Development of a Calibration Methodology for the SDS011 Low-Cost PM-Sensor with respect to Professional Reference Instrumentation

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Introduction

When low-cost laser-scattering PM-sensors came up, mainly targeted for use in commodity devices, scientific researchers and citizen scientists also became interested. The idea that popped up was to deploy them for the investigation of the outside air pollution instead of using expensive professional equipment. It was mainly the fact, that air quality in the outdoor environment is not just an issue occurring only at a single spot but it is a spatial problem. For an in-depth investigation of particulate matter concentrations in the air and its meteorological dependencies it is required to perform simultaneous distributed measurements to obtain 3D spatial data, or at least 2D areal data, instead of collecting data solely from a few hot spots. Since professional PM-measurement equipment is still extremely costly, the idea to equip the nodes of a sensor network distributed across a large city or even larger regions with professional equipment is simply infeasible. However, when a sensor for such a network node is available for several tens of Euro, then it becomes a highly attractive option to really implement such a network based measurement system.

Many studies were carried out to compare low-cost PM sensors with professional equipment. Many of these studies simply positioned the sensors together with professional equipment in the outdoor environment and compared the results. The particle spectra changed with meteorology and the location where the sensors where positioned. Since the computation of a PM value such as PM10 actually means to integrate the particle mass distribution from the lower detection limit up to the 10um size (to be correct, a certain fractional efficiency characteristic should be also taken into account), the specific influence of a certain particle mass distribution on the result is lost. Therefore, such comparisons weren't really able to state the accuracy of the sensors in dependence of different particle spectra. As a result, the sensors performed reasonable under very typical conditions where the mass distribution was comparable to conditions assumed by the manufacturers but failed for conditions where the particle mass was distributed in an unexpected way.

However, as soon as more detailed lab investigations were published, the envisioned area of application narrowed down. Several significant deficiencies and sources of measurement errors for low-cost PM sensors become apparent. The very low-cost PM sensors mostly designed and manufactured in China are PM2.5 sensors. Often, they also provide an additional PM10 or even a PM1 value output without providing specifications of accuracy differently for each PM class. During lab measurements, it became clear that these sensors aren't really able to measure particle sizes larger than 5um. The size limitation also became pretty obvious when artificial light pulses of different intensity and frequency were injected into the measurement chamber to simulate scattering pulses of particles of different size and concentration or when the pulses at the transimpedance amplifier output are substituted by precisely controlled pulses from a pulse generator. Therefore, it must be assumed, that at least the values for PM10 are simply extrapolations from particle sizes between 0.3 and 2.5um, the low-cost sensor is still able to detect.

It also became evident, that most of these very low-cost devices do not calculate a PM value from a multi-bin histogram but either average the signal from the scattering light detector or do a simple two or three threshold comparison to determine a PM value. Since in such a case, only a coarse average mass can be assigned to the counted number of scattering light pulses, the sensor overestimates the mass of smaller particles and underestimates the mass of larger particles. The actual relationship between mass and size, which according to the ideal spherical theory is a function of the third power of the particle size, is rarely reflected correctly by low-cost sensors. However, at least one of the investigated sensors really does a histogram based PM calculation and outputs PM1, PM2.5 and PM10 values calculated from 16 bins in a comprehensible way (Alphasense OPC-N2).

Finally, a severe issue that became apparent when using low-cost PM sensors for environmental investigations is related to humidity: Most governmental regulations require the PM concentrations to be measured using gravimetric methods in laboratory. In order to match these laboratory results with laser scattering equipment measuring online, the air taken in from the measurement device must be dried to remove humidity. A low-cost PM sensor based on laser scattering however sees the particles under the influence of hygroscopic growth. Particles released in the urban environment often contains hygroscopic salts that start to grow in volume when being exposed to relative humidity already at 60-70%. Since dust prone meteorological situations in winter often correlate with high relative humidity, the particle growth factors related to particle mass is in the range of 2-5 leading to heavily overestimated PM values when not being corrected for the humidity influence. For professional laser scattering PM-measurement equipment it was shown that a humidity correction is possible when no air dryer is used and finally yields comparable results to the measurement with an air dryer or with gravimetric measurements as requested by regulation authorities.

The issues described above raise the question, if it is possible to calibrate a low cost-sensor to professional reference equipment in order to overcome the measurement deficiencies. Theoretically, a calibration measurement in the lab or in the field should be possible, comparing a low-cost sensor to the reference equipment from which a calibration factor or function is obtained. Then it can be expected that during the application of the low-cost sensor the calibration data can be used to compensate the differences to a reference instrument to a certain degree, such that the final measurement accuracy after calibration is improved compared to the accuracy without the calibration.

Assumed the humidity effect is treated separately, the challenge for the design of a calibration algorithm is the dependency of the measurement error on the shape of the particle mass distribution versus size. It seems to be obvious that the absence of binning the particles into size classes for many low-cost PM sensors results in strong deviations when the measured particle spectrum does not match the one for which the sensor was designed. Typically, a mass distribution determined at the curbside of a road in an area heavily loaded with traffic is dominated by large particles. This means that the center of gravity in such a particle spectrum is located at a size larger than 5um. On the other hand, in urban residential areas with low traffic load the mass distribution is normally dominated by small particles. Therefore, the center of gravity in such a particle spectrum is located below 5um. As a result, the ratio between the PM values of the low-cost sensor and the reference equipment will be different in both locations. As a consequence, a calibration should take into account any information available on the shape of the particle mass distribution and has to be designed rather as a calibration function than as a simple fitting factor.

Particle Generation Experiments

In most cases where comparative measurements were taken in the field yielding simultaneous PM data from low-cost sensors and the reference instrument the influence of the mass distribution on the PM results couldn't be analyzed in a controlled way. Therefore, in this study the idea was to investigate this dependency in a measurement chamber of a particle generator in laboratory where particle spectra could be generated with a controlled distribution.

For this purpose, a particle generator was developed that is able to disperse very small particles from a smoke generator as well as large particles from a powder disperser. The smoke generator is constructed from a heater that nebulizes a smoke liquids as used by model railways (paraffin, glycol). The powder disperser is constructed from a bass loudspeaker driven from a low-frequency AC source. The powder is loaded on the speaker membrane and is dispersed by the oscillating movement of the membrane. Both particle sources are electronically controlled. The heating element of the smoke generator is controlled from a PWM modulated microcontroller via a MOSFET power switch and the powder disperser is driven from a sinusoidal AC source with controlled frequency and amplitude.

Both particle sources are arranged in the upper portion of a measurement chamber whereas the device under test and the reference instrument are arranged in the lower portion of the chamber to ensure enough homogenization of the particle concentration in the air when the particle sediment under the influence of gravity (see fig. 1).

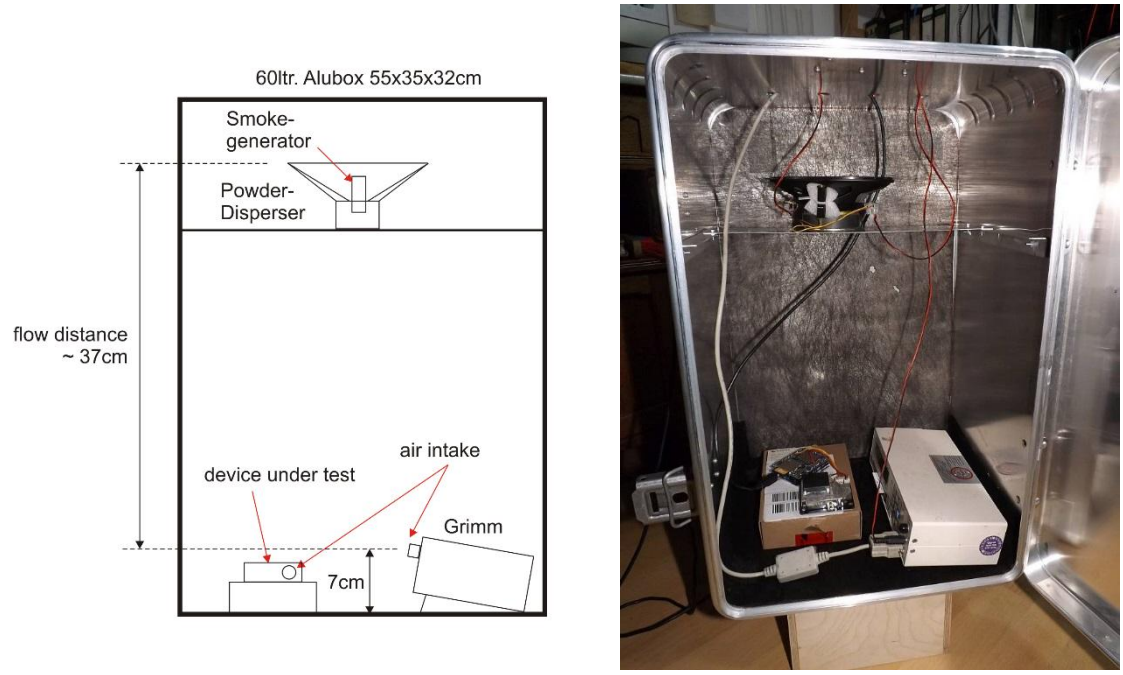

Fig. 1: Conceptual drawing and implementation of the particle generator used for the calibration measurements

Several smoke liquids as well as powders were tested to generate distinct particle distributions that result in different PM10/PM2.5 ratios. With respect to the goal of developing a calibration scheme, it turned out that with the two dispersing methods two extreme particle distributions can be generated in a complementing way. Whereas the smoke generator typically generates a particle spectrum with particle mass distributed between the lower detection limit of the reference instrument (0.3um) up to 1um, the powder disperser typically generates a particle spectrum where the mass is distributed between 2um and 15um. The powder that is used for such a spectrum is either milled mineral powder available as pharmaceutical product (Luvos Heilerde) or pastry flower (type 405).

PM-measurement observations for different particle spectra

When particles with a broadly distributed mass spectrum are released into the measurement chamber, the sedimentation process induces a change of the mass distribution of the particle spectrum during the subsequent measurement time. Since larger particles sediment faster than small particles, the center of gravity shifts towards smaller sizes over time. As a consequence of this shift and due to the fact that the low-cost sensors typically underestimate the large particle mass concentrations, it can be observed that the ratio between the low-cost sensor values and the professional equipment values also changes. With a particle spectrum where the mass is initially dominated by large particles, the ratio of low-cost PM values and professional PM values typically starts significantly below 1 and then shifts towards a ratio of 1 after a certain amount of time. Towards the end of the measurement, the large particles are already settled to the ground and only small particles are left in the air volume. A requirement to clearly observe this behavior is an overall mass concentration that is small enough with

respect to the maximum range of the low-cost sensor to avoid non-linearity issues due to coincidence effects during particle counting.

