Community Air Sensor Network (CAIRSENSE) Project: Lower Cost, Continuous Ambient Monitoring Methods

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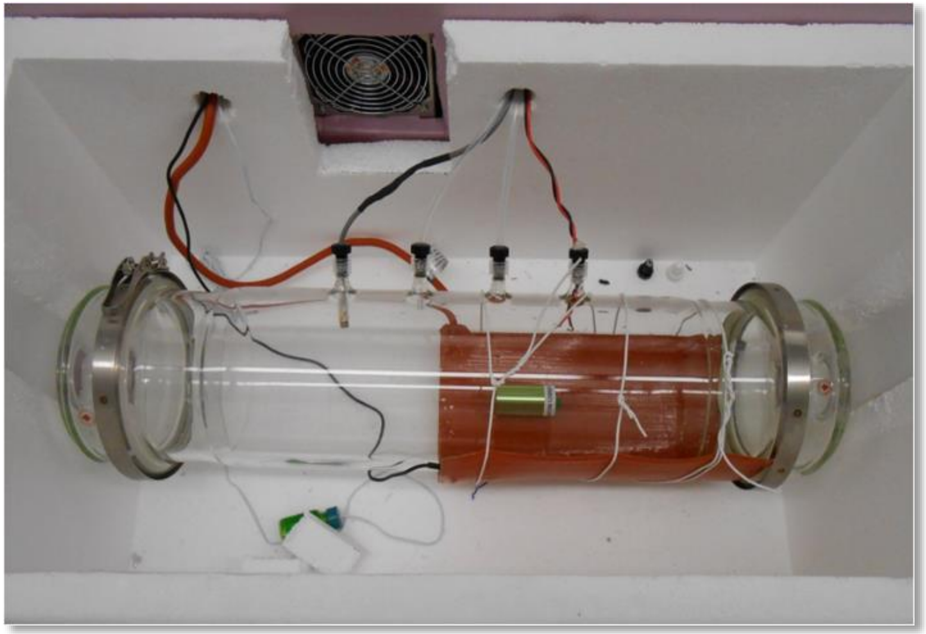
Low Cost Sensors

- ***Pros:*** Low cost allows for different applications than traditional monitors
- ***Cons:*** Without testing, questions about data quality, reproducibility, etc.
- Lots of current research on low cost sensors:
  - Calibration
  - Interferences
  - Drift
  - Reproducibility



Typical sensor testing setup, EPA ORD

Next-Generation Air Measurement (NGAM) Technology Groups

Group	Cost Range	Example applications
1	<$500	In-home sensor devices; wearable personal monitor.
2	$500-2K	Hand-held, short-term monitoring by citizens; bicycle-mounted sensors to map air quality.
3	$2-10K	Stationary multipollutant sensor deployment in a community; portable sensors for harder-to-measure pollutants.
4	$10-100K	Long-term, multipollutant community monitoring system; higher-end portable pollutant detection system.
5	>$100K	Wide-area emissions detection system; instruments to detect difficult-to-measure pollutants.

Community Air Sensor Network (CAIRSENSE) Project Overview

- **Participants:**
  - EPA Regions 4, 1, 5, 7, and 8; EPA Office of Research and Development (ORD); EPA Office of Air Quality Planning and Standards (OAQPS); and Georgia Environmental Protection Division (EPD).
- **Objectives:**

1. Evaluate in situ the ***long-term comparability of several lower cost sensors of interest*** against regulatory monitors.

2. Determine the capabilities and limitations of a ***long-term multi-node wireless sensor network applied for community air monitoring***, in terms of operational stability (communications, power) and long-term data quality under ambient conditions.

General Project Timeline

Year 1 Priorities defined, Study design

Year 1 site and sensor selection; Quality Assurance Project Plan (QAPP) Development

Year 1 Data Collection in Atlanta, Review, and Analysis; Develop Year 2 priorities

Winter 2013 — **Summer 2014**

Year 2 Priorities defined, Study design

Year 2 site and sensor selection; QAPP Amendment

Year 2 Data Collection in Denver, Review, and Analysis; Disseminate results

Winter 2014 — **Summer 2015***

*Summer of 2015→ transition from Atlanta to Denver

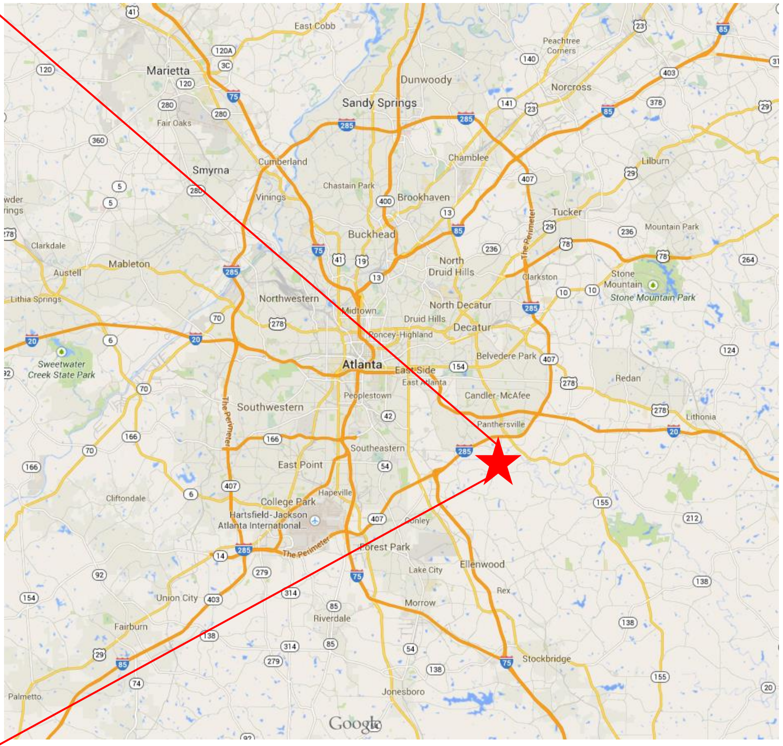
CAIRSENSE sensor selection

Selection Criteria: Overarching goal to test sensors or sensor systems with potential near-term wide use

1. Priority on **criteria pollutants (NAAQS)**
2. General **upper cost limit at $2000 per pollutant** (e.g., $2000 for a one pollutant sensor device, $4000 for a two-pollutant sensor device, etc.)
3. Priority to test **commercially available** sensors, with potential near-term high degree of use
4. Priority to test sensors **already in use by general public**.
5. **Real time or continuous monitoring technologies** of gases and particulates were of interest (no laboratory analysis)
6. Priority to test sensors that are **turnkey** – lower priority to develop custom electronics for raw sensors.

South Dekalb Air Monitoring Site

- National Core (NCore) regulatory monitoring site in suburban Atlanta
- Extensive suite of measurements including criteria pollutants and precursors, air toxics, and meteorology
- Long historical data record



CAIRSENSE Project Design

Module 1: Wireless sensor network (WSN)

- >6 month field test
- 4 sensor node locations (1 located at NCore site)
- 1 sensor per pollutant, per node
- Wireless data streaming of entire network to an off-site server
- Operating primarily on solar power

Module 2: Sensor ad-hoc field testing (SAFT)

- >30 day test
- All sensors at NCore site
- Replicates of the same sensor co-located; multiple sensor types for the same pollutant
- Data logging vary by sensor technology
- Land power provided

CAIRSENSE Locations

= Regulatory site

B Base station for local wireless network

N wireless sensor network nodes

AT Ad-hoc testing location

Wireless sensor network (WSN) ancillary equipment

Sensor network configuration:

Node 1:
Sensors: PM, NO/O_3, O_3
Plus: XBee antenna, SD card data storage
LARGE SOLAR PANEL

Node 2:
Sensors: PM, NO/O_3
Plus: XBee antenna, SD card data storage
SMALL SOLAR PANEL

Node 3:
Sensors: PM, NO/O_3
Plus: XBee antenna, SD card data storage
SMALL SOLAR PANEL

Data via ZigBee

Data via ZigBee communication

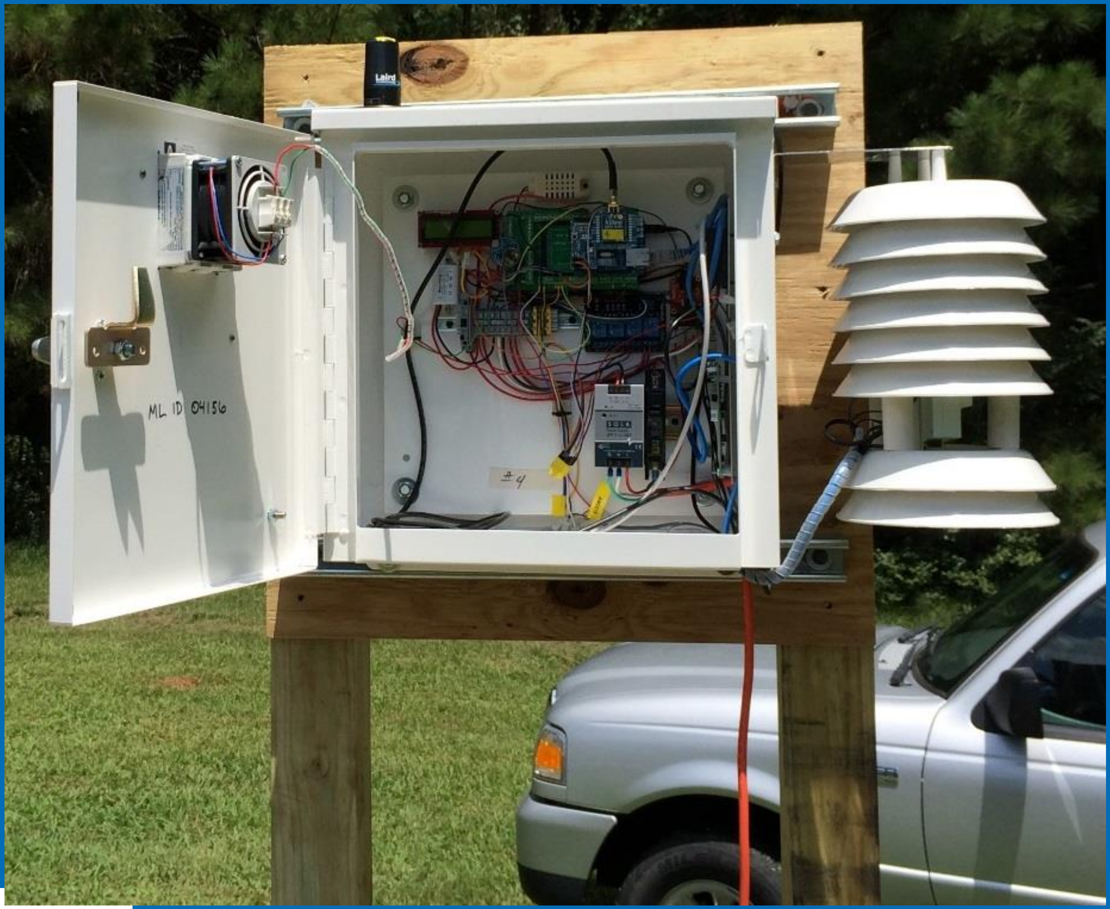
Data via ZigBee

Node 4 + Base Station at NCORE site
Sensors: PM, NO/O_3, O_3
Plus: XBee antenna, Cellular modem, SD card data storage
LAND POWER

Data to server via cell modem

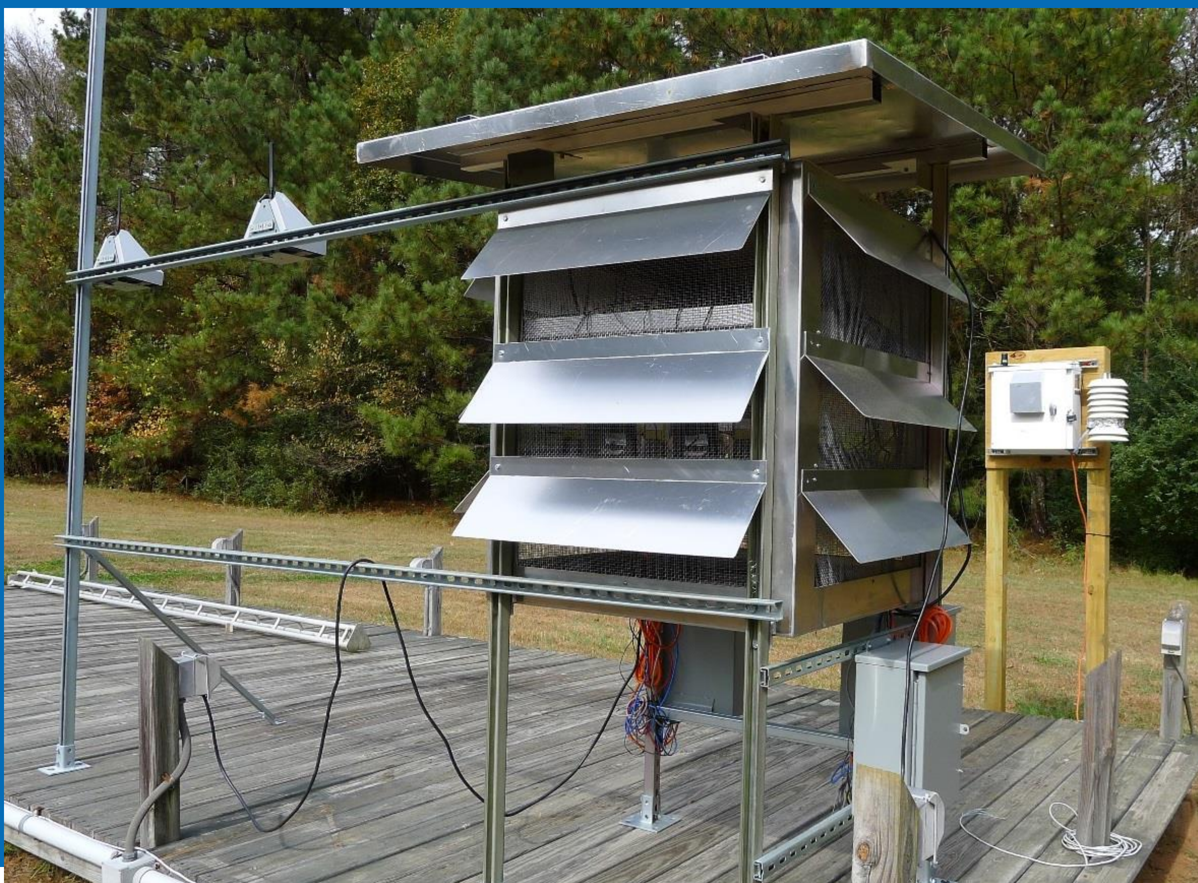
EPA United States Environmental Protection Agency

Wireless Sensor Network (WSN) components example

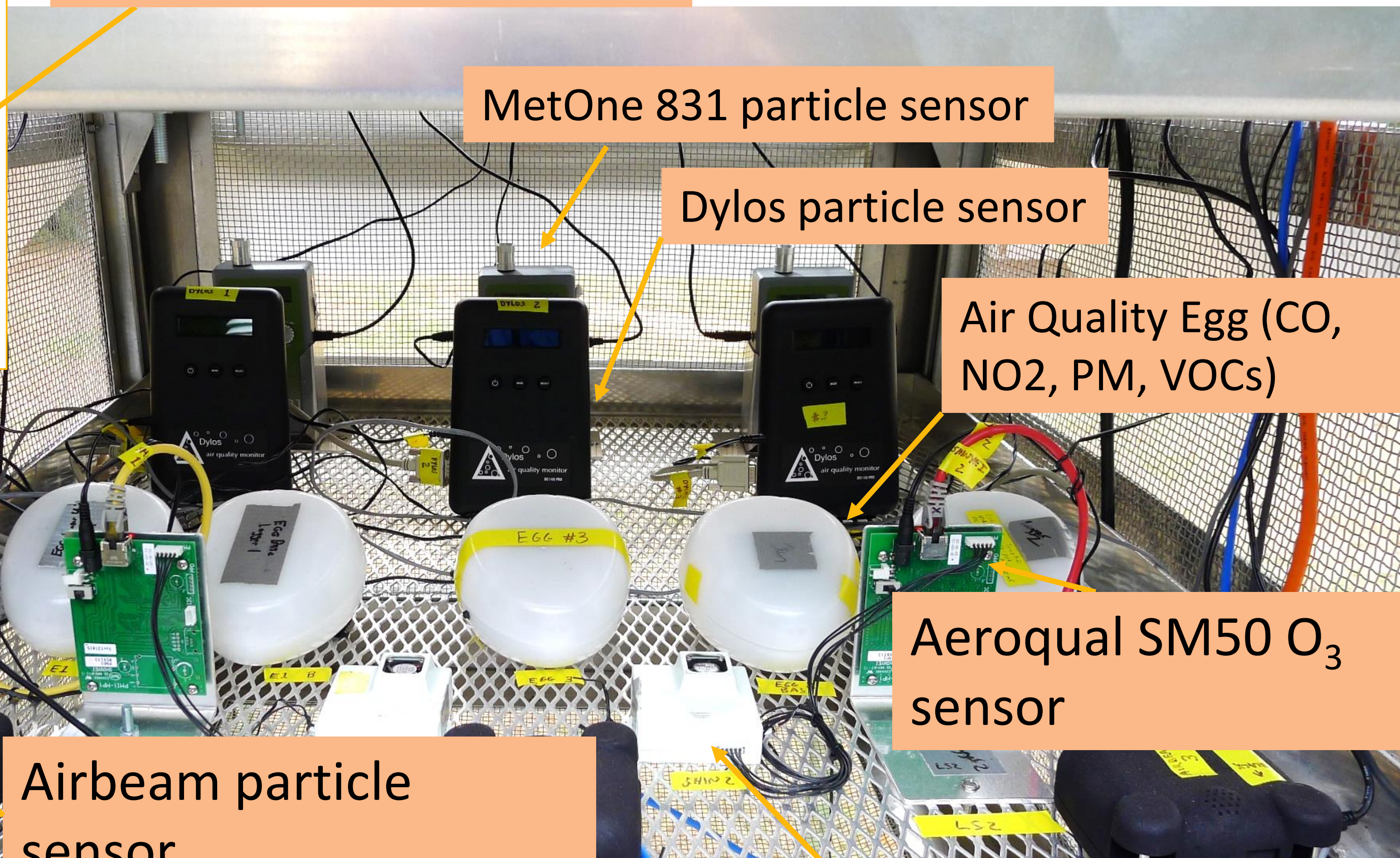


United States
Environmental Protection
Agency

Sensor Ad-hoc Field Testing (SAFT) components example

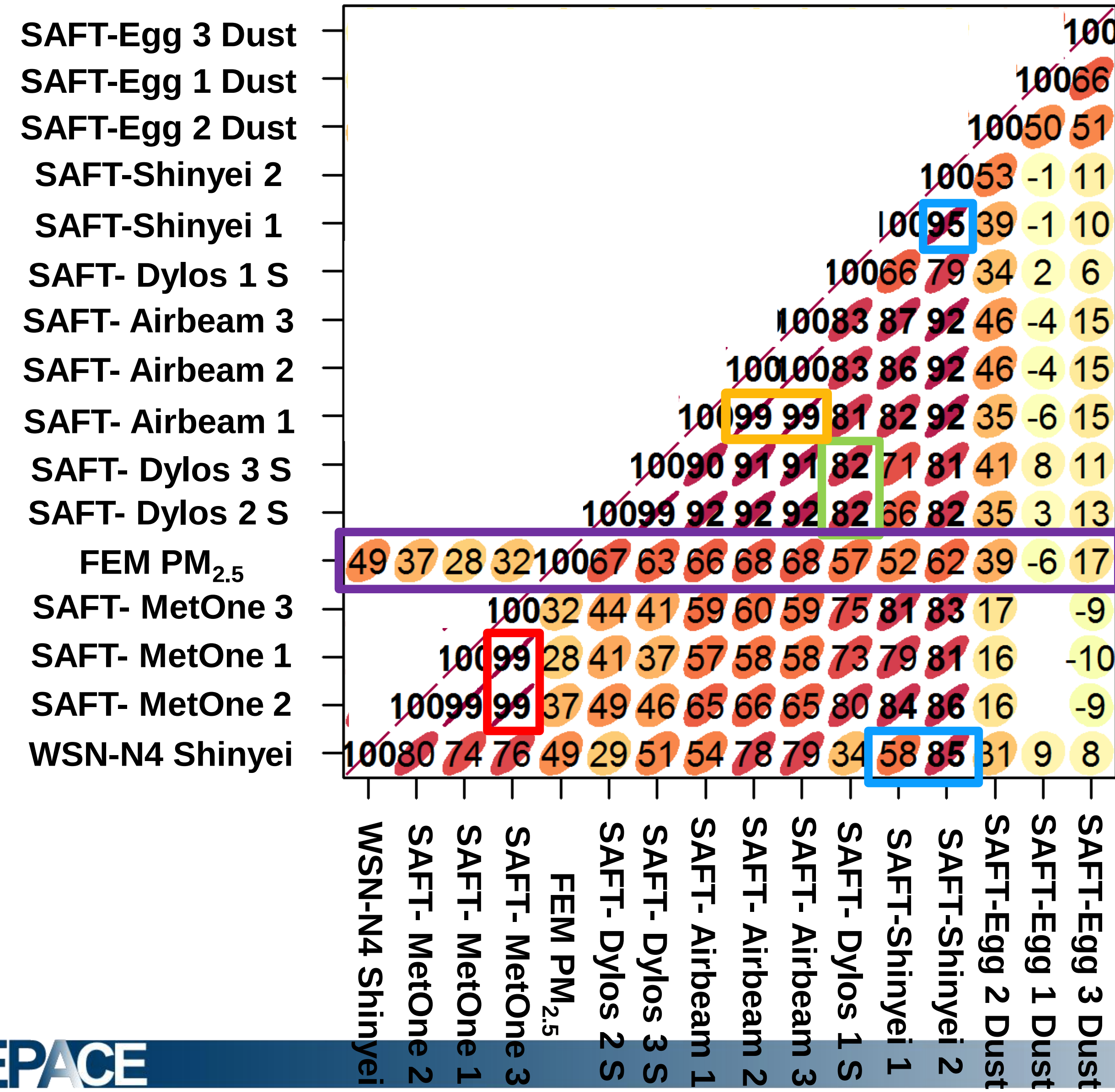


Ad-Hoc Testing: Initial sensors to test



Not shown: Cairpol NO_2/O_3 sensor

Correlation matrix (Pearson correlation) of 12-hr average PM between sensors and co-located FEM

