AIRCOA

Autonomous Inexpensive Robust CO_2 Analyzer

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User's Manual

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Table of Contents

1. Introduction

This manual describes the operation of the autonomous, inexpensive, robust CO_2 analyzer (AIRCOA). Making accurate CO_2 measurements requires careful attention to gas handling, numerous automated quality control diagnostics, and a suite of reference cylinders closely linked to the WMO CO_2 calibration scale. AIRCOA is based on a single-cell infrared gas analyzer (IRGA), which has moderate short-term noise and instrument drift rate. The short-term noise is overcome with signal averaging and instrument drift with frequent calibrations. Additional potential sources of CO_2 measurement bias that are addressed with automated diagnostics include: incomplete flushing of the sample cell and dead volumes, incomplete drying of the sample air, IRGA sensitivity to pressure broadening, IRGA sensitivity to temperature, leaks to ambient air, leaks of calibration gas through solenoid valves, and modification of CO_2 concentrations by the drying system or plastic components. The last 2 pages in this section show schematics of the 5 inlet and 3 inlet AIRCOA designs, which are further described here.

The inlets consist of rain shields, and quartz wool and 30 μm polypropylene filters (30). The instrument box is generally indoors in an environment with moderate temperature variability, but it can also be outdoors. Each inlet stream passes through a mass-flow meter (F), and a 5 μm metal filter (5) and needle valve before reaching a manifold of three-way (3) and 2-way (2) solenoid valves. A brushless DC diaphragm pump (p) flushes the sample lines at 500 to 1000 sccm when they are not being analyzed. The one gas selected by these valves exits through both ends of the manifold and then passes through the first of two 2.44 m by 2.8 mm ID Nafion driers. A smaller brushless DC diaphragm pump (mp) then compresses this gas to approximately 55 kPa above ambient at which point it passes through a second 5 μm metal filter and enters a second manifold of two-way and three-way solenoid valves.

This second manifold selects either a sample gas or a calibration gas to be analyzed. When the sample gas is not being analyzed it exits the valve manifold through a needle valve set to maintain constant pressure in the upstream Nafion drier. The four calibration gases (LS2, LS1, HS1, HS2) typically span the range 350 to 480 ppm and are stored in high-pressure aluminum cylinders with Ceodeux valves fitted with two-stage brass regulators. These regulators are set to match the pressure in the sample line. A 10 L high-pressure cylinder will last 12 months at the default flows and calibration frequency. A fifth calibrated high-pressure cylinder (LT) stores a long-term surveillance gas which is run through the entire inlet system and treated as an unknown during analysis. The regulator on this cylinder is set to approximately 20 kPa above ambient and a needle valve is used to match sample pressures in the first Nafion drier.

The sample or calibration gas selected for analysis next passes through another 5 μm filter and a miniature pressure regulator (R) with an output of approximately

