TECHNICAL PAPER

An Inexpensive Dual-Chamber Particle Monitor: Laboratory Characterization

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ABSTRACT
In developing countries, high levels of particle pollution from the use of coal and biomass fuels for household cooking and heating are a major cause of ill health and premature mortality. The cost and complexity of existing monitoring equipment, combined with the need to sample many locations, make routine quantification of household particle pollution levels difficult. Recent advances in technology, however, have enabled the development of a small, portable, data-logging particle monitor modified from commercial smoke alarm technology that can meet the needs of surveys in the developing world at reasonable cost. Laboratory comparisons of a prototype particle monitor developed at the University of California at Berkeley (UCB) with gravimetric filters, a tapered element oscillating microbalance, and a TSI DustTrak to quantify the UCB particle monitor response as a function of both concentration and particle size and to examine sensor response in relation to changes in temperature, relative humidity, and elevation are presented here. UCB particle monitors showed good linearity in response to different concentrations of laboratory-generated oleic acid aerosols with a coarse (mass median diameter, 2.1 μm) and fine (mass median diameter, 0.27–0.42 μm) size distributions (average $r^2 = 0.997 \pm 0.005$). The photoelectric and ionization chamber showed a wide range of responses based on particle size and, thus, require calibration with the aerosol of interest. The ionization chamber was five times more sensitive to fine rather than coarse particles, whereas the photoelectric chamber was five times more sensitive to coarse than fine. The ratio of the response between the two sensors has the potential for mass calibration of individual data points based on estimated parameters of the size distribution. The results demonstrate the significant potential of this monitor, which will facilitate the evaluation of interventions (improved fuels, stoves, and ventilation) on indoor air pollution levels and research on the impacts of indoor particle levels on health in developing countries.

IMPLICATIONS
Although at present not showing a low enough detection limit to be of use in many developed-world settings, the UCB particle monitor seems to operate well in conditions common in hundreds of millions of developing-country households, for which it was designed. Combined with its low capital and operating costs, freedom from the need for highly trained field workers, capacity for unattended long-term monitoring on batteries, quiet operation, low weight, and small size, its potential would seem highly promising.

INTRODUCTION
In the developing world, concentrations and risks attributable to smoke from indoor solid fuels are much higher than developed nations, and adverse effects are seen in larger percentages of the population.[1] Although there is a clear rationale for analyzing these exposures to reduce the health burden in disadvantaged populations, it also presents opportunities for analyzing the mechanisms by which particles exert their effects in all populations. To do so, however, reliable methods of measuring particle levels

are needed to make the link with health or to evaluate interventions.

Unfortunately, current standard gravimetric monitoring technology is ill-suited for household studies in the developing world because of the requirement for sensitive balances in environmentally controlled environments for weighing filters, the need for calibration of pumps in the field, and the demand for careful handling of pumps, balances, and filters from laboratory to field and back. In addition, current battery-operated pumps are relatively noisy and obtrusive in households, and the available batteries limit the sampling time to a day or two at most. Finally, even when executed correctly, this technology only provides integrated estimates of particulate mass during the sampling period and does not provide information on temporal exposure patterns and peaks.

Currently available continuous, portable, data-logging particle monitors use light-scattering technology to assess particle mass concentrations. These are prohibitively expensive for use in large numbers of houses and are also limited in battery life because of active pumping requirements. An additional problem is that the sensitivity of light-scattering chambers is dependent on the size distribution and refractive index of the aerosols. In the absence of calibration with the aerosol of interest, a default value is often applied, although manufacturers recommend user calibration with the aerosol being monitored. This approach is quite limited for the study of particles in houses in the developing world, because the size distribution and nature depends on the relative contribution of resuspended dust and combustion sources, such as open flames, used for cooking. Furthermore, the size distribution of combustion-generated aerosols varies with the stages of combustion in a typical open fire or stove, and multiple phases (evaporation, volatilization, flaming, and smoldering) are likely to be present at the same time, depending on the position of the fuel in the fire. Finally, the type of fuels used in different seasons frequently changes,[2] making direct comparison difficult. Thus, the aerosol represents a complex and changing mixture for which calibration is difficult. The use of an average sensitivity value to calculate an aerosol mass concentration is likely to overestimate or underestimate by significant factors because of a lack of knowledge about the particle size distribution over time.

A further complication is that neither gravimetric nor current portable continuous devices are suitable for longitudinal studies with a duration >1 week, which are of interest in current epidemiological studies that attempt to evaluate long-term exposures. There is, thus, a clear need for economical instruments to estimate particulate exposures that may be deployed in large numbers in the population for extended periods.

Based on the 1993 suggestion of one of the authors[3] to combine modern smoke alarm and microelectronics technologies, a particle monitor has been developed at the University of California at Berkeley (henceforward referred to as UCB particle monitor) to address this need. Litton et al.[4] demonstrated the potential for using combined photoelectric and ionization measurements from such devices for real-time characterization of micrometer and submicrometer particles as a function of aerosol mass, surface, and diameter. This paper describes laboratory tests of prototype versions of the UCB particle monitor in relation to gravimetric filters, a Tapered Element Oscillating Microbalance, and a TSI DustTrak, as well as the influence of environmental parameters on sensor performance.

EXPERIMENTAL WORK

The UCB Particle Monitor

The sensors in the UCB monitor and the theoretical basis for their use to quantify combustion aerosols as a function of particle mass, surface area, and diameter are discussed in Litton et al.[4] Briefly, the UCB monitor relies on sensors from an inexpensive commercial household smoke detector that combines ionization chamber sensing (ion depletion by airborne particles) and photoelectric sensing (optical scattering by airborne particles). Ionization chambers demonstrate higher response to smaller particles produced from the exhausts of diesel engines or flaming combustion, whereas photoelectric-type detectors show greater response to the larger particles produced from smoldering combustion.[5] Litton[6] presents a detailed evaluation of differences in the sensor responses.

