The Effect of Quantization Errors on the Measurement Uncertainty of Low-Cost PM-Sensors

Bernd Laquai, Sept 14th, 2017

Introduction

Low-Cost PM-Sensors are becoming increasingly popular, particularly in countries that suffer from air pollution such as China or India. They are mainly marketed as indicators of indoor air quality with the intention to warn the users, for example when weather conditions induce a dangerous accumulation of particulate matter in the air. Typically, the mass-concentration PM2.5 is reported from commodity products using these low-cost sensors, even with a one decimal place digit suggesting a high measurement accuracy. Due to their small size, these relatively cheap sensors are also frequently used for control of air conditioning systems and other industrial applications.

Even though the target markets of low-cost PM sensors were initially aimed at commodity indoor use, these sensors are meanwhile also used for the purpose of measuring environmental PM2.5 and even PM10 outdoor values related to traffic and combustion related air pollution. Such outdoor applications are often driven by citizen science projects or NGOs focused to environmental protection to highlight the decreasing air quality in cities and to put pressure on politics. In contrast to measurements of the official authorities in charge of environmental protection, such citizen science and NGO projects use highly distributed IOT sensor networks to create area maps of pollution from a large number of sensors distributed within the city limits and beyond. In many of these cases one goal is to compare the quantitative values reported by the low-cost sensors with the high accuracy gravimetric measurements or medium accuracy laser scattering measurements of scientific instruments. Unfortunately, many users of low-cost IOT systems are completely unaware of the measurement uncertainties of their systems caused for example by the hygroscopic growth effect of particles due to high outdoor relative humidity or the effects of quantization errors due to a very coarse analog-to-digital conversion. Typically, citizen science projects do not try to compensate for sources of measurement uncertainties in their sensor nodes. They also do not report the measurement uncertainties of their sensor nodes and therefore often provide “open” but poorly accurate and even misleading data to the public.

The dominant measurement principle used in low-cost PM sensors is laser scattering. The high light intensity of today’s monochromatic laser diodes and signal amplifiers even allow to register the Rayleigh scattered light of sub-µm particles with simple photodiodes. The successful market acceptance of a first-generation low-cost sensors with a typical cost below 30 Euros, mainly manufactured in China, also waked scientific interest. However, since the measurement accuracy limitations quickly became obvious, a next generation of lower cost laser scattering sensors were developed, mainly at universities that no longer suffer from one of the most dominant sources of measurement uncertainties: the use of simple comparators for digitizing the scattered light signal. These next generation lower-cost sensors use many comparators or even a multi-bit analog-to-digital converter (ADC) to convert the intensity of the scattered light into a digital signal that can be post processed by a microcontroller. In addition, a more sophisticated control of the air volume drawn into the measurement chamber by a fan also helped to improve the accuracy of these lower-cost PM-sensor significantly. The higher accuracy achieved also contributed to a higher manufacturing cost, therefore these sensors are marketed at cost of up to several hundred Euros. However, such a sensor is still by far less expensive than a professional PM-measuring equipment and thus is still suitable for creating commodity products with a reasonable relationship between accuracy and cost.

Particularly the second-generation PM-sensors is highly attractive for scientific use, mainly because area based measurements become possible with distributed sensor nodes in a sensor network. When expensive professional scientific laser scattering instruments were used instead, a network of sensor nodes would be prohibitively expensive, making such a project impossible. Nevertheless, when using lower or medium cost PM-sensors for scientific purposes instead, it is imperative that the measurement uncertainty is well understood and minimized best as possible. Therefore, the purpose of this document is to clarify the impact of quantization caused by the different ways of digitizing the analog measurement signal versus size. At this signal processing step the main difference between the two types of first- and second-generation low/medium cost PM-sensors can be found.

PM-measurement: An illustrative analogon

Assumed, the goal is to determine the loading of a road bridge caused by the mass of vehicles driving onto it with a minimum effort and cost. Installing a weighting system would be too costly and too slow. A simple idea could be to make use of the statistically determined correlation between vehicle height and vehicle mass. This allows measuring the height with simple and fast means instead of measuring the mass. A very simple height measuring system could be a light barrier using light beams focused to a photo sensor to detect vehicles of a given height. A minimum system would require two light beams, one to detect a vehicle passing the bridge at very low height and a second light beam at a height that allows to distinguish between low height passenger cars and large height trucks.

Let's assume the height distribution of vehicles shows a bimodal distribution that shows a relative distribution maximum at 1.7m caused by passenger cars and a relative distribution maximum at 2.5m caused by the trucks. It is further assumed that the statistical mass distribution of the vehicles shows a mass of 1.5tons for vehicles at 1.7m height and a mass of 5 tons for vehicles with a height of 2.5m. The minimum vehicle height is assumed to be 1.3m

The implementation of the simplest possible measurement system would then use a light beam at the height of 1m to detect a vehicle passing the bridge, regardless of car or truck and a light beam at 2m to distinguish cars from trucks. When the photo sensors count the vehicles, we can assign a passing car with representative height of 1.7m and a mass of 1.5tons for each count signal from the lower sensor and NOT from the upper sensor and we can assign a passing truck with a representative height of 2.5m and a mass of 5 tons for each simultaneous count signal from both sensors.

The two light barriers at different height actually implement a quantization of the continuously distributed vehicle height in two digital bins. As long as the actual distribution of the vehicles is normally bimodal, and does not change significantly over time such a system allows a coarse statistically based measurement of the mass of the vehicles that drive on the bridge without the necessity to slow down the traffic.

The quantization approximates the actual continuous height distribution and thus causes quantization errors. As long as the actual distribution stays constant over time, positive and negative errors can be balanced statistically when determining a representative height and mass for each bin. However, when the distribution changes with time, the quantization error no longer is balanced and therefore causes wrong results. An extreme situation would occur, if suddenly only passenger cars of the same height would appear for a given time frame. If this height would be a little below 2m, then the representative (average) height and mass of a passenger car would be assigned to these rather big vehicles causing a maximal underestimation of mass. A respective maximal overestimation would occur for many identical small vehicles a little above 1.3m of height. A similar consideration can be done for the trucks with the upper height bin.

Using more light beams at many different heights would allow for a more precise quantization resulting in much smaller measurement errors in case the height distribution would change and thus would be much more accurate.

The above measurement principle is used with low-cost PM-sensors in a pretty similar way. What is vehicle height in the above example is particle size for PM-sensors. A quantization is used along the size axis and for very low-cost sensors just two bins are used, with the effect of very inaccurate results when the particle size distribution deviates from what was used to determine the representative size and mass of the two measurement bins.

