

Comparisons Between Continuous and Integrated Mass Measurements



**COMPARISONS BETWEEN
CONTINUOUS AND INTEGRATED
MASS MEASUREMENTS**

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COMPARISONS BETWEEN CONTINUOUS AND INTEGRATED MASS MEASUREMENTS

1 BACKGROUND

Filter-based samplers have long been employed by monitoring networks to measure aerosol mass concentrations because they are robust and the collected filters can be used for analysis of speciated mass concentrations. However, filter-based samplers have several disadvantages. Because of the lag time in collecting and analyzing filters, real-time information is not possible. Long sampling times are also typically required for analysis purposes, so observing short duration events, such as prescribed or wildfire impacts, is difficult. Collecting and analyzing filter-based samples is expensive and labor intensive and subject to sample contamination. In addition, filter-based measurements have associated sampling and analysis artifacts such as losses of semivolatile species during sampling, or retention of particle-bound water. Real-time, or continuous, mass measurements have several technical advantages. They provide real-time information with short time resolutions and are relatively labor-free. However, they are also subject to measurement biases depending on the operating principle, and therefore comparisons between other filter-based or continuous measurements are necessary to determine their accuracy under a variety of sampling and environmental conditions.

The Environmental Protection Agency (EPA) has designated Federal Reference Method (FRM) samplers for use in determining compliance with National Ambient Air Quality Standards (NAAQS). Their operating procedures are specified for uniform agreement for PM_{2.5} and PM₁₀ sampling across the United States. Using FRMs to determine the accuracy of continuous mass measurements provides a standard with which to evaluate instrument performance. However, FRMs have been associated with negative biases due to volatilization of ammonium nitrate and volatile organic carbon (e.g., Schwab et al., 2006; Zhu et al., 2007). Retention of particle-bound water may also affect measurements at the relative humidities at which the filters from the samplers are weighed (30–40%) (Malm et al., 2011). These biases must be considered when evaluating the accuracy of real-time instruments against FRMs.

This summary includes a discussion of the operating principles and calibration procedures (when available) for each instrument. It also provides a review of comparisons of continuous and integrated (filter-based) mass concentrations reported in peer-reviewed literature and government reports. Two requirements were applied for a given study to be included in this summary: (1) an FRM instrument was used as the integrated measurement (PM_{2.5} or PM₁₀), and (2) the data were reported as they were measured (no corrections applied). The studies were performed in a variety of laboratory and field environments (urban and rural) and during different seasons and represent diverse aerosol conditions.

This summary is organized in the following manner. Section 2 includes a list of the FRM instruments included in the reviewed studies and discussion of filter-based measurement biases. Section 3 provides a description of the principle of operation and associated biases of the instruments included in the review of continuous measurements. A discussion and table of results from the included studies are provided in Section 4, and Section 5 provides recommendations.

An appendix includes reported biases for all of the studies reviewed and a table of operating specifications for the instruments used for continuous measurements.

2 FEDERAL REFERENCE METHODS

The EPA provides a list of designated reference and equivalence methods for PM_{2.5} and PM₁₀ mass measurements (U.S. EPA, 2013). The FRM instruments used in these studies include the BGI PQ200(A), R&P Partisol (2000, 2025), Thermo Electron RAAS2.5-300, Andersen RAAS2.5-300, Thermo Scientific Partisol-Plus, and the Sierra-Andersen 1200. As mentioned previously, FRM measurements are subject to sampling and analytical biases due to changes in the equilibration of the sampled filter with its environment. During and after collection, the sample is exposed to uncontrolled relative humidity and temperature. Prior to weighing, the sampled filter is equilibrated at room temperature and low relative humidity. Filters are weighed at a relative humidity of 30–40% or lower. These changes in equilibrium conditions between gas and particle phase can lead to losses of volatile species, such as ammonium nitrate and semivolatile organics, or the retention of particle-bound water associated with hygroscopic particles on the filter. These biases vary as a function of season and location, depending on the abundance of these species in the atmosphere. For example, in California where ammonium nitrate is a significant fraction of PM_{2.5} mass, volatilization of ammonium nitrate led to ~20% loss of total mass on the filter during summer (Hering and Cass, 1999). Losses of semivolatile organic and nitrate species during studies in Riverside, California, led FRM samplers to underestimate PM_{2.5} mass by an average of 34% (Pang et al., 2002). In environments and seasons with high ambient relative humidity and acidic aerosols, such as the eastern United States in summer, filter-based mass measurements may be biased high by particle-bound water on the filter by an average of 3–10% (Malm et al., 2011). It is important to keep in mind when comparing continuous and integrated measurements that the integrated measurements also potentially contribute significant uncertainty to the comparison, especially in conditions dominated by semivolatile organic species, such as during smoke sampling.

3 CONTINUOUS MEASUREMENTS

Instruments included in this summary and that are commonly used to measure continuous mass concentrations include the Tapered Element Oscillating MicroBalance (TEOM), Beta Attenuation Monitor (BAM), Continuous Ambient Mass Monitor (CAMM), and Real-time Ambient Mass Sampler (RAMS). Instruments based on the principle of light scattering by particles are also used to determine real-time mass concentrations, such as the E-Sampler, DustTrak, DataRam, GreenTek, M903 Radiance Research nephelometer, and Optec NGN nephelometer. A description of each instrument and potential biases are described below.

3.1 Semi-direct Mass Measurements

The following instruments measure mass semi-directly in that the measurement is related to particle mass based on the operating principle of the instrument.

3.1.1 TEOM

The Tapered Element Oscillating MicroBalance (Thermo Scientific, Waltham, MA) measures the accumulation of mass on a heated filter attached to the tip of a tapered oscillating glass rod. The change in oscillation frequency with the addition of mass is used to determine the mass on the filter. The sample area is maintained at 50 °C to reduce the effects of thermal expansion and contractions associated with temperature fluctuations, including condensation and evaporation of water on the filter. However, heating the sample to this temperature can result in the loss of semivolatile species, resulting in a negative bias. This sampling bias depends on location and season and is potentially greater in areas with higher concentrations of semivolatile species. Some TEOMs operate at 30 °C to minimize these losses. The FDMS (Filter Dynamics Measurement System) TEOM measures the core and volatile fractions of collected mass by measuring their effects as they collect the filter. The air is first conditioned by a diffusion dryer to remove water, then the instrument uses a switching valve to change the path of the main flow every 6 minutes. Particles are removed from the purged air stream with a filter maintained at 4 °C. The flow alternates between a purged (filtered) air stream and sample air stream. During the measurement of particle-free air, the TEOM measures the change in mass due to volatilization of particles from the previous sampled air. The decrease in mass is added back to the mass measurement obtained during the particle sample. Positive and negative biases that occur during collection are monitored and reported as they occur, thereby providing an estimate of volatile and nonvolatile species.

The TEOM requires a weather-protected enclosure. The instrument is fairly large depending on the version (e.g., 17 x 19 x 55 in), and its weight ranges from 40–75 lbs (see Table A2 in Appendix). On average the TEOM underestimated mass with an average bias of 0.91 ± 0.34 (see Table 2).

3.1.2 BAM

The Beta Attenuation Monitor (Met One, Grants Pass, OR) measures mass through the attenuation of beta radiation. The difference in transmission of beta radiation through a filter tape before and after a sample has been deposited is related to mass. The mass absorption coefficient of beta radiation is determined through measurements of known standards. The filter tape is advanced automatically, resulting in continuous measurements. The BAM is often operated with a heater to reduce the relative humidity below 60%, which minimizes the effects of particle-bound water but could result in loss of semivolatile species. BAM measurements may also be somewhat sensitive to hydrogen ion concentration in particles (Chung et al., 2001). The E-BAM was designed to operate in more rugged environments.

The BAM requires a weather-protected enclosure. It is 12.25 x 17 x 16 in and weighs 54 lbs. The E-BAM is appropriate for rugged sampling and is mounted to a tripod. Its dimensions are 16.1 x 14.2 x 7.9 in and it weighs 35 lbs. The average PM_{2.5} BAM bias was 1.03 ± 0.12 and the bias in the PM_{2.5} E-BAM was 1.09 ± 0.08 (see Table 2 and Table A2 in the Appendix).

3.1.3 CAMM

The Continuous Aerosol Mass Monitor (Thermo Andersen, Smyrna, GA) measures mass through the relative difference in pressure drop between a reference channel and a channel where a sample is deposited on a filter tape. The pressure difference is related to the mass concentration deposited on the tape. The tape automatically advances for a near real-time measurement. A diffusion dryer reduces the effects of particle-bound water on the measurement.

The average bias for the PM_{2.5} CAMM was 0.85 ± 0.15 . No specifications were available for the CAMM.

3.1.4 RAMS

The Real-Time Total Ambient Mass Sampler (Brigham Young University, Provo, UT) is a research-grade instrument that determines nonvolatile and semivolatile mass through diffusion denuder and TEOM technology. The denuders remove gas-phase water, gas-phase semivolatile organic species, inorganics gases, and oxidants, sandwich filters remove semivolatiles lost from particles during sampling, and a TEOM measures the total mass of collected particles (Lee et al., 2005). The average bias was 1.01 ± 0.13 .

3.2 Indirect Mass Measurements

Indirect mass measurements, such as those made by photometers and integrating nephelometers, use the principle of scattered light by particles to derive mass concentrations. These instruments measure a voltage proportional to some integrated portion of the volume scattering function, σ . The light that is scattered in any given direction by a particle is a function of the wavelength of incident light, the particle size, composition (index of refraction), and shape. Figure 3.1 shows four volume scattering functions for three types of spherical particles and background clear air atmosphere. The blue curve represents the angular dependence of Rayleigh or background gas concentrations, while the remaining curves represent scattering from three different types and size distributions of particles. The red line represents the scattering function for an aerosol having a lognormal mass size distribution with $d_g = 0.2 \mu\text{m}$ and a $\sigma_g = 1.75$, the cyan line corresponds to a $d_g = 0.8 \mu\text{m}$ and a $\sigma_g = 1.75$, and finally the black line corresponds to a standard Arizona test dust where $d_g = 2.5 \mu\text{m}$ and $\sigma_g = 2.5$. The difference between scattering in the forward versus back direction for the $2.5 \mu\text{m}$ aerosol is nearly 500, while for an aerosol with $d_g = 0.2 \mu\text{m}$, it is still substantial at about 10.