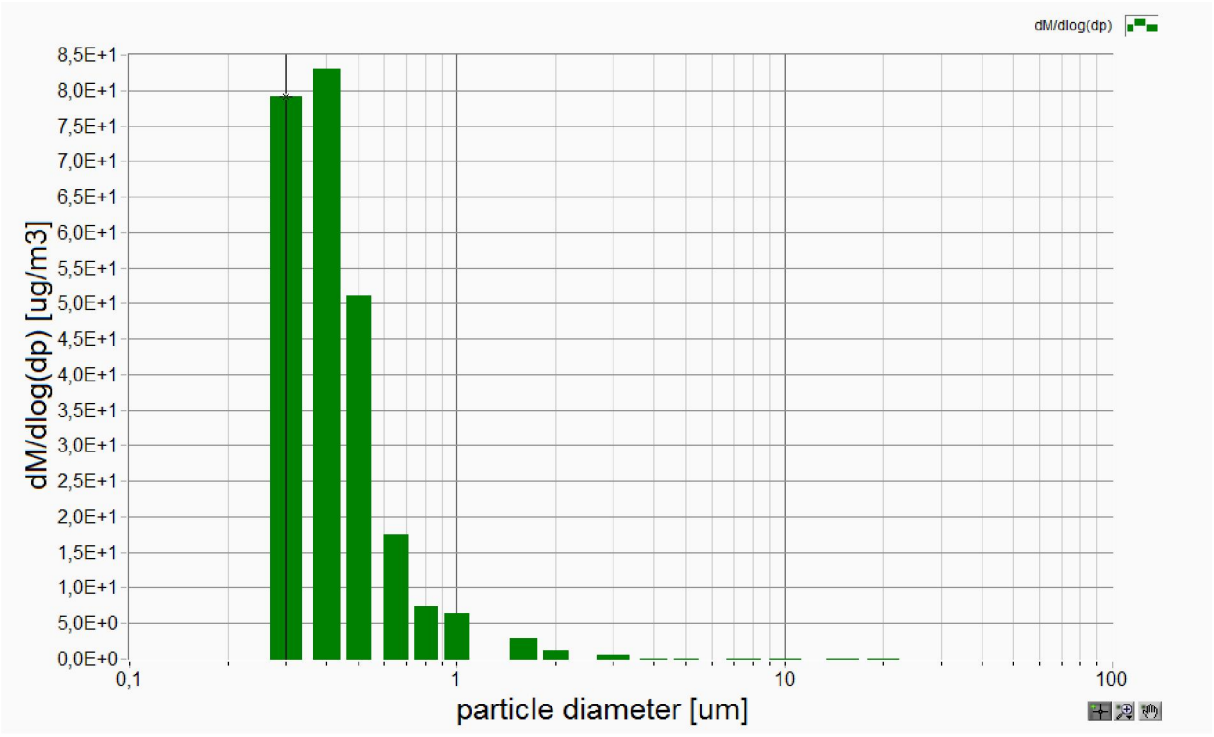

Fig. 2a: Typical particle mass distribution generated by the smoke generator (paraffin liquid)

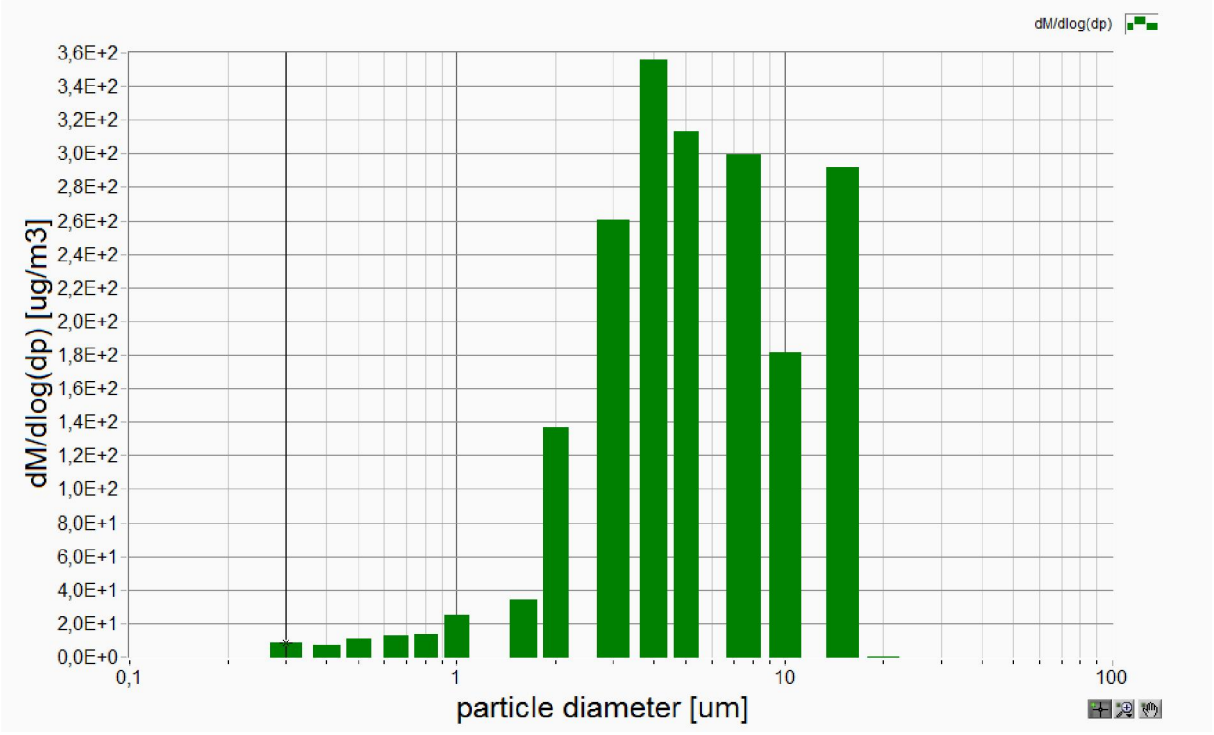

Fig. 2b: Typical particle mass distribution generated by the powder disperser (pastry flower type 405)

In this study a SDS011 sensor from Nova Fitness Co., Ltd. (China) was used as a low-cost sensor and a Grimm 1.108 aerosol spectrometer was used as reference equipment. The SDS011 device is a PM2.5 laser-scattering sensor developed mainly for air conditioning and air cleaning equipment. It also

provides a PM10 output. However, dedicated tests have clearly shown that the device is not able to detect particles larger than 5um when no small particles are contained in the particle spectrum. From previous investigations, it is also assumed that the device does not calculate a multi-bin histogram for PM-calculation. The datasheet does not provide a separate accuracy specification different for PM2.5 and PM10.

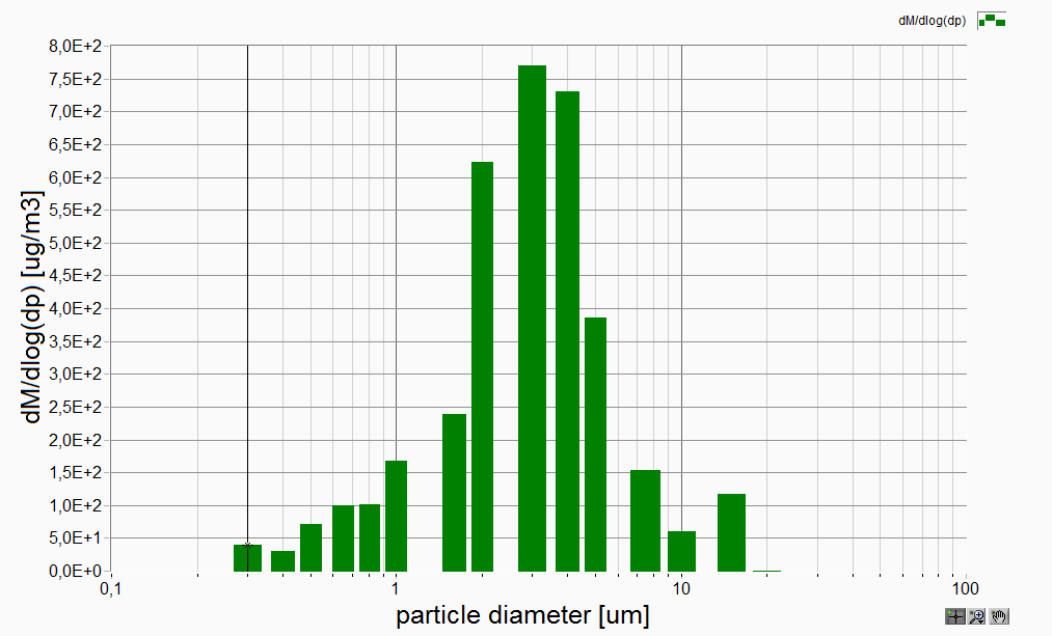

Fig. 3a: Particle mass distribution for mineral dust at the beginning of the measurement

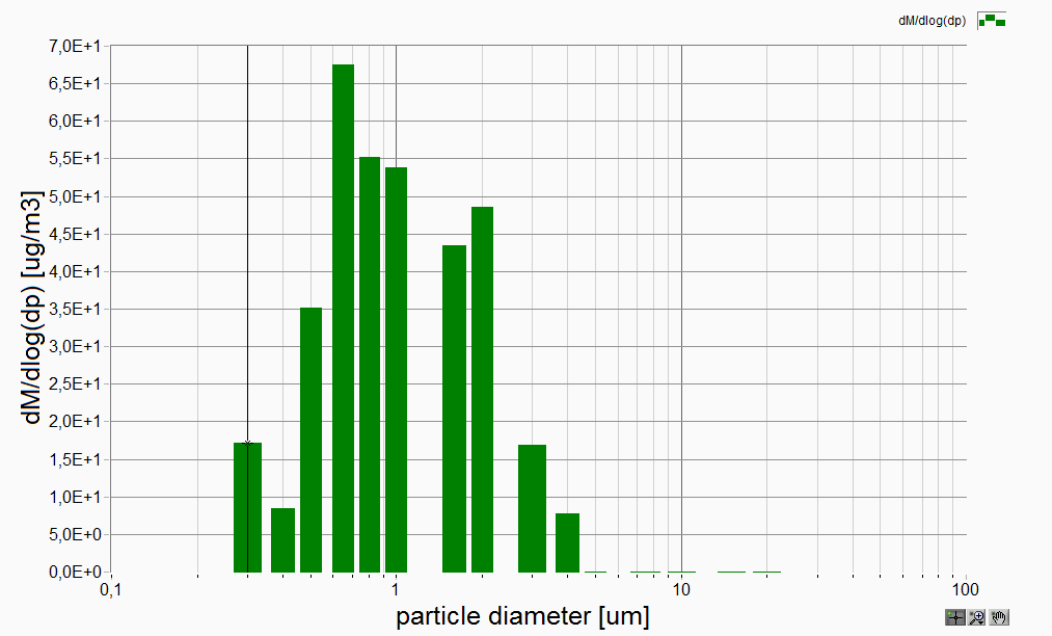

Fig. 3b: Particle mass distribution for mineral dust at the end of the measurement

A situation as described above is shown in the following first measurement example. Mineral dust with a typical mass distribution between 0.3 and 10um was released to a measurement chamber. At the beginning of the measurement, the reference instrument shows a mass distribution between 0.3 and 15um. In the course of sedimentation, the mass distribution changed and the center of gravity in the distribution shifted from about 3um towards less than 1um.

