Whitepaper – Limits of PM2.5 Optical Sensors and Gravimetric Comparison

Why optical PM sensors cannot be 100% accurate, how they compare to gravimetric and high-end optical references, and tuning Sensirion PM sensors for specific aerosols.

This whitepaper provides an overview of how optical PM sensing works, why such sensors can never achieve 100% accuracy, and how gravimetric methods and high-end optical references compare to low-cost alternatives. It also explains the distinction between accuracy and precision, and describes how the output of Sensirion PM sensors can be tuned for specific aerosols.

How Optical PM-Sensing Works

Optical particulate matter sensing is an indirect measurement method based on laser scattering technology. Optical PM sensors direct ambient suspended particles into a measurement cell inside the device. This cell contains a light source (e.g., a laser) and a photodetector. When particles interact with the light, part of the beam is scattered toward the photodetector (see **Figure 1).**

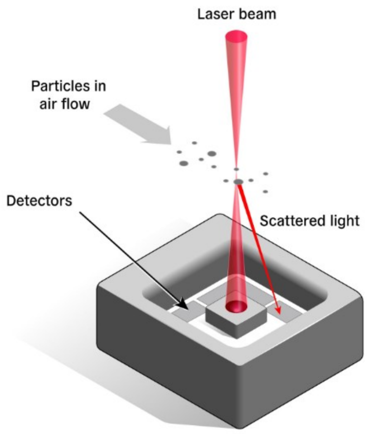

Figure 1. Measurement Principle of Optical PM-Sensors

The collected signal is then converted into real-time mass concentration values (µg/m³). While optical PM sensors are generally comparable in their ability to detect and count particles (especially low-cost PM sensors), the algorithm that maps the measured signal to mass concentration, is a key performance differentiator across manufacturers. Optical particle properties, such as refractive index and shape, strongly influence mass estimation. Consequently, each manufacturer employs a different model to translate the collected signal into µg/m³. This leads to varying sensor readings across manufacturers, even under the same environmental conditions (a fact that also holds true for high-end reference instruments). This highlights why optical PM sensors can only achieve 100% accuracy for the specific aerosol they are tuned and calibrated to. Although this is a clear limitation of optical PM sensors compared to their predecessor, the gravimetric measurement method

(explained later in this document), it is offset by the significant advantage of delivering real-time measurements and cost.
Sensirion calibrates the output of its PM sensors against the well-known and widely used TSI DustTrak DRX 8533 (Ambient Mode) reference.

Limits of low-cost PM sensors

Low-cost PM sensors typically use either LEDs or lasers as their light source. In recent years, LED-based designs have largely been pushed away from the market due to the clear superiority of laser technology. Laser light offers a much higher signal-to-noise ratio, longer lifetimes (thanks to reduced sensitivity to dust accumulation), and the ability to differentiate particle size. For this reason, the following discussion focuses exclusively on laser-based optical sensors.
A key difference between low-cost PM sensors and high-end optical reference instruments lies in the detection rate. In low-cost sensors, the detection rate is typically only around 3–5% (expensive references can reach up to 100% detection rate). As a result, these sensors rely heavily on statistical methods and extrapolation to estimate particle counts per unit volume. This limitation is less critical for small particles (<2.5 µm), which are present in very high numbers in most aerosols. However, larger particles (2.5–10 µm) occur much less frequently, even though their mass concentrations often appear similar to those of smaller particles in many aerosols. This is because particle mass scales with the cube of the radius. For example, a particle with twice the radius has eight times the mass.
Therefore, Sensirion's advanced algorithm directly derives PM4.0 and PM10 outputs from the measured raw data. Although larger particles can be detected by Sensirion's PM sensors, the integration time needed to produce statistically meaningful data would be excessively long, making direct measurement impractical for most applications.

How Gravimetric PM-Sensing Works

Gravimetric PM sensing is the oldest detection method to measure PM and is predating optical PM sensing. This is the reason why the unit µg/m³ is used today in the context of particulate matter. Gravimetric sensing works by drawing air through an impactor followed by a filter. The impactor separates particles by size, ensuring that only particles below a certain threshold reach the filter, while larger particles are removed. The filter then collects the particles of interest. Typically, air is passed through the filter for about 24 hours, after which the filter is extracted and weighed. This process provides a direct measurement in µg/m³ (by dividing the weight by the sampled air volume), unlike optical PM sensing.
However, gravimetric sensing comes with significant drawbacks: it does not provide real-time measurements and requires bulky laboratory-grade equipment. Another limitation is that impactors do not create a perfectly sharp aerodynamic cut-off between particle sizes; their separation curve is gradual rather than binary (see **Figure 2**). Depending on particle density and shape, particles larger than the nominal cut-off may still pass through the impactor, while smaller particles may be partially removed. As a result, gravimetric PM sensing is not flawless either. This limitation is fundamental to all PM measurement technologies and demonstrates that neither gravimetric nor optical methods can achieve 100% accuracy in quantifying aerosol concentrations (a physical constraint that underpins the accuracy discussion below).

Figure 2. Gravimetric sensing: gradual separation rather than binary in impactor.

Precision vs. Accuracy

As mentioned above, optical PM sensors rely on indirect measurements of particles. The complexity of the problem (different particles having different shapes, refractive indices, and other properties) makes it impossible to measure aerosols with 100% accuracy. Accuracy refers to how close the measurements are to the actual PM1.0, PM2.5, and PM10 concentrations (see **Figure 3** for comparison between accuracy & precision). The challenge is that the true ground-truth cannot be determined, neither by gravimetric references (which suffer from issues such as fuzzy impactors and very slow response times) nor by high-end optical reference instruments (which themselves rely on indirect measurements and also have drift over time). For this reason, accuracy specifications should not be used in the context of PM sensors.

