Community Air Sensor Network (CAIRSENSE) project: Evaluation of low-cost sensor performance in a suburban environment in the southeastern United States

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Abstract. Advances in air pollution sensor technology have enabled the development of small and low cost systems to measure outdoor air pollution. The deployment of a large number of sensors across a small geographic area would have potential benefits to supplement traditional monitoring networks with additional geographic and temporal measurement resolution, if the data quality were sufficient. To understand the capability of emerging air sensor technology, the Community Air Sensor Network (CAIRSENSE) project deployed low cost, continuous and commercially-available air pollution sensors at a regulatory air monitoring site and as a local sensor network over a surrounding ~2 km area in Southeastern U.S. Co-location of sensors measuring oxides of nitrogen, ozone, carbon monoxide, sulfur dioxide, and particles revealed highly variable performance, both in terms of comparison to a reference monitor as well as whether multiple identical sensors reproduced the same signal. Multiple ozone, nitrogen dioxide, and carbon monoxide sensors revealed low to very high correlation with a reference monitor, with Pearson sample correlation coefficient (r) ranging from 0.39 to 0.97, -0.25 to 0.76, -0.40 to 0.82, respectively. The only sulfur dioxide sensor tested revealed no correlation (r < 0.5) with a reference monitor and erroneously high concentration values. A wide variety of particulate matter (PM) sensors were tested with variable results – some sensors had very high agreement (e.g., r = 0.99) between identical sensors, however moderate agreement with a reference $PM_{2.5}$ monitor (e.g., r = 0.65). For select sensors that had moderate to strong

1   correlation with reference monitors (r > 0.5), step-wise multiple linear regression was

2   performed to determine if ambient temperature, relative humidity (RH), or age of the sensor in

3   sampling days could be used in a correction algorithm to improve the agreement. Maximum

4   improvement in agreement with a reference, incorporating all factors, was observed for an NO_2

5   sensor (multiple correlation coefficient $R^2_{adj-orig} = 0.57$, $R^2_{adj-final} = 0.81$); however, other sensors

6   showed no apparent improvement in agreement. A four-node sensor network was successfully

7   able to capture ozone (2 nodes) and PM (4 nodes) data for an 8 month period of time and show

8   expected diurnal concentration patterns, as well as potential ozone titration due to near-by

9   traffic emissions. Overall, this study demonstrates a straightforward methodology for

10   establishing low-cost air quality sensor performance in a real-world setting and demonstrates

11   the feasibility of deploying a local sensor network to measure ambient air quality trends.

12   **1 Introduction**

13   Air quality monitoring, including measurements of common gas-phase and particulate matter

14   pollutants, has traditionally been conducted by regulatory organizations using specific

15   instrumentation and protocols. For example, the United States Environmental Protection

16   Agency (EPA) monitors criteria pollutants under the National Ambient Air Quality Standards

17   (NAAQS) via a network of ambient monitoring sites operating Federal Reference Methods

18   (FRM) or Federal Equivalent Methods (FEM). FRM and FEM designation for instruments is

19   established through a strict testing protocol (Hall et al., 2014) and the overall network produces

20   very high quality data, however generally sparse in geographic coverage.

21

22   Meanwhile, numerous field studies have established that outdoor air pollution can vary

23   considerably at a fine spatial scale due to localized impacts of source emissions (e.g., Karner et

24   al., 2010). Recent and fast-paced technology development has brought to the market portable

25   and low-cost air sensor devices that may have potential to provide hyper-local air quality data

26   through individual use or application in a dense sensor network (Jovasevic-Stojanovic et al.,

27   2015;Kumar et al., 2015;Snyder et al., 2013). Low-cost sensor devices, defined here as below

28   $2000 USD per pollutant (i.e., under $4000 USD for a two-pollutant device, and so on),

29   typically utilizing electrochemical or metal oxide sensors for gas-phase pollutants such as

30   carbon monoxide (CO), nitrogen dioxide (NO_2), nitrogen oxide (NO), ozone (O_3), and to some

31   extent, total volatile organic compounds (VOCs). Commercially-available particle sensor

32   devices currently use laser-based or light-emitting diode (LED)-based optical detection of

1   particles. Currently, no direct-mass measurement of particulate matter is commercially

2   available, however ongoing research is in progress to develop a true mass measurement

3   (Paprotny et al., 2013).

4

5   Research groups have built custom devices using available original equipment manufacturer

6   (OEM) sensor components - such as the integration of the particulate PPD42NS sensor

7   (Shinyei) into field-ready devices (Gao et al., 2015;Holstius et al., 2014;Johnson et al., in

8   review) – which generally involves adding an enclosure, microprocessor, battery or AC

9   electricity connection, wireless communications and/or on-board data storage, and potentially

10   other environmental sensors. Most research groups working with low cost OEM sensors have

11   tested their sensor performance in field settings, with varying results. For particulate sensors,

12   PPD42NS sensor comparison at low to moderate ambient concentrations revealed good

13   correlation with a reference monitor (Holstius et al., 2014), however the same particle sensor at

14   very high concentrations had nonlinear response and authors used high-order model fits to

15   correct their data (Gao et al., 2015). A modified commercially available particle sensing device

16   (Dylos) was shown to compare closely with a research grade monitor in low ambient

17   concentrations (Northcross et al., 2013).