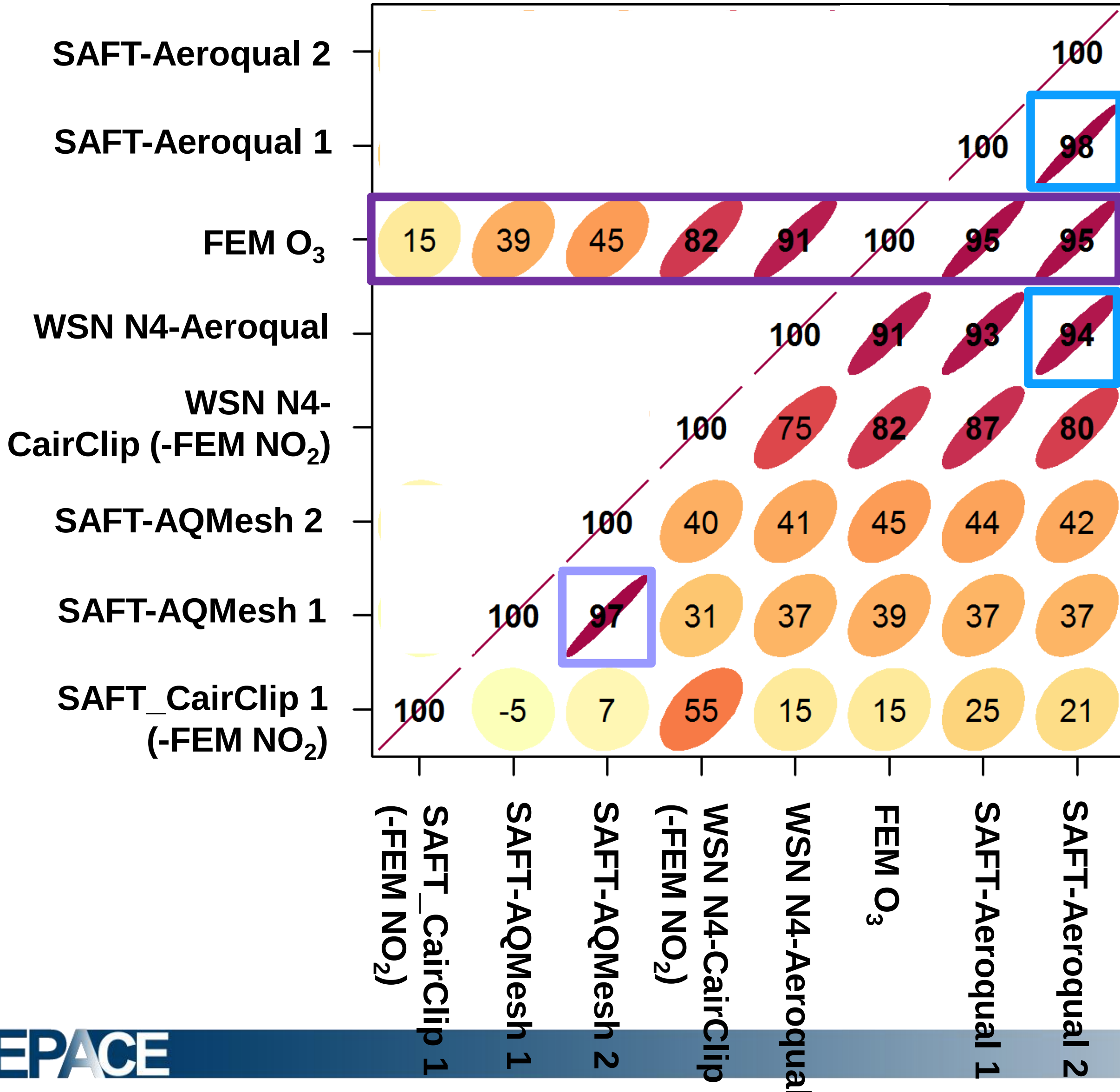


Moderate to high correlation between most identical units



Variable correlation with reference (r = -0.06 to 0.68)

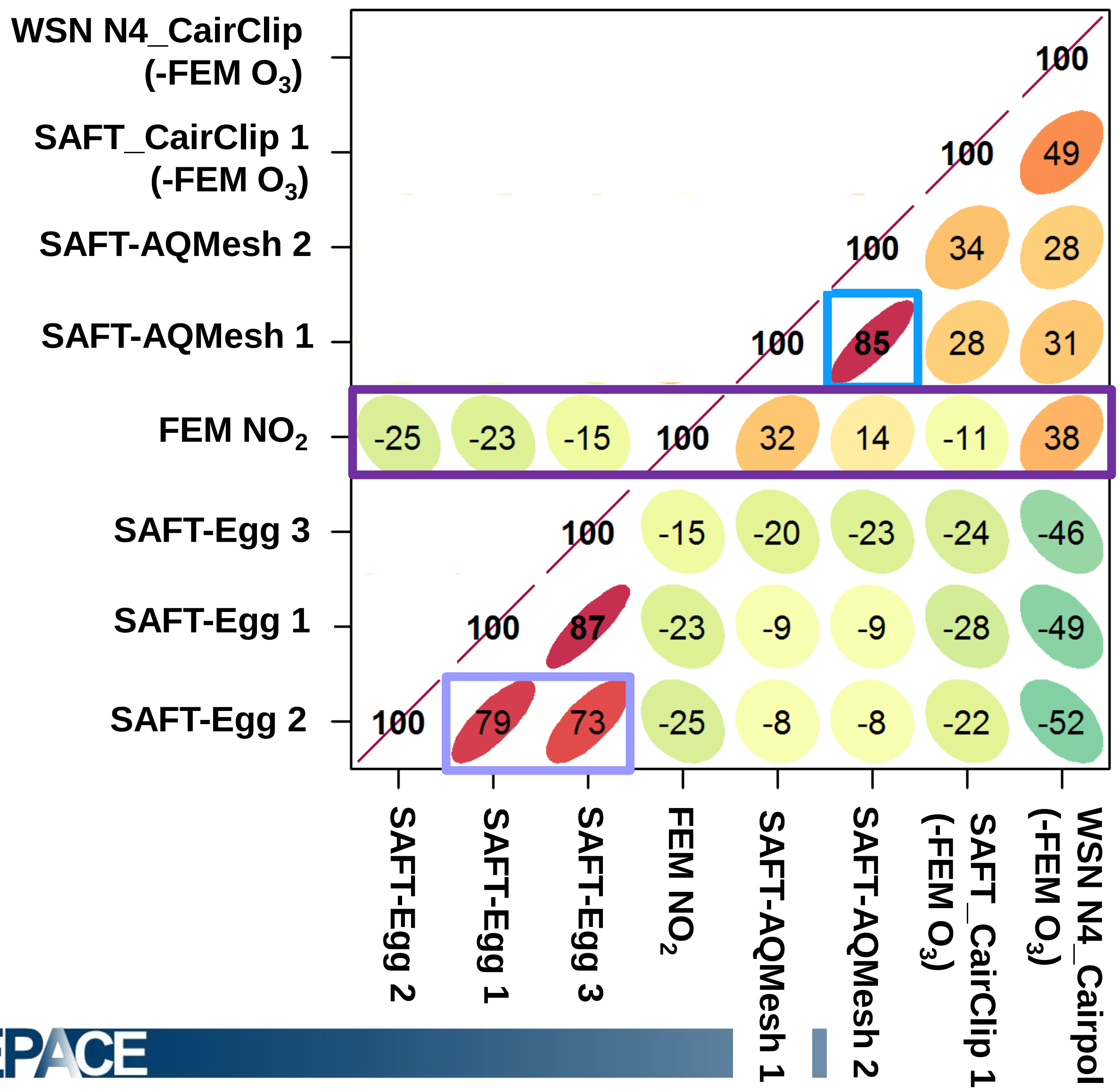
Correlation Matrix of Hourly Average O_3 between Sensors and Co-located FEM



Strong correlation between identical units

Variable correlation with reference (r = 0.15 to 0.95)

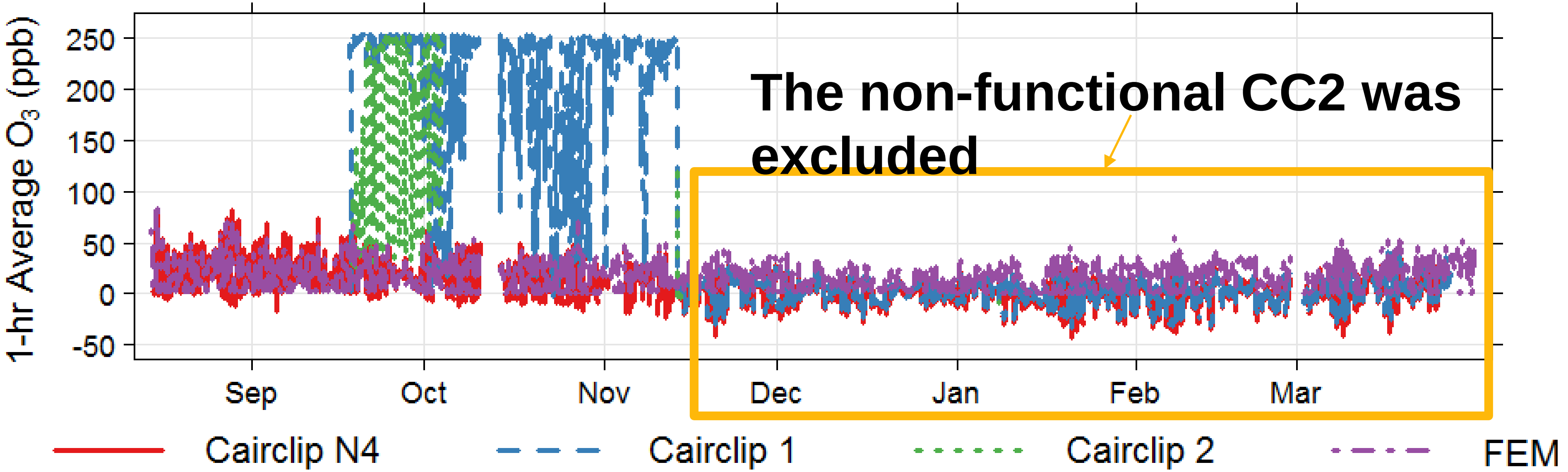
Correlation Matrix of Hourly Average NO_2 between Sensors and Co-located FEM

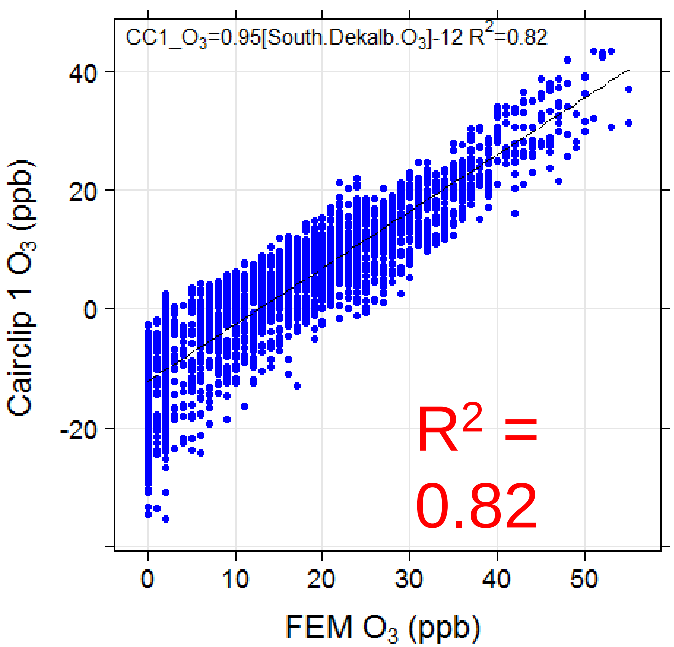


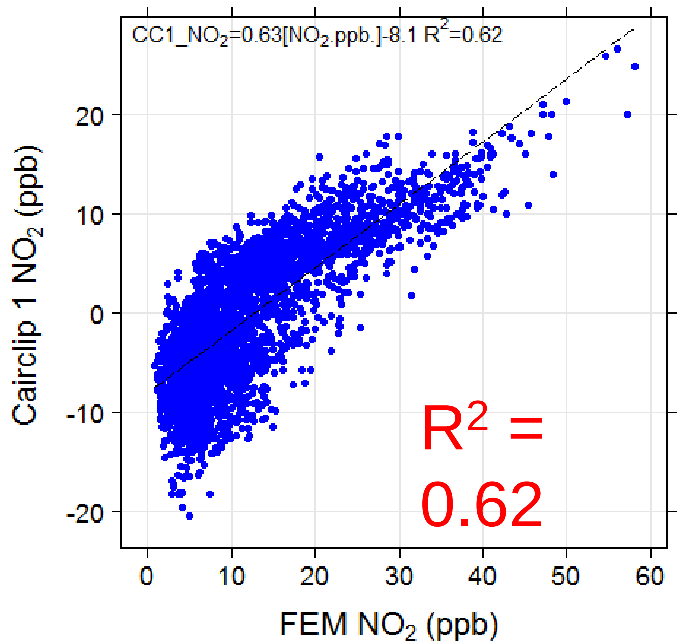
Moderate to high correlation between most identical units

Poor correlation with reference (r = -0.25 to 0.38)

Technical maintenance for SAFT-CairClip 1 sensor





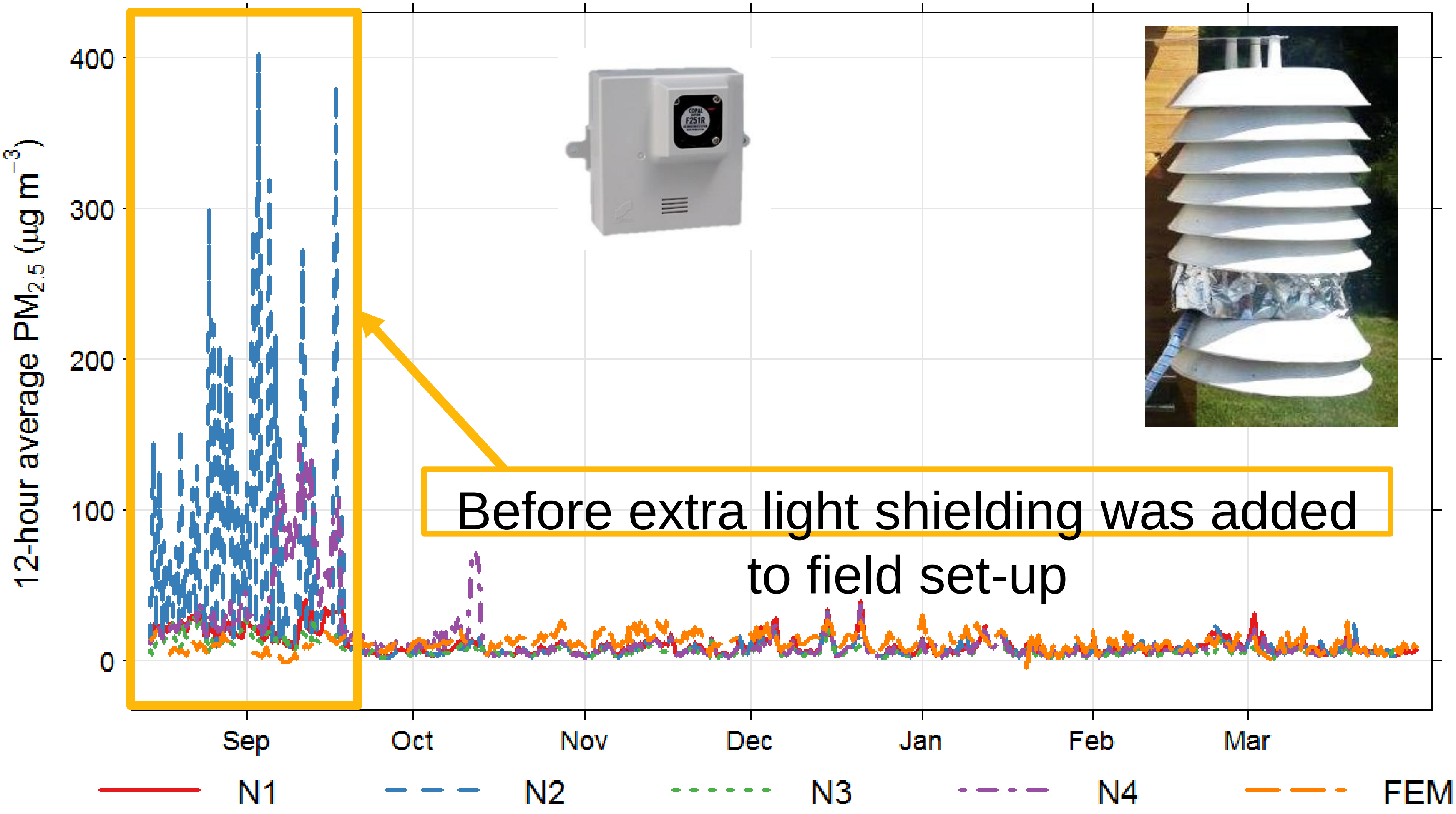


Improved correlation with reference after sensor replacement

Wireless Sensor Network (WSN)

- Radio transmission:
  - Initial success tested in RTP (~ 1 mile range)
  - Limited communication in South Dekalb area
  - Manual download
- Sensors
  - PM: light interference issue resolved with adding aluminum foils, deviations related to possible local sources
  - Ozone: tracked well with FEM but showed some spatial variability (r from farthest N1 of 0.85 to co-located N4 of 0.91)

Light interference for some PM sensors



Conclusions

- Variable sensor performance under real-world conditions
- A wide range of field utility for long-term data collection
- Some sensors have desirable traits for flexible field use, but many require further development to support ease of application, and provide adequate accuracy and precision performance

Future Work

- Explore temperature/humidity artifact corrections
- Complete analysis for all pollutants measured will be shown in a separate journal paper (in preparation)
- Year 2 deployment in Denver to include additional sensors

Thank you!

- CAIRSENSE EPA contacts:
  - Region 4: Ryan Brown (brown.ryan@epa.gov); Daniel Garver (garver.Daniel@epa.gov)
  - ORD: Ron Williams (williams.ronald@epa.gov) and Gayle Hagler (hagler.gayle@epa.gov)

- Funding: EPA Regional Methods Project

Disclaimer: Mention of trade names or commercial products does not constitute endorsement or recommendations for use. Although this work was reviewed by EPA and approved for publication, it may not necessarily reflect official Agency policy.

Appendix

(1) Shinyei PM sensor
(2) Dylos PM sensor
(3) Airbeam PM sensor
(4) Met One PM sensor
(5) Aeroqual O_3 sensor
(6) CairClip O_3/NO_2 sensor
(7) AQMesh
(8) Air Quality Egg

Shinyei Sensor Base Design

- **Model:** PM Sensor Evaluation Kit (http://www.shinyei.co.jp/stc/optical/main_pmmonitor_e.html):
  - PM Sensor PM1, Connection Interface board I/F, Cable harness, AC adapter (DC12V), Evaluation software
- **Measurement:** $PM_{2.5}$ in unit of $\mu g/m^3$
- **Mechanism:** light scattering using an internal light emitter (suggested environmental light intensity to be <500 lux)
- **Power:** 12 VDC is required
- **Data retrieval and/or logging:** Arduino microcontroller with an Ethernet shield to return string into PM concentration and store onto a micro-SD card
- **Enclosure:** need to put under a cover or in an enclosure for environmental protection and from incidental contact with metal objects
- **Field utility:** once configured and communication is established, Shinyei device is reliable and easy to deploy

Shinyei Field Setup

Figure A-1. Housing for the CAIRSENSE ad-hoc sensor testing in Atlanta.

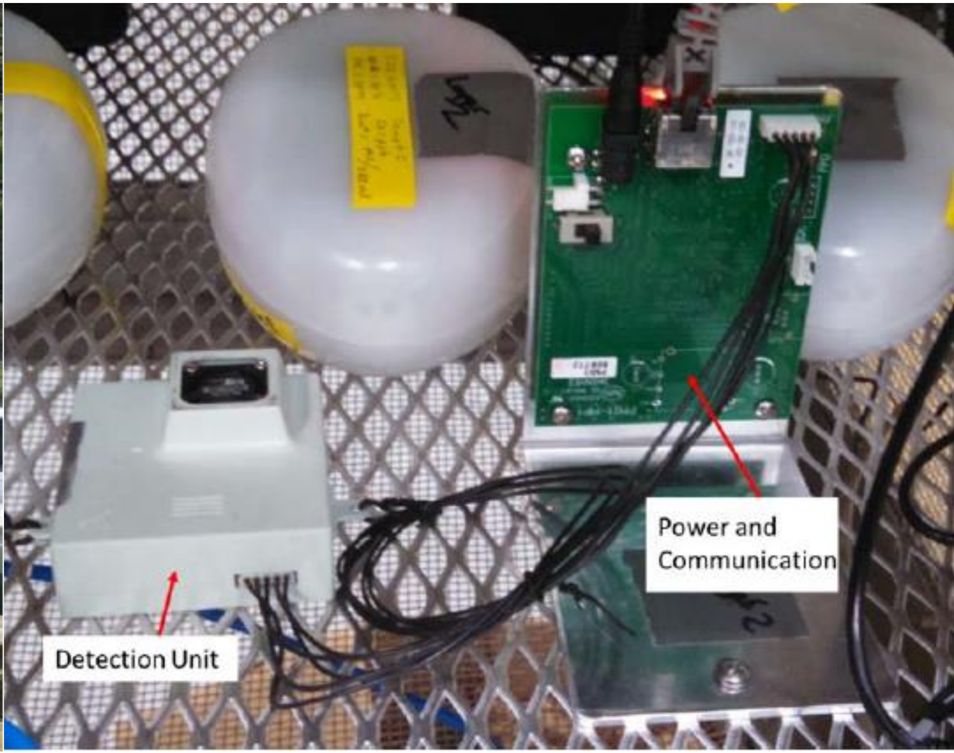
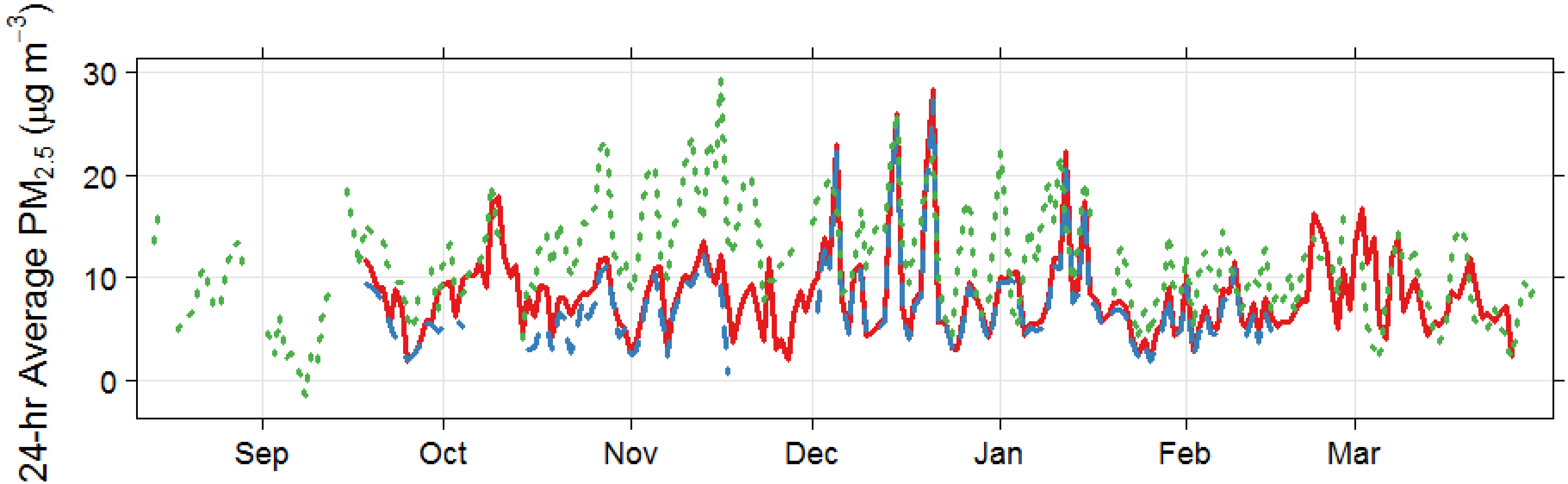
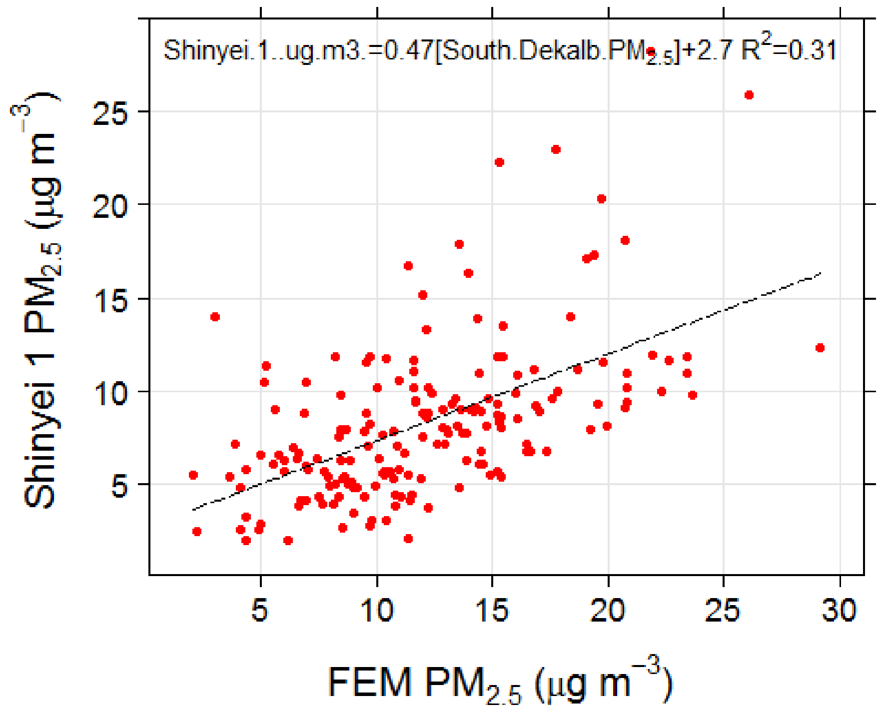
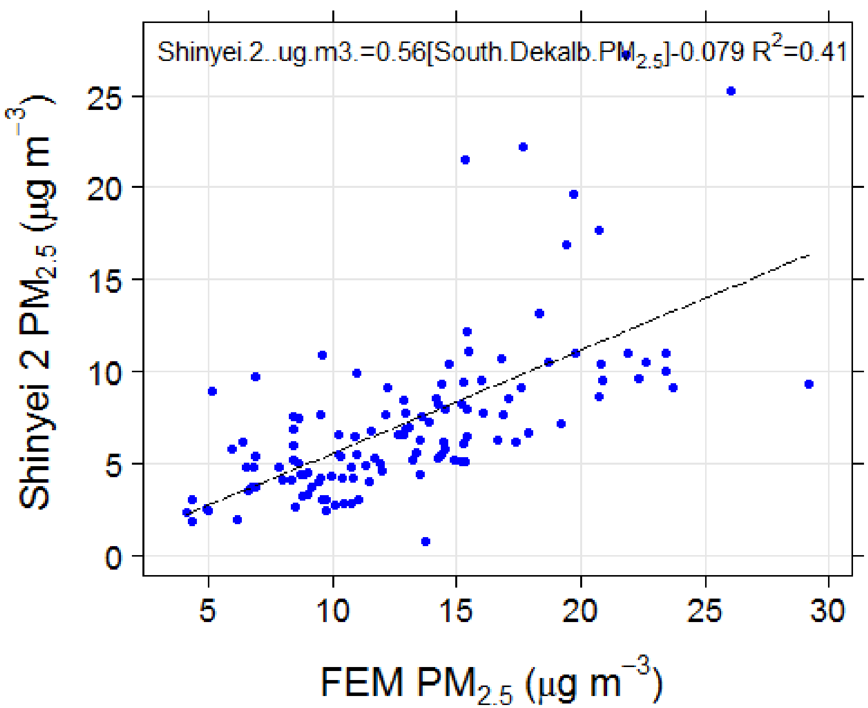
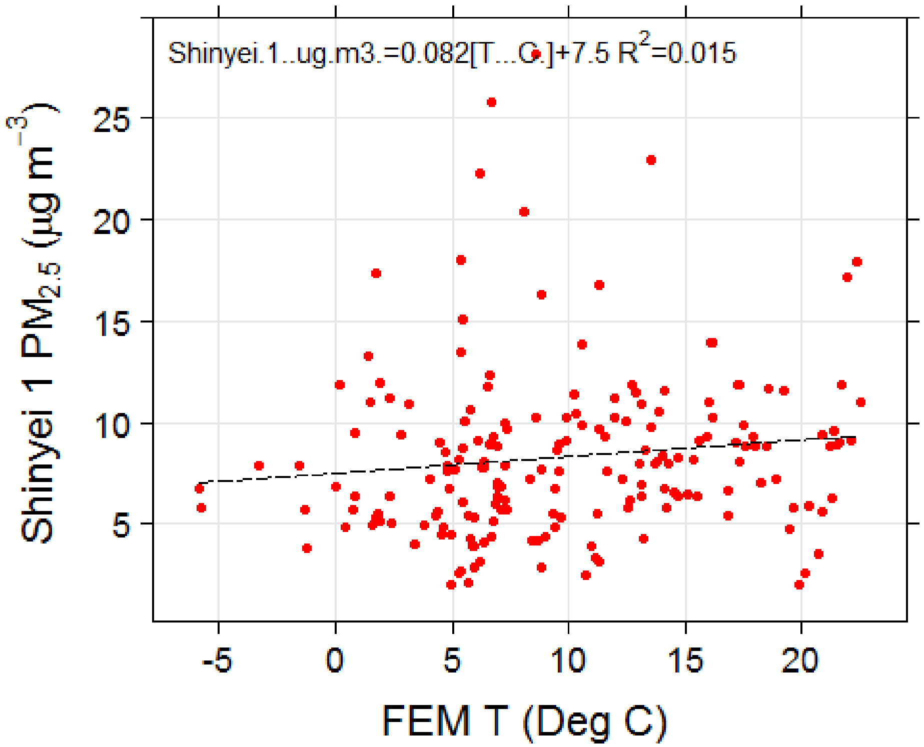


