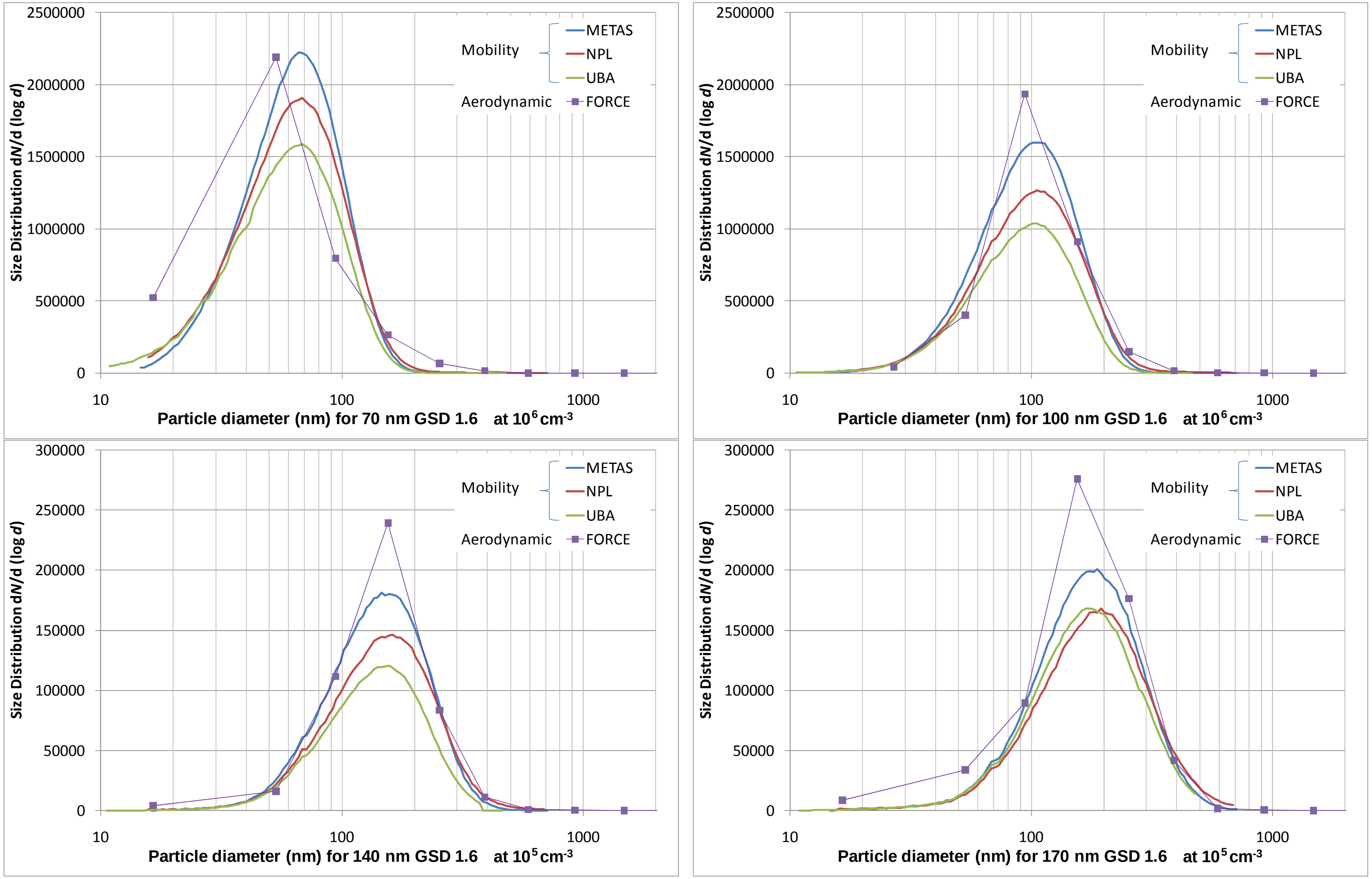



Figure 9 Comparison of size distributions shows a good agreement for the mode and width of distribution with SMPS. ELPI has a relatively poor size resolution.

