Impact of Particle Mass Distribution on the Measurement Accuracy of Low-Cost PM-Sensors

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Impact of Particle Mass Distribution on the Measurement Accuracy of Low-Cost PM-Sensors

Bernd Laquai, 20.10.2017

Commodity PM-measurement devices are used more and more by citizens concerned about air pollution for being warned about potential hazard events induced by critical meteorological conditions and sometimes also to put pressure on politics to intervene in the ever-growing traffic considered as a major source of air pollution. The significant difference in cost between high precision professional instrumentation for particle mass concentration measurement and the low-cost PM sensors as well as a difference in size and power consumption, makes the low-cost PM-sensors highly attractive for designing such devices. The low-cost PM-sensors also became attractive for scientific research focused on spatially distributed or mobile measurements. Since citizen scientists already have implemented IOT based sensor networks with several hundreds of PM-measuring sensor nodes, the authorities in charge of monitoring air pollution for ensuring legal compliance become more and more concerned about the second source of PM measurement data alienating the general public with values that differ from the officially communicated PM-values.

All these trends urge experts involved in particle measurement to clarify the measurement uncertainties when PM concentrations are measured with low-cost sensors either by citizen scientists or in professional research. One major source of discrepancy has already been identified, it is the hygroscopic growth of particles in the presence of high humidity, often strongly correlated with the meteorological conditions that favor high PM accumulation in the atmosphere of large cities. Whereas the official PM mass concentration measurements determine the dry PM mass concentration after drying wet particles in complex drying systems, low-cost sensors measure without any drying of particles. Since the hygroscopic growth of particles related to mass may reach factors of 3 and more, low-cost sensors may report PM values significantly higher compared to the court-proof PM-values provided by the official authorities.

Even though hygroscopic growth is probably the larges source of measurement inaccuracy when referring to PM related dry mass concentration in humid environment, there are further sources of non-negligible inaccuracies. Further research related to low-cost PM sensors revealed that the mass distribution of a particle spectrum with respect to particle size a low-cost sensor is exposed to, often causes significant mismatches in measurement results compared to high precision measurement equipment. This is particularly the case when a low-cost sensor is determining the PM mass concertation without binning detected particles into different sizes bins to avoid costly computational intensive histogram calculations.

Simultaneously, it is a big challenge for the manufacturers of very small low-cost sensors, to detect and count particles in a wide size range as occurring under typical environmental conditions. It is well known, that high volumes of traffic generate particles with diameters exceeding 10um due to abrasive processes in brakes and at the tire-to-road interface. On the other hand, combustion processes in engines or heating systems typically generate particle distributions containing a huge number of particles much smaller than

1um even extending into the nanometer regime. Detecting such small particles requires high amplification of very small scattering light intensities and fast counting. On the opposite large particles occur with a rate of less than once per second in the small measurement volume of a low-cost sensor and produce scattering light intensities that are by orders of magnitude larger than those of sub-um particles. Therefore, covering both extremes in a particle distribution is a huge challenge in presence of the cost limits for low cost commodity sensors.

In this investigation two representative low cost devices were compared to a professional high precision reference instrument (Grimm 1.108), the SDS011 Laser PM2.5 Sensor from Nova Fitness Co. Ltd., China and the OPC-N2 Particle Monitor from Alphasense Ltd., UK. Whereas no indication could be found that the SDS011 is using a histogram based method to calculate the PM10 and PM2.5 values it reports, the OPC-N2 is definitely using a histogram method clearly described by the manufacturer. Despite both PM sensors may be designated as low-cost sensors compared to the cost of professional high precision equipment, there is a significant cost difference of a factor 10 between the cheaper SDS011 and the costlier OPC-N2.

Provided low-cost PM-sensors using laser-scattering are operated in ambient air with less than 60% relative humidity, the expectation is, that the measured mass of particulate matter is comparable to what is determined with professional equipment using a drying system at least with an acceptable cost related limitation of measurement uncertainty. However even in dry air, very low-cost PM-sensors still show massive deviations from expected values making them useless for meaningful measurements. These deviations are obviously strongly related to the particle mass distribution over size. This dependency is shown for the very low-cost sensor SDS011 from Nova Fitness and the low-cost PM sensor OPC-N2 from Alphasense.

First indications of a distribution dependency for the SDS011 PM-sensors were obtained by experiments, where the effect of scattered light from particles was substituted by artificial light injected into the measurement volumes by a pulsed LED or by electrical signals from a pulse generator fed into the A/D converter input. In those cases, the following observations for slowly increasing pulse amplitudes could be made:

- Even for very small amplitudes both the PM2.5 and the PM10 readings were increasing, but PM10 values increased more than the PM2.5 values. The expectation was that PM2.5 and PM10 would be equal for small scattering light amplitudes.
- For increasing amplitudes starting with a certain amplitude, the PM2.5 readings seemed to saturate towards a level only weakly increasing with PM10. The expectation was that PM2.5 readings should drop to zero again for large amplitudes that correspond to large particle diameters.
- With increasing large amplitudes, the PM10 readings were increasing almost linearly. The expectation was that with large particle sizes and thus with large scattering light signals the PM10 readings should increase with the 3rd power of the amplitude reflecting the proportionality ~d^3 to the particle diameter.

Fig. 1: Opened low-cost PM-Sensor (SDS011) with LED inserted into measurement chamber for generating artificial scattering light pulses