18

19   Results of gas-sensor performance in real-world environments have also had promising but

20   variable results. Spinelle et al. (2015) used multiple statistical approaches to maximize the data

21   quality from O_3 and NO_2 sensors, finding a simple linear regression for an electrochemical

22   ozone sensor was sufficient to achieve strong correlation with a reference monitor, however

23   even advanced supervised learning strategies were not able to achieve strong correlation for

24   NO_2 sensors. Mead et al. (2013) noted a 100% ozone interference issue for an electrochemical

25   NO_2 sensor, which could be corrected by sampling both parameters simultaneously.

26

27   Researchers are already employing low cost sensors in exploratory research, to assess spatial

28   variability of urban air quality (Gao et al., 2015;Heimann et al., 2015;Moltchanov et al., 2015),

29   and the growing number of commercially-available devices is anticipated to create an

30   exponential increase in air quality data. The consumer product potential has motivated a

31   number of new business ventures, some initiated through crowd-sourced funding (e.g.,

32   Kickstarter, Indiegogo). Sensor developers are also looking to engage directly with the public,

33   with one innovative group providing particle sensors at a public library for citizens to borrow

Atmospheric
Measurement
Techniques
Discussions

1   for their personal use (Page-Jacobs, 2015). While the public interest is quickly growing, the

2   quality of the air sensor data remains uncertain, particularly for commercial devices that may

3   be utilized by citizens and community groups without access to reference monitoring sites for

4   collocation. In order to better understand the performance of commercially available air sensor

5   devices, EPA established the Community Air Sensor Network (CAIRSENSE) project, which

6   involves testing the feasibility of a wireless sensor network application as well as extensive

7   collocation of multiple identical sensor devices with reference monitors over an extended

8   period of time. The CAIRSENSE project is a multi-year effort, involving field testing emerging

9   air quality sensors in multiple locations in the United States, including Decatur, Georgia;

10   Denver, Colorado; and Research Triangle Park, North Carolina. This paper presents the

11   CAIRSENSE testing results of a variety of particulate and gas sensors in a suburban

12   environment of Decatur, Georgia, which is located in the southeastern United States, from

13   August, 2014 to May, 2015.

2 Methodology

2.1 Field study design

16   Two main testing components –the sensor ad-hoc field testing (SAFT) and the wireless sensor

17   network (WSN) – were included in the CAIRSENSE project (Fig. 1). The SAFT involved a

18   minimum 30 day testing period of duplicate or triplicate sensors located at a state regulatory

19   monitoring site. Meanwhile, the WSN involved long-term (> 7 months) deployment of several

20   selected sensors in multiple locations over an approximately 1 mi^2 spatial range. With the

21   overarching goal to test sensors with potential near-term wide use, candidate sensors were

22   selected based upon several criteria and market research. Criteria pollutants – including

23   particulate matter (PM), carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2),

24   and ozone (O_3) – were given priority in sensor type selection. Other sensor selection criteria

25   included a general upper cost limit at $2000 per pollutant (e.g., $2000 for a single pollutant

26   sensor device, $4000 for a two-pollutant sensor device, etc.), commercial availability,

27   continuous measurement, and low maintenance. The SAFT sensor set included five types of

28   PM sensors (Shinyei, Dylos, Airbeam, MetOne, and Air Quality Egg), three types of ozone

29   sensors, three types of NO_2 sensors, two types of CO sensors, and one SO_2 sensor (Table 1).

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Atmospheric
Measurement
Techniques
Discussions

1   The SAFT component included two or three identical sensor devices co-located and operated

2   on 115 V AC power. The sensors were placed in a shelter providing full exposure to ambient

3   air while also protecting from rainfall (Fig. 1 A and D). To understand the basic sensor device

4   functionality, each SAFT sensor was operated according to manufacturer's recommendations

5   and data were output in their default format. For example, PM sensors reported concentrations

6   in a variety of units including $\mu g/m^3$, pt/0.01cf (particles per 0.01 cubic feet or 283 ml), and

7   hppcf (hundreds of particles per cubic feet). For one sensor – the Air Quality Egg – units were

8   unclear for gas measurements and the data output appeared to be raw voltage signals. All SAFT

9   sensor data were logged locally to the extent possible – for sensors which were designed to

10 transmit data primarily to an internet server (AirBeam, Air Quality Egg), a microprocessor code

11 variation was written to support local logging. One exception was the AQMesh, a commercial

12 system that utilizes multiple electrochemical sensors to measure gases and wirelessly transmits

13 the data to the manufacturer's server. In this case, the data were provided to the research team

14 from the manufacturer on a weekly basis during the field study. The AQMesh data analyzed

15 were already post-processed by manufacturer proprietary algorithms prior to analysis.

16

17 In addition, four WSN nodes plus one base communications station were deployed to test the

18 feasibility of deploying a local wireless sensor network. The CAIRSENSE network was

19 designed based on a star topology with the NCore (National Core) location serving as the base

20 station, while every other node connects to it. The design goal was for all of the nodes to

21 wirelessly report their data in near real time to the base station, then data subsequently were

22 transmitted to a server through cellular communication. Digi's Xbee-PRO 900HP 900 MHz 10

23 Kbps radios were chosen as the backbone of the WSN based on their relative low cost and

24 extended line-of-sight range. An omnidirectional antenna was selected for the base station while

25 directional Yagi antennas were chosen for the remote nodes. Prior to the field deployment, the

26 communication protocol and wireless range were tested between a remote node and the base

27 station. Range tests were conducted in a mixed suburban environment in North Carolina with

28 conditions similar to those found surroundings the NCore station. While the manufacturer lists

29 a line-of-sight range of up to 9 miles for the selected Xbee radios, actual tests indicated a

30 maximum communication range of approximately 1 mile with mixed open, forested, and

31 commercial buildings located between the radios.