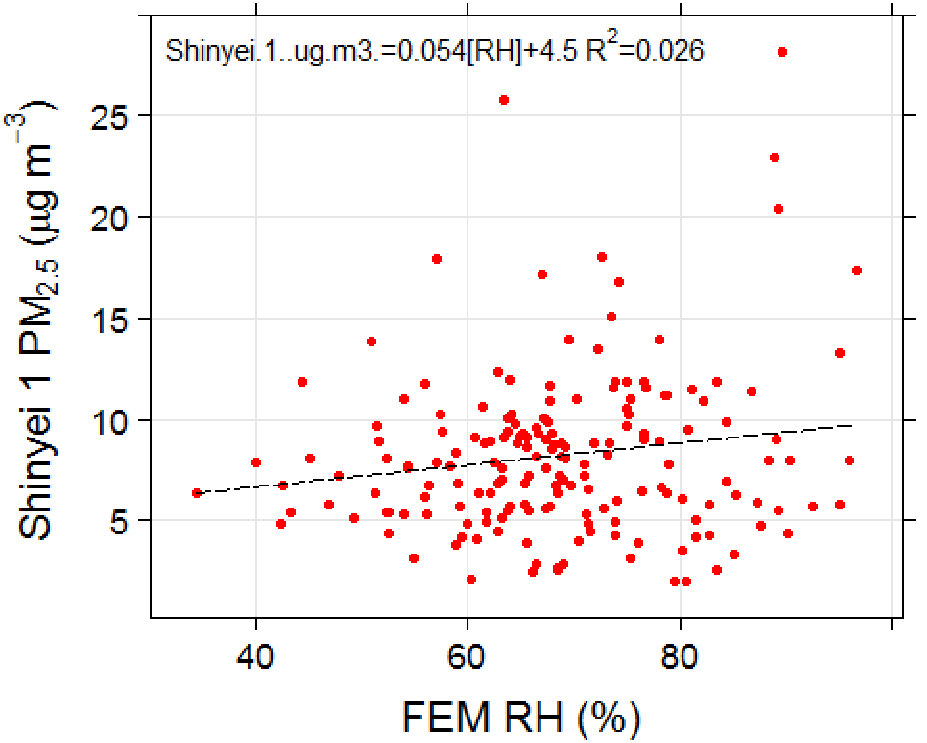
Figure A-2. Shinyei detection and power/communication units inside the chamber (Figure A-1) during field deployment.


24-hr Average $PM_{2.5}$ ($\mu g\ m^{-3}$)
30
20
10
0
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Shinyei 1
Shinyei 2
FEM


Shinyei.1..ug.m3.=0.47[South.Dekalb.$PM_{2.5}$]+2.7 R^2=0.31
Shinyei 1 $PM_{2.5}$ ($\mu g\ m^{-3}$)
FEM $PM_{2.5}$ ($\mu g\ m^{-3}$)
5
10
15
20
25
30


Shinyei.2..ug.m3.=0.56[South.Dekalb.$PM_{2.5}$]-0.079 R^2=0.41
Shinyei 2 $PM_{2.5}$ ($\mu g\ m^{-3}$)
FEM $PM_{2.5}$ ($\mu g\ m^{-3}$)
0
5
10
15
20
25
30


Shinyei.1..ug.m3.=0.082[T...C.]+7.5 R2=0.015
Shinyei 1 PM2.5 (µg m-3)
FEM T (Deg C)


Shinyei.1..ug.m3.=0.054[RH]+4.5 R2=0.026
Shinyei 1 PM2.5 (µg m-3)
FEM RH (%)

Dylos Sensor Base Design

- **Model:**
  - DC1100 PRO with PC interface, quantity × 2 (http://www.dylosproducts.com/dcproairqumo.html)
  - DC1100 with PC interface, quantity × 1 (http://www.dylosproducts.com/dcairqumowip.html)

- **Measurement:**
  - DC1100 PRO: small (≥0.5 μm) and large (≥2.5 μm) particles in unit of pt/0.01cf
  - DC1100: small (≥1 μm) and large (≥5 μm) in unit of pt/0.01cf
- **Mechanism:** laser particle counter
- **Power:** battery-operated, can be run continuously by connecting the cable to a powered USB port
- **Data retrieval and/or logging:** Arduino microcontroller with an Ethernet shield to return PM concentration and store onto a micro-SD card
- **Enclosure:** The instrument has a rugged enclosure as it is designed for portability, but it is not designed for outdoor installation and must be placed under a cover or in an enclosure to protect it from the elements.
- **Field utility:** once configured and communication is established, Dylos device is reliable and easy to deploy

Dylos Field Setup

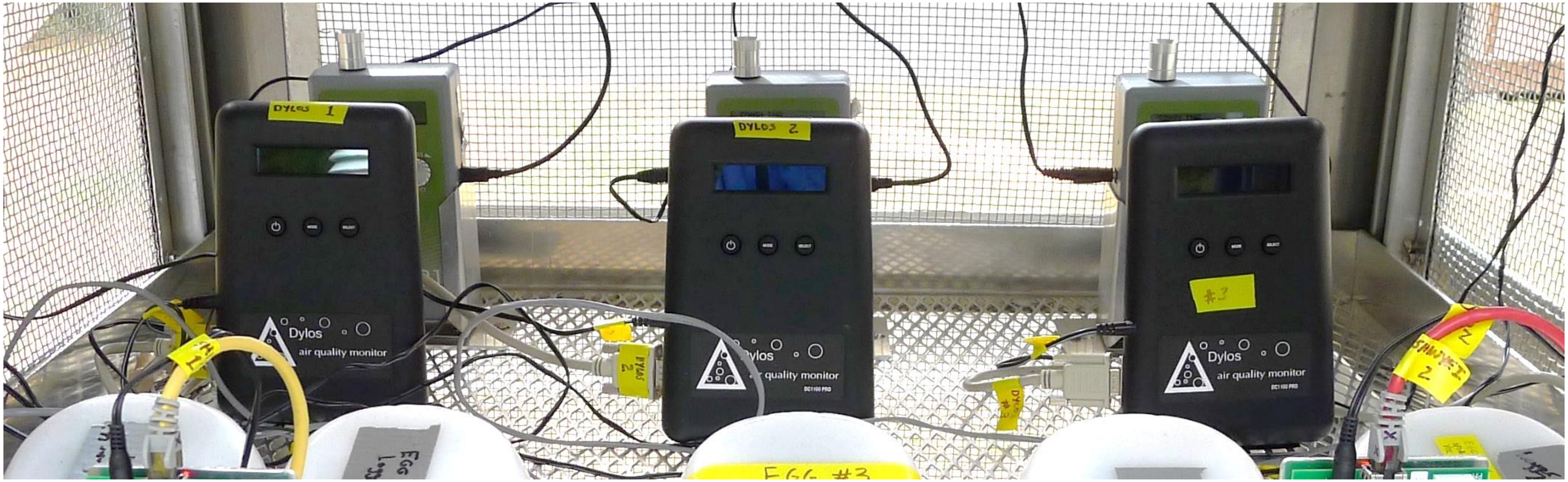
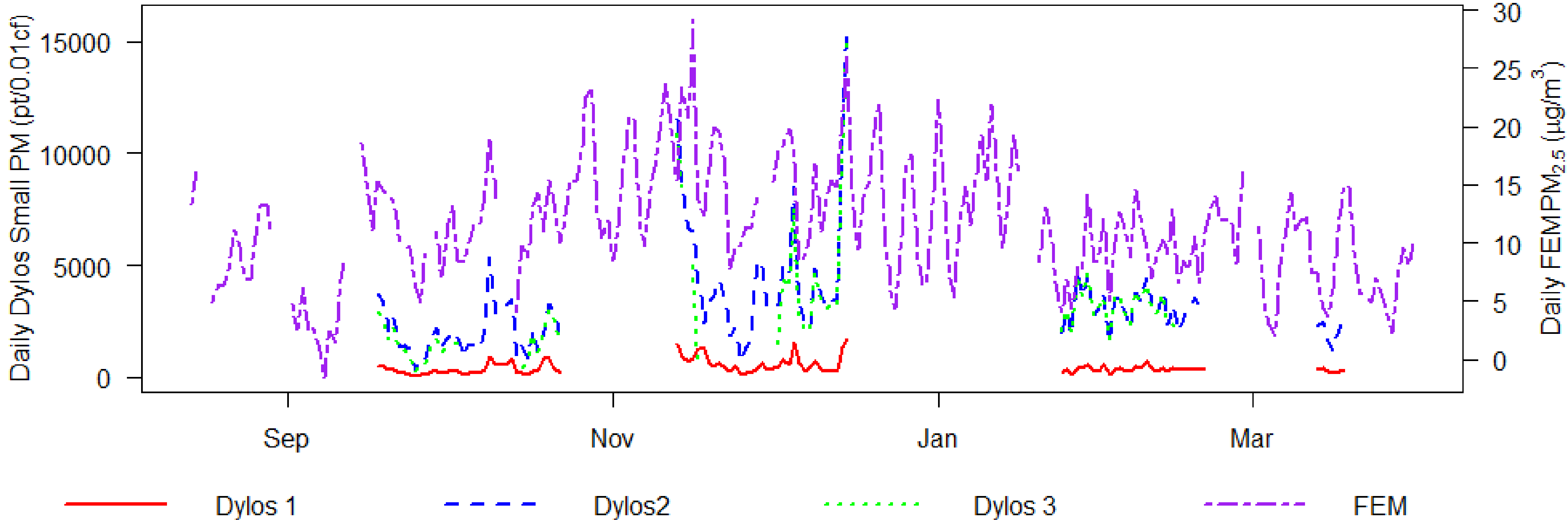
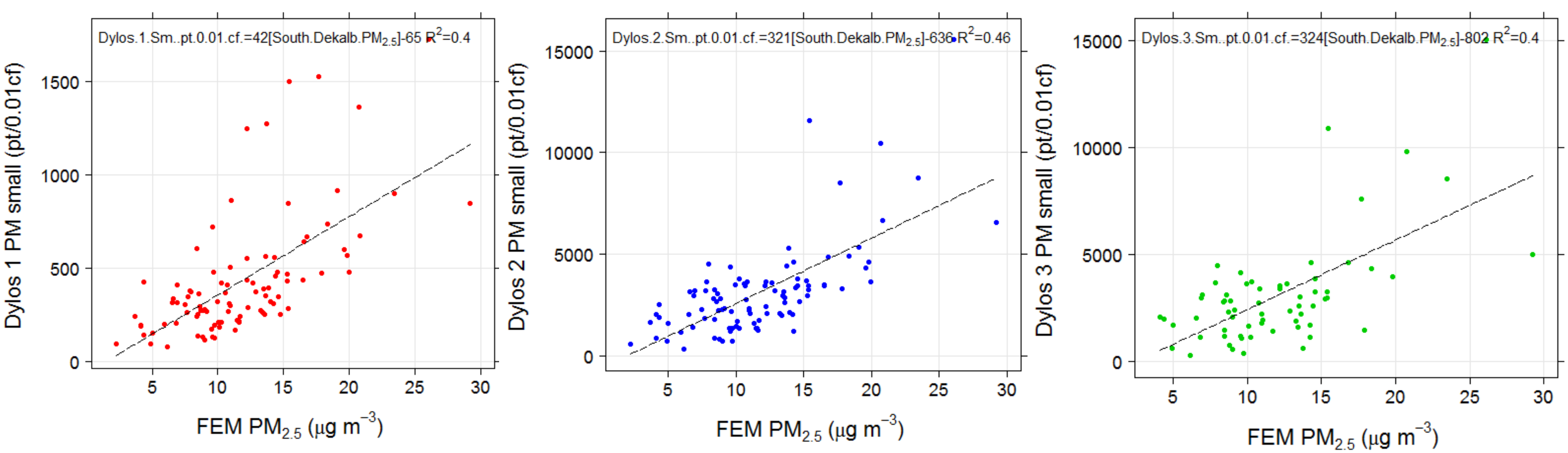
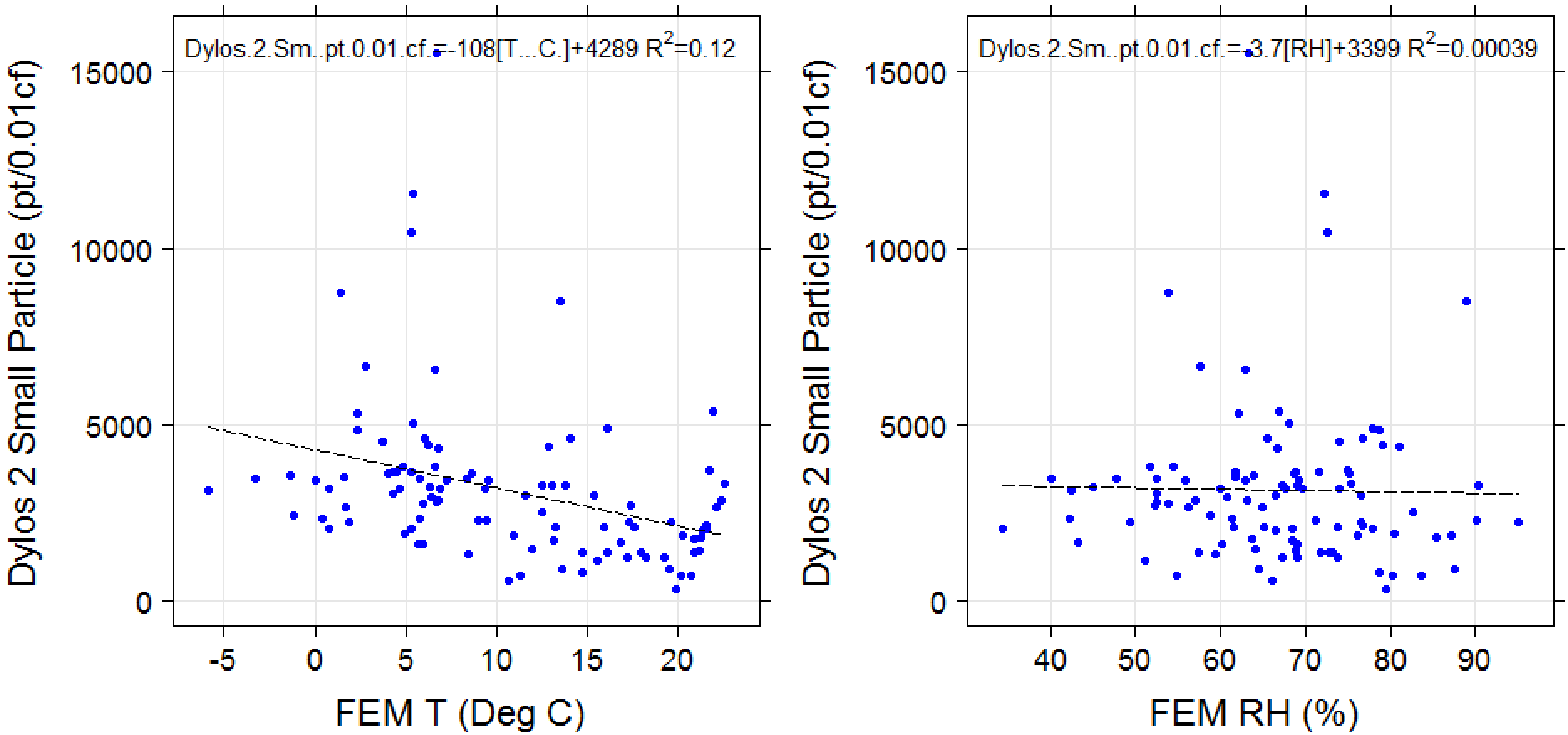


Figure A-3. Dylos units inside the chamber (Figure A-1) during field deployment.


Daily Dylos Small PM (pt/0.01cf)
Daily FEM PM2.5 (µg/m3)
15000
10000
5000
0
30
25
20
15
10
5
0
Sep
Nov
Jan
Mar
Dylos 1
Dylos2
Dylos 3
FEM


Dylos.1.Sm..pt.0.01.cf.=42[South.Dekalb.PM2.5]-65 R2=0.4
Dylos 1 PM small (pt/0.01cf)
FEM PM2.5 (µg m-3)
Dylos.2.Sm..pt.0.01.cf.=321[South.Dekalb.PM2.5]-636 R2=0.46
Dylos 2 PM small (pt/0.01cf)
FEM PM2.5 (µg m-3)
Dylos.3.Sm..pt.0.01.cf.=324[South.Dekalb.PM2.5]-802 R2=0.4
Dylos 3 PM small (pt/0.01cf)
FEM PM2.5 (µg m-3)



Dylos.2.Sm..pt.0.01.cf.=-108[T...C.]+4289 R^2=0.12
Dylos 2 Small Particle (pt/0.01cf)
15000
10000
5000
0
-5
0
5
10
15
20
FEM T (Deg C)
Dylos.2.Sm..pt.0.01.cf.=-3.7[RH]+3399 R^2=0.00039
Dylos 2 Small Particle (pt/0.01cf)
40
50
60
70
80
90
FEM RH (%)

Airbeam Sensor Base Design

- **Model:** Airbeam, sometimes referred to as AirCasting (http://aircasting.org)
  - Shinyei PPD60PV particle sensor, MaxDetect RH03 T&RH sensor, Nova MDCS42 version 2.1+EDR Bluetooth, Atmel Atmega32U4 microcontroller, Arduino Leonardo bootloader

- **Measurement:** $PM_{2.5}$ in hppcf, temperature and relative humidity
- **Mechanism:** light scattering (air is drawn through a sensing chamber wherein light from an LED bulb scatters off particles in the airstream)
- **Power:** battery-operated (a few hours), can be run continuously by connecting the cable to a powered USB port
- **Data retrieval and/or logging:** Arduino microcontroller with an Ethernet shield to return string into PM concentration and store onto a micro-SD card; bluetooth enabled, Andriod app available to initiate and log data
- **Enclosure:** need to put in an enclosure for environmental protection and allow it to be freely exposed to the atmosphere
- **Field utility:** once configured and communication is established, Airbeam device showed excellent responsiveness