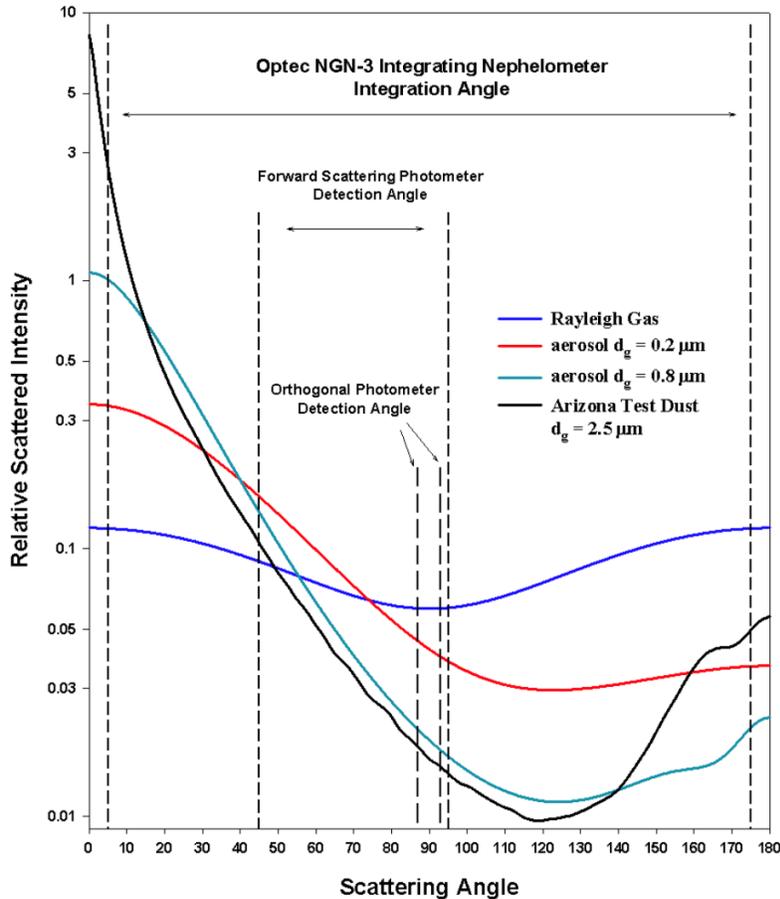


Figure 3.1: Normalized scattering phase functions for a Rayleigh calibration gas, 0.2 μm and 0.8 μm aerosol size distributions, and Arizona Test Dust used to calibrate forward scattering and orthogonal photometers. Detector acceptance angles for various nephelometers and light scattering photometers are indicated.

With respect to incident wavelength, particles with sizes comparable to the wavelength of the light source scatter light more efficiently, so fine particles scatter more light at visible wavelengths (typical of the lasers used) than do coarse particles. Particle composition is characterized by density and refractive index. Particles with lower density scatter more light on a per mass basis relative to high density particles. Fine-mode atmospheric aerosols composed mainly of dry inorganic salts and organic species have lower densities ($1.5\text{--}1.7\text{ g cm}^{-3}$) relative to dust aerosols ($\sim 2\text{ g cm}^{-3}$). Particles with a high refractive index scatter more light at a given incident wavelength; dust particles generally have higher refractive indices (1.8) relative to dry inorganic salts and organic species (1.5). In addition, the uptake of water by hygroscopic salts in high relative humidity environments can affect all of these properties by lowering refractive index and density but increasing mass.

Integrating nephelometers collect the scattered light in the entire scattering volume (approximately). Photometer measurements focus on a smaller scattering volume, such as forward scattering probes or over some integrated scattering angles such as $45\text{--}90^\circ$. Also, there are instruments that collect light that is approximately orthogonal to the incident radiation (90° photometers).

Converting an integrating nephelometer instrument scattering response or light scattering coefficient (b_{sp}) to mass concentration (M) requires a mass scattering efficiency α ($b_{sp} = \alpha M$) that characterizes the amount of light scattered per mass. For dry particles, α is most sensitive to size and density, followed by refractive index. A typical dry α corresponding to a mixed fine-mode aerosol is around $3.6 \text{ m}^2 \text{ g}^{-1}$, and α for a mixed coarse-mode aerosol is around $1.0 \text{ m}^2 \text{ g}^{-1}$ (Hand and Malm, 2007). The inherent variability in a dry aerosol α for typical background conditions is about 50%, and for a smoke aerosol it is about 25%. If the aerosol is not dried either with a diffusion denuder or by heating, that variability goes up to over 200%, implying an error factor of 3. This variability in α directly translates into the same inherent uncertainty in mass determination from a nephelometer measurement just based on the inherent variability of mass scattering efficiency.

Interpreting a photometer measurement in terms of mass concentration is even more problematic because of variability in the volume scattering function as a function of particle type and calibration. Photometers that are calibrated with Arizona Test Dust assume that all of the measured aerosols have similar characteristics to the test dust, namely a large size distribution (d_g of 2–3 μm , σ_g of 2.5) and large density (2.65 g cm^{-3}). Arizona Test Dust does have a refractive index similar to dry, fine-mode aerosols (1.5), but due to its size and density, it has a much lower mass scattering efficiency ($\sim 1.1 \text{ m}^2 \text{ g}^{-1}$, Molenaar, 2002). Assuming for a moment that the size distribution of the measured aerosol is similar to the test dust, then the dominant factor in the calibration is density. The error in reported mass concentration is then just the ratio of the density of the calibration to measured aerosol, or $2.65/1.4 \approx 1.9$. The mass estimate from a nephelometer or photometer measurement will be overestimated by about a factor of 2. If the size of the measured aerosol is in the fine mode and the instrument only measures scattering at 90° (see Figure 3.1), there will be another factor of 2 overestimation. The combined error could be as high a factor of 4 for some types of photometers.

Based on this discussion, if a photometer-type measurement is to be interpreted in terms of mass concentration, it is critical to calibrate the instrument with the same type of aerosol that is to be measured, in this case, a smoke aerosol.

3.2.1 Integrating Nephelometer

The basic configuration of an integrating nephelometer is shown in Figure 3.2.

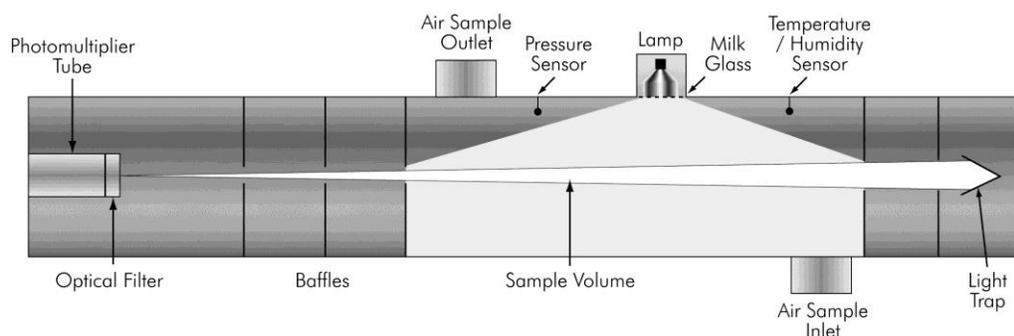


Figure 3.2: Diagram of a typical integrating nephelometer.

Assume the light source has the property that its intensity in any given direction is represented by $I_o \cos \beta$. Given the geometry of the instrument, shown in Figure 3.2, it can be shown that the luminance or radiance at the detector is given by

$$B = I_o/L \int_0^\pi \sigma(\beta) \text{Sin}(\beta) d\beta \quad 3.1$$

where $\sigma(\beta)$ is the volume scattering function, β is the scattering angle, and L is the length of the sample volume.

Fundamentally (Van de Hulst, 1981),

$$b_{sp} = \int_{4\pi} \sigma(\bar{r}, \beta) d\Omega = 2\pi \int_0^\pi \sigma(\bar{r}, \beta) \text{Sin}(\beta) d\beta \quad 3.2$$

Comparing equations 3.1 and 3.2 shows that if the light source is a Lambertian surface the luminance measured at the detector is directly proportional to atmospheric scattering, whether it is from particles or the atmosphere itself (Rayleigh scattering). The instrument can be fitted with particle size inlets such that only scattering associated with fine or coarse particles are considered, filters can be placed in front of the detector so that wavelength dependent scattering can be measured, and some instruments have been fitted with a shutter such that only back scattering is measured. Backscattering is of interest to the earth's radiation balance calculation.

An issue with the use of this type of instrument is that the limits of angular integration are dependent on the geometry of the enclosure, light source, and detector. Typically, the integration is from about 10° to 170°, and therefore calibration to a standard gas with one volume scattering function and measuring particles with a different scattering function can yield systematic errors or uncertainties. Furthermore, because the sampling chamber is enclosed and heated by radiation from the lamp and nearby electronics, the difference between chamber and ambient temperatures can be as high as 10 °C or more. Therefore hygroscopic particles such as sulfates are dried out, and measured sulfate scattering is substantially less than in the ambient atmosphere. If “dry” particle scattering is of interest, it is essential to pre-dry the aerosol before entering the nephelometer chamber such that “dry” particle scattering is measured. If the goal of the measurement is to measure ambient scattering, then the temperature/relative humidity inside the sampling chambers must be measured so that ambient scattering can be estimated. In any case, measuring scattering at some unknown relative humidity is a relatively useless measurement. It cannot even be used to set a meaningful upper or lower bound estimation of scattering or mass concentration.