Ionization-detector technology, commonly found in commercial smoke detectors, uses α particles generated from a small radioactive source (^{241}Am) to cause a negative distortion in a small current between the charged plates of the ionization chamber by creating ions from air molecules. When airborne particles enter the chamber, the ionized air molecules attach to them, and the current is disrupted proportionately to the product of the particle number and particle diameter of the airborne particles in the active chamber. The photoelectric or light-scattering sensor uses a light-emitting diode (LED) and a photodiode that measures the intensity of scattered light. In the UCB, the LED emits at 880 nm, and scattered light is detected at an angle of 45 ° measured from the forward direction.

In the UCB monitor, the smoke alarm circuitry was modified so that the sensors could be powered at consistent levels, signals could be measured continuously, and the information could be stored in a data logger within the monitor during programmable time intervals for subsequent downloading into a personal computer. Also added were temperature and relative humidity (RH) sensors and a clock that is synchronized with the computer clock before initiation of monitoring, along with the ability to interface additional sensors if desired.

Experimental

Initial tests were performed at the facilities of Aerosol Dynamics, Inc. Test aerosols were of oleic acid (density of 0.89 g/cc and a refractive index of 1.45, typical of ambient aerosol). Fine particles were produced by nebulizing 0.1%, 0.2%, or 0.4% solutions of oleic acid in isopropyl alcohol. Particles >1 μm (henceforward referred to as coarse particles) were produced by nebulizing a 50% oleic acid in isopropyl alcohol solution.

A laser particle counter (Model Spectro 0.3, Climet Instruments Co.) was used to estimate the size of the coarse particle distribution. For the coarse particles generated with the 50% oleic acid solution, the mass median diameter was measured as 2.1 μm. Size distributions for

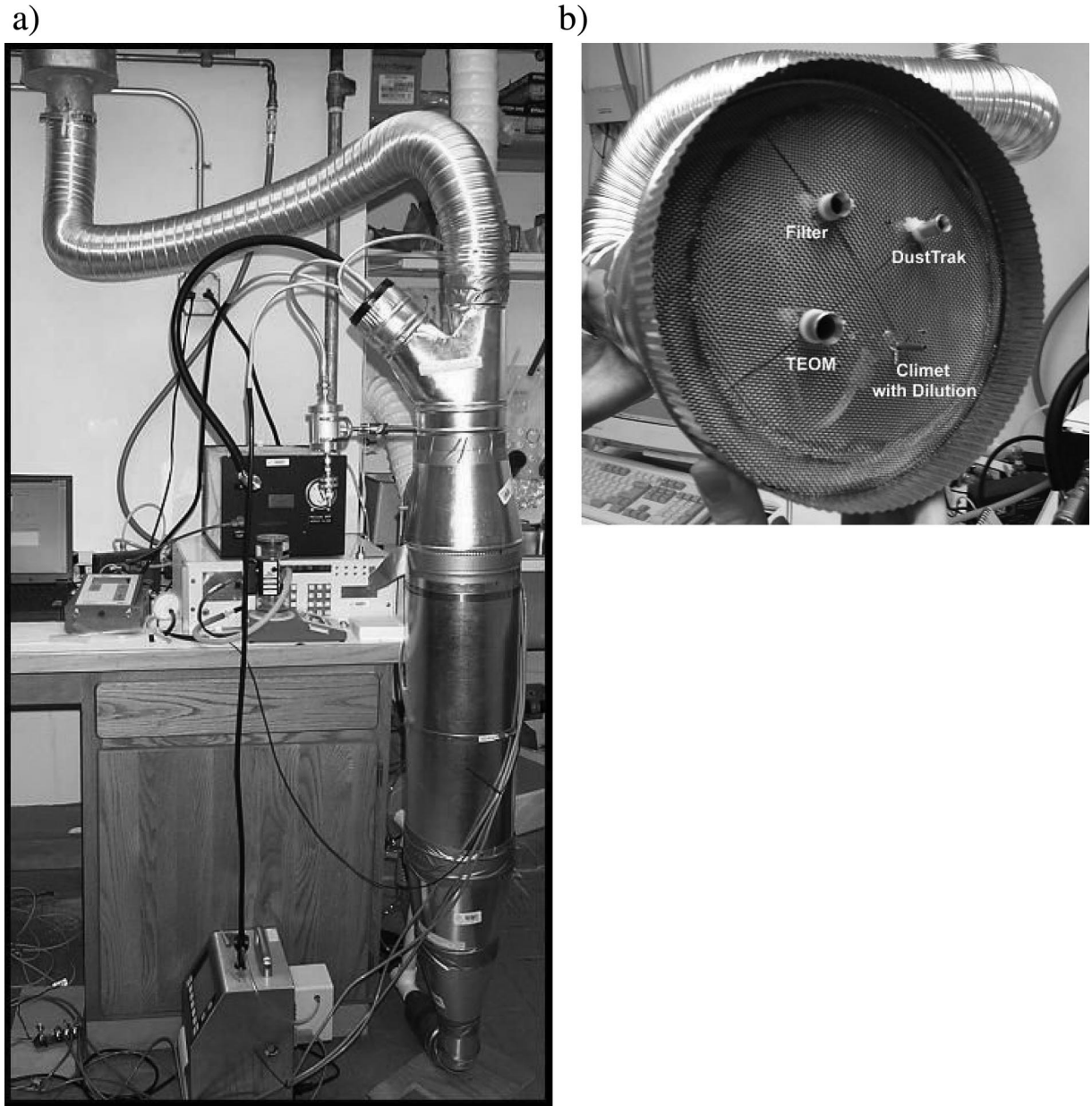

Figure 1. (a) Experimental setup; (b) Sampling inlets for TSI DustTrak, TEOM, laser particle counter, and 47-mm Teflon filter.

the fine particles could not be measured directly, because the laser particle counter had a detection limit of 0.3 μm. The mass median diameter for these aerosols was estimated assuming constant nebulized droplet size. For a mass median diameter varying as the cube root of the solution concentration, calculated mass median diameters are 0.27, 0.33, and 0.42 μm for solutions of 0.1%, 0.2%, and 0.4%, respectively.