This behavior can be observed even better when a 3D color graded contour plot is generated from the particle mass distribution across the time. From this plot, it can be seen that the large particles vanish quickly and then a shift of the center of gravity in the distribution occurs towards smaller particle sizes.

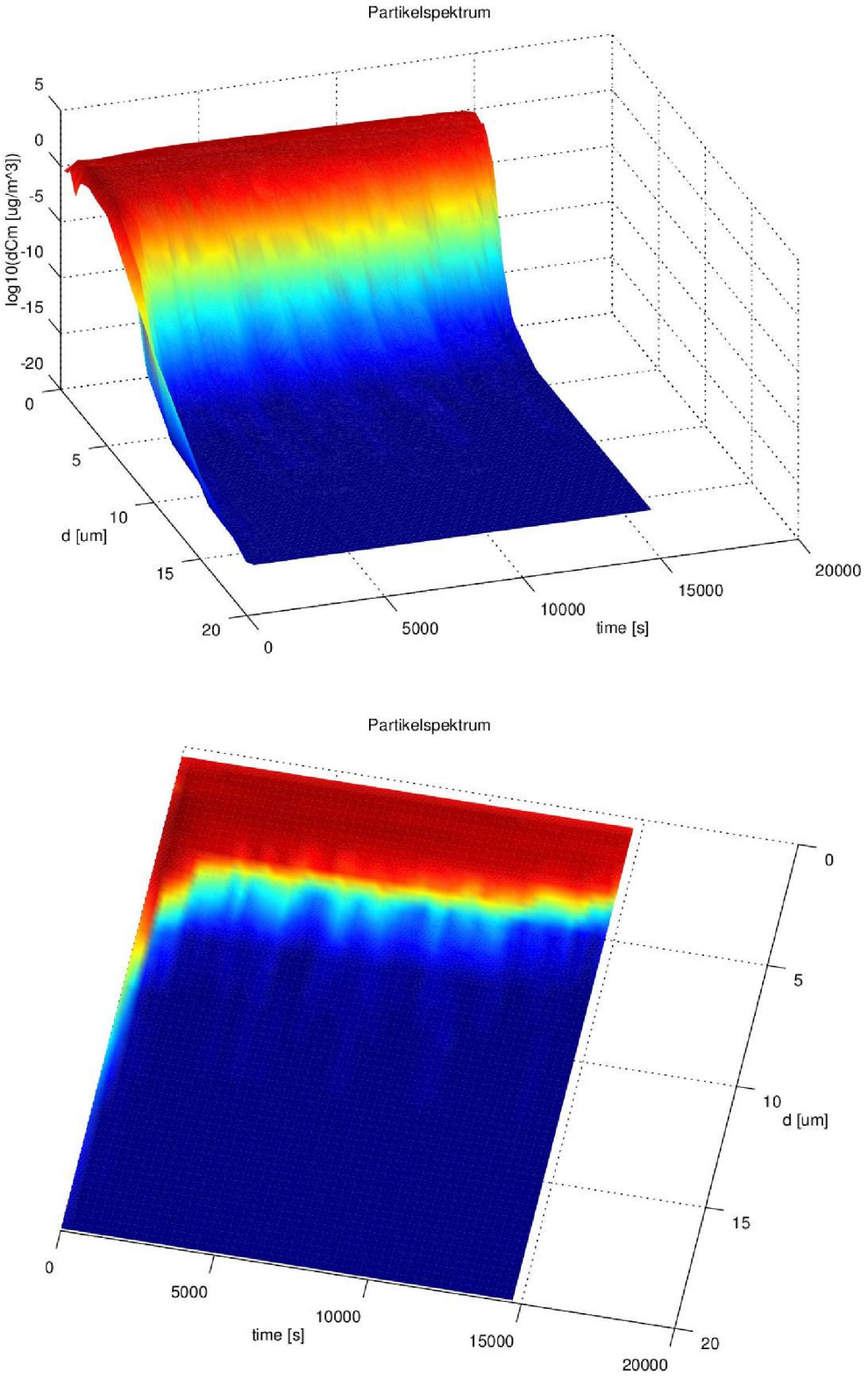

Fig. 4: Color graded contour plot of the particle mass distribution (logarithmic scale) versus size and measurement time for the mineral dust experiment

In fig. 5a and b the PM10 and PM2.5 measurement result for both the SDS device and the Grimm reference instrument are shown. From the reference instrument results that is supposed to be correct, it can clearly be seen that initially, a distinct peak appears where PM10 is significantly larger than PM2.5. During this initial peak the mass is dominated by particles larger than 2.5um. When the ratio of PM10/PM2.5 is evaluated, the reference instrument shows an initial PM10 value that is by a factor of 4 larger than PM2.5. After a certain amount of time the large particles are settled to the ground and the PM10/PM2.5 ratio tends towards 1, since only small particles still remain in the air and the PM10 and the PM2.5 values become almost equal. The SDS011 device however, reports a large initial PM10/PM2.5 ratio of about 6.5, mainly because PM2.5 was measured much smaller during this phase. For the rest of the measurement the ratio PM10/P2.5 remains between 5 and 4. During this phase, the PM10 values estimated by the SDS011 are much larger than that of the reference instrument (see fig. 6 and 7).

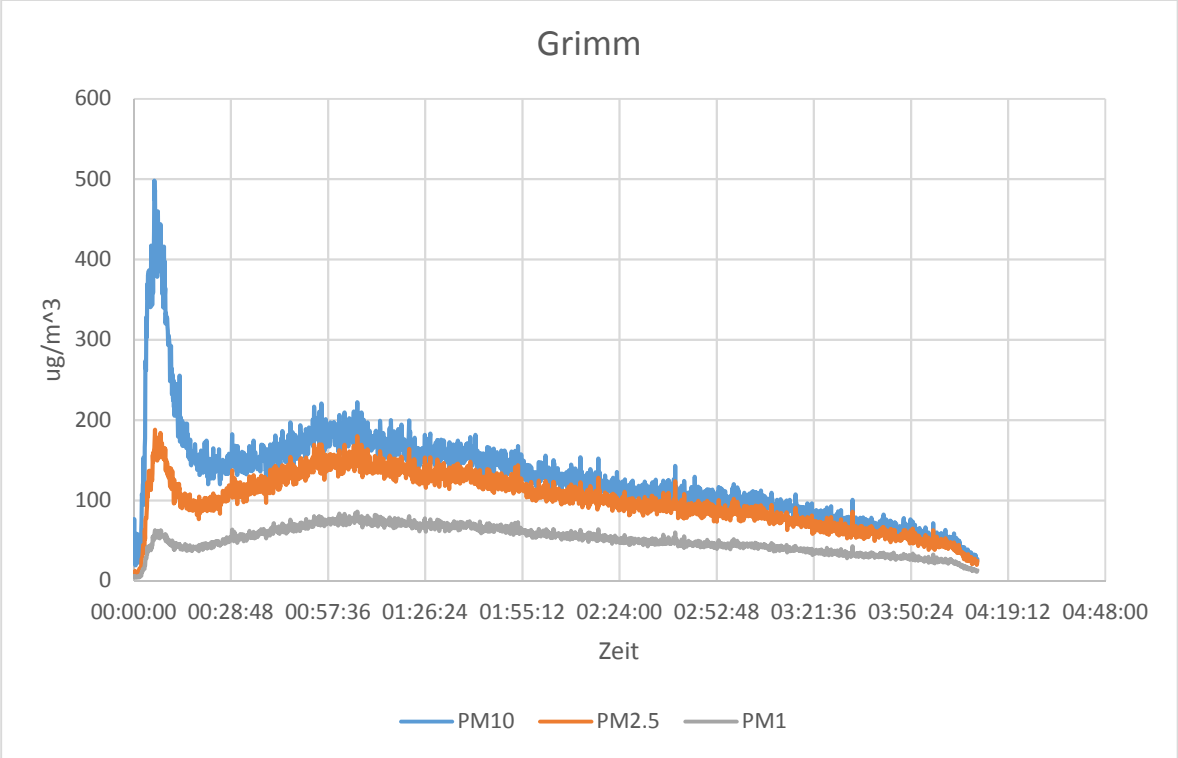

Fig. 5a: PM measurement result of the reference instrument (Grimm 1.108) for the mineral dust experiment

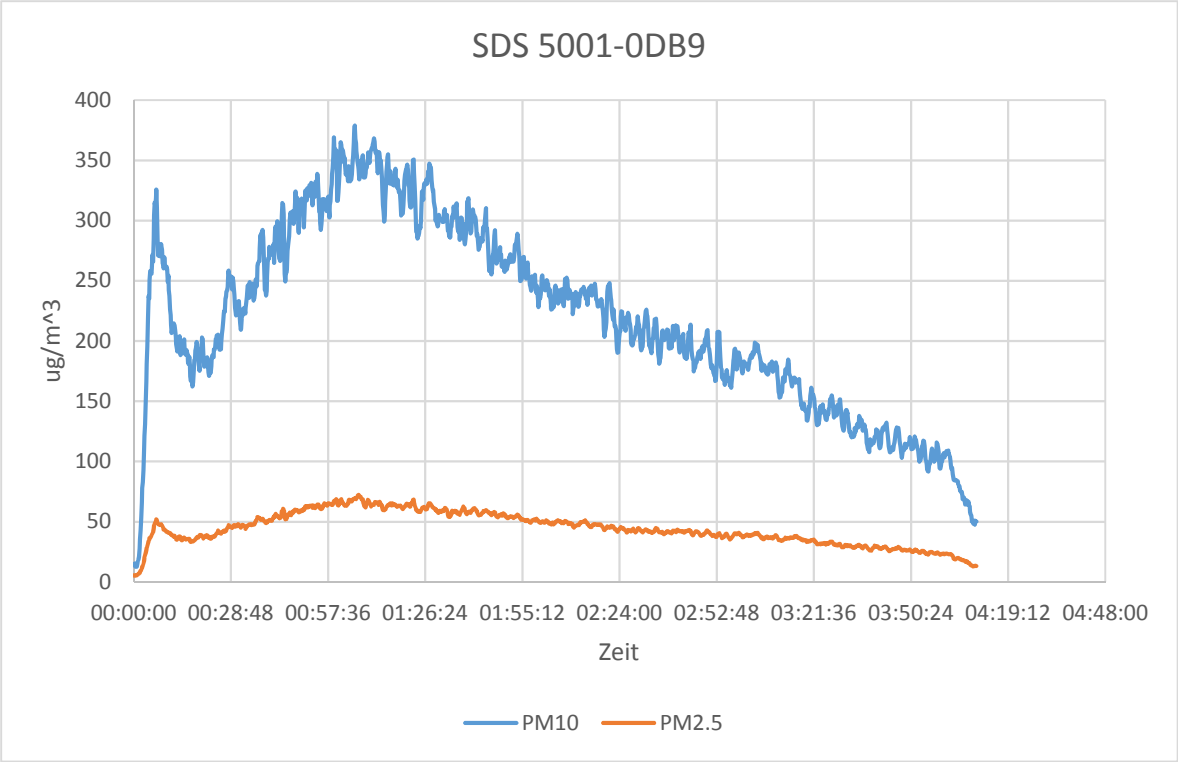

Fig. 5b: PM measurement result of the SDS011 low-cost sensor for the mineral dust experiment