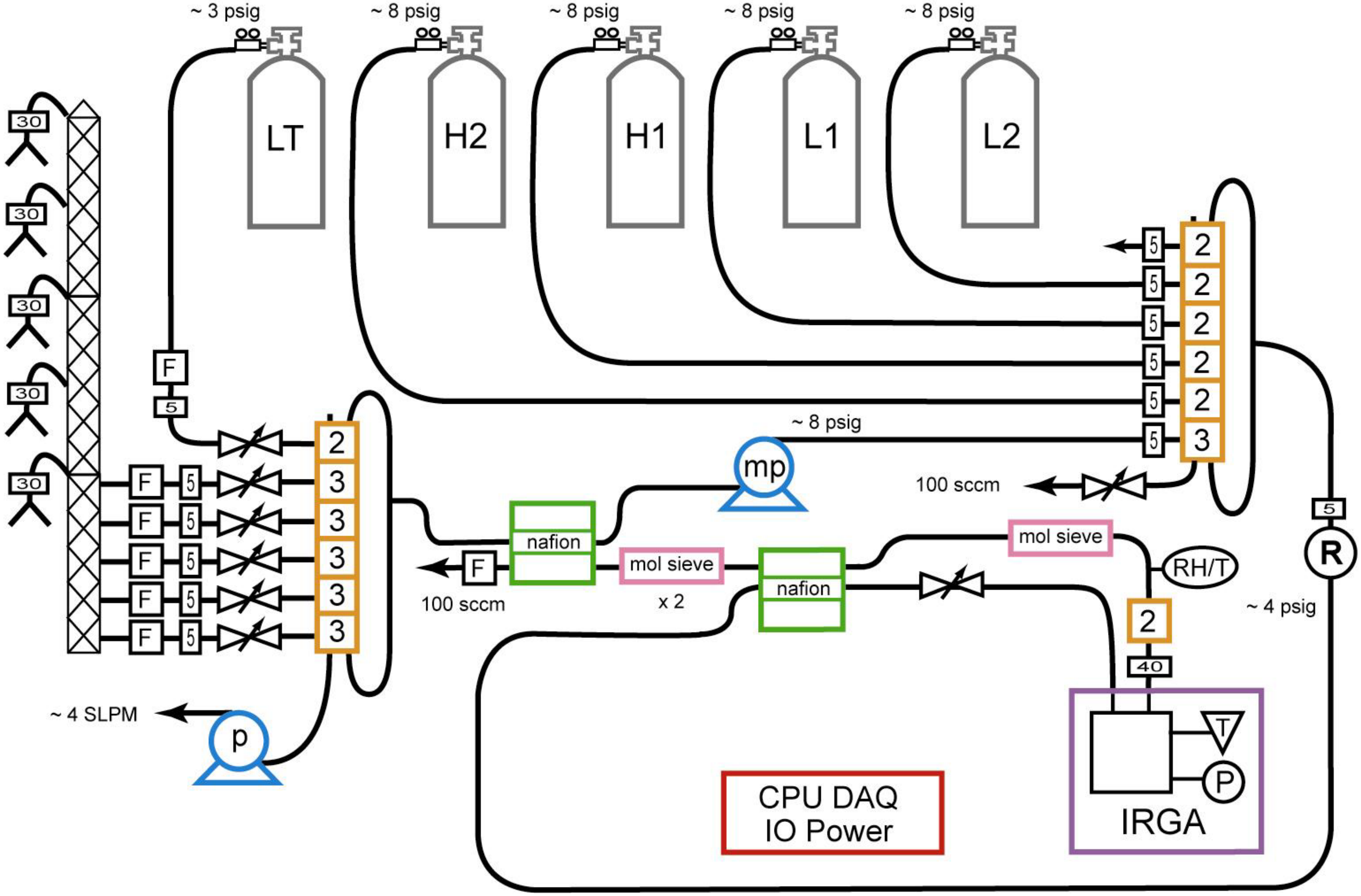
30 kPa above ambient. The gas is then dried by a second Nafion drier and reduced in pressure by a needle-valve before reaching a single-cell IRGA. This needle valve is normally adjusted to set the sample flow to 100 sccm. After leaving the IRGA, the gas passes through a 40 μm metal filter (40), a normally-open needle valve used for leak checking purposes, and a humidity and temperature sensor (RH/T) used to verify drier performance. The gas is then completely dried once with 13X molecular sieve to be used as the purge gas on the second Nafion drier, and then dried a second time to be used as the purge gas on the first Nafion drier. Most of the moisture in the ambient air exits the first Nafion without ever reaching the mole sieve driers. The instrument uses three 200 ml molecular sieve driers, the quickest filling of which lasts 5 to 10 months depending on outside humidity. The gas passes through a final mass-flow meter before exhausting to the room. There is little flow impedance between the Li820 cell and this exhaust such that sample and calibration measurements are both closely matched to ambient pressure.