Airbeam Field Setup

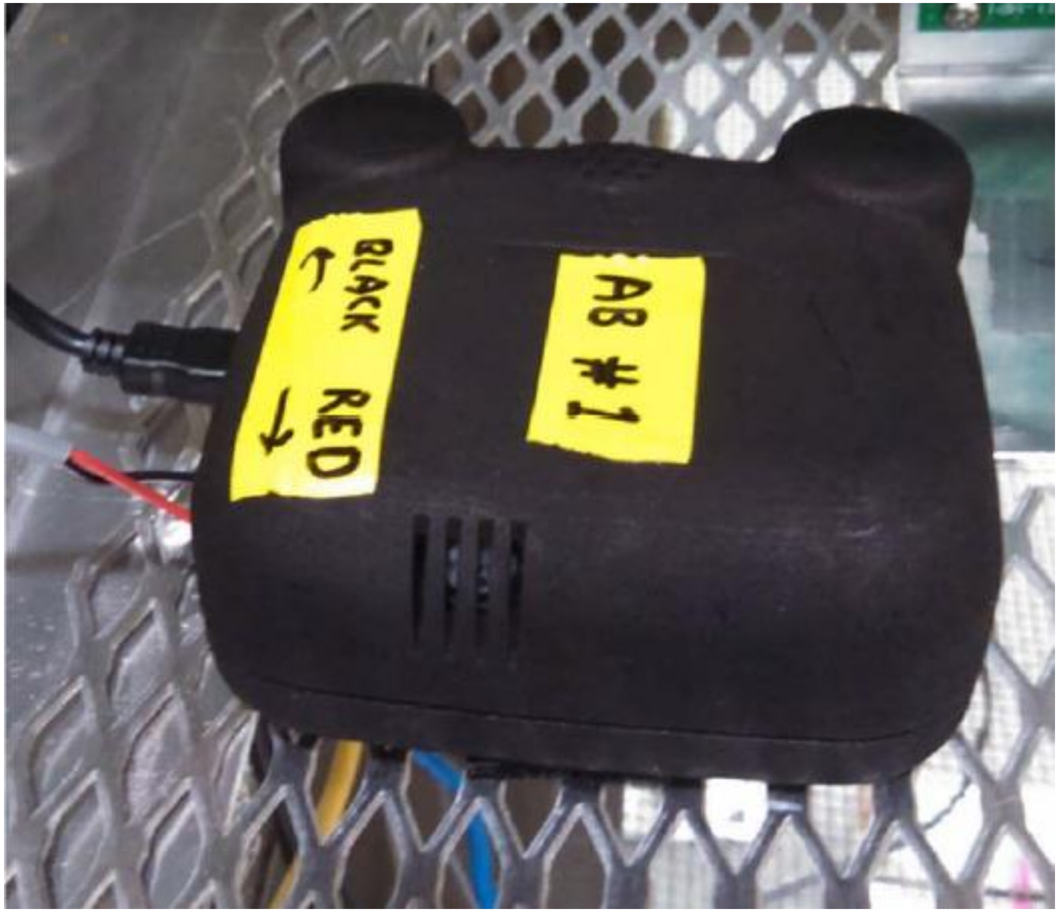
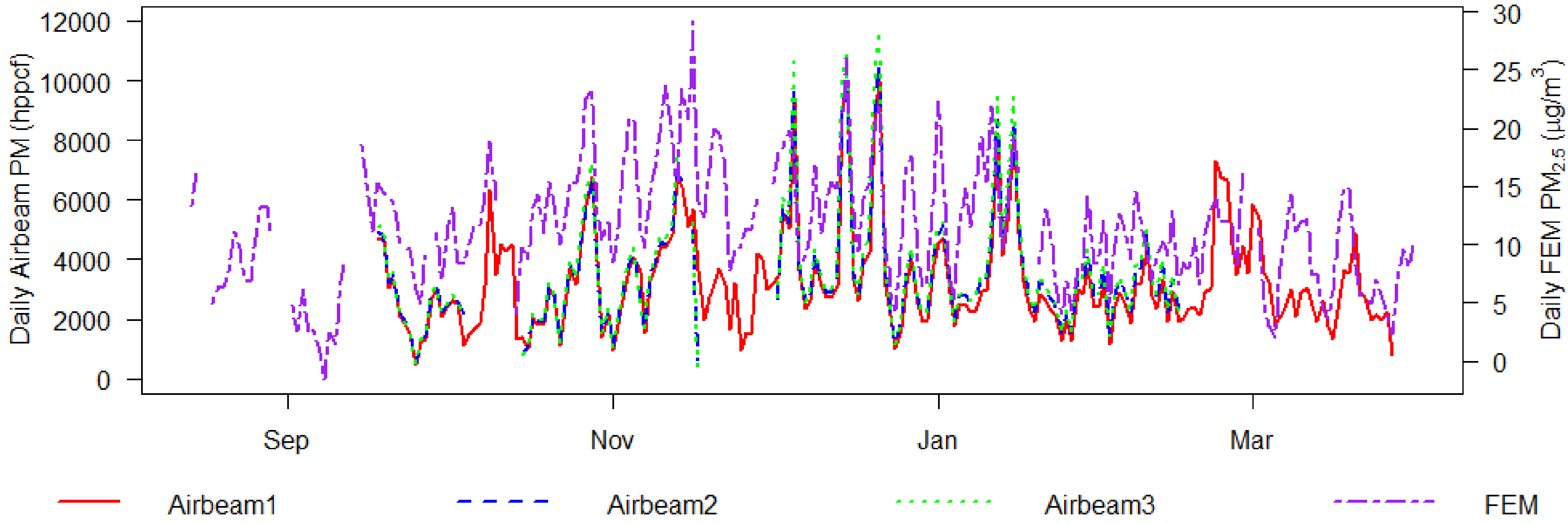
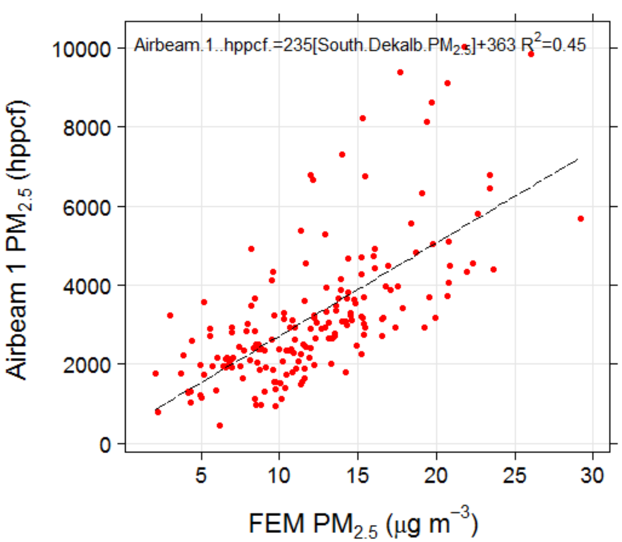


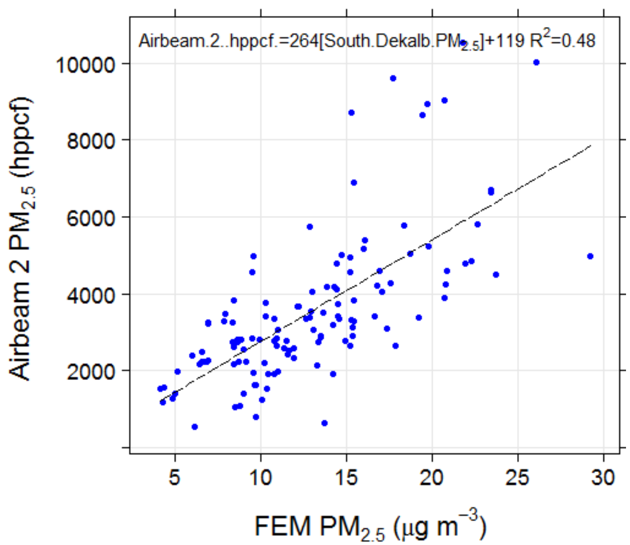
Figure A-4. Airbeam air monitoring device inside the chamber (Figure A-1) during field deployment.



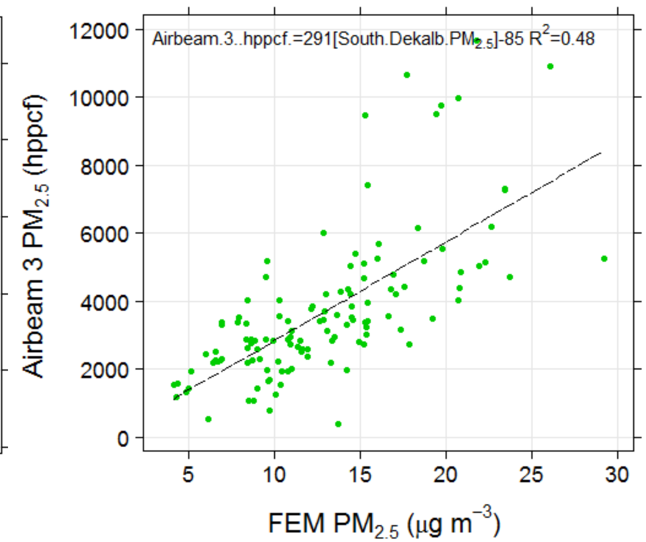
Daily Airbeam PM (hppcf)
Daily FEM PM2.5 (µg/m3)
12000
10000
8000
6000
4000
2000
0
30
25
20
15
10
5
0
Sep
Nov
Jan
Mar
Airbeam1
Airbeam2
Airbeam3
FEM



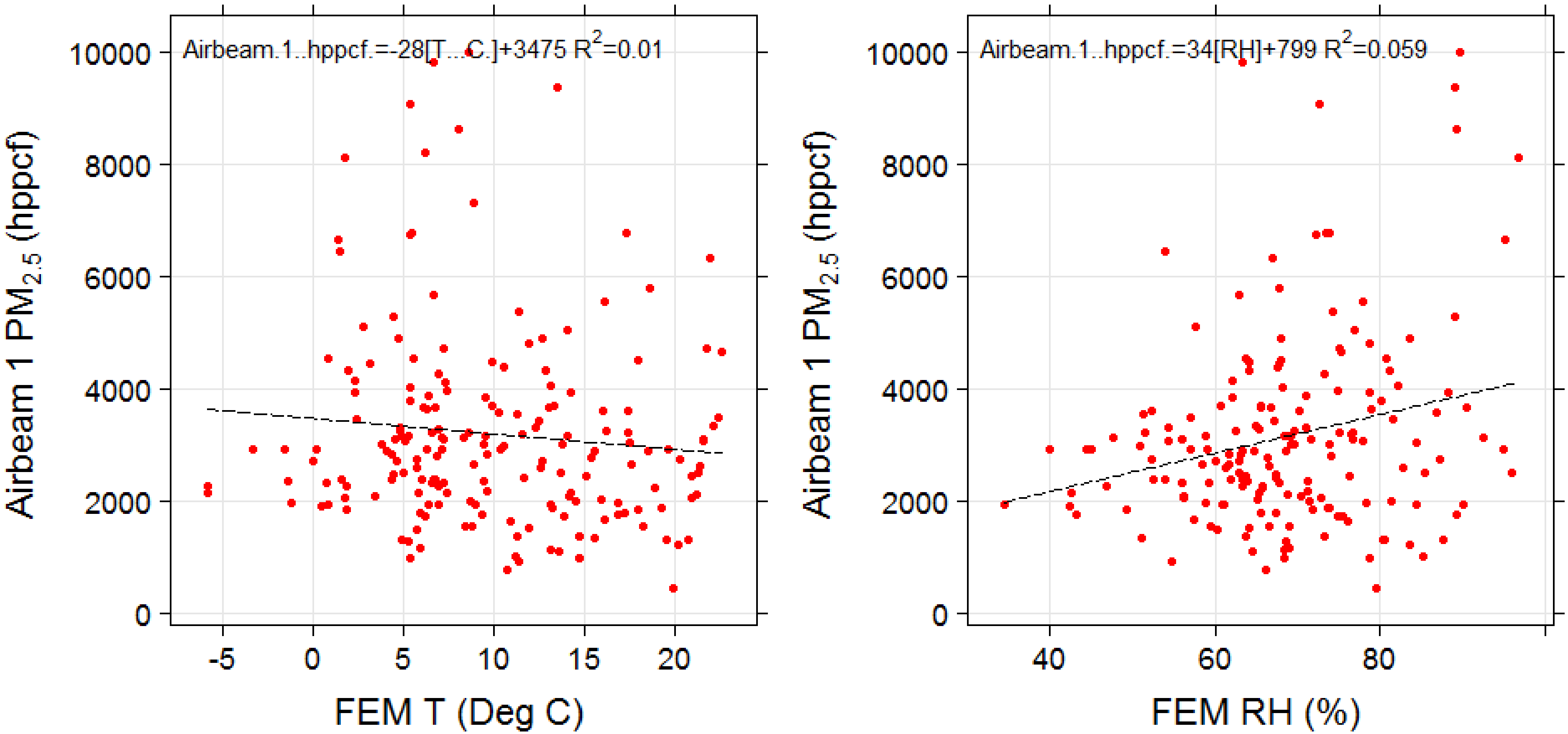
Airbeam.1..hppcf.=235[South.Dekalb.PM2.5]+363 R2=0.45
Airbeam 1 PM2.5 (hppcf)
FEM PM2.5 (µg m-3)



Airbeam.2..hppcf.=264[South.Dekalb.PM2.5]+119 R2=0.48
Airbeam 2 PM2.5 (hppcf)
FEM PM2.5 (µg m-3)



Airbeam.3..hppcf.=291[South.Dekalb.PM2.5]-85 R2=0.48
Airbeam 3 PM2.5 (hppcf)
FEM PM2.5 (µg m-3)


Airbeam.1..hppcf.=-28[T...C.]+3475 R^2=0.01
Airbeam 1 PM2.5 (hppcf)
10000
8000
6000
4000
2000
0
-5
0
5
10
15
20
FEM T (Deg C)
Airbeam.1..hppcf.=34[RH]+799 R^2=0.059
Airbeam 1 PM2.5 (hppcf)
10000
8000
6000
4000
2000
0
40
60
80
FEM RH (%)

Met One Sensor Base Design

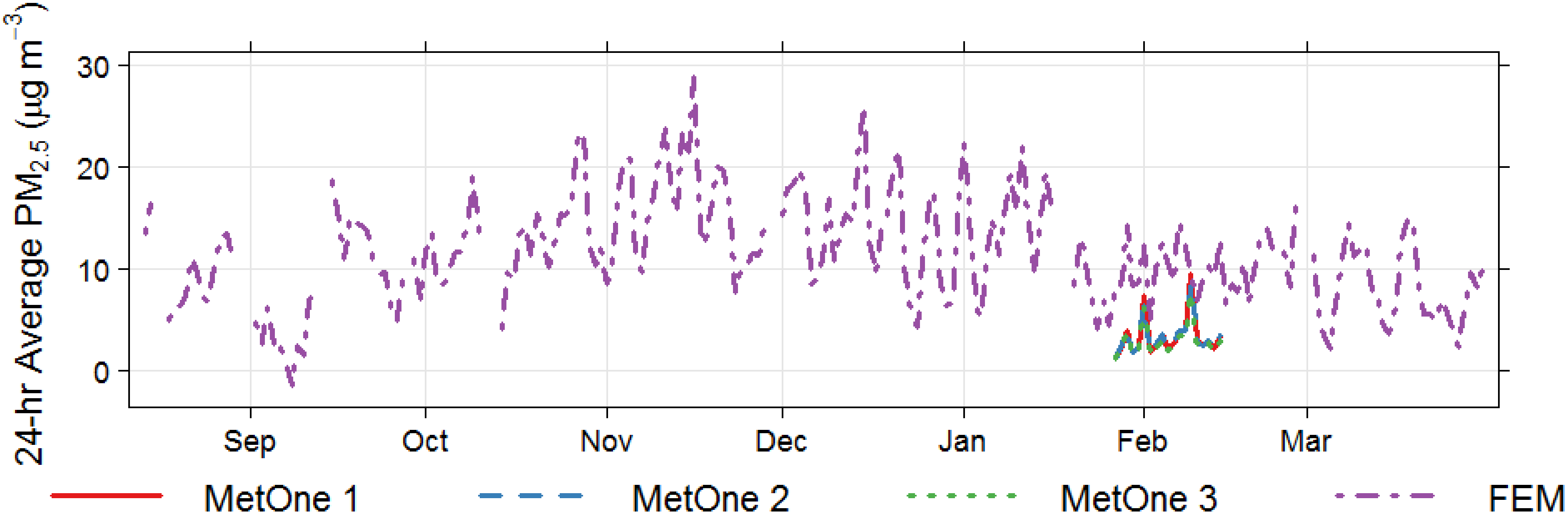
- **Model:** Met One Aerocet 831 (http://www.metone.com/particulate-831.php)
- **Measurement:** PM_1, $PM_{2.5}$, PM_4, PM_{10} and TSP in unit of µg/m^3
- **Mechanism:** particles drawn through the inlet nozzle located on top of the instrument are sized via light scattering (laser diode, 780 nm, 40 mW)

- **Power:** battery-powered (8 hours for continuous sampling), can be operated for an extended period by connecting the instrument to a DC power supply.
- **Data retrieval and/or logging:** The Met One outputs a serial string to its USB port at the end of each sampling period. However, the appropriate drivers for the Arduino to communicate with the 831 USB port are not available. The 831 data were logged to a separate Panasonic Toughbook running a custom MS Visual Basic program. Data was retrieved manually by visiting the site. Met One also provides “Comet” software that can be used to view and analyze data stored on the 831.
- **Enclosure:** The instrument has a rugged enclosure as it is designed for portability, but it is not designed for outdoor installation and must be placed under a cover or in an enclosure to protect it from the elements.
- **Field utility:** Aside from the current inconvenience of logging data to a separate laptop, the Met One 831 is reliable and easy to deploy. Data communication is reliable and the instrument itself appears to be robust. Another potential drawback is that only 2500 records can be internally saved.

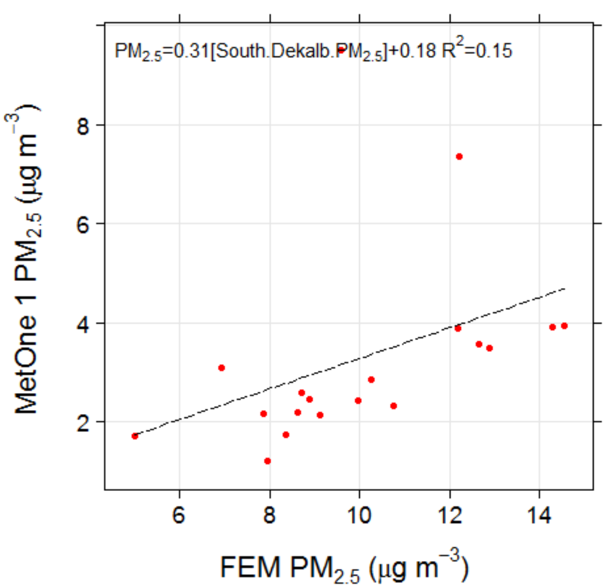
Met One Field Setup

Figure A-5. Met One 831 air monitoring device.

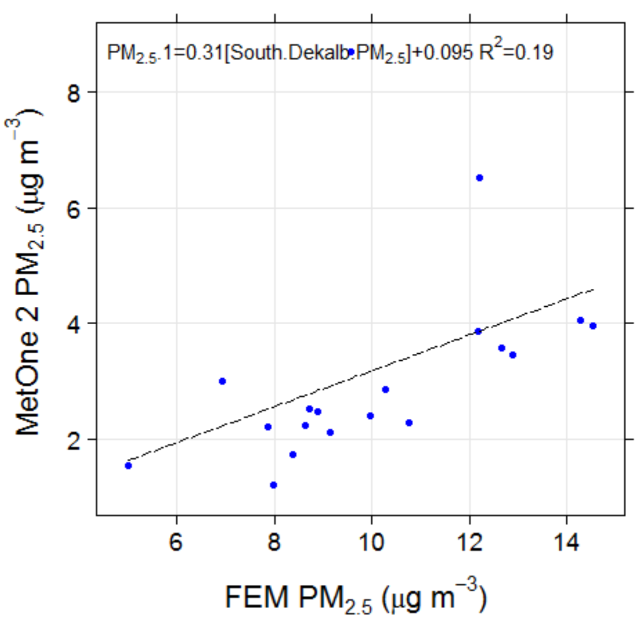
Figure A-6. Met One inside the chamber (Figure A-1) during field deployment (behind a Dylos instrument).



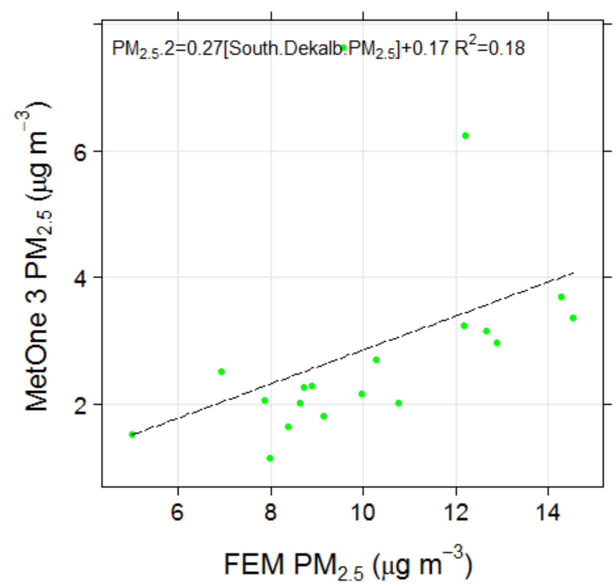
24-hr Average PM2.5 (µg m−3)
30
20
10
0
Sep
Oct
Nov
Dec
Jan
Feb
Mar
MetOne 1
MetOne 2
MetOne 3
FEM



PM2.5=0.31[South.Dekalb.PM2.5]+0.18 R2=0.15
MetOne 1 PM2.5 (µg m−3)
FEM PM2.5 (µg m−3)



PM2.5.1=0.31[South.Dekalb.PM2.5]+0.095 R2=0.19
MetOne 2 PM2.5 (µg m−3)
FEM PM2.5 (µg m−3)



PM2.5.2=0.27[South.Dekalb.PM2.5]+0.17 R2=0.18
MetOne 3 PM2.5 (µg m−3)
FEM PM2.5 (µg m−3)

Aeroqual Sensor Base Design

- **Model:** Aeroqual SM50 ozone sensor circuit (http://www.aeroqual.com/product/sm50-ozone-sensor-circuit)
- **Measurement:** ozone concentration in ppb (range: 0-0.15 ppm, LDL: 1 ppb)
- **Mechanism:** Aeroqual's proprietary gas sensitive semiconductor (GSS) sensors which incorporate a dynamic baseline adjustment to reduce sensor drift

- **Power:** The SM50 module will run off a DC input voltage in the range 11 - 24 VDC. Connect power to the V+ and GND screw terminal connectors or to the VIN and GND pins on the micromatch connectors. Power consumption varies depending on the SM50 sensor in the range 2.5 to 6W.
- **Data retrieval and/or logging:** There are multiple outputs fitted as standard including diagnostic LEDs, 0-5V signal, relay, RS232, and RS485 digital communications. Gas concentration data and diagnostic information is available on the RS232 and Rs485 digital communication. The study uses Arduino microcontroller with an Ethernet shield to connect the RS232 and store the data onto a micro-SD card.
- **Enclosure:** The SM50 comes in as a sensor circuit board, which needs to be put in an enclosure for environmental protection and allow it to be freely exposed to the atmosphere.
- **Field utility:** The SM50 provides analyzer-like performance, with 1ppb detection limits, yet cost as much as 4-5 times less then the most cost effective ozone analyzers on the market. But it has higher power draw than other sensors.

Aeroqual Field Setup

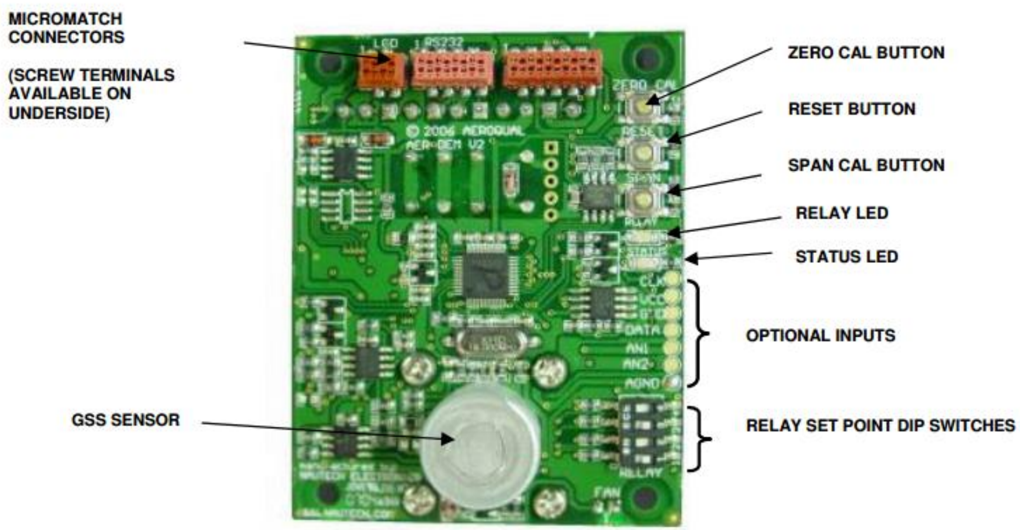


Figure A-7. Aeroqual SM50 ozone sensor circuit.

