Introduction to the MODULAIR™-PM

This document covers a general overview of the MODULAIR-PM particulate matter sensor including its general operating principle and corrections.

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Introduction

Particulate Matter (PM) pollution is regulated by national and local government agencies (e.g., the US EPA in the United States) and is typically measured using certified reference methods that are both accurate and precise. Unfortunately, these methods are often expensive, consume large amounts of power, and require large enclosures that are environmentally controlled. Over the past decade, new devices have been introduced to the market that are physically small, low power, and lower cost[1]. Such devices are ideally suited to build large, distributed networks of sensors for making air quality measurements.

The existing technologies for measuring particulate matter at low cost – namely optical particle counters and nephelometers – suffer from fundamental limitations caused by their design and operating principles. QuantAQ, Inc. developed the MODULAIR™-PM to accurately measure and record size-resolved aerosol across the full particle size range of interest (i.e., PM_1, $PM_{2.5}$, and PM_{10}). This application note covers the basic operating principle of the device and how data is corrected to allow for transparency in the scientific process.

How does the MODULAIR-PM work?

General Operating Principle

The MODULAIR™-PM combines nephelometry with single particle scattering to measure and record the total integrated mass of aerosol across different size ranges. An optical particle counter (OPC) is used to count and size particles above 350 nm and a nephelometer is used to estimate the mass below the detection threshold of the OPC. Below is a brief overview of each technology. For a more detailed explanation of how low-cost particle sensors work, see Hagan and Kroll (2020)[4].

Optical Particle Counter (OPC)

An OPC counts and sizes particles individually as they pass through a laser beam. The height – and sometimes width – of the peak measured by a photodetector is converted to a particle diameter based on its scattering cross-section and is assigned to a size bin (i.e., a histogram). This process is repeated for every particle in the ensemble such that the number concentration of particles in each bin is generated as a histogram (see the red boxes in Figure 1). After sampling for a period of time (often 1- 5 seconds), a stepwise integration is performed to integrate the total mass of aerosol between two diameters. Assumptions about the physical and optical properties of the aerosol (e.g., refractive index, density, shape) are made to convert from number concentration to mass.

Nephelometer

Nephelometers gather the total light scattered by a population of particles across a wide range of angles, avoiding near-forward and near-backward scattered light. In practice, most low-cost nephelometers which use small fans to aspirate are unable to detect particles larger than 1 μm[2,3]. The scattered light signal – a scalar – is converted to mass via a linear correlation to a reference measurement, either in a laboratory setting or an ambient co-location.

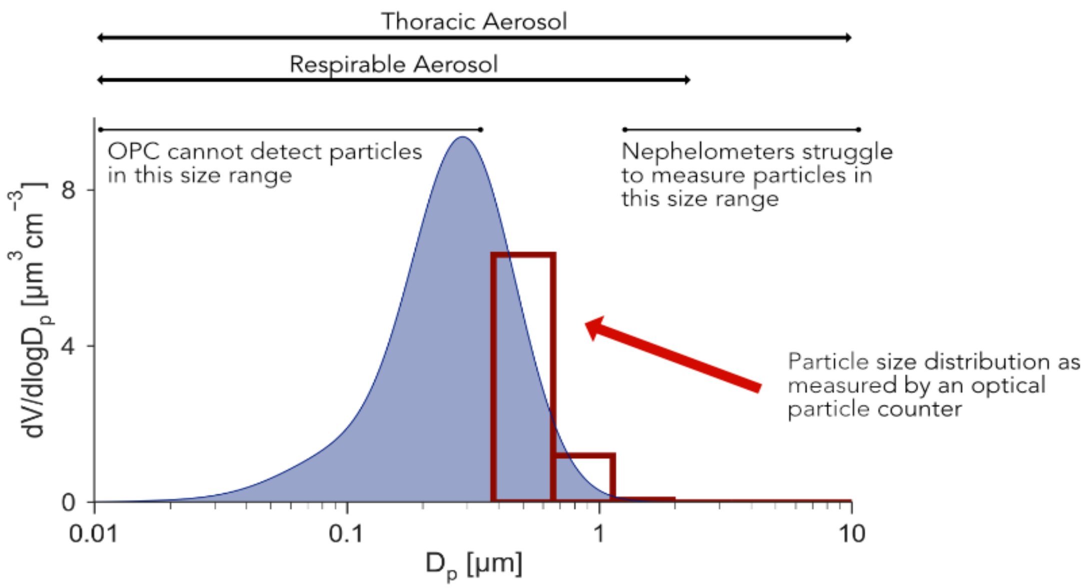

Figure 1. Optical particle counters, especially low-cost versions, cannot detect particles smaller than ~300 nm while nephelometers struggle detect particles larger than 1 µm.

