TECHNICAL NOTE

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Photometer Calibration: The Case for Two-Point Calibration and Multi-Point Verification

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Abstract

Aerosol photometers are calibrated at two extreme ends of the intended concentration range. The two-point calibration has been in practice since the advent of portable photometers in the 1960s. This technical note outlines the reasons for the validity of the calibration practice both in theory and in practice. Specifically, the principle of light scattering in the Mie regime dictates that the photometric response to a polydisperse aerosol is linearly proportional to its mass concentration, and that it is on the condition of constant aerosol properties (refractive index, particle density, and particle size distribution (PSD)) that the linear relationship stands. The dictation establishes the validity of the two-point calibration. There are also practical considerations that favor the two-point calibration over a multi-point calibration, in which one or more aerosol calibration standards (i.e., standards of measurement) are obtained by diluting the aerosol used to set the span (the high end of the concentration measurement range) of the photometer. We identify and discuss two significant sources of error during multi-point calibration—one originating from the changes in aerosol PSD when adjusting aerosol concentration and the other concerning gravimetric measurements of aerosol calibration standards. Such errors are avoided (in the case of changes in aerosol PSD among multiple concentrations) or minimized (in the case of aggregating errors in each aerosol standard) in the two-point calibration, making it the preferred calibration approach in practice. To complement the two-point calibration, a verification step is strongly advised to confirm the linearity of photometric responses to aerosol mass concentrations throughout the measurement range. Herein, calibration refers to the process of adjusting the response of the device under test to an established standard of measurement,

whereas verification means the comparison between the device response and the standard without adjusting the device response. The combination of the two-point calibration and multi-point verification ensures photometer performance and validity of testing results.

Introduction to Photometer Calibration and Verification

Aerosol photometers measure aerosol mass concentration based on optical photometry technology, whose principle is a linear relationship between the intensity of the light scattered by aerosol particles and the mass concentration of the aerosol. Photometry has the advantages of being much faster (real time) and having much greater sensitivity (able to measure significantly lower concentrations) than a gravimetric measurement, in which a balance is used to weigh the mass of aerosol particles accumulated on a filter sample. Additionally, compared to other optical light-scattering based instruments, such as an optical particle counter, photometers have a much wider dynamic range of concentrations that can be measured without needing to dilute the aerosol. Thanks to these characteristics and advantages, photometers are used in numerous applications globally where it is required to monitor and test aerosol concentrations. These applications include, but are not limited to, filter leakage/integrity testing, indoor and outdoor air quality monitoring, testing the fit and integrity of respirator masks, and testing filters or filter media for particle filtration efficiency.

As an example, aerosol photometers designed and manufactured by Air Techniques International (ATI) are used to test for the presence and location of leaks in High Efficiency Particulate Air (HEPA) filters. A filter leakage test involves introducing a challenge aerosol upstream of the filter and measuring the aerosol concentrations upstream and downstream of the filter with a photometer. If the photometer readings result in a percent of aerosol penetrating the filter exceeding a pre-determined threshold, the filter is determined to have a leak. Because photometers are used for HEPA filter leakage testing in critical infrastructure (pharmaceutical cleanrooms, nuclear facilities, biosafety cabinets, and other life safety infrastructure), it is essential that they are calibrated accurately; erroneous photometer calibrations can lead to test results that incorrectly certify HEPA filters.

Photometers are typically calibrated at the upper and lower ends of the expected aerosol concentration measurement range, with a linear calibration line assumed in the range between those two points. This practice, referred to as two-point calibration in this note, contrasts the calibration of other instruments, which prescribe multiple calibration points spanning the measurement range. Nonetheless, the two-point calibration has been widely adopted since the inception of photometers to measure aerosol mass concentration.

In this technical note, we provide the rationale, both in theory and practice, of using the two-point calibration, and introduce a verification step in tandem with the calibration. Specifically, we demonstrate that this best practice, combining the two-point calibration and the verification, eliminates calibration errors that would otherwise arise inevitably when obtaining multiple standards of measurements between the two calibration points. The supplementary verification detects any flaws in the design, manufacturing, and performance of the calibrated photometer, which would not be discovered through the calibration procedures. To avoid confusion, calibration herein refers to the process of adjusting the response of the device under test to an established standard of measurement, whereas verification means the comparison between the device response and the standard without adjusting the device response.