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Atmospheric
Measurement
Techniques
Discussions

1   The WSN nodes were designed to be small, weatherproof, and self-powered. The compact

2   size was important to facilitate deployment and minimize the installed footprint. Each WSN

3   node consisted of a weatherproof enclosure that was approximately a 0.4 x 0.4 x 0.15 m in

4   size, supporting several low cost (< $1000) sensors ($PM_{2.5}$, O_3, NO_2), an Arduino based

5   microcontroller, micro SD card, Xbee wireless radio, Xbee antenna, solar panel, solar power

6   controller, and a 12 VDC battery. A photo of a typical node is shown in Fig. 1 with

7   components listed in Table 2. Like the remote nodes, the base station had an Arduino

8   microcontroller and Xbee radio to receive signals from the nodes and an SD card for on-board

9   data logging. The base node included a Sierra Airlink® GX440 cellular gateway and

10   associated antenna to connect the base node to the internet. Data were uploaded and stored on

11   a remote server in a Microsoft SQL database and displayed on private webpage that updated

12   every minute. The webpage displayed the data in a tabular format and supported direct data

13   downloading. The communication base station and the sensor node 4 collocated at the NCore

14   site used 120 V (nominal) AC electricity, while the remaining satellite stations (nodes 1-3)

15   operated on solar power with battery backup.

16

17   Preliminary review after WSN deployment revealed brief spurious PM readings (e.g., 10 to 50

18   times higher than FEM) that occurred during mid-day, which appeared to be caused by side-

19   scattered sunlight intrusion to the Shinyei sensor. As an experimental measure, aluminum foil

20   was placed surrounding the radiation shielding that encompassed the sensor to reduce light

21   penetration, while still allowing the sensor to have access to ambient air. After foil was

22   applied, very high values were greatly reduced (Fig. A-4); therefore, the foil covers were left

23   in place for the remainder of the WSN data collection.

24   **2.2 Study location**

25   The State of Georgia South Dekalb regulatory monitoring site is located in the suburban Atlanta

26   area Decatur (AQS ID: 130890002; Latitude/Longitude: 33.68808/-84.29018), The South

27   Dekalb station is operated year-round as an NCore multipollutant monitoring network site and

28   includes an extensive suite of measurements including criteria pollutants and precursors, air

29   toxics, and meteorology. The surrounding area has mature trees, single-family residential

30   houses, sports fields, and schools (Fig. 2). No known major point source emissions were located

31   nearby. A nearby highway (I-285; 145,000 annual average daily traffic) is located

32   approximately 400 m to the north of the site.

Atmospheric
Measurement
Techniques
Discussions

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2   The SAFT component was located only at the NCore site. The WSN nodes were located in the

3   surrounding area. Node 1 (WSN-N1) was positioned at a nearby medical center (~1.2 miles

4   from the South Dekalb) and about 30 meters away from the major highway. Node 2 (WSN-N2)

5   was near a sports field (~0.5 mile from the South Dekalb). Node 3 (WSN-N3) was outside a

6   school property (~0.1 mile from the South Dekalb). Node 4 (WSN-N4) and the communications

7   base station were co-located with the NCore site.

8   **2.3 Analytical methods**

9   Sensor data were checked and analysed bi-weekly during the first three months to ensure all

10   sensors were working properly. Subsequently, data was recovered on a monthly basis. The

11   statistical software R (http://www.r-project.org/) version 3.2.1 with the "base" and "openair"

12   packages was used for all data processing and analysis. Multiple sensors reporting the same

13   pollutant of interest were compared against readings recorded by the NCore federal equivalent

14   methods (FEM). For duplicate or triplicate sensors evaluated in SAFT, readings were compared

15   between identical sensors to understand the reproducibility of sensor performance. Several

16   statistical measures are used to compare the co-located sensor measurements with the FEM

17   data, including: 1) the Pearson sample correlation coefficient (r) between individual sensor and

18   FEM; 2) the average values of sensor and FEM measurements in their original units; and, 3)

19   the slope, intercept, and coefficient of determination (r^2) of ordinary least squares (OLS)

20   regressions of individual sensor measurement on FEM. In addition, to enable basic comparison

21   of PM values with a reference monitor, data from PM sensors that had at least moderate

22   correlation (r > 0.5) were converted to $\mu g/m^3$ units based on upon an OLS regression equation.

23   Local meteorology was anticipated to be a driver of spatial variability in local pollutant trends

24   as well as potentially affecting sensor performance, as some sensors may have temperature

25   and/or humidity-based artifacts. The NCore wind, temperature, and humidity data were used as

26   the benchmark for comparison. In addition, sensor aging is another potential factor causing a

27   measurement factor – for example, solid-state gas sensors may undergo a loss of sensitivity

28   over time. Therefore, the sensor measurements were compared with FEM by number of days

29   measured to determine if an aging effect existed. Similar to the analysis by Holstius et al.

30   (2014), artifact effects are assessed by comparing the adjusted regression coefficients (R^2_{adj})

31   among multiple linear regressions of all possible variable combinations.

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Atmospheric
Measurement
Techniques
Discussions

1 For the WSN, the first step of the analysis was to conduct an experimental approach at a network

2 calibration, where data were subset for a period presumed to be representative of similar

3 atmospheric conditions at all sites – namely, hours of 01:00-04:00 am and during periods with

4 wind upwind of the highway (wind direction from 75-235 degrees). For this study, all data

5 representing those conditions were grouped and compared with FEM, with OLS regressions

6 conducted by having FEM values as the dependent variable and sensor values as the

7 independent variable, which yielded a regression equation that was used to convert individual

8 sensor values to the corresponding FEM units. For sensors revealing at least marginal

9 agreement with FEM data ($r > 0.4$), exploratory analyses are presented showing node-to-node

10 comparison in trends.