Test aerosols were passed through a 2.5-cm–diameter polyvinyl chloride pipe with two polonium strips for aerosol neutralization, after which it entered the bottom of a test duct consisting of a 155-cm section of 20-cm–diameter metal duct (Figure 1a). The main duct airflow was provided by unfiltered air drawn from the room by a roof blower, expanded into a 10-cm–diameter metal elbow and then expanded again to the 20-cm–diameter test section. Low-flow velocity conditions were achieved by closing of a flapper valve to restrict airflow into the test duct.

Three prototype UCB particle monitors (UCB-1, -2, and -3) were mounted along the test section, 120 ° from each other, with a vertical separation of 18 cm. A metal screen at the top of the test section (Figure 1b) supported four sampling inlets for the following instruments: (1) DustTrak (TSI Inc.) photoelectric aerosol monitor using manufacturer's size selection inlet for particles <1 μm in diameter (PM_1); (2) tapered element oscillating microbalance ([TEOM] Rupprecht & Patashnick Co.) particulate monitor preceded by a 2.5-mm size-cut cyclone; (3) laser particle counter; and (4) 47-mm Teflon filter for gravimetric mass preceded by a 2.5-mm greased impactor. Flow rate through the impactor was 3 L/min, and filters were preweighed and postweighed on a microbalance (Sartorius MC 5) to obtain sample mass.

Table 1. Particle size, air velocity, temperature (T), and relative humidity (RH) during tests.

Air Velocity	Particle Size	
	Fine (MMD = 0.3–0.4 μm)	Coarse (MMD = 2.1 μm)
16 cm/sec	0.08–7.4 mg/m^3 (18 concentration levels) T = 25 ± 1 °C, RH = 37 ± 1%	3–19 mg/m^3 (6 concentration levels) T = 26 ± 1 °C, RH = 35 ± 1%
37 cm/sec	0.05–2.9 mg/m^3 (18 concentration levels) T = 25 ± 1 °C, RH = 37 ± 1%	1–13 mg/m^3 (5 concentration levels) T = 26 ± 1 °C, RH = 35 ± 1%

Air velocity was measured as the average of anemometer readings across the diameter of the test section. A typical run at 16 cm/sec had six different concentrations held for 10 min each. Data from each concentration period were averaged for further analysis. A typical run at 37 cm/sec was shorter (3 min per concentration).

Table 1 displays the sampling frame of experiments encompassing the combinations of coarse and fine particles at two different air velocities using a range of different concentrations. The range of concentrations tested is shown with the number of different concentration levels. Sizes shown are mass median diameters (MMD).

Static Chamber Tests

A series of static chamber tests were undertaken at the air pollution laboratory (SE 1 Room 134) at the University of California at Irvine. A sealed chamber 55 cm × 55 cm × 55 cm made from smooth hardboard was used to reduce electrostatic effects. Airflow from a separate combustion chamber was drawn into the chamber through a 3.8-cm–diameter duct and the chamber sealed with a valve. An internal mixing fan during the first 2 min after sealing ensured a fully mixed chamber. Particle concentrations measured by 2 UCB particle monitors (UCB-305 and -306) and a DustTrak (zero calibrated, PM_1 greased impactor, 1.7 L/m flow rate) were averaged for a 20-min period after mixing in a similar manner to the tests above. Mean temperature and RH were 23 °C ±0.38 and 58% ± 1.33, respectively, during the tests.

RESULTS

Relationship between UCB Particle Monitor Response and Gravimetric Mass

Figure 2 shows a comparison of the DustTrak and UCB particle monitor photoelectric and ionization response in comparison to gravimetric mass measurements. Both DustTrak and UCB particle monitor show good linearity in relation to gravimetric measurements, although the DustTrak overestimates mass by a factor of 3 for fine particles. Similarly, the TEOM overestimated mass by a factor of 1.22 (r^2 = 0.997) compared with gravimetric mass. The photoelectric detector of the UCB particle monitor shows a similar slope relationship as the DustTrak, which is not surprising given that both rely on light scattering, although using different wavelengths and scatter angles. The DustTrak data presented in the following figures have been normalized to gravimetric mass concentrations using the relationship presented in Figure 2.

Results at increased air velocities measured for shorter periods were quite similar to the lower air velocity condition, only with more sensor noise in the ionization chamber. Little difference was observed for the photoelectric chamber (Figure 3). Because objectives of the current study are to evaluate UCB particle monitor performance for applications in indoor settings, the results for the lower air velocity are presented below.

Figure 4 shows photoelectric and ionization response to fine particles from nebulized 0.1% oleic acid. Similar relationships were observed for 0.2% and 0.4% oleic acid

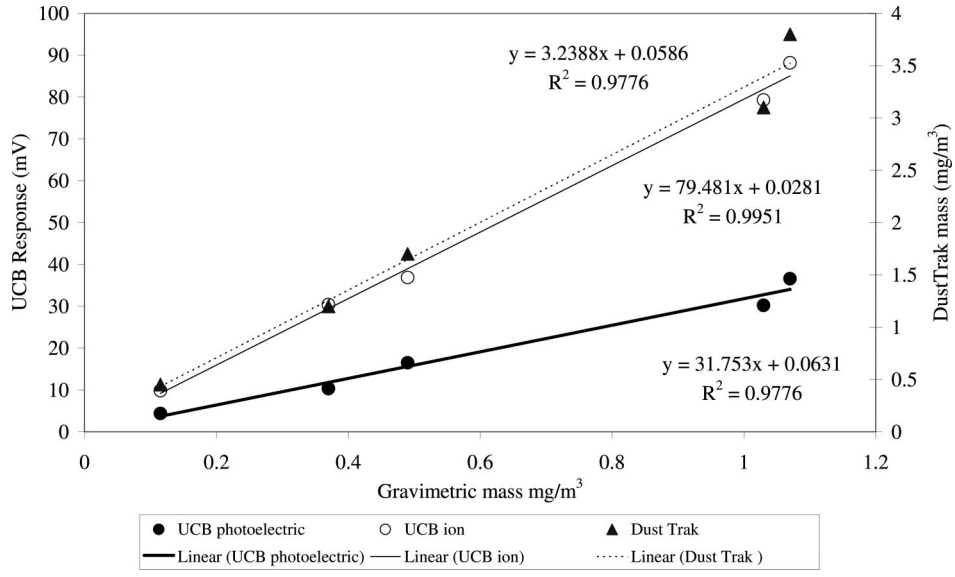

Figure 2. DustTrak and average UCB photoelectric and ionization response compared with gravimetric mass for fine particles (0.1%, 0.2%, and 0.4% oleic acid).

