Electronic Supplementary Information

# Design and evaluation of a portable $PM_{2.5}$ monitor featuring a low-cost sensor in line with an active filter sampler

Jessica Tryner, Casey Quinn, Bret C. Windom, and John Volckens

*Department of Mechanical Engineering, Colorado State University, Fort Collins, Colorado, USA*

## S1 Methods

### S1.1 Laboratory testing

All laboratory tests were conducted in the 0.75-$m^3$ aerosol chamber shown in Figure S1. When the MARS units were operated with a sample flow rate of 1.0 L·$min^{-1}$, the $PM_{2.5}$ cyclone described by Volckens et al.[1] was attached using the 3-D printed plastic adapter shown in Figure S2.

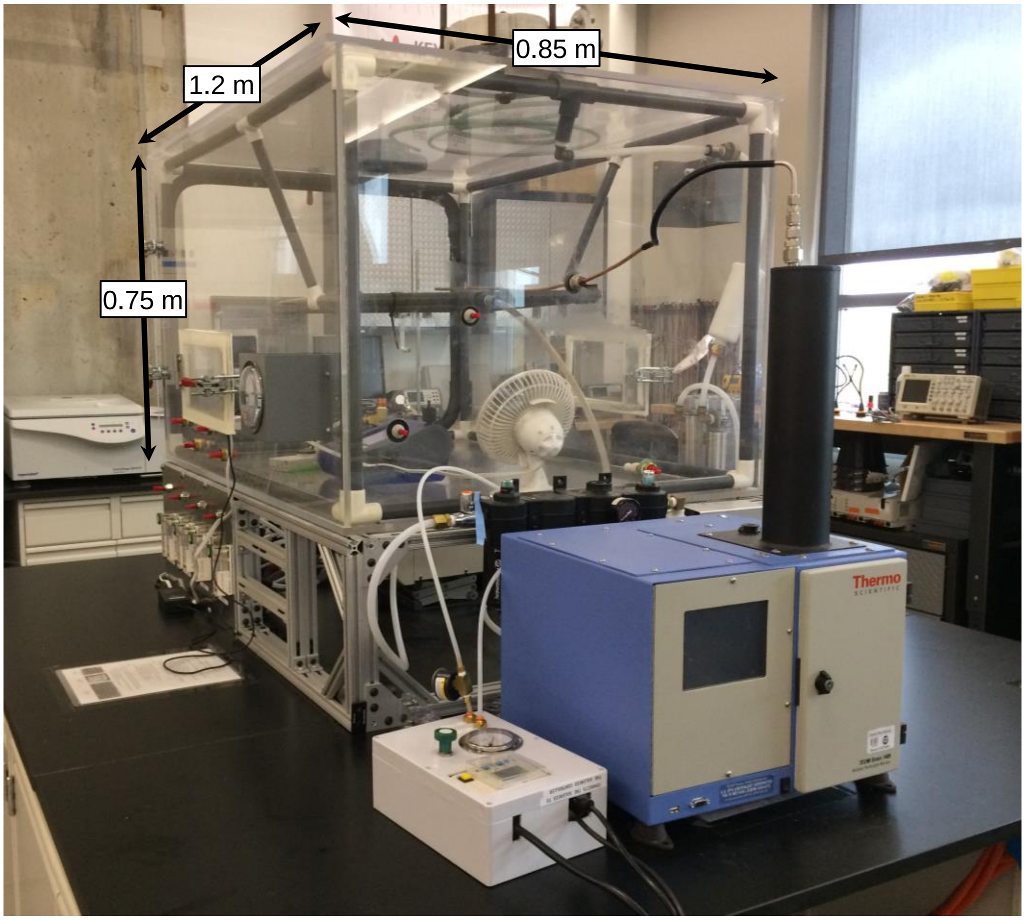


**Fig. S1** The aerosol chamber in which all laboratory tests were conducted. A continuous flow of dilution air entered the chamber through a series of 2.4-mm diameter holes in the plastic piping that runs along each edge of the chamber. Exhaust exited the chamber through a series of 4-mm diameter holes in the plastic piping that forms a ring in the center of the chamber. Air inside the chamber was mixed using the small white fan.

**Fig. S2** A photograph of the MARS with a 1 L·min$^{-1}$ cyclone attached via a plastic adapter.

The limit of detection (LOD) and limit of quantification (LOQ) for the 25-mm filter samples collected with the MARS sampling at 0.25 L·min$^{-1}$ were calculated from the change in mass of six handling blanks. Handling blanks were pre-weighed, loaded into cartridges, loaded into the MARS, removed from the MARS, removed from their cartridges, and post-weighed just as the sample filters were, but no air was sampled through the blanks.

The LOD and LOQ were calculated as:

$$LOD = \bar{x}_{blank} + 3s_{blank} \tag{S1}$$

$$LOQ = \bar{x}_{blank} + 10s_{blank} \tag{S2}$$

where $\bar{x}_{blank}$ was the average change in mass for the six blanks (0.5 $\mu$g) and $s_{blank}$ was the standard deviation of the change in mass for the six blanks (3.9 $\mu$g).

The uncertainty in the mass accumulated on each sample filter was taken to be the standard deviation of the mass accumulated on the six handling blanks ($s_{blank}$).

### S1.2 Field demonstration

Three MARS and six UPAS were deployed inside a personal residence in Fort Collins, Colorado, USA for one week (March 8–16, 2019). One MARS and two UPAS were placed in each of three locations inside the home: (1) near a home heating furnace that burned pine wood pellets, (2) in the kitchen, and (3) in the master bedroom (see Figure S3). The MARS sampled $PM_{2.5}$ onto a 25-mm diameter PTFE filter (PT25P-PF03, Measurement Technology Laboratories, Minneapolis, MN, USA) for gravimetric analysis. One UPAS sampled $PM_{2.5}$ onto a 37-mm diameter quartz filter (TISSUEQUARTZ 2500QAT-UP, Pall Corporation, Port Washington, NY, USA); the other UPAS sampled air through a $PM_{2.5}$ cyclone and a 37-mm diameter PTFE filter (PT37P-PF03, Measurement Technology Laboratories) followed by a 37-mm diameter quartz filter. Samples collected on quartz filters were subsequently analyzed for elemental and organic carbon using a Lab OC-EC Analyzer (Sunset Laboratories, Tigard, OR, USA).