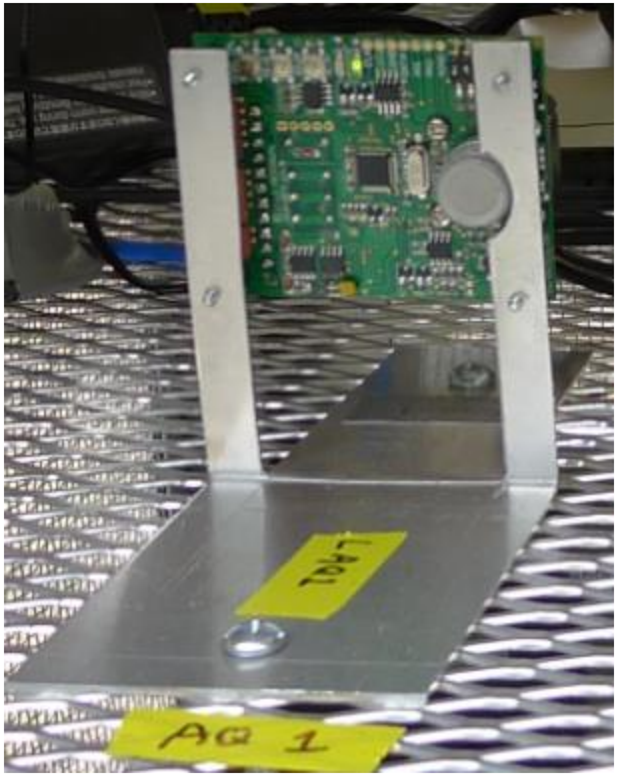
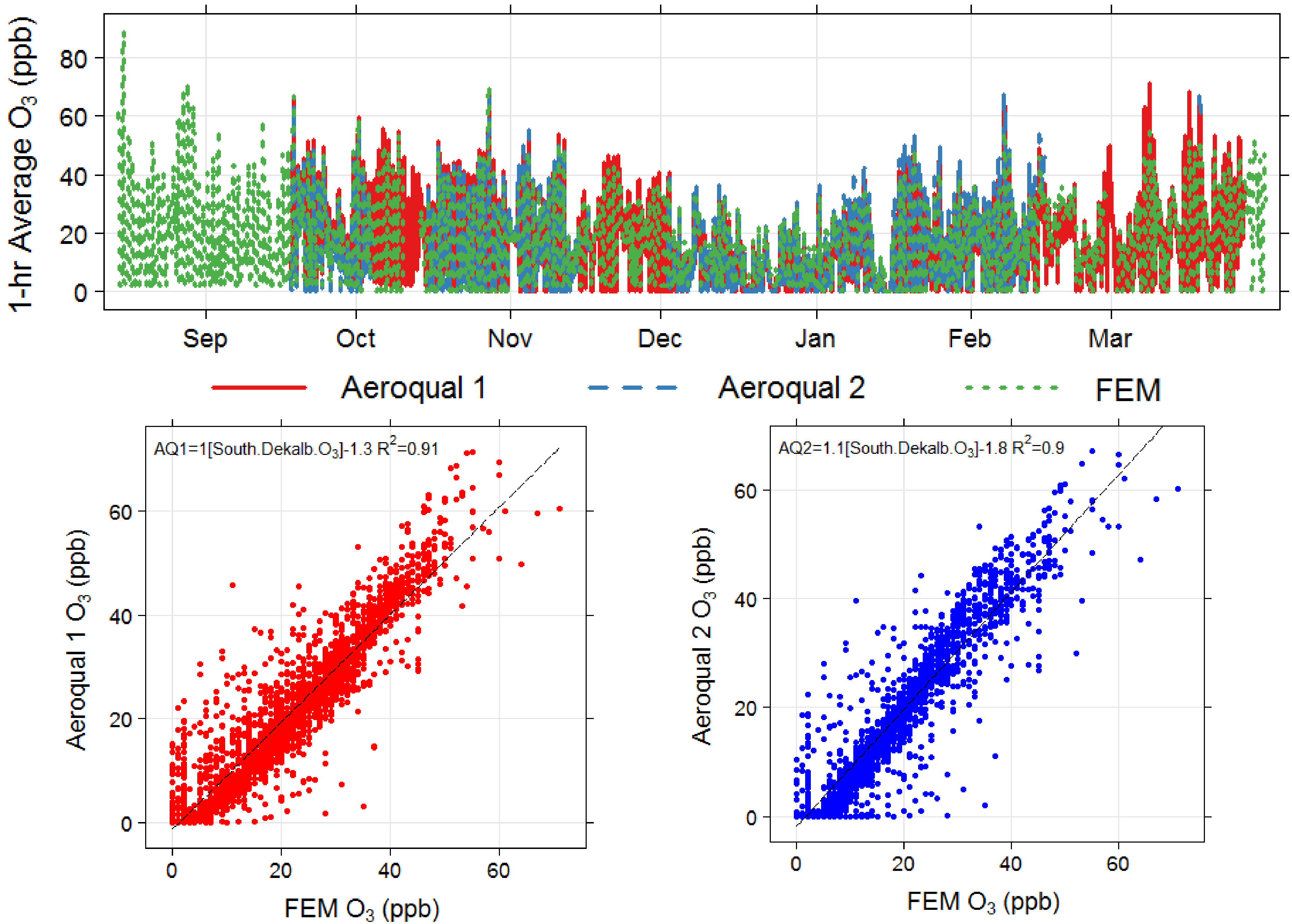
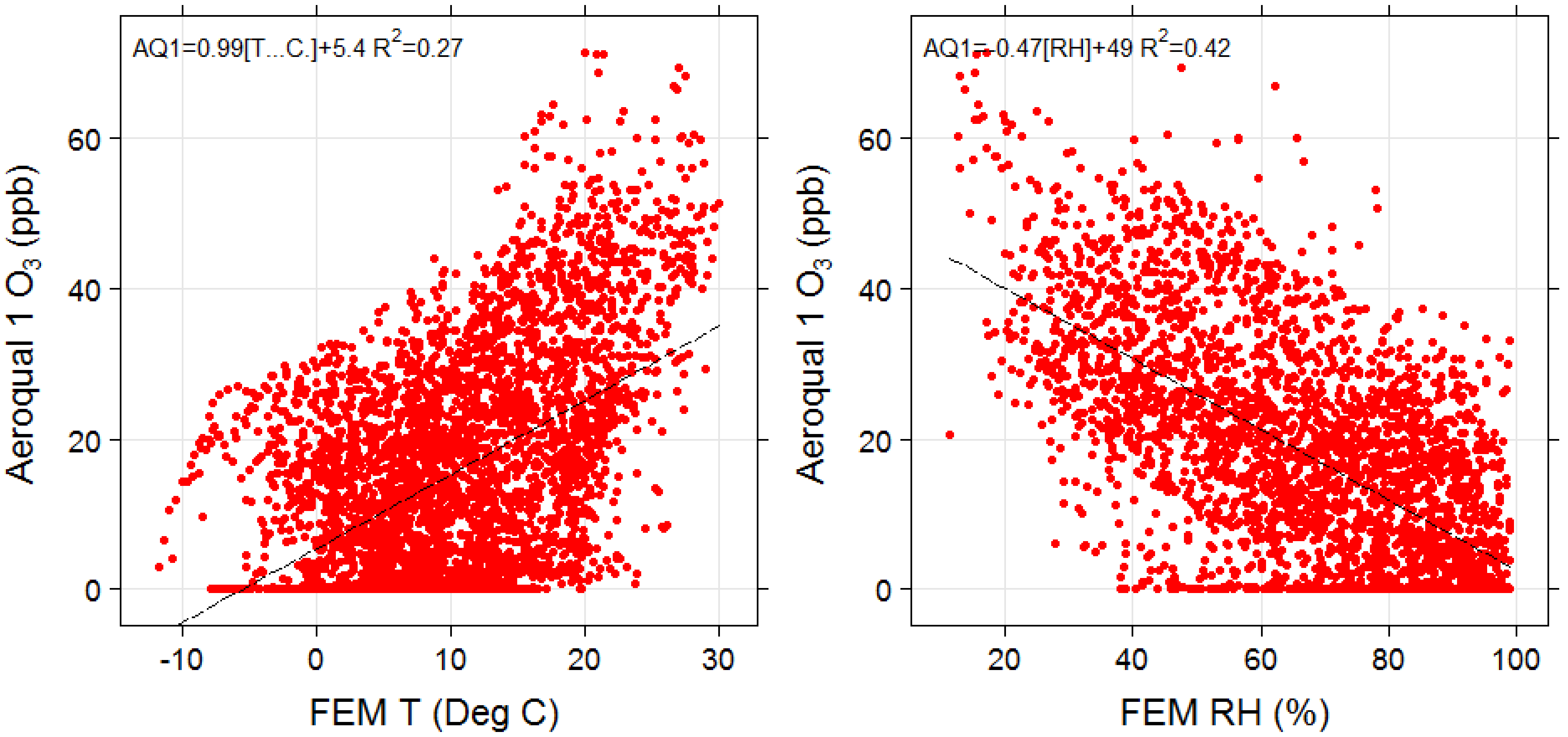


Figure A-8. Aeroqual board inside the chamber (Figure A-1) during field deployment.



1-hr Average O_3 (ppb)
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Aeroqual 1
Aeroqual 2
FEM
AQ1=1[South.Dekalb.O_3]-1.3 R^2=0.91
Aeroqual 1 O_3 (ppb)
FEM O_3 (ppb)
AQ2=1.1[South.Dekalb.O_3]-1.8 R^2=0.9
Aeroqual 2 O_3 (ppb)
FEM O_3 (ppb)


AQ1=0.99[T...C.]+5.4 R2=0.27
Aeroqual 1 O3 (ppb)
FEM T (Deg C)
AQ1=-0.47[RH]+49 R2=0.42
Aeroqual 1 O3 (ppb)
FEM RH (%)

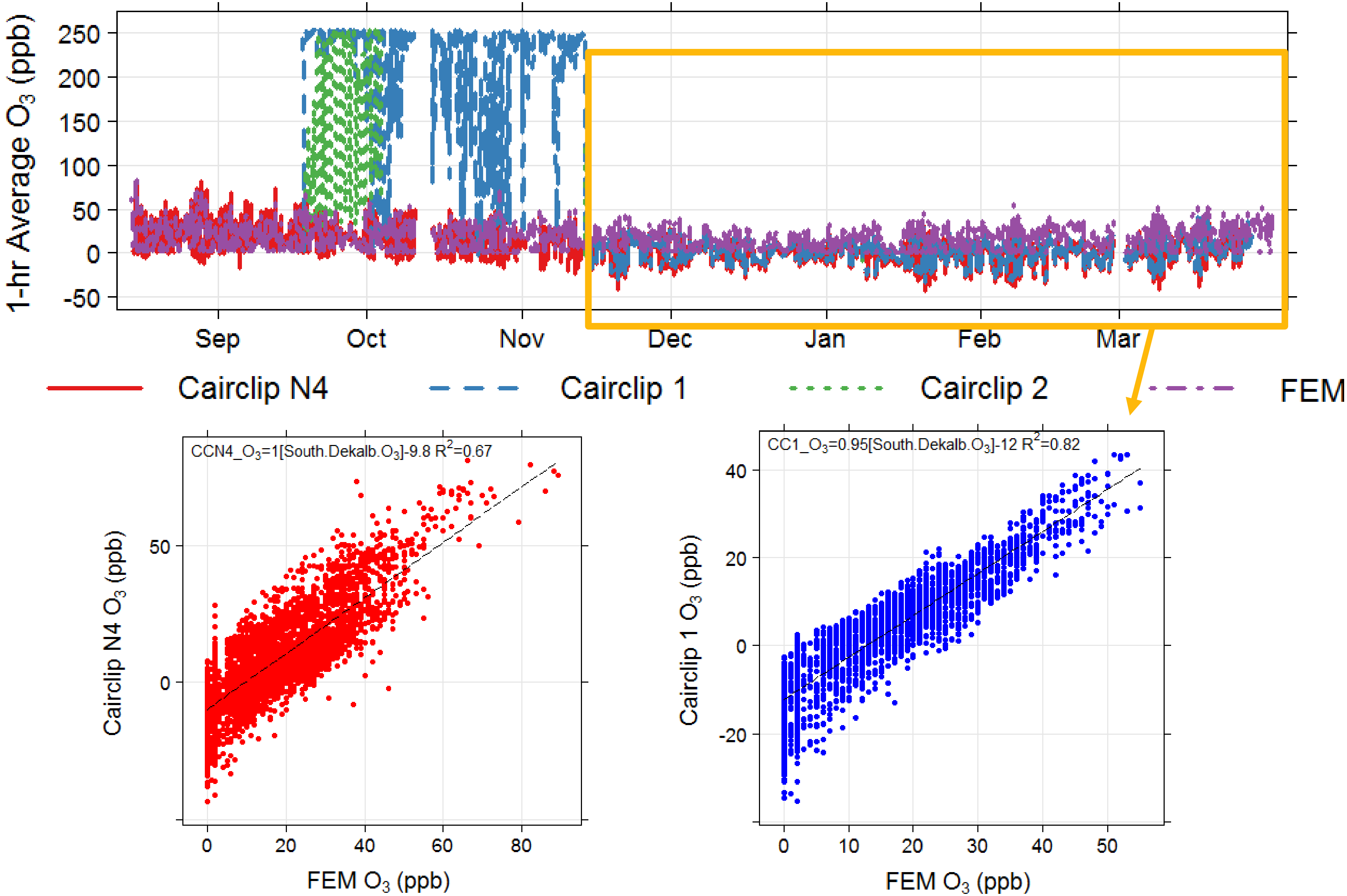
CairClip Sensor Base Design

- **Model:** CairClip O_3/NO_2 UART version – applications require extended runtime and interface with supervisory data loggers (http://www.cairpol.com/)
- **Measurement:** combined O_3 + NO_2 concentration in ppb (range: 0 to 250 ppb)
- **Mechanism:** The amperometric sensor consists of three electrodes: working electrode (anode), counter-electrode (cathode) and the reference electrode. The electrical signal generated between anode and cathode is proportional to the concentration.
- **Power:** The UART version does not include a battery and must be powered via the mini USB connection. Power is supplied via a DC/DC converter that converts 12 VDC to 5 VDC.
- **Data retrieval and/or logging:** The serial string is 3.3 VDC TTL logic and must be converted to 5 VDC TTL logic for direct input into an Arduino. Cairpol has written a manual to describe the details of the serial communication protocol including how to poll the unit and interpret the response.
- **Enclosure:** The CairClip device is a small individual unit and requires no assembly. It has no environmental protection and is therefore best deployed in a well ventilated enclosure for long term outdoor deployments.
- **Field utility:** The UART version sometimes report an unrealistically high number due to the power supply problem. Serial communication is not always reliable but typically do not last for a long time. Its compact size, robustness, low power usage, and ease of use make it potentially useful for field deployment. Possible interference include abrupt variation in RH and T.

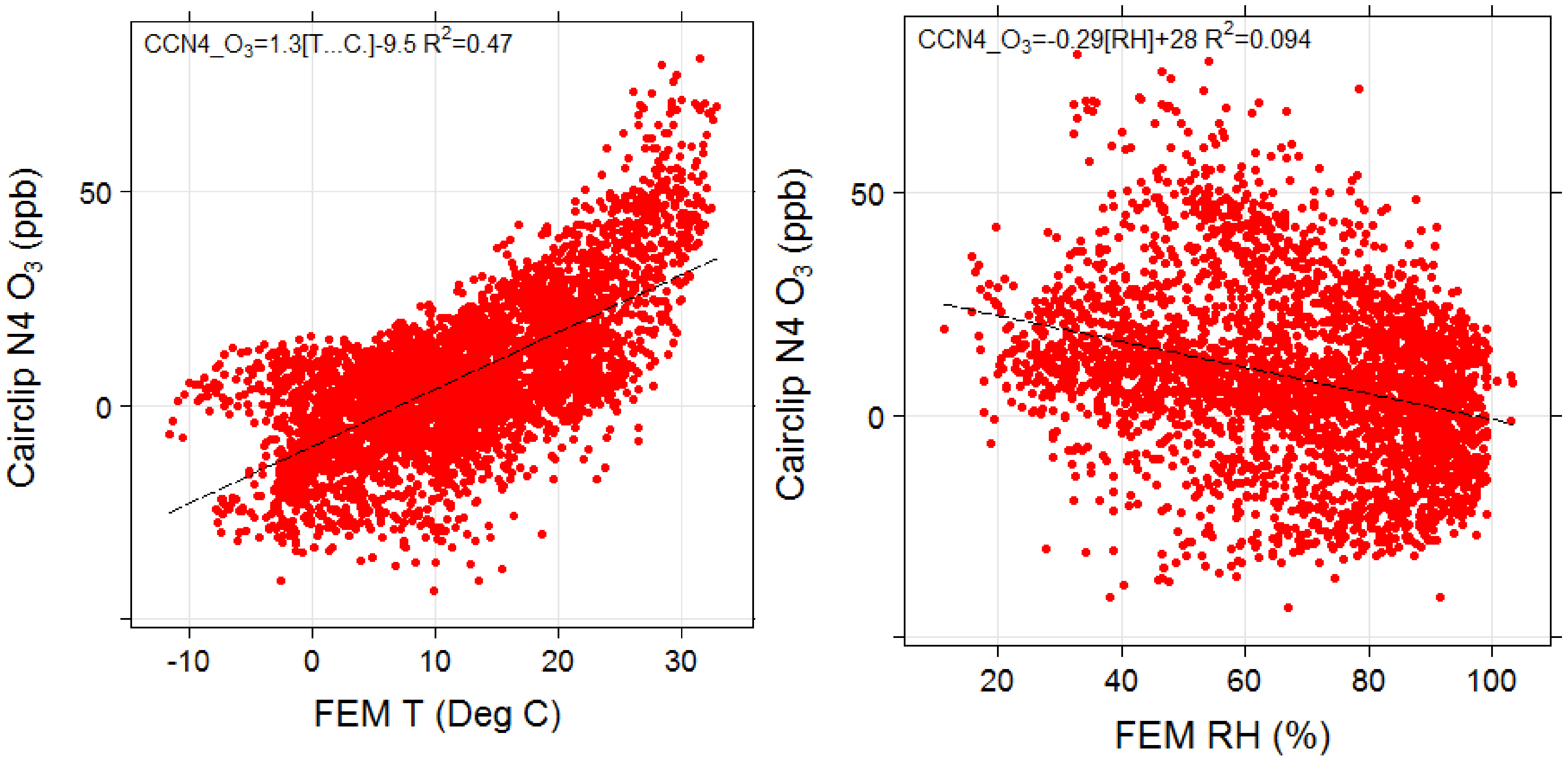
CairClip Field Setup

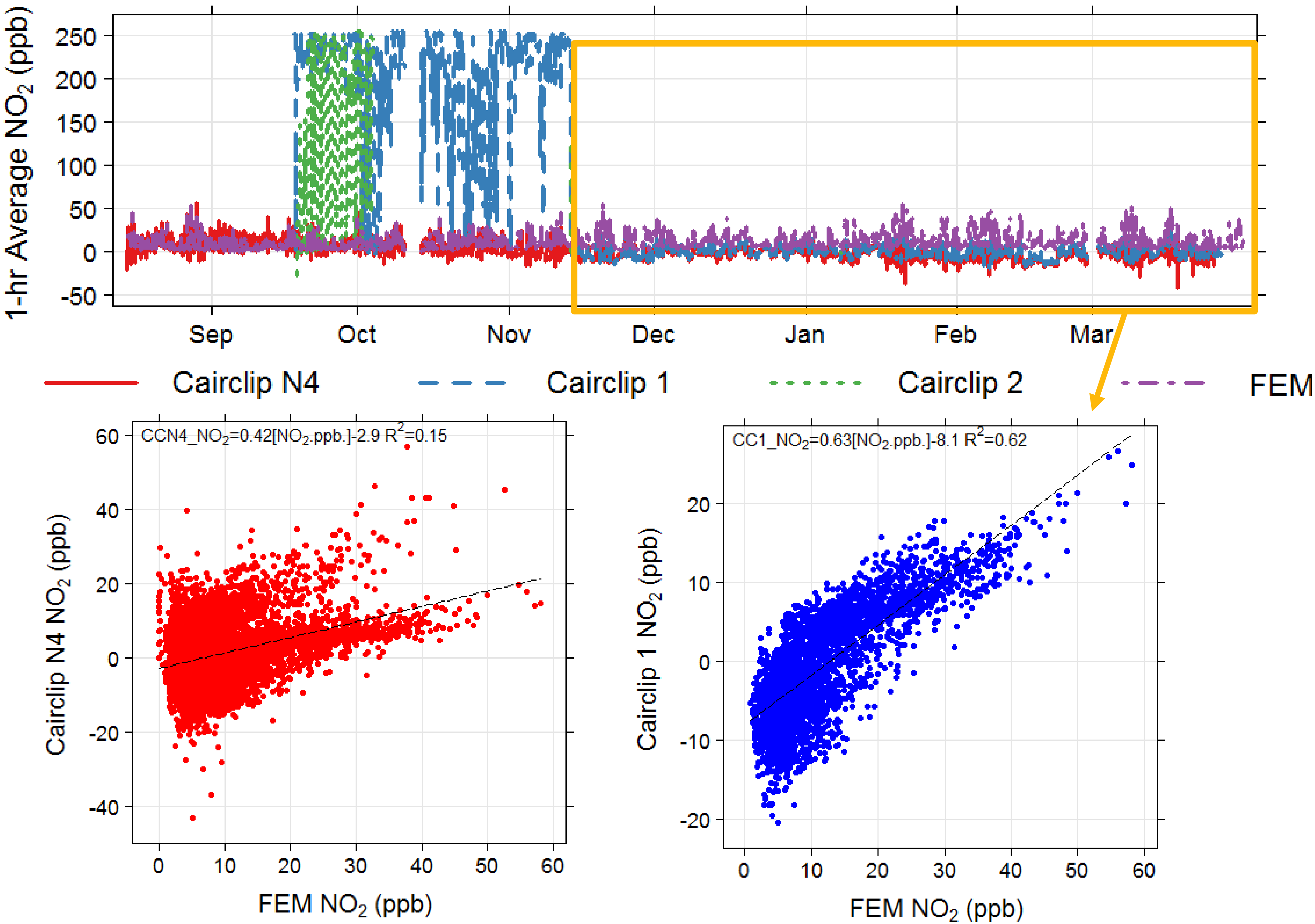
Figure A-9. CairClip O_3/NO_2 sensor.

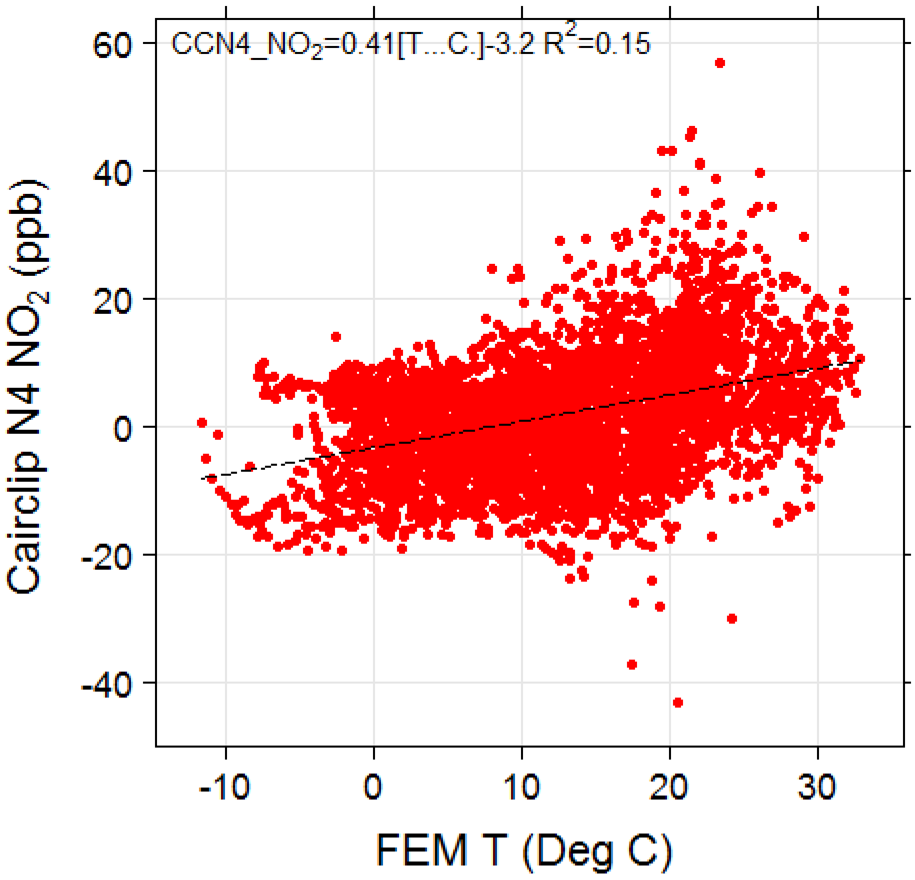
Figure A-10. CairClip sensor inside the chamber (Figure A-1) during field deployment.