3.2.2 Polar Nephelometers or Photometers

Polar nephelometers, schematically shown in Figure 3.3, measure scattered radiant energy from some small volume at specific angles between $0^\circ < \beta < 180^\circ$ either through moving a detector through multiple angles such as shown in Figure 3.3 or by arranging a detector or multiple detectors at fixed angles around the scattering volume V. The scattered radiant intensity, J, is given by

$$J = H\sigma(\beta)V \quad 3.3$$

so,

$$\sigma(\beta) = \frac{J(\beta)}{HV} = \text{const}J(\beta). \quad 3.4$$

where J is the scattered radiant intensity of the incident beam (watt/steradian), H is the irradiance of the incident beam (watt/m^2), V is the scattering volume (m^3), β is the scattering angle and const is a constant of calibration. Therefore the units on the volume scattering function are $\text{watt}/\text{m}\cdot\text{steradian}$ or energy per unit time per unit distance per solid angle.

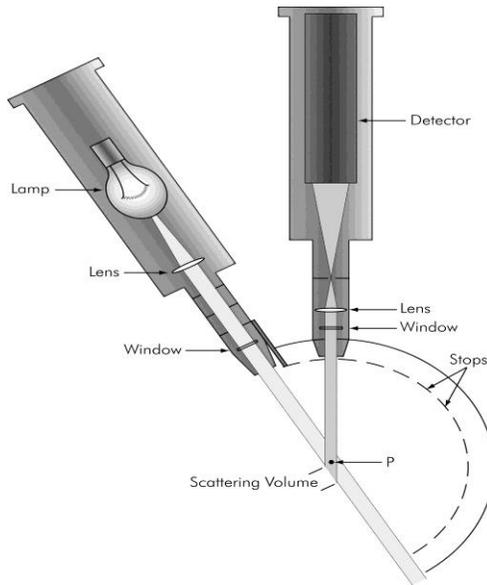


Figure 3.3: Diagram of a polar nephelometer.

Calibration of this type of mass concentration measurement, m , corresponds to determining some constant C such that

$$m = C \int_{\beta_1}^{\beta_2} \sigma(\beta) d\beta \quad 3.5$$

where β_1 and β_2 are the limits of integration. For the DustTrak instrument, the integration is from 87° to 90° . The integration is effectively done by having the detector geometry designed so that it accepts scattering radiation of the desired solid angle.

3.2.3 Forward- and Back-Scatter Photometers

Forward- and back-scatter photometers are similar to polar nephelometers or photometers discussed above but with light source detector geometries arranged so that radiation from some predetermined solid angle is measured. Figure 3.4 is a diagram of a forward-scatter instrument designed to measure scattering at $45^\circ \pm \theta$ over some solid angle Ω . θ varies from instrument to instrument. There are a wide variety of forward-scatter meters on the market, and it is worth noting that starting in 1994, the United States National Weather Service (NWS) in cooperation with the Federal Aviation Administration (FAA) deployed nearly 1000 forward-scatter meters.

The system, which involves other weather-related weather instrumentation, is referred to as the Automated Surface Observing System (ASOS). Forward-scatter instrument manufacturers purport to measure “visibility” under all types of weather and haze conditions.

The least amount of variability in the volume or scattering phase function occurs at about 45° , hence the selection of 45° as the angle between the light source and detector for most forward-scatter meters. However, even at 45° , the ratio of scattering to total scattering is not constant. The percent difference in light scattered into a solid angle encompassing 40° – 50° for an ammonium sulfate aerosol with a lognormal mass size distribution with $d_g = 0.2 \mu\text{m}$ and $\sigma_g = 1.7$ and a sulfate aerosol with $d_g = 0.5 \mu\text{m}$ and $\sigma_g = 2.0$ is 10%. So a small shift in the accumulation-mode particle size distribution can result in uncertainties on the order of 10–15% in the reported scattering coefficient. Furthermore, the index of refraction for organics and ammonium sulfate and nitrate are all about the same, so there is very little variability in scattering due to variation in the aerosol mixture. However, the light scattered into a solid angle encompassing 40° – 50° for an aerosol with $d_g = 0.2$ and one with $d_g = 5.0 \mu\text{m}$ is on the order of a factor of 2. Therefore forward-scatter meters calibrated to fog, as are airport runway visibility meters, or to Arizona dust will overestimate scattering and therefore underestimate the visual range associated with a smoke-type aerosol.

Forward-scatter meters are also used as atmospheric particle mass concentration meters. Here the error is even more significant because the density of the particle comes into play. Dust particles have a density near 4 g/cm^3 , while organic-type particles have densities in the range of 1.2 – 1.4 g/cm^3 . So, dust and organic particles with the same scattering cross-section could have mass uncertainties associated with density differences alone of between 100% and 200%, depending on which particle is chosen as the reference. That is, the reported mass concentration could be in error by more than a factor of 2, just based on particle density variation!

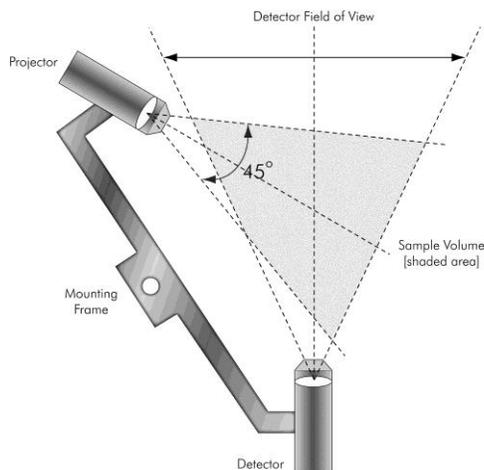


Figure 3.4: Diagram of a forward-scatter nephelometer that measures scattering at a scattering angle of approximately $45^\circ - \theta < \beta < 45^\circ + \theta$, where θ typically is about 22° .

For the practical considerations of operating and interpreting the output from the nephelometers and photometers reviewed here, it is important to consider (1) the calibration aerosol used (e.g., Arizona Test Dust), (2) the angles over which scattered light is collected, (3) the wavelength of operation, and (4) the effects of high ambient relative humidity on the scattering response when

evaluating performance. If no specifications are provided by the manufacturer regarding these characteristics, then it is impossible to estimate the inherent limitations of the instrument. These properties are described below for each instrument and summarized in Table 3.1 (as provided by the manufacturer or peer-reviewed journals).

Table 3.1: Summary of operating characteristics for the optical instruments included in the review.

Instrument	Type	Wavelength (nm)	Calibration	Scattering Angles (degrees)
E-Sampler	Photometer	670	PSL/User-specified	Near-forward
DustTrak	Photometer	780	Arizona Test Dust	90
DataRAM	Integrating Nephelometer	880, 660/880	Arizona Test Dust	Not provided
GreenTek (GT640A)	Photometer	780	Not provided	Forward
M903 Radianc Research	Integrating Nephelometer	530	Clean air/Span gas	10-165
Optec NGN-2/3	Integrating Nephelometer	550	Clean air/Span gas	5-175

3.2.4 E-Sampler

The E-Sampler (Met One, Grants Pass, OR) is a laser photometer that operates on the principle of light scattering by particles and outputs mass concentration. It also includes a filter for analysis and weighing. The instrument includes a near-forward light scatter sensor and is calibrated by polystyrene latex spheres (refractive index of 1.588). The E-Sampler operates at a wavelength of 670 nm. The user can input a calibration factor to convert from light scattering to mass concentration.

The E-Sampler is designed for rugged sampling and is mountable on a tripod, pole, or wall. It is battery operated or can run of AC power. Its dimensions are 10.5 x 9.25 x 5.7 in and it weighs 13 lbs. The average E-Sampler bias was 1.13 ± 0.05 (see Table 2).

3.2.5 DustTrak

The DustTrak (TSI, Shoreview, MN) is a laser photometer that operates on the principle of light scattering by particles. A sensor detects scattered light at 90° to forward scattering. A wavelength of 780 nm is used. The instrument outputs mass concentration based on a calibration using a standard A1 test dust (Arizona Test Dust).

Several versions of desktop or handheld exist (see Table A2 in the Appendix). The DustTrak II also includes in-line filter measurements for custom calibrations. The DustTrak DRX can simultaneously measure five size segregated mass fraction concentrations. They are all relatively small and low in weight (<5 lb) and are suitable for harsh sampling conditions. The average PM₁₀ DustTrak bias was 3.13 ± 0.11 .

3.2.6 DataRam

The DataRam (Thermo Scientific, Waltham, MA) is an integrating nephelometer that operates on the basis of light scattering by particles. Depending on the version, it operates with either a single wavelength (DataRam 2000, 880 nm) or dual-wavelength (DataRam4, 660 and 880 nm). It outputs data in mass concentration based on a calibration by Arizona Test Dust.

The DataRam 4 requires a weather-protected enclosure. It weighs 12 lbs and its dimensions are 5.28 x 7.25 x 13.63 in. Hand-held DataRam instruments are also available (DataRAM pDR-1500) that weigh around 2 lbs or less. The average PM_{2.5} DataRAM bias was 1.81 ± 0.92 .

3.2.7 GreenTek (GT640A)

The GreenTek (GreenTek, Atlanta, GA) is a laser photometer that has a forward light-scattering detector that detects scattered light from a 780 nm light source. It outputs a mass concentration based on the manufacturer internal calibration (no information provided). The average bias was 0.98 ± 0.37 . No size or weight specifications were provided.

3.2.8 M903 Radiance Research Nephelometer

The Radiance Research M903 nephelometer (wavelength of 530 nm) (Radiance Research, Seattle, WA) has the geometry of a standard integrating nephelometer and detects light from 10 to 165°. It is calibrated against clean air and span gas. It outputs light scattering coefficients that can be converted to mass concentrations by the user. The average bias for adjusted measurements it was 1.45 ± 0.28 . It operates with a weather-protected enclosure, its dimensions are 22 x 5.1 x 6.7 in, and it weighs 5.7 lbs.