11

12 While the EPA has a clearly defined method for approving technologies for use in a regulatory

13 application (e.g., Hall et al., 2014), there currently are no clearly defined nor universally

14 accepted criteria by which to provide a "pass" or "fail", or alternative grading scheme,

15 judgement on a particular sensor model. Developing such criteria will be challenging, given

16 the diversity of research applications and related data quality objectives. In addition, sensor

17 performance may be affected by both the air pollutant mixture and concentration level, as well

18 as the environmental conditions. Therefore, the results in this paper are communicated

19 quantitatively by their correlation, or lack thereof, in comparison to regulatory-grade monitors.

20 **3 Results and Discussion**

21 Sensor field testing and the wireless sensor network were conducted over a wide range of

22 atmospheric conditions. The South Dekalb NCore site measured ambient temperature from -

23 12 to 33°C during the CAIRSENSE deployment, with an average of 14 °C. Meanwhile, the

24 RH varied from 11 to ~100%, with an average of 68%.

25 **3.1 Particle sensor evaluation**

26 All particle sensors evaluated detected particles via a light-scattering method. No sensors

27 directly measured particulate mass nor had defined size cuts preventing large particles from

28 entering the optical cell. Based on the project goal of understanding whether these types of

29 low cost sensor data could be indicative of fine particulate matter ($PM_{2.5}$) trends, a

30 comparison against the FEM $PM_{2.5}$ monitor, MetOne BAM 1020, is utilized. FEM monitors

31 are designed according to their application for use in determining compliance with the US

Atmospheric
Measurement
Techniques
Discussions

1   EPA National Ambient Air Quality Standards (NAAQS), which are at a 24-hour or annual

2   time basis. The beta-attenuation approach utilized in the MetOne requires having sufficient

3   particle mass deposited to the internal filter for an adequate signal to noise ratio. Given that

4   research applications of PM sensors may desire to use the data at a sub-daily time interval,

5   preliminary analysis was conducted to determine whether the raw MetOne BAM 1020 data

6   could be used at a faster time resolution than 24 hours, resulting in 12 hour averaging period

7   utilized for the FEM $PM_{2.5}$ data comparisons.

8

9   Summarized in Table 3, the various particle sensors had widely variable initial output

10   quantities and correlation with the FEM monitor. The three collocated Air Quality Egg units,

11   with internal Shinyei PPD42NS sensors, had poor correlation with the FEM (r = -0.06 to

12   0.40). The three MetOne 831 monitors also had weak correlation (r = 0.32 to 0.41). The

13   three Shinyei PM sensors had moderate agreement (r = 0.45-0.60), followed by relatively

14   higher correlation by the AirBeam (r = 0.65-0.66), and Dylos units (r = 0.63-0.67 for the

15   PRO-PC version, r = 0.58). Comparison of identical sensors revealed generally highest

16   agreement (Fig. A-1) – for example, while the three MetOne monitors had weak correlation

17   with the FEM, they had nearly perfect correlation between identical units (r = 0.99). This

18   finding suggests that some sensor sets may have excellent precision supporting use to

19   evaluate relative concentration levels, however caution must be exercised in presuming the

20   resulting measurements are representative of $PM_{2.5}$ reference measurements. Some factors

21   that likely contribute to the strong agreement among optical particle sensors, but weaker

22   agreement with $PM_{2.5}$ FEM monitors, includes the following: differing physicochemical

23   properties between calibration aerosol and real-world aerosol mixtures, light-scattering signal

24   by particles larger than 2.5 μm, and for some sensors, particle count as the reported value

25   which generally emphasizes the numerous but smallest detected particles.

26

27   Several particle sensors with at least fair correlation (r > 0.5) were further investigated for

28   artifacts based upon temperature, humidity, or days of use. For three selected sensors that

29   showed the highest correlation with FEM among identical sensors– the Shinyei SAFT-2,

30   Dylos SAFT-2, and Airbeam SAFT-2 – incorporation of artifacts such as temperature, RH,

31   and number of measurement days made some minor improvements in agreement with the

32   FEM as indicated by R^2_{adj} values from the multiple linear regression analysis (Table 5). No

33   single factor provided much improvement to the Shinyei or Airbeam sensor agreement.

Atmospheric
Measurement
Techniques
Discussions

1   However, accounting for days of use significantly increased the Dylos unit R^2_{adj} by 0.11, but

2   incorporation of RH revealed no improvement and temperature revealed only minor

3   improvement (+0.03 in R^2_{adj}).

4   **3.2 Gas-phase sensor evaluation**

5   Gas-phase sensor measurements of O_3, NO_2, NO, CO, and SO_2 were compared with hourly

6   average NCore reference monitors (Table 4). Of all the sensors discussed, the CairClip NO_2/O_3

7   sensor is unique in having a single data value output that nominally represents the addition of

8   NO_2 plus O_3. Therefore, CairClip NO_2 or O_3 values discussed represents the initial summation

9   minus a FEM reading (i.e., $CairClip_{NO2} = CairClip_{NO2/O3} - FEM_{O3}$; $CairClip_{O3} = CairClip_{NO2/O3}$

10 $- FEM_{NO2}$). Since CairClip readings were not calibrated with FEM, any negative values resulted

11 from the subtraction were kept in the correlation analysis. In addition, it should be noted that

12 two CairClip sensors at the SAFT site showed apparent operation failure at the outset of testing.

13 Sensor replacement was conducted in the mid-November for one sensor, which is included in

14 the analysis. The other failing sensor was deemed nonfunctional and is not incorporated into

15 further analysis.

16 **3.2.1 Ozone**

17 Of the ozone sensors tested, weak correlation was evident for two AQMesh units (r = 0.39-

18 0.45), high for two CairClip sensors (r = 0.82-0.94), and consistently very high for three

19 Aeroqual SM50 sensors (r = 0.91-0.97) when compared to FRM/FEM measurements (Fig. A-

20 2). For the Aeroqual SM50 sensor, no apparent improvement in agreement was observed when

21 temperature, RH, or sampling day length factors were incorporated (Table 5). However,

22 incorporating RH appeared to provide some improvement (+0.07 in R^2_{adj}) to the CairClip sensor

23 agreement with a reference monitor.

