# Development and evaluation of a lightweight sensor system for aerial emission sampling from open area sources

**Extended Abstract #40**

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## INTRODUCTION

A new sensor system for mobile and aerial emission sampling was developed for open area pollutant sources, such as prescribed forest burns. The sensor system, termed "Kolibri", consists of multiple low-cost air quality sensors measuring $CO_2$, CO, samplers for particulate matter with diameter of 2.5 μm or less ($PM_{2.5}$), and volatile organic compounds (VOCs). The Kolibri is controlled by an Arduino-based motherboard which can record and transfer data in real time through an Xbee radio module. Selection of the sensors was based on laboratory testing for accuracy, response delay, cross-sensitivity, and precision. The Kolibri was compared against continuous emission monitors (CEMs) and another sampling instrument (the "Flyer") that had been used in over ten open area pollutant sampling events. Our results showed that the time series of CO and $CO_2$ concentration and the $PM_{2.5}$ measured by the Kolibri agreed well with those from the CEMs and the Flyer. The emission factors of VOCs derived using the Kolibri are comparable with existing literature values. In the future, the Kolibri system can be applied to various open area sampling challenge such as fires, lagoons, flares, and landfills.

## METHODS

A new sensor system was designed to measure CO, $CO_2$, $PM_{2.5}$ and VOC. Three major factors ranked by importance determined our selection of sensor parts: feasibility, quality, and cost. We first found sensors that would fit a specific load limit (both weight and size) and excluded sensors with high power consumption which would increase the onboard battery weight and shorten the sampling duration. Then we evaluated the performance of some light-weight and power-efficient sensors in our laboratory. Sensor accuracy, precision, and response delay were quantified against benchmark equipments. Lastly, we chose the least-expensive sensor when both feasibility and quality criteria were satisfied.

We selected a non-dispersive infrared (NDIR) gas analyzer (DX6220) for $CO_2$ measurement, manufactured by RMT Ltd (Moscow, Russia). It has a measurement range of 0-20% and a rated accuracy of less than 1% of reading. Temperature and pressure effects are compensated based on the ideal-gas law using built-in temperature and pressure sensors.
We used an electrochemical (EC) sensor for CO measurement, which either oxidize or reduce the contacting gas at an electrode and produces an electrical current with magnitude linearly proportional to the gas concentration.[1] EC sensors have low cross-sensitivity with interfering gases and low power consumption, however, they are relatively expensive ($50 to $100 USD) and need more complicated measurement circuitry. In this study, we used an EC sensor (EC4-500-CO from SGX Sensortechm, Essex, UK) with a self-designed amplify circuit compatible with our datalogger.

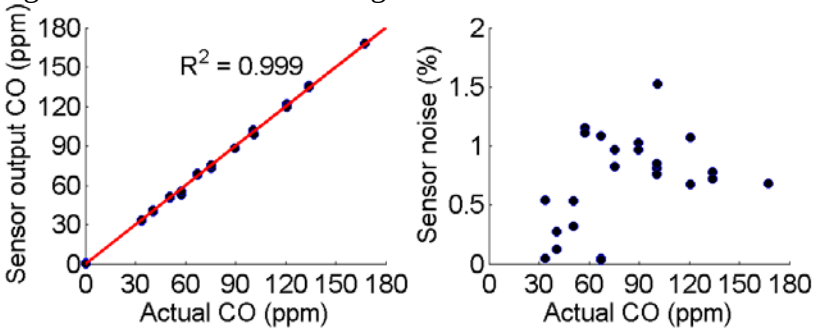
$PM_{2.5}$ was sampled using a small and light-weight sampler (personal environmental monitor from SKC, Eighty Four, USA) including an inertial impactor operating at a constant pump flow rate of 10 L/min. The sampler contained a 37 mm diameter Polytetrafluoroethylene (PTEF) filter with a pore size of 2.0 µm. The $CO_2$ concentration served as an indicator of combustion pollutants, triggering on (off) a micro air pump (Sensidyne Inc., St. Petersburg, USA) when the $CO_2$ concentration was higher (lower) than a user-specified value. When the pump was running, a control board was used to maintain the 10 L/min required flow rate by the sampler.

VOCs were sampled using a Tenax sorbent tube (Tenax TA 35/60 from Supelco, Bellefonte, USA) which is designed specifically for trapping certain VOCs and semi-VOCs. A small pump (Sensidyne Inc., St. Petersburg, USA) is used to maintain a flow rate of 0.25 L/min through the Tenax tube. The Tenax tube is analyzed for certain VOCs by gas chromatography and mass spectrometer after sampling.