Generic architecture and functionality of low-cost PM sensors

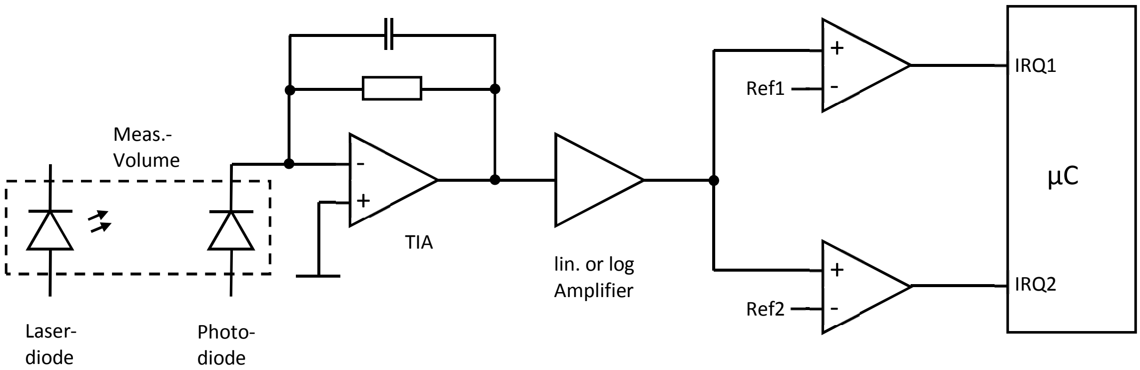

Fig. 1: Signal processing chain of a low-cost PM sensor

The basic structure of the analog signal path of a low-cost PM sensor is shown in fig. 1. The particles get drawn into a measurement volume inside the sensor by the air stream of a fan. The monochromatic light with a wavelength between 500 and 600nm from the mostly modulated laser diode gets scattered by the particles and is detected by a photo diode that is placed in a distance of several mm perpendicular to the laser beam. The scattered light signal can be described by a stochastic process that consists of randomly occurring peaks modulated in amplitude according to the size of the particles. The photo diode, mostly a PIN-diode, converts the light pulses into current pulses. The photo diode and the following amplifiers need to be fast enough to detect pulses at high rate when the particle density is high and needs to be of a low-noise noise type to be able to even detect the ultra-small light quantities caused by Rayleigh scattering of particles down to several 100nm. A transimpedance amplifier (TIA) or a charge sensitive amplifier (CSA) is used to covert the current pulses (or charge pulses) into voltage pulses. The TIA or CSA is typically configured for a very high input impedance and therefore also generates significant noise that limits the minimum detectable particle size. Therefore, the use of a low-noise amplifier is also critical in this application.

Depending on the quality and cost of the sensor, the further signal processing may differ between different products. The cheapest implementation may just use two comparators to distinguish small from large particles. The two comparator signals may simply trigger two different interrupt inputs of a microcontroller that counts the pulses resulting in a bimodal discrete density distribution.

In a more sophisticated approach the TIA or CSA stage is followed by a further driver amplifier stage that drives the input of an N-bit ADC (see fig. 3). In this case the ADC needs to sample the input signal fast enough to safely digitize all incoming impulses with a resolution that later allows a proper quantization and binning of the impulse height representing the size of the particles. A linear N-bit ADC allows to quantize the impulse height into 2^N equally spaced levels. It is obvious that the quantization error caused by a finite ADC resolution introduces an error that depends on the effective number of bits (ENOB), the ADC actually achieves in presence of the noise in the system.

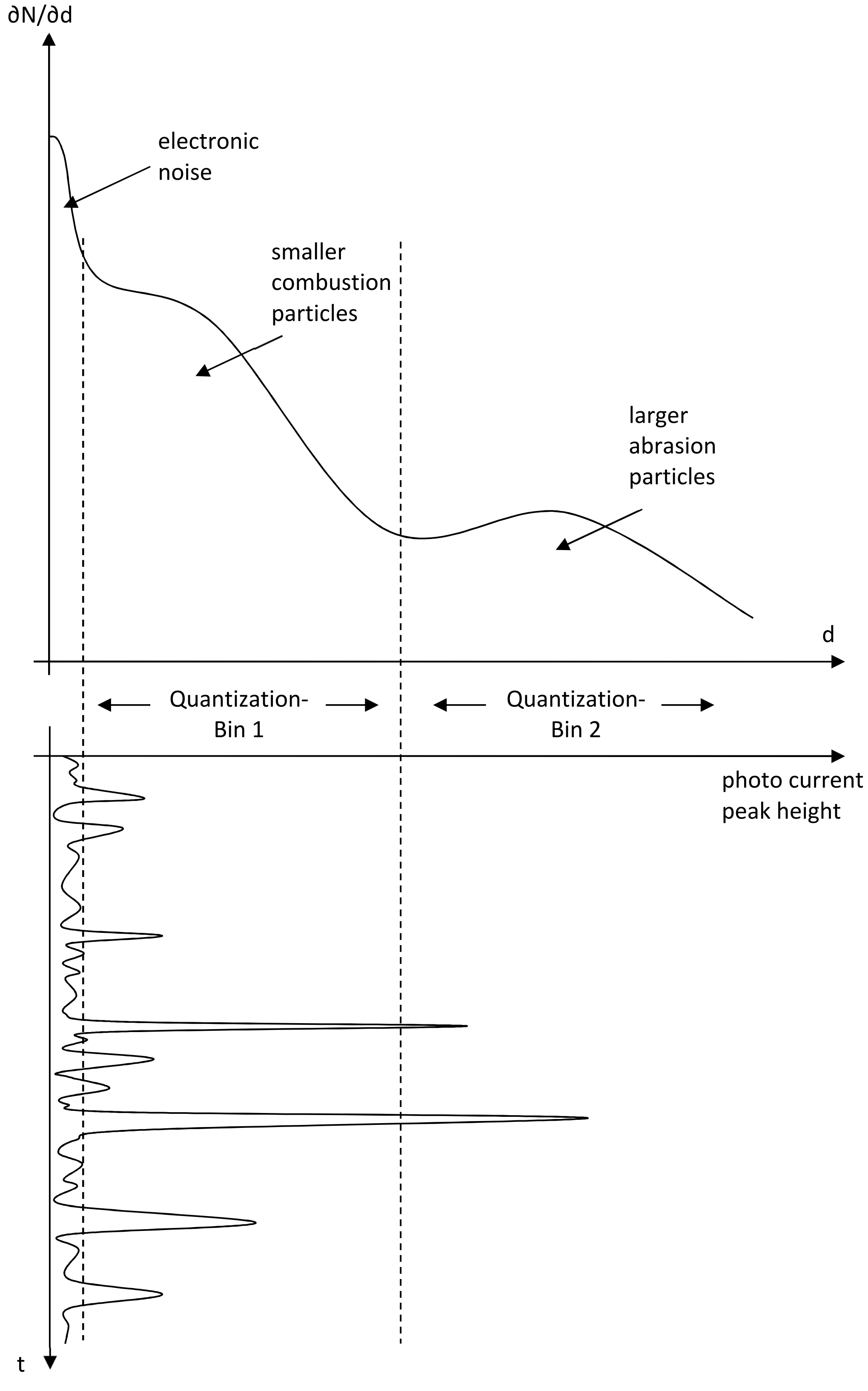

Fig. 2: Using the photo-current peak height for measuring and binning particle size

Since the scattered light is a strongly non-linear function of the particle diameter and the light intensity drops dramatically with the particle size, it may be advantageous to either use a non-linear (e.g. logarithmic) amplifier or to implement the analog to digital conversion with non-linear spaced comparator thresholds. The latter approach means that the quantization of the pulse height is actually performed by a parallel arrangement of comparators implementing M non-equally spaced comparator thresholds for binning into M size bins. If a conventional linear ADC is used and the amplifier stages do not compensate the strongly non-linear dependency of scattered light on the particle size, the ADC needs to have a sufficiently large resolution to later allow a software based binning into M particle size bins.

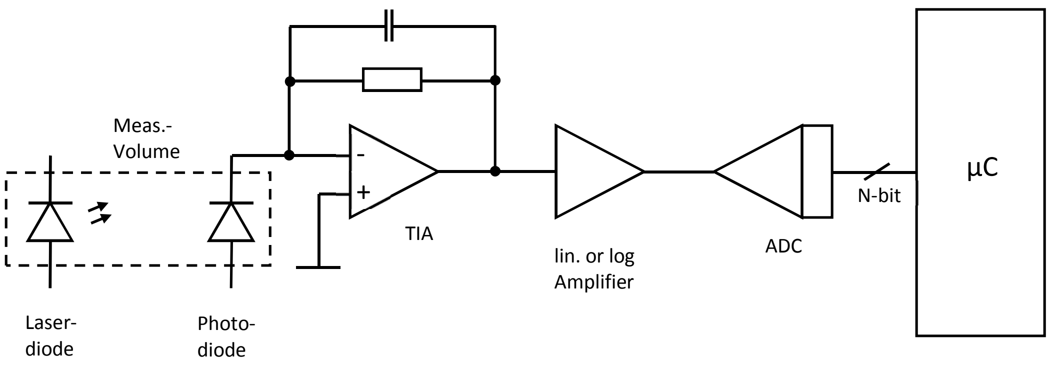

Fig. 3: Use of an ADC for quantization of particle size

A fast and cheap 8-bit ADC would not be able to do the job described above, this can be shown from a simple consideration: Assumed the range of the sensor should cover aerodynamic diameters between 300nm and 18µm, and a monochromatic red laser diode with a wavelength of about 500nm is used as light source, then Rayleigh scattering will dominate in the range between 300nm and 500nm and Lorenz-Mie scattering will dominate the range between 500nm and 20µm. This means, that the intensity I of scattered light shows the following exponential dependency from the aerodynamic diameter d:

$I \sim d^6$ for $0.3\mu \leq d \leq 0.5\mu m$ (Rayleigh range)
$I \sim d^2$ for $0.5\mu \leq d \leq 20\mu m$ (Lorenz-Mie range)

Let's further assume, the current or charge pulses from the photo diode are linearly amplified such that the ADC is at full scale (FS) with the pulse height of the 20um particles, then we'll get a pulse height of 1/1600 FS at 500nm and a pulse height of 1/34294 FS at 300nm. This means that the ENOB needs to be at least 15 ($2^{15} = 32768$). Since the ENOB is typically less than the specified ADC resolution, we can conclude from this consideration that a linear ADC needs to have at least 16bit when linear amplification is used.

The quantization error for a simple mass calculation method

Assumed a low-cost PM sensor is able to correctly classify the particles detected into M size bins, either by using individual comparators or an ADC, the subsequent step is to count the pulses accumulated in each size bin yielding the number of particles dN in each size bin. dN is often called the differential count of a size bin. Counting the particles is achieved easily by a microcontroller, once the numbers dN are available in the digital domain. A much more difficult job however is the subsequent translation of the bin specific counts dN into the so called differential mass concentrations dM of particles counted in each bin.

With a simplified theory for perfect spherical particles the mapping of the differential counts per bin dN into differential mass per bin can be performed according to the relationship:

$dM = dN * \pi/6 * d^3 * \rho$

Strictly speaking, this relationship is only valid when the aerodynamic diameter d of the particles is large enough such that the Stokes law determines their final settling velocity. This is the case in the µm range. For sub-µm particles, a so-called Cunningham slip correction is typically performed in addition to account for the fact that the particles collide with air molecules rather than moving smoothly through the "air-fluid". When the particles no longer can be assumed to resemble spheres, a further form factor χ needs to be introduced to account for a different aerodynamic behavior of different shapes. Since the mass of particulate matter is typically reported with respect to the normal density of $1g/cm^3$ (water droplets), the relationship also needs to be adapted to the bulk density of the particle substance. However, assuming all these corrections not to be necessary, and without the loss of generality, we can estimate the number of spherical particles with unit density counted in a volume of $1\ cm^3$ when rearranging the above equation for dN. For a fixed differential mass concentration dM of $10µg/m^3$, we get the following differential counts:

0.2um: dN=2387.3241/cm^3
0.5um: dN=152.7887/cm^3
1um: dN=19.0986/cm^3
2um: dN=2.3873/cm^3
5um: dN=0.1528/cm^3
10um: dN=0.0191/cm^3

When we plot a graph of dN for 50 log spaced bins, the shape of the count distribution that belongs to constant mass distribution becomes obvious (fig. 4).

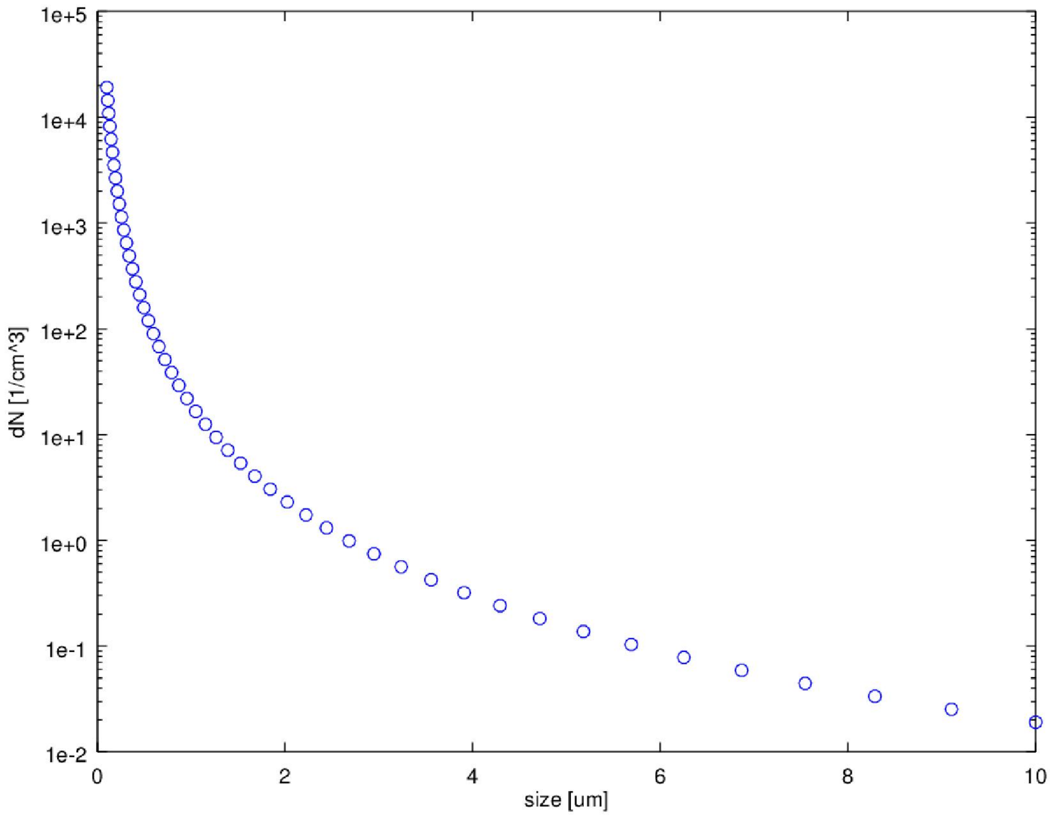

Fig. 4: Theoretical count distribution for a constantly distributed mass

When an effective sampling volume of 0.1l (= $100cm^3$) is achieved by using a respective fan that draws the air stream through the measurement chamber with a precisely controlled constant velocity, then the numbers are by a factor of 100 higher and range between coarsely 2 and 200000 particles. If the measurement rate should be 1value/s then the count rates have to be between 5Hz and 5MHz. When we assume that a scattered light pulse of a few us duration needs to be quantified correctly for its height, we recognize that the required ADC sampling speed should be at least an order of magnitude higher to reach enough samples per impulse. In other word a respective ADC should reach at least a sampling rate of 10Msps, which already is a significant cost factor assuming a 16-bit ADC. This consideration explains why the more economic comparator based solution is the solution preferred by many manufacturers who want to address particularly the very-low-cost commodity market.

The particle count is actually a random variable over time, continuously distributed over the particle size. Since the size is mapped to pulse height of the scattered light the particle count is in the same way continuously distributed over the pulse height, as long as we assume that the light intensity is uniquely mapped to the particle size. Therefore, the mass associated with particle size is on one hand proportional to the particle count but on the other hand also continuously distributed over size or pulse height respectively. This means that the determination of mass requires both, the mapping of particle count density per size to mass density per size and a subsequent integration over size.

In contrast, a quantization of the particle size values (the classification into differential size bins) at the transition from the analog to the digital signal processing domain in a PM-sensor implies that the measured pulse heights are quantized and the results are counted in discrete bins. The mapping of the counts per bin to mass per bin finally results in a discrete distribution of the respective mass rather than in a continuous mass distribution. Therefore, the bins of the discrete mass distribution have to be summed up to determine the final mass of the particulate matter. However, the summing up of discrete bins rather than the integration of a distribution induces a quantization error, because the discrete bins just approximate the actual continuous size distribution function of a given particle spectrum. It is pretty obvious that this approximation introduces an error that is the larger the less bins are used for quantization.