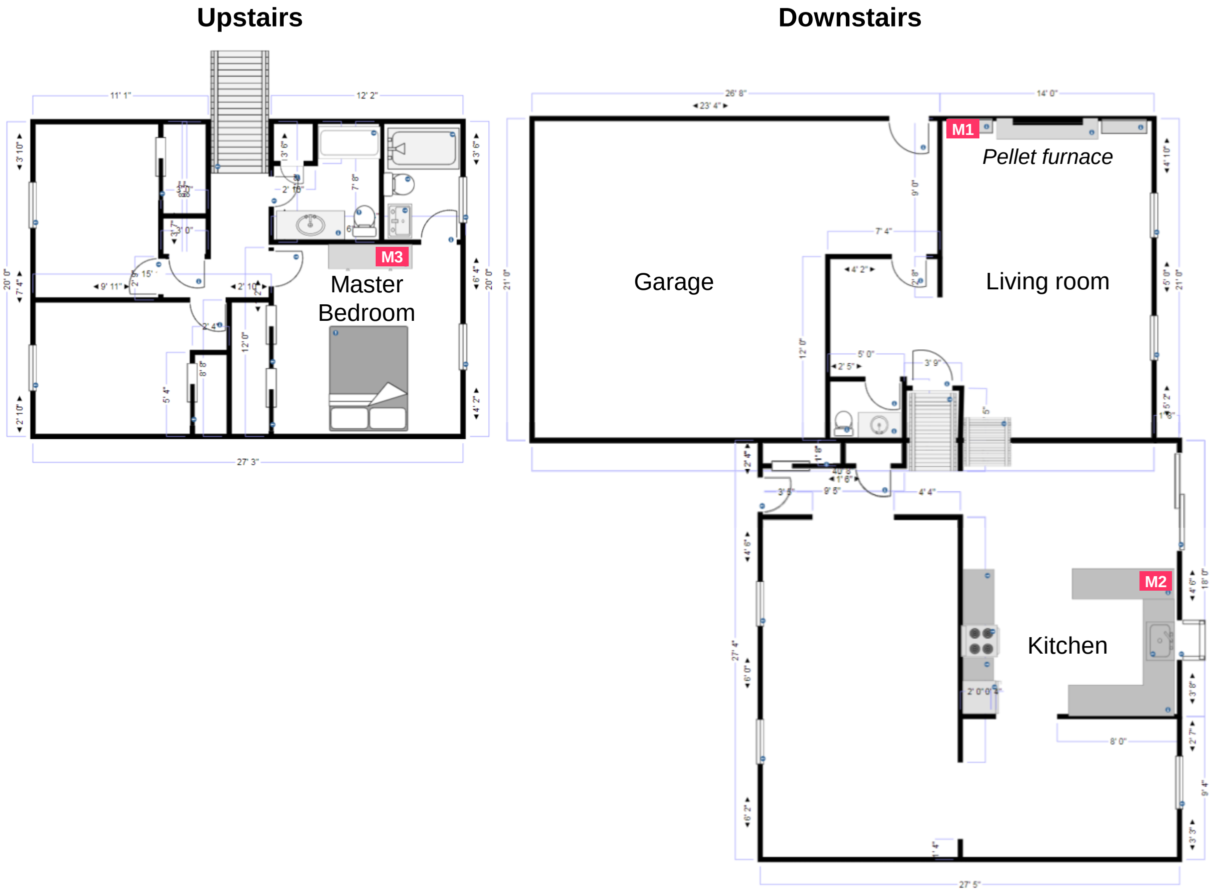


**Fig. S3** A floorplan of the residence illustrating locations of the three MARS units (labeled "M1", "M2", and "M3"). Each MARS was collocated with two UPAS. Note that the downstairs level of the residence was a split level.

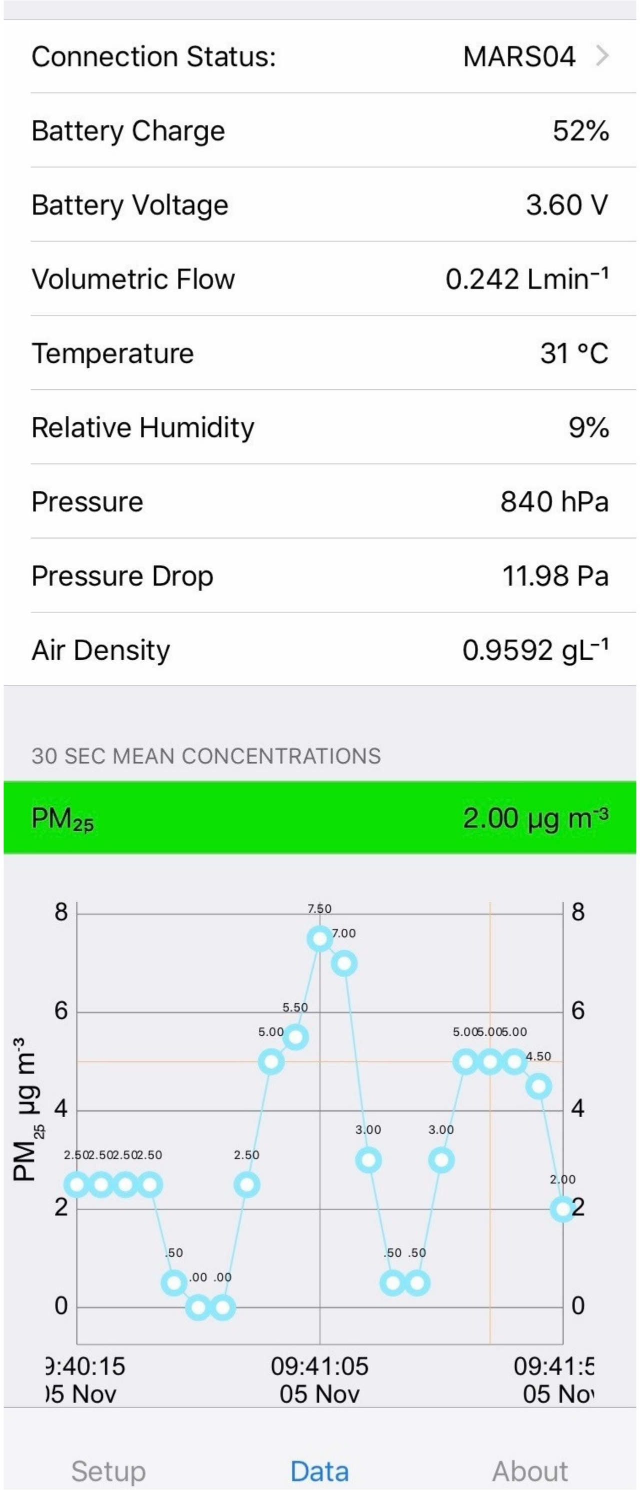
After post-weighing, the 25-mm PTFE filters were analyzed for sodium, magnesium, aluminum, silicon, sulfur, chlorine, potassium, calcium, titanium, chromium, manganese, iron, nickel, copper, zinc, gallium, arsenic, selenium, cadmium, indium, tin, tellurium, iodine, and lead using an energy-dispersive x-ray fluorescence spectrometer (ARL QUANT'X EDXRF, Thermo Fisher Scientific, Waltham, MA, USA). Each filter was analyzed at five different conditions. Each condition used different optical filters and x-ray power settings to analyze elements of interest with greater sensitivity. The quantitative mass concentration of each element was determined empirically using a linear standard curve. The Wintrace software was set to perform spectral peak calculations with XML. Deconvolution was assisted by importing peak profiles into the analysis method to designate peak beginning/end kV levels and account for spectral peak overlapping.

