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An inexpensive light-scattering particle monitor: field validation

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Abstract

We have developed a small, light, passive, inexpensive, datalogging particle monitor called the "UCB" (University of California Berkeley particle monitor). Following previously published laboratory assessments, we present here results of tests of its performance in field settings at high particle concentrations. We demonstrate the mass sensitivity of the UCB in relation to gravimetric filter-based $PM_{2.5}$ mass estimates as well as commercial light-scattering instruments co-located in field chamber tests and in kitchens of wood-burning households. The coefficient of variation of the unadjusted UCB mass response in relation to gravimetric estimates was 15%. Although requiring adjustment for differences in sensitivity, inter-monitor performance was consistently high ($r^2 > 0.99$). Moreover, the UCB can consistently estimate $PM_{2.5}$ mass concentrations in wood-burning kitchens (Pearson $r^2 = 0.89$; $N = 99$), with good agreement between duplicate measures (Pearson $r^2 = 0.94$; $N = 88$). In addition, with appropriate cleaning of the sensing chamber, UCB mass sensitivity does not decrease with time when used intensively in open woodfire kitchens, demonstrating the significant potential of this monitor.

Introduction

The University of California at Berkeley particle monitor, referred to as the "UCB", was developed principally to support exposure and epidemiologic studies of indoor air pollution in households using solid fuels (biomass and coal) in developing countries, for which measurements of fine particulate matter (less than 2.5 μm in diameter) are the best single indicator of risk for many disease endpoints. Such a monitor provides a significant advance

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in the capacity to estimate adverse health effects from indoor smoke exposures in developing-world settings as current integrated assessment methods such as pumps, filters, and size-cut devices are relatively expensive, labor-intensive, require laboratory backup, and only reveal average multi-hour concentrations. On the other hand, currently available commercial continuous datalogging instruments are too expensive, large, heavy, and shortlived (battery life) for our applications.

We previously reported on the theoretical background of the sensors used in the UCB.[1] Laboratory validation, presented in Edwards *et al*.[2] to define the response of the particle monitor to laboratory generated micrometre and sub-micrometre oleic acid aerosols, demonstrated that the UCB shows good linearity with gravimetric filters, a tapered element oscillating microbalance (TEOM), and a TSI DustTrak. Although performing well in this controlled setting, laboratory-generated aerosols do not reflect the range of aerosols that may be encountered in the field. Furthermore, lab environmental conditions do not reflect the ranges of temperature and relative humidity in rural households.

Thus, to validate the use of this particle monitor for indoor air pollution assessments in households using solid fuels, we describe two types of validations of the UCB's light-scattering sensor against standard instruments using woodsmoke aerosols, one in field-based calibration chambers in rural Mexico under partly controlled conditions and the other in wood-burning village households in Guatemala. The objectives were to:

- determine variability in response between instruments,
- validate consistency of the UCB particle monitor mass sensitivity after repeated use in conditions with high particulate concentrations,
- compare the sensitivity of the UCB particle monitor with other commercial light-scattering instruments and gravimetric $PM_{2.5}$ samples, and
- estimate default particle mass conversion coefficients for biomass-burning stoves in rural households that can be used when calibration with the target aerosol is not feasible.

Methods

The UCB particle monitor

The UCB relies on sensors from a commercial residential smoke alarm (First Alert SA302) that combines ionization (ion depletion by airborne particles) and photoelectric (optical scattering by airborne particles) sensor chambers. The light-scattering chamber discussed here uses a light-emitting diode (LED) with an output wavelength of 880 nm and a photodiode that measures the intensity of scattered light at an angle of 45° from the forward direction. Although the UCB does not select particles using a traditional size cut device (cyclone or impactor), the photoelectric sensor is most sensitive to particles less than 2.5 mm in aerodynamic diameter ($PM_{2.5}$) and the ionization sensor is most sensitive to particles less them 1.0 μm.1† Temperature correction and data filtering were as described in Edwards

†We do not report data from the ionization chamber in this paper.

et al.[2] Briefly, the 1 min logged values represent a weighted moving average of the previous sixty 1 s particle concentrations. Temperatures were recorded every 15 s and averaged for 1 min logged values.

In order to compensate for inter-instrument variability, controlled chamber tests to compare sensitivity between instruments were conducted in the laboratory prior to deploying the UCBs in the field. In addition, when deployed in the field, UCBs were zeroed before and after every monitoring event by placing them inside a low-particle sealed plastic bag for a minimum of 30 min. After monitoring, the light-scattering sensing chamber of the UCB was cleaned with a wipe dubbed in 70% isopropyl alcohol, air dried, and the UCB monitor stored in particle free plastic bags until the next sampling event. Frequent cleaning during periods of intensive use causes small increases in the baseline mV signal, probably due to changes in the interior walls of the chamber. Like all nephelometers, however, zeroing before and after each individual sampling period controls for this shift in the baseline and instrument sensitivity is not affected.