The IRGA measures the pressure, temperature, and CO_2 concentration of the gas. It actively and precisely controls the optical bench to 50 ˚C and has excellent stability with respect to ambient temperature of around 0.05 ppm/C. By default, the IRGA is configured to use a 2 second digital filter and the instrument logs values at 1 Hz. These filtered values have a 1-sigma rms noise of 0.6 ppm which averages to 0.1 ppm over 100 seconds. The instrument switches the gas being analyzed every 150 seconds and the processing software ignores the first 50 seconds after each switch to allow for flushing of gases through the system. The instrument cycles between the three or five inlet lines on a 7.5 or 12.5 minute schedule, respectively. The processing software makes a calculation based on measured flows of how long the measured gas takes to get from the inlet to the sample cell and adjusts the times of reported measurements accordingly. Every 30 minutes the instrument analyzes one of the 4 calibration gases to allow the estimation of drift in the IRGA zero offset, while every 4 hours it measures all four calibration gases to allow estimation of linear and 2^{nd}-order calibration coefficients for the IRGA. The instrument alternates the sequence of these 4 gases to allow detection of problems associated with incomplete flushing of the sample cell and any dead volumes. Every 8 hours the instrument analyzes the long-term surveillance gas.

Every 4 to 8 hours the instrument also performs automated system checks to determine the IRGA pressure sensitivity and to measure system leak rates to ambient at positive pressure and from the solenoid valves at ambient pressure. Because of silicone seals in the IRGA; plastic fittings on the Nafion driers; Viton seals in the solenoid valves, Nafion driers, and manifolds; and plastic and Viton seals in the micropump the instrument is designed to support efforts to minimize and monitor system leaks.

A PC104-based computer running Linux performs automated data acquisition and valve control. This system can be accessed through an internet connection and data and system diagnostics can be retrieved, processed, and displayed in near real time. If any of the automated diagnostics suggest a problem, the instrument allows more detailed troubleshooting to be performed interactively. This direct connectivity and rapid processing is critical for maintaining the system and producing high-quality CO_2 measurements.

The following sections describe all steps necessary to test, deploy, and maintain the instrument and to store, transfer, and process the data to obtain accurate CO_2 measurements.