After counting the quantized impulse heights, the microcontroller software of the PM-sensor therefore needs to map the differential count dN in each bin to a mass dM in each bin. When the differential mass for an individual size bin is calculated, only a single representative assignment of size can be done for all the sizes that fall into the bin to calculate the mass for the counted number of. The less bins are used, the larger the bins are with respect to size and the more an actual particle size in a bin can deviate from a single representatively chosen size for the mass calculation. A natural choice for a representative size would be to take it from the center of gravity of that bin. In this case, the mass of particles in the same bin that have sizes below the center of gravity will be lower and thus will be overestimated whereas the mass of the particles in the same bin that lie above the center of gravity is higher and thus will be underestimated.

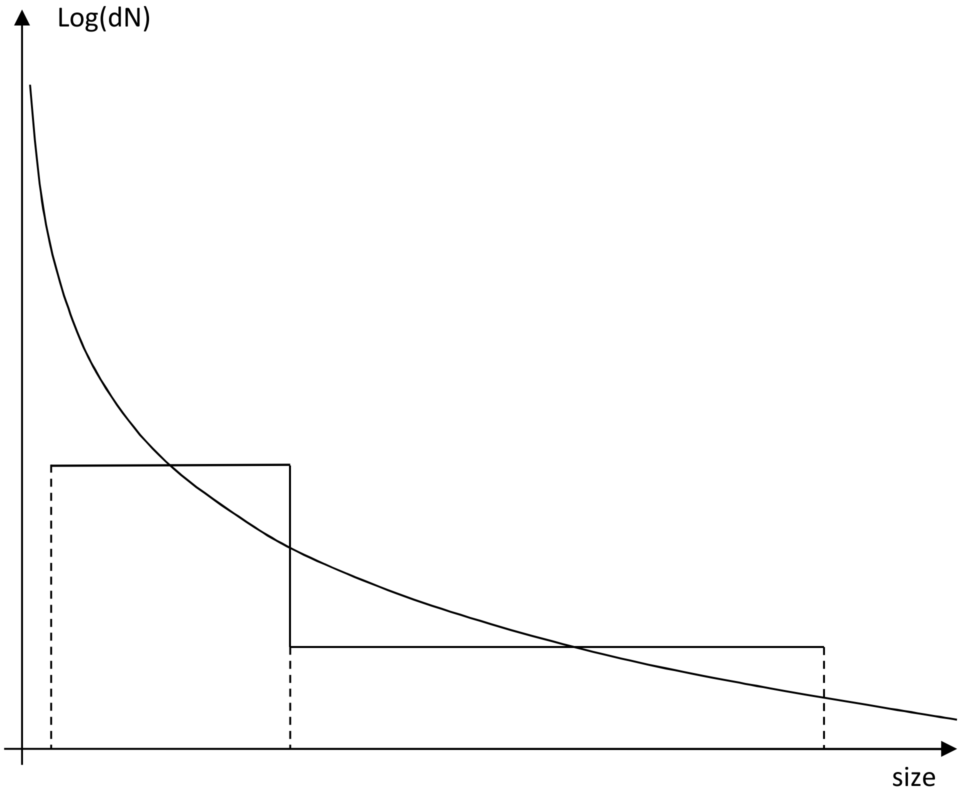

Fig. 5a: Approximation of a count distribution with only two size bins

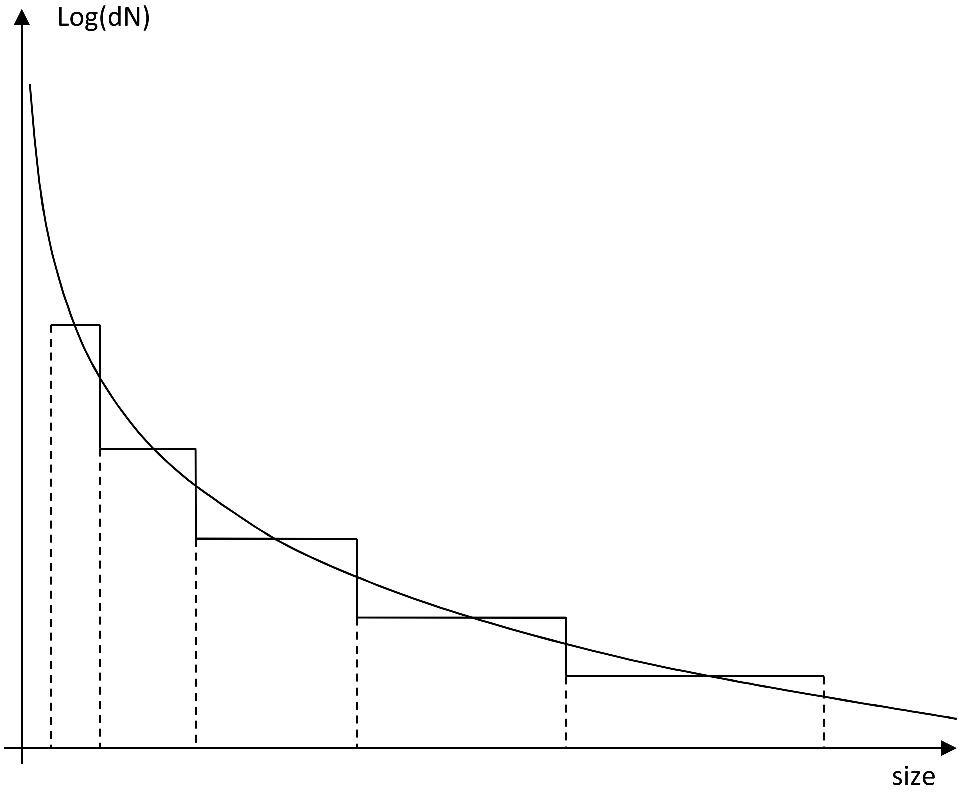

Fig. 5b: A more accurate quantization of the count distribution using 5 bins

The error caused by quantization will be dramatic when only two bins are used for quantization (see fig. 5a). Two size bins mean that the lower bin is counted up by the sensors microcontroller whenever particles are detected that are smaller than a given threshold but otherwise regardless of their size. If monodisperse particles of a size that just can be detected by the sensor are used (the lower bound of the bin), then the mass of the counted particles will be dramatically smaller than the representative mass at the center of gravity of that bin. As a result, the differential mass determined from monodisperse particles of this size will also be dramatically higher than the actual mass. In contrast, when monodisperse particles of a size close to the threshold to the second bin are used (the upper bound of the bin), then the mass of the counted particles will be significantly larger than the representative mass at the center of gravity of that lower bin. As a result, the differential mass determined from monodisperse particles of this size will also be significantly smaller than the actual mass. When the sensor is exposed to a particle spectrum with continuously distributed particles these errors may cancel out to a certain degree but only for one given size distribution of the spectrum that was used to determine the error-balancing representative size and mass.

Therefore, we can already conclude from this consideration, that a coarse size quantization only yields useful results when a particle spectrum is measured that is balanced with respect to the quantization errors and the representative size per bin correctly reflects the integrated mass distribution in each bin. It also can be concluded from this consideration that a calibration with monodisperse particles of a single size does not make sense, when only a very coarse quantization of particle sizes is implemented in a low-cost PM-sensor.