Controlled co-location tests in Mexico

In order to examine how the sensitivity of the UCB to particulate mass was affected by continuous monitoring in open fire households with high particulate loadings, a series of controlled co-location chamber tests were conducted in rural Mexico as part of a comprehensive evaluation of the environmental and social impacts of installing an improved stove with a chimney.[3] The controlled co-locations were used for two reasons: (1) to adjust for inter-instrument variabilities in aerosol sensitivity, and (2) to examine potential decay in individual UCB response over time as a result of particle coatings on the walls of the photoelectric chamber from combustion by-products and degradation of UCB components with heavy usage in open fire kitchens. A 1.1 m^3 cylindrical sheet steel chamber, that can be readily set up in field project sites for inter-instrument comparisons (Fig. 1), was used to conduct 4 controlled co-location tests over the course of a 6 week period while the UCBs were being used 5 days a week to monitor kitchens of open fire households. During each co-location test, the chamber contained 19 UCBs, a DustTrak (Model 8250 with $PM_{2.5}$ inlet) and 2 filter types (Teflon and PVC) with identical pumps, cyclones, and flow rates. All 19 UCBs hung at the same height: 60 cm above the floor of the chamber along the inner chamber wall. Gravimetric cyclones and the DustTrak inlet were at the same height as the UCBs in the chamber as well.

Gravimetric $PM_{2.5}$ samples were collected using standard air sampling pumps (Model 224-PCXR8, SKC Inc., Eighty Four, PA) with $PM_{2.5}$ cyclones (BGI Triplex Cyclone, BGI Inc., Waltham, MA) using a flow rate of 1.5 l min^{-1}. Flow rates were measured before and after installation of the sampling equipment in the chamber with a rotameter (Matheson Trigas, Montgomeryville, PA, USA) calibrated using an SKC Ultra Flow bubblemeter (SKC Inc., Eighty Four, PA, USA). $PM_{2.5}$ particulate matter was collected on 37 mm, 2.0 μm pore size, Teflon filters (SKC Inc., Eighty Four, PA, USA). Filters were equilibrated for 48 h at 21 ± 2 °C and 40 ± 5% relative humidity before weighing on an electronic microbalance (Cahn Microbrobalance, Model 29, Thermo Electron Corp., Waltham, MA, USA). Calibration of the microbalance response was checked with NIST certified calibrations standards.

Laboratory blank measurements were weighed before and after weighing of samples, and were within 5% of the average for all weighing periods.

Prior to the tests the chamber was sealed and vented for 1 h using a 12 V venting fan through an aperture in the bottom, with HEPA filters covering inlet apertures in the top of the chamber. After 1 h the fan was switched off and the aperture sealed. Combustion aerosols were generated using small pieces of fuelwood from a field site in Mexico.[4] A small piece was combusted away from the chamber, the flame extinguished and smoke from the continued combustion introduced through an aperture into the co-location chamber in which there was a small mixing fan to minimize spatial heterogeneity in the chamber. After 30 min, the apertures at the bottom and inlet holes at the top were unsealed and the venting fan switched on until the DustTrak displayed background concentrations. The venting fan continued venting HEPA filtered air into the chamber for 20 min to ensure no residual concentrations from the previous burn event were present. The next combustion event was then initiated. To obtain a more representative estimate of UCB response, combustion aerosols were introduced into the chamber in a series of 5 discrete intervals at increasing peak concentrations. The duration of each test was approximately 7 h.

Wood-burning kitchens in Guatemala

Comparisons of the UCB response compared to gravimetric $PM_{2.5}$ filter samples in kitchens of rural households in Guatemala were performed as part of RESPIRE (Randomized Exposure Study of Pollution Indoors and Respiratory Effects), conducted in the highlands of rural Guatemala (altitude: 2200–3000 m) from August 2002 to January 2005.[5] One-eighth (n = 69) of the 530 households in RESPIRE, were intensively monitored for particulate matter and carbon monoxide. Reported here are the results of deploying two separate UCBs in each intensively monitored household with simultaneous gravimetric assessment of fine particulate matter ($PM_{2.5}$) every three months. Standard protocols were followed in placing equipment on the wall of the kitchen: 145 cm above the floor, 100 cm from the edge of the combustion zone of the cooking stove and at least 150 cm away (horizontally) from openable doors and windows. $PM_{2.5}$ was measured over 48 h in the kitchen using the SKC 224-PCXR8 pump programmed to operate every 1 min out of 5 using a BGI SCC1.062 Triplex cyclone with a flow rate of 1.5 l min^{-1}. Initial 24 h supervision, and 48 h final flow rates were measured with a rotameter to ensure proper functioning of equipment. The rotameter was calibrated with a laboratory Gilibrator (Gilian Model, Sensidyne, Clearwater, FL, USA) every 3 months. 37 mm PTFE TEFLO filters (SKC Inc., Eighty Four, PA, USA) with pore size of 1 micron were used as the particle collection media. The filters were pre-weighed and post-weighed with a 6-place Mettler Toledo MT-5 microbalance at the Harvard University School of Public Health. The weighing room was controlled for temperature (21.9 ± 0.8 °C) and relative humidity (41.8 ± 1.7%); barometric pressures (101.4 ± 1.1 kPa) were also noted. Static electricity was discharged before each weighing by passing each side of the filter near a polonium 210 alpha-radiation source for a few seconds. Lab blanks were weighed every 10 filter weights to ensure the lab blank readings were within 5 μg of the standard reading during the entire weighing session. Each sample filter was weighed at least 2 times until the mass difference between the repeated weighing was equal to or less than 5 μg. Field blanks were assessed concurrently (average change in weight of −0.001 ± 0.005

mg, $n = 48$). Since this was negligible, no blank subtraction was performed. Laboratory and field sampling forms and UCB results were double entered and discrepancies resolved against data collection forms. Subsequently, to see if any error was found, filter weights were merged using SAS (Version 9.1) and 20% of pre and post filter weights checked manually.