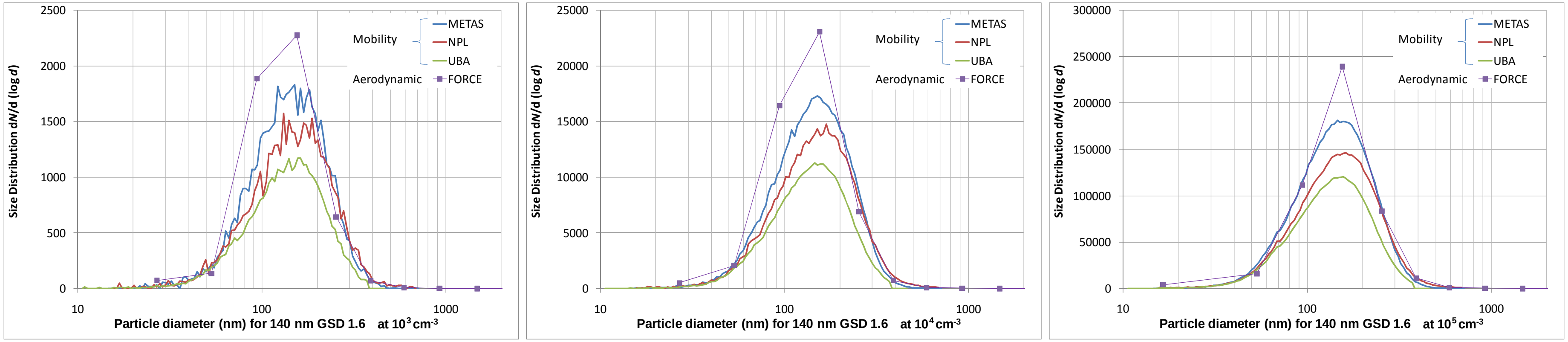



Figure 10 Comparison of size distributions as a function of the concentration shows a better correspondence for higher particle concentrations.

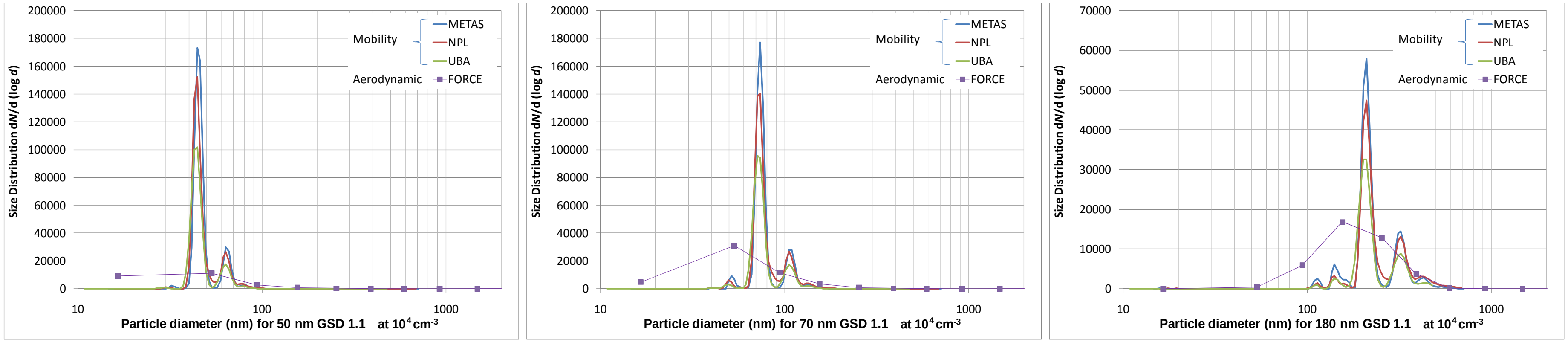



Figure 11 Comparison of quasi monodisperse size distributions. The size resolution of ELPI is not adequate for this kind of comparison.

# Results from the raw size data (method 1)

## General remarks

The size distribution data were cropped such that only the primary peak was considered. The calculation for method 1 was performed by the software from the instrument manufacturer.

The reference values for the particle diameter are calculated for mode and geometric mean separately. They are calculated as the average from the three SMPS-systems (from METAS, NPL, and UBA).

## Results

Figure 12 and Figure 13 show the comparison of the mode and the geometric mean of the size distributions.

- The results from the SMPSs deviate by less than 5 % for all sizes and both size measurands.
- A slight tendency for smaller deviations can be observed at higher concentrations.
- For the “natural” size distributions, a very small influence of cropping can be observed for the mode and the geometric mean.
- All SMPS users applied the diffusion correction for the size distribution calculation that is provided by the instrument manufacturer (TSI). The algorithm for this correction is proprietary. Because the diffusion losses are higher for small particles, the application of the correction algorithm shifts the geometrical mean towards smaller particles (e.g. for particles with 70 nm and $\sigma_g$ = 1.6 the shift reaches 10 %).
- The ELPI results were lower than the SMPS results by 10 to 30 % depending on the size and the type of measure. The best correspondence between aerodynamic and mobility diameters was found at 140 nm. (The exception is the mode at monodisperse particle size of nominal 50 nm, when the low resolution of the ELPI is expected to be a major factor). The deviation by the ELPI has various possible reasons:
  a) different charging methods (ELPI: unipolar charging, SMPS: neutralizing);
  b) different counting methods requiring different analysing algorithms (ELPI: electro-meter; SMPS: condensation particle counter);
  c) different size measurands (ELPI: aerodynamic diameter using an assumption for the particle density, SMPS: mobility diameter),
  d) the size resolution of ELPI is inadequate for this experiment.

The changes of air viscosity and mean free path length due to the altitude of METAS (550 m above sea level with an average ambient pressure of 950 hPa) have been neglected for this experiment. Future experiments should consider these factors.