3.2.9 Optec NGN Nephelometer

The Optec NGN nephelometer (Optec, Lowell, MI) is an integrating nephelometer that collects light from 5 to 175° for open-air configurations (no size cut). It operates at a wavelength of 550 nm. The Optec NGN-2 outputs light scattering coefficients while the Optec NGN-3 outputs both light scattering coefficients and mass concentrations by converting light scattering coefficients to mass using a region-specific, user-selected conversion factor (efficiency). The Optec NGN-3 also incorporates a PM_{2.5} size cut and a heater for dry aerosol measurements. The Optec dimensions are 10.7 x 8.2 x 16.5 in and it weighs 27 lbs. The Optec NGN-2 has an “open-air” design which minimizes inlet and heating losses. It is appropriate for outdoor sampling. The average bias in the Optec NGN was 1.0 ± 0.28 .

4 DISCUSSION

A literature review was performed to summarize measurements and comparisons between continuous mass measurements and filter-based FRM samplers. We aggregated linear regression statistics as reported by each study to investigate the overall accuracy of continuous mass measurements, including both indirect and direct, as discussed in Section 1. We report average bias, defined as the average of the slopes from each linear regression, and the average square of the correlation coefficient (r^2). In all cases, the independent variable is the FRM (integrated)

measurement and the continuous measurement is the dependent variable, so that slopes greater than one correspond to an overestimation of mass by the continuous measurement. Not all studies reported intercepts, so we do not include these in the summary, but they are included in Table A1. Keep in mind when evaluating linear regression statistics that the slope (interpreted here as the bias) is less meaningful for low r^2 values. Results were grouped by the instruments and methods discussed in Section 3. These studies represent diverse aerosol conditions depending the location (including both laboratory and field studies) and time period of the studies (ranging from seasons to years). Table 4.1 reports statistical summaries for each instrument and method; Table A1 (Appendix) includes all of the comparisons.

Table 4.1: Summary of linear regression statistics for comparisons between continuous mass measurements and Federal Reference Method samplers.

Instrument	Average Bias ^a	Standard Deviation in Bias	Average Correlation (r^2)	Minimum Bias	Maximum Bias	N ^b
Direct Mass Measurements						
ALL PM _{2.5} TEOM	0.91	0.34	0.86	0.40	1.28	10
FDMS PM _{2.5} TEOM	1.20	0.09	0.94	1.09	1.28	4
PM _{2.5} TEOM 50 °C	0.58	0.26	0.73	0.40	0.95	4
PM _{2.5} TEOM 30 °C	1.01	0.11	0.96	0.93	1.09	2
PM ₁₀ TEOM 50 °C	0.69	0.17	0.76	0.37	0.97	20
ALL PM _{2.5} BAM	1.03	0.12	0.95	0.86	1.28	16
PM _{2.5} BAM	0.99	0.13	0.94	0.86	1.28	10
PM _{2.5} E-BAM	1.09	0.08	0.98	1.01	1.21	6
PM ₁₀ BAM	1.10	0.11	0.96	1.01	1.25	4
PM _{2.5} CAMM	0.85	0.15	0.91	0.74	1.02	3
PM _{2.5} RAMS	1.01	0.13	0.84	0.92	1.10	2
Indirect Mass Measurement						
PM _{2.5} E-Sampler	1.13	0.05	0.95	1.08	1.18	3
PM _{2.5} DustTrak	1.86	NA	0.84	1.86	1.86	1
PM ₁₀ DustTrak	3.13	0.11	0.95	3.00	3.25	4
PM _{2.5} DataRam	1.81	0.92	0.74	0.70	2.87	20
PM _{2.5} GreenTek	0.98	0.37	0.92	0.47	1.52	8
M903 Radiance Research Unadjusted (m^2g^{-1})	4.62	0.73	0.93	3.42	5.63	8
M903 Radiance Research Adjusted	1.45	0.28	0.92	1.12	1.90	7
PM _{2.5} Optec NGN	1.00	0.28	0.91	0.68	1.36	4

^aAverage bias is determined as the average of all slopes from the linear regressions reported (see Table A1). The FRM measurement is the independent variable and the continuous measurement is the dependent variable.

^bN = number of studies

4.1 Direct Measurements

TEOM comparisons were separated depending on the specific sampling version and size cut. The overall PM_{2.5} TEOM measurements underestimated fine mass relative to the FRM, with an average bias of 0.91 ± 0.34 ($r^2 = 0.86$, $N = 10$). Accuracy varied considerably depending on the version of the instrument. The FDMS TEOM (measures volatile and nonvolatile species) overestimated mass (bias = 1.2 ± 0.09 , $r^2 = 0.94$, $N = 4$), perhaps due to losses in the FRM, while

the TEOM, operated with a 50 °C heater, had the greatest underestimation (bias = 0.58 ± 0.26 , $r^2 = 0.73$, $N = 4$). This underestimate was not surprising given the reported loss of volatile and semivolatile species (Chow et al., 2006). In fact, the greatest underestimation (bias = 0.4) occurred during a study in Fresno, California, where nitrate species are abundant. The most accurately performing TEOM was operated with a 30 °C heater (bias = 1.01 ± 0.11 , $r^2 = 0.96$, $N = 2$) for only two studies, though they were operated in very different environments (Seattle, Washington, and Houston, Texas, Lee et al., 2005). All PM_{10} TEOM studies ($N = 10$) were operated with the 50 °C heater, and they all reported an underestimation (bias = 0.69 ± 0.17 , $r^2 = 0.76$), ranging from a bias of 0.37 (Bakersfield, California, Chung et al., 2001) to 0.97 at the Norwegian Institute for Air Research (Patashnick and Rupprecht, 1991).

The BAM measurements were separated into three categories: $PM_{2.5}$ BAM, $PM_{2.5}$ E-BAM, and PM_{10} BAM. The overall $PM_{2.5}$ BAM (average of $PM_{2.5}$ BAM and $PM_{2.5}$ E-BAM) measurements agreed closely with FRM data (average bias = 1.03 ± 0.12 , $r^2 = 0.95$, $N = 16$). The largest underestimation (0.86) occurred during a wintertime field study in Ewing, New Jersey, in 2004–2005 (Zhu et al., 2007), and the largest overestimation (1.28) occurred in Queens, New York (January 2003 to December 2004, Schwab et al., 2006), perhaps due in part to losses in the FRM. The accuracy of the BAM and E-BAM (equipped for more rugged sampling) were similar. The PM_{10} BAM measurements reflected the same level of accuracy (bias = 1.10 ± 0.11 , $r^2 = 0.96$, $N = 4$), ranging from 1.01 to 1.25.

Fewer studies reported measurements with the CAMM sampler relative to the TEOM or BAM. The average bias of the $PM_{2.5}$ CAMM was 0.85 ± 0.15 ($r^2 = 0.91$, $N = 3$), with an underestimate of mass compared to the FRM. Slopes ranged from 0.74 to 1.02. The largest underestimation occurred during a study at Bakersfield, California, in winter (1998–1999, Chung et al., 2001).

The RAMS sampler comparisons were conducted as a part of two studies in Seattle, Washington, and Houston, Texas, in 2000 and 2001, respectively (Lee et al., 2005). The average bias was 1.01 ± 0.13 ($r^2 = 0.84$), ranging from 0.92 to 1.10.

4.2 Indirect Measurements

The $PM_{2.5}$ E-Sampler comparison studies were part of a series of experiments conducted by the U.S. Forest Service where biomass, usually pine needles, was burned in a large chamber while the instruments sampled the smoke emissions. Smoke from laboratory burns is young and may have different physical-chemical and optical properties compared to aged smoke. The light scattering response to the sampled smoke was converted to a mass concentration using an internal conversion factor. The E-Sampler overestimated mass concentrations, although not considerably (average bias = 1.13 ± 0.05 , $r^2 = 0.95$, $N = 3$).

The only $PM_{2.5}$ DustTrak 8520 comparison was performed during a field study in Fresno, California (Chow et al., 2006). Recall that the DustTrak is calibrated by Arizona Test Dust, which has physical, chemical, and optical properties that likely differ from urban, fine-mode aerosol. Wang et al. (2009) showed that density differences between the test dust ($\rho = 2.65$) and typical urban aerosol ($\rho = 1.45$) could account for the overestimation observed (bias = 1.86, $r^2 = 0.84$). Four PM_{10} DustTrak studies resulted in very consistent overestimations, though larger than the $PM_{2.5}$ comparisons (average bias = 3.13 ± 0.11 , $r^2 = 0.95$). The lowest bias (3.0)

occurred in Bakersfield, California, in winter of 1998–1999 (Chung et al., 2001), and the largest overestimation (3.25) occurred during a smoke chamber study (Trent, 2006). The larger overestimation for the PM₁₀ comparisons could not be explained by density differences alone. During the smoke studies, a PM_{2.5} and a PM₁₀ DustTrak were operated simultaneously to test the effects of the size cut, and these comparisons showed near-perfect agreement (slope = 1.0, $r^2 = 1.0$). The causes for the much higher overestimation for the PM₁₀ DustTraks are unexplained but likely are associated with an inappropriate calibration.

Three versions of the DataRAM were used in these studies: the personal DataRAM 1200 (Chakrabarti et al., 2004), the DataRAM 2000, and the upgraded DataRAM 4. According to Chakrabarti et al. (2004), the instrument operates at a wavelength of 880 nm, and the manufacturer calibration was performed with Arizona Test Dust, which as mentioned earlier has very different physical and chemical properties compared to fine smoke. Whether the DataRAM 2000 and DataRAM 4 were also calibrated with the test dust is unclear. The DataRAM 4 is a dual-wavelength instrument that incorporates the spectral response at both wavelengths to apply adjustments to the mass conversion factor. The DataRAM consistently overestimated FRM mass concentrations for nearly all of the twenty studies examined (average bias = 1.81 ± 0.74 , $r^2 = 0.92$). The maximum overestimation was 2.87 during chamber smoke studies (Trent, 2003). Underestimations occurred for three studies. Chakrabarti et al. (2004) reported an underestimation of 0.91 ($r^2 = 0.93$) at the Los Angeles, California, Supersite. The other underestimates were reported by Trent et al. (2000) for comparisons of smoke aerosol at low relative humidity (RH < 70%) using heaters. At high RH (>70%) with no heaters, the DataRAMS overestimated mass (biases of 1.38 and 1.48 for two instruments). The size adjustment based on the dual-wavelength response was applied for some of these measurements, but Trent (2003) reported little difference with these adjustments for the comparisons between continuous and integrated mass concentrations (see Table A1 in the Appendix).