~ 3 psig
~ 8 psig
~ 8 psig
~ 8 psig
~ 8 psig
LT
H2
H1
L1
L2
30
30
30
30
30
F
5
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F
5
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5
F
5
F
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~ 4 SLPM
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mp
nafion
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100 sccm
mol sieve
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mol sieve
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2
2
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3
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100 sccm
RH/T
2
40
5
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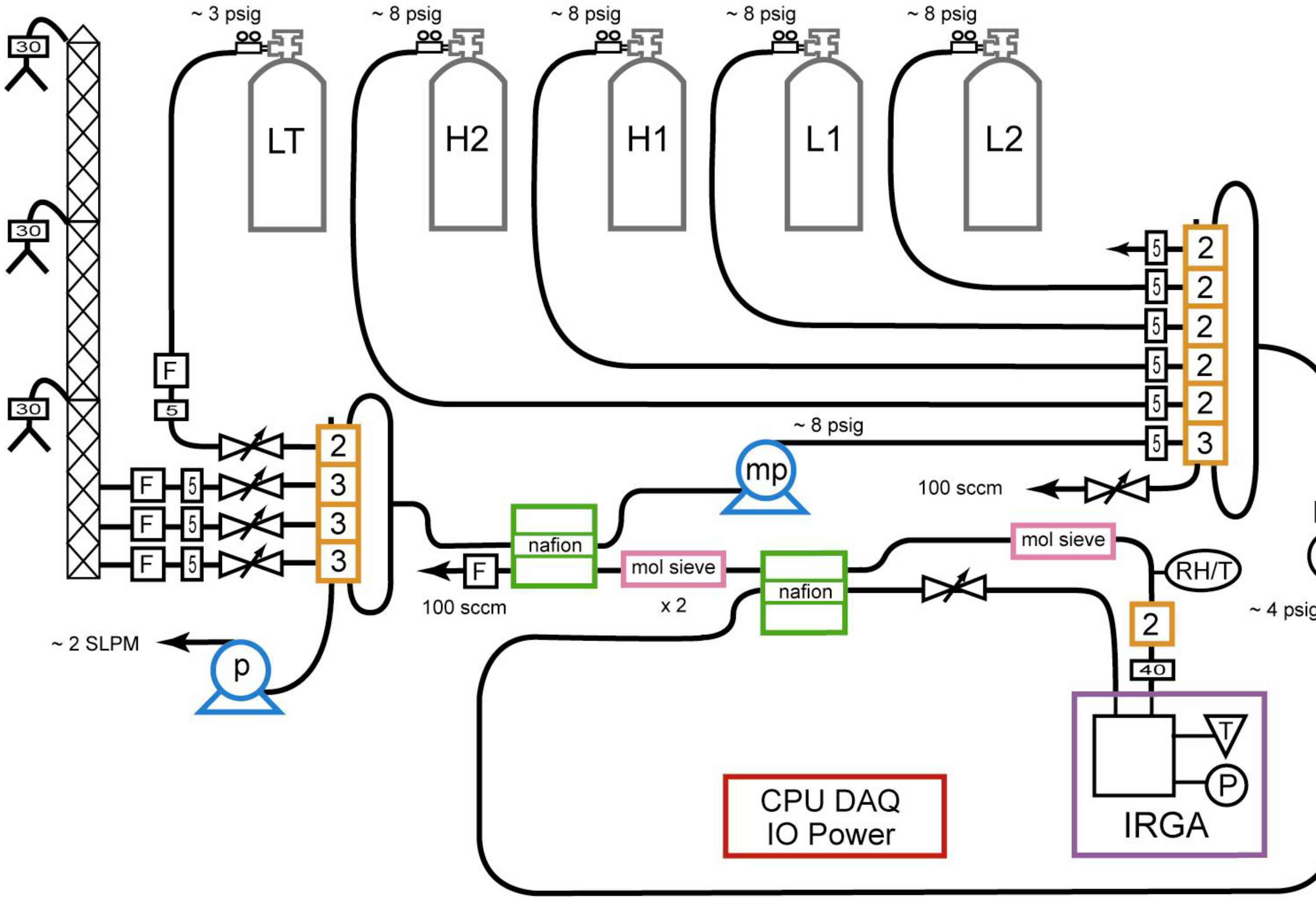
T
P
IRGA
CPU DAQ
IO Power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LT
H2
H1
L1
L2
30
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100 sccm
F
~ 2 SLPM
p
T
P
IRGA
CPU DAQ
IO Power

2. Getting Started

A. Unpack the instrument

Check for any obvious damage or loose fittings that may have resulted from shipping. Place the instrument on a lab bench with the door open.

B. Power up the instrument

The internal power supply can take 88-264 VAC at 47-63 Hz. For operation in Europe, a plug adapter is required. After plugging the instrument in, the tower pump should start immediately and several LEDs on the computer stack will light green. If a terminal is connected to COM port 2 (see below) it will display standard boot-up and any error messages from the computer. After several minutes, the computer will finish booting and it will start the measurement program which will activate one or more relays and turn on the sample pump. At this point the instrument begins automatically switching valves and logging data according to its prescribed schedule (see Appendix B).

C. Connect to the instrument computer

There are 3 different means of making a data connection to the instrument computer.

Serial output stream:

In the default configuration, the program sends ascii data to COM port 3 at 9600 baud (N, 8, 1). If you connect a serial terminal to COM port 3 using a null modem cable, you should see the following values streaming:

```
Time (HH:MM:SS.S), Li820 CO2 (ppm), Li820 Pressure (kPa), Li820
Temperature (C), Valve Setting (hexadecimal), Box Temperature Signal
(V), RH Signal (V), Sample Flow Signal (V), Line 1 Flow Signal (V),
Line 2 Flow Signal (V), Line 3 Flow Signal (V), Line 4 Flow Signal
(V), Line 5 Flow Signal (V), LT Flow Signal (V)
```

For a 3 inlet unit the Line 4 and Line 5 flow values will be missing.