As depicted in Figure 1, an OPC quantifies the size and number of larger particles and the nephelometer quantifies the total scattered light signal below 1 µm. Together, these unique spectra can be combined to leverage the strengths of each individual approach, while mitigating their weaknesses.

Figure 2 depicts the operation of the MODULAIR™-PM as a flow diagram. Air is sampled through a common inlet and is split between a nephelometer and an OPC. The OPC continuously measures the particles in the sample and generates a histogram while the nephelometer sums the scattered light signal across the entire sample period. After a sample period is complete (typically, every 1.5 seconds), the spectra are combined, and a total mass loading is calculated per Eq. 1.

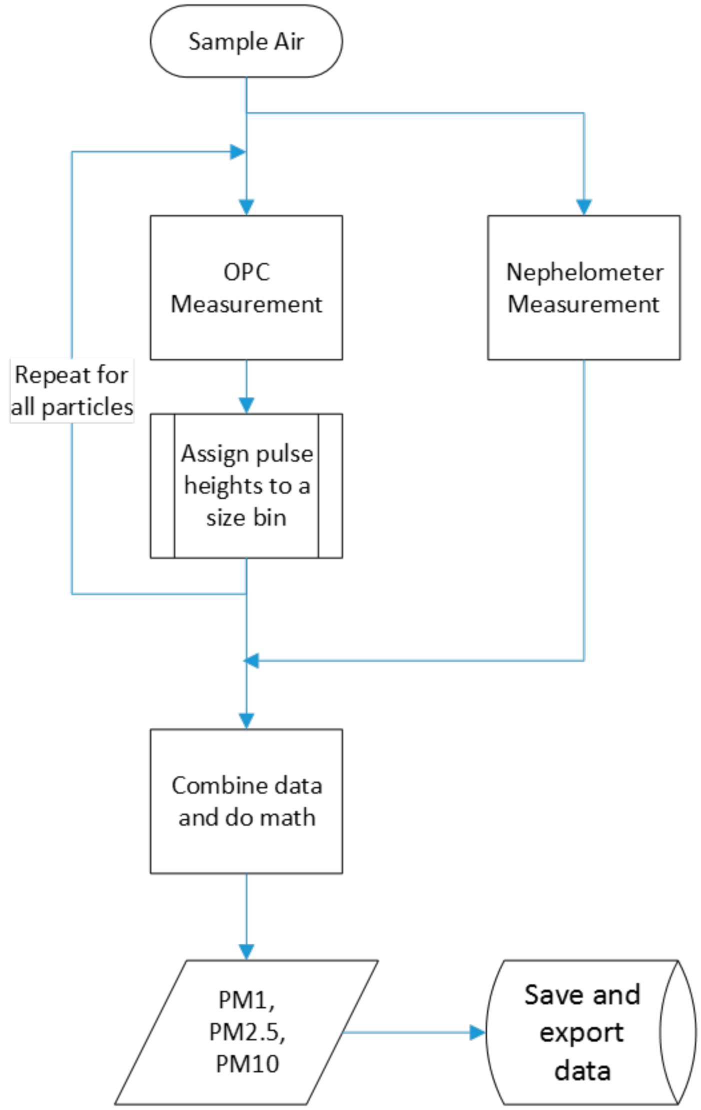

Figure 2. The MODULAIR-PM uses both a nephelometer and optical particle counter to quantify the full range of aerosols.

Together, the mass integration can be expressed as the following:

$$PM_i = MM_j + \sum_k 1/AE_k * \rho_k * N_k \frac{\pi}{6} D_{p,k}^3$$

(Eq. 1)

where MM_j represents the integrated mass below the detection limit of the OPC, AE_k represents the aspiration efficiency for particles in *bin k*, ρ_k represents the density in bin

k, N_k represents the number of particles in bin k, and $D_{p,k}$ represents the midpoint diameter for particles in bin k.