The standard curves used in the XRF analysis were generated from 30 calibration standards (Micromatter Inc., Montreal, Canada). The quality of the XRF analysis method was evaluated by analyzing standard PM filters (SRM 2783, National Institute of Standards Technology, Gaithersburg, MD, USA). The uncertainty for each measurement was calculated based on peak and background counts, and concentration values lower than two times the uncertainty were reported as below the limit of quantification.

# S2 Results

## S2.1 Design

A mobile application was developed to: (1) program the MARS prior to the start of sampling and (2) display the readings from the PMS5003 sensor in real time. The real-time display of MARS data on a smartphone is illustrated in Figure S4.



| | |
|---|---|
| Connection Status: | MARS04 > |
| Battery Charge | 52% |
| Battery Voltage | 3.60 V |
| Volumetric Flow | 0.242 Lmin$^{-1}$ |
| Temperature | 31 °C |
| Relative Humidity | 9% |
| Pressure | 840 hPa |
| Pressure Drop | 11.98 Pa |
| Air Density | 0.9592 gL$^{-1}$ |

30 SEC MEAN CONCENTRATIONS

$PM_{25}$ 2.00 µg m$^{-3}$

Fig. S4 The smartphone application screen used to display real-time MARS data.

## S2.2 Laboratory testing

### S2.2.1 Unmodified PMS5003 sensors

The relationship between the TEOM-reported $PM_{2.5}$ concentrations and the $PM_{2.5}$ CF=1 values reported by the unmodified PMS5003 sensors appeared linear over the range of concentrations tested (Figure S5). The $PM_{2.5}$ CF=1 values reported by the unmodified PMS5003 sensors correctly-estimated the concentration of NIST urban PM but underestimated the concentrations of ammonium sulfate, Arizona road dust, and match smoke (Table S1). Among the eight PMS5003 sensors tested, the mean gravimetric correction factor was 1.4 for ammonium sulfate, 1.7 for Arizona road dust, 1.0 for urban PM, and 1.5 for match smoke. In contrast, Bulot et al. reported that PMS5003 sensors installed outdoors in Southampton, UK tended to overestimate hourly ambient $PM_{2.5}$ concentrations, relative to concentrations reported by a TEOM installed 1 to 3 km away.[2] Sayahi et al. also reported that PMS5003 sensors installed outdoors in Salt Lake City, UT, USA overestimated hourly $PM_{2.5}$ concentrations, relative to concentrations reported by a collocated TEOM, during the winter (when the $PM_{2.5}$ composition was dominated by ammonium nitrate) and during wildfire season (when the $PM_{2.5}$ composition was dominated by organic carbon).[3]

**Table S1** Bias of and gravimetric correction factors for the test-averaged $PM_{2.5}$ concentrations reported by the unmodified Plantower PMS5003 sensors. Bias was calculated relative to the TEOM. Gravimetric correction factors were calculated relative to the average concentration derived from three replicate 16.7 L·min$^{-1}$ filter samples. Mean, minimum, and maximum values were calculated from the bias and gravimetric correction factor determined for each of the eight PMS5003 sensors tested.

| | Test-averaged bias relative to TEOM (%) | | | | Gravimetric correction factor | | | |
|---|---|---|---|---|---|---|---|---|
| | CF=1 | | ATM | | CF=1 | | ATM | |
| Aerosol | Mean | (Range) | Mean | (Range) | Mean | (Range) | Mean | (Range) |
| Ammonium sulfate | -26 | (-33, -20) | -50 | (-55, -46) | 1.4 | (1.3, 1.5) | 2.1 | (1.9, 2.3) |
| Arizona road dust | -36 | (-46, -29) | -56 | (-62, -51) | 1.7 | (1.5, 2.0) | 2.4 | (2.2, 2.8) |
| Urban PM | -9 | (-17, 0) | -38 | (-42, -32) | 1.0 | (1.0, 1.1) | 1.5 | (1.4, 1.6) |
| Match smoke | -33 | (-36, -31) | -55 | (-57, -53) | 1.5 | (1.4, 1.5) | 2.2 | (2.1, 2.3) |

Linear models fit to the TEOM-reported concentrations and the $PM_{2.5}$ CF=1 values shown in Figure S5 had coefficients of determination $\geq 0.97$ (Table S2); however, the F test identified a significant lack of fit between the data and the linear model for all three aerosols. Weighted residuals for each linear model are shown in Figure S7. Note that multiplying the $PM_{2.5}$ CF=1 concentrations by the average gravimetric correction factor calculated using Equation 6 does not correct for any nonlinearity that exists in the sensor response.