The quantization error caused by the particle size binning reduces the more bins are used. For a known mass distribution, the error can be calculated at least at the bin boundaries. Assuming a constant mass distribution for example, the center of gravity lies in the center of that bin. When d_l is the lower bin boundary and d_u is the upper boundary, the center of gravity lies at $d_c = (d_l + d_u)/2$. When the bin size is dD the lower boundary lies at $dl = dc – dD/2$ and the upper at $du = ds + dD/2$. Since the mass is assumed to be constantly distributed with dM0, the respective continuous count distribution dN(d) as a function of size d can be computed from the following equation:

$$dN = dM_0 / (\pi/6 * d^3 * \rho)$$

Inserting d_l and d_u into this equation gives the counts at the bin boundaries dN_l and dN_u:

$$dN_l = dM0 / (\pi/6 * d_l^3 * \rho)$$
$$dN_u = dM0 / (\pi/6 * d_u^3 * \rho)$$

Therefore, when the size d_c representing the differential mass dM_0 in the center of gravity is used for each particle, independent of size and only with the condition that the size falls in the that bin, we can calculate the maximum quantization error from the bin boundaries in this case. At the bin boundaries, we'll get largest differential masses that deviate from dM_0:

$$dM_l' = dN_l * \pi/6 * d_c^3 * \rho$$
$$dM_u' = dN_u * \pi/6 * d_c^3 * \rho$$

The respective errors therefore are:

$$e_l = dM_0 - dN_l * \pi/6 * d_c^3 * \rho$$
$$e_u = dM_u - dN_u * \pi/6 * d_c^3 * \rho$$

From a more in depth calculation it can be shown that the errors at the bin boundaries remain constant when a logarithmic spacing of the bin boundaries is chosen. When the resulting error is simulated for a constant mass distribution it quickly becomes clear, that taking the size at the center of gravity for calculating the representative differential mass in each bin isn't the best choice with respect to the error at the boundaries. Actually, at least for very few bins, the size for the mass calculation needs to be chosen very close to the lower boundary to balance the errors at the lower and at the upper boundary.

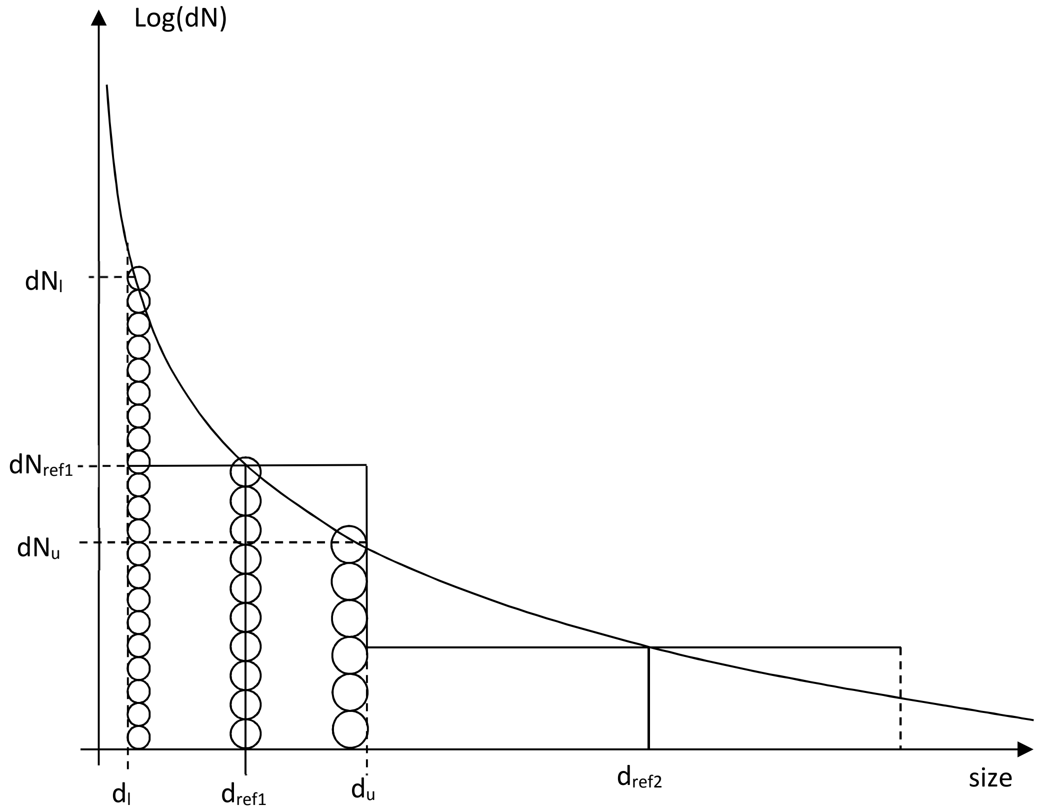

Fig. 6: Illustrated impact of quantization error for two bins

When the size for the representative mass is calculated from a weighted average at the upper and lower boundaries according to the equation:

$$d_c = (1*d_u + W*d_l)/(W+1)$$

using the weights 1…W, simulations show that the error can be made more symmetric for small numbers of bins. The below simulations show the resulting quantization errors versus the number of used bins when the bins are filled with particles of size at the lower bound (blue curve) or at the upper bound of each bin and a total mass of 100ug/m^3 with a constant differential mass in each bin is achieved. The range of the sensor was restricted to a minimum particle size of 1um and a maximum size of 10um and the bin boundaries were distributed logarithmically (fig. 7a, b).

With these simulations, several aspects become obvious. The error increases dramatically towards small number of bins. As expected, using only two bins for quantization result in dramatic errors, particularly when the range is extended towards small particle sizes. For only a few number of bins, the size used to calculate the representative mass for particles that fall in that bin, needs to be chosen the closer towards the lower boundary the less bins are used. The error at the upper boundary and the error at the lower boundary show a different behavior versus the number of bins. The error at the lower bound shows a sharp increase when using less than 4 bins. In contrast, the error at the upper bound behaves smoother versus the number of bins. When using more than 16 bins the error is less than +/-2.5% and the center size between upper and lower bound of a bin can becomes suitable for the mass calculation balancing the errors towards the upper and the lower bound.