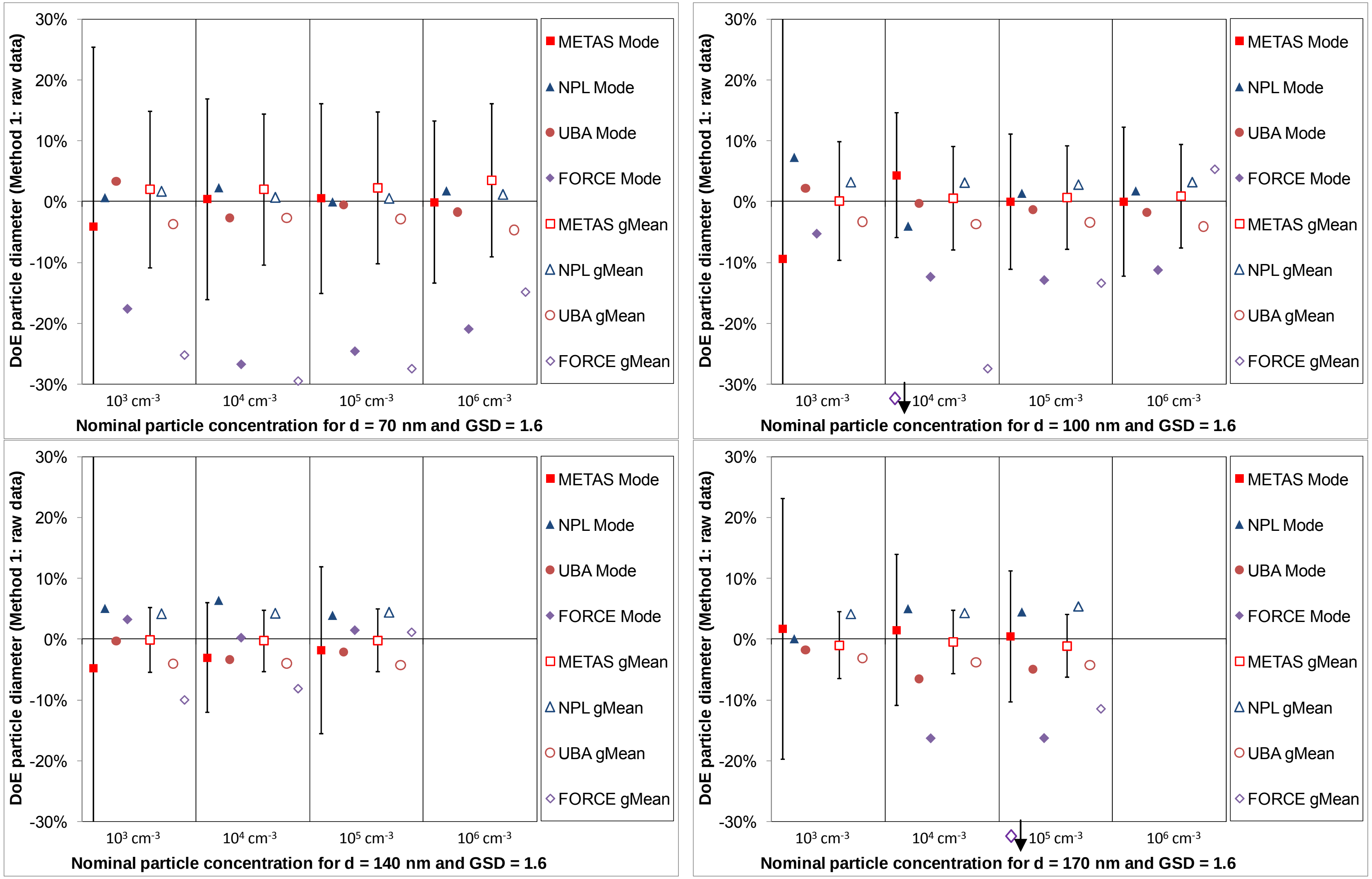



Figure 12 Method 1: Comparison of diameter measurement for natural size distributions at nominal diameters 70 nm, 100 nm, 140 nm, and 170 nm. “Mode” and “gMean” (Geometric Mean) are normalised to average SMPS results for Mode and Geometric Mean separately (3 values each). The bars indicate the uncertainties ($k$ = 2). Remark: Not all participants have results for all diameters. The graphs contain all data.

