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Supplement of

The next generation of low-cost personal air quality sensors for quantitative exposure monitoring

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Supplementary Information for "The next generation of low-cost personal air quality sensors for quantitative exposure monitoring"

1.1. Fresh versus aged MOx results

Results from the 2nd co-location period in January showed better agreement with the reference monitors for CO and O_3, likely due to the replacement of the aged MOx sensors with fresh ones. Median standard errors among the M-Pods during the 2nd co-location were 0.28 ppm for CO (range 0.27-0.31 ppm), and 4.0 ppb for O_3 (range 3.3-4.2 ppb). These values compare favorably to the December co-location's median standard errors of 0.44 ppm (range 0.38-0.54 ppm) and 6.4 ppb (range 4.4-15.4 ppb) for CO and O_3. The fit with NO_2 was very similar to the first co-location, with median standard error of 8.8 ppb (range 5.4-9.0 ppb). Similarly, correlations among all M-Pods were higher than in the first co-location, with median CO, NO_2, and O_3 correlations of 0.94, 0.89, and 0.98, respectively. Fig. S1 shows an example time series for CO using Equation 3. During this co-location 6 M-Pods were used, although one did not provide data due to a faulty power connection.

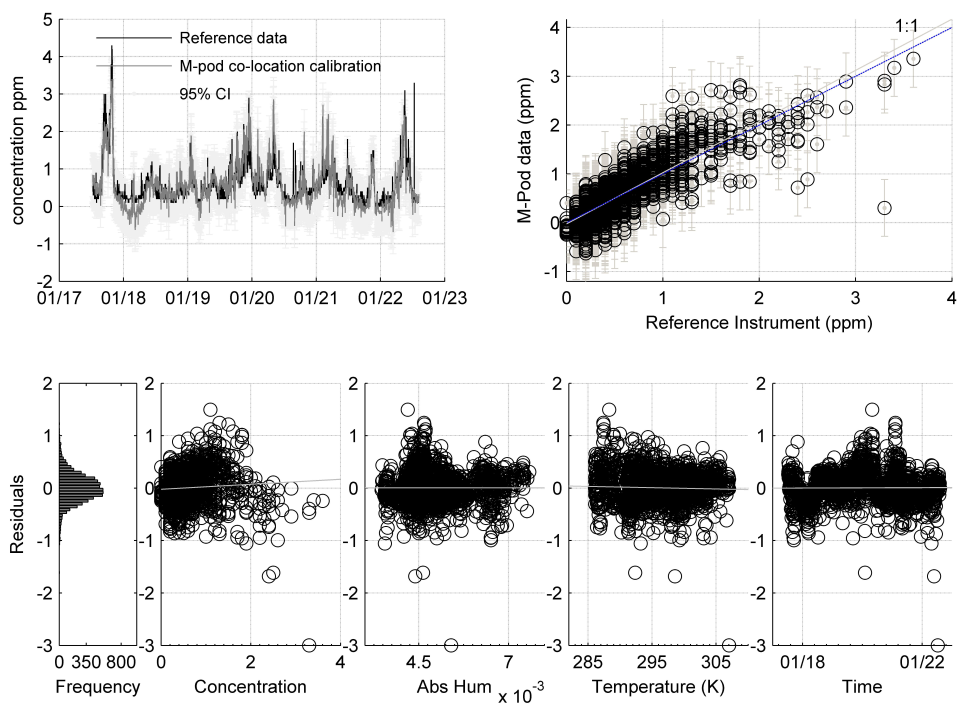

Figure S1 Comparison of CO measurements from the reference monitor and M-Pod 19 during the co-location in January 2013.

1.2. MOx Sensor Drift

Linear drift correction (Haugen et al., 2000) was found to modestly improve the performance of all sensors during the co-location calibrations (Table 1), and during the user study portion (Table S1). The CO and NO_2 sensors generally exhibited drift corresponding with increasing sensor resistance over time. Reversible and irreversible binding of gas molecules to sensor surfaces have been discussed in past works, and could increase sensor resistance due to removal of free electrons from the lattice. This would effectively remove a surface site from having the ability to interact with the target gas. However, adding a model term that allowed for flexibility in span over time did not improve the fit, and there appeared to be no significant changes in sensitivity of the sensors over the course of the experiment, though that may be a concern in longer-term use.