Serial control interface:

COM port 2 is available as a direct interface to the Linux computer, using a setting of 115200 baud (N, 8, 1). If you connect a serial terminal with these settings to COM port 2 using a null modem cable and hit ‘enter’ you should see the command prompt:

```
/ #
```

indicating that your are in the root directory (/). If this terminal is connected when the instrument is powered up you will see all of the standard Linux boot messages.

Ethernet connection:

An ethernet connection is available on the outside of the instrument box via a bulkhead fitting and a supplied adapter cable, and also inside the box if necessary by disconnecting the cable from the bulkhead fitting to the computer. By default, the instrument is set up to find an IP address using DHCP. If it is connected to a DHCP enabled network on boot-up, you will simply need to use the serial control interface (above) and enter the command:

```
/ # ifconfig
```

to learn what its IP address is. Alternatively, you can use the serial control interface to edit the file /etc/rc.sysinit to specify an IP address (see Section 3 below). Once you know the IP address, you can connect to the instrument using ssh as root with a command like:

```
> ssh root@123.45.67.89
```

the default root password for the CarboEurope AIRCOA units is:

```
hlkbbp!
```

Please feel free to change this using the command:

```
/ # passwd
```

Once you are successfully logged in you should see the command prompt:

```
~ #
```

indicating that you are in the home directory for user root (/root).

D. Run the relay control program

The instrument computer has a program for manually controlling the relays and viewing data which is called ‘rrelay’ and resides in the /usr/local/bin directory. This program can be started with the command:

```
~ # /usr/local/bin/rrelay localhost
```

or by using the shortcut jobfile:

```
~ # /rr.job
```

which resides in the root directory and contains this same command. After starting, this program displays the following menu:

```
Commands:
h: stop output, show this help.  Enter g to restart output
?: same as h
p: pause output
g: go, restart output
s: show state of relays in binary form (0=open,1=closed).
   Enter g to restart output
o: open all relays
number <space or return>: toggle a relay open->closed or closed->open.
  You must enter a space or carriage return after the number.
  There are 15 relays, so enter a number
  between 0 and 14.
r: resume relay program control of relays
q: quit rrelay (relay program will resume control)
Q: terminate entire data acquisition program
```

This menu can be called up at any time by hitting ‘h’ or ‘?’. After typing ‘g’ the screen will display measured data in the same format as for the COM port 3 output stream:

```
Time (HH:MM:SS.S), Li820 CO2 (ppm), Li820 Pressure (kPa), Li820
Temperature (C), Valve Setting (hexadecimal), Box Temperature Signal
(V), RH Signal (V), Sample Flow Signal (V), Line 1 Flow Signal (V),
Line 2 Flow Signal (V), Line 3 Flow Signal (V), Line 4 Flow Signal (V),
Line 5 Flow Signal (V), LT Flow Signal (V)
```

where the Line 4 and Line 5 flow values are missing on a 3 inlet unit. Typing ‘s’ stops the data output and displays the relay status in binary form, e.g.:

```
relays :
 19 18 17 16 15 14 13 12 11 10  9  8  7  6  5  4  3  2  1  0
  0  0  0  0  0  0  1  0  0  0  0  0  0  1  0  0  0  0  1  0
```

indicates that relays 13 (micropump), 6 (sample air), and 1 (line 2) are on, corresponding to a hexadecimal value of 2042. Typing any number between 0 and 19 followed by <space> or <enter> will toggle that relay number, although only relays 0 through 13 are currently used [note: the statement in the program menu that relay 14 is used is out of date].

The relays correspond to:

Relay	Inlet Line	Relay	Selected	Relay	Other
0	Line 1	6	Air	12	Leak Check Valve
1	Line 2	7	LS2	13	Micro Pump Power
2	Line 3	8	LS1		
3	Line 4	9	HS1		
4	Line 5	10	HS2		
5	LT	11	Guest Cal.		