The GreenTek GT-640 generally underestimated mass concentrations from the FRM samplers for five of the eight studies that used the instrument. Most of these studies were performed while sampling smoke aerosols from controlled laboratory burns (see Table A1). The average bias for the GreenTek was 0.98 ± 0.37 ($r^2 = 0.92$). The greatest underestimation (0.47) occurred during smoke laboratory studies at low relative humidity (Trent et al., 2000). Higher RH tests resulted in somewhat closer agreement (although still underestimated), regardless of whether heaters were used. The highest overestimate (1.52) occurred during smoke studies (Trent et al., 2001). The GreenTek mass measurements are also derived through the application of an unknown internal conversion factor that does not necessarily represent the actual aerosol conditions.

The M903 Radiance Research (RR) nephelometer is an integrating nephelometer that typically outputs measurements as light scattering coefficients (b_{sp}), not mass concentration. The conversion between the two corresponds to the average mass scattering efficiency of the aerosols being measured. If no calibration or bias corrections were applied to the RR data before the regression, then the slope derived from a linear regression of the measured b_{sp} and the concurrent FRM measurement actually corresponds to the mass scattering efficiency (m^2g^{-1}). The studies comparing RR data were separated depending on whether mass scattering efficiencies were reported or whether b_{sp} was converted to a mass before performing the linear regression. Table A1 clearly shows the differences in slopes for these two cases. For the studies that report the slope as a mass scattering efficiency, the average value was $4.62 \pm 0.73 \text{ m}^2\text{g}^{-1}$ ($r^2 = 0.93$) (Chow et

al., 2006). This value, which was within range of typical fine-mode mass scattering efficiencies (Hand and Malm, 2007), suggests that the instruments were performing adequately but does not allow for the comparisons of mass concentrations. For the other studies, it is unclear how mass concentrations were converted from b_{sp} . The overall average bias for these studies was 1.45 ± 0.28 ($r^2 = 0.92$), ranging from 1.12 to 1.90 (Trent et al., 2000, 2001).

Optec NGN-2 and Optec NGN-3 integrating nephelometers both were used in comparison studies with FRM mass measurements. The Optec NGN-2 is an open-air nephelometer, and the Optec NGN-3 is similar in design to the Optec NGN-2, except with a $PM_{2.5}$ size cut, heater, and a region-specific, user-selected conversion factor to convert b_{sp} measurements to mass concentrations. The average bias for the comparisons was 1.0 ± 0.28 ($r = 0.91$, $N = 4$). The closest agreement (bias = 1.03) occurred during a study in Bakersfield, California (Chung et al. 2001), using an Optec NGN-2 and $PM_{2.5}$ mass concentrations. The authors in this study applied a conversion factor based on historical IMPROVE data. Mass concentrations measured during two smoke chamber studies were underpredicted by the Optec NGN-3 (biases of 0.68, 0.94), suggesting the conversion factors used to derive mass concentrations were too large.

5 RECOMMENDATIONS

This review does not address in any detail the reliability and ease of operation of the many instruments reviewed. In actual operating environments, it is important to consider how much attention must be given to an instrumentation package in order to maintain reliable measurements. Under smoky conditions, instrument optics can become dirty and require constant recalibration, plumbing can become obstructed, heat and mechanical stress can cause instrument failure, and so forth. Size, weight, shelter, and power requirements are all important considerations and must be weighed against instrument performance. Table A2 in the Appendix provides some of this information for the type of instruments reviewed here, if available.

Without consideration for ruggedness of operation, based on the comparisons between integrated and continuous mass measurements included in this review, less bias existed for direct continuous measurements than for indirect measurements, although most of the comparisons were in general highly correlated, regardless of direct or indirect method. The direct measurements (e.g., TEOM, BAM, etc.) are less sensitive to the range in atmospheric aerosol characteristics typically observed than indirect measurements. Calibrations and conversions used to derive mass measurements from indirect mass instruments operating on the principle of light scattering typically correspond to one type of aerosol that can differ significantly from that being measured, especially smoke. However, the ease of use, portability, and the ability to deploy nephelometers/photometers in more hostile environments with little operator attention gives these instruments an advantage.

Given these considerations, it is recommended that

- some effort be expended to field test various candidate instruments with an eye toward ease of operation and reliability,
- any indirect measurement (photometers, nephelometers) be calibrated to the type of aerosol being measured, in this case, smoke. If an indirect measurement is to be used, it is essential to develop calibration standards that reflect the optical/physical characteristics

of smoke. With representative standards, the bias between indirect and an FRM measurement could probably be brought down to less than 50% from the 100% plus error associated with using standards such as Arizona Test Dust. The precision of the indirect instruments is quite good.

It seems that the monitoring of smoke aerosol mass concentration falls into at least three different categories. There is a need to measure mass concentrations in sensitive areas such as high population density areas such as an urban environment. In this type of environment, it may be desirable to operate a dedicated monitoring site that is protected from the elements, with temperature control. A second type of monitoring system might be an easily deployable, environmentally exposed system that measures mass concentrations in relatively high population centers that are transient in nature, such as staging base camps or operation centers for fighting wildfires. A third type of monitor would be a personal monitor capable of assessing the smoke exposure of line-operations personnel who are sometimes exposed to “extreme” levels of smoke particulate matter. Therefore three separate recommendations are put forth based on the deployment platform of the instrument: (1) weather-protected enclosure, (2) exposed/mounted in the sampling environment, and (3) personal/hand-held.

- Weather-protected Enclosure

The BAMS sampler and FDMS TEOM both had low biases when compared to the FRM measurements. The FDMS TEOM characterizes volatile and nonvolatile species and would avoid potential losses during sampling of organic-laden smoke aerosols. The advantage of these instruments is lower biases associated with sensitivity to particle properties.

- Environmental-exposure/Mounted

The E-BAMS was accurate and can be mounted on a tripod for outdoor sampling. The E-Sampler was also accurate and can be mounted for outdoor sampling; however, it is a forward-light-scattering photometer, and calibration of the instrument using an appropriate aerosol would need to be performed.

- Personal Monitor (<5 lbs)

Several versions of the DataRAM or DustTrak photometers exist for personal hand-held monitoring. Biases due to calibration factors and humidity effects influence the measurements of both instruments, and appropriate calibration would need to be performed to reduce the biases.

6 APPENDIX

Table A1: Linear regression statistics as reported for comparisons between continuous and integrated (FRM) mass measurements.

The independent variable is the FRM (integrated) mass concentrations and the continuous measurement is the dependent variable.

Instrument	Method	FRM	Slope	Intercept	r ²	Reference	Study Details
TEOM							
PM2.5 TEOM FDMS	TEOM	Partisol- Plus 2025	1.25	-0.63	0.95	Schwab et al. (2006)	Queens, NY, January 2003-December 2004
PM2.5 TEOM FDMS	TEOM	Partisol- Plus 2027	1.088	-0.004	0.95	Schwab et al. (2006)	Addison NY, January 2003- December 2004
PM2.5 TEOM FDMS	TEOM	R&P Partisol 2025	1.28	-0.9	0.96	Zhu et al. (2008)	Ewing NJ September 2004
PM2.5 TEOM FDMS	TEOM	R&P Partisol 2028	1.17	-1.57	0.91	Zhu et al. (2008)	Ewing NJ Dec 2004- Feb 2005
PM2.5 1400A TEOM 50C	TEOM	PM2.5 R&P Partisol 2025	0.42	1.24	0.63	Charron et al. (2004)	Oxfordshire, England (rural), Sept 7, 2000 - Jun 19, 2002
PM2.5 TEOM 1400 50C	TEOM	R&P Partisol 2026	0.95	2.26	0.94	Zhu et al. (2008)	Ewing NJ September 2004
PM2.5 TEOM 1400a 50C	TEOM	RAAS 100	0.4	4.66	0.55	Chow et al. (2006)	Fresno, CA, Dec 2, 1999-Feb 3, 2001
PM2.5 TEOM1400 50C	TEOM	R&P Partisol 2029	0.54	4.75	0.81	Zhu et al. (2008)	Ewing NJ Dec 2004- Feb 2005
PM2.5 TEOM 30C	TEOM	R&P Partisol- Plus	1.09	0.21	0.94	Lee et al. (2005)	Houston, Aug 12- Sept 15, 2000. Part of the Texas Air Quality Study 2000
PM2.5 TEOM 30C	TEOM	URG MASS	0.93	1.2	0.97	Lee et al. (2005)	Seattle, WA, Jan 28 - Feb 21, 2001
PM10 1400A TEOM 50C	TEOM	PM10 R&P Partisol 2026	0.52	0.88	0.76	Charron et al. (2004)	Oxfordshire, England (rural), Sept 30, 2000- July 2, 2002
PM10 TEOM 50C	TEOM	Sierra - Andersen	0.96	-2.92	0.99	Patashnick and Rupprecht (1991)	Birmingham, AL, May 1990
PM10 TEOM 50C	TEOM	Sierra - Andersen	0.97	0.23	0.99	Patashnick and Rupprecht (1991)	Norwegian Institute for Air Research- Spring 1989
PM10 TEOM 1400 50C	TEOM	PM10 Sierra Andersen 1200	0.37	6.63	0.95	Chung et al. (2001)	Bakersfield CA Dec 2 1998-Jan 31 1999
PM10 TEOM 1400 50C	TEOM	Sierra- Anderson Model 1200	0.62	13	0.59	Allen et al. (1997)	Rubidoux, CA- summer, various years