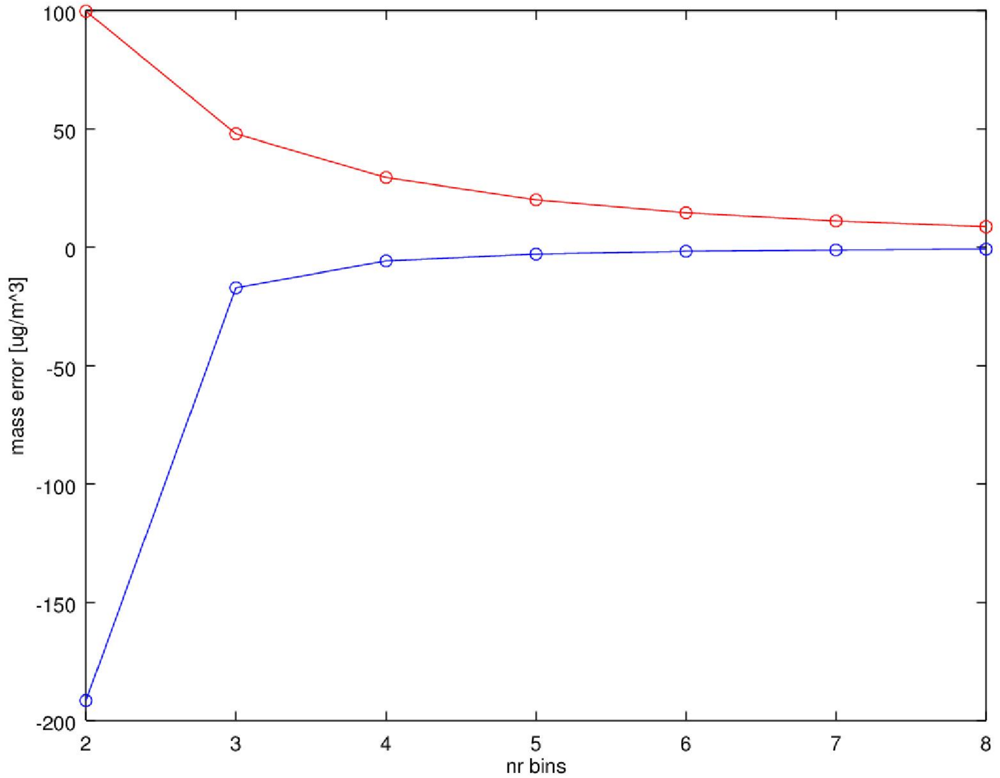

Fig. 7a: Simulated impact of quantization errors for 2 to 8 bins, W=20

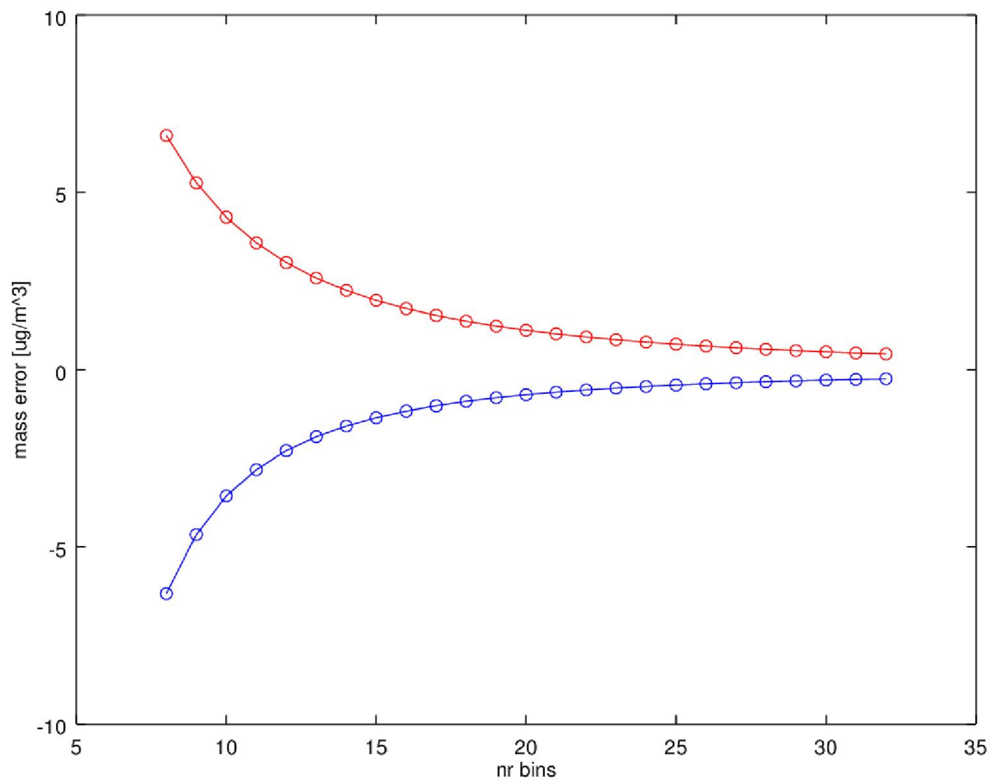

Fig. 7b: Simulated impact of quantization errors for 8 to 32 bins, W=2

When using an ADC as a means of quantization instead of individual comparators, the number of bins increase dramatically. Using a 16-bit ADC creates 65536 bins for quantization and in case each bin would be used for mass calculation per bin, the quantization error would be negligible. However, the computational effort would also increase significantly with the number of bins. Since the required mathematical operations are not just simple additions or multiplications, the required computational performance of the microprocessor has to be high and large amounts of memory might be required as well. This again may jeopardize the cost goal of a low-cost sensor. Therefore, it can be assumed, that a solution to minimize the cost of digital processing is again a reduction of the bins. However, this can be achieved by software now. A low-cost sensor for example could digitize the pulse heights with 16-bit, but a dramatically reduced number of software bins can be implemented by grouping together multiple ADC-bins. Therefore, it seems to be a favorable compromise for a lower-cost sensor to implement 16 or 32 software bins to achieve a significantly lower and tolerable quantization error without the requirement for a costly digital processing engine running the full mass calculation algorithm on all bins of a 16-bit ADC.

Investigations on a real implementation of a low-cost PM sensor

For most of the commercial products, the manufacturers treat the used mass calculation algorithms as intellectual property (IP). For the very-low-cost sensors there is also no indication given in the datasheet how many internal size bins the sensor uses for its calculation. However, to a certain degree reverse engineering is possible for some sensor products without destroying them.

One option is to simulate the scattering light from particles with a fast, red LED. A small, but super-bright LED can be inserted into the air inlet to generate the light pulses at rates up to 20kHz and with very high dynamic range of light intensity. When such a LED is operated from a pulse generator, the rate of the particles entering the measurement volume can be adjusted with the frequency of the pulse generation and the light intensity detected by the sensors photodiode is a product of the pulse width and LED current that both can be adjusted at the pulse generator in a wide range.