Fig 2: SDS011 sensor readings for PM10 and PM2.5 as reaction to LED light pulses (5us duration, frequency 300Hz) with increasing amplitude
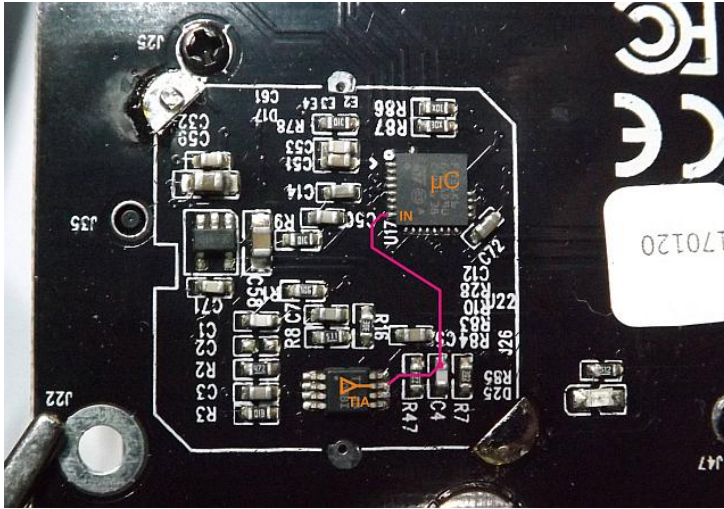
Fig. 3: Assembly side of the SDS011 PCB after removing the shielding cover. The graphic overlay indicates the signal path from the TIA to the analog input of the microcontroller where electrical pulses were injected to simulate scattering events
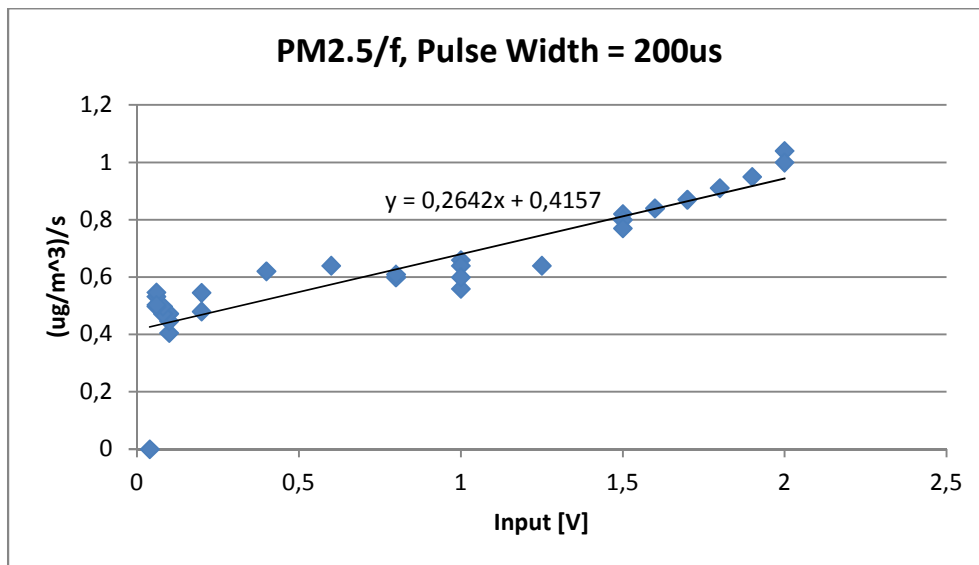
Fig 4a: PM2.5 readings per frequency for increasing signal amplitudes
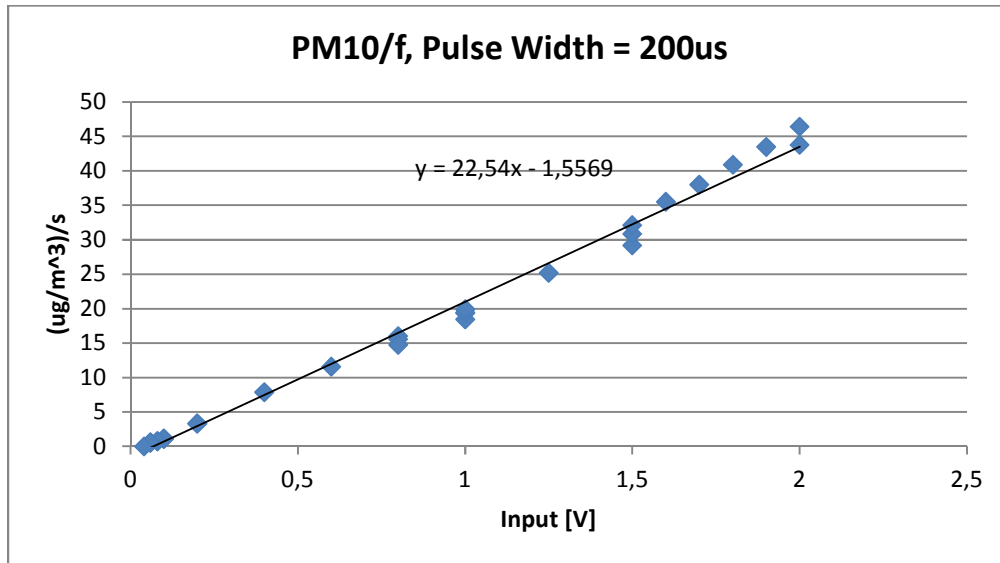
Fig 4b: PM10 readings per frequency for increasing signal amplitudes

In order to investigate this dependency further, a particle generator was built to also generate extreme situations of real particle distributions. These particle distributions however, were still kept distinct from monodisperse particles distributions. On one hand the goal was to generate a distribution that has its center of mass at diameters significantly lower than 2.5um such that no mass contribution occurs contributing to PM10. On the other hand, the goal was to generate also the opposite, a distribution with a center of mass significantly above 2.5um such that no particles occur with a mass contribution to PM2.5. The particle generator was built to allow switching easily between both distributions within one measurement.

To meet the requirements for a quick change of particle distributions, the particle generator was equipped with two distinct particle sources that can be controlled independently. One particle source represents a smoke generator dispersing an aerosol from a smoke liquid with a heater element similar to an e-cigarette. Such an aerosol is characterized by a particle distribution with particles smaller than 2um and a center of mass at about 0.5um. The heater element can easily be controlled from a microcontroller via an electronic (MOSFET) power switch. The other particle source is a sputtering membrane for powders. The powder chosen was pastry flour of type 405 (German grading system). The dust generated from sputtering pastry flour is characterized by a particle distribution with a mass center around 5um and a width of distribution between 2 and 15um. The sputtering membrane was also controlled electronically from a 60Hz sinusoidal signal generator. The sputtering membrane and the smoke generator was arranged 30cm above the sensors under test in a 60Liter measurement chamber to ensure a homogeneous spatial distribution, even for large particles with high sedimentation velocity.
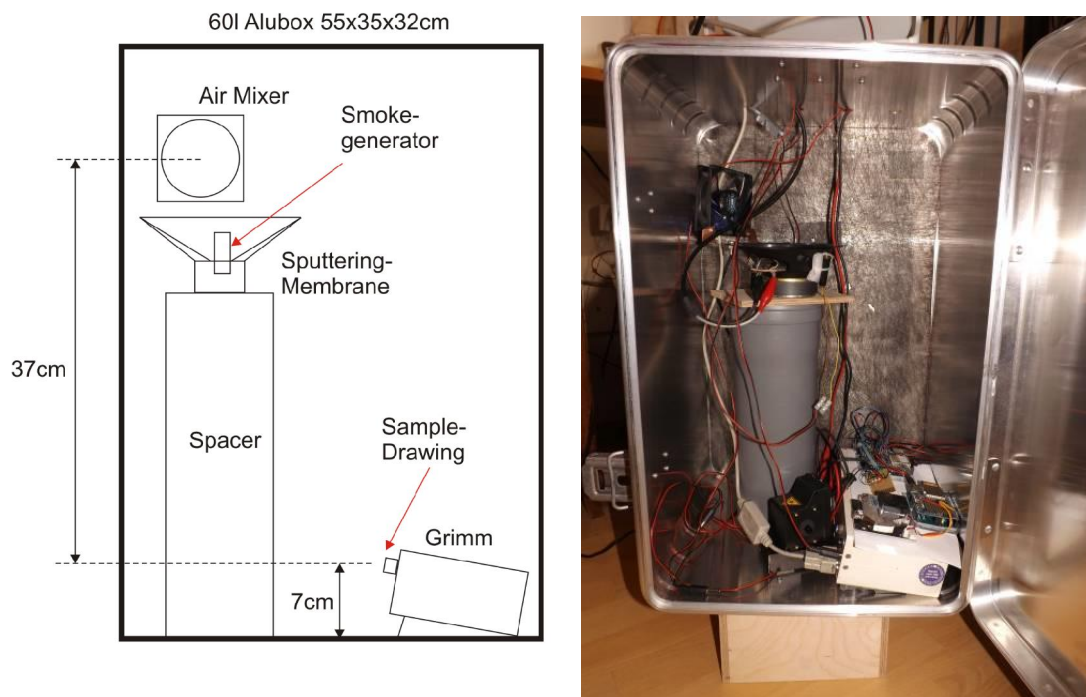
Fig 5: Particle generator built to change particle distributions during a measurement
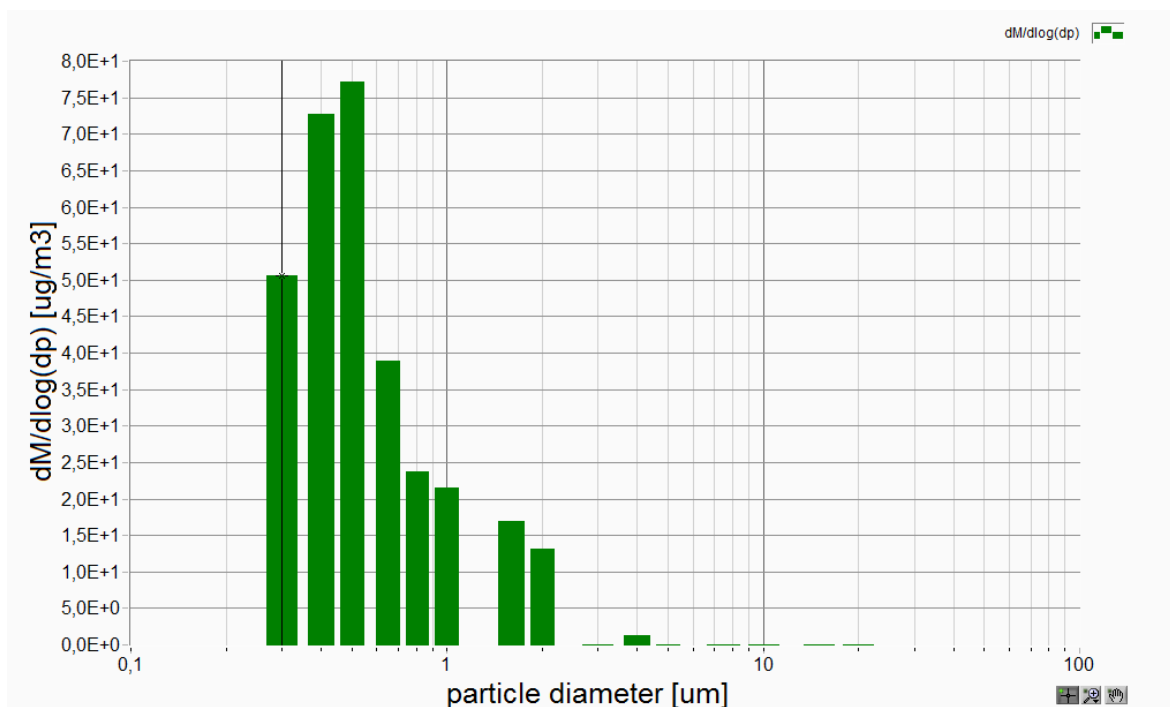