Theoretical Background for Photometry

A photometer measures aerosol mass concentration by actively drawing the aerosol through its optical detection cell, through which a light beam is directed. The incident light is scattered by the aerosol cloud in the viewing volume, and the scattered light is detected and converted to an electrical voltage signal. The measurement is dependent on specific design parameters of the photometer such as the geometry of the detection cell and the optical system (incident light source and photodetector) as well as the aerosol characteristics. Photometers from ATI, for instance, have historically been based on a forward-light-scattering design.

The principle of forward light scattering has been well documented in the literature (Mie, 1908; Knudson and White, 1945; Hodkinson and Greenfield, 1965; Smith et. al., 1987). The following is an excerpt from Gorner et. al. (1995), describing the working theory behind photometers based on the principle.

> When *N* spherical particles are illuminated (in the viewing volume) by a single ray of unpolarized plane wave carrying unit energy flux per unit area, the flux *I* collected by the aperture (of the collecting lens) is given by
>
> $$I = N\frac{\lambda^2}{8\pi^2}\int_{D=0}^{D=\infty}\int_{\theta=\varphi-\beta}^{\theta=\varphi+\beta}[i_1(D,\theta,n)+i_2(D,\theta,n)]\cdot\omega(\theta,\varphi)\cdot F_N(D)dDd\theta \qquad (1)$$
>
> where
>
> - $i_1(D,\vartheta,n)$ and $i_2(D,\vartheta,n)$ are the intensity functions calculated from the Lorenz-Mie theory for the spatial distribution of scattered light (where *D* is the diameter of the particle considered, ϑ is the scattering angle, and *n* is the refractive index of the particle) (Mie, 1908).
> - $(\lambda^2/8\pi^2)i_1$ and $(\lambda^2/8\pi^2)i_2$ are the fluxes scattered by a spherical particle of diameter, *D,* per unit solid angle in the direction ϑ, respectively, polarized in and normal to the plane containing the direction of incidence and observation (Hodkinson and Greenfield, 1965; Tonna, 1974).
> - $F_N(D)$ is the aerosol size distribution based on number (count), *N*, and *D*.
> - $\omega(\vartheta,\phi)$ is the solid angle of photometer light scattering detection defined by Hodkinson and Greenfield (1965) by
>
> $$\omega(\theta,\varphi) = 2\sin\theta\,.\cos^{-1}\left[\frac{\cos\beta-\cos\theta\,.\cos\varphi}{\sin\theta\,.\sin\varphi}\right] \qquad (2)$$
>
> Integration of equation (1) by using equation (2) yields a flux of scattered light collected by the photometer. This flux is expressed as power in an arbitrary unit (a.u.).
>
> When the particle density is known, one can define the mass sensitivity of the photometer $S_M(D)$ of the photometer as a function of the particle diameter (Smith *et al.*, 1987). For one particle of diameter *D*
>
> $$S_M(D) = \frac{\lambda^2}{8\pi^2}\cdot\frac{1}{M(D)}\int_{\theta=\varphi-\beta}^{\theta=\varphi+\beta}(i_1+i_2)(D,\theta,n).\,\omega(\theta,\varphi)d\theta \qquad (3)$$
>
> where $M(D) = \rho_p\pi D^3/6$ is the mass of the particle of diameter, *D*.
>
> The photometer response is directly proportional to the number of particles (Armbruster, 1987). The monodisperse (all particles having the same diameter) aerosol volume weighted sensitivity $S_c(D)$ can be defined by applying the mass sensitivity to the whole sensing volume *V,* and it can be shown that

$$S_c(D) = S_M(D)V \tag{4}$$

By using the volume weighted sensitivity $S_c(D)$, the theoretical response R of a photometer can be calculated for a polydisperse aerosol of mass concentration C and particle size mass distribution $F_M(D)$:

$$R = C \int_0^\infty S_c(D) F_M(D) dD \tag{5}$$

where R is the intensity of the detected scattered light in an arbitrary unit (a.u.). For a constant $F_M(D)$ the response R is a linear function of aerosol mass concentration with a slope $A_{cal} = R/C$ (Figure 1).