**Table S2** Coefficients for the linear models fit to the TEOM-reported $PM_{2.5}$ concentrations and the $PM_{2.5}$ CF=1 concentrations reported by unmodified Plantower PMS5003 sensors ($c_{CF1} = \beta_0 + \beta_1 c_{TEOM} + \varepsilon$). If F is greater than $F_{critical}$, there is a significant lack of fit between the data and the linear model ($\alpha = 0.05$).

| Aerosol | $\beta_0$ (95% CI) | $\beta_1$ (95% CI) | $R^2$ | F | $F_{critical}$ |
|---|---|---|---|---|---|
| Ammonium sulfate | -0.73 (-1.2 , -0.22) | 0.70 (0.68, 0.73) | 0.98 | 15.9 | 2.27 |
| Arizona road dust | -1.3 (-2.0 , -0.59) | 0.67 (0.64, 0.69) | 0.97 | 21.0 | 2.27 |
| Urban PM | 0.88 (-0.32, 2.1 ) | 0.98 (0.95, 1.0 ) | 0.99 | 11.5 | 2.27 |

The $PM_{2.5}$ ATM values reported by the unmodified PMS5003 sensors were equal to the $PM_{2.5}$ CF=1 values at concentrations below 30 $\mu$g·m$^{-3}$, but were lower than the $PM_{2.5}$ CF=1 values at concentrations above 30 $\mu$g·m$^{-3}$ (Figure S6). The $PM_{2.5}$ ATM values reported by the unmodified PMS5003 sensors underestimated the concentrations of all four aerosols (Table S1).

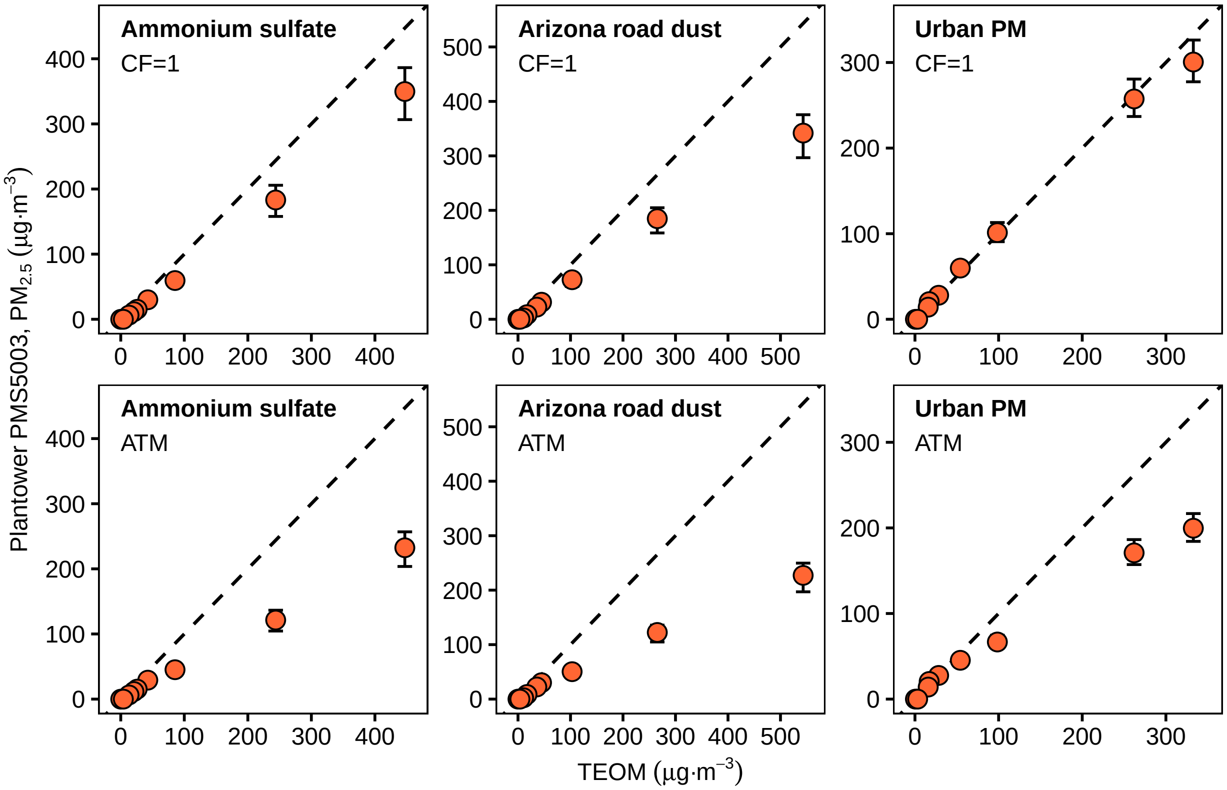


**Fig. S5** Comparisons of $PM_{2.5}$ concentrations measured by the TEOM and the unmodified PMS5003 sensors. Results are shown for both the $PM_{2.5}$ CF=1 and the $PM_{2.5}$ ATM concentrations reported by the PMS5003 sensors. Markers represent the mean and error bars represent the total range of concentrations reported by eight sensors.