## RESULTS

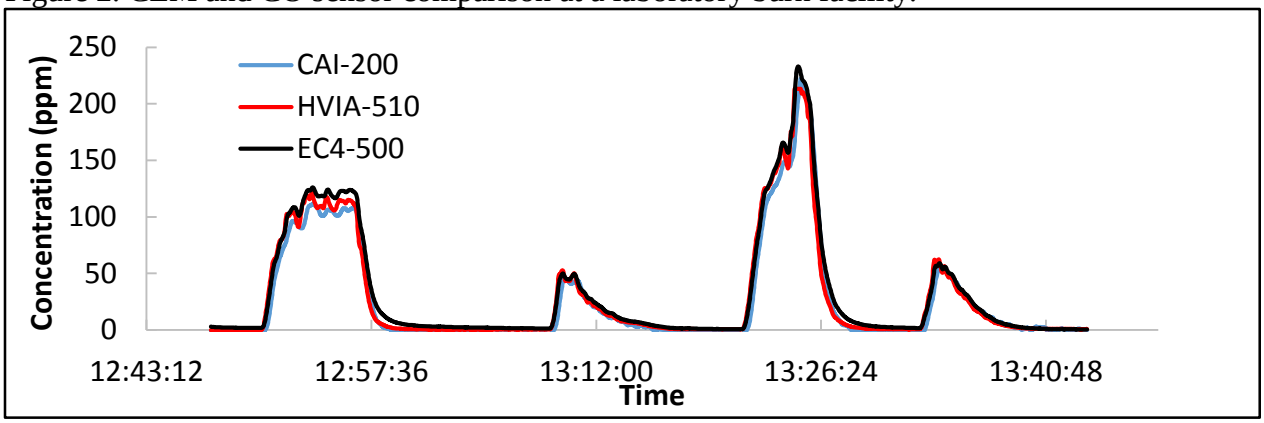
The accuracy and precision of the selected CO sensor was quantified based on several laboratory tests using supplied calibration gas (Fig. 1). After calibration, the sensor showed a very high accuracy ($R^2$=0.999) within the range of 0-180 ppm. In addition, we <2% sensor noise, which was evaluated as the standard deviation of stablized sensor readings, indicated high sensor precision. The response time ($t_{90}$), or the averaged amount of time the sensor took to reach the 90% level of the concentration gas, was less than 15 seconds.

Figure 1. CO sensor lab tesing



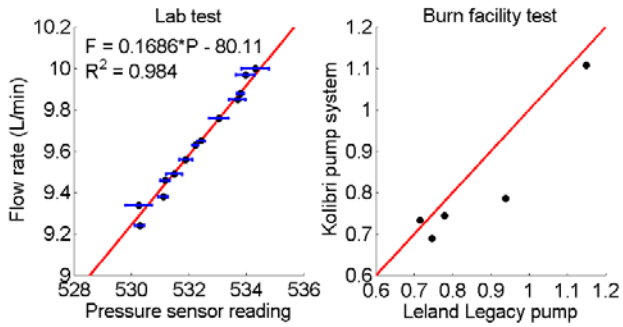
This CO sensor was also tested in our burn facility for cross-sensitivity (Fig. 2) to other gases. Two types of CEM instruments for CO measurement were used in this test, a California Analytical Instruments Model 200 (CAI-200, California Analytical Instruments Inc., Orange, USA] and a Horiba VIA-510 Gas Analyzer (HVIA-510, Horiba Ltd., Kyoto, Japan). In this test, the exhaust from the CO sensor was connected to the inlet of the CEMs with a flow rate of 0.6 L/min. The CO concentration measured during biomass burn tests using the EC4-500 sensor, the CAI-200, and the HVIA-510 instruments are plotted below. All instruments were calibrated based on a three-point calibration method using compressed gas before the actual test. Biomass (Kentucky Blue Grass stubble) was used in the first two burns and wheat stubble was used in the final two burns. The measurements from all sensors agree well with each other during the following three burns, with one exception from the first burn event which shows about 10% over-estimation from the EC-500 sensor compared to the CEMs.

Figure 2. CEM and CO sensor comparison at a laboratory burn facility.