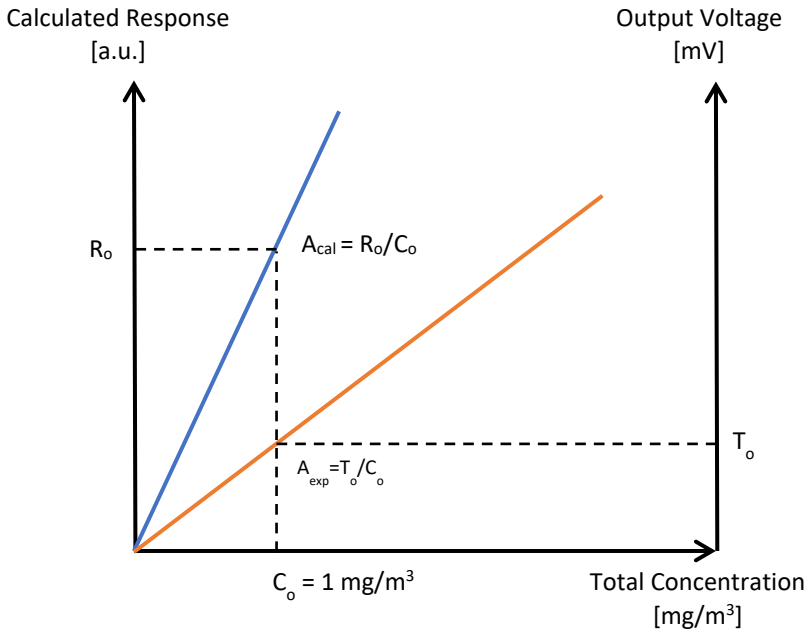

***Figure 1**. Relationship between calculated response and experimental photometer voltage output.*

The particle size mass distribution $F_M(D)$ is calculated using equation (6) and (7) from the particle size count distribution $F_M(D)$:

$$F_M(D) = \frac{M(D)}{\bar{M}} F_N(D) \tag{6}$$

with the average mass of particles

$$\bar{M} = \int_0^\infty M(D) \cdot F_N(D) dD \tag{7}$$

The ratio of the experimental and calculated slopes gives a calibration constant k relating the real photometer output T in millivolts (mV) to the intensity of detected scattered light R in arbitrary units (a.u.) (Bemer *et al.*,

1990). One can experimentally derive the calibration constant *k* of a photometer by calculating the ratio of the experimental and calculated slope as graphically indicated in Figure 1 and as given in the following equations.

$$k = \frac{A_{exp}}{A_{cal}}, \qquad \text{and for a } C = C_0, k = \frac{T_0}{R_0} \tag{8}$$

where T_0 is the mV response and R_0 is the a.u. response at C_0. For any given aerosol, the *k* remains constant if the photometer calibration does not change. The calculated response can then be expressed as:

$$T(mV) = Rk \tag{9}$$

Finally, the output voltages can be converted into a mass concentration by using a factory set conversion factor, *CF,* of the instrument that is the analog to the numerical conversion factor:

$$C_{ph}(mg.m^{-3}) = T(mV).CF \tag{10}$$

Put simply, Equations (5) and (10) in the excerpt above state that the photometric response detected at a fixed angle is linearly proportional to the mass concentration of an aerosol with constant properties—particle size distribution, particle density, and refractive index.

KEY POINTS

- The physical principle on which photometry is designed dictates that the photometric response is linearly proportional to the aerosol mass concentration.
- The linear relationship between photometric response and aerosol mass concentration rests on the condition that aerosol properties—particle size distribution, particle density, and refractive index—remain constant.

Aerosol Photometer Calibration

General Photometer Calibration Practices

As described above, a photometer converts an optical signal originating from light scattered by aerosol particles to an electrical signal, which then correlates with the mass concentration of the aerosol. The correlation enables the photometer to measure aerosol mass concentration, and is established with photometer calibration, in which a known mass concentration of a calibrating aerosol is assigned to the resultant electrical signal as the intended photometric response. This is not different from calibrations of other scientific measurement instruments. The distinction lies in the methodology employed to derive the calibration curve.

Aerosol photometers are generally calibrated at only two points at the extreme ends of the expected measurement range. In the two-point calibration protocol, the lower calibrating point sets the "zero" level in the photometer, while the upper calibrating point establishes the response range, also referred to as the span, of measurable aerosol mass concentration. The span of a photometer is generally set at 100 mg/m^3 (or 100 µg/l) with a controlled polydisperse oil aerosol, and the aerosol concentration is determined with a gravimetric measurement. When establishing the "zero" point, the photometer pulls air through an internal HEPA filter to deliver a clean air stream to the optical cell. The detected baseline signal is set as the "zero" calibration point. A linear calibration curve is then established in the photometer by connecting the two calibration points. This calibration protocol has been in practice since the advent of portable photometers in the 1960s.