Temporal sensor drift was found to affect the results more during the user study than the co-location calibrations, likely due to exposing the sensors to diverse pollutants and environments, accelerating aging and increasing irreversible binding frequency. This drift was compensated for using a linear correction, but as others have found (Romain et al., 2010), the drift has a stochastic component and is difficult to predict. Performing an additional co-location, we found substantial drift in the direction opposite from which it had previously been drifting, possibly due to a "recovery" period, since the M-Pods were in a clean lab environment between those two calibrations.

1.3. Lab calibration procedure

Laboratory calibrations were performed within a Teflon coated chamber, or inside a small customized refrigerator. In both cases, a specially made carousel (Fig. S2) was used to hold the M-Pods in place to receive uniform and consistent airflow.

Figure S2 The carousel used to hold up to 12 M-Pods during calibration. The gas mixture is fed in through the Swagelock fitting in the middle of the lid. The hole to the left of the fitting is for a temperature and humidity probe that provides feedback to the control system. The M-Pod inlet holes are placed facing the center to receive the gas sample directly from the source.

An example calibration time series and calibration surface for CO is presented below in Fig. S4 to illustrate the typical behavior in the calibration chamber.

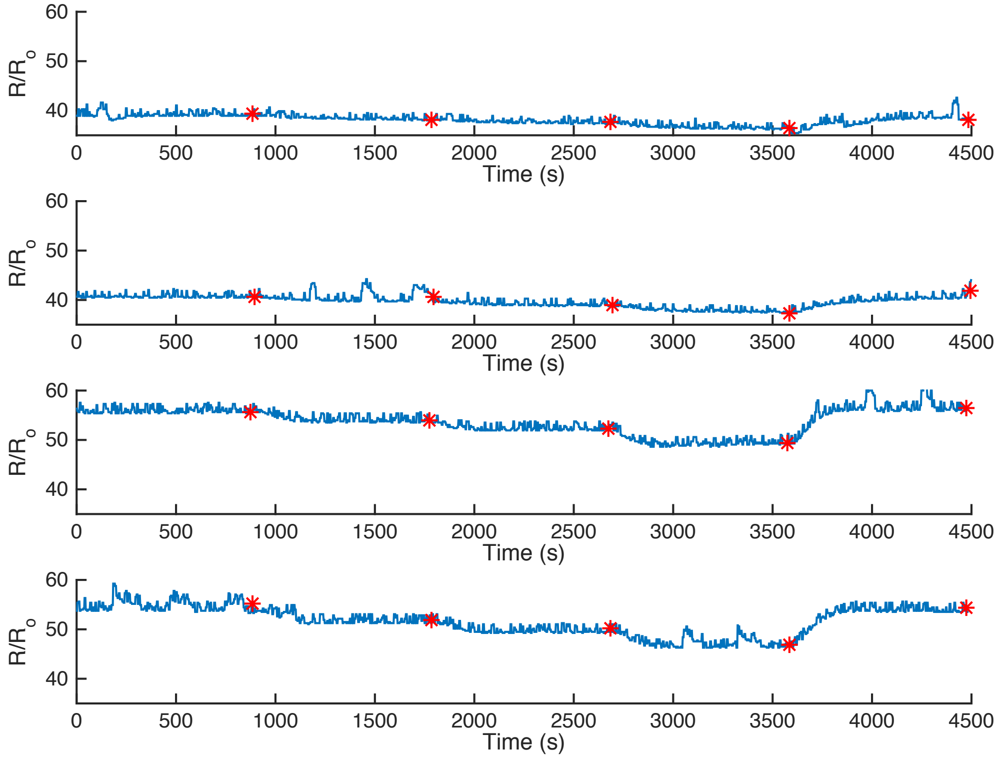

Figure S3 Calibration time series for the SGX-5525 CO sensor from M-Pod 19. Concentration steps for the shown data were 0.0-1.0-2.0-4.2 ppm. Red points are the selected steady state values, and the data is shown without averaging or filtering. Two humidity levels and two temperature levels were used for this calibration.