Correcting for aerosol physiochemical properties

Correcting for aerosol density

Aerosol composition – and therefore the density of the aerosol – can range between 1.35 gcm^{-3} (urban aerosol) and 2.6 gcm^{-3} (dust) under normal conditions. Most commercial sensors assume a constant density value and scaling corrections can be made by adjusting this factor. The MODULAIR™-PM assumes a size-dependent density that ranges from urban aerosol for smaller particles to dust for larger particles. Mathematically, this takes the form of a logistic curve, as seen in Figure 3.

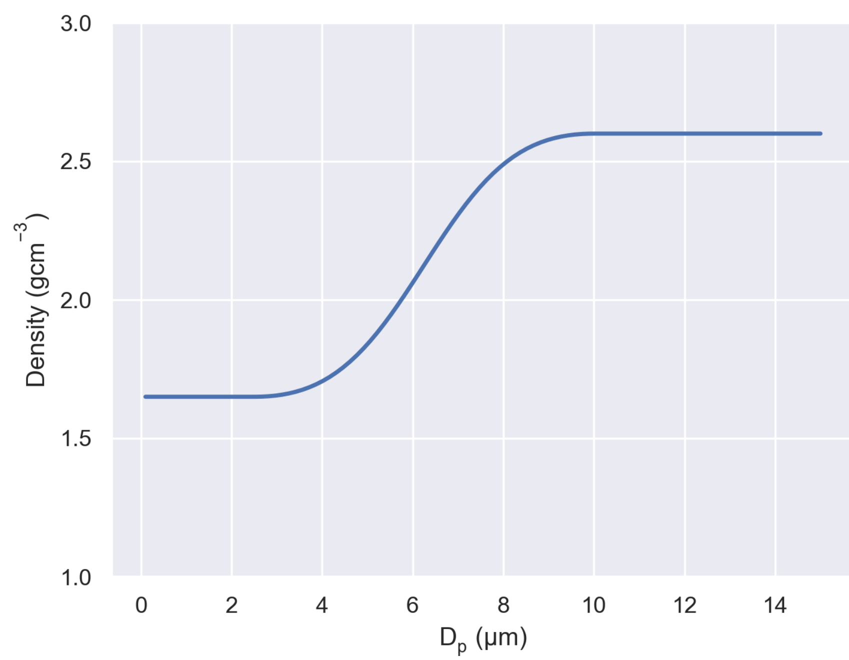

Figure 3. Aerosol density as a function of midpoint diameter.

The size-dependent density is factored into the overall mass integration using Eq. 1 for each data point.

Correcting for aspiration efficiency

The aerosol aspiration efficiency describes the total number particles of a given size that are detected by the MODULAIR™-PM relative to the total number of particles of a given size present in the sample. An aspiration efficiency of 0 means that no particles were detected by the instrument and an aspiration efficiency of 1 means that 100% of the particles were detected by the instrument. As particles become larger and as the wind speed increases, it becomes more difficult for them to make it into the instrument. To correct for the measurement loss of larger particles, QuantAQ has experimentally determined the appropriate correction factor as a function of particle size. Table 1 lists the aspiration efficiency correction as a function of size.

Particle Size (µm)	Aspiration Efficiency
1 µm	1.0
2.5 µm	1.0
5.0 µm	0.65
7.5 µm	0.3
10.0 µm	0.3

Table 1. Lookup table for the aspiration efficiency of aerosols.

Correcting for environmental factors

The MODULAIR™-PM does not include a heated inlet and thus is susceptible to overestimating mass loadings under high relative humidity if not properly accounted for. As relative humidity increases, hygroscopic particles become larger as they take up water, leading to an increase in scattered light caused by their increase in size. For light-scattering based instruments, this can cause an uncertainty in the mass measurement of more than 200% for highly hygroscopic aerosol such as marine aerosol[4]. This effect is most pronounced when the humidity exceeds ~75%. As described in Hagan et al. (2020), the overall increase in scattered light is different for an OPC and a nephelometer, requiring different approaches to correct the data for hygroscopic growth.