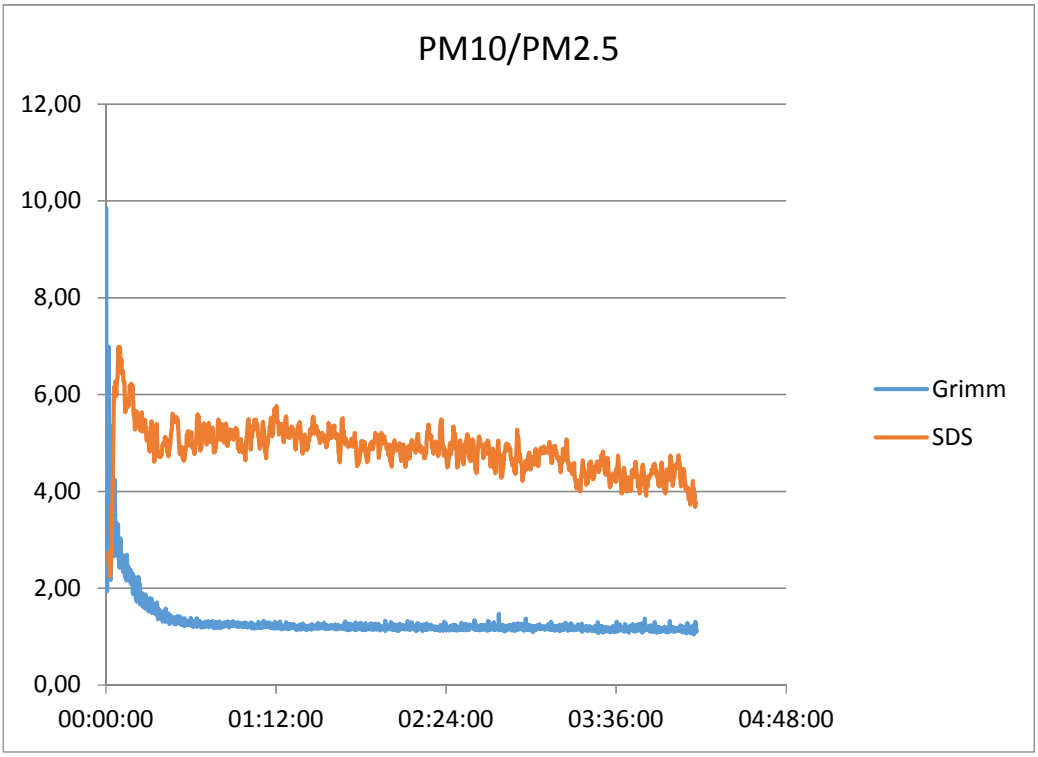

Fig. 6: PM10/PM2.5 ratios for low-cost sensor and reference instrument

When comparing the results of both devices it becomes obvious that the ratio SDS/Grimm initially is smaller than 1 for PM10 (and PM2.5) and after the large particles have settled, this ratio approaches 2 for PM10. In contrast, for PM2.5, the SDS/Grimm ratio stays between 0.3 and 0.6.

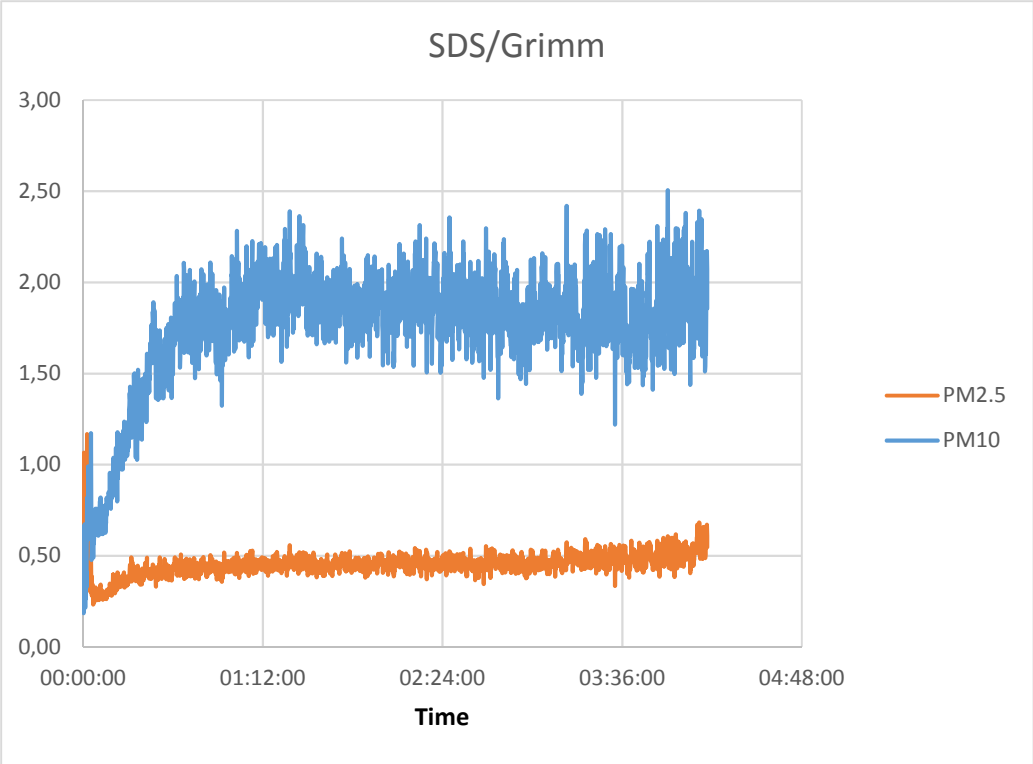

Fig. 7: The ratio of PM results for low-cost sensor versus reference instrument (averaged), a strong deviation of the low-cost sensor becomes visible

These observations are repeatable and can also be reproduced with other types of dust as long as the mass is distributed broadly. There is also only minimal variation when different low-cost sensor devices of the same manufacturing batch are used. It clearly shows that for such a particle spectrum the SDS011 low-cost device shows a large measurement inaccuracy. Other devices similar in cost from different manufacturers (Plantower, Bjhike) were also investigated and even showed a worse behavior.

In the following second measurement example, the smoke generator was used with a paraffin liquid to generate a particle spectrum. Fig. 7 shows the mass distribution versus time indicating that the particle mass is initially distributed across diameters < 5um and at the end of the measurement the particles contributing to the mass are smaller than 2um. Therefore, with respect to the particle mass distribution, this spectrum complements the previous spectrum.

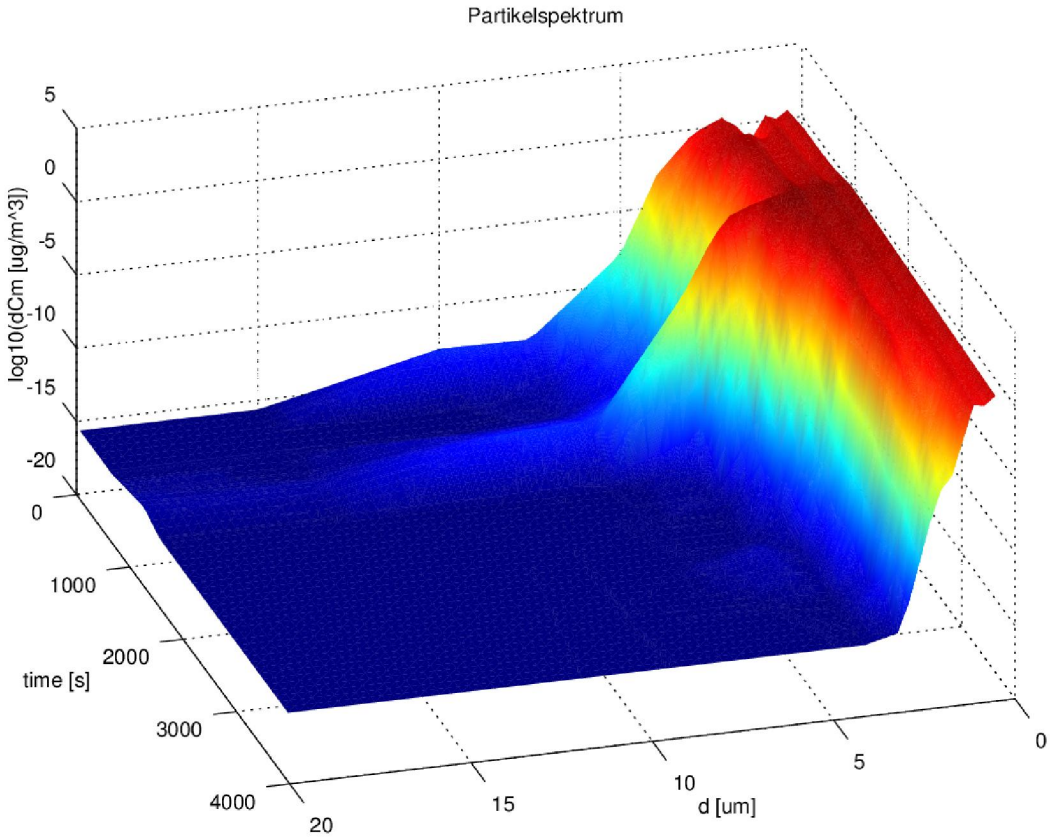

Fig. 8: Color graded contour plot of the particle mass distribution (logarithmic scale) versus size and measurement time for the paraffin smoke experiment

As a consequence of the missing mass contribution from particles > 2.5um (except during start of the measurement), the reference instrument reports a PM10 value almost equal to PM2.5. The low-cost sensor however shows a PM10 value that remains much larger than PM2.5 throughout the whole measurement. The reason for this behavior is the fact, that the low-cost sensor actually is a PM2.5 sensor and does not measure PM10 but estimates it from smaller particle sizes. As it can be seen, under this conditions of the given particle spectrum, the low-cost sensor performs a fairly wrong estimation of PM10 with a PM10/PM2.5 ratio between 1.5 and 2.5 instead of ideally 1 after the larger particles have settled (fig. 9a, b).