24 **3.2.2 Nitrogen dioxide**

25 The CairClip, AQMesh, and Air Quality Egg measurements of NO_2 were highly variable

26 compared with a reference monitor, with r ranging from 0.42 to 0.76, 0.14 to 0.32, and -0.25 to

27 -0.22, respectively (Fig. A-3). Only one CairClip NO_2 sensor that had sufficient correlation

28 was further explored for artifact correction. Significant improvement was evident when

29 temperature and RH were incorporated as adjustment factors, with very slight additional

30 improvement by incorporating days of use (Table 5).

Atmospheric
Measurement
Techniques
Discussions

3.2.3 Nitrogen oxide

One sensor device – the AQMesh – was tested that reported NO measurements. The two identical AQMesh units had very high agreement with the reference monitor (r = 0.88-0.93). No apparent improvement in agreement was determined when incorporating environmental or days of use as adjustment factors (Table 5). In absolute terms, the NO original sensor output also agreed closely with mean FEM values (Table 4).

3.2.3 Carbon monoxide

The AQMesh and Air Quality Egg incorporated electrochemical and metal oxide CO sensors, respectively. The AQMesh reported CO in ppb units, whereas the Air Quality Egg had no clear indication of units. Good correlation (r = 0.79-0.82) was observed between the AQMesh and a reference monitor. Incorporating days of use provided significant improvement in the AQMesh CO data (Table 5), with a clear slope drift with time evident (Fig. 3). The Air Quality Egg CO sensors had poor agreement with a reference (r = -0.40 to -0.14).

3.2.4 Sulfur dioxide

Only one sensor device was available that measured SO_2 – the AQMesh. The reported SO_2 values by the AQMesh were generally far higher than the reference monitor, on average a factor of 172 and 163 higher. While the two AQMesh units had high correlation with one another for SO_2 (r = 0.94), they had little correlation (r = 0.13-0.17) with a reference monitor.

3.3 Sensor network

3.3.1 Data communications

Based upon preliminary tests establishing an approximate 1 mile maximum range utilizing XBee antennas for the direct point-to-point communication, the initial WSN installed consisted of four nodes over a 1 mi^2 area transmitting data to the base node located at the South Dekalb site. However, the location of several buildings and mature forest canopy in the South Dekalb area limited the communication range of the network. Two of the WSN nodes communicated reliably with the base station (nodes 3 and 4), whereas data from the more distant Nodes 1 and 2 were not received. Therefore, data retrieval was conducted via manual SD card downloads for Nodes 1 and 2. Some experimentation was conducted by adding a repeater node mid-way between the base station and nodes 12, which had some success in

Atmospheric
Measurement
Techniques
Discussions

1   establishing communications between the two nodes but was unable to successfully transmit

2   data to the base station.

3   **3.3.2 Spatial and temporal trends**

4   Comparison of the hourly average WSN with FEM data during periods of time with

5   presumably similar pollution readings in all locations – hours of 01:00-04:00 AM and all sites

6   upwind of the highway – revealed moderate to good correlation between the WSN O_3 and

7   FEM O_3 (two nodes, r = 0.62 to 0.87) and WSN PM and FEM $PM_{2.5}$ (four nodes, r = 0.4 to

8   0.45). While the CairClip total output compared well (two nodes, r = 0.79 to 0.9) with the

9   addition of FEM O_3 and NO_2 methods, the result was not replicated when isolating and

10   comparing the WSN NO_2 component. A simple subtraction of either the onboard O_3 sensor

11   data (SM50) or the FEM O_3 data from the CairClip total output revealed effectively no

12   correlation between WSN NO_2 and FEM NO_2 (r < 0.1). This finding indicates that the

13   CairClip NO_2/O_3 sensor readings may not be entirely additive and field performance may not

14   replicate the strong agreement observed in a laboratory evaluation (Williams et al., 2014).

15   Further evaluation is needed to understand how to separate the NO_2 portion of the signal.

16   Based on these results, analysis of spatial and temporal trends were constrained to O_3 and

17   $PM_{2.5}$ sensor data sets.

18

19   After data were adjusted based upon linear regression analysis of WSN and FEM data sets

20   during the early morning and upwind time periods, wind directional plots indicated lower O_3

21   concentrations at the roadside site when air is transported from the highway (wind direction

22   from the N) with no directional signal observed at the site > 400 m from the highway.

23   Therefore, the O_3 sensors appear to have observed an ozone titration signal that has been

24   observed in other near-road field settings (Beckerman et al., 2008). Meanwhile, the PM

25   sensors had fairly uniform concentrations at all four sites and over the full range of wind

26   conditions (Fig. A-5). This finding is similar to past near-road studies, which generally see a

27   low signal change in particulate mass (Karner et al., 2010).

28

29   Diurnal signals of ozone revealed that the two sensor nodes replicated the typical afternoon

30   peak in ozone, however the amplitude of the cycle was smallest for the roadside site (Fig. A-

31   5). PM sensors had repeatable trends at all sites of maximum early morning concentrations

1   (06:00-08:00), which may attributed to lower atmospheric mixing and commute traffic

2   periods.