Results and discussion

Controlled co-location tests in Mexico

Fig. 2 shows the different concentration peaks generated to evaluate the UCB and DustTrak responses. Peak combustion events were chosen rather than continuous exposure periods because (1) they are indicative of the dynamic range of concentrations over a 24 h period in rural households that rely on biomass in open fires for energy provision both in terms of concentration and in terms of the dynamic changes in concentration during cooking periods; and (2) they provide a better evaluation of instrument performance as decreases in sensitivity over the study period are easier to identify. A mixing fan was present to minimize spatial concentration differences that may impact the estimation of instrument performance.

The correlation matrix in Table 1 shows the Pearson r^2 exceeding 0.99 for each pair of instruments in one co-location test, and Table 2 shows the summarized results for the 4 different co-location tests. As might be expected for different monitors, the slope of the response was slightly different for each UCB, highlighting the need for individual instrument calibrations, similar to many other air pollution monitors. Although slightly lower, as seen in Table 2, correlations were highly and consistently correlated with the DustTrak, with average Pearson r^2 values exceeding 0.986 for each co-location.

Fig. 3 shows a comparison of DustTrak and unadjusted UCB response for each peak exposure event in the 4 tests showing that the UCB sensitivity remained linear through a wide range of peak concentrations that would be found in biomass-burning kitchens (slope = 0.06; see also Table 2).Adjustment for inter-instrument differences in sensitivity can, therefore, be applied across the range of these concentrations without significant bias introduced. Although the UCB showed consistently good relationships with DustTrak sensitivity on a minute by minute basis (Table 1), as peak particulate masses increase, the UCB is more sensitive than the DustTrak for the size distributions generated in these tests. The slightly poorer correlation between the UCB : DustTrak and the UCB : UCB in the tests are due to these sensitivity differences between the UCB and the DustTrak response. This is not surprising between nephelometers using different wavelengths.

Fig. 4 shows the relationship between the UCB mV response and gravimetric filters collected during the different chamber tests. For clarity, only 3 UCBs are displayed in the graph, but the remaining 16 showed similar response (Table 2). The UCB response correlated well with gravimetric filter mass, although each UCB showed a slightly different sensitivity compared to gravimetric mass, as would be expected between different monitors. UCB response also agreed well with DustTrak response shown in the graph, although, as has been reported by others,[6–9] the unadjusted DustTrak without calibration with the aerosol of interest overpredicted the mass of this combustion aerosol by a factor of 3.1 compared to

Teflon $PM_{2.5}$ mass estimates over the course of the 4 experiments. No decay in UCB particulate mass sensitivity in relation to $PM_{2.5}$ gravimetric estimates was observed between the 4 co-location tests, even though at the time, the UCBs were being used 5 days a week over a 6 week period in an intensive monitoring exercise of kitchens using open fires in Mexico. Therefore, the results demonstrated that the UCB, with an appropriate cleaning protocol as described in the methods, may be used to provide consistent estimates of $PM_{2.5}$ mass over the course of most field monitoring exercises. Clearly, to ensure proper UCB performance during the entire duration of very long field projects that sample in high particulate environments, a consistent quality assurance monitoring strategy such as the controlled co-location tests presented here should be used.

The relationship between the UCB mV response and both PVC and Teflon $PM_{2.5}$ mass estimates in co-location tests are presented in Table 3. The coefficient of variation of the unadjusted UCB mass response in relation to gravimetric estimates was 15%. Therefore, if such controlled co-location tests are not performed between UCBs in field studies, a bias of 15% can be expected between mass estimates of different UCBs because of innate differences in sensitivity among the commercial smoke detector chambers. As a result, to check for defective components, controlled comparisons such as these are performed routinely after manufacture but prior to deployment in the field. Although identical pumps and cyclones were used, $PM_{2.5}$ mass estimates were higher for PVC filters compared to Teflon filters in these co-location tests. As correlations between filter types were high, a systematic difference in particle capture efficiency may exist between them. To standardize any bias in gravimetric estimates, therefore, Teflon filters should probably be used when making these comparisons.