Note: the leak check valve/manifold connected to relay 12 is configured to be normally open, so activating it closes the valve. Note also: the computer has 20 relays (0-19) and in case they are needed later relays 14-17 are routed to switch 12 V to connectors on the interconnect board (see Appendix E).

Typing 'o' will turn off all relays. Once you have asserted manual control over the valves by turning a relay on or off, the program continues logging data but stops its automated switching of relays. To indicate that the program is under manual control, bit 20 of the binary relay code is set to 1, which adds 100000 to the hexadecimal value displayed on screen and recorded to the data file. To resume automated switching of valves according to the prescribed schedule, type 'r' or 'q'. If the rrelay program is left under manual control with either the menu or valve status showing (but no data outputting to screen), it will revert back to automated valve switching after 5 minutes.

IMPORTANT: If the rrelay program is left under manual control with data outputting to the screen, it will not revert to automated valve switching. This is a useful feature for leak checking and other interactive procedures, but requires that care be taken to exit this program or at least stop the output to the screen if resumption of normal operations is desired.

Typing 'Q' stops both the manual relay control and the automated instrument control program ('aircoa'). The manual relay control program will not run unless the aircoa program is running. To tell if the aircoa program is running, use the command:

```
~ # ps
```

which will show approximately 9 aircoa processes if the program is running. To restart the aircoa program, use the command:

```
~ # /home/isff/aircoa.sh
```

or alternatively, use the same command that is called in /etc/rc.sysinit on start up:

```
~ # /home/isff/aircoa.sh 2>&1 | /usr/bin/logger -p local4.info &
```

which also sets up error logging to the file /var/tmp/log/messages.

While running, the aircoa program logs data in the directory /data/aircoa which corresponds to the mounted USB drive. You can confirm data recording by listing the contents of this directory. The file naming structure is:

```
af_%y%m%d_%H%M%S.dat
```

where the letter following the first two letters indicate the specific aircoa unit (k-o for the CarboEurope units). The letter code of your unit can be determined with the command:

```
~ # hostname
```

The year, month, and day in the filename are the current day, and the hour, minute, and second correspond to the start of the file. The default configuration is for the program to write three files a day, ending in *000000.dat, *080000.dat, and *160000.dat, but any time the program is stopped and restarted it will begin a new output file with the corresponding time in the filename.

The format of these data files is currently a binary time/sensor/checksum stamp followed by ascii data on each line [Note: a software upgrade is planned so that they will be all ascii]. The ascii portion can be viewed, but a separate program (see Section 6) is required to convert the binary portion to ascii.

E. Connect the calibration gases

Follow NOAA GMD guidelines for the handling of calibration gas cylinders, including venting regulators 4 times after installation, checking for leaks with snoop, and not over tightening CGA fittings (use Teflon tape on CGA nipples if necessary). In addition, we recommend orienting the cylinders on their sides in a stable temperature environment as this has been shown to minimize drift in cylinder CO_2 concentration. Four calibration gases are required for AIRCOA operation: low-span 2 (LS2), low-span 1 (LS1), high-span 1 (HS1), and high-span 2 (HS2), with nominal concentrations of 350, 380, 410, and 480 ppm, respectively. If sampling at low heights at night in a forest is planned, the HS2 value should be increased to span the highest anticipated measured value. The AIRCOA system also requires a long-term (LT) surveillance gas which should be near ambient (380 ppm) CO_2 concentration. After connecting, venting, and leak checking regulators for the 4 calibration cylinders and the surveillance gas, connect the regulator outputs to the instrument at the appropriate 1/8” bulkhead fittings, using cleaned 1/8” stainless steel tubing (Valco Part number TSS285 or equivalent).