3   **4 Conclusions and discussion**

4   Emerging air sensor technology is of widespread interest to increase the spatial resolution of

5   air quality data sets and empower communities to measure air quality in their own

6   environments. The CAIRSENSE project is a multi-year, multi-city effort to assess emerging

7   ambient air quality sensors with existing or near-term commercial availability. Long-term

8   evaluation of duplicate or triplicate sensors in Decatur, Georgia, revealed widely variable

9   sensor performance under real-world conditions. The selected testing location represents a

10   generally low concentration, suburban environment (e.g., mean $PM_{2.5}$ ranging ~9-12 $\mu g/m^3$)

11   with temperate winters and hot, humid summers. As recently discussed in Johnson et al.,

12   (2016), sensor performance has been shown to vary with location and concentration regime.

13   Therefore, testing in multiple climates and air pollution mixtures is desirable to characterize

14   emerging air sensor technology.

15

16   At the Decatur testing site, some sensors were observed to have very strong agreement with

17   FEM over an extended period of time (e.g., SM50 O_3 sensor) and no artifact adjustment was

18   required to improve the agreement. Other sensors had good agreement with FEM (e.g.,

19   AQMesh CO sensor), that improved even further when days of use, temperature, or humidity

20   were incorporated as parameters in a multilinear regression equation. Other sensors had poor

21   or even negative agreement with FEM data sets; and, in some cases, substantially weaker field

22   performance than what had been shown in a laboratory setting. These results underscore the

23   importance of individual sensor performance testing prior to field use, and the corresponding

24   higher uncertainty in sensor datasets that do not incorporate field testing in their application.

25

26   Application of select sensors in a local wireless sensor network revealed useable ~8 month

27   data sets for both ozone and particulate matter. ZigBee-based network communications were

28   feasible over short ranges (e.g., 0.5 km), with the data communications range reduced from

29   the nominal ~1.5 km by the surrounding mature trees and several structures in the area.

30   Selecting early morning and upwind hours provided a means to adjust the data sets against the

31   nearby FEM data and subsequently investigate diurnal and wind-directional trends. Ozone

32   and PM trends were similar to repeatable past near-road field study observations.

1

2 Air quality sensor technology is quickly developing, with research efforts underway

3 worldwide to apply sensors for multiple uses including long-term outdoor monitoring, short-

4 term field studies, stationary and mobile applications, and personal monitoring. This field

5 study demonstrates a very wide range of sensor performance in an outdoor, suburban setting.

6 While the results of this study are likely transferable to environments that may have similar

7 pollution concentration ranges and environmental conditions, one complicating and

8 uncontrollable factor is the potential variability in the sensor manufacturing process. To

9 maximize the potential of this emerging technology, incorporating co-location with a

10 reference monitor into future field study designs is highly encouraged.

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Atmospheric
Measurement
Techniques
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Discussions
EGU

1 **Table 1.** Sensors selected for collocation ad-hoc field testing (SAFT)

2

Sensor/Manufacturer	Measured Pollutants/Internal Sensor (units)	Mechanism	N
PMS-SYS-1/Shinyei (Japan)	$PM_{2.5}$ ($\mu g/m^3$)	Light scattering	2
Dylos Particle Counter (DC1100-PRO-PC)/Dylos Corporation (Riverside, CA, USA)	Particle ≥ 0.5 μm (pt/0.01cf)	Light scattering	2
Dylos Particle Counter, DC1100-PC/Dylos Corporation (Riverside, CA, USA)	Particle $\geq 1\mu m$ (pt/0.01cf)	Light Scattering	1
Airbeam/HabitatMap (Brooklyn, NY, USA)	$PM_{2.5}$/Shinyei PPD60PV (hppcf)	Light scattering	3
Aercet 831/MetOne (Grants Pass, OR, USA)	PM_1, $PM_{2.5}$, PM_4, PM_{10} and TSP ($\mu g/m^3$)	Light scattering	3
SM50/Aeroqual (New Zealand)	O_3 (ppm)	Gas sensitive semiconductor (GSS)	2
Cairclip/Cairpol (France)	NO_2 and O_3 combined (ppb)	Electrochemical	2
Air Quality Egg/Wicked Device(Ithaca, NY, USA)	NO_2/e2v MiCS-2710, CO/e2v MiCS-5525, VOC/e2v MiCS-5521, PM/Shinyei PPD42 (pt/283ml)	Electrochemical for gases, light scattering for PM	3
AQMesh (Gen. 3)/AQMesh Corp. (UK)	NO, NO_2, CO, SO_2 , O_3 (all in ppb)	Electrochemical	2

3

4 **Table 2.** Wireless sensor network components

5

Parts/Manufacturer	Function	Node
PM Sensor/Shinyei (Japan)	Measures $PM_{2.5}$ in $\mu g/m^3$	1, 2, 3, 4
CairClip/Cairpol (France)	Measures NO_2/O_3 in ppb	1, 2, 3, 4
SM50/Aeroqual (New Zealand)	Measured O_3 in ppm	1, 4
AM2315 temperature & humidity sensor/Aosong (China)	Temperature and humidity reading	1, 2, 3, 4
Arduino Mega 2560 microprocessor/ Smart Projects (Italy)	On-board processing of data and transmission	1, 2, 3, 4
A09-Y11NF XBee antenna/ Digi International (Minnetonka, MN, USA)	900 MHz directional wireless communication to base station via ZigBee network protocol	1, 2, 3, 4
A09-F5NF-M-ND XBee antenna/ Digi International (Minnetonka, MN, USA)	900 MHz omnidirectional wireless communication via ZigBee network protocol	base
Solar panel and battery - SPM110P-FSW, SolarTech 55Ah battery[a]/SolarTech (Ontario, CA, USA)	Rechargeable power for system	1
Solar panel and battery - SPM055P-F, SolarTech 35 Ah battery[a]/ SolarTech (Ontario, CA, USA)	Rechargeable power for system	2, 3
Airlink® GX440 cellular modem/Sierra (Canada)	Transmission of data to server	base

6 [a]A larger solar-power system was utilized for node 1, supporting the inclusion of the SM50 ozone sensor . The other location
7 that included the sensor, node 4, was operated on landpower.