In a multi-point calibration, one or more additional calibration points are performed with aerosols obtained by diluting the calibrating aerosol used to set the span of a photometer. The calibration curve can be linear by deriving the "best-fit" line among the calibration points, or non-linear by simply connecting consecutive calibration points. As will be discussed below, multi-point photometer calibration is not recommended in practice because of errors it would introduce.

KEY POINTS

- Two-point calibration sets the span and zero in a photometer, with a linear calibration curve established between the two points.
- This calibration protocol has been in practice since the advent of portable photometers in the 1960s.
- Multi-point calibration employs more calibration points, and the calibration curve can be linear by deriving the "best-fit" line among the calibration points, or non-linear by simply connecting consecutive calibration points. It is not recommended due to errors it would introduce, as illustrated below.

Calibration Error Due to Changes of Particle Size Distribution in Multiple Aerosol Calibration Standards

As described in the theoretical section, the photometric response of a photometer is linearly proportional to the mass concentration of an aerosol on the condition that aerosol properties (refractive index, particle density, particle size distribution) remain constant throughout the calibration range. Refractive index and particle density are intrinsic properties to the aerosol reagent used and generally accepted as constant. Aerosol particle size distribution (PSD), however, cannot be assumed to be constant when multiple aerosol calibration standards (or standards of measurement) originate from a single source of aerosol.

Particle agglomeration and impaction are well studied phenomena that can change aerosol PSD (Schmoluchowski, 1917; May and Clifford, 1967; Lehtinen, 1997). Particle impaction is the process of particle collision with and deposition on an obstacle, as

the particle, due to inertia, is unable to follow the gas streamline to bypass the obstacle. The inertial impaction process alters aerosol PSD by removing larger particles in an aerosol system. Particle agglomeration is the process of particle-particle collision and subsequent formation of larger particles. As a result, aerosol PSD also changes with the conversion of smaller particles to larger particles. Particle agglomeration can be caused by, among all factors, turbulence and Brownian motion.

Both particle agglomeration and impaction are present in an aerosol system that generates and delivers the calibrating aerosol. For example, a tube fitting might inevitably act as an inertial impactor as it connects an aerosol generator and an aerosol mixing chamber. Furthermore, the turbulence in the aerosol mixing chamber, caused by the introduction of dilution air, can lead to particle agglomeration. While those processes certainly change aerosol PSD from the point of generation to the point of delivery in an aerosol system, what is critical in photometer calibration is that the aerosol PSD remains consistent at the point of delivery. In the two-point calibration practice, only one aerosol concentration is involved and hence the aerosol PSD of concern is at that concentration, generally the high concentration used to set the span of the photometer. We can then identify in the aerosol system a steady state, in which the impacts of particle impaction and agglomeration remain constant and the aerosol PSD consistent at the single aerosol concentration.

For a multi-point calibration, aerosols at different concentrations are produced and their PSDs need to be consistent to perform a valid photometer calibration. The additional concentrations, however, add to the complexity of the aerosol system by introducing to the aerosol system new levels of turbulence and/or new pathways to transport aerosols. The extra complexity inevitably results in differences in aerosol PSD at different aerosol concentrations. One obvious example concerns increasing the dilution air to lower aerosol concentration. Consider reducing a high concentration of 100 mg/m^3 to 50 mg/m^3, which requires approximately doubling the flow of dilution air. Aerosol particles will travel at twice the velocity once mixed with the dilution air. Acting as an inertial impactor, a tube fitting will now remove larger particles at a smaller cutoff size in a stream of aerosol traveling with the elevated momentum. Consequently, the aerosol at 50 mg/m^3 will feature a PSD with a lower count median diameter than at 100 mg/m^3. When trying to achieve even lower concentrations in this setup, such changes in PSD may be greater. When those generated aerosols are used as calibration standards, variations in aerosol PSD at different concentrations translate to errors in the calibration curve. These errors are avoided in the two-point calibration practice by employing a controlled aerosol at one single concentration.