Fig 6a: Typical particle mass distribution generated during the first phase of the measurement as seen by the Grimm, particles contributing to mass are smaller than 2um
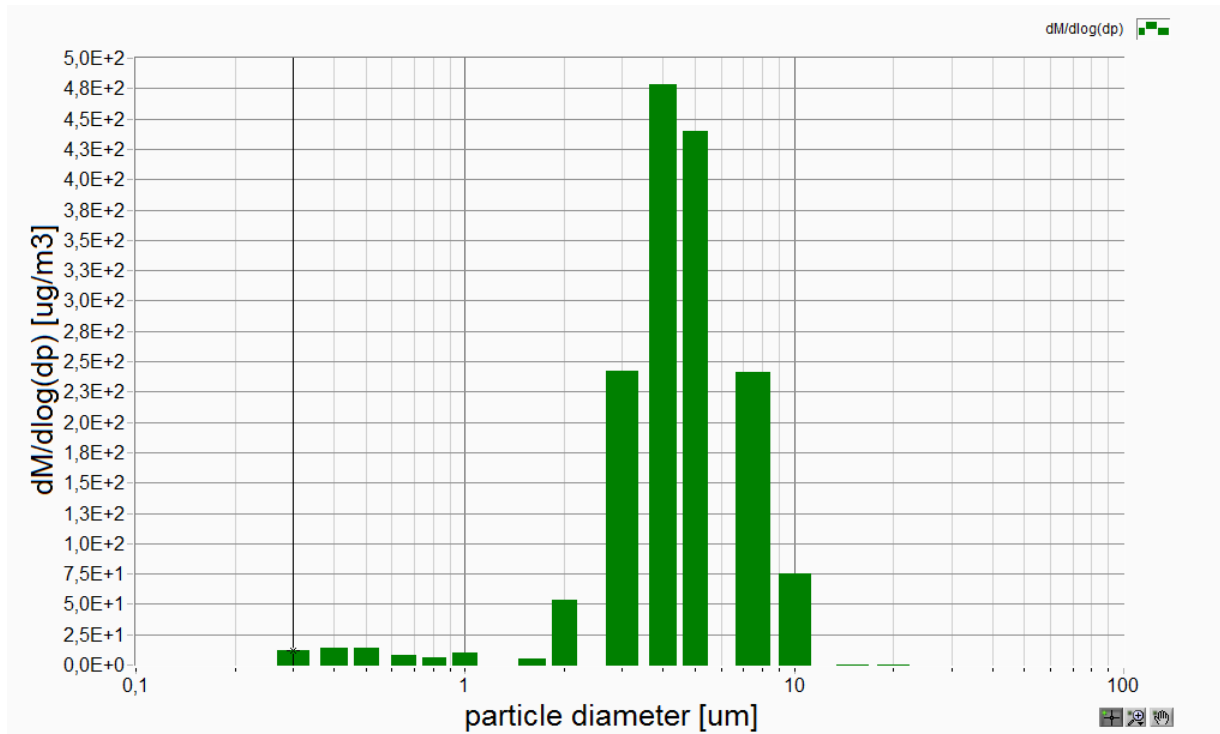
Fig 6b: Typical particle mass distribution generated during the first phase of the measurement as seen by the Grimm, particles contributing to mass are larger than 3um