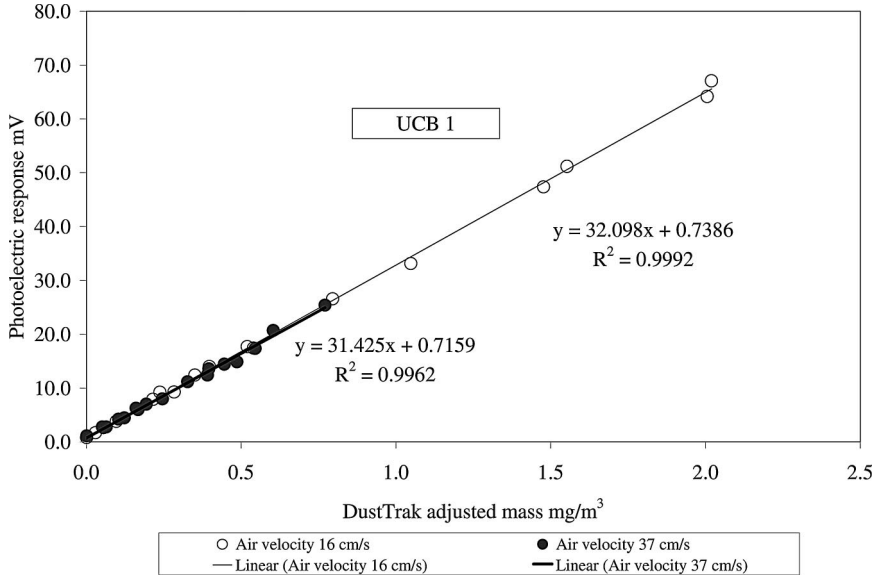

Figure 3. UCB photoelectric response to fine oleic acid particles under different air velocities.

(Table 2). Both photoelectric and ionization chambers show good linearity, although there were significant differences in the slopes among the three UCB monitors.

Figure 5 shows the photoelectric and ionization response to coarse particles from nebulized 50% oleic acid. Although these responses show similarly good linearity for both detectors, the slope of the response is significantly different from the responses observed for fine particles (Table 2). In addition, the change in response of the photoelectric detector and the ionization chamber with particle size are in opposite directions. The photoelectric detector is more sensitive to coarse compared with fine particles, and the ionization detector has the reverse sensitivity trend (Figure 6).

Effect of Environmental Parameters

Ionization Chamber. The potential across the ionization chamber is dependent on the number of ions generated by the interaction of the α particles with air molecules. The current will also be affected, however, by other parameters that change the number of air molecules in the active chamber relative to the radiation source. The main parameters with significant effects are temperature, RH, and atmospheric pressure (and, therefore, altitude). Modeled effects of these parameters on the potential across the ionization chamber may be described linearly, with best fit resulting in r^2 of 0.97, 0.83, and 0.96 for temperature, RH and elevation, respectively (eqs 1–3).[7] The initial value of the collection electrode voltage is decreased as each parameter (temperature, RH, and elevation) is increased.

$$CEV\ (volts) = -0.0083 \times temperature\ (°C) + 4.3177 \quad (1)$$

$$CEV\ (volts) = -0.0022 \times RH\ (\%) + 4.288 \quad (2)$$

$$CEV\ (volts) = -0.0001 \times elevation\ (m) + 4.199 \quad (3)$$

Figure 7 shows the theoretical response of ionization chambers to monodisperse particles with a diameter of 100 nm and a mass concentration range of 0–2 mg/m^3 over ranges of elevation, temperature, and RH. Although there were some variations in sensitivity, they appear evenly distributed around the mean value and, thus, no systematic bias would be expected in the computation of aerosol mass. More importantly, sensitivities at fixed values of these parameters in the laboratory should also be valid under other environmental conditions in the field. Thus, measurement of sensor performance and mass response to aerosols in the laboratory should not require significant adjustment under field conditions, and corrections for temperature, RH, and elevation can be made after data collection (see Discussion below). Clearly, however, as with other monitoring instruments, responses to aerosols of different size and composition from different sources would result in different sensitivities.[8]

Photoelectric Chamber. Figure 8 shows a sample plot (UCB-093) of the response of UCB photoelectric chambers to temperature fluctuations inside a low-particle sealed environment with high-efficiency particulate–filtered air. UCB monitors were run over a 48-hr period in which temperature fluctuated naturally. Other UCB monitors showed similar relationships but with slightly differing regression slopes. As temperature increases, there is a corresponding decrease in the resting potential of the photoelectric chamber. Because calculation of mass in response to a test aerosol would involve subtraction of the resting potential from the response to the aerosol, correction for this variability in relation to temperature is required.

Electronic Noise and Sensitivity. Figure 9 shows the standard deviation of the photoelectric response while in a low-particle environment defined by a signal below the detection limit of the DustTrak. The standard deviation represents the electronic noise level of the photoelectric