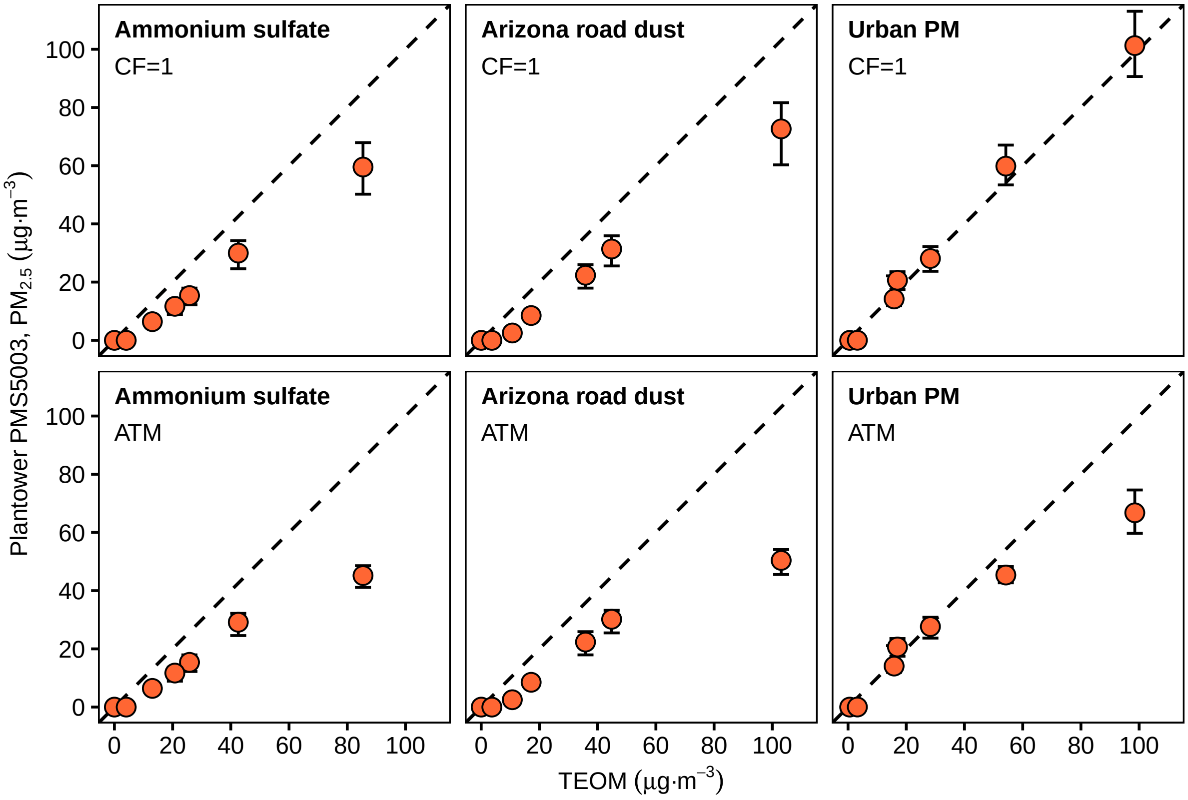


**Fig. S6** The results from Figure S5 shown over the range of 0 to 100 $\mu g \cdot m^{-3}$.

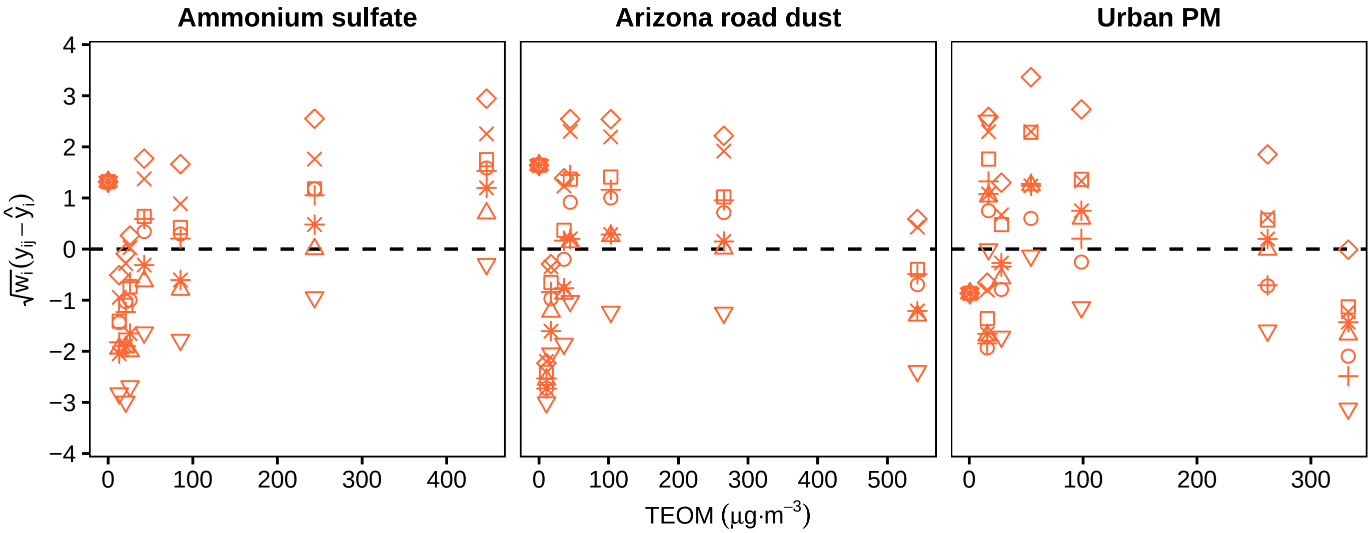


**Fig. S7** Weighted residuals for the linear models fit to the $PM_{2.5}$ concentrations reported by the TEOM and the $PM_{2.5}$ CF=1 concentrations reported by unmodified PMS5003 sensors. The eight different marker shapes represent the eight sensors tested.

### S2.2.2 MARS real-time sensors

When the MARS sampled at 0.25 L·min$^{-1}$, the relationship between the TEOM-reported $PM_{2.5}$ concentrations and the $PM_{2.5}$ CF=1 values reported by the PMS5003 sensor installed in the MARS appeared linear over the range of concentrations tested (Figure 3). Linear models (Equation 7) fit to the TEOM-reported concentrations and the corrected $PM_{2.5}$ CF=1 values shown in Figure 3 had coefficients of determination $\geq 0.97$ (Table S3); however, the F test identified a significant lack of fit between the data and the linear model for all three aerosols. Weighted residuals for these linear models are shown in Figure S8.

**Table S3** Coefficients for the linear models fit to the TEOM-reported $PM_{2.5}$ concentrations and the filter-corrected $PM_{2.5}$ CF=1 concentrations reported by the MARS real-time sensors ($CF_{CF1} \cdot c_{CF1} = \beta_0 + \beta_1 c_{TEOM} + \varepsilon$). If F is greater than $F_{critical}$, there is a significant lack of fit between the data and the linear model ($\alpha = 0.05$).

| Flow rate (L/min) | Aerosol | $\beta_0$ (95% CI) | $\beta_1$ (95% CI) | $R^2$ | F | $F_{critical}$ |
|---|---|---|---|---|---|---|
| 0.25 | Ammonium sulfate | -5.6 (-6.0, -5.1) | 0.82 (0.77, 0.88) | 0.98 | 16.0 | 2.96 |
| 0.25 | Arizona road dust | 0 (-0.003, 0.003) | 0.77 (0.72, 0.82) | 0.98 | 5.51 | 2.45 |
| 0.25 | Urban PM | -0.31 (-0.33, -0.28) | 0.76 (0.70, 0.81) | 0.97 | 7.64 | 2.58 |
| 1.00 | Ammonium sulfate | -1.8 (-3.0, -0.60) | 1.3 (1.2, 1.3) | 0.99 | 18.7 | 2.74 |
| 1.00 | Arizona road dust | -0.004 (-0.033, 0.026) | 0.93 (0.88, 0.99) | 0.98 | 67.9 | 2.74 |
| 1.00 | Urban PM | -0.69 (-0.75, -0.63) | 1.2 (1.1, 1.3) | 0.97 | 44.3 | 2.74 |

When the MARS sampled at 1.0 L·min$^{-1}$, the relationship between the TEOM-reported $PM_{2.5}$ concentrations and the $PM_{2.5}$ CF=1 values reported by the PMS5003 sensor installed in the MARS began to appear nonlinear (Figure 4). Linear models fit to the TEOM-reported concentrations and the corrected $PM_{2.5}$ CF=1 values shown in Figure 4 had coefficients of determination $\geq 0.97$ (Table S3); however, the F test identified a significant lack of fit between the data and the linear model for all three aerosols. Weighted residuals for these linear models are shown in Figure S9.