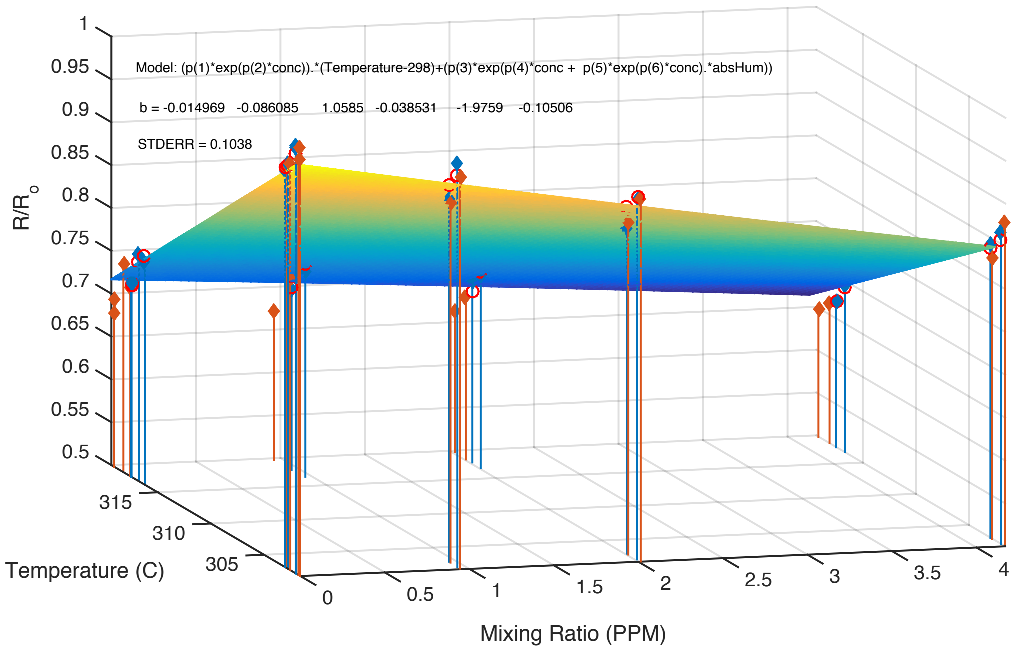

Figure S4 The calibration surface generated using the calibration function from Eq. 1. Blue points are measured R/R_o values, while red points are the fitted concentrations.

1.4. User Study Results

Table S1 shows summary statistics. Median CO and CO_2 exposure were 0.58 ppm and 949.0 ppm, respectively. Median O_3 exposure was 14.0 ppb, and Fig. S5 has an example histogram and time of day trend plot for a user's O_3 exposure.

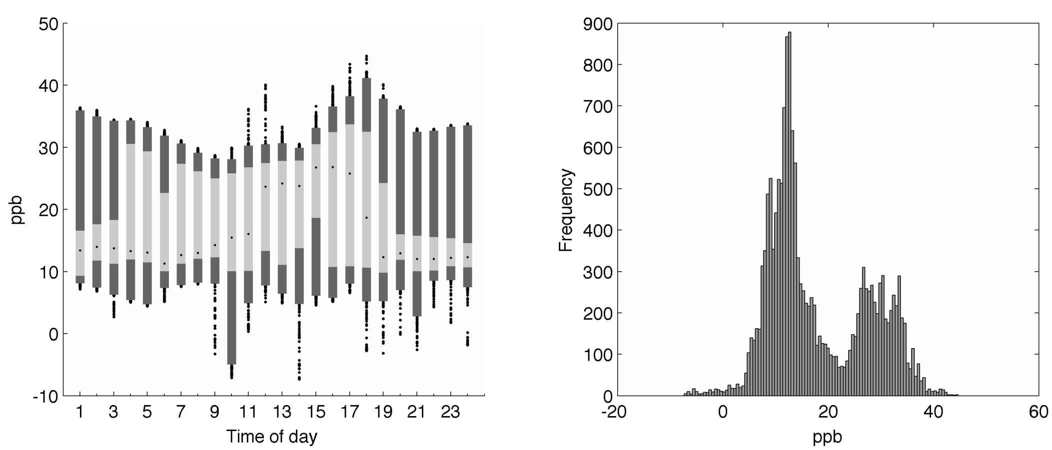

Figure S5 Time of day trend and histogram for O_3 from M-Pod 23.