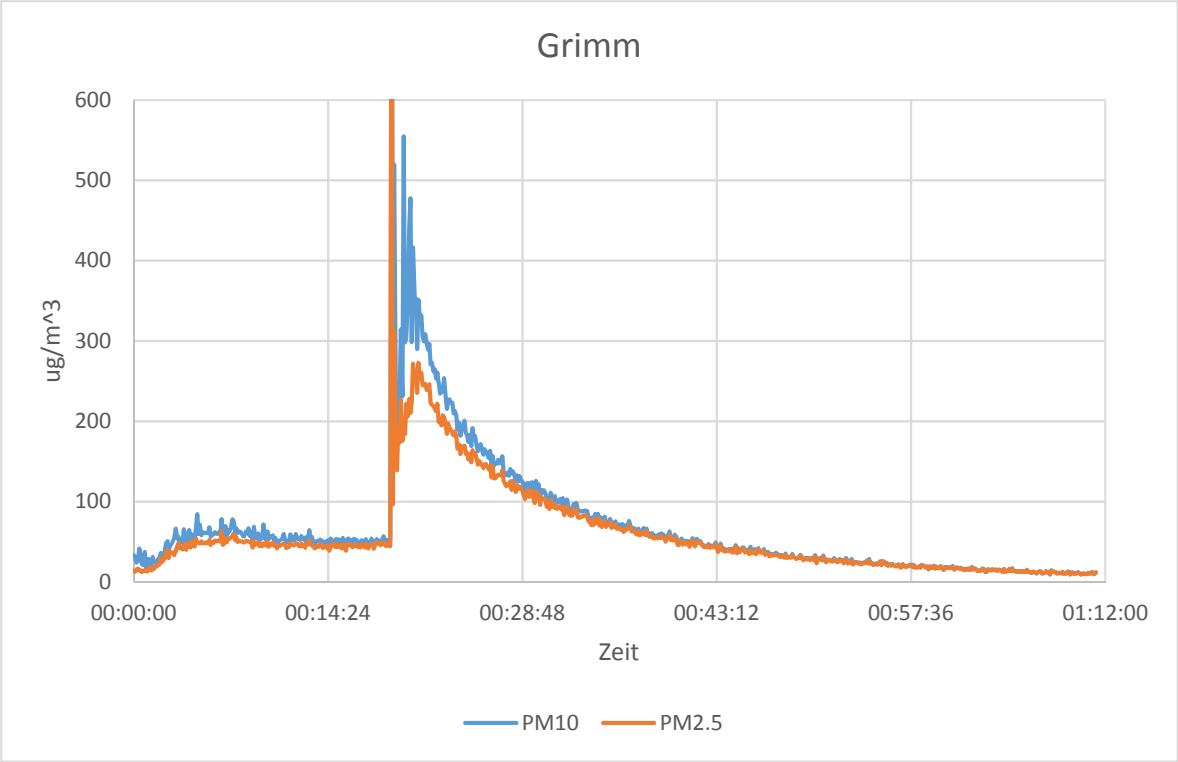

Fig. 9a: PM measurement result of the reference instrument (Grimm 1.108) for the paraffin smoke experiment

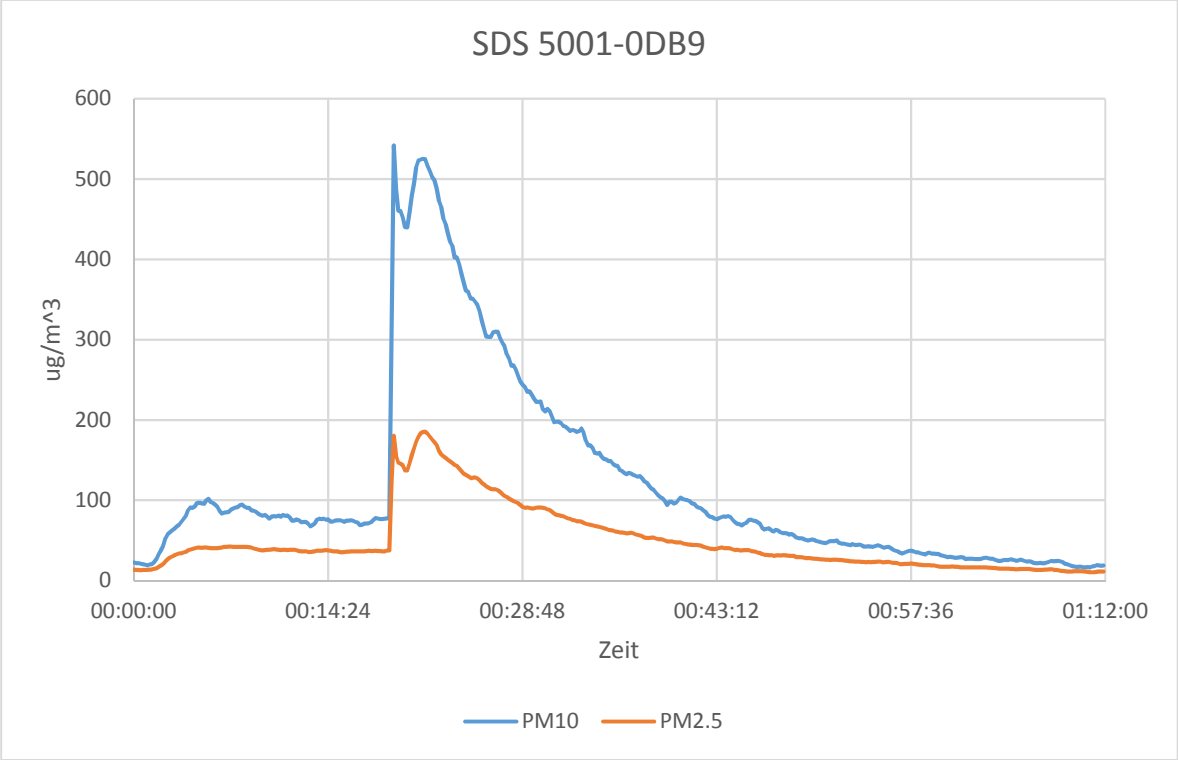

Fig. 9b: PM measurement result of the SDS011 low-cost sensor for the paraffin smoke experiment

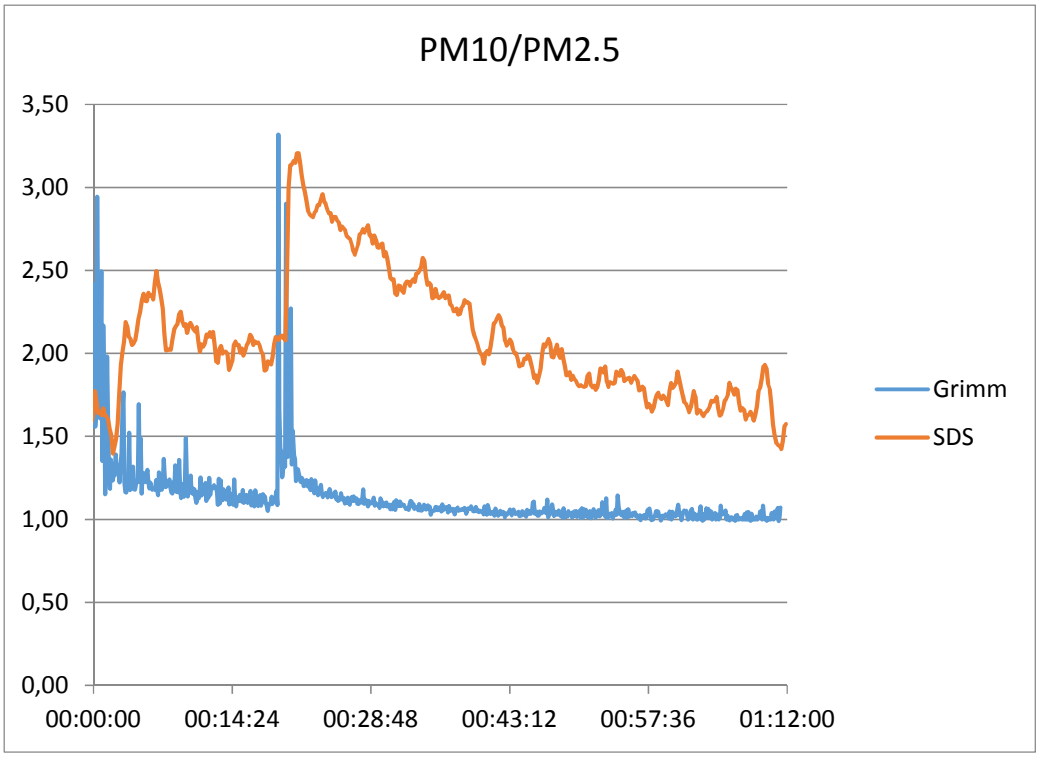

Fig. 10: PM10/PM2.5 ratios for low-cost sensor and reference instrument

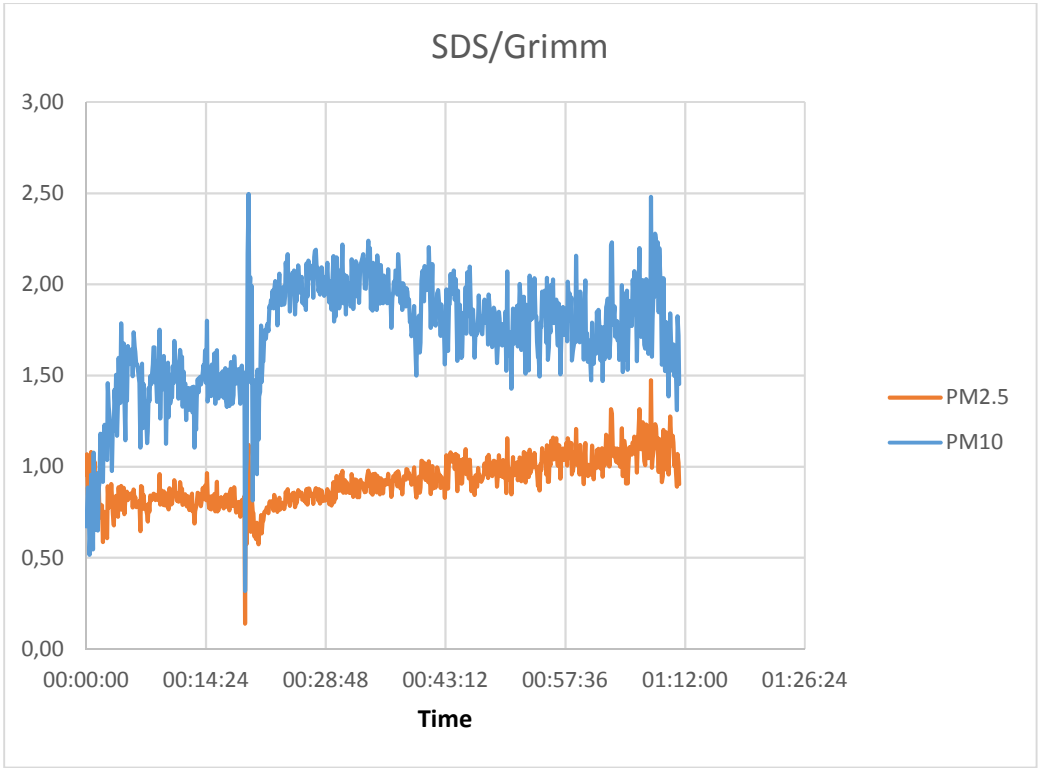

Fig. 11: The ratio of PM results for low-cost sensor versus reference instrument; PM2.5 of the low-cost sensor is close to the reference, PM10 of the low-cost sensor shows a strong deviation from the reference

Since it is known that the SDS011 device is marketed as a PM2.5 sensor and the PM10 values of the SDS011 device are just extrapolations from measurements in the PM2.5 size range, there is no expectation that PM10 can be calibrated to the reference instrument in a meaningful way. Therefore, in this study the development of a calibration method was restricted to PM2.5. The PM2.5 values

however, seem to be based on real measurements and show results that are not too far away from the reference instrument. Therefore, a calibration of the PM2.5 measurement with the low-cost sensor seems to be feasible.