Atmospheric
Measurement
Techniques
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Discussions

Table 3. Comparison Statistics for 12-hour Average PM Measurements at South Dekalb NCore Site

Manufacturer, Model		Name	Sampling Time (days)	Original Sensor Measurement			r > 0.5	Comparison with FEM				Converted to FEM unit (µg/m³)	FEM Concentration[c] (µg/m³)
								OLS Regression (FEM = a×Sensor + b)					
				Mean	Unit	CV		r²	Slope	Intercept		Mean	
Shinyei, PM Sensor		SAFT-1	251	8.31	µg/m³	0.61	N			NA			11.13
		SAFT-2	168	6.56	µg/m³	0.69	Y	0.36	0.72	7.48		12.18	12.21
		WSN-N4[a]	285	12.56	µg/m³	1.51	N			NA			10.81
Dylos	DC1100 PC (small, ≥ 1 µm)	SAFT-1	108	423.1	pt/0.01cf	0.83	Y	0.33	0.0086	8.08		11.71	11.60
	DC 1100 PRO-PC (small, ≥ 0.5 µm)	SAFT-2	108	3054.04	pt/0.01cf	0.77	Y	0.45	0.0015	7.20		11.67	11.60
		SAFT-3	71	2948.3	pt/0.01cf	0.85	Y	0.40	0.0013	7.78		11.64	11.66
Airbeam (internal PM sensor: Shinyei, PPD60PV)		SAFT-1	251	2982.57	hppcf	0.62	Y	0.42	0.0020	5.24		11.20	11.13
		SAFT-2	168	2977.22	hppcf	0.58	Y	0.43	0.0018	6.01		11.48	12.22
		SAFT-3	168	3033.84	hppcf	0.61	Y	0.43	0.0017	6.40		11.45	12.22
MetOne, 831[b]		SAFT-1	21	3.21	µg/m³	0.67	N			NA			9.60
		SAFT-2	21	3.12	µg/m³	0.62	N			NA			9.60
		SAFT-3	21	2.8	µg/m³	0.62	N			NA			9.60
Air Quality Egg (internal PM sensor: Shinyei, PPD42NS)		SAFT-1	121	277.59	n/a	0.53	N			NA			13.81
		SAFT-2	196	3.31	n/a	0.46	N			NA			11.90
		SAFT-3	115	89.42	n/a	0.89	N			NA			11.11

a. With aluminum foil added after 2014/09/18
b. Short, discontinuous testing period from January-May, 2015
c. FEM $PM_{2.5}$ instrument: MetOne, BAM 1020 (Grants Pass, OR, USA)

Atmospheric
Measurement
Techniques
Discussions

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Table 4. Comparison Statistics for Hourly Gas Measurements at South Dekalb Ncore Site

Pollutant	Manufacturer, Model	Testing component ID	Sampling Time (Days)	Original Sensor Measurement Mean	Unit	CV	r > 0.5	Comparison with FEM OLS Regression (FEM = a×Sensor + b) r²	Slope (a)	Intercept (b)	Converted to FEM unit	Concurrent FEM Concentration[d] (ppb)
O₃	Aeroqual, SM50	SAFT-1	251	0.0177	ppm	1.03	Y	0.94	888.26	2.56	18.3	18.3
		SAFT-2	168	0.0182	ppm	1.06	Y	0.94	811.52	2.84	17.6	17.6
		WSN-N4	281	0.016	ppm	0.93	Y	0.82	955.26	2.91	18.2	18.2
	Cairpol, CairClip[a]	SAFT-1[c]	194	7.2	ppb	2.38	Y	0.88	0.851	12.451	18.6	18.6
		WSN-N4	285	6.3	ppb	2.67	Y	0.68	0.685	12.203	16.5	16.7
	AQMesh Corp, AQMesh	SAFT-1	111	11.8	ppb	0.81	N			NA		14.9
		SAFT-2	110	11.6	ppb	0.71	N			NA		14.8
NO₂	Cairpol, CairClip[b]	SAFT-1[c]	194	0.18	ppb	40	Y	0.57	0.955	11.391	11.6	11.7
		WSN-N4	285	1	ppb	9.32	N			NA		11.2
	AQ Mesh Corp, AQMesh	SAFT-1	111	17.5	ppb	0.80	N			NA		10.0
		SAFT-2	110	29.1	ppb	0.65	N			NA		10.0
	Wicked Device, Air Quality Egg (e2v MiCS-2710)	SAFT-1	121	31514.7	n/a	2.58	N			NA		10.6
		SAFT-2	196	35927.7	n/a	2.1	N			NA		12.1
		SAFT-3	115	32873.4	n/a	2.46	N			NA		11.3
NO	AQMesh Corp, AQMesh	SAFT-1	111	19.4	ppb	1.84	Y	0.77	0.892	1.060	18.4	18.3
		SAFT-2	110	21.8	ppb	1.76	Y	0.87	0.883	-0.765	18.5	18.5
CO	AQMesh Corp, AQMesh	SAFT-1	111	318.3	ppb	0.70	Y	0.63	8.09E-04	6.95E-02	0.3272	326.2
		SAFT-2	110	345.4	ppb	0.68	Y	0.68	7.99E-04	5.12E-02	0.3272	326.3