To demonstrate the change in aerosol PSD when adjusting aerosol concentration, we characterized at various concentrations (determined gravimetrically) the PSD of aerosols delivered from an optimized calibration aerosol system (the ATI CALIBRA™ 800 Precision Aerosol Source). This aerosol system delivers aerosols with stable PSD at each concentration. At 100 mg/m^3, for instance, the aerosol PSD was monitored for eight days with multiple PSD measurements performed throughout each day, and the count median diameter (CMD) was found to be 209.0 ± 1.1 nm (n = 96). Similar stability was observed at other concentrations (to be supported by data that will be generated in Tolerance Testing). Such data demonstrates the stability of aerosols produced in the aerosol system and thus its capability to conduct valid (minimal-error) two-point calibration as well as multi-point verification (to be discussed later) of aerosol photometers. When comparing aerosol PSD across various calibration points up to 100 mg/m^3 as shown in Figure 2, however, the CMD ranged from 206 nm to 216 nm, a difference of 10 nm. That variation in aerosol PSD, although small, would certainly add to the errors in a multi-point calibration, in which photometer responses are established at each concentration. It should be noted that such a small variation in aerosol PSD (< 5%) across a wide concentration range does not introduce errors to photometers in a multi-point

verification process, in which photometer performance is validated qualitatively against aerosols of known concentrations. We explore an aerosol-based multi-point verification approach in a later section.

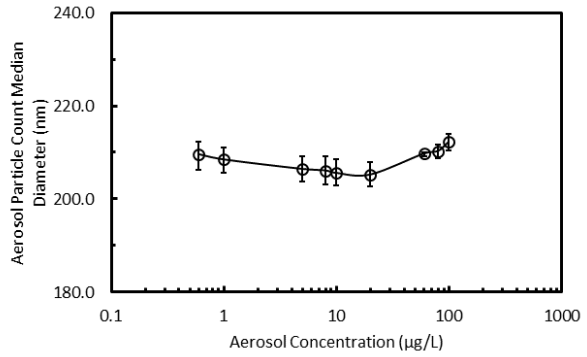

***Figure 2**. Count media diameter (CMD) of aerosols changes with aerosol concentration (determined gravimetrically) due to aerosol agglomeration and impaction when obtaining aerosol standards at those concentrations. When multiple such standards are used to calibrate photometers, the variations in aerosol PSD (i.e., CMD), although small, will inevitably introduce errors in photometer calibrations; however, the small variations provide sufficient margin to verify photometer performance, which does not alter photometer response.*

KEY POINTS

- Aerosol PSD is subject to change when creating multiple aerosol calibration standards at different concentrations. The change in aerosol PSD is a result of particle agglomeration and impaction, both of which are inevitable in the process of achieving multiple aerosol concentrations.
- Changes in aerosol properties (aerosol PSD) violate the conditions on which the principle of photometry operates in a consistent linear range, thus adding error in multi-point calibration.
- Two-point calibration avoids such error by involving only one stream of aerosol calibration standard.

Calibration Error in Gravimetric Measurements of Aerosol Calibration Standards

Another source of error in the calibration of aerosol photometers concerns the accuracy of the gravimetric calibration standards used. As described earlier, calibrating an aerosol photometer involves correlating the electrical signal the photometer produces detecting an aerosol at a known concentration to the numerical known concentration. Aerosol concentration is determined with a gravimetric method, which prescribes loading the calibrating aerosols on a filter for a specified period of time and at a specified flowrate. The loaded mass is measured on a high-precision balance and used to calculate the aerosol concentration. Aerosols with known concentrations are referred to as gravimetric calibration standards herein.

While calibrating a photometer at a concentration point takes mere seconds, the timeframe to measure aerosol concentration gravimetrically is orders of magnitude longer. For example, employing an analytical balance with a readability of 0.01 mg and a sampling flowrate of 28.3 lpm (or 1 CFM, typical flowrate for filter leakage testing), it takes approximately 10 minutes to load an appreciable amount of aerosol particles at 100 mg/m^3 on a 47-mm filter for the balance to reliably weigh, 20 minutes at 20 mg/m^3, and 70 minutes at 0.6 mg/m^3. The time requirements imply that aerosol properties, aerosol PSD and concentration, need to remain stable at least during those timeframes. An aerosol "detected" by the filter during the required time in the gravimetric method, in such a case, will agree with that detected instantaneously by the photometer during calibration at any point of the gravimetric measurement. Empirical evidence suggests that the longer the gravimetric duration, the more likely it is to introduce variation to aerosol properties in an aerosol system, however. The amount of aerosol particles loaded for gravimetric measurements, additionally, also determines the accuracy of the gravimetric standards. For a given balance for gravimetric measurements, its uncertainty