Calibration Methodology

During the above type of measurements, it becomes obvious that not only the difference in the type of the individual mass distribution for each of the two particle dispersion systems cause major differences in the results of the PM2.5 measurement of low-cost sensor and reference instrument. Also, the shift of the center of gravity in each mass distribution during a measurement causes a varying deviation of the low-cost sensor from the reference instrument. When the ratio between the PM2.5 values of low-cost sensor versus reference instrument is formed, it becomes clearly visible that it is not possible to just use a constant correction factor for the compensation of the low-cost sensor results with respect to the reference instrument. In case of the mineral dust for example, the PM2.5 ratio between both sensors varies between 0.25 and 0.65 (fig. 12a) and in the case of the smoke aerosol the ratio varies between 0.6 at the release time of the particles (relative time 00:20:42) and 1.1 at the end of the measurement (fig. 12b). As a consequence, a compensation function must be found that yields values between 0.25 and 1.1 to correct the low-cost sensor results with respect to the reference instrument for the whole variability seen in both types of particle spectra including the intra-spectral shifts.

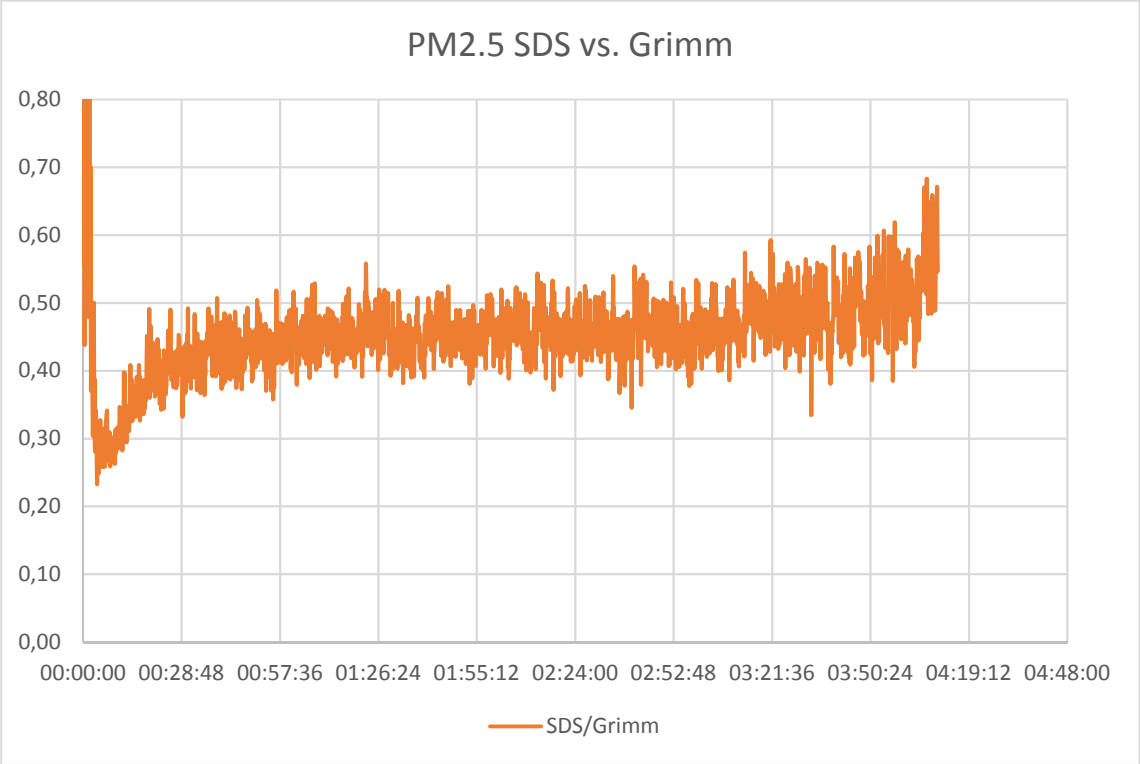

Fig. 12a: Variability of the ratio in the PM2.5 results for low-cost sensor versus reference instrument for the mineral dust experiment

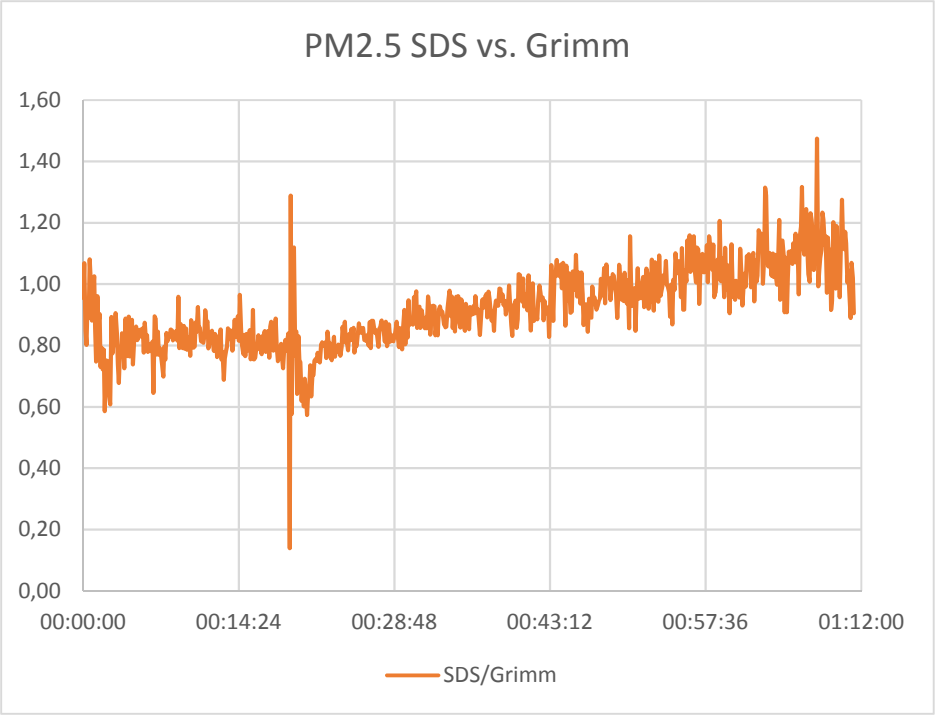

Fig. 12b: Variability of the ratio in the PM2.5 results for low-cost sensor versus reference instrument for the paraffin smoke experiment

The design of a compensation function requires the identification of a measurable dependency that is linked to the change in the compensation factor. Since the low-cost sensor only outputs a PM2.5 and a PM10 value, the PM10/PM2.5 ratio is the most obvious value that provides information about the shape of the particle mass spectrum, even though it remains unclear how the PM10 value is actually calculated from the firmware of the sensor.

A very surprising observation in this respect is the effect that the ratio in the PM2.5 values between low cost sensor and reference instrument is visibly correlated in an almost linear way to the PM10/PM2.5 ratio reported by the low-cost sensor. This correlation was visible for both types of particle sources, however, the slope of the linear regression curve was different.

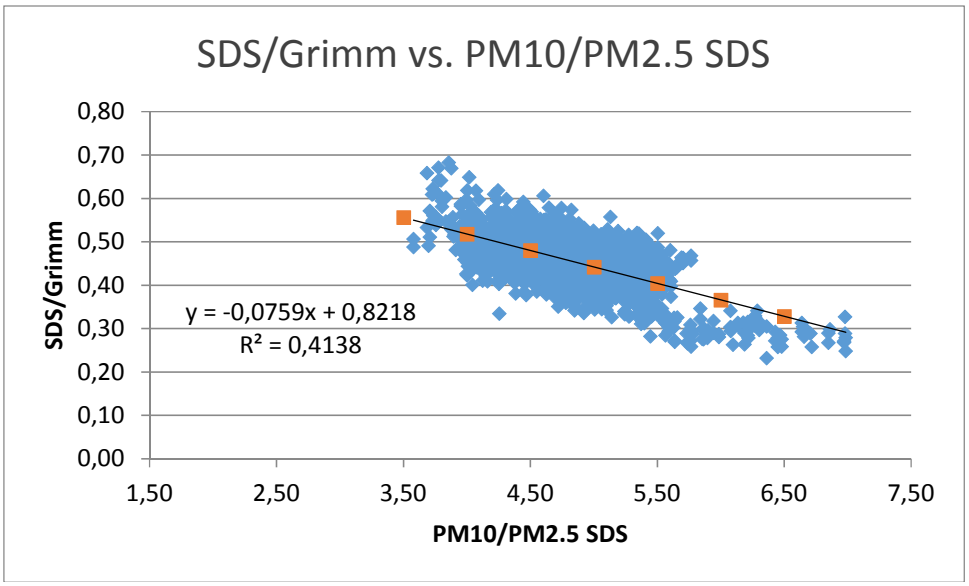

Fig. 13a: Correlation between the ratio of the PM2.5 values of low-cost sensor and reference and the PM10/PM2.5 ratio of the low-cost sensor for the mineral dust example

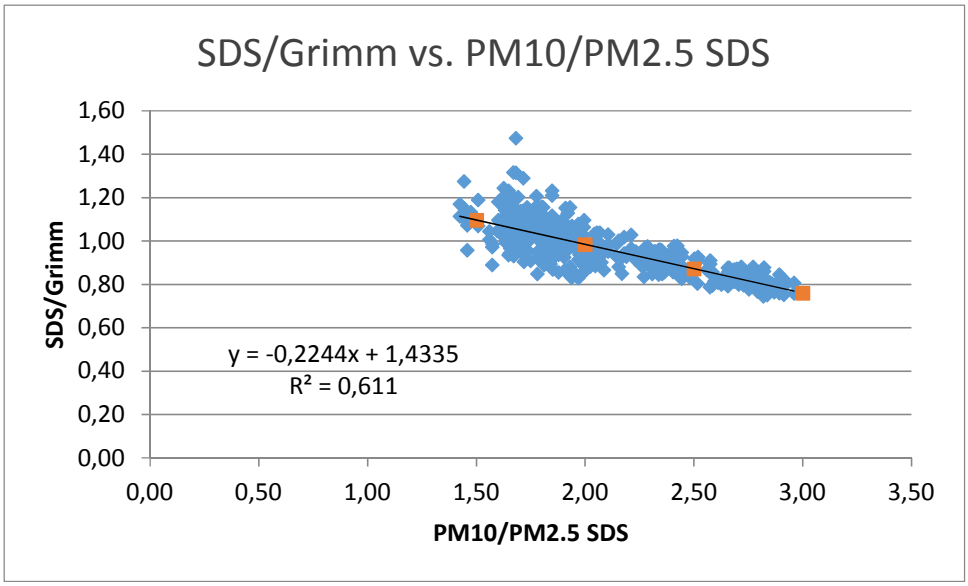

Fig. 13b: Correlation between the ratio of the PM2.5 values of low-cost sensor and reference and the PM10/PM2.5 ratio of the low-cost sensor for the paraffin smoke example

For further investigation, several measurements were run with particle spectra from dispersing other aerosols and powders with either the smoke generator or the powder disperser. In each case the dependency between the ratio in the PM2.5 values between low cost sensor and reference instrument as well as the PM10/PM2.5 ratio reported by the low-cost sensor was analyzed and a linear regression curve was fitted through the data points over the range covered by the measurement. Only a few data points were calculated on each regression curve and plotted into an overall graph for further decimation of the data (fig. 14).