	CO [ppm]										
	% logged/ possible	%used/ logged	N	mean	std	med	5th %	95%	R^2	Drift ppm/day	s/n
M-Pod 4	46.7%	88.1%	17107	0.52	0.62	0.37	-0.14	1.76		1.63	1.63
M-Pod 6	29.0%	79.8%	10595	0.47	1.30	0.48	-0.66	2.18	0.48	1.52	1.52
M-Pod 9	19.7%	84.5%	7214	1.26	0.68	1.27	0.11	2.17		7.18	7.18
M-Pod 15	23.8%	85.3%	8710	8.83	1.27	8.90	6.47	10.59	0.50	6.09	6.09
M-Pod 16	28.2%	86.4%	10308	1.54	0.60	1.54	0.51	2.48		4.58	4.58
M-Pod 17	32.3%	50.8%	11816	-0.15	0.53	-0.14	-0.97	0.74		-0.36	-0.36
M-Pod 20	0.0%	0.1%									
M-Pod 23	44.6%	89.3%	16322	0.77	0.57	0.68	0.04	1.78	0.76	2.71	2.71
M-Pod 25	41.3%	80.4%	15097	0.34	0.78	0.21	-0.59	1.78		1.22	1.22
Median	29.0%	84.5%	11206	0.64	0.65	0.58	-0.05	1.98	0.50	1.63	1.63

	O3 [ppb]									
	% logged/ possible	%used/ logged	N	mean	std	med	5th %	95%	R^2	Drift ppm/day
M-Pod 4	46.7%	75.5%	17107	32.7	12.5	33.4	14.4	53.6		1.4
M-Pod 6	29.0%	79.8%	10595	14.6	13.7	12.3	-2.1	44.2	0.35	0.0
M-Pod 9	19.7%	84.5%	7214	32.8	15.6	31.3	11.7	55.2		-0.5
M-Pod 15	23.8%	68.4%	8710	15.4	18.3	17.5	-11.2	43.2	0.04	2.0
M-Pod 16	28.2%	52.1%	10308	31.8	5.5	31.6	23.7	43.4		-0.5
M-Pod 17	32.3%	50.8%	11816	10.2	6.0	9.7	3.0	21.0		0.2
M-Pod 20	17.1%	48.5%	6265	-48.4	28.2	-53.7	-79.6	11.3		-2.6
M-Pod 23	44.6%	89.3%	16322	17.9	9.4	14.0	6.5	34.2	0.24	0.2
M-Pod 25	41.3%	73.0%	15097	-14.1	35.2	-8.1	-77.6	43.8		-1.3
Median	29.0%	73.0%	10595	15.4	13.7	14.0	3.0	43.4	0.24	0.0

	NO2 [ppb]										
	% logged/ possible	%used/ logged	N	mean	std	med	5th %	95%	R^2	Drift ppm/day	s/n
M-Pod 4	46.7%	88.1%	17107	69.0	9.5	68.7	54.2	83.3		-0.1	6.3
M-Pod 6	29.0%	79.8%	10595	48.7	29.2	45.5	-12.3	86.0	0.88	0.2	4.0
M-Pod 9	19.7%	84.5%	7214	58.7	37.0	60.1	2.8	112.0		-1.6	11.1
M-Pod 15	23.8%	85.3%	8710	84.6	16.1	81.2	68.7	112.9	0.90	0.5	9.1
M-Pod 16	28.2%	86.4%	10308	84.2	14.5	81.7	68.8	107.6		0.2	9.5
M-Pod 17	32.3%	50.8%	11816	63.4	13.7	61.9	47.7	88.1		0.4	6.0
M-Pod 20	17.2%	30.5%	6283	30.1	17.7	33.3	0.6	51.9		2.3	4.6
M-Pod 23	44.6%	89.3%	16322	50.4	14.2	54.3	25.6	69.7	0.90	0.0	6.3
M-Pod 25	41.3%	81.8%	15097	50.6	11.4	54.1	30.5	62.9		0.3	6.1
Median	29.0%	84.5%	10595	58.7	14.5	60.1	30.5	86.0	0.90	0.2	6.3