Atmospheric
Measurement
Techniques
Open Access
Discussions

Wicked Device, Air Quality Egg (e2v MiCS-5525)	SAFT-1	121	28500	n/a	0.25	N	NA	328.1
	SAFT-2	196	25636.7	n/a	0.28	N	NA	328.1
	SAFT-3	115	24882.8	n/a	0.31	N	NA	307.1
SO₂ — AQMesh Corp, AQMesh	SAFT-1	111	41.8	ppb	0.79	N	NA	0.243
	SAFT-2	110	39.9	ppb	0.89	N	NA	0.245

a. By subtracting the FEM NO_2 data
b. By subtracting the FEM O_3 data
c. After sensor replacement on 2014/11/15
d. FEM instrument – O_3: Thermo Scientific, 49i; NO_2: Thermo Scientific, 42C; NO: Thermo Scientific, 42C; CO: Thermo Scientific, 48C; SO_2: Thermo Scientific, 43i-TLE (Waltham, MA, USA)

Table 5. Comparison of Adjusted Regression Coefficients (R^2_{adj}) of Multiple Linear Regression Models between FEM Concentrations against Individual Sensor[a], Ambient Temperature, Humidity, and/or Number of Measurement Days

Variable Combination	PM (12-hr average)			O_3 (hourly)		NO_2 (hourly)	NO (hourly)	CO (hourly)
	Shinyei SAFT-2	Dylos SAFT-2 Sm	Airbeam SAFT-2	Aeroqual SAFT-1	CairClip SAFT-1[b]	CairClip SAFT-1[b]	AQMesh SAFT-1	AQMesh SAFT-1
Sensor	0.36	0.45	0.43	0.94	0.88	0.57	0.77	0.63
Sensor+T	0.36	0.48*	0.43	0.94*	0.90*	0.70*	0.77	0.71*
Sensor+RH	0.40	0.45	0.46*	0.93	0.95*	0.64*	0.75	0.52
Sensor+Day	0.37*	0.56*	0.46*	0.94*	0.88*	0.60*	0.77	0.75*
Sensor+T+RH	0.41	0.50*	0.46	0.93	0.95*	0.81*	0.75	0.61
Sensor+T+Day	0.37	0.56	0.46	0.94*	0.90*	0.70*	0.77	0.75*
Sensor+RH+Day	0.42*	0.60*	0.51*	0.94	0.95*	0.68*	0.75	0.68
Sensor+T+RH+Day	0.43	0.60	0.50	0.94	0.96*	0.82*	0.75	0.68

a. Representative sensors were selected when the correlation coefficient (r) between individual sensor and FEM ≥ 0.5.
b. After the sensor replacement on 2014/11/15.
*. Significant at p-value < 0.05.

Figure 1. CAIRSENSE field equipment, including: A: SAFT instrument enclosure; B and C: solar-powered WSN node; D: Interior of SAFT instrument shelter; and E: WSN node utilizing 120 V (nominal) AC electricity.

Figure 2. CAIRSENSE project Wireless Sensor Network (WSN) and Sensor Ad-hoc Field Testing (SAFT) locations.
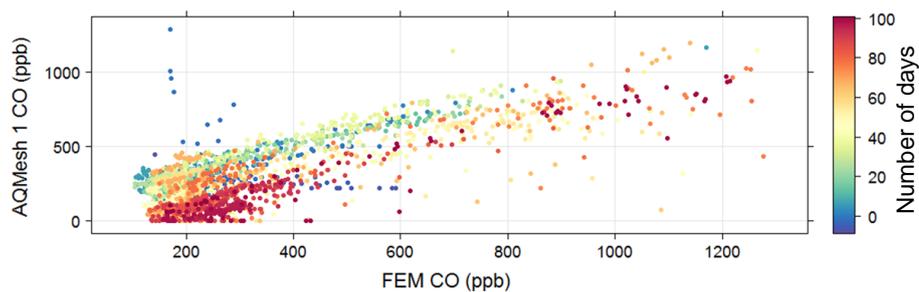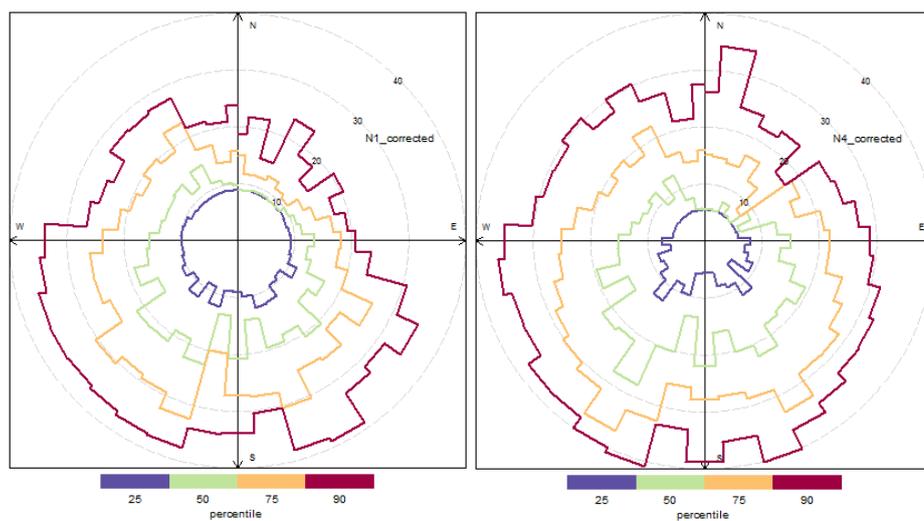
Atmospheric
Measurement
Techniques
Discussions

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Figure 3. AQMesh vs. FEM carbon monoxide comparison, with markers colored by the number of days of sensor use.

(a) Near-road Node 1 Aeroqual O_3 (b) NCore co-located Node 4 Aeroqual O_3

Figure 4. Example Percentile rose plots between near-road sensor node (N1) and Ncore co-located node (N4) for hourly FEM-corrected ozone between August 2014 and early March 2015.