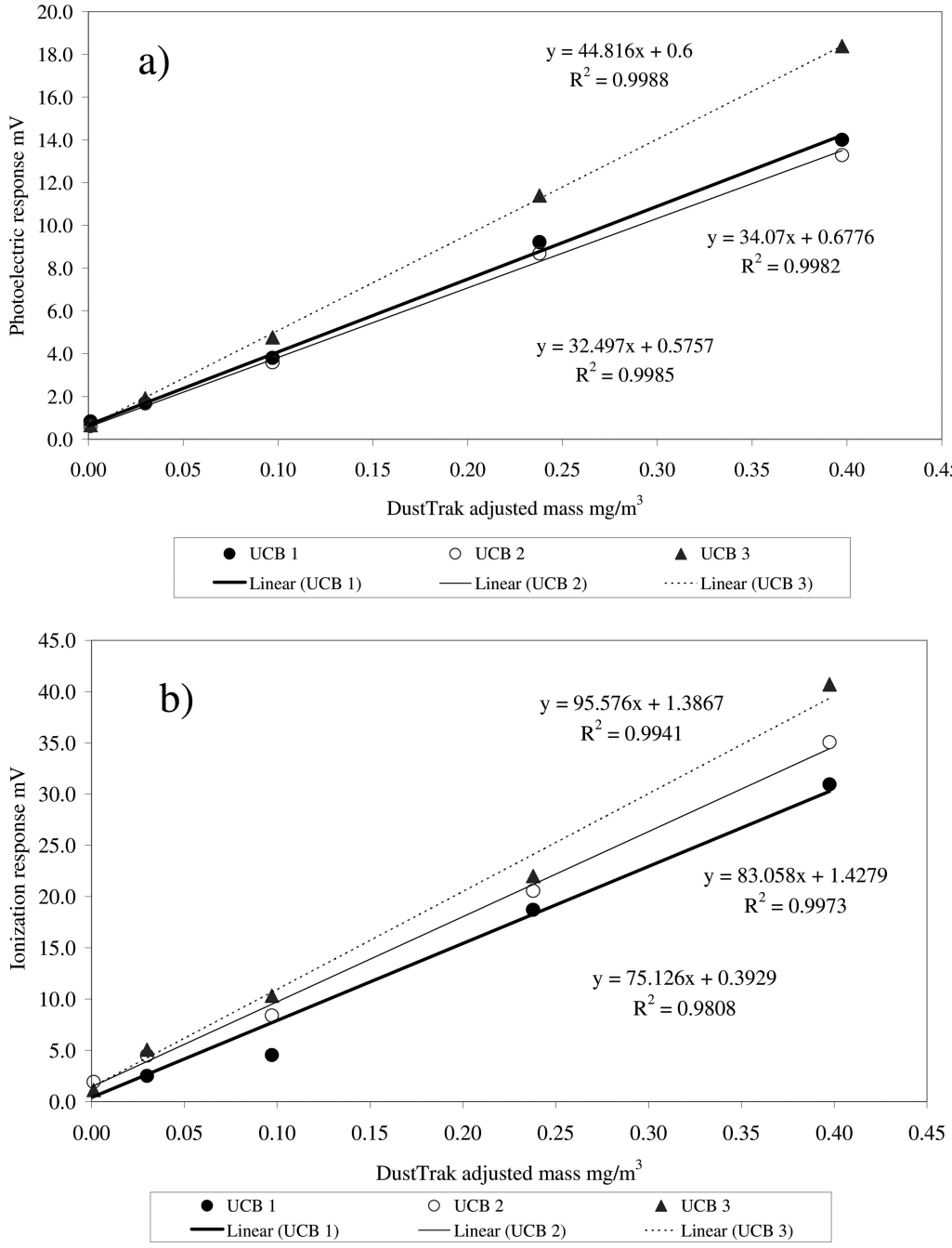

Figure 4. UCB photoelectric and ionization response to fine particles from nebulized 0.1% oleic acid (MMD <0.3 μm): (a) Photoelectric response; (b) Ionization response.

signal. In addition to the standard deviation of the raw output from the sensors in mV, Figure 9 shows the reduction in the standard deviation with signal processing in the laboratory tests presented here and further reduction in the standard deviation from signal processing incorporated since these tests. Using a 15-min moving average corresponds to a standard deviation of 0.087 mV or 81% reduction in standard deviation compared with signal processing used in the current tests. Using a standard definition of signal-to-noise ratio of three times the standard deviation of the noise to define detection limits, the reduction in the standard deviation represents an improvement in sensitivity provided that the particle events that are of interest occur on a longer time scale than the time interval used in the signal averaging.

Combustion Aerosols

Figure 10 shows the photoelectric response of two UCB particle monitors for smoldering incense combustion where six discrete concentrations were generated in the sealed test chamber and monitored over a 20-min period. There is similarly good linearity of photoelectric response ≤ 120 mg/m^3 as reported by the DustTrak, although the top data point is above the reported upper range of DustTrak with standard calibration (100 mg/m^3). DustTrak mass was not adjusted, as in the laboratory tests, because

Table 2. Summary of photoelectric and ionization response to oleic acid particles (MMD in parentheses).

	0.1% Oleic Acid (0.27 μm)		0.2% Oleic Acid (0.33 μm)		0.4% Oleic Acid (0.42 μm)		Coarse (2.1 μm)	
Response	**Slope[a]**	**r^2**	**Slope[a]**	**r^2**	**Slope[a]**	**r^2**	**Slope[a]**	**r^2**
Photoelectric								
UBC 3	44.8	0.9988	42.6	0.9999	41.2	0.9999	220.8	0.9975
UBC 2	32.5	0.9985	31.5	0.9999	30.7	0.9999	151.0	0.9967
UBC 1	34.1	0.9982	32.7	0.9999	31.7	0.9999	166.5	0.9972
Ionization								
UBC 3	95.6	0.9941	84.5	0.9978	96.4	0.9943	16.3	0.9999
UBC 2	83.1	0.9973	75.0	0.9986	89.0	0.9926	15.3	0.9983
UBC 1	75.1	0.9808	73.2	0.9956	80.4	0.9947	14.1	0.9981

[a]Expressed as mV response per mg/m^3.

no gravimetric measurements with this aerosol were made. If the coefficients derived for oleic acid filter measurements from the laboratory tests are used, which were similar to those reported in the literature[9] to adjust both the photoelectric mV response and the DustTrak mass, however, the resulting slope is ~0.85, demonstrating the need for calibration of the UCB photoelectric detector with the aerosol of interest. Based on these coefficients, however, linearity of response of the UCB can be extended to equivalent gravimetric mass of 40 mg/m^3.