For the first measurement 3 low-cost sensor devices of type SDS011 were placed in the measurement chamber together with the Grimm 1.108 aerosol spectrometer as a reference instrument. In a first phase, the smoke generator was activated for several seconds. The Grimm reports the subsequent aerosol concentrations with a nearly ideal exponential decay within 45 minutes. The amount of initial smoke generated was selected such that the decay reached PM concentrations typical for environmental research. As soon as PM2.5 readings reached values close to 10ug/m³, the second source was activated beginning the sputtering of large particles. This source had to be kept on during measurement, since the large particles sediment pretty quickly. However, since only a small amount of powder was deposit on the sputtering membrane, the reservoir empties gradually with the consequence of decreasing PM concentrations.
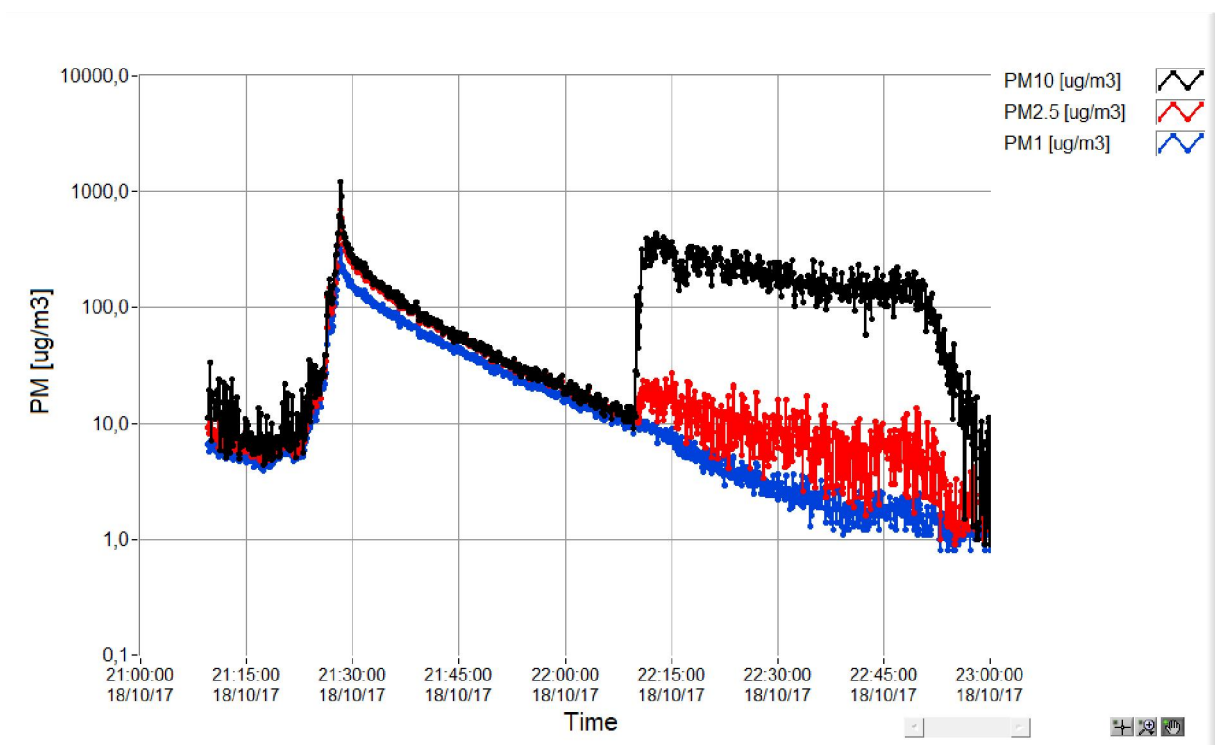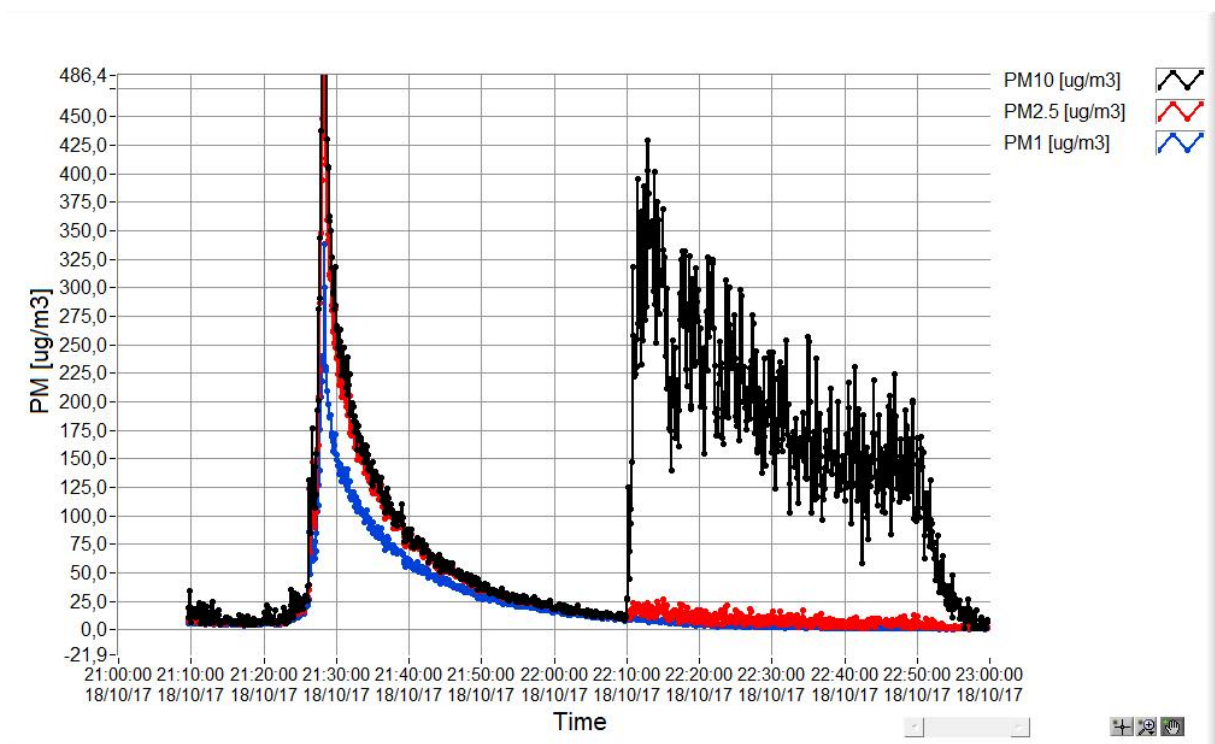
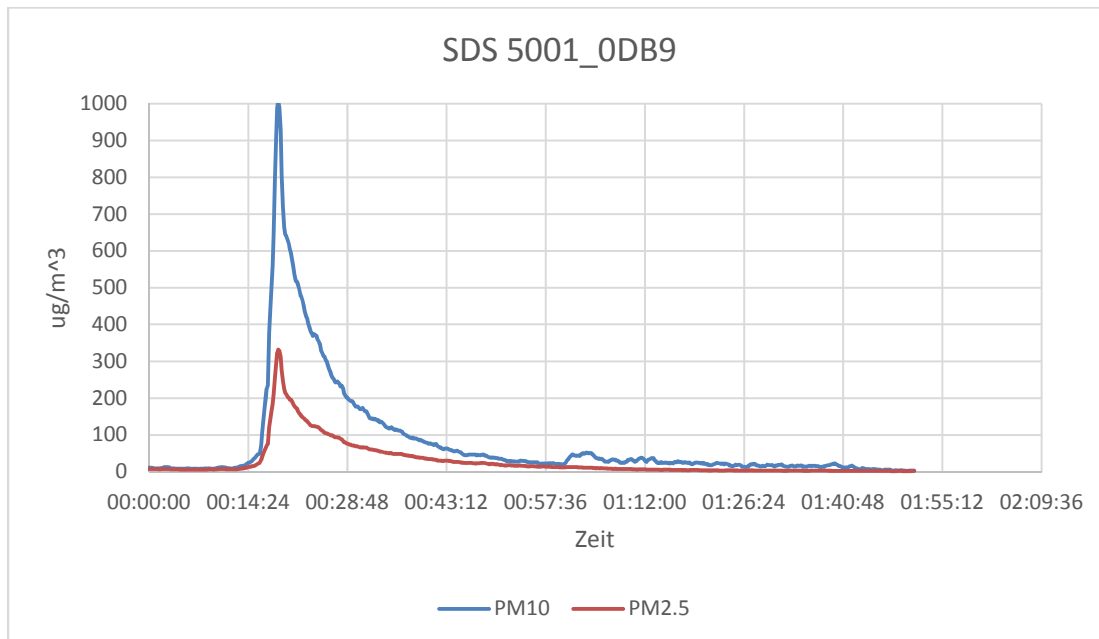Fig. 7: PM-mass concentration during the measurement as seen by the Grimm, clearly the two distinct phases can be seen (PM10=PM2.5 and PM10 >> PM2.5)

Fig. 8: PM-mass concentration during the measurement as seen by one of the SDS011 low cost sensors, during the first phase PM10 > PM2.5, during second phase PM10 is negligible
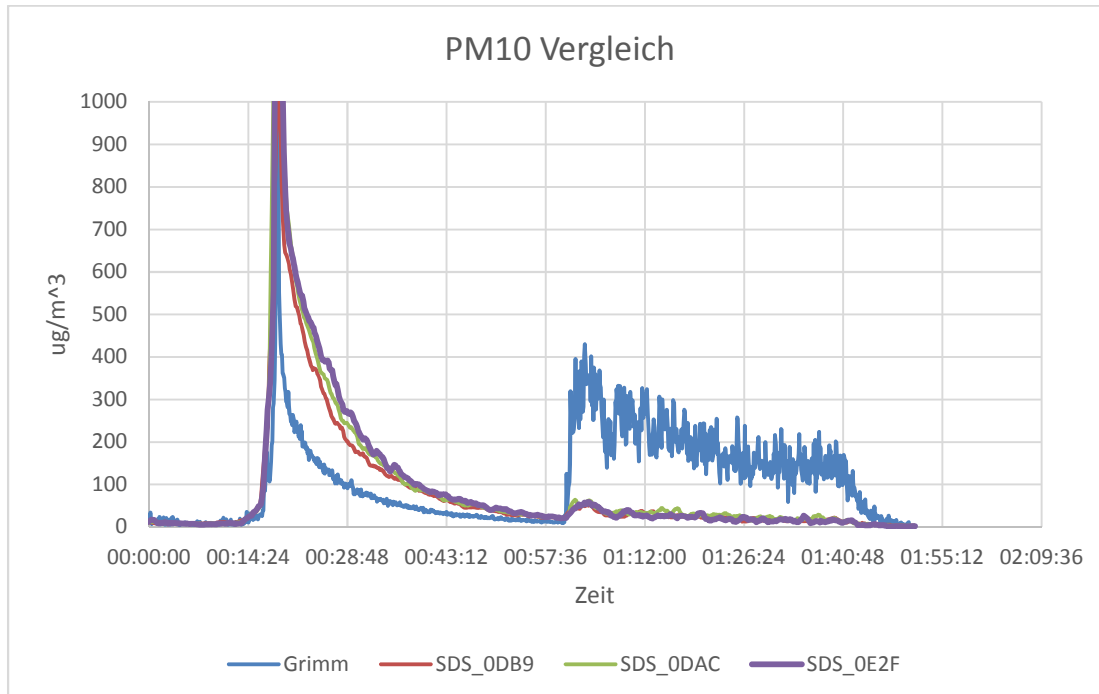