Instrument	Method	FRM	Slope	Intercept	r ²	Reference	Study Details
PM10 TEOM 1400 50C	TEOM	Sierra-Anderson Model 1200	0.51	12	0.86	Allen et al. (1997)	Rubidoux, CA-winter
PM10 TEOM 1400 50C	TEOM	Sierra-Anderson Model 1200	0.89	-1	0.9	Allen et al. (1997)	Long Beach, CA-summer
PM10 TEOM 1400 50C	TEOM	Sierra-Anderson Model 1200	0.58	8	0.81	Allen et al. (1997)	Long Beach, CA-winter
PM10 TEOM 1400 50C	TEOM	Sierra-Anderson Model 1200	0.96	2	0.85	Allen et al. (1997)	Atascadero, CA-summer
PM10 TEOM 1400 50C	TEOM	Sierra-Anderson Model 1200	0.68	4	0.8	Allen et al. (1997)	Atascadero, CA-winter
PM10 TEOM 1400 50C	TEOM	Sierra-Anderson Model 1200	0.46	15	0.27	Allen et al. (1997)	Tlalnepantla, Mexico City-Jan-Jun
PM10 TEOM 1400 50C	TEOM	Sierra-Anderson Model 1200	0.81	-2	0.35	Allen et al. (1997)	Merced, CA-Jan-Jun
PM10 TEOM 1400 50C	TEOM	Sierra-Anderson Model 1200	0.69	8	0.61	Allen et al. (1997)	Pedregal, Mexico City-winter
PM10 TEOM 1400a 50C	TEOM	GMW 1200	0.67	2.17	0.65	Chow et al. (2006)	Fresno, CA, Dec 2, 1999-Feb 3, 2001
PM10 TEOM 1400a 50C	TEOM	GMW 1200	0.66	12.55	0.69	Chow et al. (2006)	Bakersfield, CA, Dec 2, 1999-Feb 3, 2001
PM10 TEOM 1400a 50C	TEOM	GMW 1200	0.74	2.53	0.97	Chow et al. (2006)	Livermore, CA, Dec 2, 1999-Feb 3, 2001
PM10 TEOM 1400a 50C	TEOM	GMW 1200	0.65	5.57	0.73	Chow et al. (2006)	Modesto, CA, Dec 2, 1999-Feb 3, 2001
PM10 TEOM 1400a 50C	TEOM	GMW 1200	0.7	2.48	0.78	Chow et al. (2006)	Sacramento, CA, Dec 2, 1999-Feb 3, 2001
PM10 TEOM 1400a 50C	TEOM	GMW 1200	0.82	1.46	0.96	Chow et al. (2006)	San Jose CA, Dec 2, 1999-Feb 3, 2001
PM10 TEOM 1400a 50C	TEOM	GMW 1200	0.61	6.67	0.74	Chow et al. (2006)	Stockton, CA, Dec 2, 1999-Feb 3, 2001
BAM							
PM2.5 BAM 1020	beta	PM2.5 RAAS 2.5-300	0.95	1.36	0.99	Chung et al. (2001)	Bakersfield CA Dec 2 1998-Jan 31 1999
PM2.5 BAM 1020	beta	Andersen Reference Ambient Air Sampler 2.5-300 OR Partisol 2000	1	3	0.98	Motallebi et al. (2003)	Fresno, CA July 1999-May 2001
PM2.5 BAM 1020	beta	RAAS 100	0.95	4.4	0.96	Chow et al. (2006)	Fresno, CA, Dec 2, 1999-Feb 3, 2001
PM2.5 BAM 1020	beta	RAAS 300	0.97	-2.25	0.98	Chow et al. (2006)	Bakersfield, CA, Dec 2, 1999-Feb 3, 2001

Instrument	Method	FRM	Slope	Intercept	r²	Reference	Study Details
PM2.5 BAM 1020	beta	RAAS 300	0.92	3.08	0.92	Chow et al. (2006)	Corcoran, CA, Dec 2, 1999-Feb 3, 2001
PM2.5 BAM 1020	beta	RAAS 300	0.94	2.63	0.91	Chow et al. (2006)	San Jose CA, Dec 2, 1999-Feb 3, 2001
PM2.5 BAM1020	beta	Partisol-Plus 2026	1.28	1.27	0.88	Schwab et al. (2006)	Queens, NY, January 2003-December 2004
PM2.5 Beta Gauge (Anderson)	beta	R&P Partisol 2031	0.86	0.4	0.94	Zhu et al. (2008)	Ewing NJ Dec 2004-Feb 2005
PM2.5 Beta Gauge (Metone)	beta	R&P Partisol 2027	1.15	0.32	0.87	Zhu et al. (2008)	Ewing NJ September 2004
PM2.5 Beta Gauge (Metone)	beta	R&P Partisol 2030	0.89	0.5	0.95	Zhu et al. (2008)	Ewing NJ Dec 2004-Feb 2005
PM10 BAM	beta	PM10 Sierra Andersen 1201	1.01	1.55	0.99	Chung et al. (2001)	Bakersfield CA Dec 2 1998-Jan 31 1999
PM10 BAM 1020	beta	GMW 1200	1.05	4.76	0.95	Chow et al. (2006)	Fresno, CA, Dec 2, 1999-Feb 3, 2001
PM10 BAM 1020	beta	GMW 1200	1.08	8.05	0.96	Chow et al. (2006)	Bakersfield, CA, Dec 2, 1999-Feb 3, 2001
PM10 BAM 1020	beta	GMW 1200	1.25	3.25	0.93	Chow et al. (2006)	Corcoran, CA, Dec 2, 1999-Feb 3, 2001
PM2.5 E-BAM	beta	BGI PQ-200	1.21	-23.77	0.99	Trent (2003)	Rocky Mountain Research Station Fire Sciences Laboratory, Missoula MT. White pine needles burned
PM2.5 E-BAM	beta	BGI PQ-200	1.14	-24.15	0.99	Trent (2003)	Rocky Mountain Research Station Fire Sciences Laboratory, Missoula MT. White pine needles burned
PM2.5 E-BAM	beta	BGI PQ-200	1.1	-11.49	0.99	Trent (2003)	Rocky Mountain Research Station Fire Sciences Laboratory, Missoula MT. White pine needles burned
PM2.5 E-BAM	beta	BGI PQ-200	1.09	-13.8	0.99	Trent (2003)	Rocky Mountain Research Station Fire Sciences Laboratory, Missoula MT. White pine needles burned
PM2.5 E-BAM (ac pump)	beta	BGI PQ-200	1.01		0.96	Trent (2006)	Rocky Mountain Research Station Fire Sciences Laboratory, Missoula MT, pine needles burned.

Instrument	Method	FRM	Slope	Intercept	r ²	Reference	Study Details
PM2.5 E-BAM (dc pump)	beta	BGI PQ-200	1.01		0.97	Trent (2006)	Rocky Mountain Research Station Fire Sciences Laboratory, Missoula MT, pine needles burned.
Camm							
PM2.5 Camm	Camm	R&P Partisol-Plus	1.02	1.62	0.89	Lee et al. (2005)	Houston, Aug 12-Sept 15, 2000. Part of the Texas Air Quality Study 2000
PM2.5 Camm	Camm	URG MASS	0.8	3.5	0.87	Lee et al. (2005)	Seattle, WA, Jan 28 - Feb 21, 2001
PM2.5 Camm	Camm	PM2.5 RAAS 2.5-302	0.74	10.85	0.96	Chung et al. (2001)	Bakersfield CA Dec 2 1998-Jan 31 1999
RAMS							
PM2.5 RAMS	RAMS	R&P Partisol-Plus	1.1	0.68	0.89	Lee et al. (2005)	Houston, Aug 12-Sept 15, 2000. Part of the Texas Air Quality Study 2000
PM2.5 RAMS	RAMS	URG MASS	0.92	0.2	0.78	Lee et al. (2005)	Seattle, WA, Jan 28 - Feb 21, 2001
E-Sampler							
PM2.5 E-Sampler	LS	BGI PQ-200	1.08		0.96	Trent (2006)	Rocky Mountain Research Station Fire Sciences Laboratory, Missoula MT, pine needles burned.
PM2.5 E-Sampler	LS	BGI PQ-200	1.18		0.94	Trent (2006)	Rocky Mountain Research Station Fire Sciences Laboratory, Missoula MT, pine needles burned.
PM2.5 E-Sampler	LS	BGI PQ-200	1.13	3.41	0.96	Trent (2003)	Rocky Mountain Research Station Fire Sciences Laboratory, Missoula MT. White pine needles burned
DustTrak							
PM2.5 DustTrak 8520	LS	RAAS 100	1.86	12.46	0.84	Chow et al. (2006)	Fresno, CA, Dec 2, 1999-Feb 3, 2001
PM10 Dusttrak	LS	PM10 Sierra Andersen 1202	3	-13.6	0.92	Chung et al. (2001)	Bakersfield CA Dec 2 1998-Jan 31 1999
PM10 DustTrak	LS	BGI PQ-200	3.25		0.96	Trent (2006)	Rocky Mountain Research Station Fire Sciences Laboratory, Missoula MT, pine needles burned.