Although substantially improving accuracy compared to no calibration with combustion aerosols, controlled co-location tests such as these do not fully simulate actual field conditions because of the potential for different size distributions of combustion aerosols in the households compared to the controlled co-location tests even when the same fuel is used. In real biomass-burning households, for example, there is a mixture of flaming and smoldering combustion, which generate aerosols with quite different size distributions.[10,11] In the co-location tests, we consistently used smoldering pieces of fuel for several reasons: (1) it is extremely difficult to effectively control the balance of flaming and smoldering phases during combustion events in a test. Small differences in this balance between different phases of combustion would significantly impact the particle size distributions present at each burn in these comparisons tests, and thus decrease correlations even though the actual instrument performance would remain the same; (2) it is impossible to determine what balance of the flaming and smoldering combustion phases would adequately represent conditions in households, especially as the balance between these two phases would vary according to the cooking behavior of the cook, quality of fuel, type of cooking, use of pots, and other parameters that vary in unpredictable ways among households and seasons. Therefore, controlled co-location tests such as these should be performed either in the laboratory or in the field to adjust for inter-instrument variability. Similar to other nephelometers, calibration with the aerosol of interest with gravimetric comparisons in the field is recommended. Clearly, even though we present here a relatively easy approach to

conducting these tests in the field, these are not feasible in all situations, especially when testing the effectiveness of interventions by non-research oriented groups.

Wood-burning kitchens in Guatemala

Since controlled comparisons with other particle monitoring instruments as presented above are not feasible in all situations, we present here comparisons between UCB responses and gravimetric filters in wood-burning households by estimating a default particle mass conversion coefficient and applying it for all instruments uniformly. This mass conversion coefficient was estimated by comparing the UCB photoelectric response in mV with $PM_{2.5}$ gravimetric results collected on both Teflon and PVC filters as shown in Table 3 and described earlier. No inter-instrument adjustment was conducted. The potential bias in using UCB unadjusted for inter-instrument differences is shown in Fig. 5 and 6. Fig. 5 shows that even UCBs that were not adjusted for inter-instrument differences in sensitivity were reasonably well-correlated between kitchens in Guatemala (Pearson $r^2 = 0.885$; $N = 99$). Fig. 6 shows good agreement between unadjusted UCB duplicate mass estimates in kitchens (Pearson $r^2 = 0.940$; $N = 88$). These results suggest that approximately one half of the error in mass estimates can be addressed through adjustment of inter-instrument sensitivities, and the other half is most likely due to differences in the size distributions of the aerosols between households and errors associated with gravimetric mass measurements.

Fig. 7(a) shows good agreement in the mass estimates for co-located UCB and gravimetric measurements in open-fire kitchens. The mean total fine particulate concentration estimated by the UCB was 630 μg m^{-3} (SD: 402 μg m^{-3}, $N = 50$) compared to 636 μg m^{-3} (SD: 402 μg m^{-3} $N = 50$) estimated with gravimetric filters, showing good agreement between mass estimates. When split into sequential bin sizes of increasing 48 h mass estimates, similar agreement of the UCB and gravimetric estimates was observed (Fig. 7(a)). Fig. 7(b) shows the overall agreement for the chimney-stove kitchens measured in this dataset. The mean fine particulate concentration estimated by the UCB was 110 μg m^{-3} (SD: 90 μg m^{-3}, $N = 49$) compared to 69 μg m^{-3} (SD: 89 μg m^{-3}, $N = 49$) estimated with gravimetric filters. Fig. 7(b) shows the agreement when split into sequential bin sizes of increasing mass. The errors in the mass estimates appear to be greater for the lower concentration ranges. It thus appears that the UCBs tend to overpredict at these relatively low concentrations, particularly when the reported gravimetric measurements are below 50 μg m^{-3}, which is consistent with the UCB's estimated detection limit of 30-50 μg m^{-3}.2‡

Commercial cyclones and impactors are rated such that a particle of the specified size has a 50% collection efficiency. Although the UCB does not use a traditional sharp size cutoff point, the field results suggest that for biomass households, the UCB serves as a good proxy in estimating $PM_{2.5}$ gravimetric mass. This accords well with the theoretical background of the sensors presented in Litton *et al.*,[1] which indicates that the photoelectric sensor is most sensitive to size ranges less than 2.5 μm in diameter. Further, although the UCB is a passive monitor, excellent correlations were obtained both on a minute by minute basis with the DustTrak (Table 1), and with 48 h integrated gravimetric samples (Fig. 5).

‡Detailed presentation of the air pollution reductions due to introduction of the chimney cookstove in RESPIRE will appear elsewhere.

Several investigators have reported humidity effects on the aerosol when relative humidities were above 60%. Wu *et al*. for example, observed both negative and positive drifts in the baseline of the MIE DataRam (pDR) compared to gravimetric $PM_{2.5}$, but found that these could be reduced using a relative humidity (RH) correction equation.[12] In addition, Chakrabarti *et al*. showed that humidity effects followed predictable trends and provided a correction scheme that improved the accuracy of a pDR in comparison with gravimetric $PM_{2.5}$ samples.[13] Relative humidities during the Mexican tests were less than 60% and, therefore, did not require correction. The co-location work in Guatemala, however, was conducted year-round in relative humidities spanning 52.3%–82.8% (mean RH = 68.5% ± 7.1%). Although RH corrections might have helped reduce the greater data scatter compared to the Mexico results, even the uncorrected results were acceptable.