Fig. 9a: PM10 mass concentration compared between 3 SDS011 devices and the Grimm, all SDS devices behave similar
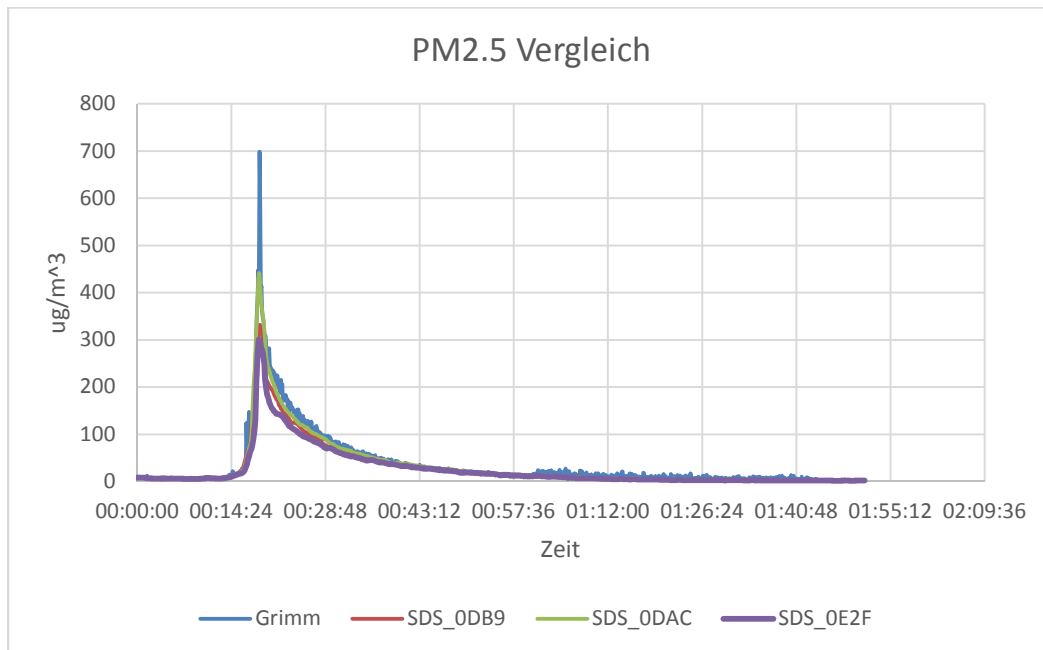
Fig. 9b: PM2.5 mass concentration compared between 3 SDS011 devices and the Grimm, all SDS devices behave similar
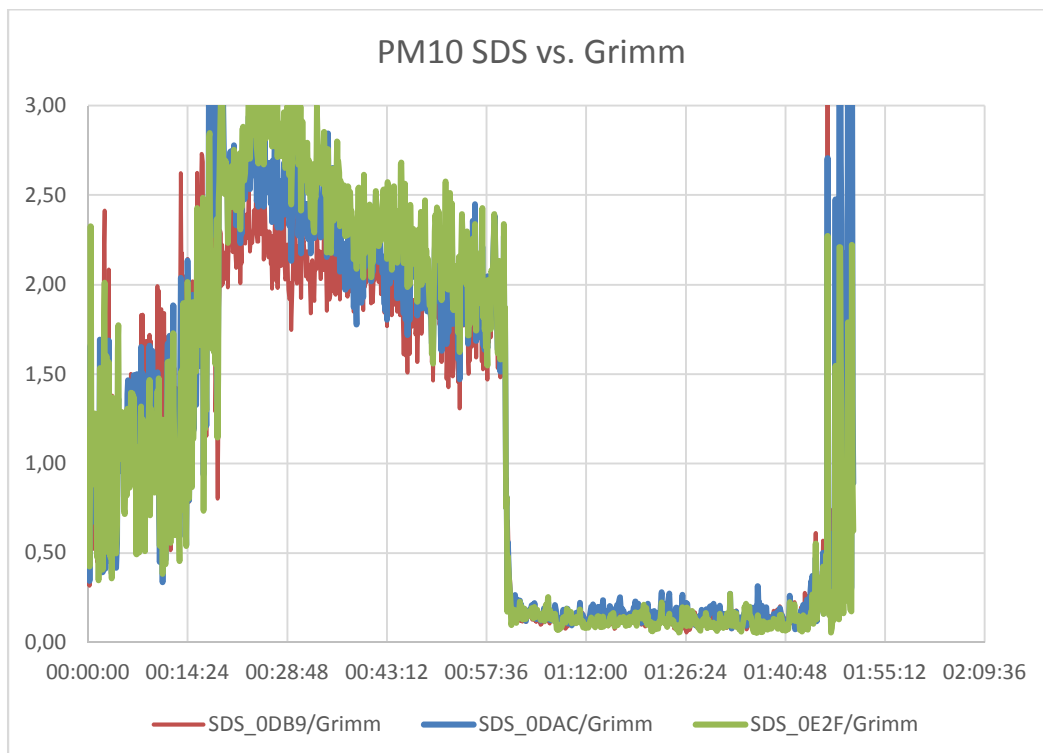

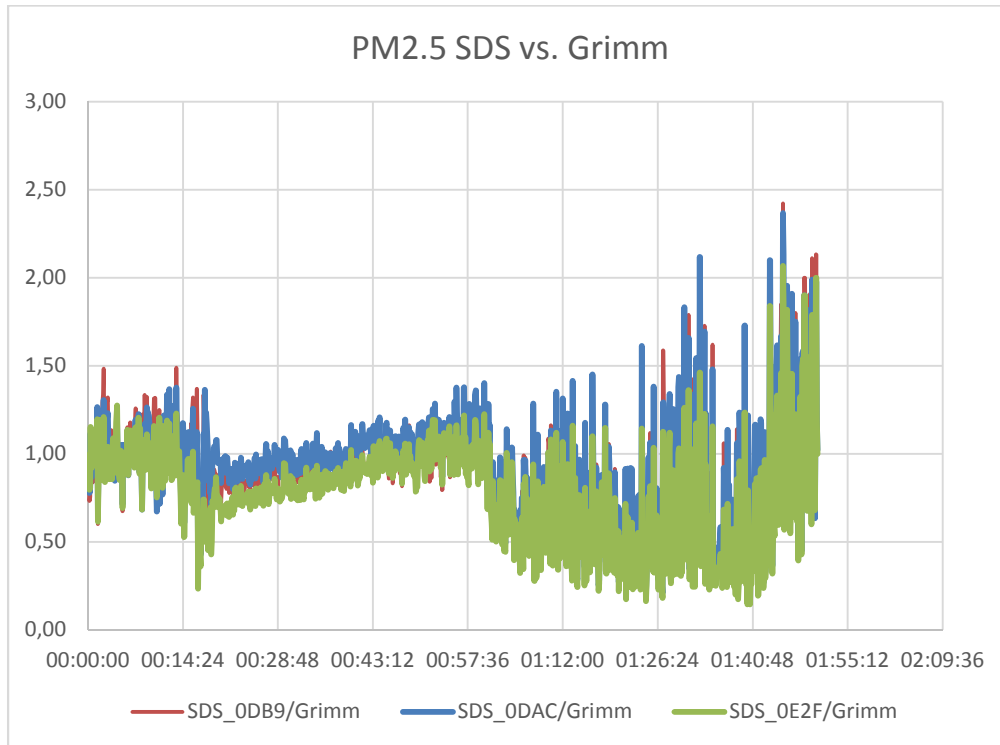Fig. 10a: The ratio of PM10 of 3 SDS011 devices with respect to the Grimm

Fig. 10b: The ratio of PM2.5 of 3 SDS011 devices with respect to the Grimm

When looking at the Grimm PM representation versus time, it can clearly be observed that the two different types of mass distributions were almost perfectly mapped into respective PM-readings. In the first phase, only small particles with d<2.5um contributed to the PM mass. Accordingly, the PM10 readings are almost equal to the PM2.5 readings, since no mass is contributed for large particles sizes. Therefore, the PM10 curve does not significantly differ from the PM2.5 curve. In the second phase, only particles with d>2.5um contribute to the PM mass. Accordingly, the PM2.5 readings are pretty small and PM10 readings are significantly larger than the PM2.5 readings differing by the mass that only contributes to the large size bins.