Instrument	Method	FRM	Slope	Intercept	r ²	Reference	Study Details
PM10 DustTrak	LS	BGI PQ-200	3.18		0.96	Trent (2006)	Rocky Mountain Research Station Fire Sciences Laboratory, Missoula MT, pine needles burned.
PM10 DustTrak	LS	BGI PQ-200	3.09		0.96	Trent (2006)	Rocky Mountain Research Station Fire Sciences Laboratory, Missoula MT, pine needles burned.
DataRAM							
PM2.5 DataRam	LS	R&P Partisol 2000	2.16		0.97	Trent et al. (1999)	March/July 1998 Laboratory tests, ponderosa pine, duff
PM2.5 DataRam	LS	R&P Partisol 2001	1.93		0.97	Trent et al. (1999)	March/July 1998 Laboratory tests, ponderosa pine, duff
PM2.5 DataRam 2000	LS	BGI-PQ 200	2.28		0.98	Trent et al. (2001)	Missoula Aug-Sept 2000
PM2.5 DataRam 2000	LS	BGI-PQ 200	2.1		0.98	Trent et al. (2001)	Hamilton Aug-Sept 2000
PM2.5 DataRAM 1200 personal	LS	Partisol 2025	0.91	1.85	0.93	Chakrabarti et al. (2004)	University of Southern California, Los Angeles Supersite, Dec 6 2000- Feb 19, 2003
PM2.5 DataRam 2000	LS	BGI PQ-200	1.25		0.97	Trent (2006)	Rocky Mountain Research Station Fire Sciences Laboratory, Missoula MT, pine needles burned.
PM2.5 DataRam 2000	LS	BGI PQ-200	1.3		0.97	Trent (2006)	Rocky Mountain Research Station Fire Sciences Laboratory, Missoula MT, pine needles burned.
PM2.5 DataRam 2000	LS	BGI PQ-200	0.89		0.97	Trent (2006)	Rocky Mountain Research Station Fire Sciences Laboratory, Missoula MT, pine needles burned.
PM2.5 DataRam 4	LS	BGI PQ-200	2.61		0.95	Trent (2006)	Rocky Mountain Research Station Fire Sciences Laboratory, Missoula MT, pine needles burned.
PM2.5 DataRam 4	LS	BGI PQ-200	2.19		0.96	Trent (2006)	Rocky Mountain Research Station Fire Sciences Laboratory, Missoula MT, pine needles burned.

Instrument	Method	FRM	Slope	Intercept	r ²	Reference	Study Details
PM2.5 DataRam 4	LS	BGI PQ-200	2.58		0.95	Trent (2006)	Rocky Mountain Research Station Fire Sciences Laboratory, Missoula MT, pine needles burned.
PM2.5 DataRam 4	LS	BGI PQ-200	2.37		0.96	Trent (2006)	Rocky Mountain Research Station Fire Sciences Laboratory, Missoula MT, pine needles burned.
PM2.5 DataRAM-size correction enabled	LS	BGI PQ-200	2.87	22.54	0.99	Trent (2003)	Rocky Mountain Research Station Fire Sciences Laboratory, Missoula MT. White pine needles burned
PM2.5 DataRAM-size correction enabled	LS	BGI PQ-200	2.57	51.49	0.97	Trent (2003)	Rocky Mountain Research Station Fire Sciences Laboratory, Missoula MT. White pine needles burned
PM2.5 DataRAM-no size correction enabled	LS	BGI PQ-201	2.87	27.32	0.93	Trent (2003)	Rocky Mountain Research Station Fire Sciences Laboratory, Missoula MT. White pine needles burned
PM2.5 DataRAM-no size correction enabled	LS	BGI PQ-202	0.92	-20.94	0.99	Trent (2003)	Rocky Mountain Research Station Fire Sciences Laboratory, Missoula MT. White pine needles burned
PM2.5 Mie DataRam	LS	BGI PQ-200	0.8		0.79	Trent et al. (2000)	2000 Laboratory test, low RH, with heater
PM2.5 Mie DataRam	LS	BGI PQ-200	0.7		0.76	Trent et al. (2000)	2000 Laboratory test, low RH, with heater
PM2.5 Mie DataRam	LS	BGI PQ-200	1.38		0.73	Trent et al. (2000)	2000 Laboratory test, high RH (>70%), no heater
PM2.5 Mie DataRam	LS	BGI PQ-200	1.48		0.71	Trent et al. (2000)	2000 Laboratory test, high RH (>70%), no heater
GreenTek GT-640							
PM2.5 Met One GreenTek GT-640	LS	BGI PQ-200	1.1		0.35	Trent et al. (2000)	1999 Field Test
PM2.5 Met One GreenTek GT-640	LS	BGI PQ-200	0.6		0.78	Trent et al. (2000)	2000 Rocky Mountain Research Station Fire Sciences Laboratory, Missoula MT, low RH
PM2.5 Met One GreenTek GT-640	LS	BGI PQ-200	0.47		0.73	Trent et al. (2000)	2000 Rocky Mountain Research Station Fire Sciences Laboratory, Missoula MT, low RH

Instrument	Method	FRM	Slope	Intercept	r ²	Reference	Study Details
PM2.5 Met One GreenTek GT-640	LS	BGI PQ- 200	0.94		0.61	Trent et al. (2000)	2000 Rocky Mountain Research Station Fire Sciences Laboratory, Missoula MT- high RH (> 70%), with heater
PM2.5 Met One GreenTek GT-640	LS	BGI PQ- 200	0.85		0.63	Trent et al. (2000)	2000 Rocky Mountain Research Station Fire Sciences Laboratory, Missoula MT- high RH (>70%), with no heater
PM2.5 MetOne GT-640	LS	BGI-PQ 200	0.88		0.87	Trent et al. (2001)	Hamilton, MT
PM2.5 MetOne GT-640	LS	BGI-PQ 200	1.52		0.99	Trent et al. (2001)	Missoula, MT
PM2.5 GreenTek GT640A	LS	RAAS 100	1.44	-2.95	0.91	Chow et al. (2006)	Fresno, CA, Dec 2, 1999-Feb 3, 2001
M903 Radiance Research Nephelometer							
PM2.5 M903 Radiance Research	LS	RAAS 100	4.07	-9.52	0.9	Chow et al. (2006)	Fresno, CA, Dec 2, 1999-Feb 3, 2001
PM2.5 M903 Radiance Research	LS	R&P Partisol 2002	1.9		0.97	Trent et al. (1999)	March/July 1998 Laboratory tests, ponderosa pine, duff
TSP M903 Radiance Research	LS	RAAS 100	4.49	-9.79	0.95	Chow et al. (2006)	Fresno, CA, Dec 2, 1999-Feb 3, 2001
TSP M903 Radiance Research	LS	RAAS 300	5.63	-24.71	0.94	Chow et al. (2006)	Bakersfield, CA, Dec 2, 1999-Feb 3, 2001
TSP M903 Radiance Research	LS	RAAS 300	5.09	23.05	0.91	Chow et al. (2006)	Corcoran, CA, Dec 2, 1999-Feb 3, 2001
TSP M903 Radiance Research	LS	RAAS 300	4.09	1.06	0.98	Chow et al. (2006)	Livermore, CA, Dec 2, 1999-Feb 3, 2001
TSP M903 Radiance Research	LS	RAAS 300	3.42	0	0.91	Chow et al. (2006)	San Jose CA, Dec 2, 1999-Feb 3, 2001
TSP M903 Radiance Research	LS	RAAS 300	5.18	-19.13	0.92	Chow et al. (2006)	Stockton, CA, Dec 2, 1999-Feb 3, 2001
TSP M903 Radiance Research	LS	RAAS 300	5	-14.6	0.91	Chow et al. (2006)	Visalia, CA, Dec 2, 1999-Feb 3, 2001
TSP M903 Radiance Research	LS	BGI-PQ 200	1.45		0.94	Trent et al. (2001)	Missoula, MT, inlet heater
TSP M903 Radiance Research	LS	BGI-PQ 200	1.39		0.99	Trent et al. (2001)	Hamilton, MT, inlet heater

Instrument	Method	FRM	Slope	Intercept	r²	Reference	Study Details
TSP M903 Radiance Research	LS	BGI PQ- 200	1.14		0.9	Trent et al. (2000)	2000 Rocky Mountain Research Station Fire Sciences Laboratory, Missoula MT.
TSP M903 Radiance Research	LS	BGI PQ- 200	1.12		0.9	Trent et al. (2000)	2000 Rocky Mountain Research Station Fire Sciences Laboratory, Missoula MT.
TSP M903 Radiance Research	LS	BGI PQ- 200	1.65		0.84	Trent et al. (2000)	2000 Rocky Mountain Research Station Fire Sciences Laboratory, Missoula MT, high RH (>70%), no heater
TSP M903 Radiance Research	LS	BGI PQ- 200	1.51		0.87	Trent et al. (2000)	2000 Rocky Mountain Research Station Fire Sciences Laboratory, Missoula MT, high RH (>70%), with heater
Optec NGN Nephelometer							
PM2.5 Optec NGN-2	LS	PM2.5 RAAS 2.5- 301	1.03	-6.41	0.99	Chung et al. (2001)	Bakersfield CA Dec 2 1998-Jan 31 1999
PM2.5 Optec NGN-3	LS	BGI-PQ 200	1.36		1	Trent et al. (2001)	Combined Missoula MT and Hamilton MT data
PM2.5 Optec NGN-3	LS	BGI PQ- 200	0.68		0.81	Trent et al. (2000)	2000 Rocky Mountain Research Station Fire Sciences Laboratory, Missoula MT
PM2.5 Optec NGN-3	LS	BGI PQ- 200	0.94		0.84	Trent et al. (2000)	2000 Rocky Mountain Research Station Fire Sciences Laboratory, Missoula MT, RH> 70%

Table A2: Specifications for instruments discussed in the review.