At this point several additional leak checks should be performed. With either the system powered down or at least all solenoid valves closed, increase the regulator output pressures to around 8 psi and then back out (turn counter-clockwise) the regulator adjustment knob all the way. Also, close the cylinder valves and note all 5 upstream and all 5 downstream regulator pressures. If the system is going to be left unattended for more than a few days we recommend performing the high-side pressure test over at least 1 hour to protect against an undetected leak depleting a cylinder. Record these 10 pressures every 15 minutes until you are confident there are no leaks upstream or downstream of the regulators - pressures should be constant after allowing for any room temperature swings and imprecision in reading the gauges. Note: the Model-14 regulator pressure-gauge needles can stick against the clear covers and these gauges should be lightly tapped before any reading to ensure reproducible results. Finally, be sure to remove any plug on the guest-cal bulkhead fitting as this line is used to vent air during the automated leak checks.

F. Connect the inlet lines

Note: we recommend running the instrument in lab for several weeks to become familiar with its operation and to ensure proper operation before field deployment. Inlet lines should be 1/4" Synflex 1300 (formerly Dekoron Type 1300 Dekabon) composite tubing. Connect these lines to the appropriate 1/4” bulkhead fittings on the instrument box. The provided inlets consist of a 47 mm filter holder and a funnel rain shield. We recommend stuffing a small amount of glass wool in the inlet to the filter holder to discourage entry by large insects and using 30 μm polypropylene filter papers in the filter holders to exclude smaller particles.

3. Diagnostic and Tuning Procedures

A. Standard procedures and checksheets

The AIRCOA system has been designed to run autonomously for months at a time, but requires occasional manual diagnostics and tuning procedures to ensure that the automated operation is working correctly. The two two-page check sheets included in the following pages describe these procedures for the 3 inlet and 5 inlet units separately. We recommend that a full tune be carried out before deployment, after any major system changes, and every several months as allowed by normal field visits. Once the system flows and pressures have been initially tuned, these procedures run much more quickly. Here and in Appendix A we outline some of the rationale for the steps and settings in these check sheets.

Leak checking:

The system performs automated high-pressure (to detect leaks to ambient) and ambient-pressure (to detect leaks of calibration gases through solenoid valves) several times a day. To diagnose detected leaks these often must be done manually. Note: the inline Beswick regulator and the LT regulator must be set (~ bottom of first page) before the high-pressure leak detection procedure will work. The LT regulator is purposefully set to a lower pressure than the inline Beswick regulator so that when using the LT gas to do a high-pressure leak check the inline Beswick regulator will allow free gas flow in both directions. Using a pressure lower than the inline Beswick regulator set point would allow the potential for flow through the regulator to mask any downstream leaks. The high-pressure leak check will detect leaks in the area between the inlet line selection manifold and the leak check valve. To further localize a detected leak, this check can alternately be run with the sample air valve closed (relay 6 off) to only detect leaks between the gas selection manifold and the leak check valve.

It is difficult to estimate the influence of leaks on measurement accuracy. For leaks through the calibration gas solenoid, we can estimate the effect assuming a standard sample flow rate of 100 sccm and a calibration gas concentration 100 ppm different than ambient. In this case, a leak rate of 0.1 sccm would lead to a bias of 0.1 ppm. Assuming an interior volume and pressure during the leak check procedure of 30 cc at 101.3 kPa, this leak rate would cause a pressure increase of 0.3 kPa/min. For a positive pressure leak to ambient, the effect would depend on the leak location and the outside CO_2 concentration, but it is clear that leak rates corresponding to pressure decreases of several tenths of a kPa/min can have an adverse effect. Operationally, we find that in both cases leak rates of 0.05 kPa/min or better can be obtained with a reasonable level of effort and that as good as 0.02

kPa/min is also possible. Therefore, we use 0.05 kPa/min as our pre-deployment target and a trigger for field maintenance. Cut-off levels for when to include or exclude data must be determined by the user, but should not be much higher than 0.05 kPa/min and certainly lower than 0.3 kPa/min. Note: if both positive-pressure leaks to ambient and leaks of a calibration gas through a solenoid valve are present, they can offset and cause falsely favorable readings during these leak checks. If necessary, this can be ruled out by performing a high pressure leak check with the calibration gas cylinder regulators turned off and the lines vented.