Conclusion

A significant advantage of the UCB is that its low cost and ease of use in the field enables us to simultaneously deploy multiple instruments in multiple microenvironments. A penalty of using inexpensive off-the-shelf smoke detector technology is that there is substantial variation among individual units. The coefficient of variation of the unadjusted UCB mass response in relation to gravimetric estimates is 15%. We demonstrate here, however, that the UCB still relates well to gravimetric $PM_{2.5}$ estimates in rural biomass-using households in Guatemala, but that it is necessary to conduct controlled co-location tests in the laboratory and preferably also in the field to assure consistent performance between monitors. We have also presented a field-based method for conducting the required quality assurance tests. In this paper, therefore, we have:

- validated consistency of the UCB particle monitor sensitivity through controlled co-location tests conducted while the monitors were being used intensively for assessment of high particulate concentrations found in wood-burning households,
- validated the response of the monitor in co-located comparisons with other commercial light-scattering instruments, with $PM_{2.5}$ gravimetric samples, and with duplicate comparisons in field households,
- estimated default particle mass conversion coefficients that can be used when calibration with the target aerosol (woodsmoke) is not available, and
- found good agreement with gravimetric $PM_{2.5}$ measures in these households even without using traditional size cut-off devices.

These results demonstrate the significant potential of this monitor for investigation of acute and long-term adverse health effects from high particle levels (> 50 μg m^{-3}), and to facilitate the evaluation of interventions (improved fuels, stoves, and ventilation) for reduction of indoor air pollution levels in developing countries.

The UCB monitor was made possible by combining three separate lines of technological development in which capacity per unit cost has increased by orders of magnitude in recent decades: smoke detectors, microchip dataloggers, and personal computers. The wide availability of the last, even in developing countries, makes it possible now to deploy the

UCB widely for particle research in parts of the world that have, to date, been previously poorly characterized.

Acknowledgments

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Fig. 1.

Test chamber (1.2 m diameter × 1 m height) set up in Mexican field station showing placement of UCBs and cyclone during testing.

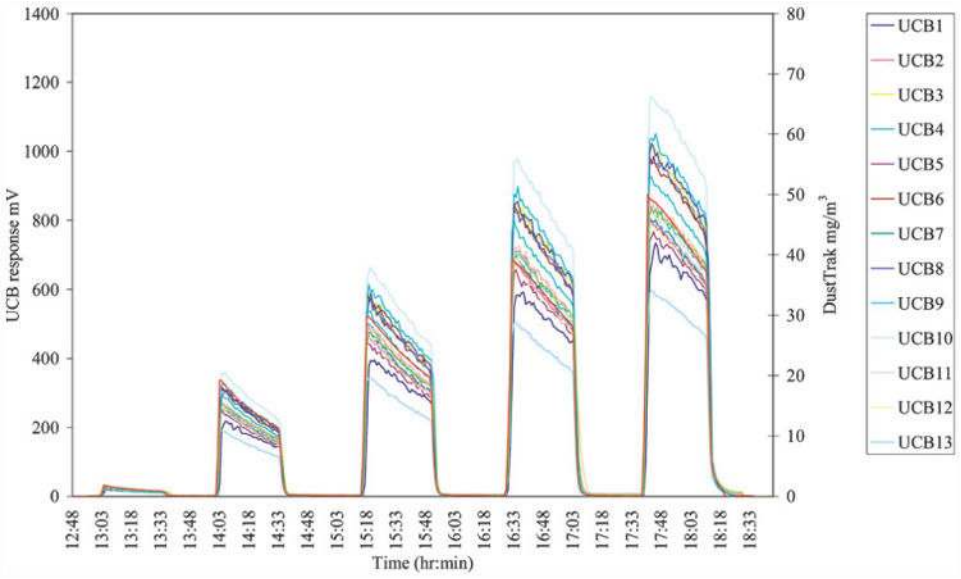

Fig. 2.
Responses of 19 UCBs and DustTrak during chamber tests.