When looking at the 3 SDS011 devices however, a significantly different behavior can be observed. In the first phase the PM10 readings are not equal to the PM2.5 readings. This means the device reports mass contributions that fall into size bins for particles larger than 2.5um. PM10 therefore appears larger than PM2.5. This is obviously an erroneous behavior. The PM2.5 readings however follow pretty closely the PM2.5 readings of the reference instrument. This finding is in agreement with the findings for artificially generated electrical signals substituting the scattered light from particles. In these experiments, it was found that the PM10 reading is always larger than the PM2.5 reading even for the smallest light pulses generated. In the second phase, the different behavior is even more dramatic. The 3 SDS011 devices only see a small fraction for the PM10 values reported by the reference instrument. It appears as if the SDS011 devices are kind of blind for large particles. Interestingly all 3 randomly selected devices behave nearly identical inside the particle measurement chamber.

This finding is again in agreement with the findings for artificially generated electrical signals substituting the scattered light from particles. These electrical signals were fed directly into the A/D converter input of the on-board microcontroller of the SDS011. During these experiments, only a linear increase with the electrical signal pulse amplitude and even a saturating behavior for the optical pulse amplitudes could be observed when increasing signal amplitudes. Since mass is related with the 3rd power of the particle size, a much stronger increase in the characteristic would have been expected.

In the first phase a further effect can be observed. The SDS011 devices show a linear increase in PM2.5 values versus the Grimm reference instrument. It appears very likely that this effect is linked to the fact, that the mass distribution changes towards smaller particles since small particles sediment more quickly and the particle source is only active at the very beginning. This can be seen in a 3D-graph of differential mass concentration as measured by the Grimm along the measurement time. The plot actually shows the logarithm of the differential mass to cover the large dynamic range. In this graph a shift of the center of mass towards smaller particle sizes with time is visible during the first phase.
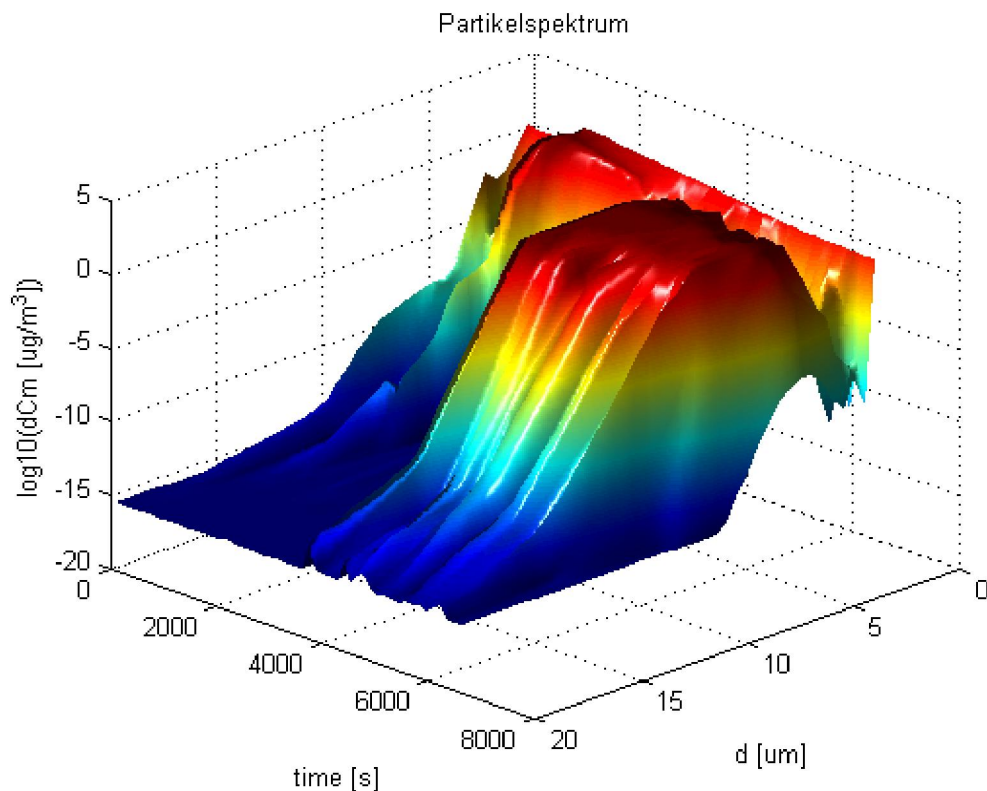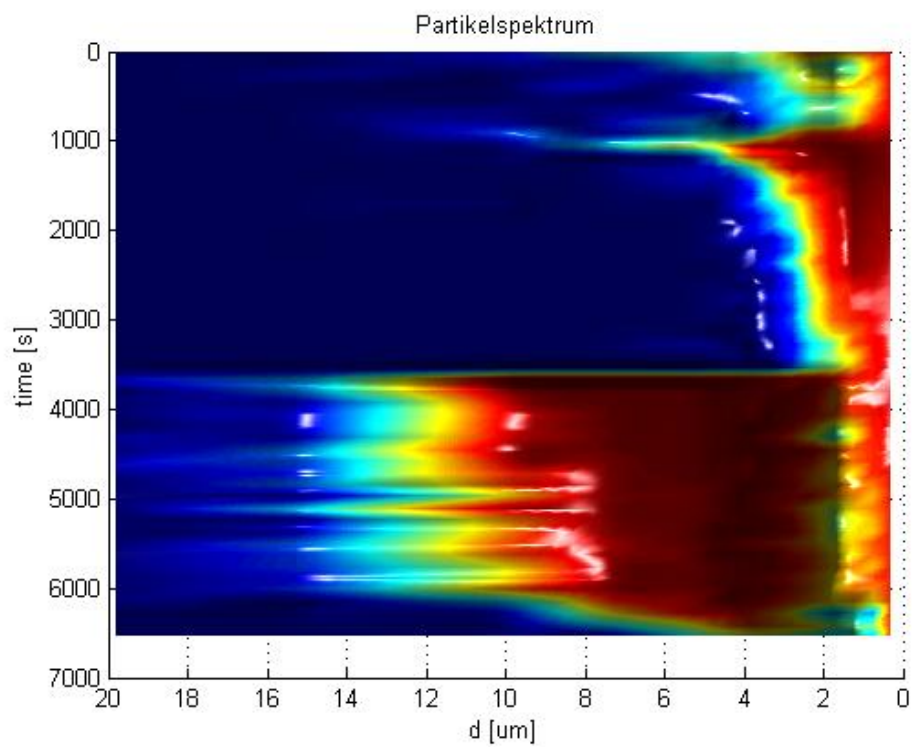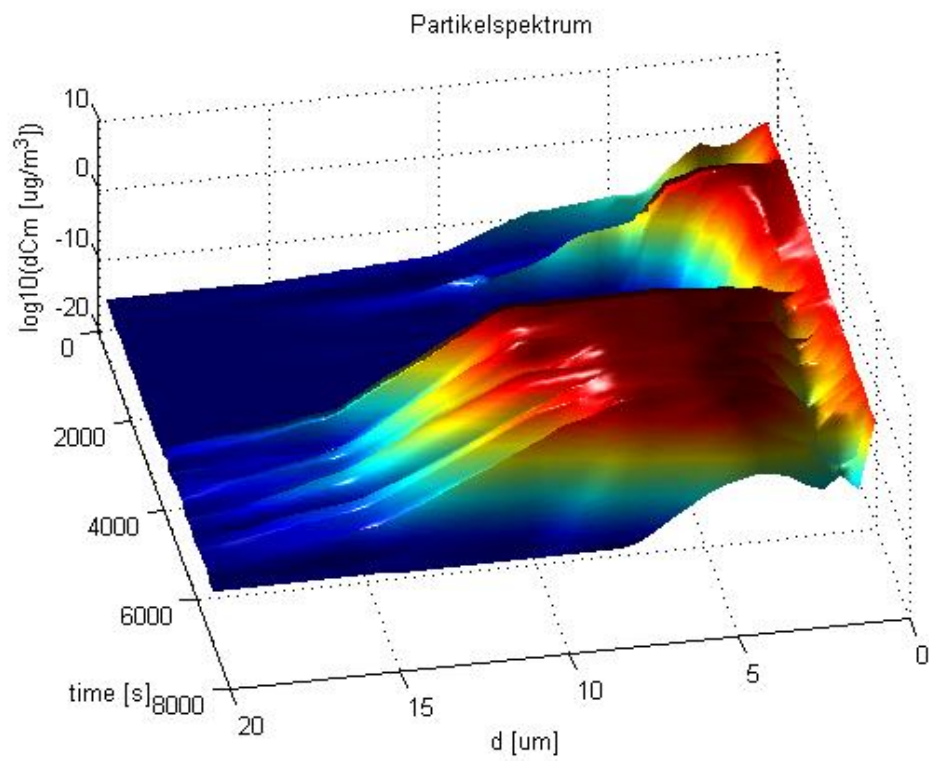
Fig. 11a-c: Particle distribution during the experiment plotted as 3D contour plot from different viewing angles