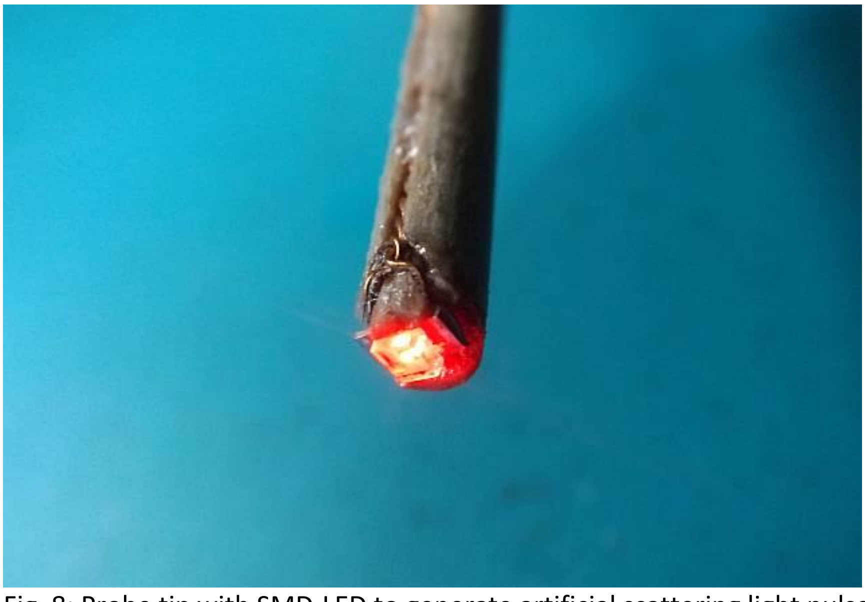

Fig. 8: Probe tip with SMD-LED to generate artificial scattering light pulses

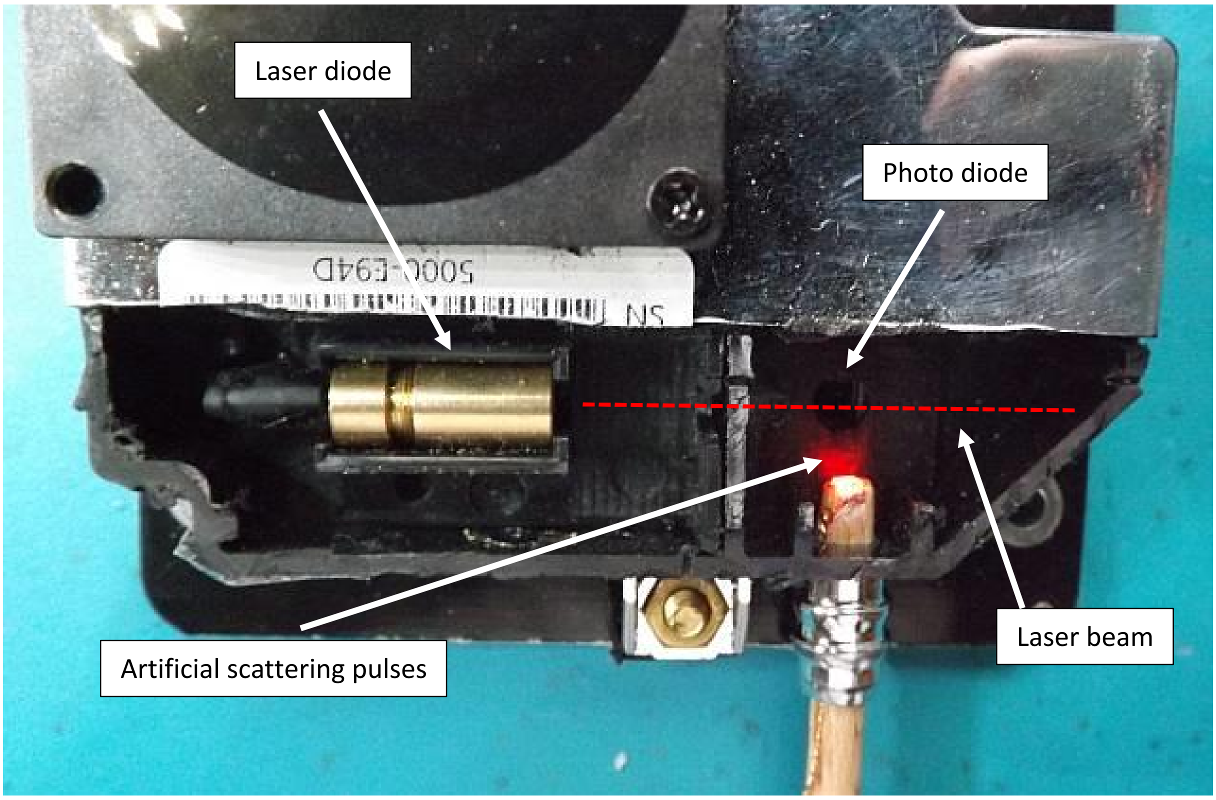

Fig. 9: Opened low-cost PM-Sensor (SDS011) with probe inserted into measurement chamber

As an example, a low-cost PM sensor (SDS011, Nova Fitness, China) was used for such a reverse engineering experiment. One defective part was opened to design the LED probe that is inserted into the measurement chamber. For this sensor product, the air inlet (5mm Φ) leads directly into the measurement chamber. A 0603 SMD LED was placed on the tip of a round probe stick inserted into the chamber. The insertion length was optimized with respect to the maximum PM values reported by the device. The pulse generator (Keysight 33260A) has an internal source impedance of 50ohm, so the source voltage was used to control the LED current. A bias of 500mV was used to achieve a faster switching speed of the LED.

In a first experiment, it could be validated that the sensor indeed reports proportionally higher PM values the higher the pulse rate (frequency) of the pulse generation was chosen. In a further experiment, it could also be shown, that the sensor distinguishes small intensity light pulses from large intensity pulses giving different readings for the PM2.5 values and the PM10 values. In the following experiments, different pulse widths and pulse rates were used to coarsely adjust the light intensity range, in which the sensor was operated. The fine adjustment of light intensity was done with the source voltage of the pulse generator. The generators source voltage amplitude was typically stepped in 100mV steps.

For the first measurement, a very small pulse width of 5us and a high pulse rate of 300Hz was used, mainly to observe the PM2.5 channel response. Indeed, for very small light intensities, the PM2.5 and the PM10 readings are fairly identical. This means the sensor treats this light pulses as small particles that belong to the PM2.5 class. With further increasing the light intensity, the PM10 reading further increases while the PM2.5 reading remains at a constant value. This indicates that the sensor implements a threshold that limits the PM2.5 readings. However, the expectation would have been, that the sensor outputs low PM2.5 readings rather than keeping them constant for increasing light intensity when size is crossing this threshold.

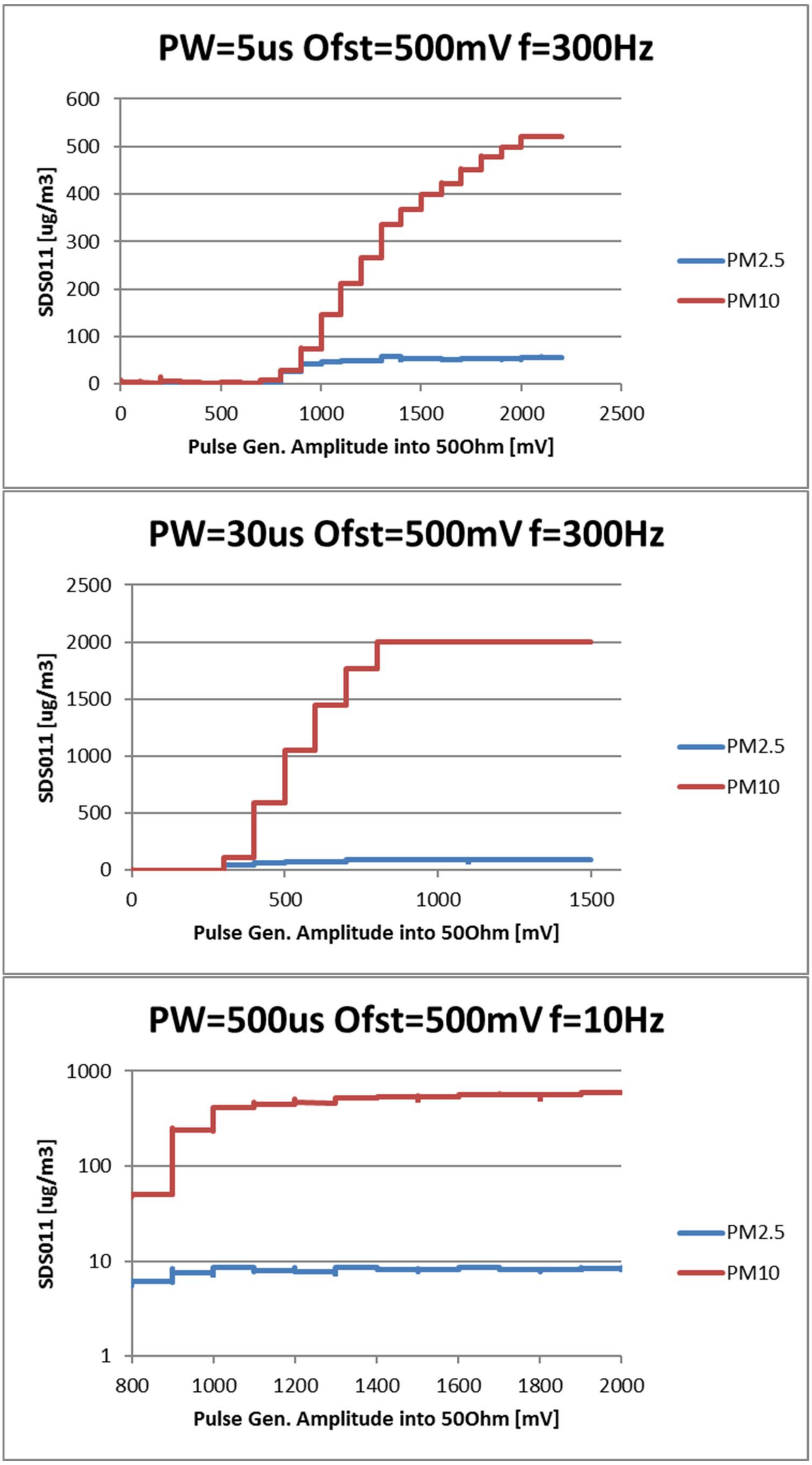

Fig. 10a-c: Transfer characteristic of artificially generated scattering light pulses on PM readings for different light intensities and pulse rates

For achieving medium intensity light pulses, a larger pulse width of 30us at the same pulse rate was used. A similar behavior can be observed in this case, except that the PM10 readings now settle quickly at the maximum level of 2000ug/m^3.