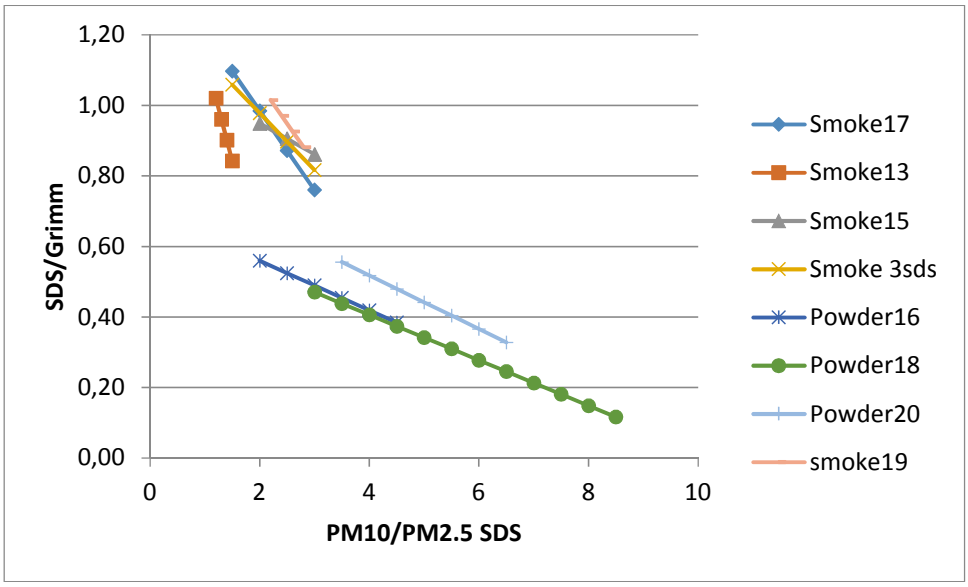

Fig. 14: Correlation results for different measurements and different particle sources

The resulting graph visualizes the overall dependency including the variability of the different particle sources and the individual shifts within each particle spectrum. Clearly a distinct behavior for particle spectra dispersed from the smoke generator and the powder dispenser can be recognized. The spectra generated from the smoke generator covers a SDS/Grimm ratio for PM2.5 of 0.8 to 1.1 while the spectra from the powder disperser cover larger ranges of ratios SDS/Grimm of 2 to 8 due to the much larger particle sizes.

Nevertheless, a clear trend is visible when a trend line is fitted through the supporting points from the individual measurements from both particle sources (fig. 15). This trend line gives a best regression performance (r^2) when a logarithmic dependency is assumed. This characteristic also makes sense with respect to the construction related difficulty of the low-cost sensor to detect large particles on one hand and the tendency to overestimate the mass of very small particles on the other hand.

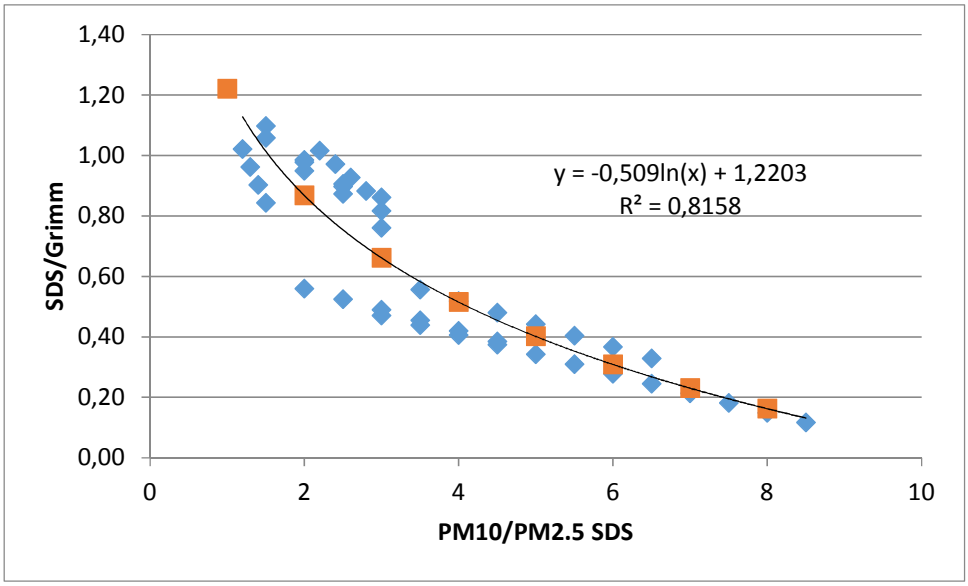

Fig. 15: Logarithmic regression into the overall dependency visible from all measurements

The actual calibration function for the SDS011 low cost sensor was finally taken from the fitting of a logarithmic regression curve:

$PM2.5_{SDS\ calibrated}/PM2.5_{Grimm} = -0.509*\ln(PM10_{SDS}/PM2.5_{SDS})+1.2203$

For compensation, the actual ratio $PM10_{SDS}/PM2.5_{SDS}$ measured by the low-cost sensor was taken to correct the measured $PM2.5_{SDS}$ value:

$PM2.5_{SDS\ calibrated} = PM2.5_{SDS} / (PM2.5_{SDS\ calibrated}/PM2.5_{Grimm})$

The resulting PM2.5 measurement values for the SDS011 that is now calibrated for the reference instrument are shown in fig. 16 for the mineral dust particle spectrum generated from the powder disperser. For this type of particle spectrum, the deviation of the low-cost sensor was particularly strong due to the dominance of large particles.

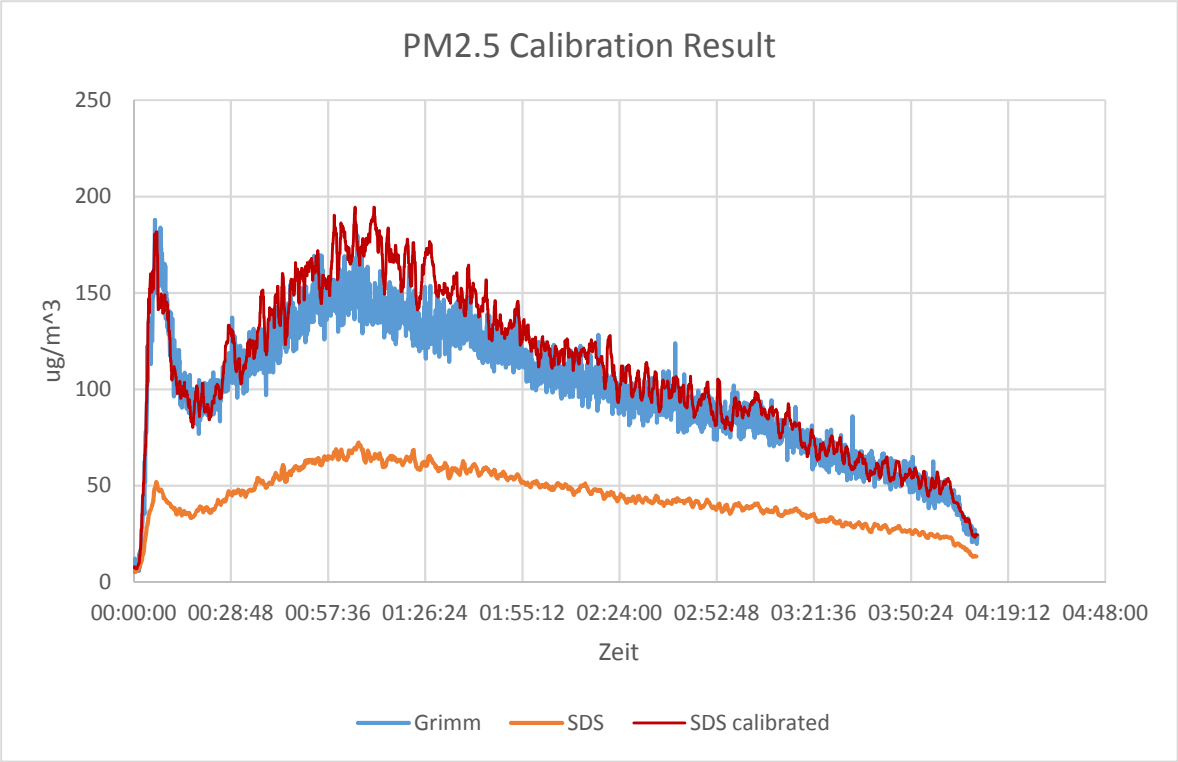

Fig.16: Result of the calibrated low-cost sensor (red) with respect to the uncalibrated low-cost sensor and the reference instrument for the mineral dust experiment