of measurement plays a lesser role in the actual measurements at higher readings. It is generally expected that the higher the aerosol concentration, the more mass loaded for gravimetric measurement. In other words, there are more errors in the gravimetric standards at lower concentrations. While this shortcoming can be circumvented by using higher precision balances or extending sampling time, it is not always practical. For example, it would require 1667 minutes (or 27.8 hours) to load the same amount of aerosol particles at 0.6 mg/m^3 as that at 100 mg/m^3, in the example above. In lieu of the above, it can be concluded that greater error is expected when obtaining gravimetric calibration standards at lower concentrations. Indeed, the empirical intuition is corroborated with theoretical calculations in the Chinese JJF 1800-2020 specification (Annex B), which shows the relative measurement uncertainty of gravimetric measurements at 0.6 mg/m^3 is twice that at 100 mg/m^3.

The same mechanisms of particle agglomeration and impaction apply during obtaining gravimetric calibration standards. Since photometer calibration essentially correlates the signal detected by the photometer to the concentration "detected" by the filter in the gravimetric method, it is critical that both detection approaches see aerosols with the same aerosol PSD and concentration. Yet that is extremely difficult to achieve in practice. One obvious factor is the sampling flowrate, which can be easily adjusted to decrease the time needed in a gravimetric measurement in order to reduce error in the gravimetric standard. The flowrate, at the same time, directly affects the turbulence of an aerosol and the inertia of aerosol particles, which result in particle loss due to particle agglomeration and impaction in the flow path to the filter. The loss of particles causes additional error in the gravimetric calibration standards. In this case, careful selection of a sampling flowrate is required to reduce calibration error caused by the two opposing mechanisms. Many other factors contribute to those mechanisms that change aerosol PSD and concentration, and they warrant a separate technical note to discuss in detail and identify best practices when obtaining gravimetric calibration standards.

It is worth pointing out that when the errors in gravimetric calibration standards are combined with those caused by different aerosol PSD at different concentrations in a multi-point calibration, the inaccuracy of such a calibration is exacerbated, defeating the ultimate goal of any calibration—accuracy. Due to the reasons laid out above, ATI strongly advocates for the two-point calibration practice, which minimizes such errors.

KEY POINTS

- Multi-point calibration also suffers from errors in the gravimetric measurements of aerosol calibration standards at low concentrations. The errors arise as a result of potential instability of aerosol properties during the extended gravimetric measurements and of disparity of aerosol properties between aerosols detected by the photometer and those by the gravimetric filter. Therefore, multi-point photometer calibration is not recommended.
- The higher the aerosol concentration, the more mass loaded for gravimetric measurement, and the more accurate the gravimetric standard. Two-point calibration employs one gravimetric standard at the highest aerosol concentration to set the span recognized in the industry.
- Two-point calibration minimizes the errors in gravimetric measurements and avoids the errors due to changes in aerosol PSD at different concentrations, which warrants its preference over multi-point calibration.

Multi-Point Photometer Performance Verification

A two-point calibration of an aerosol photometer assumes photometric responses are intrinsically linearly proportional to aerosol concentration, given constant aerosol properties (refractive index, PSD, and particle density). The assumption is based on the theory of forward light scattering in the Mie regime. While valid, the assumption needs to be verified to ensure photometer performance in the real world for various reasons. One reason is that the implementation of photometry involves various physical components, which are subject to defects and imperfections. A defective optical component may alter the intended response profile in a photometer. Leaks are also a possible cause. Another concern is a possible faulty process of manufacturing and/or servicing a photometer. Yet another rationale for performance verification is the algorithms that process the final electrical signal and output the test results in the photometer. Design flaws in photometer algorithms can compromise photometer performance and lead the photometer to operate against the very principle on which it is designed.

Consequently, photometer performance verification is strongly advised following calibration. In contrast to the two-point calibration, photometer performance verification should be conducted at multiple concentration points throughout the intended range. The significance of photometer performance verification is indeed being recognized in the industry. For example, the Chinese national JJF1800-2020 (2020) standard mandates such performance verification and specifies tolerances at different concentrations (0.6 mg/m^3, 20 mg/m^3, and 100 mg/m^3) within which a photometer is verified to be compliant with the standard.