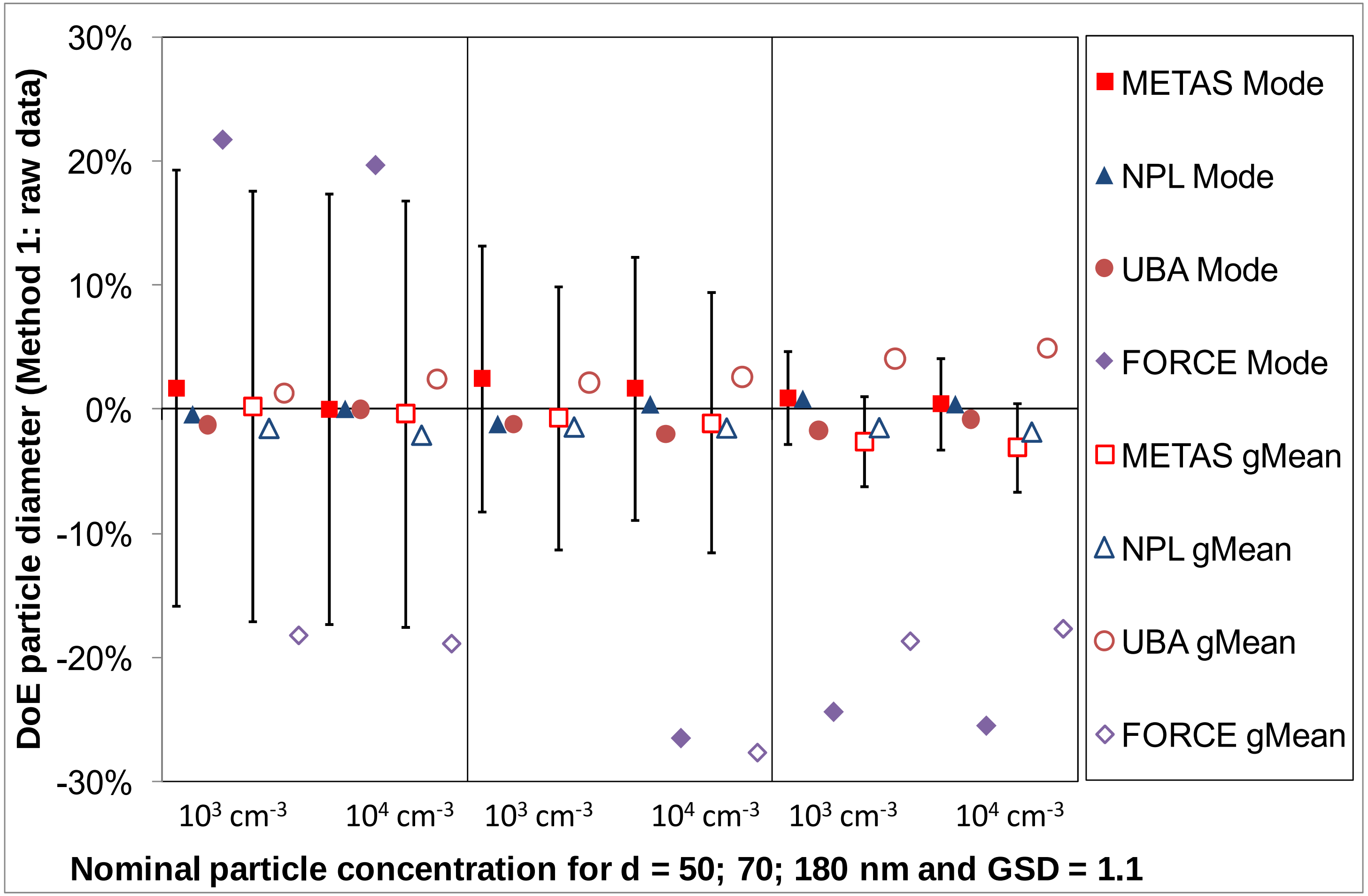



Figure 13 Method 1: Comparison of diameter measurement for monodisperse size distributions at nominal diameters 50 nm, 70 nm, and 180 nm. “Mode” and “gMean” (Geometric Mean) are normalised to average SMPS results for Mode and Geometric Mean separately (3 values each).The bars indicate the uncertainties ($k$ = 2). Remark: Not all participants have results for all diameters. The graphs contain all data.

## Results for particle size parameters using methods 2 and 3

Only METAS and NPL reported data based on independent curve fitting, whether to lognormal curves (method 2) or asymmetric lognormal curves (within method 3).

Given this limited participation, and the peripheral nature of this work to the main aims of the study, these data will not be reported or discussed within this report.

## Particle shape and size with an atomic force microscope

DFM used another particle sizing principle: the atomic force microscope (AFM). For this, particles were trapped on sample discs that were exposed to an aerosol flow of 500 mL/min for 30 minutes at the highest concentrations.

Geometrical analysis of single particles was integrated with the observed structure of the agglomerates and resulted in particle volumes being calculated. The volumes were compared to those of spheres with the SMPS mobility diameters. This first order comparison gives reasonable agreement (Figure 14).