In general, this means the SDS011 devices have a design related issue with PM10 values when the mass of particulate matter is concentrated on larger sizes. The more a particle mass distribution is concentrated towards small particles sizes, the higher are the reported PM10 values compared to the reference instrument. The PM2.5 values however seem to be more or less correct. In the second phase this effect is extreme. PM10 readings drop to about 20% of the readings from the reference instrument. During the second phase, no meaningful statement on PM2.5 can be made, since the mass concentrations had been negligible.

Finally, the ratio of PM10 to PM2.5 is pretty illustrative for the distribution dependency of this design related deficiency when to comparing the first and the second phase. The Grimm reference instrument indeed shows a PM10/PM2.5 ratio close to 1 for the first phase whereas the SDS011 sensors deviate significantly with ratios > 4. In the second phase the Grimm shows a large PM10/PM2.5 ratio > 20 (in average) as expected whereas the SDS011 devices only reach a ratio of 6.5 as a result of underestimating PM10.
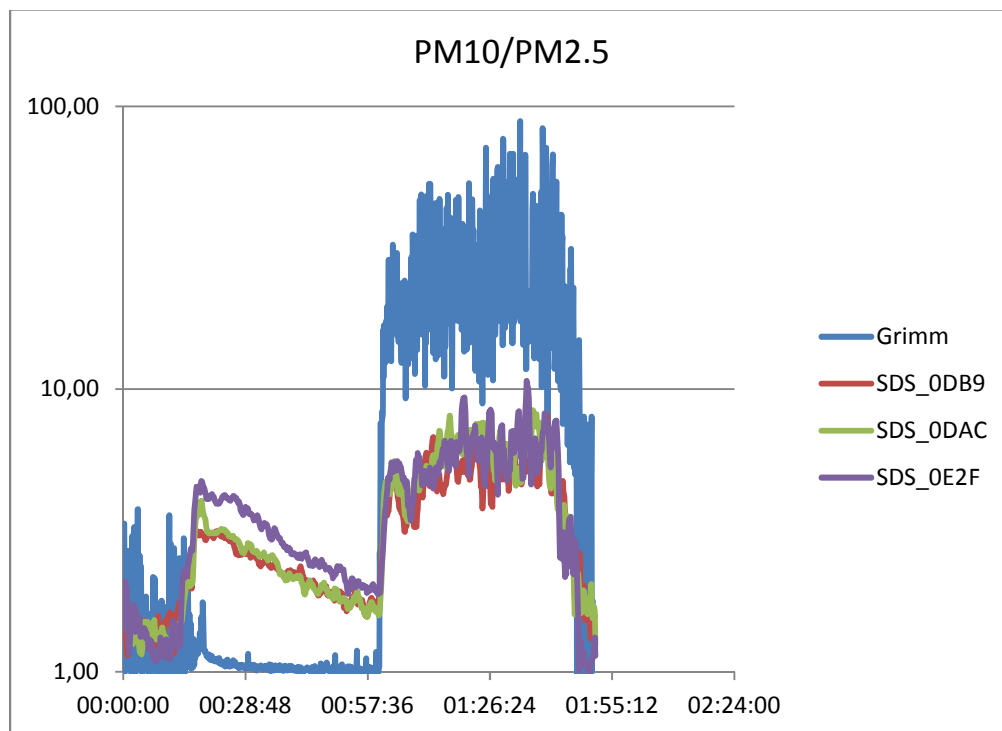

Fig. 12: PM10/PM2.5 ratio for the 3 SDS011 devices and the Grimm

In a second experiment, the particle generation sequence was repeated. However, an Alphasense low-cost PM sensor was placed in the chamber with one of the SDS011 devices. In the PM10 comparison of the PM10 to PM2.5 ration it becomes evident, that during the first phase the Alphasense OPC-N2 device correctly reports PM10 values equal to the PM2.5 values as expected. During the second phase, the OPC-N2 also shows PM10 readings much larger than PM2.5, even though the ratio isn't that extreme as with the Grimm. When comparing absolute values, it becomes apparent that the Alphasense reports larger values for PM2.5 (and thus also for PM10) than the Grimm reference instrument (factor 2) whereas in the

second phase however the readings are almost equal to the reference. In contrast, the SDS reports PM2.5 almost equal to the Grimm reference instrument (with wrong PM10 values) during the first phase.
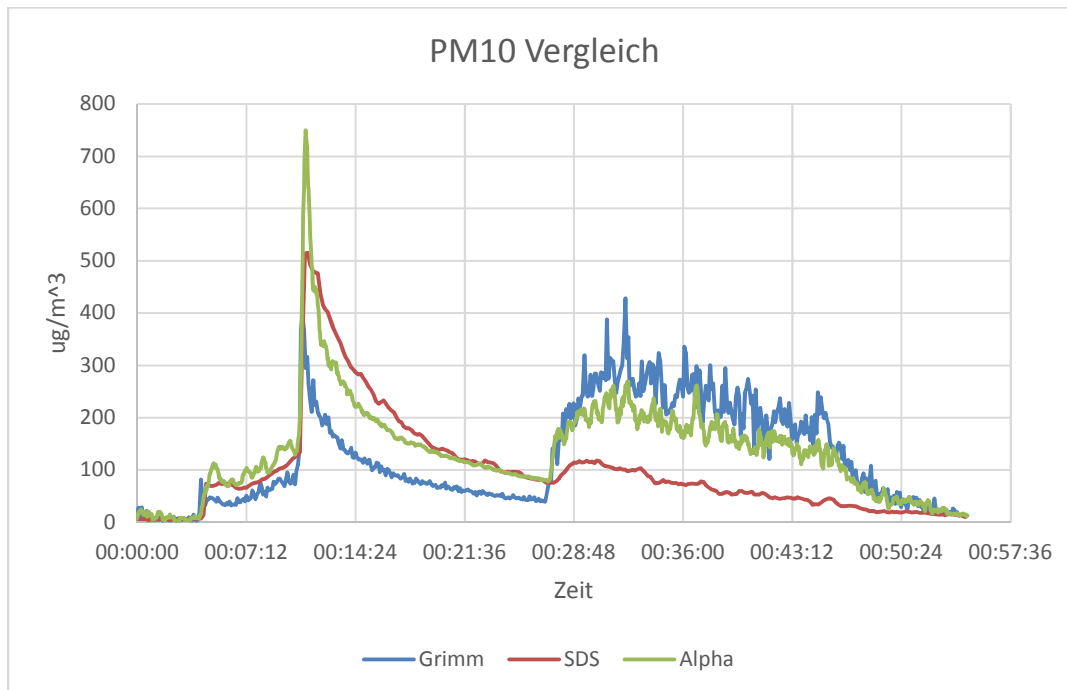