Sensirion addresses this by specifying *precision*, defined as the variation between measurements from multiple sensors of the same product line. In this context, precision (also referred to as device-to-device variation) describes how closely a sensor's output matches that of other sensors of the same make. Even if both outputs deviate somewhat from the true ground-truth (in practice this difference is usually quite small), they remain consistent with each other (see **Figure 3**). Responsible manufacturers therefore specify precision rather than accuracy, acknowledging this fundamental physical limitation. Accuracy claims, by contrast, should be treated with caution.

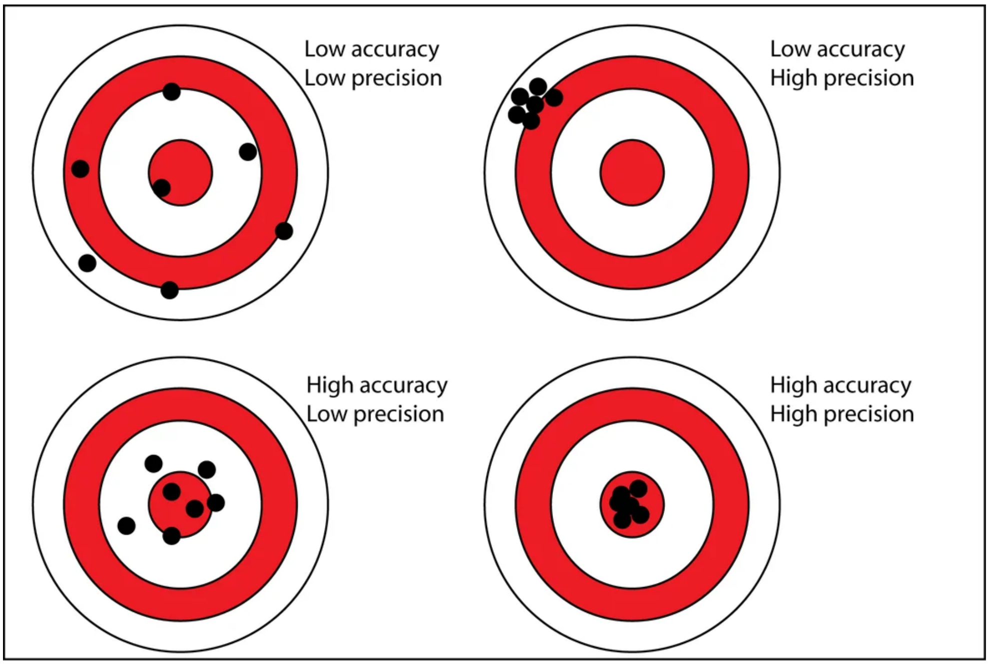

Figure 3. Precision vs. Accuracy

How the Output of PM sensors can be Adapted to Specific Aerosols

For specific applications and aerosols, the output of the SEN6x can be tuned by applying a constant correction factor to the sensor's readings. As discussed earlier, the sensor may deviate slightly from the true concentration, but this offset remains consistent for a given aerosol since precision is maintained.

The correction factor can be determined by comparing the sensor output to a gravimetric reference while exposing both instruments to the target aerosol. This approach ensures that the correction reflects the actual aerosol properties relevant to the intended application.

Important Notices

Warning, Personal Injury

Do not use this product as safety or emergency stop devices or in any other application where failure of the product could result in personal injury (including death). Do not use this product for applications other than its intended and authorized use. Before installing, handling, using or servicing this product, please consult the data sheet and application notes. Failure to comply with these instructions could result in death or serious injury.

If the Buyer purchases or uses SENSIRION products for any unintended or unauthorized application, Buyer shall defend, indemnify and hold harmless SENSIRION and its officers, employees, subsidiaries, affiliates and distributors against all claims, costs, damages and expenses, and reasonable attorney fees arising out of, directly or indirectly, any claim of personal injury or death associated with such unintended or unauthorized use, even if SENSIRION is allegedly negligent with respect to the design or the manufacture of the product.

ESD Precautions

The inherent design of this component causes it to be sensitive to electrostatic discharge (ESD). To prevent ESD-induced damage and/or degradation, take customary and statutory ESD precautions when handling this product. See application note "ESD, Latchup and EMC" for more information.

Warranty

SENSIRION solely warrants to the original purchaser of this product for a period of 12 months (one year) from the date of delivery that this product is of the quality, material and workmanship defined in SENSIRION's published specifications of the product. Within such period, if proven to be defective, SENSIRION shall as sole and exclusive remedy, in SENSIRION's discretion, repair this product or send a replacement product, free of charge to the Buyer, provided that:

- notice in writing describing the defects shall be given to SENSIRION within fourteen (14) days after their appearance;
- such defects shall be found, to SENSIRION's reasonable satisfaction, to have arisen from SENSIRION's faulty material or workmanship;
- the defective product shall be returned to SENSIRION's factory at the Buyer's expense; and
- the warranty period for any repaired or replaced product shall be limited to the unexpired portion of the original period.

The Buyer shall at its own expense arrange for any dismantling and reassembly that is necessary to repair or replace the defective product. This warranty does not apply to any product which has not been installed or used within the specifications recommended by SENSIRION. EXCEPT FOR THE WARRANTIES EXPRESSLY SET FORTH HEREIN, SENSIRION MAKES NO WARRANTIES, EITHER EXPRESS OR IMPLIED, WITH RESPECT TO THE PRODUCT. ANY AND ALL WARRANTIES, INCLUDING WITHOUT LIMITATION, WARRANTIES OF MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE, ARE EXPRESSLY EXCLUDED AND DECLINED.
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