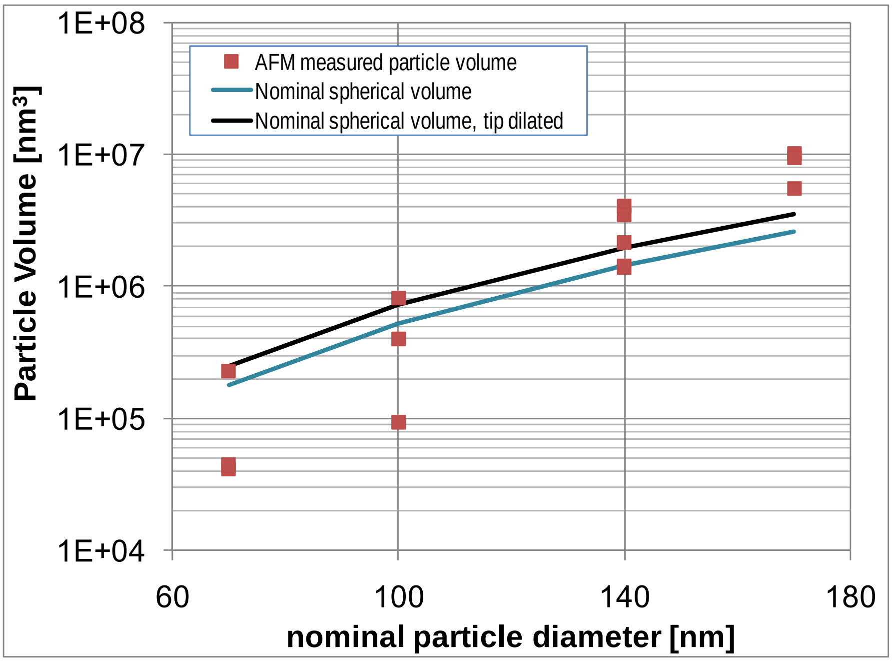



Figure 14 Comparison of AFM Volume calculations with spherical volume from nominal particle diameter (mobility), with and without AFM tip correction.

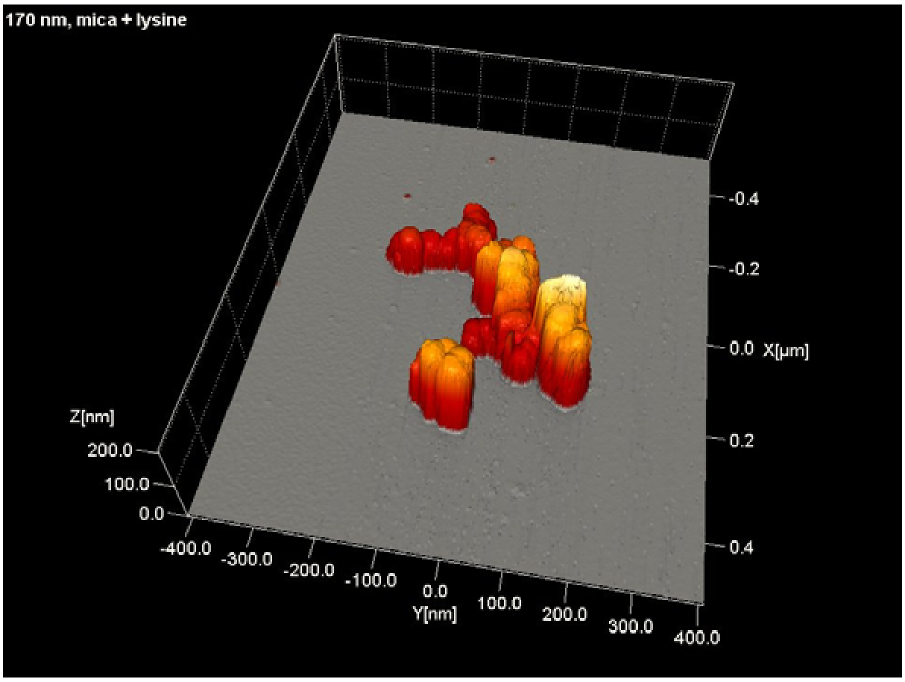
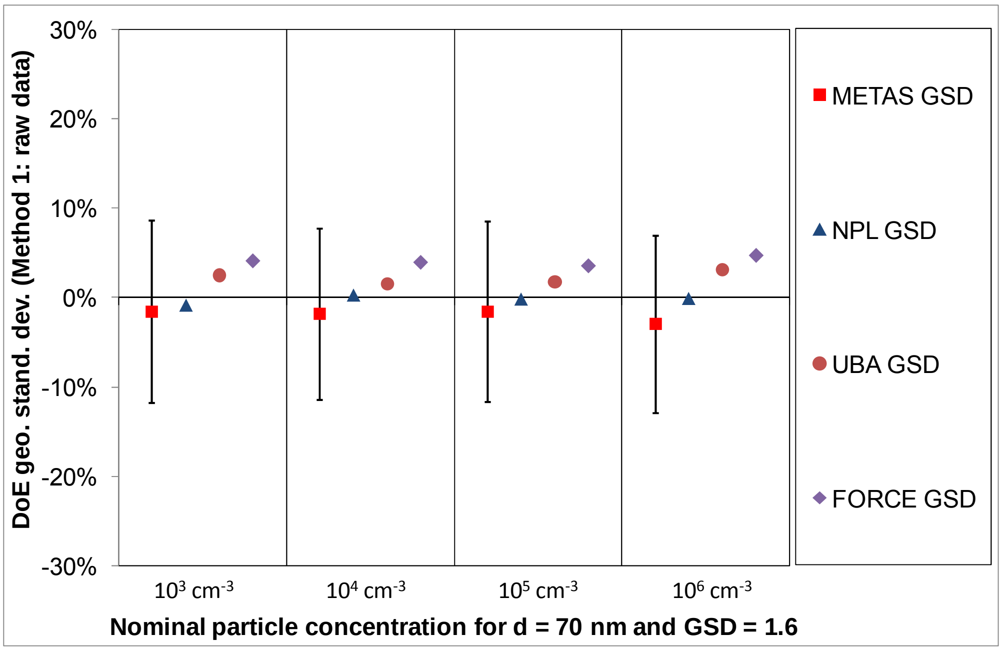


Figure 15 3D plot of a 170 nm particle. Topographic colour shading.