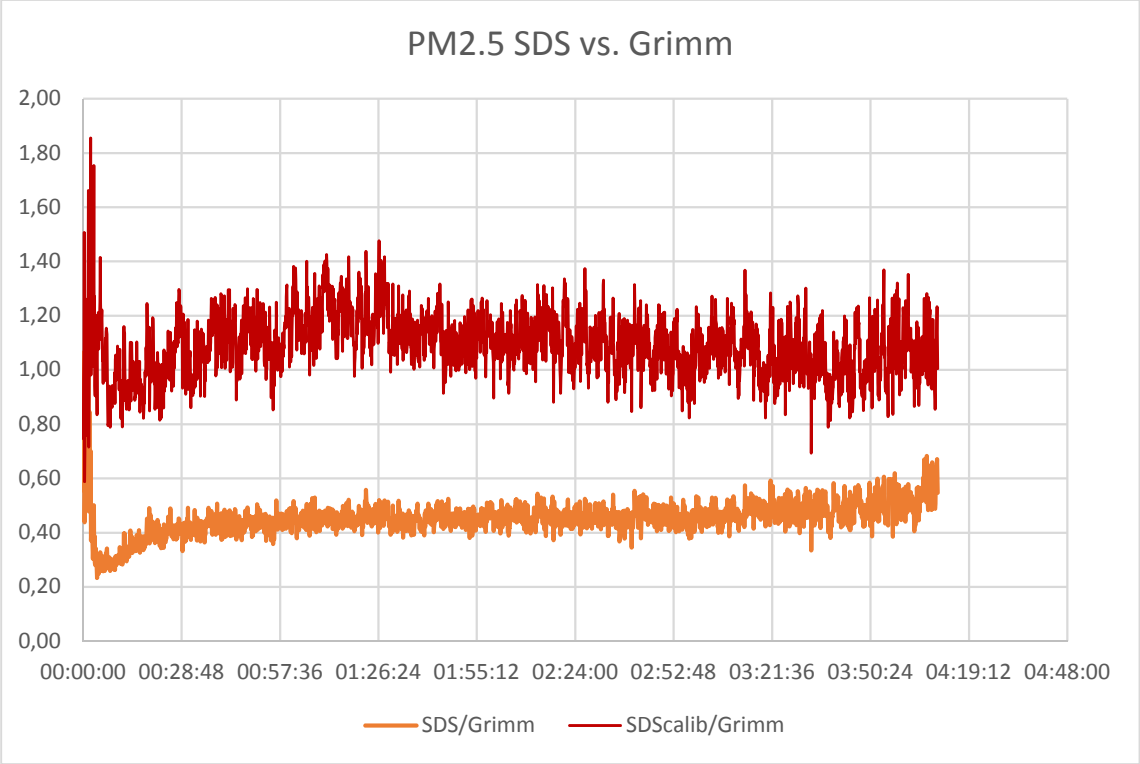

Fig. 17: Ratio of PM2.5 values between the low-cost sensor and the reference before and after calibration for the mineral dust experiment

During the initial spike where larger particles appear in the particle spectrum a close fit of the calibrated sensor can now be observed. The same is the case for the end of the measurement when the small particles dominate the spectrum. The fit is less perfect for the midrange. However, the ratio

between low-cost sensor and reference is now much closer to the reference instrument (factor 1.2) than without calibration (factor 0.45). The overall RMS-error was 59.93µg/m^3 before calibration and is now 16.00µg/m^3 after calibration. Assuming an average measurement value of 200ug/m3 this means an accuracy improvement from 30% before calibration and 8% after calibration.

For the particle spectra generated with the smoke generator the deviation of the uncalibrated SDS011 low-cost sensor with respect to the reference instrument was less pronounced particularly at the end of the measurement when almost only small particles dominated the spectrum. Therefore, the expectation for the calibrated sensor was that the application of the compensation will not worsen the match between both instruments. Fortunately, the calibrated SDS011 shows even a small improvement at the beginning of the measurement (factor 1.15 instead of 0.8 with respect to the reference instrument). At the end of the measurement the perfect match (factor 1) indeed remained even after the calibration. In this experiment the overall RMS-error was 33.98µg/m^3 before calibration and is now 30.27µg/m^3 after calibration (fig. 18 and 19).

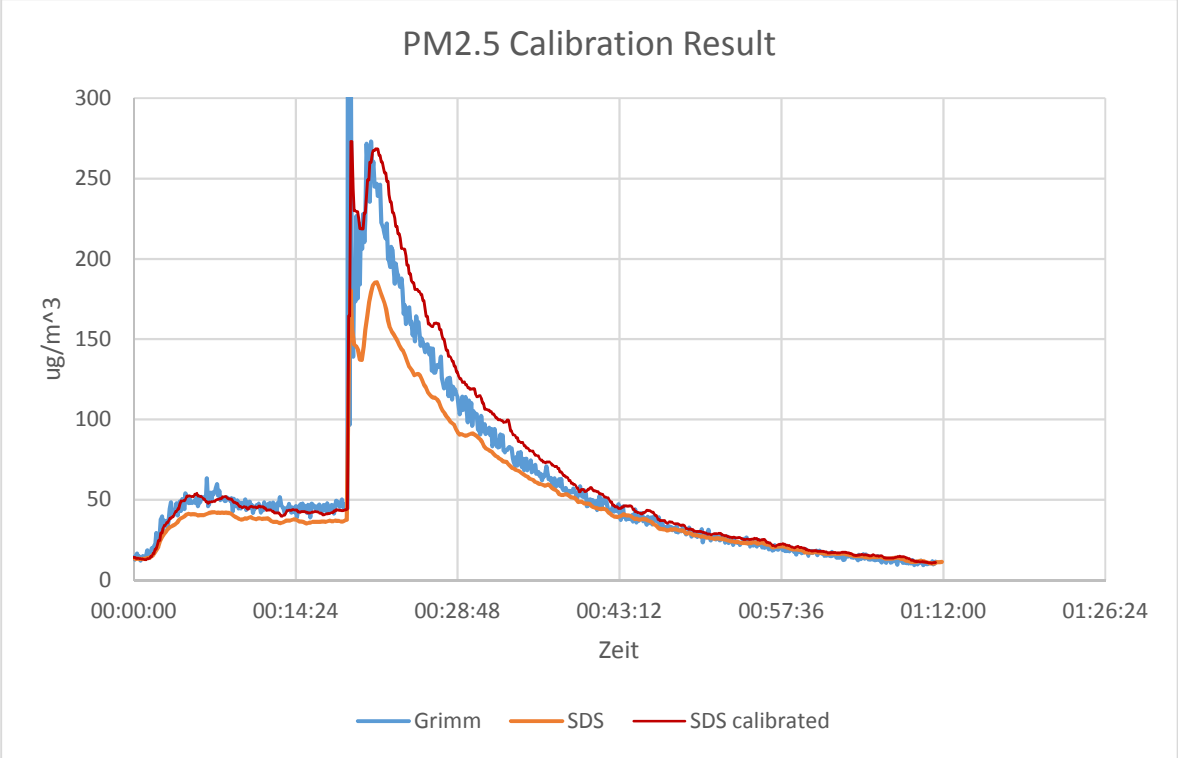

Fig. 18: Result of the calibrated low-cost sensor (red) with respect to the uncalibrated low-cost sensor and the reference instrument for the paraffin smoke experiment

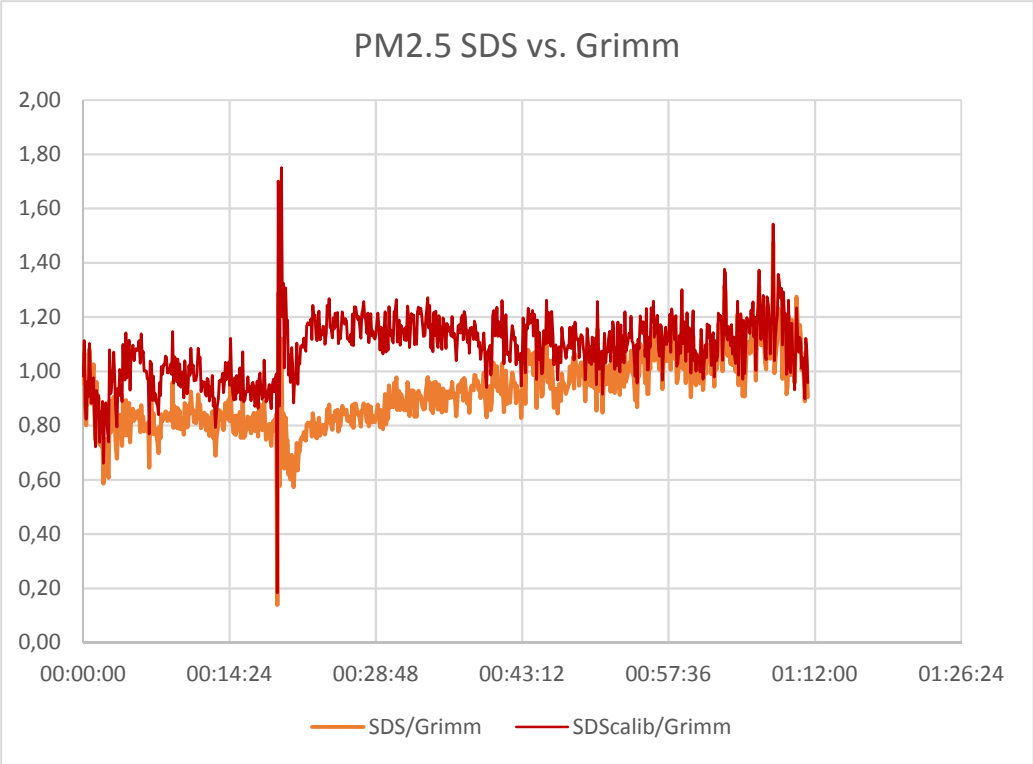

Fig. 19: Ratio of PM2.5 values between the low-cost sensor and the reference before and after calibration for the paraffin smoke experiment

Conclusion

Low-cost PM2.5 sensors that also provide a PM10 measurement output such as the SDS011 manufactured by Nova Fitness Inc. may significantly deviate in their measurement results compared to reference equipment due to their cost-efficient construction. This deviation may be large for PM10 since the device is actually not able to measure PM10 correctly but simply does an extrapolation from a measurement of particle sizes much smaller than 10µm. However, for PM2.5 this deviation is moderate and a calibration of the PM2.5 with respect to the reference instrumentation is feasible and makes sense. Even though the PM10 measurement output often does not reflect the value measured with reference instrumentation correctly, it still provides additional information that can be used for calibration of the PM2.5 output.

In this study a calibration concept was developed that is based on the finding that the PM10/PM2.5 ratio of the low-cost sensor gives an indication for the particle mass distribution that significantly influences the PM2.5 measurement inaccuracies. Therefore, the PM10/PM2.5 value ratio of the low-cost sensor was used to describe the dependency of the match between the low-cost sensor results and a reference instrument. The dependency was measured for different conditions and different particle spectra during a calibration measurement. A special particle generator was constructed for the purpose of calibration to cover a wide range of particle sizes for different and complementing particle mass distributions.

Based on the dependency of the measurement inaccuracy of the low-cost sensor on its own PM10/PM2.5 value ratio a compensation function was derived that in turn helps to correct the PM2.5 values of the low-cost device such that it matches the result of the reference instrument with higher accuracy. For particle spectra dominated by small particles such as smoke from paraffin generated by a smoke generator the match of the low-cost sensor was already good without calibration and could be slightly improved by the calibration method. For particle spectra that contained large particles such as mineral dust, the improvement achieved with the present method was significant.

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