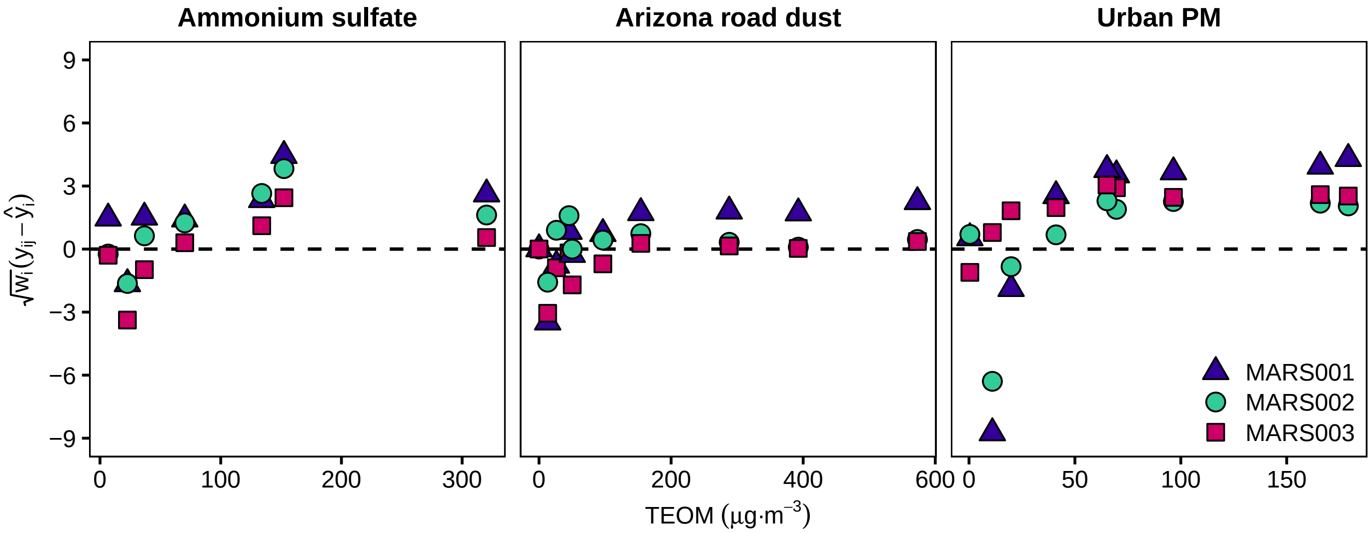


**Fig. S8** Weighted residuals for the linear models fit to the $PM_{2.5}$ concentrations reported by the TEOM and the filter-corrected $PM_{2.5}$ CF=1 concentrations reported by the PMS5003 sensors inside the MARS units. These data were collected with the MARS sampling at 0.25 L·min$^{-1}$.

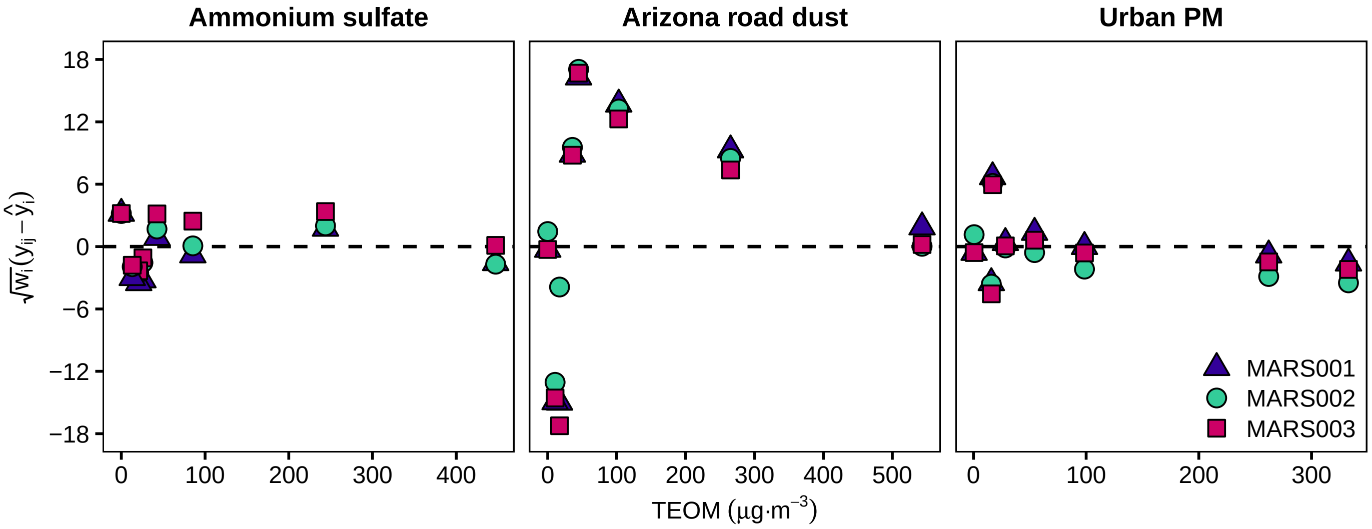


**Fig. S9** Weighted residuals for the linear models fit to the $PM_{2.5}$ concentrations reported by the TEOM and the filter-corrected $PM_{2.5}$ CF=1 concentrations reported by the PMS5003 sensors inside the MARS units. These data were collected with the MARS sampling at 1.0 L·min$^{-1}$.