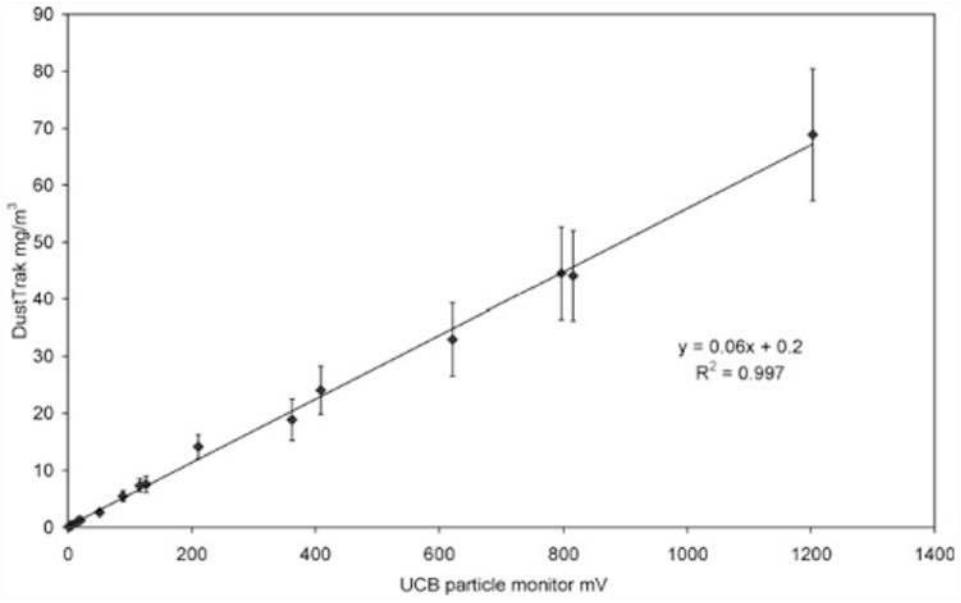

Fig. 3.

Correlation of mean UCB peak response with DustTrak during 4 chamber tests ($N = 19$).

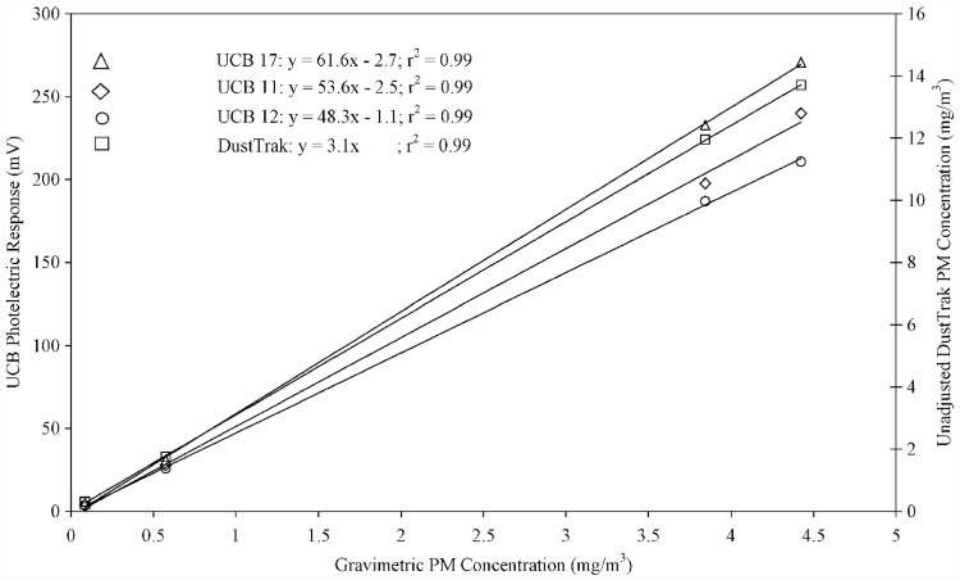

Fig. 4.

Correlation of UCB response with $PM_{2.5}$ Teflon gravimetric filters collected during 4 tests.

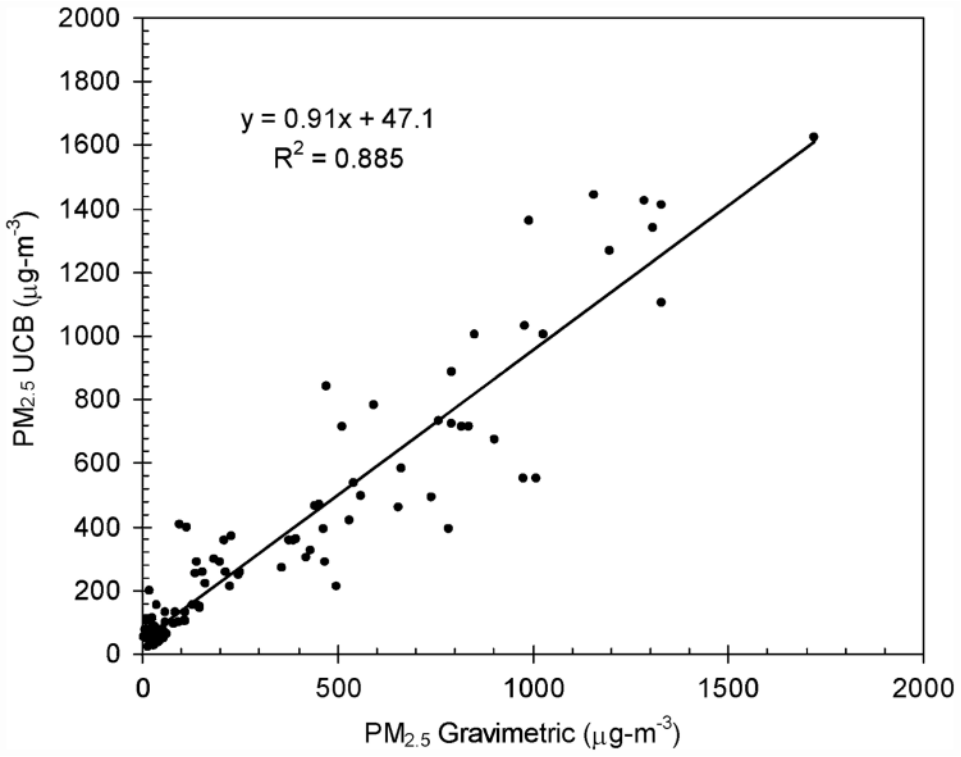

Fig. 5.