# Geometric Standard Deviation

The geometric standard deviation $\sigma_g$ assesses the width of the particle size distribution and is convolved with the properties of the measuring instrument. The width of the transfer function in the DMA dominates the value of $\sigma_g$ for monodisperse particles.

The geometric standard deviation results for natural size distributions were much less of a focus for this comparison than the size parameters, and these results are given in Figure 16 without further discussion.



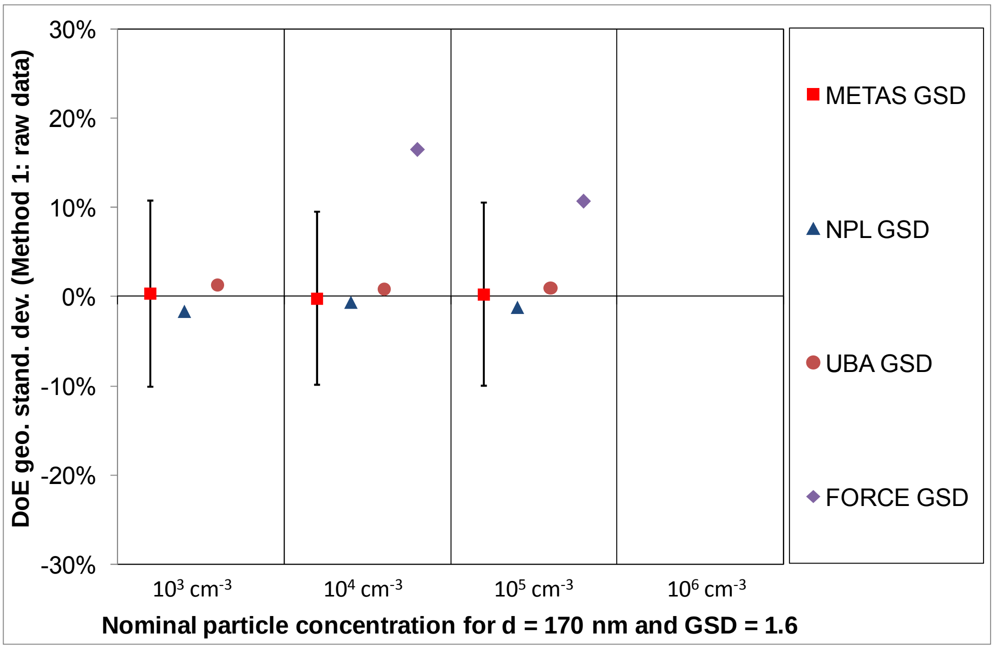




Figure 16 Comparison of Geometric Standard Deviation for natural size distribution at nominal diameters 70 nm and 170 nm. The results are normalised to average SMPS results. The bars indicate the uncertainties ($k$ = 2). Remark: Not all participants have results for all diameters. The graphs contain all data.

# Further work

## Goal

The goal for future work is to find common definitions and procedures for measuring particle number concentrations and size distributions at metrology institutes. These procedures must be relevant to real applications.

These measurements can then be incorporated into the metrology framework used for other analytical measurements, with a process of key comparisons and calibration and measurement capabilities (CMCs), within the auspices of BIPM: http://kcdb.bipm.org/

## Refinement for future comparisons

The following points should be considered when organizing future comparisons:

- Separating size distribution comparisons from number concentration comparisons.

- Which particle types shall be used?
  Combustion particles, oil droplets, NaCl, polystyrene spheres, $NH_4SO_4$, $TiO_2$, etc.
  The chemistry of particles is specific for the field of application.

- Which size range?
  23 nm, 50 nm, and 70 nm are important for the automotive industry (UNECE regulation 83); 70 nm is important for ambient studies.

- Which size distribution width?
  Monodisperse: $\sigma_g < 1.1$ (artificial test aerosol); unimodal: $\sigma_g > 1.3$ (combustion aerosol); multimodal (ambient aerosol).