In order to check if a further threshold is implemented to discriminate very large particles that no longer should fall into the PM10 class, the pulse width was increased to 500us. In order not to count too many particles of very large size and not to drive the sensor to the maximum limit, the pulse rate was reduced to 10Hz. As it can be seen, no precise threshold is implemented for high light intensities. Obviously, it is just the saturation effect of the electronics that limits the evaluated light intensity at the upper end. Since at the lower end, for very small particles, the amount of light that can be detected by the photodiode automatically implements a limitation, a high evidence is given that the SDS011 just implements one threshold to divide into small and large particles for counting and therefore just uses two bins for the PM calculation using two representative sizes for the respective mass calculation in the low size and the high size bin.

It is therefore assumed, that for this sensor massive quantization errors occur when the particle spectrum is non-continuous and particle sizes deviate significantly from the two representative sizes that are used to calculate the representative mass in both bins. Furthermore, it must be concluded that the SDS011 sensor can't reliably be calibrated with a single size of monodispersive particles that differ in their size from what the manufacturer uses for the representative mass calculation.

A further conclusion is, that using a broadly distributed aerosol spectrum as a calibration source might also be of limited help for improving the sensors measurement accuracy since real environmental situations show significant changes in their quantitative particle size distributions over time resulting in wrong PM measurement results.

As another example, the Alphasense OPC-N2 (developed at University of Herfordshire) was considered as another lower- (or medium-cost) PM sensor and was investigated with respect to the quantization error. In contrast to the SDS011 this investigation was pretty easy. The datasheet already clearly specifies 16 software bins for quantizing particle sizes between 0.38um and 17um. It therefore can be assumed that internally an ADC is used with a higher bit resolution and the size bins are obviously grouped by software as with professional equipment. As it was shown in previous simulations the quantization error using 16 bins yields acceptable measurement uncertainties. The datasheet shows differential count histograms (dN) for a 5um alumina test aerosol that is distributed between 3 and 8um in 4 bins (estimated 1 sigma values). It therefore quickly becomes clear that it will be possible to calibrate such a product even with monodisperse particles without introducing significant quantization errors. Therefore, when a well-known measurement uncertainty is important, this type of second-generation lower-cost PM-sensor is a much better choice compared to the very-low-cost sensors of the first generation.

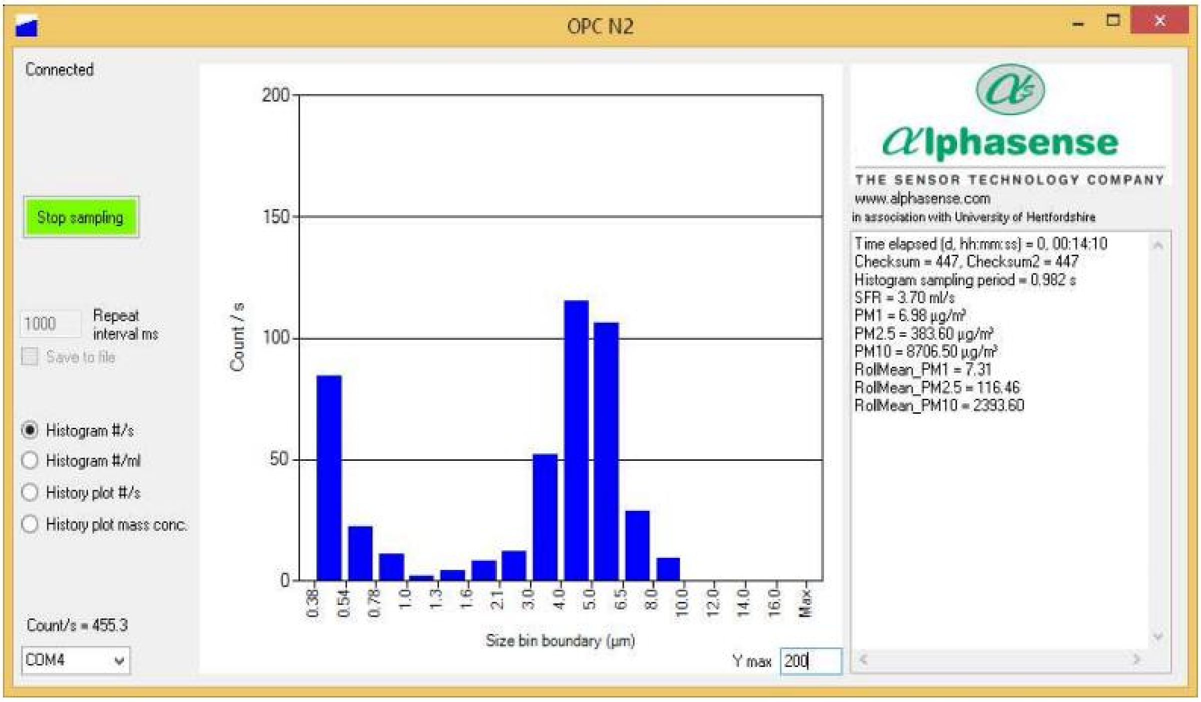

Fig. 11: Example of a differential counts measurement with the lower-cost PM-Sensor OPC-N2 from Alphasense using 16 bins (source Alphasense OPC-N2 datasheet)

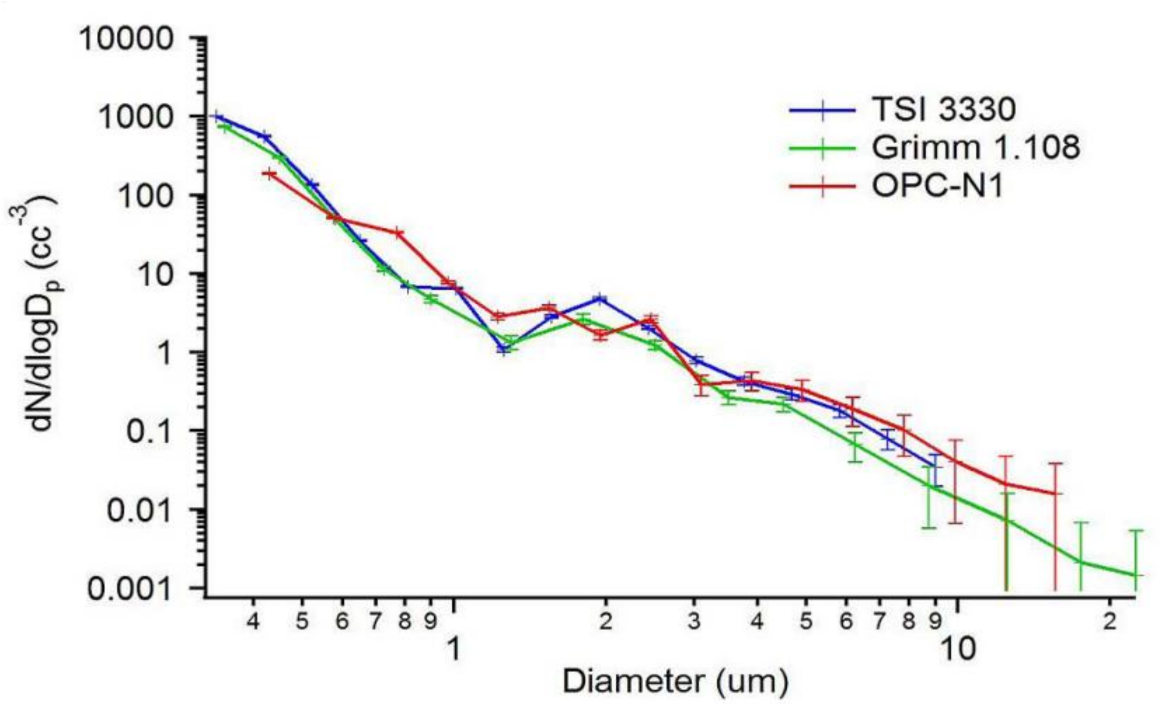

Fig. 12: Measurement of the lower-cost PM-Sensor OPC-N2 from Alphasense in comparison with costly professional equipment (source Alphasense OPC-N2 datasheet)

Literature

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