To correct the scattered light signal from the nephelometer, MODULAIR™-PM uses a κ-Köhler theory approach suggested initially by Crilley et al. (2018)[5], which is summarized below.

$$PM = \frac{PM_{raw}}{1 + \frac{\frac{\rho_w}{\rho_p}\kappa}{-1 + \frac{1}{a_w}}}$$

(Eq. 2)

where ρ_w and ρ_p are the density of water and the aerosol, PM_{raw} is the uncorrected scattered light signal, a_w is the water activity, and κ is the hygroscopic growth factor[6]. This correction approach assumes a particle density and uses the instruments' relative humidity measurement to compute the water activity for a given data point.

Correcting data from the optical particle counter is a bit more involved, as we must account for the misallocation of particle count to a given size bin. To do so, the MODULAIR™-PM follows the approach described Di Antonio et al. (2018)[7] in which we adjust the midpoint diameter for each particle size bin for each data point, which can be described in Eq. 3 below.

$$\frac{D_{wet}}{D_{dry}} = \left(1 + \kappa * \frac{RH}{100 - RH}\right)^{\frac{1}{3}}$$

(Eq. 3)

The hygroscopic growth factor (κ) is estimated and is size-dependent, like the density assumption above. A logistic curve is used to estimate the growth factor as a function of particle size, ranging from more hygroscopic at smaller particle sizes to less hygroscopic at larger particle sizes.

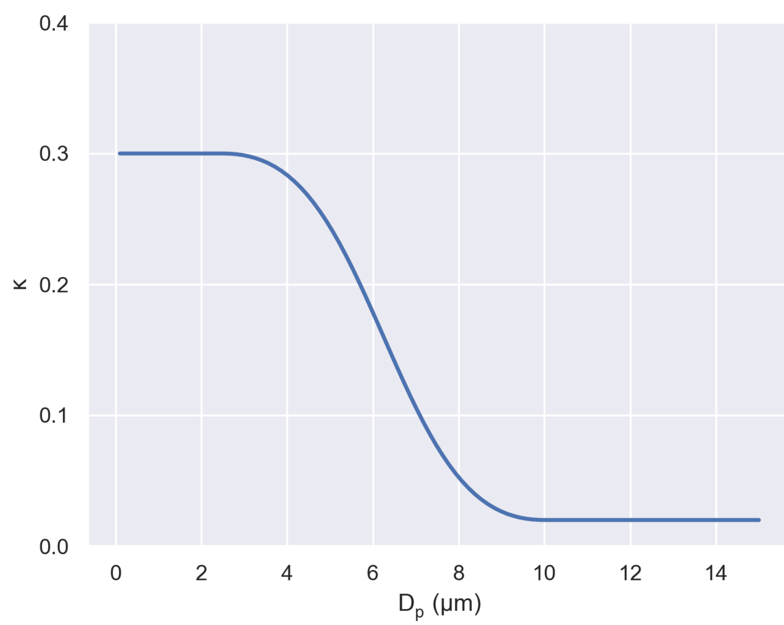

Figure 4. Hygroscopic growth factor as a function of particle diameter.

Are there other ways to measure PM?

There are several alternative approaches for measuring PM at low cost, with the most common approaches summarized below. An extensive list of low(er) cost particulate matter sensors can be found on the AQ-SPEC website:

http://www.aqmd.gov/aq-spec/evaluations.

Nephelometers

Many commercially available low-cost nephelometers can be used to measure PM. The most common is the Plantower PMSX003 which is found in many commercial air quality sensors including the PurpleAir. While the PMSX003 is good for estimating sub-micron aerosol, it is unable to measure particles larger than 1 μm which may or may not be an issue depending on your use case.

Optical Particle Counters

There are a few commercially available low-cost optical particle counters including the OPC-N3 and OPC-R2 manufactured by Alphasense, Ltd (Essex, United Kingdom). Most OPCs require higher-cost electronic components such as a photomultiplier tube which dictates the cost of the device. Mid-range OPCs such as those manufactured by Particles Plus (Stoughton, MA) are also available.

Other approaches

While the nephelometer and OPC are the most common ways to measure PM at low cost, there are novel methods, such as the UPAS (Access Sensor Technologies, CO, USA) which combines a nephelometer for real-time data with a gravimetric sampler.

Citing this document

If you would like to reference this document, please use the citation format listed below. For more information, please visit the direct link on Zenodo. The method of detection described in this document is filed under US Patent Application US17/495,766.

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