# Annex A: Table of Instrumentation

| Institute | Instrument | Measurand | Tubing and flow rate | Connection at manifold | Residence time | Penetration[1] for 100 nm | Number of Channels[2] | Size range |
|---|---|---|---|---|---|---|---|---|
| FORCE | ELPI DEKATI | aerodynamic diameter distribution | 8 x 1.25 m @ 10 L/min | 2, 3, 4, 5, 6, 11,17 | 1.1 s | 99.3 % | 12 total | 7…9890 nm |
| METAS | SMPS: DMA TSI3080, CPC TSI3775 | electrical mobility diameter distribution | 1.4 m @ 2.2 L/min + 0.26 m @ 0.3 L/min | 1 | 1.6 s | 98.9 % | 64 per decade | 14.6 … 710.5 nm |
| NPL | SMPS: DMA TSI3080, CPC TSI3022A | electrical mobility diameter distribution | 1.3 m @ 1.1 L/min + 0.1 m @ 0.3 L/min | 9 | 1.7 s | 98.9 % | 64 per decade | 15.7 … 685.4 nm |
| UBA | SMPS: DMA TSI3080, CPC TSI3010 | electrical mobility diameter distribution | 2.0 m@ 1 L/min | 14 | 2.2 s | 99.0 % | 64 per decade | 10.6 … 371.8 nm<br>10.9 … 478.3 nm |
| AIST | CPC TSI3010 | number concentration | 2.0 m@ 1 L/min | 19 | 2.2 s | 99.0 % | - | - |
| METAS | Diluter Palas VKL100 CPC TSI3022 | number concentration | 1.4 m @ 2.2 L/min + 0.26 m @ 0.3 L/min | 1 | 1.6 s | 98.9 % | - | - |
| METAS | CPC Grimm5.400 | number concentration | 1.4 m @ 2.2 L/min + 0.26 m @ 0.3 L/min | 1 | 1.6 s | 98.9 % | - | - |
| NPL | CPC TSI3022A | number concentration | 1.3 m @ 1.1 L/min + 0.1 m @ 0.3 L/min | 9 | 1.7 s | 98.9 % | - | - |
| UBA | CPC TSI3776 | number concentration | 3.0 m @ 1.5 L/min | 15 | 2.2 s | 99.0 % | - | - |
| DFM | Atomic Force Microscope | geometric size | 1.3 m @ 1.1 L/min + 2 x 1.5 m @ 0.5 L/min | 9 | 7.8 s | 97.1 % | - | - |

[1] The penetration was calculated from the diffusion lost Chapter 7 in William C. Hinds (1982) Aerosol Technology – Properties, Behaviour, and Measurement of Airborne Particles, John Wiley & Sons

[2] Sizing instruments give the results in size channels. All SMPS instrument used the Software AIM 8.0.0.0 with diffusion correction and for ELPI the software ELPIVI 4.02 with correction algorithm for diffusion losses was applied. The multiple charge correction was applied in all cases.

# Annex B:
# Protocol for number concentration measurements

## Instrument Data (Template):

| **Participant Name** | | |
|---|---|---|
| | | |
| Instrument Operating Parameters | | Only use this template for reporting results from a number concentration instrument (NOT an integrated size distribution). A separate template is available for size distribution instruments. |
| | | |
| Data entry in green cells only! | | |
| | | |
| | Value | Comments |
| General Instrument Information | | |
| Manufacturer | | |
| Model Number | | |
| Serial Number | | |
| Further Details | | |
| | | |
| Particle Detector Instrument Used (CPC/FCE/???) | | |
| Manufacturer | | |
| Model Number | | |
| Serial Number | | |
| Further Details | | |
| Working Fluid (for CPCs only) | | |
| Detector flow rate (lpm) | | |
| Inlet flow rate (lpm) | | |
| Reference temperture (°C or ambient) | | |
| Reference pressure (hPa or ambient) | | |
| | | |
| Software Information | | |
| | | |
| Manufacturer | | |
| Name / Version number | | |
| | | |
| Software Settings | | |
| Scheduling details | | |

## Reported Data (template extraction)

| Samples are in chronological order | Value | Relative Standard Uncertainty |
|---|---|---|
| **Sample Name** | 100 nm GSD 1.6 1k P/ccm | |
| Notes during measurement (eg errors & observations) | | |
| **Average Number Concentration** | | |
| | | |
| **Sample Name** | 100 nm GSD 1.6 10k P/ccm | |
| Notes during measurement (eg errors & observations) | | |
| **Average Number Concentration** | | |
| | | |
| **Sample Name** | 100 nm GSD 1.6 100k P/ccm | |
| Notes during measurement (eg errors & observations) | | |
| **Average Number Concentration** | | |
| | | |
| **Sample Name** | 100 nm GSD 1.6 1M P/ccm | |
| Notes during measurement (eg errors & observations) | | |
| **Average Number Concentration** | | |
| | | |
| **Sample Name** | 140 nm GSD 1.6 1k P/ccm | |
| Notes during measurement (eg errors & observations) | | |
| **Average Number Concentration** | | |
| | | |
| **Sample Name** | 140 nm GSD 1.6 10k P/ccm | |
| Notes during measurement (eg errors & observations) | | |