Traditionally, photometer performance has been verified using an electronic test method, in which the analog signal from the photodetector is replaced with an adjustable current source. This method, leveraging current sources with accuracy through seven to nine decades of range, provides a direct way to demonstrate the linearity of a photometer's electronics. However, the electronic method leaves untested critical elements of the photometer, especially the optical chamber and photodetector. This drawback can be addressed by adopting an aerosol-based method, in which a source of actual aerosol is introduced to the photometer under test and device reading is then compared to the concentration of the aerosol used. While the aerosol-based method covers the entire photometric system, both optical and electronic, it is limited in the concentration range due to practical reasons (methodology and error of measuring extremely low aerosol concentrations). Therefore, the aerosol-based method and the electronic method complement each other in testing photometer performance. In a separate technical note, we discuss in detail such an aerosol-based verification method, also referred to as linearity verification testing (LVT) in photometer performance verification. Briefly, the aerosol-based LVT entails generating aerosols at multiple concentrations covering the intended operating range of the photometer, minimizing changes in aerosol properties (refractive index, PSD, particle density, and concentration stability) throughout the range, and comparing the photometer response and gravimetric measurements at each aerosol concentration.

Multi-point verification, despite its simplicity, is challenging for the same reasons that may alter aerosol properties, particularly aerosol PSD. Yet the difference between a two-point calibration and a multi-point verification is that the calibration establishes the photometer response, whereas the verification assesses if the photometer responds linearly in the calibration range. As such, the tolerance in verification can be slightly wider to accommodate for errors due to changes in aerosol properties. When combined, the two-point calibration and multi-point verification ensure photometer performance and validity of testing results.

KEY POINTS

- Multi-point verification is necessary to validate photometer performance, which can be compromised due to flaws in photometer components, manufacturing and servicing processes, and algorithms. The importance of photometer performance verification is being recognized in the industry and standards such as the Chinese JJF1800-2020.
- Photometer performance has traditionally been verified with an electronic method, which checks for the linearity of the electronic components in a photometer and leaves the critical optical components untested. An aerosol-based multi-point verification approach addresses the drawback by testing both the optical and electronic components in the photometer.
- Multi-point verification complements two-point calibration in ensuring photometer performance and validity of testing results.

Conclusions

Aerosol photometers are used in critical applications that call for valid photometer calibrations periodically. Herein, calibration refers to the process of adjusting the response of the device under test to an established standard, whereas verification means the comparison between the device response and the standard without adjusting the device response. The decades-old two-point calibration is a best practice, which has been challenged by the multi-point calibration method used in calibrating other measurement instruments. Here we systematically explain the rationale for the preference of the two-point calibration over the multi-point calibration. Photometers are designed on the principle that the photometric response is linearly proportional to the mass concentration of an aerosol, on the condition that aerosol properties (refractive index, particle density, and PSD) remain constant. From the theoretical perspective, both the two-point and multi-point calibration approaches are equally sound. It is extremely challenging, however, to maintain the properties (particularly aerosol PSD) of calibrating aerosols across a wide concentration range in practice. Any dilution to adjust aerosol concentration bears the impact to change the fluid dynamics in the aerosol, leading to changes in aerosol PSD due to particle agglomeration and impaction. The differences in aerosol PSD manifest as errors in a multi-point calibration, wherein aerosols at multiple concentrations are employed as standards of measurement. Therefore, it is not recommended to adjust a multi-point calibration curve, because it likely introduces such unnecessary error in calibration and hence actual measurements using the photometer with the adjusted calibration curve.

The quantification of standards of measurement at low aerosol concentrations also introduces errors in a multi-point calibration as a result of prolonged duration of gravimetric measurements. Such errors are avoided or minimized in the two-point calibration practice, which only involves a single stream of aerosol at the high concentration end. Nonetheless, the multi-point approach finds its best utility as a verification tool to check for any photometer performance anomaly during manufacturing and at scheduled maintenance and calibration intervals. When combined, the two-point calibration and multi-point verification ensure photometer performance and validity of testing results.

Abbreviations

cm	Centimeters
CMD	Count median diameter
HEPA	High efficiency particulate air
in	Inches
l	Liters
lpm	Liters per minute
LVT	Linearity verification test (of aerosol photometers)
mg/m^3	Milligrams per cubic meter
MMD	Mass median diameter
nm	Nanometers
PSD	Particle size distribution
µg/l	Micrograms per liter

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