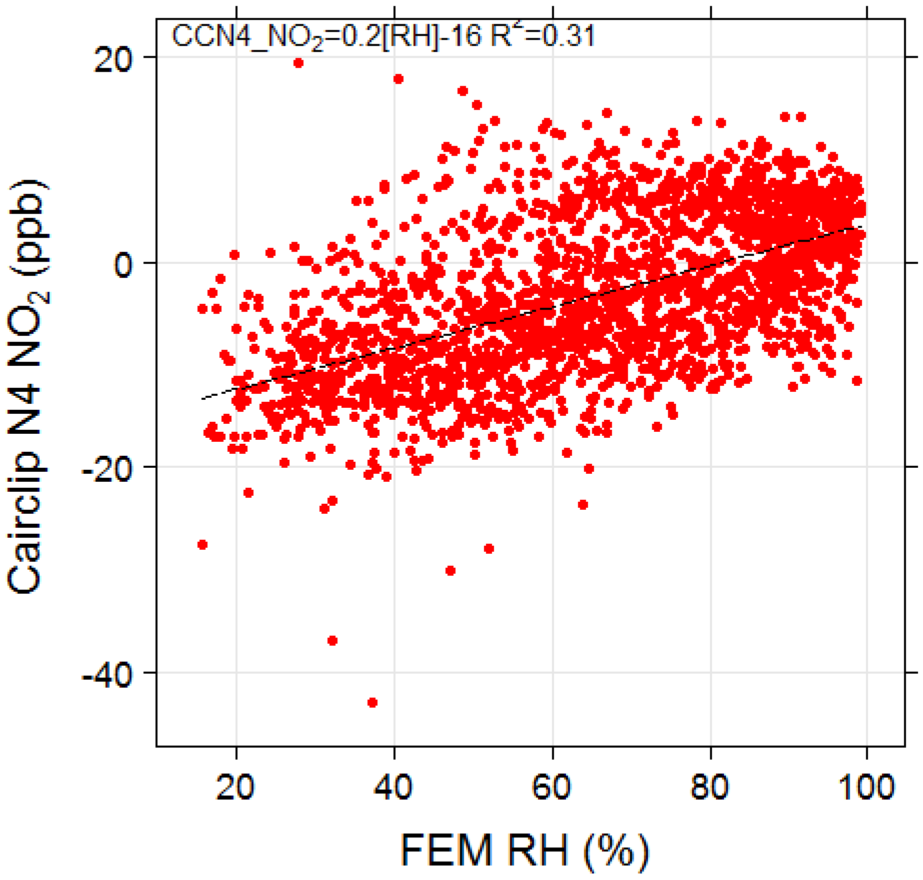
The non-functional CC2 was excluded in the analysis


CCN4_O3=1.3[T...C.]-9.5 R2=0.47
50
0
-10
0
10
20
30
Cairclip N4 O3 (ppb)
FEM T (Deg C)
CCN4_O3=-0.29[RH]+28 R2=0.094
50
0
20
40
60
80
100
Cairclip N4 O3 (ppb)
FEM RH (%)


1-hr Average NO2 (ppb)
250
200
150
100
50
0
-50
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Cairclip N4
Cairclip 1
Cairclip 2
FEM
CCN4_NO2=0.42[NO2.ppb.]-2.9 R2=0.15
Cairclip N4 NO2 (ppb)
FEM NO2 (ppb)
CC1_NO2=0.63[NO2.ppb.]-8.1 R2=0.62
Cairclip 1 NO2 (ppb)
FEM NO2 (ppb)



CCN4_NO2=0.41[T...C.]-3.2 R2=0.15
60
40
20
0
-20
-40
-10
0
10
20
30
Cairclip N4 NO2 (ppb)
FEM T (Deg C)



CCN4_NO2=0.2[RH]-16 R2=0.31
20
0
-20
-40
20
40
60
80
100
Cairclip N4 NO2 (ppb)
FEM RH (%)

AQMesh Sensor Base Design

- **Model:** AQMesh (http://www.aqmesh.com/)
- **Measurement:** one unit containing sensors for CO, NO, NO_2, O_3, CO, SO_2, pressure, temperature, and humidity
- **Mechanism:** electrochemical gas sensors

- **Power:** The onboard battery (listed to last for up to 2 years) allows for easy deployment without the need for an external power source.
- **Data retrieval and/or logging:** AQMesh logs data to a web-based remote server “AQMesh.net”. Access to the server requires a username and password from the manufacturer or local distributor. Depending on the application, the manufacturer can periodically send data to the user in Excel format via email.
- **Enclosure:** The AQMesh has its own protective enclosure and is very versatile in terms of how it may be deployed in the field. With a built in protective weather shield, it is well suited for outdoor installations.
- **Field utility:** A 5 day stabilization period plus a 2 to 4 day baseline adjustment period are required after sensor activation and should be taken into account when planning for deployment.

AQMesh Parameters

Parameter	Range	Unit	Limit of detection
STANDARD			
Nitric oxide (NO)	0-2000 ppb	ppb or µg/m^3	<5ppb
Nitrogen dioxide (NO2)	0-200ppb	ppb or µg/m^3	<5ppb
Ozone	0-200ppb	ppb or µg/m^3	<5ppb
Pod temperature	-20 to 100°C	°C	0.1°C
Atmospheric pressure	500-1,500mb	mb	1mb
Relative humidity	0-100%RH	%RH	1%RH
OPTIONAL			
Particle count *from July 2015*	1-30 µm	Particles/cm^3	1µm
Carbon Monoxide (CO)	0-5,000ppb	ppb or µg/m^3	<5ppb
Sulphur dioxide (SO2) *from July 2015*	0-100,000ppb	ppb or µg/m^3	<5ppb

Source: http://www.aqmesh.com/product/variants/

AQ Mesh Field Deployment

Figure A-11. AQ Mesh field setup.

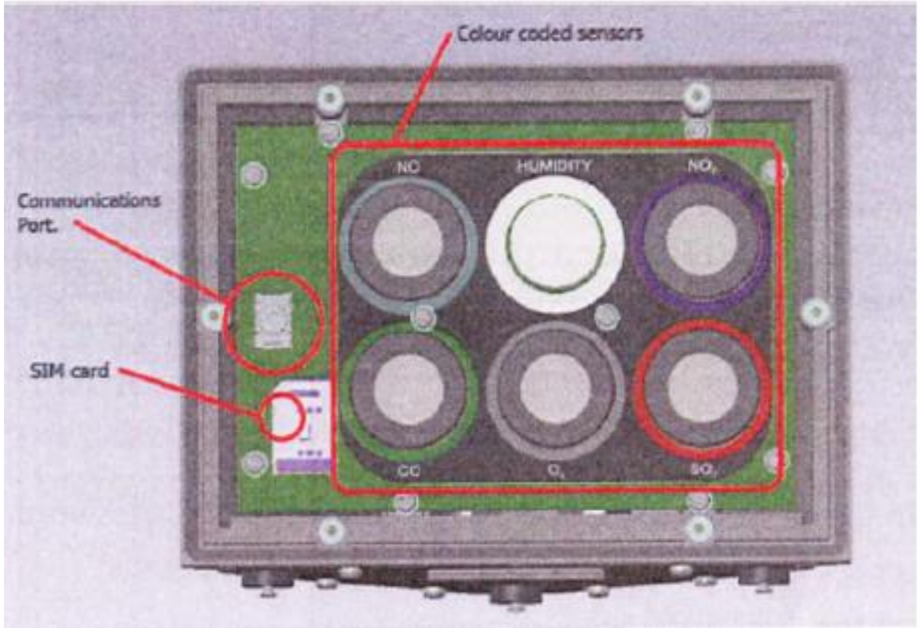
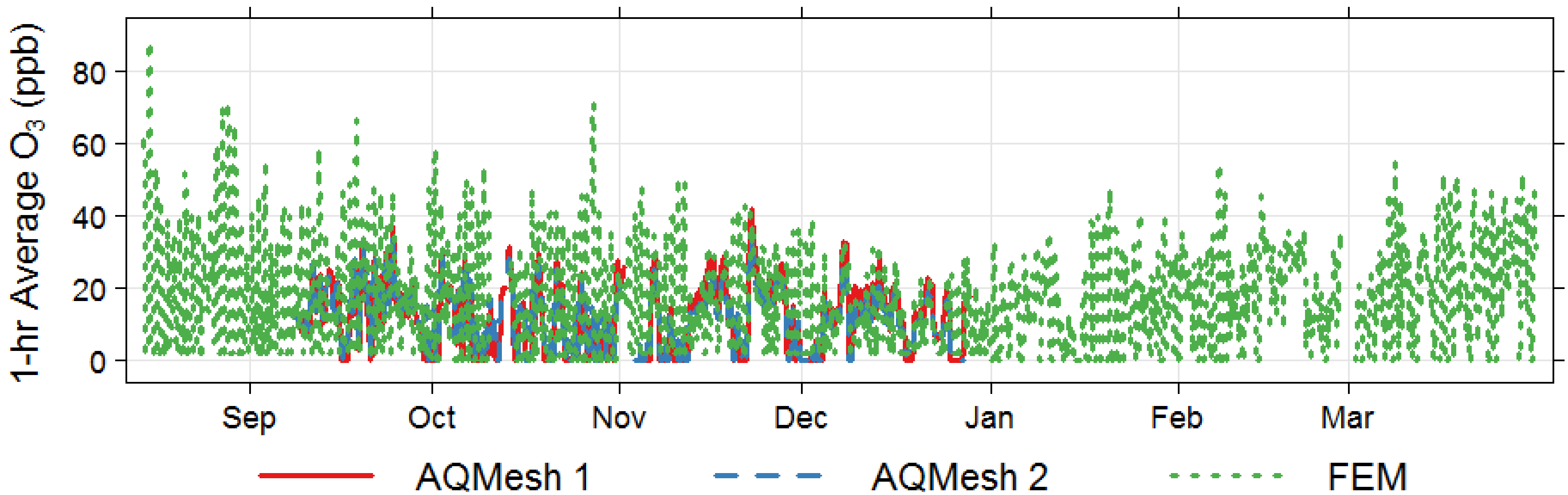
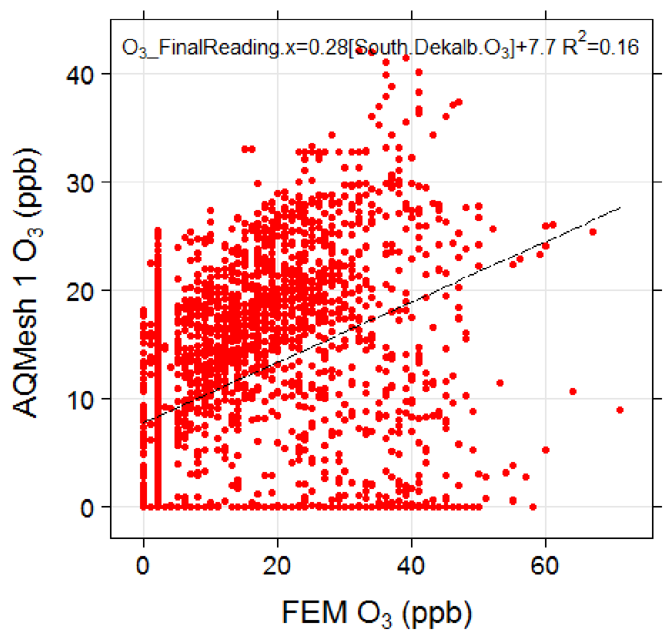
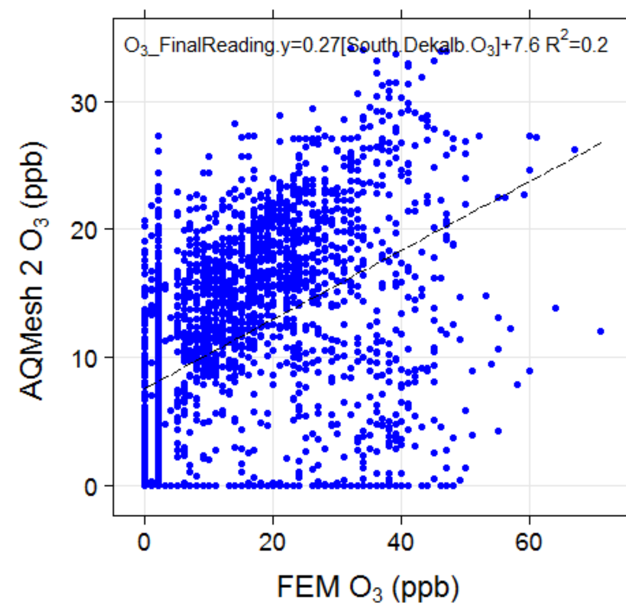


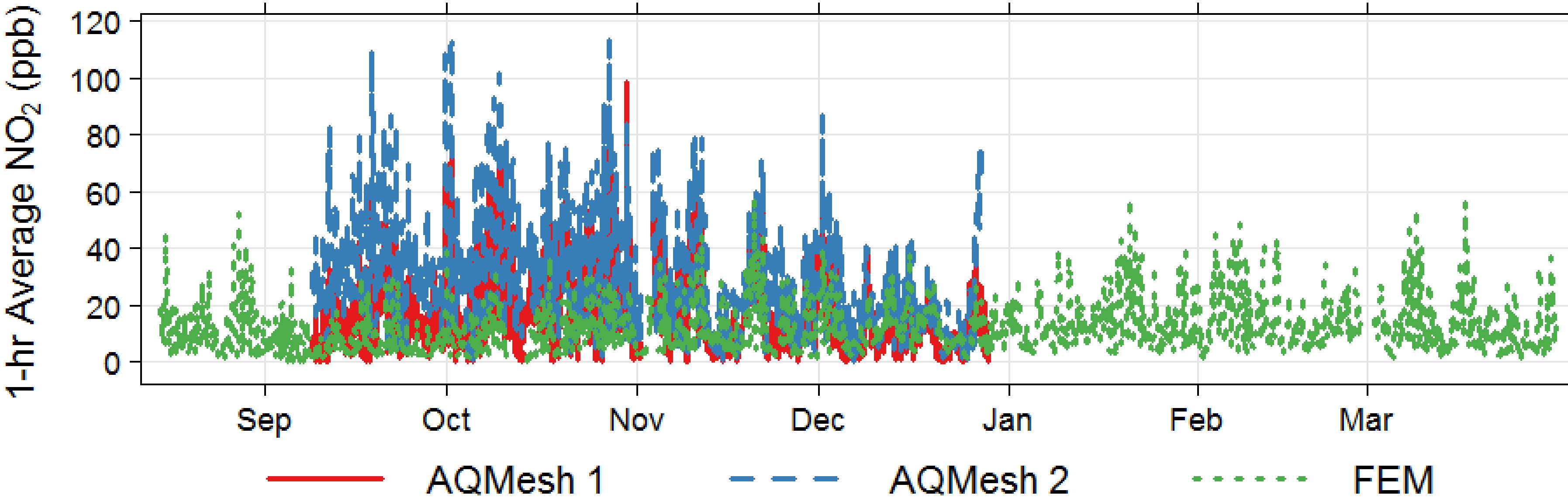
Figure A-12. Underside of the AQ Mesh unit showing the included sensors, the communication port, and the SIM card.