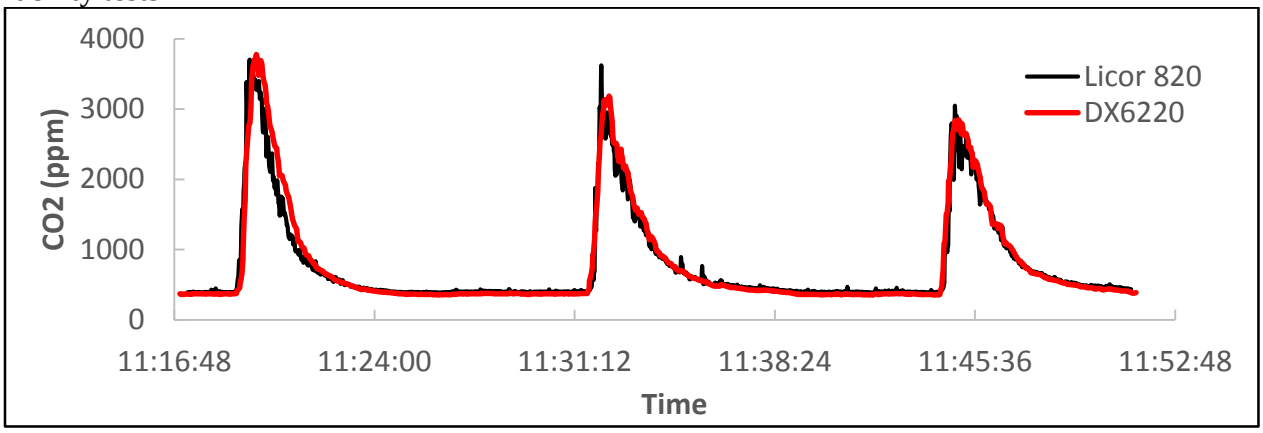

In order to maintain a constant flow rate for the $PM_{2.5}$ sampler and Tenax tube during sampling period, we designed a control board which can automatically adjust pump power based on real-time flow rate inferred from continuously monitored air pressure at the pump outlet. Though equipped with pumps of different power rating, this control board was designed to be used for both $PM_{2.5}$ sampler and Tenax tube with different set flow rate. To test this system, we first examined the linearity between the flow rate which was measured by a Gilibrator Air Flow Calibration System (Sensidyne Inc., St. Petersburg, USA) and the pressure sensor readings (Fig. 3, left). The horizontal error-bar denoted one standard deviation of the stabilized sensor readings. An accurate pressure-flow relationship can be derived from the correlation ($R^2 = 0.984$). Then, we tested the Kolibri pump system against a Leland Legacy pump (SKC, Eighty Four, USA) at burn facility and the results are shown in Fig. 3 (right). On average, the Kolibri pump system underestimated 5% of $PM_{2.5}$ concentration compared with the Leland Legacy pump, which is within the range of the measurement error for the Leland Legacy pump.

Figure 3. Kolibri pump system evaluation




The performance of the DX6220 $CO_2$ sensor in the Kolibri unit was compared during simultaneous measurements with the LICOR 820 (LI-COR Inc., Lincoln, USA) analyzer at the burn facility. Both sensors are based on NDIR, however, the DX6220 is much smaller in size. The test results are plotted in Fig. 4 for three consecutive biomass burns. In general, the measurements from the DX6220 agreed very well with those obtained from the LICOR 820, especially matching up the peak $CO_2$ values. The LICOR 820 data shows more variation comparing with the DX6220, which might be caused by the larger sampling cell and higher output resolution of the LICOR 820 analyzer.

Figure 4. DX6220 sensor comparison against the LICOR 820 CEM during laboratory burn facility tests




VOC emission factors (mass of pollutant per mass of biomass burned) from analysis of the Kolibri Tenax tube were compared with those from gas collection using an evacuated SUMMA canister at the same burn facility (Aurell and Gullett, 2013). This is an imperfect comparison because the SUMMA canister and the Tenax tubes sampled different burns and for different sampling durations (13 minutes for the Tenax sampling versus ~1 minutes from the SUMMA canister). However, we assumed that the emission factors would be sufficiently comparable given the same type of biomass. For six compounds that were analyzed, most of the emission factors measured by the two methods agreed reasonably well, given their sampling of distinctive burns and the sole Tenax sample.

Table 1. Emission factor (in µg/g biomass) sampled in the burn facility.

| Compound | Tenax tube | Summa Canister |
|---|---|---|
| Benzene | 57.36 | 284-776 |

| | | |
|---|---|---|
| Toluene | 258.58 | 123-369 |
| Ethyl Benzene | 25.36 | 26-76 |
| Xylene M+P | 22.70 | N/A |
| Xylene O | 14.15 | N/A |
| Styrene | 62.65 | 102-286 |
| Isopropylbenzene | 2.07 | N/A |
| n Propylbenzene | 3.07 | N/A |
| Trimethylebenzene 1,3,5 | 1.94 | 0.8-3.3 |
| Trimethylbenzene 1,2,4 | 7.79 | 3.7-16 |
| Isopropyltoluene p-Cymene | 6.96 | N/A |
| Butylbenzene | 1.32 | N/A |
| Dichlorobenzene 1,3 | 0.16 | N/A |
| Dichlorobenzene 1,4 | 1.39 | N/A |
| Dichlorobenzene 1,2 | 6.21 | N/A |
| Naphthalene | 30.00 | N/A |

## SUMMARY

Considerable success has been achieved in building and testing this new sensor system for mobile and aerial emission sampling. Both the CO and $CO_2$ sensors show high accuracy, low noise, and quick response. The $PM_{2.5}$ sampler equipped with pump control system performs well against a calibrated commercial pump. Emission factors of some VOCs sampled from the Tenax tube shows comparable results with previous SUMMA cannister sampling, a factor which will need further verification to examine, for example, breakthrough scenarios. In the future, this new system can be applied in open area emission sampling from ground-based or airborne platforms and can be modified to suit application-specific scenarios.

## ACKNOWLEDGEMENTS

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## REFERENCES

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## KEY WORDS

Emission sampling, sensor development, aerial sampling, CO, $CO_2$, $PM_{2.5}$, VOCs