Comparison between UCB and gravimetric $PM_{2.5}$ mass concentrations ($N = 99$) from Guatemala.

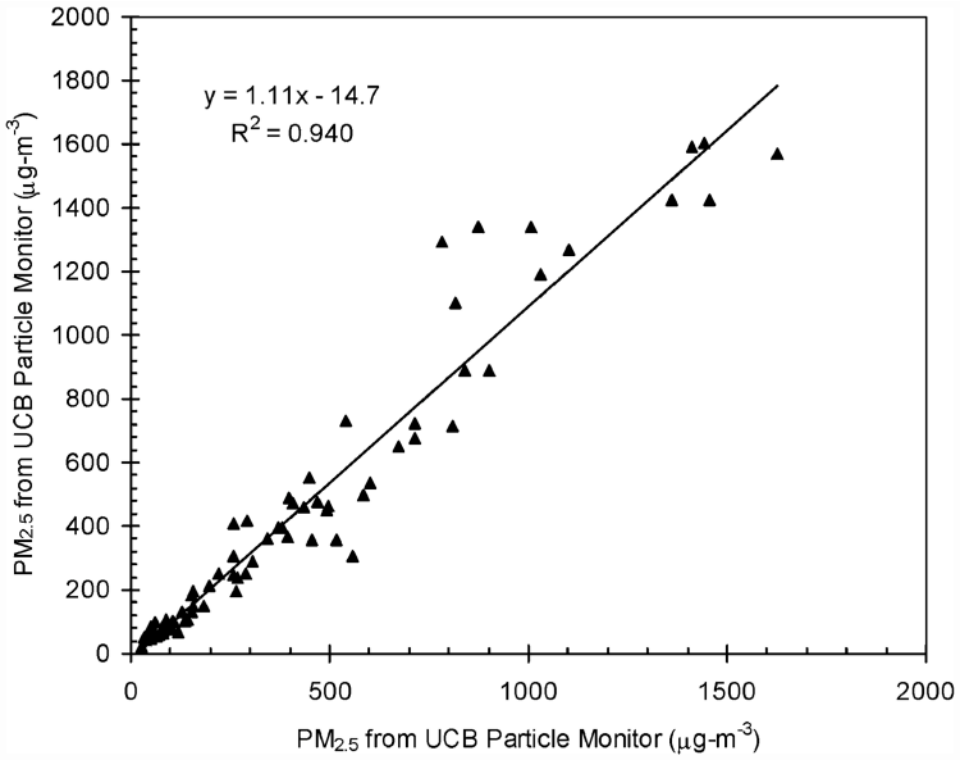

Fig. 6.
Correlation between duplicate ($N = 88$) UCB measurements.