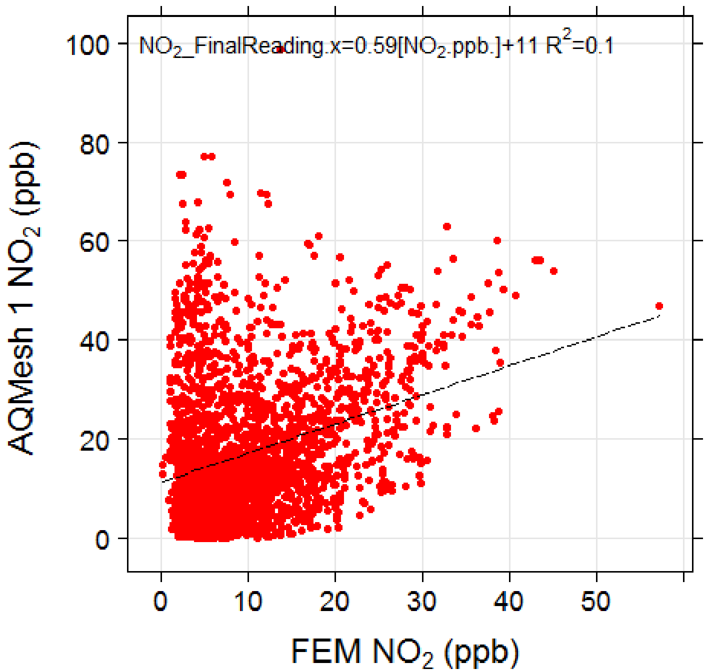


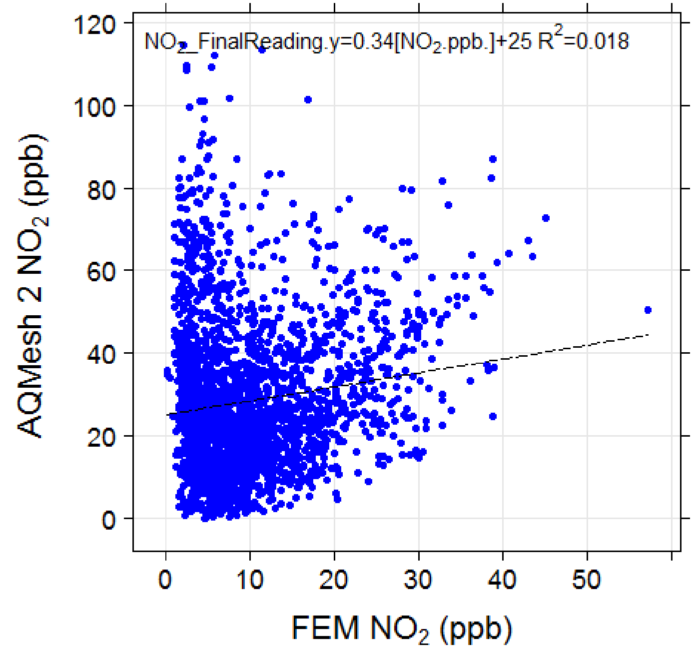




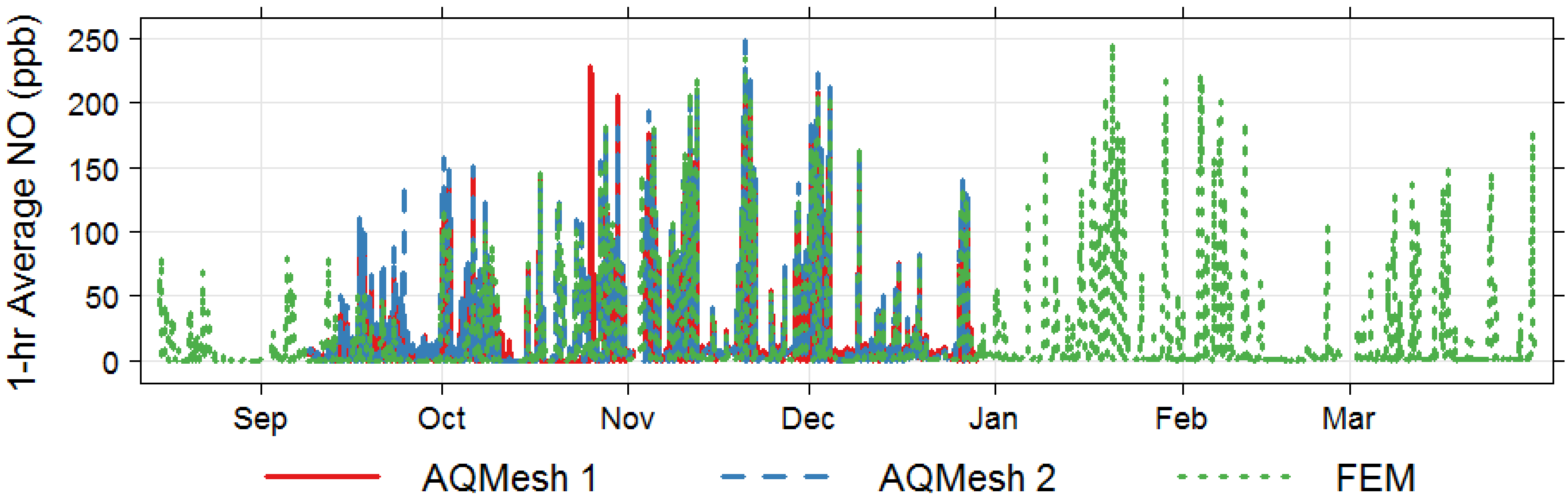
No observed T/RH effect

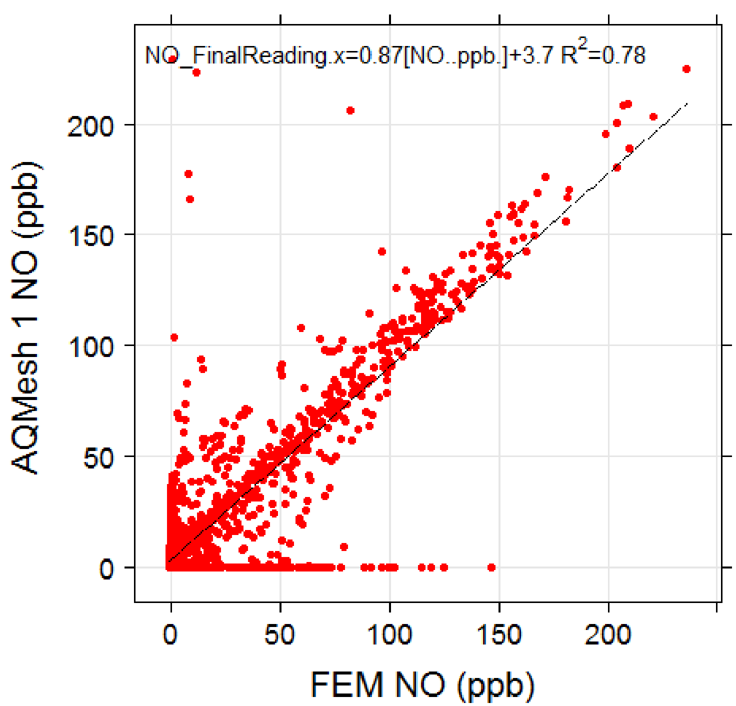


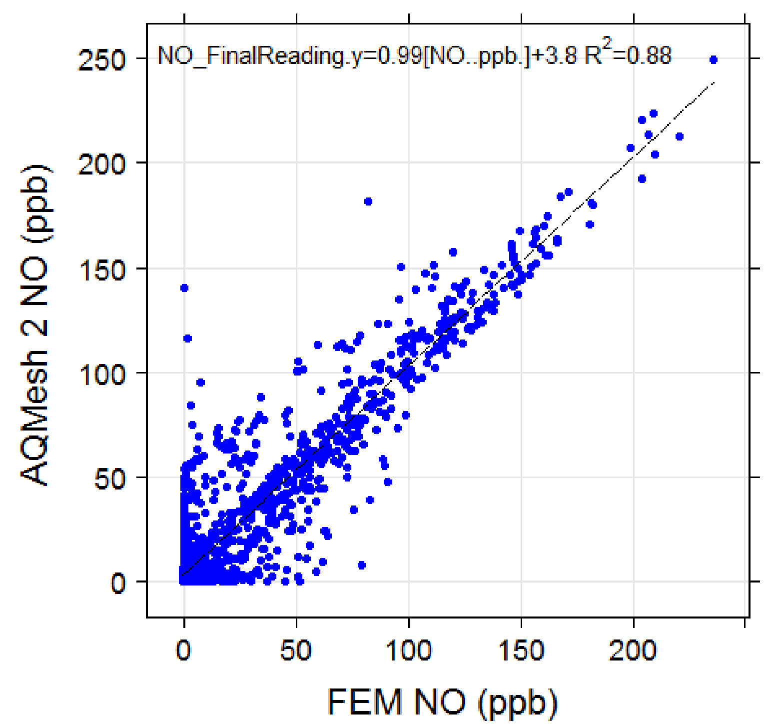


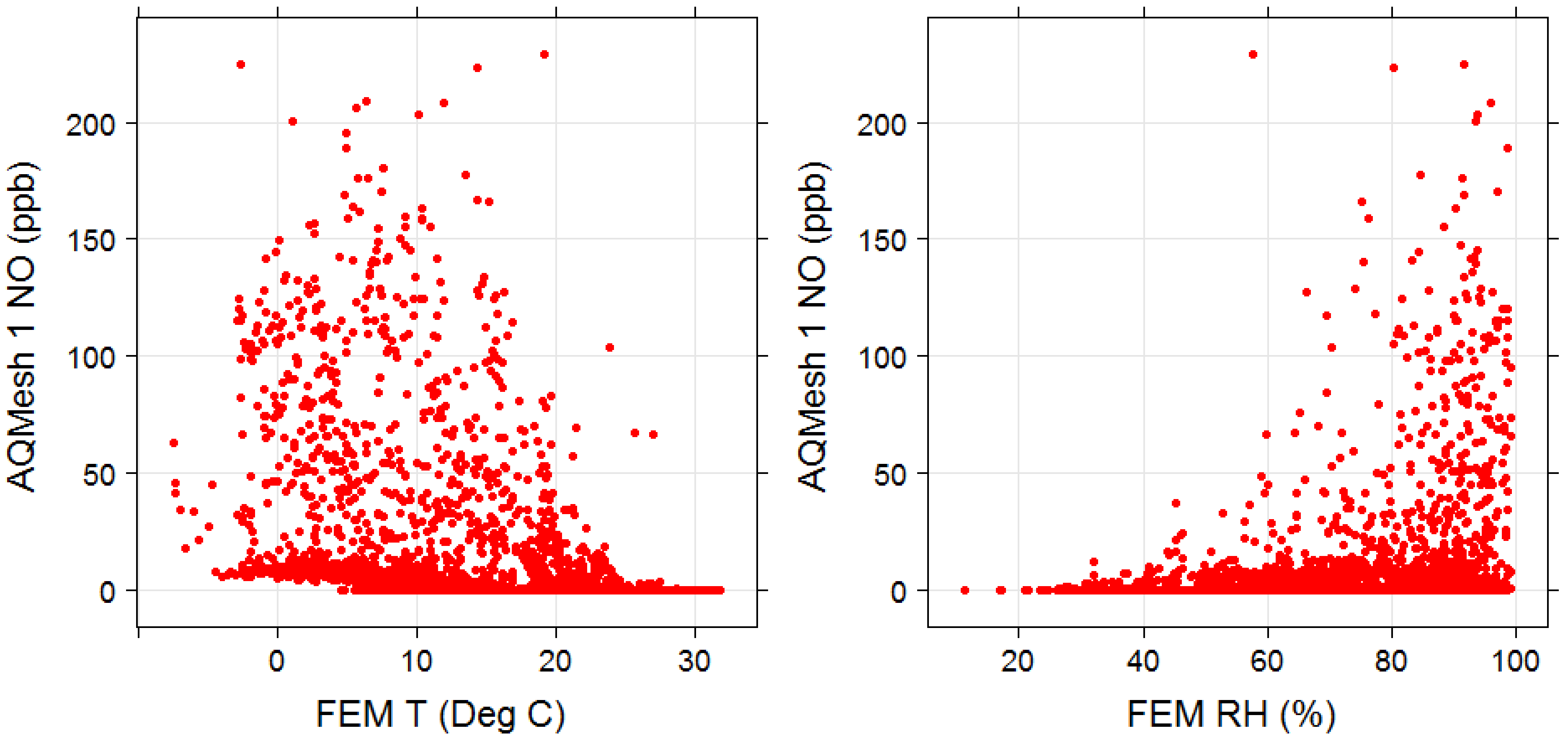


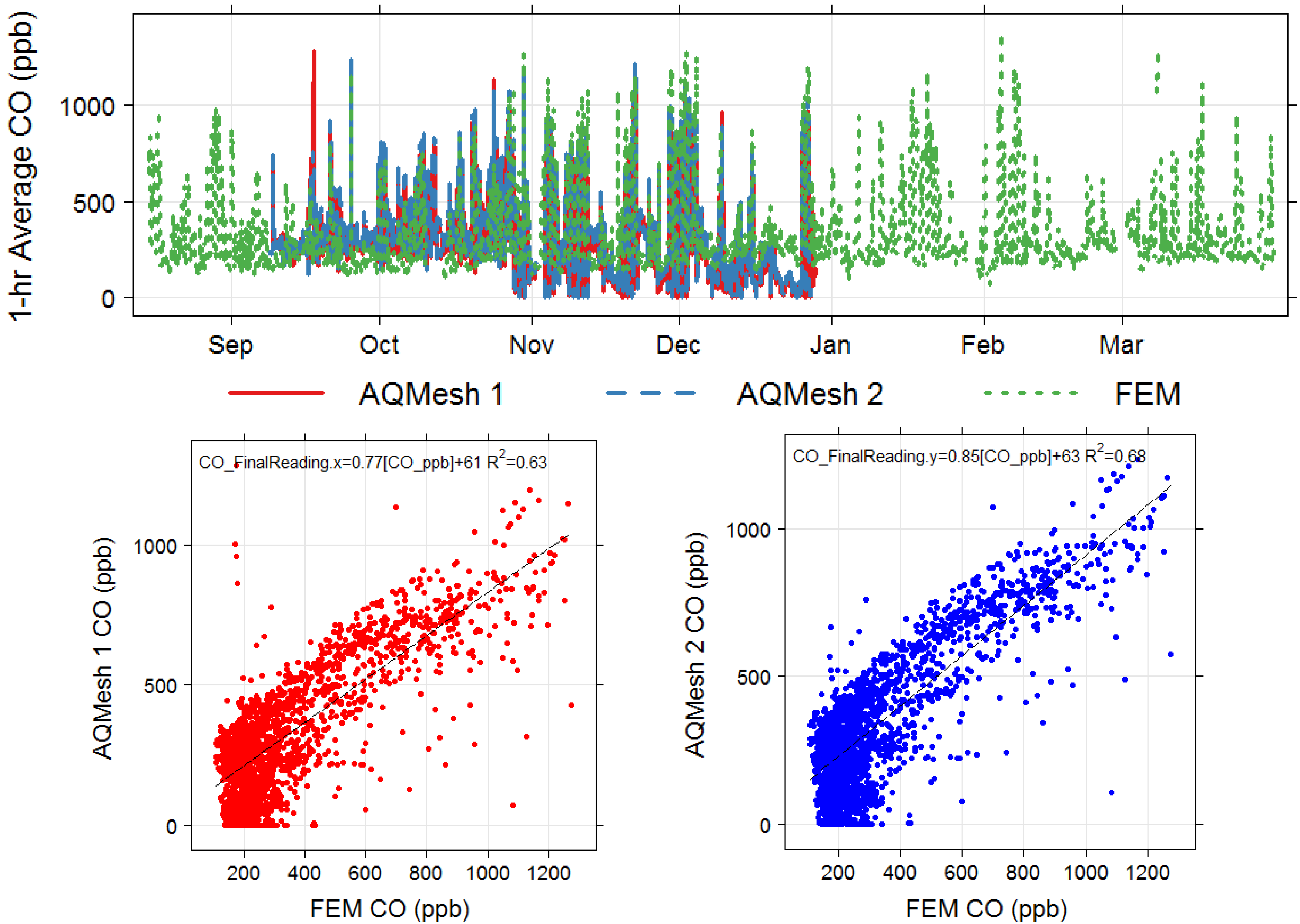
No observed T/RH effect

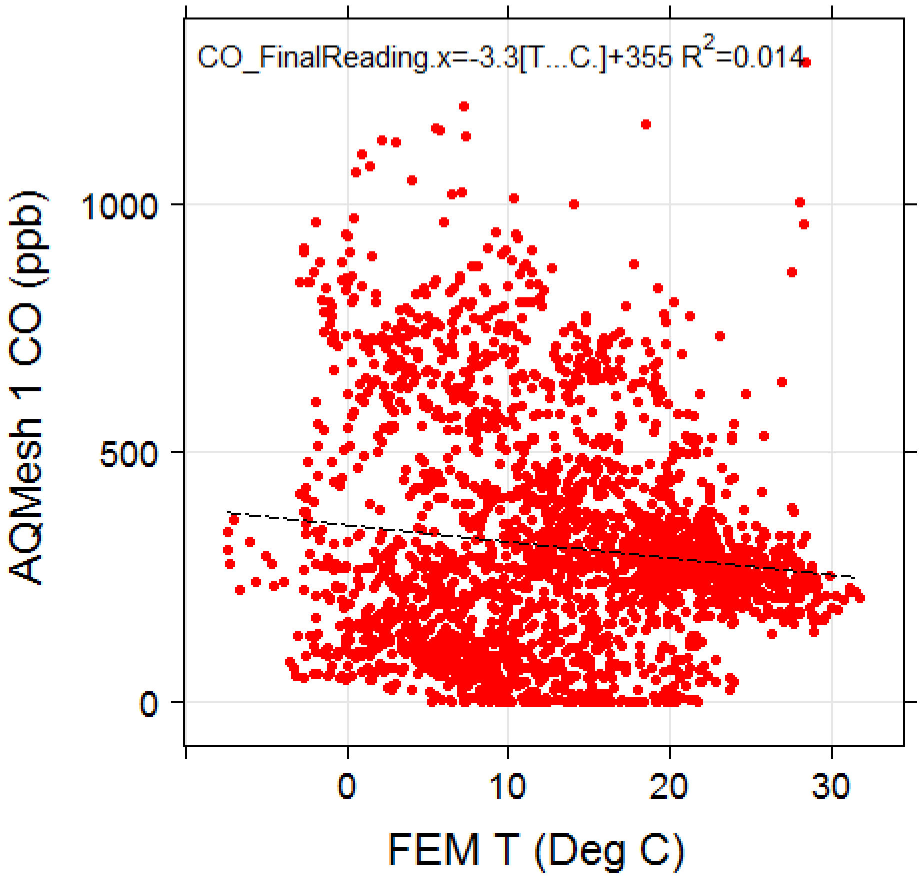

1-hr Average NO (ppb)
250
200
150
100
50
0
Sep
Oct
Nov
Dec
Jan
Feb
Mar
AQMesh 1
AQMesh 2
FEM

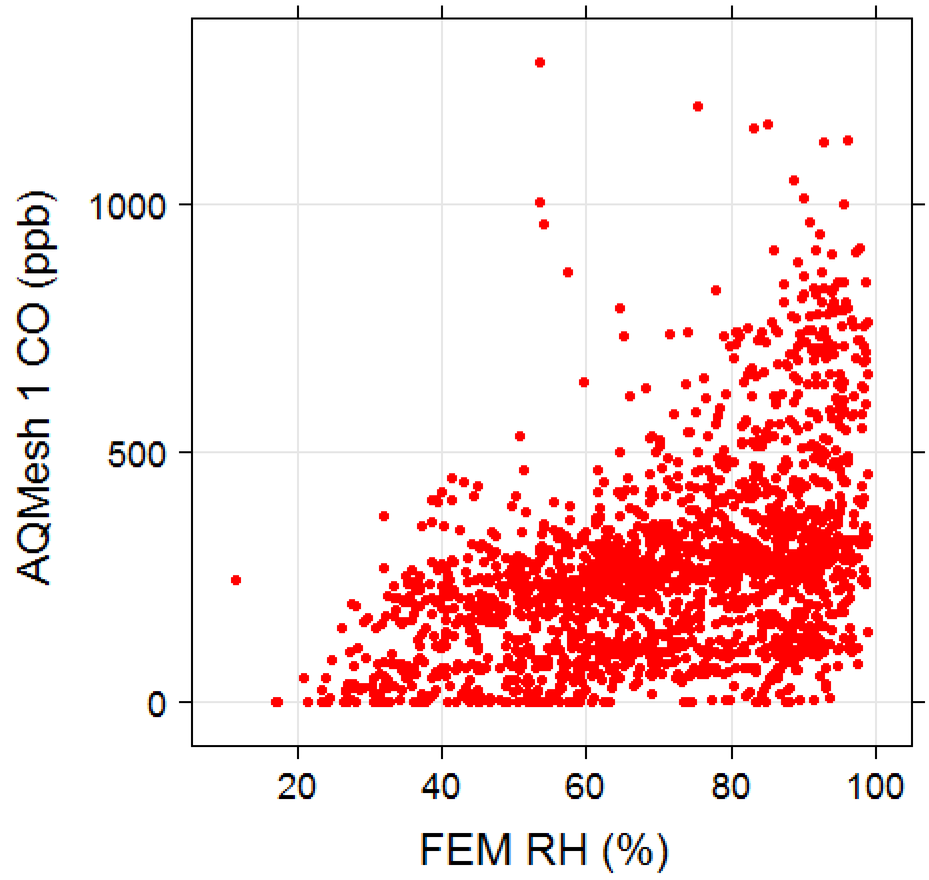

NO_FinalReading.x=0.87[NO..ppb.]+3.7 R2=0.78
AQMesh 1 NO (ppb)
200
150
100
50
0
0
50
100
150
200
FEM NO (ppb)

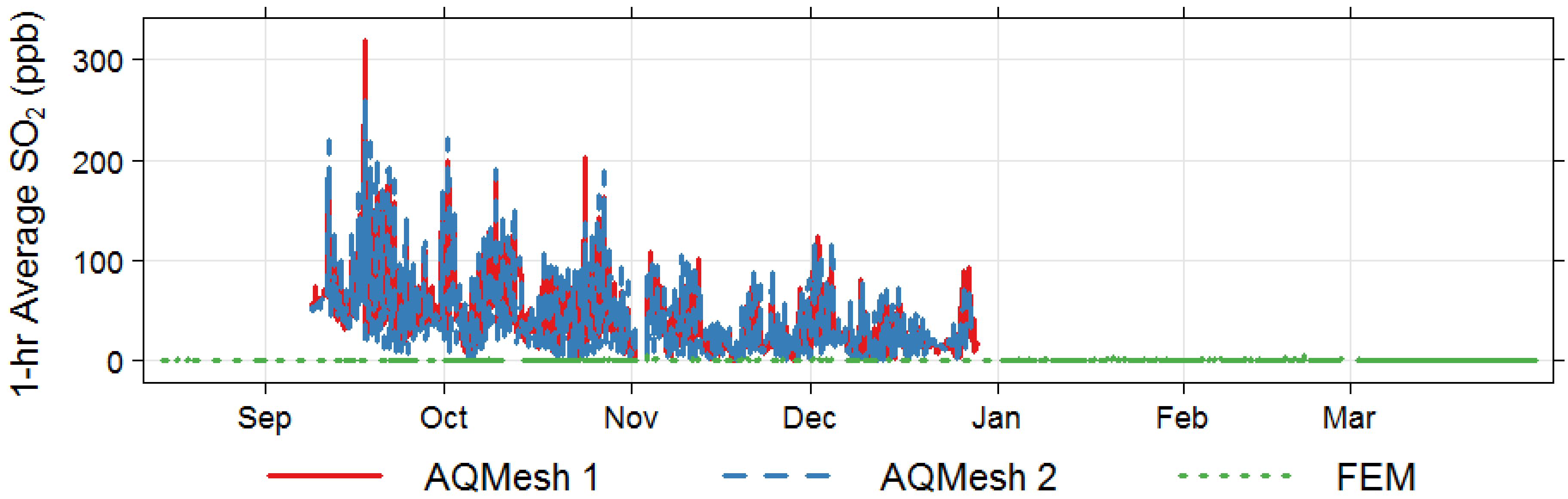

NO_FinalReading.y=0.99[NO..ppb.]+3.8 R2=0.88
AQMesh 2 NO (ppb)
250
200
150
100
50
0
0
50
100
150
200
FEM NO (ppb)

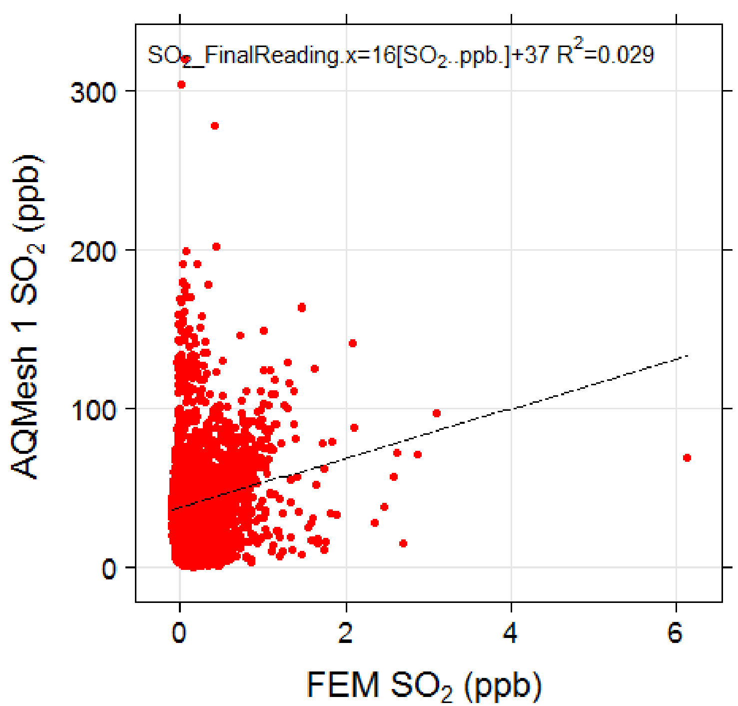

AQMesh 1 NO (ppb)
200
150
100
50
0
0
10
20
30
FEM T (Deg C)
AQMesh 1 NO (ppb)
200
150
100
50
0
20
40
60
80
100
FEM RH (%)

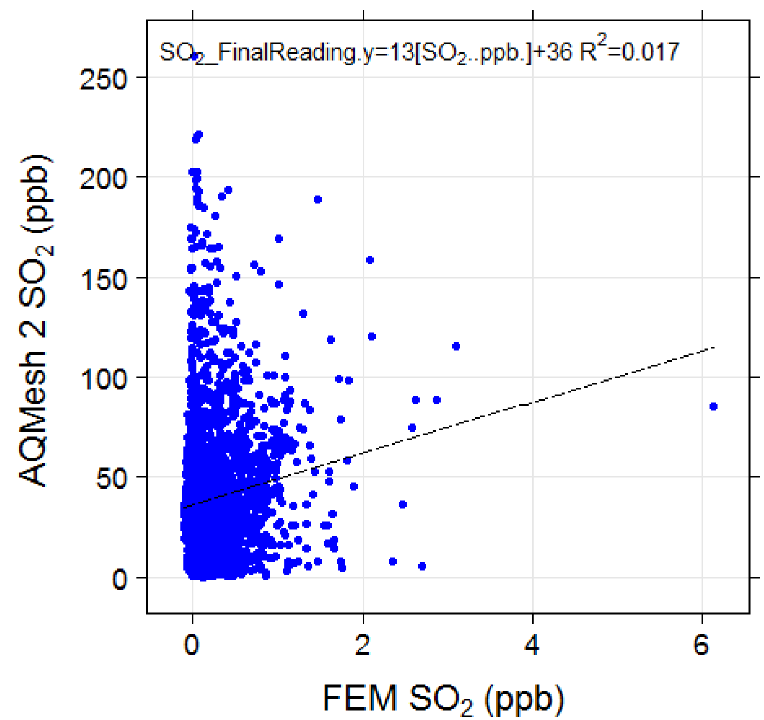

1-hr Average CO (ppb)
1000
500
0
Sep
Oct
Nov
Dec
Jan
Feb
Mar
AQMesh 1
AQMesh 2
FEM
CO_FinalReading.x=0.77[CO_ppb]+61 R^2=0.63
AQMesh 1 CO (ppb)
FEM CO (ppb)
200
400
600
800
1000
1200
CO_FinalReading.y=0.85[CO_ppb]+63 R^2=0.68
AQMesh 2 CO (ppb)
FEM CO (ppb)

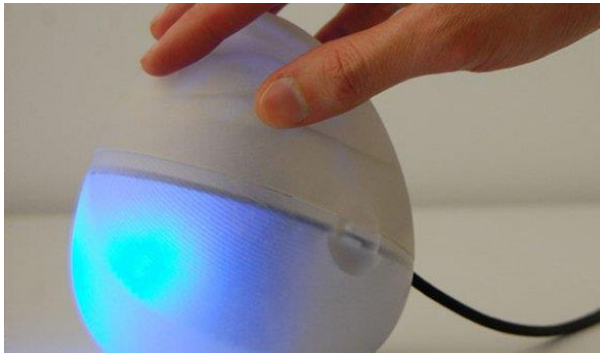

CO_FinalReading.x=-3.3[T...C.]+355 R^2=0.014
AQMesh 1 CO (ppb)
1000
500
0
0
10
20
30
FEM T (Deg C)


AQMesh 1 CO (ppb)
1000
500
0
20
40
60
80
100
FEM RH (%)


1-hr Average SO_2 (ppb)
300
200
100
0
Sep
Oct
Nov
Dec
Jan
Feb
Mar
AQMesh 1
AQMesh 2
FEM


SO_2_FinalReading.x=16[SO_2..ppb.]+37 R^2=0.029
AQMesh 1 SO_2 (ppb)
300
200
100
0
0
2
4
6
FEM SO_2 (ppb)


SO_2_FinalReading.y=13[SO_2..ppb.]+36 R^2=0.017
AQMesh 2 SO_2 (ppb)
250
200
150
100
50
0
0
2
4
6
FEM SO_2 (ppb)



Air Quality Egg Sensor Base Design

- **Model:** Air Quality Egg, including a sensor egg and a base egg (http://airqualityegg.com)
- **Measurement:** CO (e2v MiCS-5525), NO_2 (e2v MiCS-2710), VOCs (e2v MiCS-5521), PM (Shinyei PPD42), temperature, and relative humidity.
- **Mechanism:** electrochemical for gases, and light scattering for PM
- **Power:** The Egg uses a 7.5VDC, 1A, AC/DC switching power supply and requires constant access to a standard outlet for continuous operation.
- **Data retrieval and/or logging:** If using the standard Ethernet connection, then data sent to the base from the RF transmitter on the sensor unit is relayed to the Xively website. If using a data logger, it can be reprogrammed to send serial data from the base to the logger for logging to a micro-SD card. In the study, the base units were reprogrammed to output serial data to a supervisory Arduino.
- **Enclosure:** Three eggs were deployed in two different ways. For the first two systems, a "base" unit and a "sensor" unit have been used with the traditional wireless communication between them. The third egg was deployed by condensing the two units (base and sensor) into one egg.
- **Field utility:** The versatility of data acquisition lends to wide use in lengthy field settings. Laboratory characterization of the Egg units is suggested prior to field deployment to verify correct operation and response of component sensors. The wireless transmission between the base and sensor eggs appears to be robust. The sensors and fans are not well secured in the egg shells.