When the MARS sampled at 0.25 L·min$^{-1}$, the $PM_{2.5}$ ATM values reported by the real-time sensor were equal to the $PM_{2.5}$ CF=1 values at concentrations below approximately 45 $\mu$g·m$^{-3}$, but were lower than the $PM_{2.5}$ CF=1 values at concentrations above 45 $\mu$g·m$^{-3}$. The $PM_{2.5}$ ATM values reported by the MARS real-time sensor underestimated the concentrations of all four aerosols (Figure S10 and Table 1). Gravimetric correction factors for the $PM_{2.5}$ ATM values are shown in Table 1; however, caution should be exercised in applying these factors due to the clear nonlinear relationship between the TEOM-reported concentrations and the $PM_{2.5}$ ATM values (Figure S10).

The relationship between the TEOM-reported $PM_{2.5}$ concentrations and the $PM_{2.5}$ ATM values reported by the PMS5003 sensor installed in the MARS remained nonlinear at the 1.0 L·min$^{-1}$ sample flow rate (Figure S11). When the MARS sampled at 1.0 L·min$^{-1}$, the $PM_{2.5}$ ATM values reported by the PMS5003 sensor typically underestimated the TEOM-reported $PM_{2.5}$ concentrations. Gravimetric correction factors for the $PM_{2.5}$ ATM values are shown in Table 1.

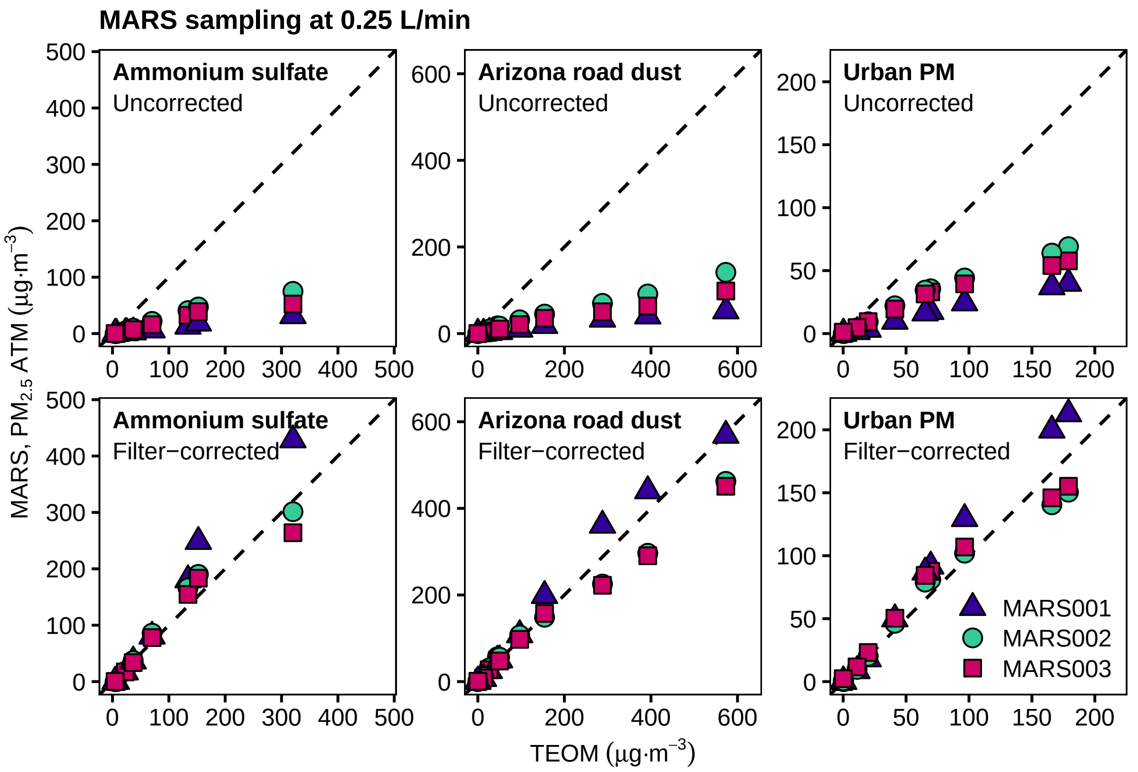


**Fig. S10** Comparisons of PM$_{2.5}$ concentrations measured by the TEOM and the MARS (with the latter sampling at 0.25 L·min$^{-1}$). The PM$_{2.5}$ ATM concentrations reported by the real-time PM sensor in the MARS are shown before (“Uncorrected”) and after (“Filter-corrected”) correction to the MARS filter sample.