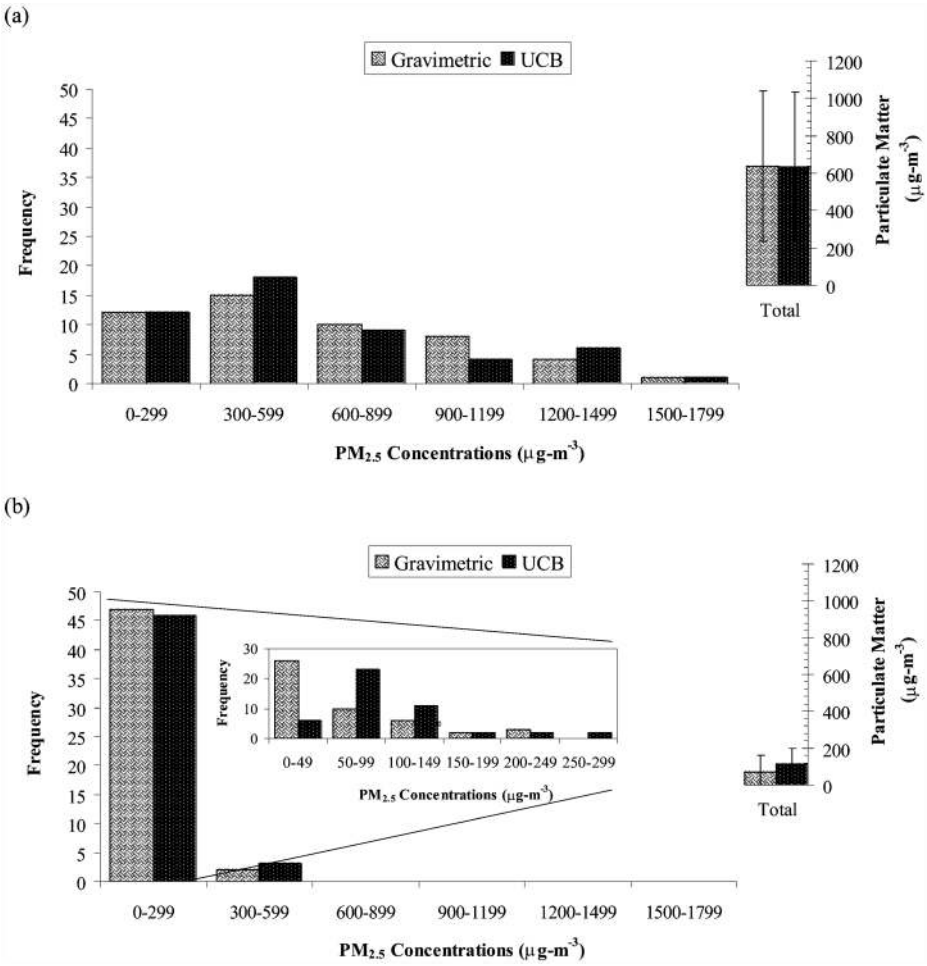

Fig. 7.

Frequency distribution of $PM_{2.5}$ concentrations from the UCB and gravimetric measurements in (a) open-fire kitchens ($N = 50$) and (b) chimney-stove kitchens ($N = 49$) in Guatemala. The error bars in the "Total" represent one standard deviation from the mean.

Table 1

Intra UCB and DustTrak correlation matrix in field co-location chamber tests

April 28, 2006																			
	UCB1	**UCB2**	**UCB3**	**UCB4**	**UCB5**	**UCB6**	**UCB7**	**UCB8**	**UCB9**	**UCB 10**	**UCB 11**	**UCB 12**	**UCB 13**	**UCB 14**	**UCB 15**	**UCB 16**	**UCB 17**	**UCB 18**	**UCB 19**	**DustTrak**
UCB1	1																		
UCB2	0.990	1																	
UCB3	0.994	0.998	1																
UCB4	0.995	0.998	0.999	1															
UCB5	0.994	0.997	0.999	0.999	1														
UCB6	0.992	0.996	0.999	0.998	0.999	1													
UCB7	0.991	0.996	0.999	0.998	0.999	1.000	1												
UCB8	0.995	0.997	0.999	0.999	0.999	0.999	0.999	1											
UCB9	0.992	0.998	0.999	0.999	0.999	0.999	0.999	0.999	1										
UCB 10	0.995	0.999	0.999	0.999	0.999	0.998	0.998	0.999	0.999	1									
UCB 11	0.995	0.998	0.999	0.999	0.999	0.998	0.998	1.000	0.999	1.000	1								
UCB 12	0.990	0.997	0.999	0.998	0.999	0.999	0.999	0.999	1.000	0.998	0.998	1							
UCB 13	0.992	0.997	0.999	0.998	0.999	1.000	1.000	0.999	1.000	0.998	0.999	1.000	1						
UCB 14	0.995	0.997	0.999	0.999	1.000	0.999	0.999	0.999	0.999	0.999	0.999	0.998	0.999	1					
UCB 15	0.992	0.998	0.999	0.998	0.999	0.999	0.999	0.999	1.000	0.999	0.999	1.000	1.000	0.999	1				
UCB 16	0.991	0.998	0.997	0.998	0.996	0.995	0.995	0.997	0.997	0.998	0.998	0.995	0.995	0.996	0.996	1			
UCB 17	0.993	0.999	0.998	0.999	0.998	0.997	0.997	0.998	0.998	0.999	0.999	0.997	0.997	0.998	0.998	0.997	1		
UCB 18	0.989	0.999	0.998	0.998	0.998	0.997	0.997	0.998	0.999	0.999	0.998	0.998	0.998	0.997	0.999	0.997	0.998	1	
UCB 19	0.995	0.998	0.998	0.999	0.997	0.996	0.996	0.998	0.997	0.999	0.999	0.996	0.996	0.998	0.997	0.999	0.998	0.997	1
DustTrak	0.981	0.993	0.994	0.992	0.993	0.995	0.995	0.993	0.995	0.993	0.993	0.996	0.996	0.993	0.995	0.990	0.991	0.995	0.989	1
	UCB : UCB	UCB : DustTrak																		
Average	0.998	0.993																		
Standard deviation	0.002	0.003																		

Table 2

Summary correlations between 19 UCBs and a DustTrak for 4 chamber tests

Pearson r^2	Co-location 1	Co-location 2	Co-location 3	Co-location 4
Average inter UCB correlation (N = 19)	0.993 ± 0.003	0.998 ± 0.002	0.994 ± 0.009	0.998 ± 0.001
Correlation between 19 UCBs and DustTrak	0.986 ± 0.002	0.993 ± 0.003	0.989 ± 0.010	0.998 ± 0.001

Table 3

Relationship between UCB mV response and Teflon and PVC $PM_{2.5}$ filter mass estimates

Co-location tests		
mg m^{-3} mV^{-1}	**UCB : Teflon**	**UCB : PVC**
Mean (N = 19)	0.018	0.021
Standard deviation	0.003	0.003
Coefficient of variation	0.15	0.16