Air Quality Egg Field Setup

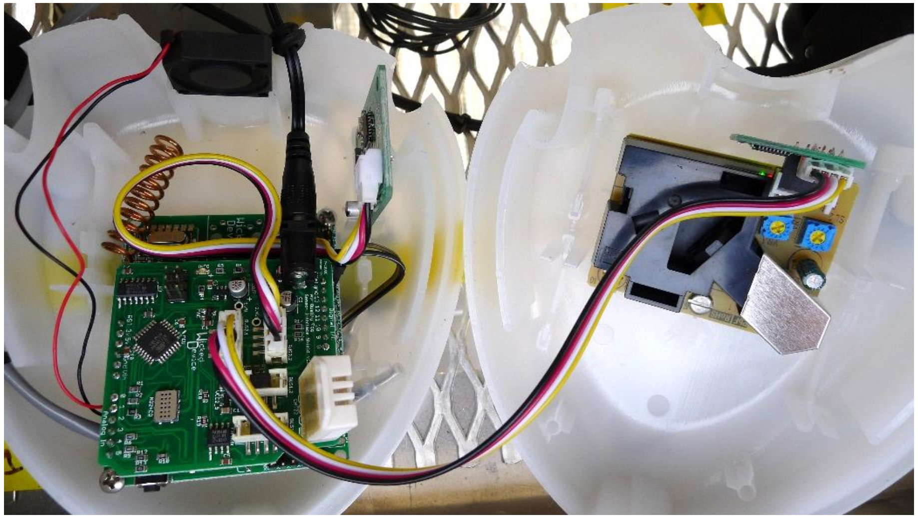


Figure A-13. Inside of Air Quality Egg.

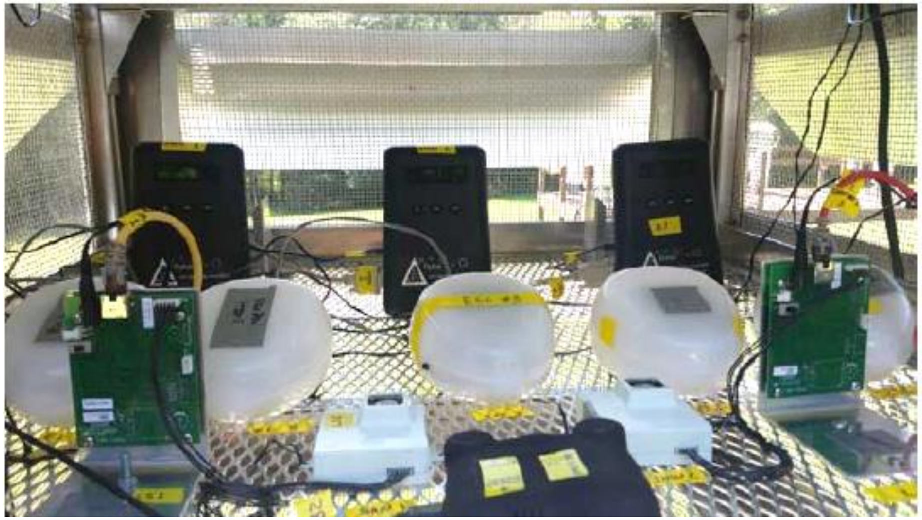
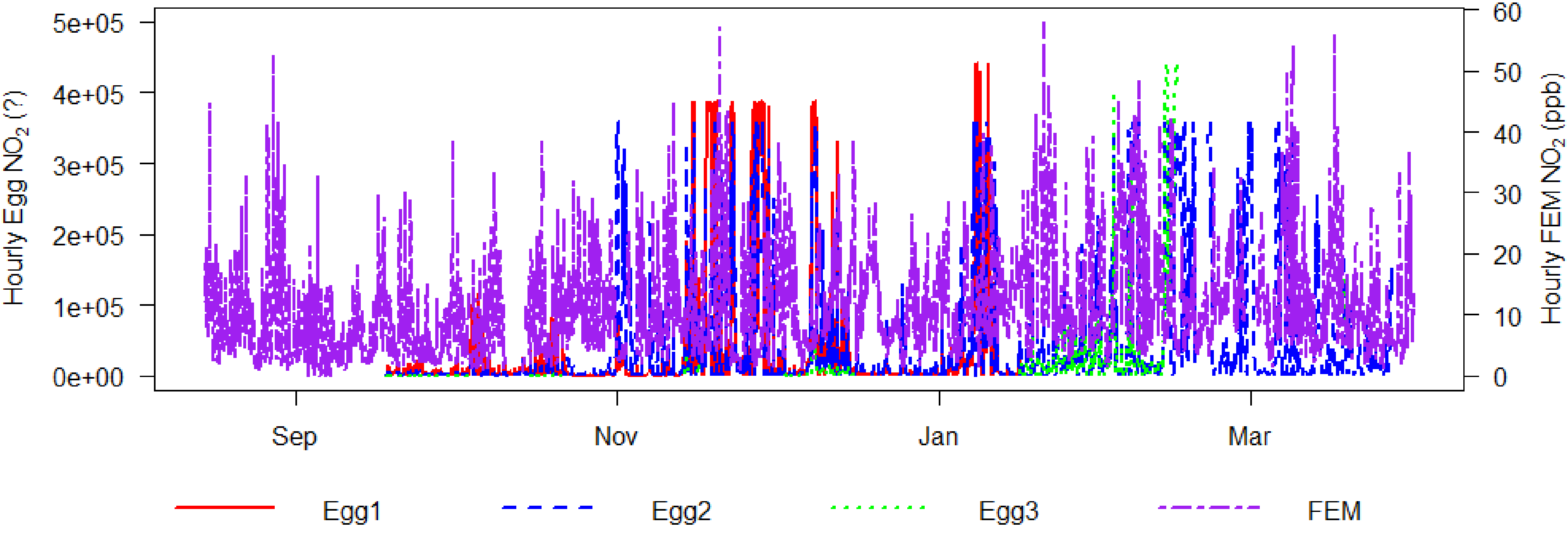
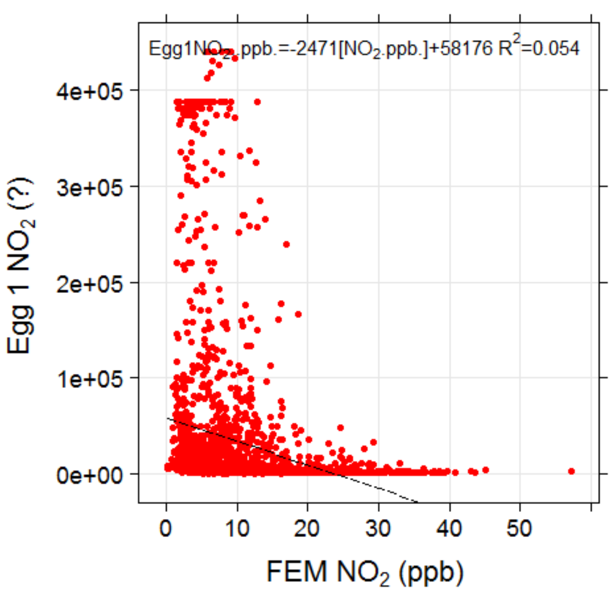
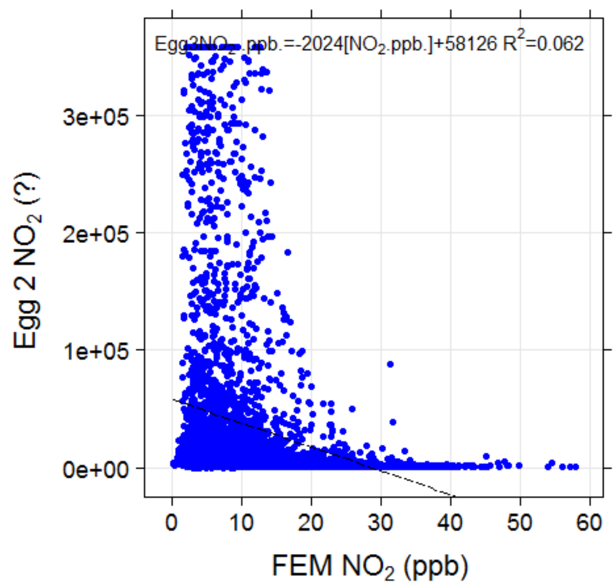
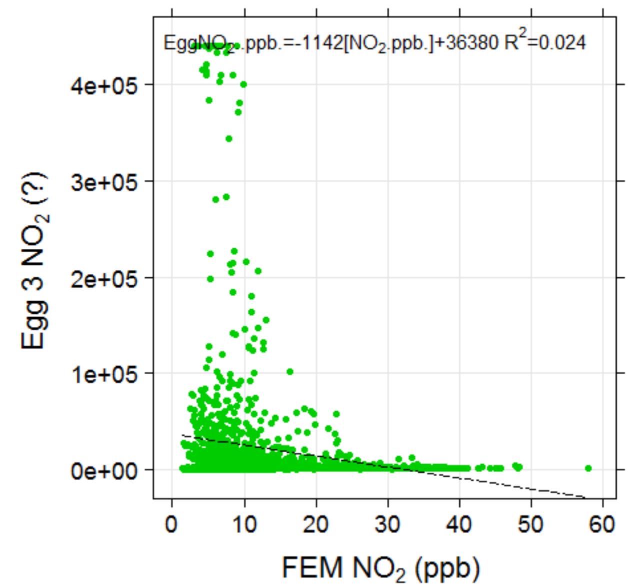


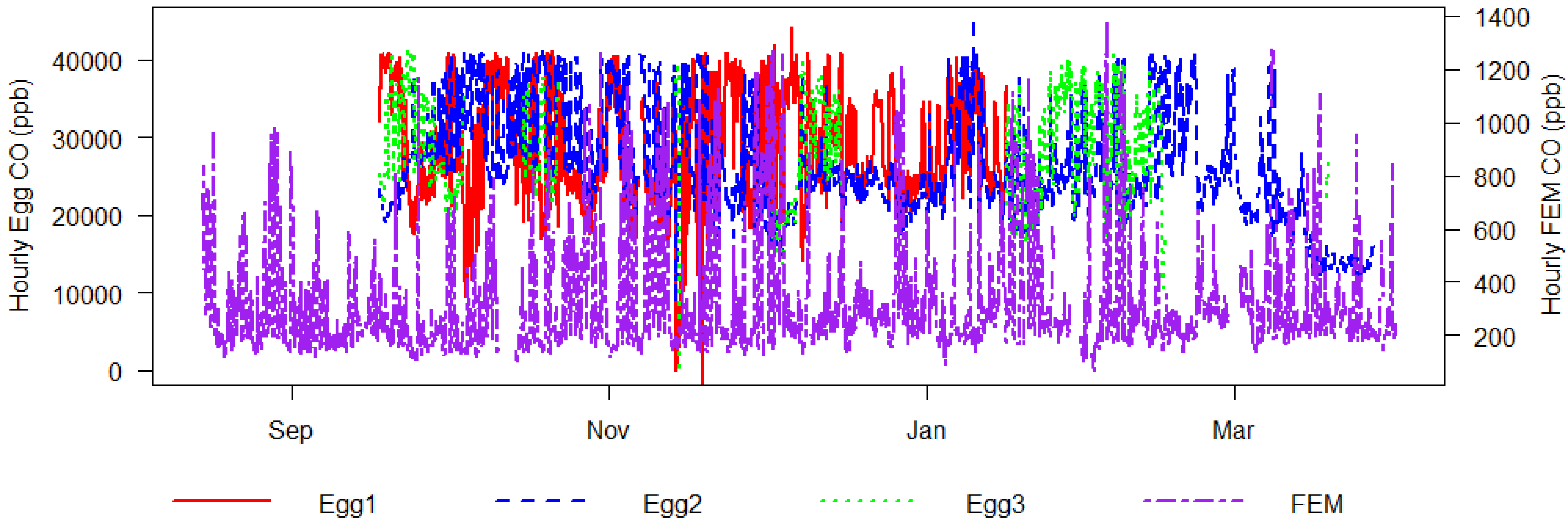
Figure A-14. Air Quality Egg inside the chamber (Figure A-1) during field deployment.

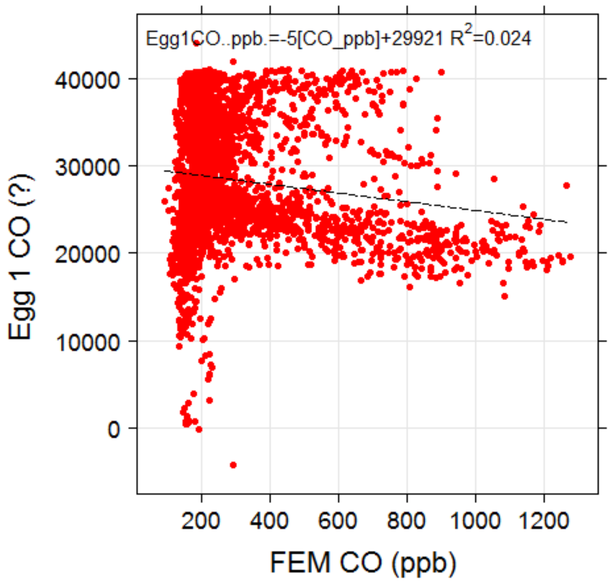

Hourly Egg NO2 (?)
Hourly FEM NO2 (ppb)
Sep
Nov
Jan
Mar
Egg1
Egg2
Egg3
FEM

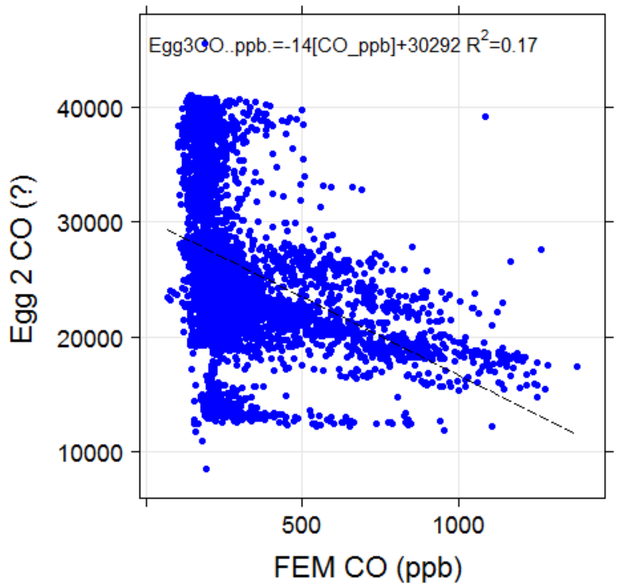

Egg1NO2.ppb.=-2471[NO2.ppb.]+58176 R^2=0.054
Egg 1 NO2 (?)
FEM NO2 (ppb)

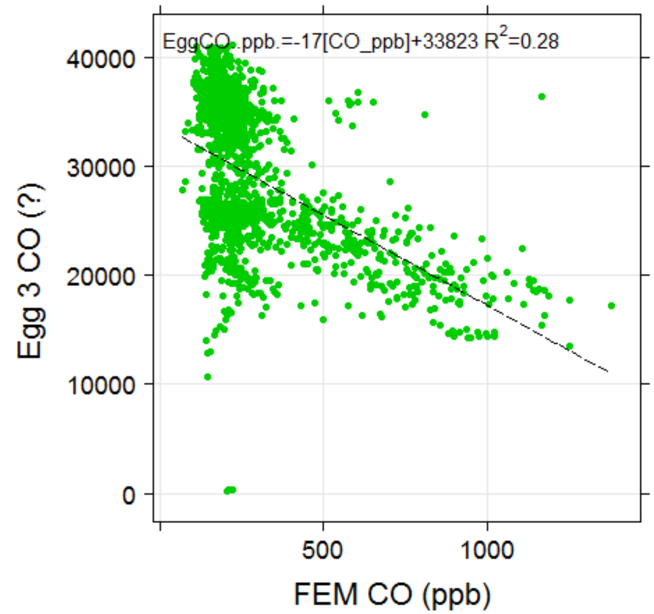

Egg2NO2.ppb.=-2024[NO2.ppb.]+58126 R^2=0.062
Egg 2 NO2 (?)
FEM NO2 (ppb)

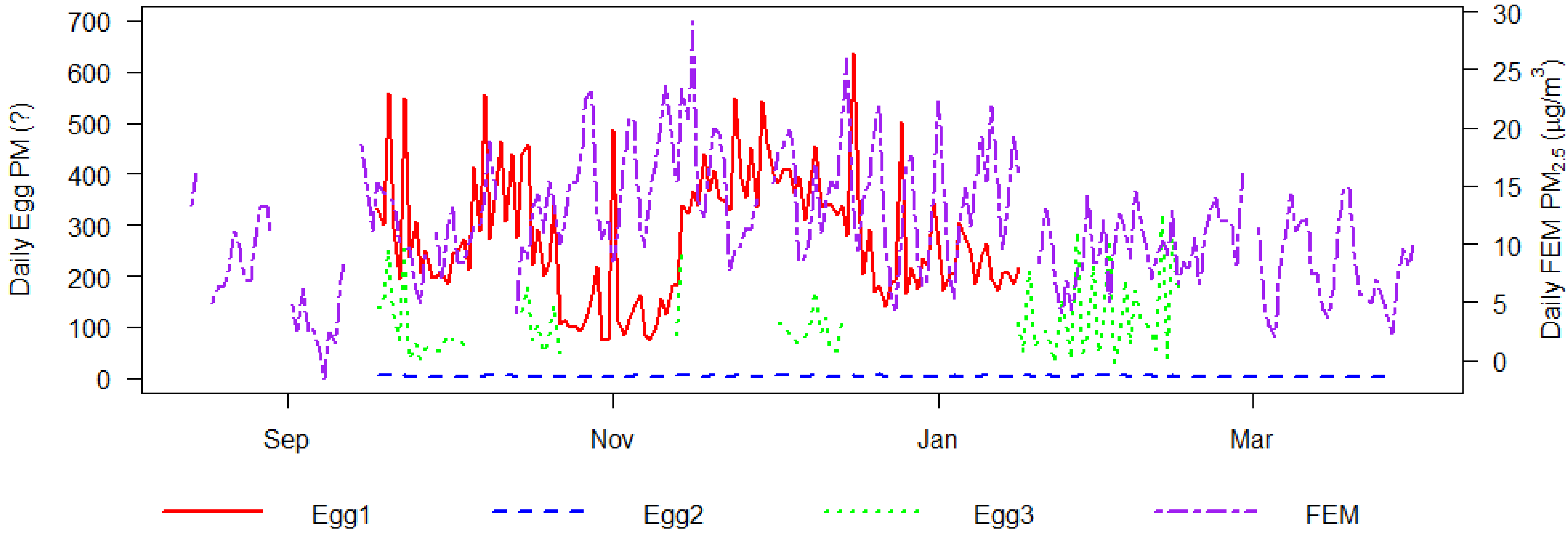

EggNO2.ppb.=-1142[NO2.ppb.]+36380 R^2=0.024
Egg 3 NO2 (?)
FEM NO2 (ppb)

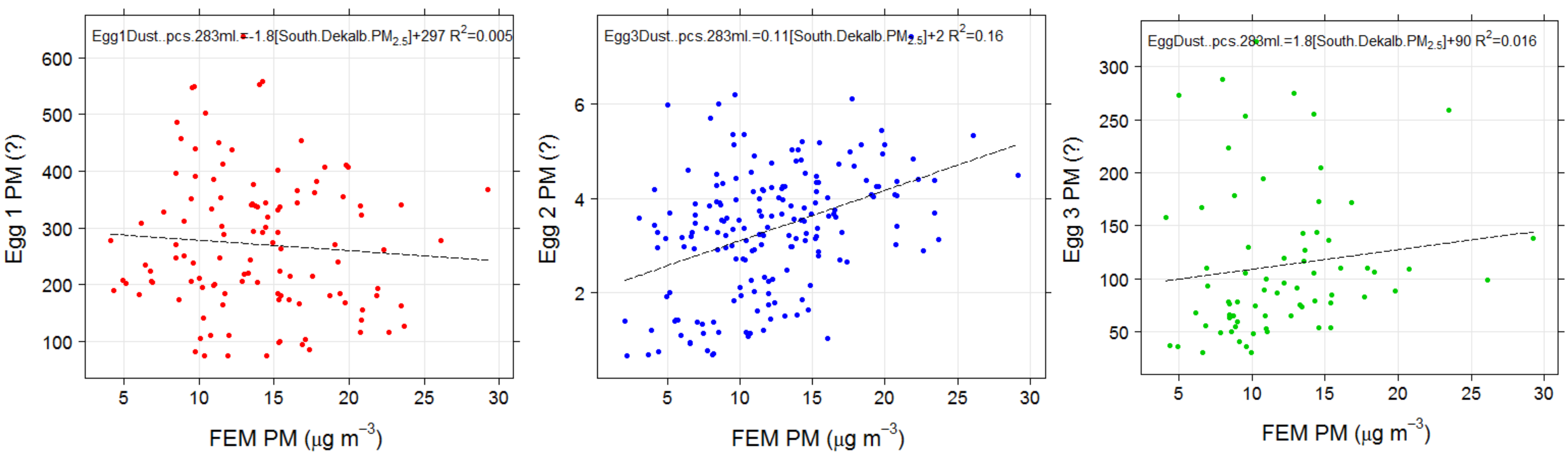

Hourly Egg CO (ppb)
40000
30000
20000
10000
0
1400
1200
1000
800
600
400
200
Hourly FEM CO (ppb)
Sep
Nov
Jan
Mar
Egg1
Egg2
Egg3
FEM


Egg1CO..ppb.=-5[CO_ppb]+29921 R2=0.024
Egg 1 CO (?)
40000
30000
20000
10000
0
200
400
600
800
1000
1200
FEM CO (ppb)


Egg3CO..ppb.=-14[CO_ppb]+30292 R2=0.17
Egg 2 CO (?)
40000
30000
20000
10000
500
1000
FEM CO (ppb)


EggCO..ppb.=-17[CO_ppb]+33823 R2=0.28
Egg 3 CO (?)
40000
30000
20000
10000
0
500
1000
FEM CO (ppb)


Daily Egg PM (?)
Daily FEM PM$_{2.5}$ (µg/m^3)
Sep
Nov
Jan
Mar
Egg1
Egg2
Egg3
FEM


Egg1Dust..pcs.283ml.=-1.8[South.Dekalb.PM$_{2.5}$]+297 R^2=0.005
Egg 1 PM (?)
FEM PM (µg m^{-3})
Egg3Dust..pcs.283ml.=0.11[South.Dekalb.PM$_{2.5}$]+2 R^2=0.16
Egg 2 PM (?)
FEM PM (µg m^{-3})
EggDust..pcs.283ml.=1.8[South.Dekalb.PM$_{2.5}$]+90 R^2=0.016
Egg 3 PM (?)
FEM PM (µg m^{-3})

Wireless Sensor Network (WSN) components

Parts/Manufacturer	Function	Node
PM Sensor, Shinyei (Japan)	Measures $PM_{2.5}$ in µg/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)	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)	900 MHz omnidirectional wireless communication via ZigBee network protocol	base
Solar panel and battery (SPM110P-FSW, SolarTech (Ontario, CA); 55Ah battery)	Rechargeable power for system	1
Solar panel and battery (SPM055P-F, SolarTech (Ontario, CA); 35 Ah battery)	Rechargeable power for system	2, 3
Airlink® GX440 cellular modem, Sierra (Canada)	Transmission of data to server	base

Sensor Ad-hoc Field Testing (SAFT) components

Sensor/Manufacturer	Measured Pollutants	Quantity
PM sensor, Shinyei (Japan)	$PM_{2.5}$ (µg/m^3)	2
Dylos Particle Counter (DC1100-PRO-PC × 2, DC1100-PC), Dylos Corporation (Riverside, CA)	small and large particle (pt/0.01cf)	3
Airbeam, HabitatMap (Brooklyn, NY)	$PM_{2.5}$ (hppcf)	3
SM50, Aeroqual (New Zealand)	O_3 (ppm)	2
Cairclip, Cairpol (France)	NO_2/O_3 (ppb)	2
Air Quality Egg, Wicked Device (Ithaca, NY)	NO_2, CO, VOC, PM (pt/283ml)	3
AQMesh (Gen. 3), LandTec (Colton, CA)	NO, NO_2, CO, SO_2 , O_3 (all in ppb)	2