DISCUSSION

Although responses of both the photoelectric and ionization chambers show good linearity in response to both coarse and fine particles, the slope of the response varies significantly between coarse and fine particles. This is summarized in Figure 6, which shows the ratio of the ionization chamber response and the photoelectric signal response to both fine and coarse particles. The ionization chamber was five times more sensitive to fine than coarse particles (measured as mV per mg/m^3), whereas the photoelectric chamber was five times more sensitive to coarse than fine. It is well established that smoke detectors respond differently to flaming fires, which typically produce particles with smaller average diameters than those produced from smoldering fires.[5] Indeed, this difference in response is the reason that more sophisticated commercial smoke alarms include both chamber types so that the alarm can be triggered by either flaming or smoldering combustion. The data in the current paper support these observations using nebulised oleic acid particles. Litton et al.[4] report that these differences in response maybe used to derive additional information about the nature of the particle distribution to improve estimates of particle mass and other characteristics. Furthermore, they report that this information has the potential to provide additional information on count mean diameter, the diameter of average surface area, and the diameter of average mass.

Both the sensitivity of an ionization chamber and an optical scattering chamber are significantly dependent on the size distribution of the aerosols. If these sensitivities could be defined when the sensor is exposed to an aerosol of known size, then the resultant mass concentration could be determined simply by dividing the voltage change by the corresponding sensitivity. Although many commercial continuous monitors, like the DustTrak, are referenced at the factory to Arizona road dust or equivalent, the manufacturers recommend recalibration to the aerosol of interest. In the absence of calibration with the aerosol of interest, a default value is often applied. Jenkins et al.[9] reported that the factory-calibrated DustTrak overreported respirable suspended particle concentrations (approximately equivalent to particles <3.5 μm in diameter) by factors of 2.6–3.1 compared with gravimetric measurements and was most in error when monitoring combustion smokes, including environmental tobacco smoke. We obtained similar overestimates of mass using the DustTrak with a greased impactor for PM_1, and regression equations indicate a slope of ~3 for fine particles in relation to gravimetric mass of oleic acid.

That the two sensors of the UCB particle monitor have substantially different sensitivities according to particle size is a characteristic that might be considered a disadvantage but in fact offers the potential for a significant additional capability. Because the ratio of the photoelectric response to the ionization responses is dependent on the differential sensitivity to the particle size distribution of the aerosol, the ratio of these signals provides an estimate of the particle distribution and, hence, the mass conversion factor that may be applied to estimate the mass of combustion-generated aerosols on a real time basis as the size distribution shifts during different phases of combustion. Further work is being undertaken to use and validate this capability.

The laboratory tests presented in this paper were for relatively short periods under relatively stable conditions and, therefore, no temperature adjustments were made. In poor rural households in highland or temperate areas, however, temperatures often fluctuate considerably and frequently range from 5 to 30 °C during a 24-hr period. For the ionization chamber, large changes in temperature and RH during the sampling period would result in a change in the baseline value, which, if uncorrected, would result in erroneous mass estimates (Figure 8). Similarly, large changes in temperature during the sampling period are likely to affect the photoelectric baseline and result in erroneous mass estimates (Figure 8). This is particularly important for time periods with lower particle mass, because this fluctuation would result in significant bias in the measurements. In addition, if measurements are made every minute over long sampling periods (frequently ≥48 hr), small mass errors in the baseline can

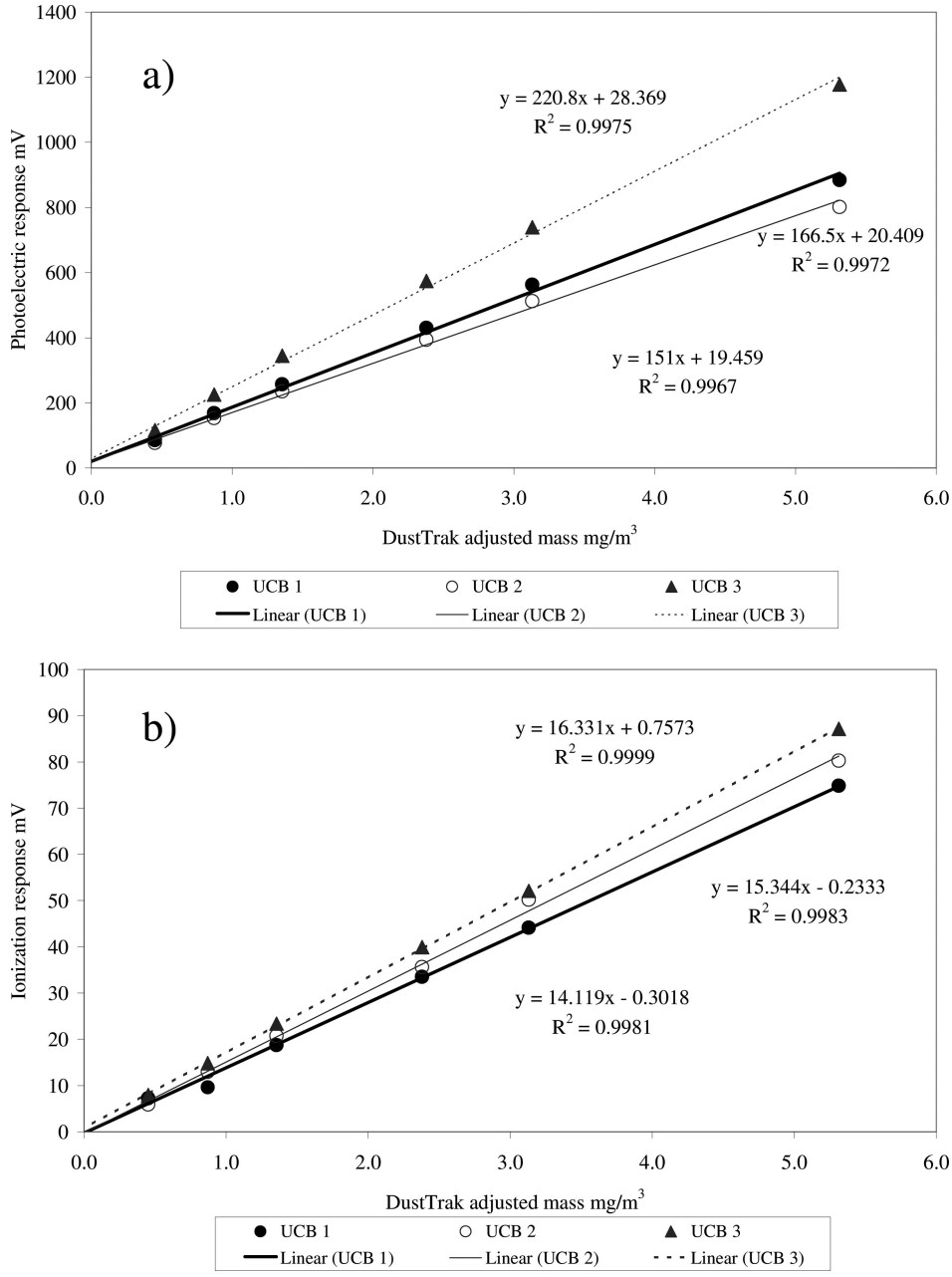

Figure 5. Photoelectric and ionization response to coarse particles from nebulized 50% oleic acid (MMD = 2.09 μm): (a) Photoelectric response; (b) Ionization response.