# Annex C:
# Protocol for size distribution measurements

## Instrument Data (template):

| | | |
|---|---|---|
| **Participant Name** | | |
| | | |
| Instrument Operating Parameters | | Only use this template for reporting results from a sizing instrument instrument (NOT a number concentration instrument). A separate template is available for number concentration instruments. |
| | | |
| Data entry in green cells only! | | Users of non-SMPS instruments, please adapt as appropriate |
| | | |
| | Value | Comments |
| General Instrument Information | | |
| Manufacturer | | |
| Model Number | | |
| Serial Number | | |
| Further Details | | |
| | | |
| Hardware Information (SMPS-type only) | | |
| | | |
| Impactor Used? | | |
| Impactor Cutoff D50 (nm) | | |
| Orifice size / Flow rate / Further Details | | |
| | | |
| Particle Detector Instrument Used (CPC/FCE/???) | | |
| Manufacturer | | |
| Model Number | | |
| Serial Number | | |
| Further Details | | |
| Working Fluid (for CPCs only) | | |
| Detector flow rate (lpm) | | |
| Inlet flow rate (lpm) | | |
| | | |
| Particle Size Classifier Used (DMA/???) | | |
| Manufacturer | | |
| Model Number (s) | | |
| Serial Number (s) | | |
| Further Details | | |
| Sheath Air Flow Rate (lpm) | | |
| Sample Air Flow Rate (lpm) | | |
| Reference temperture (°C or ambient) | | |
| Reference pressure (hPa or ambient) | | |
| | | |
| Software Information | | |
| | | |
| Manufacturer | | |
| Name / Version number | | |
| | | |
| Software Settings (if applicable) | | |
| | | |
| Direction of data collection scan (Up/Down/Both) | | |
| Scan Time (s) | | |
| Back Scan Time (s) | | |
| Number of Scans per sample recorded | | |
| Scan Frequency (s) | | |
| | | |
| Smallest Size Bin Recorded (nm) | | |
| Largest Size Bin Recorded (nm) | | |
| Bin Resolution (bins per order of magnitude) | | |
| Total Number of Bins | | |
| | | |
| Particle Detector Efficiency Correction? (Y/N) | | |
| Multiple Charge Correction? (Y/N) | | |
| Diffusion Correction? (Y/N) | | |
| Aggregate Correction? (Y/N) | | |
| Other Corrections? (Y/N) | | |
| | | |
| Air Viscosity Used (kg/ms) | | |
| Mean Free Path Used (nm) | | |
| | | |
| Calculated DMA residence time (s) | | |
| Calculated DMA/Detector transport time (s) | | |
| | | |
| Notes | | |
| Method 1 | | These values are the ones given by the software you used at the Intercomparison (AIM for most users). For the Mode, Geometric Mean and Geometric Standard Deviation please crop such that only the primary mode is considered. For the Total Concentration, please use the full measured range of your instrument. |
| Method 2 | | Please analyse your size distribution to determine the same parameters as method 1. Please submit a description of your method. |
| Method 3 | | Optional. If you wish to submit any other fitting methods, please do so in the appropirate cells. Remember to include a description of your method |

# Reported Data (template extraction)

| Samples are in chronological order | Value | Relative Standard Uncertainty | Size bin data >>>>>> | | |
|---|---|---|---|---|---|
| **Sample Name** | 100 nm GSD 1.6 1k P/ccm | | | | |
| Number of Samples Comprising Submitted Average | | | | | |
| Notes during measurement (eg errors & observations) | | | | | |
| **Average Size Distribution (full range = measurement size range)** | | | | | |
| Size Bin (nm) | | | | | |
| Concentration (dN/dlogDp) | | | | | |
| Standard Deviation in Concentration | | | | | |
| Fitted Parameters | | | | | |
| Smallest Size Bin cropped (nm) | | | | | |
| Largest Size Bin cropped (nm) | | | | | |
| **Method 1- manufacturer's software values- see notes** | | | | | |
| Mode (nm) | | | | | |
| Geometric Mean (nm) | | | | | |
| Geometric Standard Deviation | | | | | |
| Concentration (P/ccm) including all corrections, full | | | | | |
| Concentration (P/ccm) including all corrections, cropped | | | | | |
| **Method 2- symmetric log normal fit- see notes** | | | | | |
| Mode (nm) | | | | | |
| Geometric Mean (nm) | | | | | |
| Geometric Standard Deviation | | | | | |
| Concentration (P/ccm) including all corrections, full | | | | | |
| Concentration (P/ccm) including all corrections, cropped | | | | | |
| **Method 3 (optional)- see notes** | | | | | |
| Reported value 1 | | | | | |
| Reported value 2 | | | | | |
| Reported value 3 | | | | | |
| Reported value 4 | | | | | |
| | | | | | |
| **Sample Name** | 100 nm GSD 1.6 10k P/ccm | | | | |
| Number of Samples Comprising Submitted Average | | | | | |
| Notes during measurement (eg errors & observations) | | | | | |
| **Average Size Distribution (full range = measurement size range)** | | | | | |
| Size Bin (nm) | | | | | |
| Concentration (dN/dlogDp) | | | | | |
| Standard Deviation in Concentration | | | | | |
| Fitted Parameters | | | | | |
| Smallest Size Bin cropped (nm) | | | | | |
| Largest Size Bin cropped (nm) | | | | | |
| **Method 1- manufacturer's software values- see notes** | | | | | |
| Mode (nm) | | | | | |
| Geometric Mean (nm) | | | | | |
| Geometric Standard Deviation | | | | | |
| Concentration (P/ccm) including all corrections, full | | | | | |
| Concentration (P/ccm) including all corrections, cropped | | | | | |
| **Method 2- symmetric log normal fit- see notes** | | | | | |
| Mode (nm) | | | | | |
| Geometric Mean (nm) | | | | | |
| Geometric Standard Deviation | | | | | |
| Concentration (P/ccm) including all corrections, full | | | | | |
| Concentration (P/ccm) including all corrections, cropped | | | | | |
| **Method 3 (optional)- see notes** | | | | | |
| Reported value 1 | | | | | |
| Reported value 2 | | | | | |
| Reported value 3 | | | | | |
| Reported value 4 | | | | | |