Fig. 13a: Comparison of an Alphasense OPC-N2 and a SDS011 with the Grimm during a similar change of particle distributions as in the previous experiment for PM10
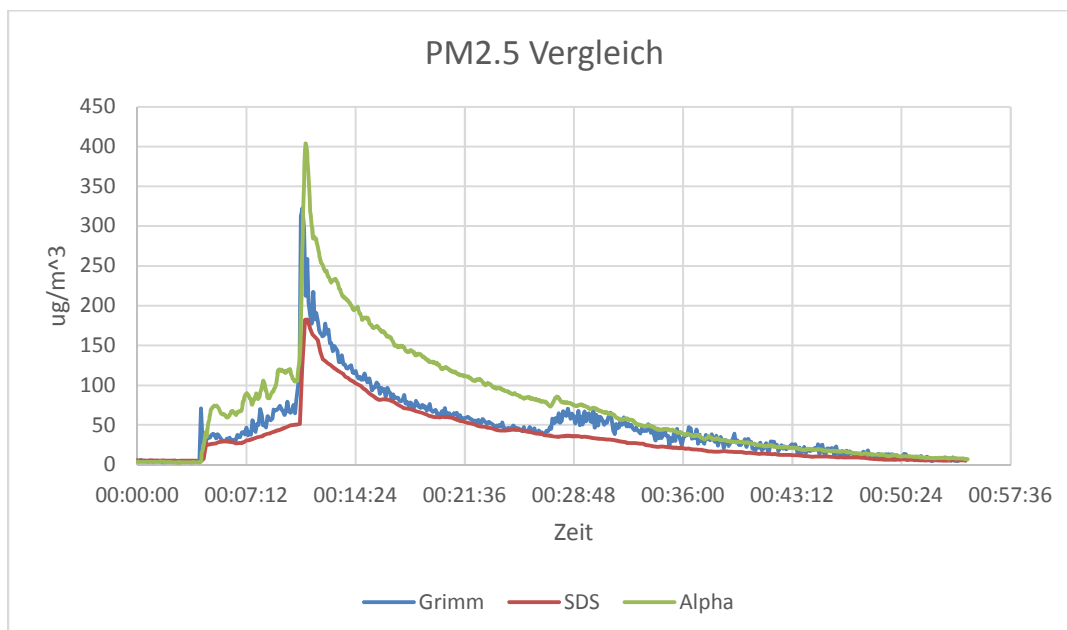

Fig. 13b: Comparison of an Alphasense OPC-N2 and a SDS011 with the Grimm during a similar change of particle distributions as in the previous experiment for PM10
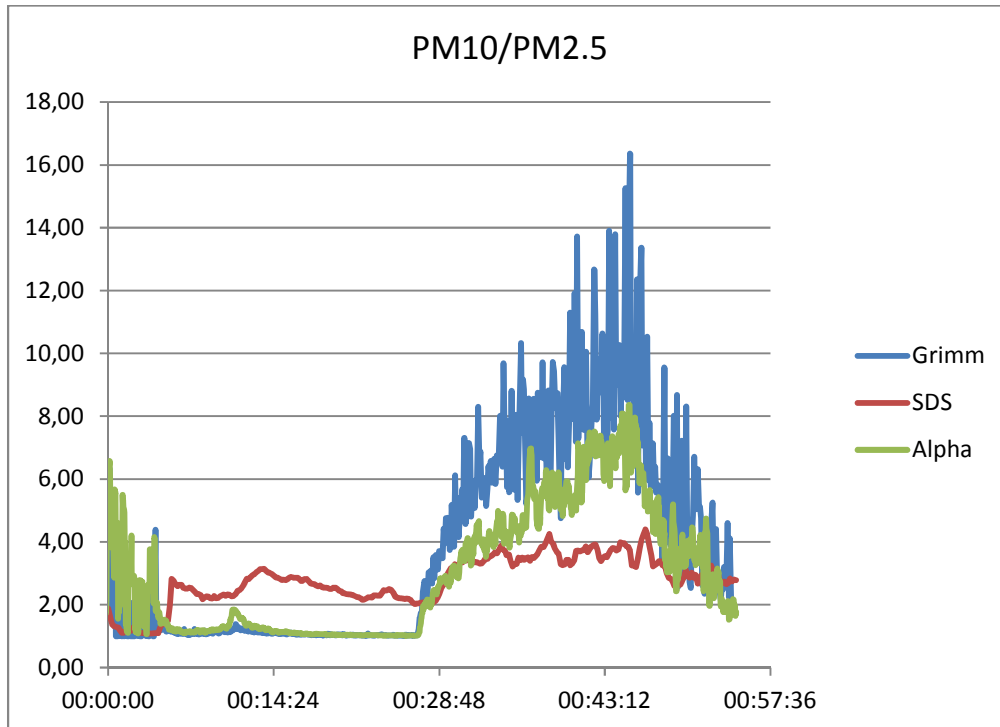
Fig. 14: PM10/PM2.5 ratio for the OPC-N2 device, the SDS011 device and the Grimm

As a consequence, we can state that the measurement uncertainty of low-cost sensors may be dependent on the particle mass distribution of the particle spectrum they are exposed to. In general, due to small measurement volumes and limited dynamic range of the electronic signal processing low-cost PM sensors tend to underestimate PM10 for dry aerosols. Whereas the SDS011 shows significant deficiencies for PM10 and thus should not be used for PM10 measurements, the Alphasense OPC-N2 sensor, despite some quantitative differences to the used reference instrument, seems to still be capable to measure PM10 appropriately and may be calibrated to the Grimm reference instrument. Both low cost PM-sensors appear to be suited for PM2.5 measurements according to this investigation and may be calibrated to a reference instrument.

For the sake of completeness however, it must be stated that the designation of the SDS011 device in the specification of the manufacturer is "Laser PM2.5 Sensor" even though it provides PM10 readings. The rated relative error does not mention PM2.5 or PM10 explicitly, but simply says "Maximum of ± 15% and ±10µg/m3" at 50% relative humidity and 25 °C temperature. Therefore, it can be assumed that this specification is valid only for PM2.5 and that the PM10 output is just a supplementary unspecified output. Restricting the specification of the SDS011 to PM2.5, the PM-sensor can be considered appropriately accurate with respect to cost.

The Alphasense OPC-N2 instead is explicitly designated as PM-sensor covering a specified particle size range from 0.38 to 17um in the specification of the manufacturer and thus should cover both, PM10 and PM2.5 measurements. According to this investigation, and keeping in mind that a reference instrument also can be inaccurate, the Alphasense OPC-N2 seem to meet the expectation of being appropriately

accurate with respect to its cost for PM2.5 as well as for PM10. It appears to be possible that both readings can be calibrated to a reference instrument.

Literature

/1/ Laser PM2.5 Sensor specification Product model: SDS011 Version: V1.3, Nova Fitness Co., Ltd. http://inovafitness.com

/2/ OPC-N2 Particle Monitor, Alphasense Ltd, Sensor Technology House, www.alphasense.com

/3/ Bernd Laquai, The Effect of Quantization Errors on the Measurement Uncertainty of Low-Cost PM-Sensors

/4/ Bernd Laquai, Assessment of Measurement Uncertainties for a SDS011 low-cost PM sensor from the Electronic Signal Processing Perspective