	CO2 [ppm]									
	% logged/ possible	%used/ logged	N	mean	std	med	5th %	95%	R^2	Drift ppm/day
M-Pod 4	48.6%	97.7%	17783	1108.6	367.2	1123.7	492.0	1772.2		-0.3
M-Pod 6	29.8%	92.3%	10910	902.3	544.5	807.8	374.9	1893.3	0.45	-2.1
M-Pod 9	19.1%	80.8%	6986	965.6	863.0	1059.9	-447.6	2364.2		74.5
M-Pod 15	23.9%	85.2%	8764	365.2	767.3	267.8	-355.0	1364.0	0.33	0.2
M-Pod 16	28.2%	86.6%	10325	644.2	211.9	591.8	450.5	1139.3		3.1
M-Pod 17	33.2%	39.1%	12135	1048.6	437.7	1047.4	444.9	1795.9		-4.2
M-Pod 20	17.3%	64.7%	6344	2047.3	1765.8	1589.0	509.2	6172.5		1.4
M-Pod 23	43.1%	86.4%	15774	572.1	512.2	444.3	63.5	1874.2	0.92	0.4
M-Pod 25	43.1%	90.3%	15787	949.0	587.9	771.0	417.5	2503.3		-0.8
Median	29.8%	86.4%	10910	949.0	544.5	807.8	417.5	1874.2	0.4	0.2

Table S1 Personal exposure summary statistics using the model in Eq. 3. Similarly shaded rows indicate paired M-Pods.

To illustrate the available data, and the typical signal responses from the M-Pod sensor, we have included a time series of a typical day of data, shown in Fig. S6. In addition to the shown data, is GPS data, and combined with the sensor data, there is a substantial amount of further exploration that could be performed with this, or similar, data sets.