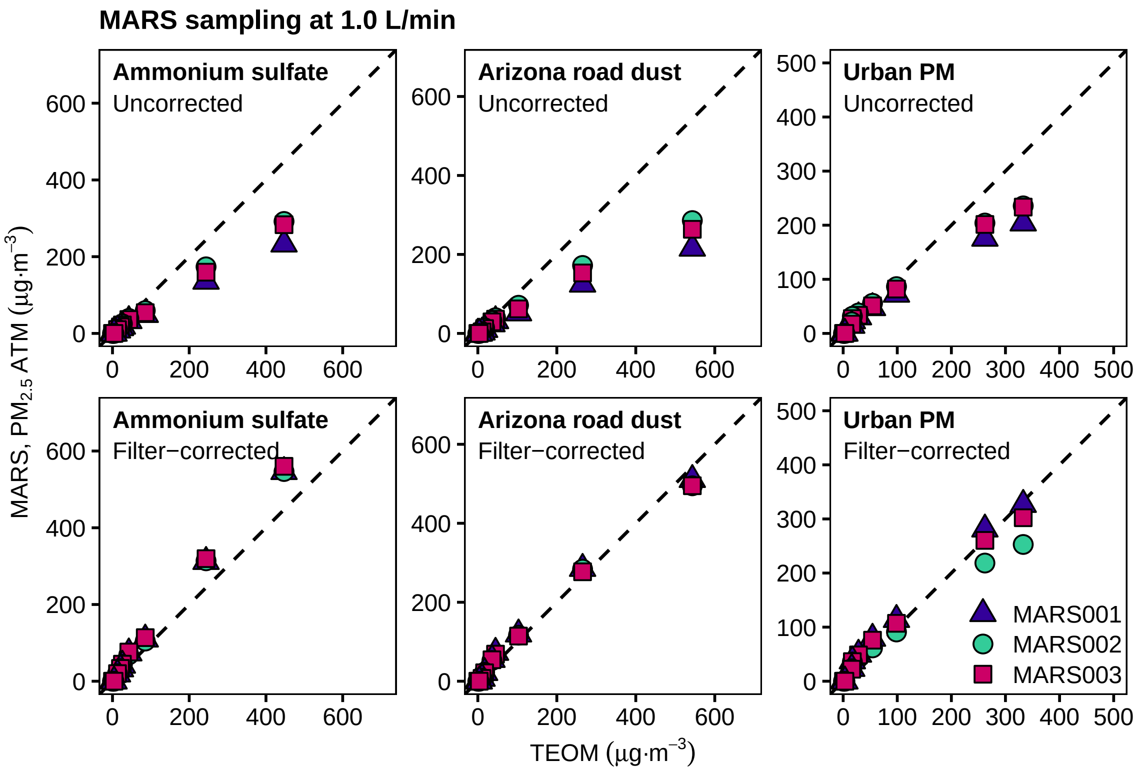


**Fig. S11** Comparisons of PM$_{2.5}$ concentrations measured by the TEOM and the MARS (with the latter sampling at 1.0 L·min$^{-1}$). The PM$_{2.5}$ ATM concentrations reported by the real-time PM sensor in the MARS are shown before (“Uncorrected”) and after (“Filter-corrected”) correction to the MARS filter sample.

### S2.3 Field demonstration

The filter-corrected real-time $PM_{2.5}$ concentrations shown in Figure 5 are also shown in Figure S12.

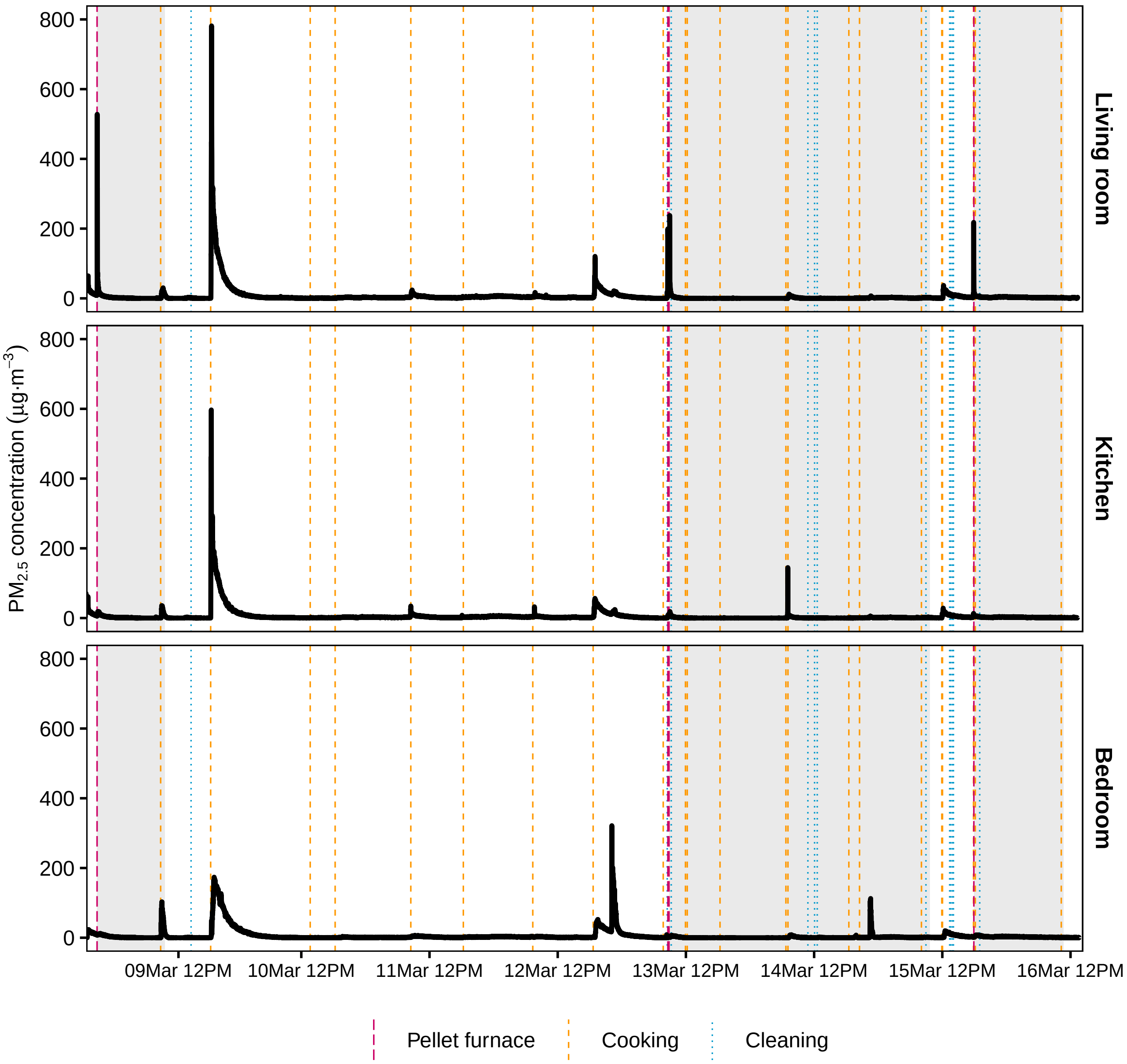


**Fig. S12** Filter-corrected real-time $PM_{2.5}$ CF=1 concentrations measured in the living room (near the pellet furnace), in the kitchen, and in the bedroom by the MARS monitors. Dashed vertical lines correspond to pellet furnace start-up, cooking events, and cleaning activities logged by home occupants. The gray background represents times when the pellet furnace blower was on.

## Notes and references

1 J. Volckens, C. Quinn, D. Leith, J. Mehaffy, C. S. Henry and D. Miller-Lionberg, Development and evaluation of an ultrasonic personal aerosol sampler, *Indoor Air*, 2017, **27**, 409–416.

2 F. M. J. Bulot, S. J. Johnston, P. J. Basford, N. H. C. Easton, M. Apetroaie-Cristea, G. L. Foster, A. K. R. Morris, S. J. Cox and M. Loxham, Long-term field comparison of multiple low-cost particulate matter sensors in an outdoor urban environment, *Scientific Reports*, 2019, **9**, 7497.

3 T. Sayahi, A. Butterfield and K. E. Kelly, Long-term field evaluation of the Plantower PMS low-cost particulate matter sensors, *Environmental Pollution*, 2019, **245**, 932–940.