result in significant deviation from gravimetric estimates. As a result of the effect of temperature and RH on the chamber signals, the UCB particle monitor is fitted with a temperature and RH chip so that these parameters can be logged simultaneously with chamber outputs. Subsequently, these parameters are used to normalize both ionization and photoelectric chamber responses during data reduction. A further adjustment for elevation has to be made with the ionization chamber if the field-sampling site is at a different elevation to that used for initial calibration and establishment of reference values (Figure 8).

For fine particles, the three UCB particle monitors demonstrated different slopes in response to oleic acid (Figures 4 and 5). The difference in response may be related to both position in the duct and to differences in the resting voltage and sensitivities between the chambers of different particle monitors. Similar tests in another facility by Litton et al.[4] revealed a similar difference in responses of the UCB particle monitors. As with most other monitoring instruments, therefore, characterization of the response of each device relative to other instruments should be performed before deployment of multiple monitors in the field.

Figure 9 shows the reduction in the standard deviation of the baseline in the absence of a test aerosol as a result of using low pass filters and subsequent averaging. Absence of a test aerosol was defined as being below detection of a DustTrak. Similar to other instruments, a series of weighted averaging algorithms are available

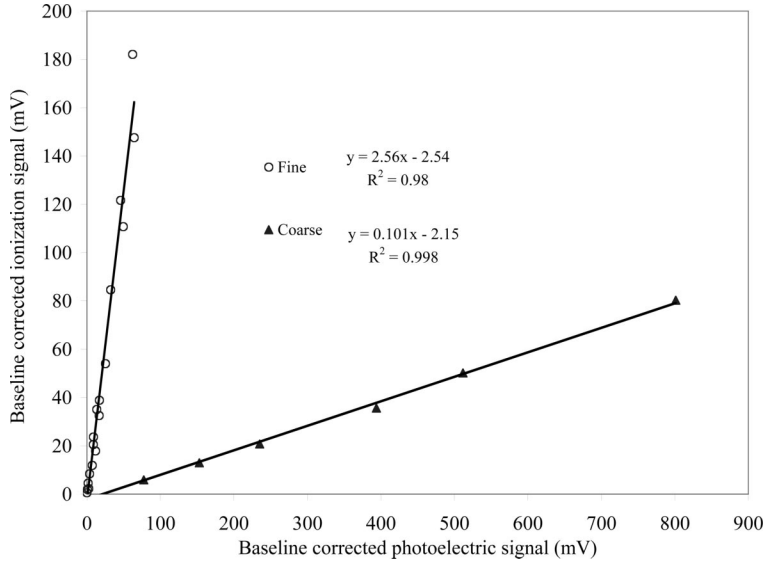

Figure 6. Ionization vs. photoelectric signals for both coarse and fine particles.

within the software for the UCB particle monitor to reduce electronic noise on a 1-sec basis relative to the 1-min logged values. Averaging of the 1-min logged values provides a second filtering step for data analysis. Using a standard definition of signal-to-noise ratio of three times the standard deviation of the noise to define detection

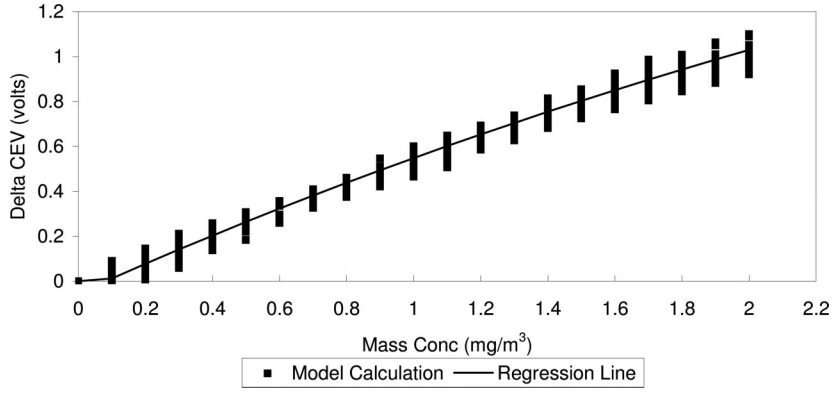

Figure 7. Modeled effect of elevation, temperature, and RH on ionization chamber sensitivity.

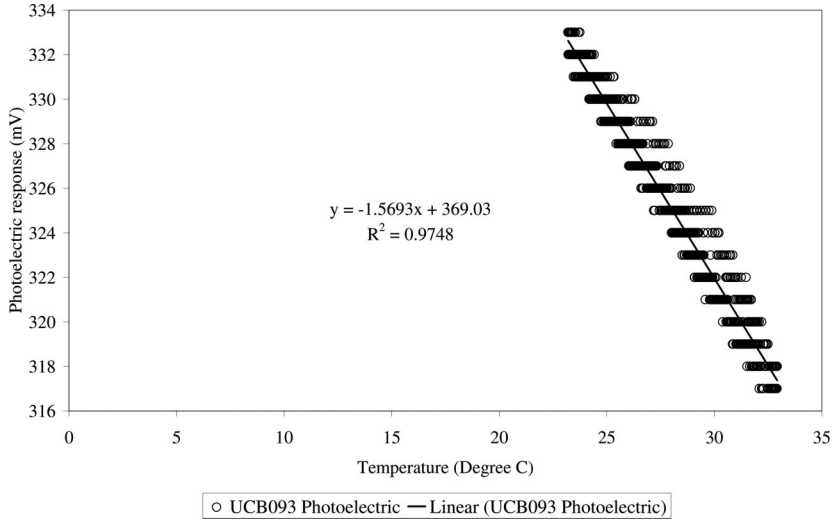

Figure 8. Measured photoelectric responses to temperature.