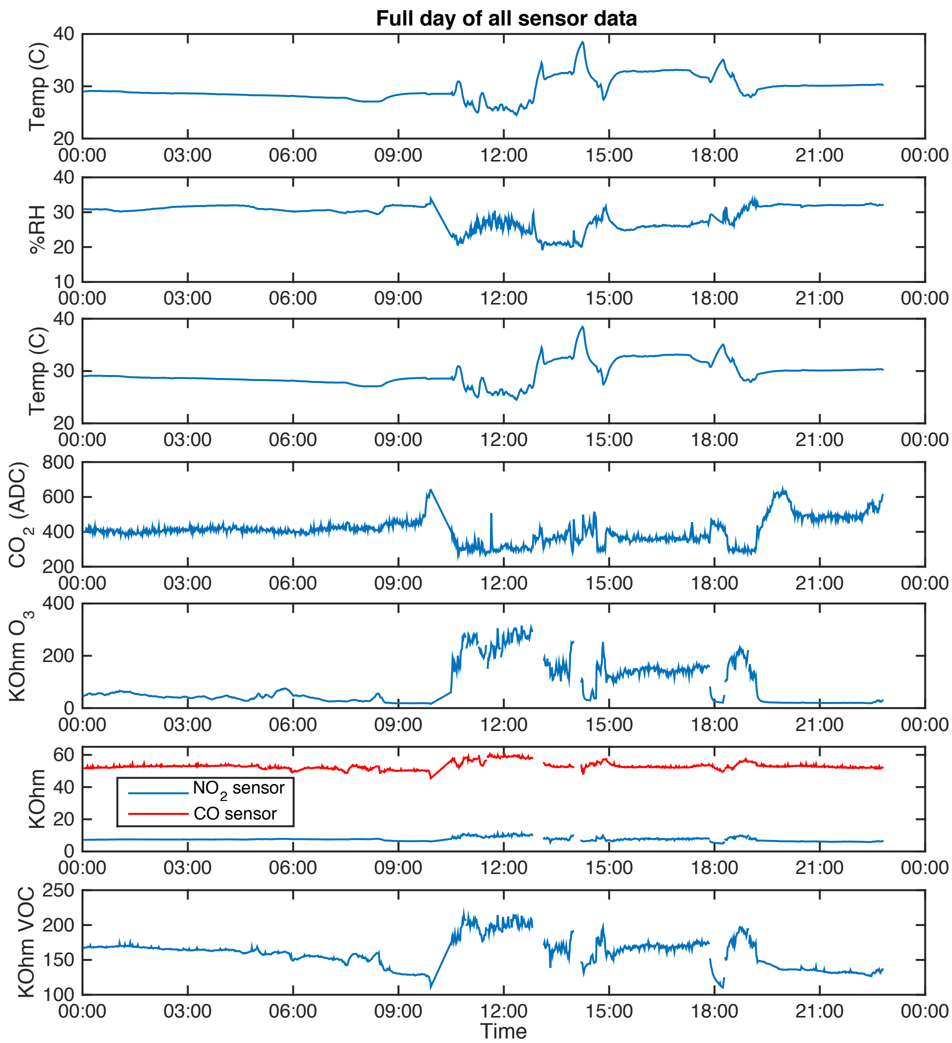

Figure S6 A typical day of data from M-Pod 6. Simple behaviors and activities can often be surmised by inspecting the time series, like the wake up time just after 8:00 AM, and the commute beginning at 10:00 AM. This data has been filtered for noise, thus the occasional gaps in data.

1.5. User study discussion

The user study data was meant as a validation trial for the instruments, and should not be compared with the highest quality personal exposure data. Users were asked to wear the monitors as much as possible, but compliance was not measured. Users were all members of the Hannigan lab, due to their willingness to cooperate, and ease of frequent equipment transferring and calibration. Median data collection rates for the sensors in the M-Pods were 29%

over the course of the user study (ranged from 0-48.6%), as some users wore them much less than others, and in one case a sensor failed for the duration of the study. Of the collected data, the median data remaining for analysis after filtering was 73.0-84.5%. The user study provided valuable insight and promoted changes in behavior of some participants. Users reported being more aware of 'stuffiness', and acted based on their data by opening windows to increase air exchange rates in their homes. They also noted increases in CO_2, CO, and NO_2 during driving, leading them to experiment with the best way to reduce exposures. One user experienced elevated nighttime CO_2 and NO_2. CO_2 levels often increase at night in rooms with little ventilation, and can lead to restlessness. NO_2 levels increase due to combustion, and in this case the use of the natural gas furnace on these cold winter nights could have increased personal NO_2 exposure substantially. With this kind of readily available concentration data, users can then adjust their behavior to reduce night time exposures.

Temporal trends generally showed higher concentrations in the morning and evening for CO and NO_2, coinciding with commute-time increases in ambient concentrations. O_3 trends followed expected outdoor patterns, peaking in the afternoon in most cases. CO_2 trends generally showed nighttime increases. The distributions had a distinct 'fresh air' mode, near ambient concentrations, and an indoor mode with a heavy tail. For other pollutants, exposure probability density function distributions varied substantially, likely due to exposure variability based on individual user behavior. One user's overnight use of a wood-fired stove is evident with increased nighttime CO exposure and a wider distribution than that of other users. Most other CO distributions were quite narrow, though slightly right-skewed. The NO_2 distributions varied between right-skewed distributions for four M-Pods, and bi-modal distributions for the other five M-Pods. These modes appear to be driven by daily differences in NO_2 exposure rather than indoor/outdoor differences.

Some users did not carry and charge their M-Pods as fastidiously as others. This may have contributed to episodes of strange sensor behavior due to low power operation. Generally, the air quality encountered was perceived to be good, based on user reports and the good regional air quality (CDPHE, 2012), and this may have diminished the perceived value of the M-Pod measurements. Unfortunately, one M-Pod from each of two of the M-Pod pairs appears to have had persistent power issues, either due to faulty batteries, or a voltage regulator operating to close to its specification limits, and therefore unable to meet the peak current demand (300mA) of the CO_2 sensor. Although the regulator is rated for 2A output at 5V, we have found that the quick peak can make the voltage sag momentarily. This would explain the low number of samples relative to their respective pairs, and worse sensor behavior during calibration. These sensors can also demonstrate substantial inter-sensor variability, which may have contributed as well.

A study shortcoming was the inability to wear reference monitors in addition to the M-Pods. This was illustrated with curiously high NO_2 concentrations, indicating that there may be problems we are not accounting for. Despite such potential issues, concentration changes near busy roadways are often apparent, showing the sensitivity and fast response of the sensors, valuable for source and trend identification.