Instrument	Manufacturer	Measurement Principle	Size Range	Dimensions	Weight	Environment	Concentration Limits	Power Source	Accuracy	Resolution
TEOM 1400ab	Thermo Scientific ¹	TEOM	PM2.5/ PM10	11x14x13 in. Control: 18x17x9 in.	Base: 40 lbs Control: 32 lb Base	Weather protected within range of 2 to 40 °C	0 to 5 g m ⁻³	120VAC 60Hz 1A; 240V 50 Hz 0.5A	±0.75%	0.1 µg/m ³
TEOM 1405	Thermo Scientific ²	TEOM	PM1, PM2.5, PM10, TSP	19 x 17 x 29.5 in.	40 lbs	Weather protected within range of 8 to 25 °C	0 to 1 g m ⁻³	10-240V, 440V 47- 63Hz	±0.75%	0.1 µg/m ³
TEOM 1405-F	Thermo Scientific ³	TEOM/FDMS	PM1, PM2.5,PM 10	17x19x55 in.	75 lbs	Weather protected within range of 8 to 25 °C	0 to 1 g m ⁻³	100- 240V 400V 47- 63Hz	±0.75%	0.1 µg/m ³
BAM 1020	Met One ⁴	Beta	PM2.5/ PM10	12.25x17x16 in.	54 lbs	Weather protected -30 to +60 °C	0 to 1 mg m ⁻³	100–230 VAC, 50/60 Hz.	Exceeds US-EPA Class III PM2.5 FEM standards for multiplicative and additive bias	0.1 µg/m ³
E-BAM	Met-One ⁵	Beta (Environment Proof)	PM2.5/ PM10	Aluminum closure on tripod 16.1 x 14.2 x 7.9 in.	35 lbs	-30 to 50 °C	0 to 65 mg m ⁻³	12 V DC @ 48 W max/Portable-Battery or Solar Panel	2.5 µg or 10% in 24 hr period	Not provided
E-Sampler	Met One ⁶	Forward light scattering, 670 nm	PM1, PM2.5, PM10,TSP	10.5x9.25x5.7 in.	13 lbs	-30 to 50 °C	0 to 65 mg m ⁻³	Internal battery (30 hours)	8% of NIOSH 0600	Not provided

Instrument	Manufacturer	Measurement Principle	Size Range	Dimensions	Weight	Environment	Concentration Limits	Power Source	Accuracy	Resolution
DustTrak 8520	TSI ⁷ (discontinued 10/31/08)	90° light scattering, 780 nm		8.7x5.9x3.4 in.	3.3 lbs with batteries	0 to 50 °C	0.001 to 100 mg m ⁻³	Four C-size batteries	Not provided	±0.1% of reading or ±0.001 mg/m ³ , whichever is greater
DustTrak DRX 8533 (Desktop)	TSI ⁸	90° light scattering, 655 nm/Combined photometer and optical particle counter	PM1, PM2.5, Respirable, PM10, Total	5.3 x 8.5 x 8.8 in.	4.5 lbs (2.0 kg) – 1 battery,	0 to 50°C	0.001 to 150 mg m ⁻³	6600 mAh Li-Ion Battery Pack	Not provided	±0.1% of reading or 0.001 mg/m ³ , whichever is greater
DustTrak DRX 8533EP (Desktop, outdoor, external pump),	TSI ⁸	90° light scattering, 655 nm/Combined photometer and optical particle counter	PM1, PM2.5, Respirable, PM10, Total	5.3 x 8.5 x 8.8 in. External pump: 4.0 x 7.0 x 3.5 in.	4.5 lbs (2.0 kg) – 1 battery,	0 to 50°C	0.001 to 150 mg m ⁻³	6600 mAh Li-Ion Battery Pack	Not provided	±0.1% of reading or 0.001 mg/m ³ , whichever is greater
DustTrak DRX 8534 (Handheld)	TSI ⁸	90° light scattering, 655 nm/Combined photometer and optical particle counter	PM1, PM2.5, Respirable, PM10, Total	4.9 x 4.8 x 12.5 in.	3.3 lbs (1.5 kg) with battery	0 to 50°C	0.001 to 150 mg m ⁻³	3600 mAh Li-Ion Battery Pack	Not provided	±0.1% of reading or 0.001 mg/m ³ , whichever is greater
DustTrak II 8530 (Desktop)	TSI ⁹	90° light scattering	M1, PM2.5, Respirable, PM10, and Total PM	5.3 x 8.5 x 8.8 in.	4.5 lbs (2.0 kg)– 1 battery,	0 to 50°C	0.001 to 400 mg m ⁻³	6600 mAh Li-Ion Battery Pack	Not provided	±0.1% of reading or 0.001 mg/m ³ , whichever is greater

Instrument	Manufacturer	Measurement Principle	Size Range	Dimensions	Weight	Environment	Concentration Limits	Power Source	Accuracy	Resolution
DustTrak II 8530 EP (Desktop, outdoor monitoring, external pump)	TSI ⁹	90° light scattering	M1, PM2.5, Respirable, PM10, and Total PM	5.3 x 8.5 x 8.8 in. External pump: 4.0 x 7.0 x 3.5 in.	4.5 lbs (2.0 kg)– 1 battery, External Pump: 3.0 lbs (1.4 kg)	0 to 50°C	0.001 to 400 mg m ⁻³	6600 mAH Li-Ion Battery Pack	Not provided	±0.1% of reading or 0.001 mg/m ³ , whichever is greater
DustTrak II 8532 (Handheld)	TSI ⁹	90° light scattering	PM1, PM2.5, Respirable, PM10, and Total PM	4.9 x 4.8 x 12.5 in.	3.3 lbs (1.5 kg) with battery	0 to 50°C	0.001 to 150 mg m ⁻³	3600 mAH Li-Ion Battery Pack	Not provided	±0.1% of reading or 0.001 mg/m ³ , whichever is greater
DataRAM 4	Thermo Scientific ¹⁰	Light scattering, two wavelengths (660nm, 880nm)	PM1, PM2.5/ PM10	5.28 x 7.25 x 13.63 in.	11.7 lbs	-10° to 50°C	0.0001 to 400 mg m ⁻³	Internal battery	±2% of reading ±precision	0.1% of reading or 0.1µg/m ³ , whichever is greater
DataRAM DR 2000	Thermo Andersen ¹¹	Light scattering	PM2.5/ PM10	5.28 x 7.25 x 13.63 in.	12 lbs	0° to 40° C	0.1 µg m ⁻³ to 400 mg m ⁻³	Sealed lead-acid battery, 24 hours operation	±5% of reading ± precision	±0.3 µg/m ³ for 10 second averaging
MIE DataRAM 4000	Thermo Andersen ¹²	Light scattering, two wavelengths (660nm, 880nm)	PM2.5/ PM10/ respirable	6.54 x 8.9 x 12.87 in.	12 lbs	Not provided	0.1 µg m ⁻³ to 400 mg m ⁻³	Sealed lead-acid battery, up to 20 hours operation or AC operation with adapter	±2% of reading	Not provided

Instrument	Manufacturer	Measurement Principle	Size Range	Dimensions	Weight	Environment	Concentration Limits	Power Source	Accuracy	Resolution
DataRAM pDR-1500	Thermo Scientific ¹³	Light scattering	PM1/ PM2.5/ PM4/PM10	7.1 x 5.6 x 3.3 in.	2.6 lbs	-10° to 50°C	0.1 µg m ⁻³ to 400 mg m ⁻³	4 AA alkaline, > 24 hour run time	±5% of reading ± precision	0.1% of reading
DataRAM pDR-1000AN	Thermo Scientific ¹⁴	Light scattering	Not provided	2.5 x 3.6 x 6.0 in.	1.1 lbs	Not provided	0.001 to 400 mg m ⁻³	Not provided	±5% of reading ± precision	0.1% of reading
M903 Radiance Research	Radiance Research ¹⁵	Light scattering, Integrating nephelometer (530 nm)	PM2.5/ PM10	22 x 5.1 x 6.7 in.	5.7 lbs	Not provided	0 to > 1 km ⁻¹	12 VDC	Not provided	Not provided
Optec-NGN2a	Optec Inc ¹⁶	Light scattering, Integrating nephelometer, 550 nm	Open (all)	10.7x8.2x16.5 in.	27 lbs	-20 to 45°C	Extinction limits (0.01 to 7 km ⁻¹)	13.8 V at 4.5 amps	±10% of true value of air near Rayleigh conditions	±1 count
Optec NGN3a	Optec Inc ¹⁷	Integrating nephelometer, dry, 530 nm	PM2.5	10.7x8.2x16.5 in.	27 lbs	Not provided	Not provided	13.8 VDC at 3 amps.	Not provided	Not provided

Links to websites:

¹ TEOM 1400ab

<https://www.thermoscientific.com/ecommerce/servlet/productsdetail?productId=11960558&groupType=PRODUCT&searchType=0&storeId=11152&from=search>

² 1405 TEOM

<https://www.thermoscientific.com/ecommerce/servlet/productsdetail?storeId=11152&langId=-1&productId=11960557>

³ 1405-F TEOM

<https://www.thermoscientific.com/ecommerce/servlet/productsdetail?storeId=11152&langId=-1&productId=11960554>

⁴ BAM 1020

http://www.metone.com/documents/BAM-1020_6-08.pdf

⁵ E-BAM

http://www.metone.com/documents/E-BAM_Datasheet_Rev_Aug09.pdf

⁶ E-Sampler

http://www.metone.com/documents/E-SAMPLER_Brochure.pdf

⁷ DustTrak 8520

http://www.tsi.com/uploadedFiles/_Site_Root/Products/Literature/Spec_Sheets/2980077_DustTrak_8520.pdf

⁸ DustTrak DRX

http://www.tsi.com/uploadedFiles/_Site_Root/Products/Literature/Spec_Sheets/DustTrak-DRX-6001981_USA-web.pdf

⁹ DustTrak II

http://www.tsi.com/uploadedFiles/_Site_Root/Products/Literature/Spec_Sheets/DustTrak-II-6001986-USA-web.pdf

¹⁰ DataRAM 4

<https://www.thermoscientific.com/ecommerce/servlet/productsdetail?productId=11961406&groupType=PRODUCT&searchType=0&storeId=11152&from=search>

¹¹ DataRAM DR 2000

http://ashtead-technology.com/product/instruments/mie_dataram/

¹² MIE DataRAM 4000

http://ashtead-technology.com/product/instruments/mie_dataram_4000/

¹³ DataRAM pDR1500

<https://www.thermoscientific.com/ecommerce/servlet/productsdetail?productId=11961321&groupType=PRODUCT&searchType=0&storeId=11152&from=search>

¹⁴ DataRAM pDR1000AN

<https://www.thermoscientific.com/ecom/servlet/productsdetail?productId=11954958&groupType=PRODUCT&searchType=0&storeId=11152&from=search>

¹⁵ M903 Radiance Research Nephelometer

http://www.esrl.noaa.gov/gmd/aero/instrumentation/RR903_manual.pdf

¹⁶ Optec NGN-2 Nephelometer

<http://www.optecinc.com/visibility/ngn-2a.htm>

¹⁷ Optec NGN-3 Nephelometer

<http://www.optecinc.com/visibility/ngn-3a.htm>

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