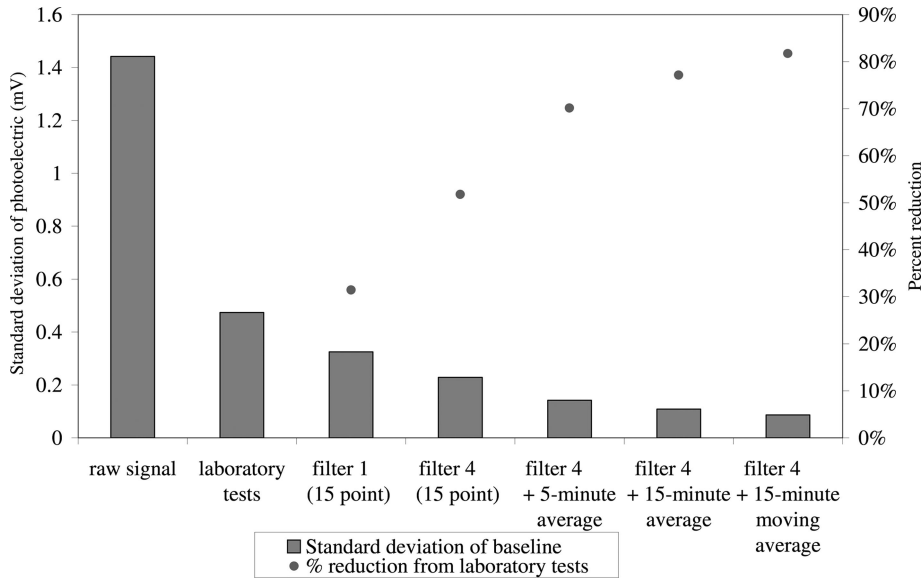

Figure 9. Percentage reduction in standard deviation of measured photoelectric baseline relative to laboratory tests presented above.

limits,[10] the reduction in the standard deviation because of filtering represents a corresponding improvement in sensitivity provided that the particle events that are of interest occur on a longer time scale than the time interval used in the signal averaging. Using a 15-min moving average, the standard deviation of the baseline corresponds to a theoretical lower detection limit for the photoelectric sensor of 17.5 $\mu g/m^3$ for fine particles. Because indoor concentrations in the solid-fuel-using households are generally higher and often much higher than this value, this limit is not a serious constraint.

CONCLUSIONS

The laboratory experiments described here support the use of this inexpensive device for field conditions where fine or coarse particle levels exceed a few tens of $\mu g/m^3$. In particular, the experiments showed the following: (1) UCB particle monitors showed good linearity in response to different concentrations of laboratory-generated oleic acid aerosols with a constant particle size distribution; (2) theoretical model prediction of ion chamber response indicated linear dependency of the resting potential on temperature, RH, and elevation; (3) in laboratory tests, the photoelectric chamber showed a dependency of the resting potential on temperature; given wide fluctuations of temperature and RH in many households in the developing world, continuous correction for these parameters is necessary in the reduction and analysis of data; (4) sensors and data logging for temperature and humidity have been incorporated into the device for this purpose; (5) the photoelectric and ionization chambers show a wide range of sensitivity based on particle size; the ionization chamber was about five times more sensitive to fine than coarse particles, whereas the photoelectric

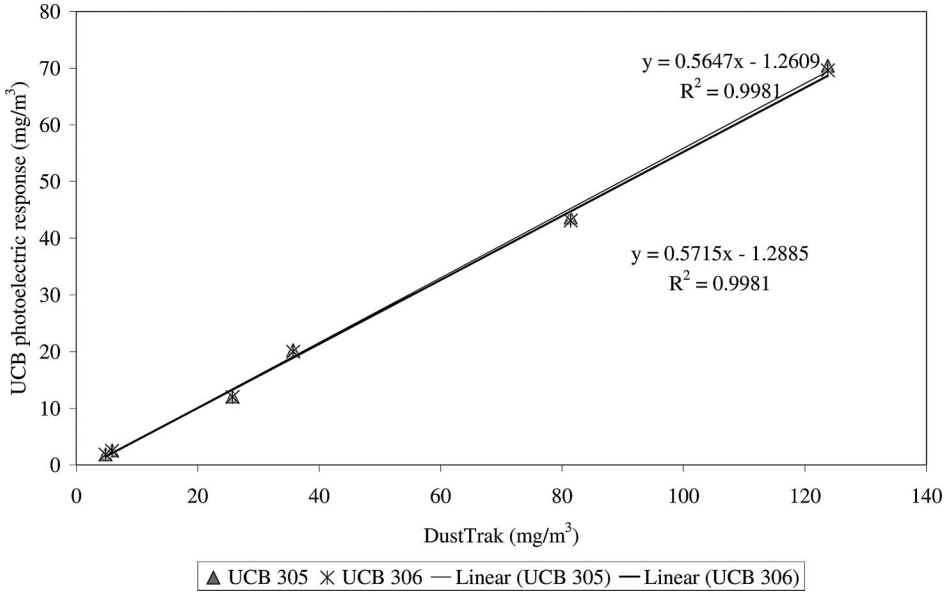

Figure 10. UCB response to smoldering incense test aerosol.

chamber was five times more sensitive to coarse than fine; this results in a ratio of sensitivities of ~25 between the two chambers for the different size ranges; (6) like other light-scattering particle monitors, each device needs to be each calibrated against the aerosol of interest; (7) the detection limit of the device is ~17 $\mu g/m^3$ for fine particles using a 15-min moving average; at longer averaging times, however, the lower detection limit should be reduced; and (8) the upper detection limit was not determined in our tests, but linearity extended to an equivalent gravimetric mass of 40 mg/m^3.

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