Two common places for leaks to develop are at the internal o-ring seal between the plastic tee and the Nafion inner tube and also at the hose-barb fittings to the sample micropump. Leaks at the pump fittings can sometimes be detected using snoop. To further isolate where a leak is, the Nafion tubes can be bypassed with a short length of 1/4" tubing with Ultratorr fittings on either end, and the pump can be bypassed with a short length of 1/4" tubing with Swagelok fittings on either end. A leak at a Nafion o-ring can sometimes be addressed by tightening the o-ring compression fitting, but caution should exercised as over tightening can easily lead to crossed threads on this fitting. Alternatively, the fitting can be disassembled and the o-ring replaced, cleaned, and/or lightly greased. To address a leak at the micropump, remove pull the Bev-a-line tubing and retaining clip and off the hose barbs, cut the tubing back or replace it, replace the retaining clip, and remake the fitting.

Leak checks on the calibration and sample inlet lines, upstream of the valve manifolds should also be performed occasionally and anytime flow or cylinder pressure readings indicate a possible leak. For the sample lines, this can be done by plugging the bulkhead fittings on the outside of the box and then opening the line selection valves during a standard leak check procedure. For the calibration gases, this can be done by backing off the regulator pressures and then opening the gas selection valves during a standard leak check procedure.

Inlet needle valve adjustment:

This procedure assumes you want the maximum flush-flow through each line. These flows should be the same for all lines so that the combined needle-valve and tubing impedance to flow is the approximately the same for each line and consequently the pressure on the inlet Nafion drier will be similar for each line. The flush flows can be set lower if necessary. The processing software accounts for these flow rates and the tubing lengths in calculating the actual time a sample entered the inlet.

Calibration gas regulator adjustment:

Only the HS2, HS1, LS1, and LS2 calibration gas regulators should be set to 9 psi. IMPORTANT: If the LT surveillance gas regulator pressure is set higher than 4 psi the sample pump can be damaged.

Inline Beswick regulator adjustment:

These regulators are adjusted by turning the small thumb screw clockwise to increase pressure and counter-clockwise to decrease pressure. The larger knob is a lock nut that must be loosened before adjustment and tightened after.

LT regulator adjustment:

Normally this results in a regulator gauge reading of around 3 psig.

Flow control needle valve adjustment:

This Swagelok valve is the primary point of flow adjustment for the instrument.

Calibration pressure and flow check:

If all calibration pressures differ significantly from the previously recorded sample gas pressures it is likely that the sample pump is having problems. If any of the calibration pressures are significantly different than the others it is possible that the cylinder regulator is set incorrectly or that there is a leak or obstruction in that calibration line.

Line purge needle valve adjustment:

The gas selection manifold has 2-way valves for the calibration gases so that they will not flow when not selected, but a 3-way valve for the sample gas so that when it is not selected it continues to flow out a bypass line and the upstream Nafion drier experiences constant pressure. This step adjusts the impedence on this bypass line to match that through the Beswick regulator and flow control needle valve. Because the bypass line does not have a mass-flow meter the sample line mass-flow meter is borrowed for this step.

LT needle valve fine tune:

The LT needle valve is set through the purge line while the sample line mass-flow meter is still attached to the purge line. This allows the delivery impedance of air from the regulator through this needle valve to be matched to the delivery impedance of air from one of the sample lines, which would not be possible if the through the analysis line which includes the inline regulator. IMPORTANT: Fine tuning this needle valve requires REVERSE control. The sample pump does not operate well with high upstream pressure, such that opening this needle valve actually decreases the flow through the pump. Conversely closing this needle valve will increase the flow (of course closing it all the way will eventually reduce the flow).

Sample pressure and flow check:

Ensure that pressures and flows are similar between lines and between sample and the previously recorded calibration values. If the LT pressure or flow is significantly different than the sample line pressure or flow, redo the LT needle valve fine tune and check again.

High side pressure recording:

Cylinder pressures should be recorded whenever possible to establish a history of depletion to evaluate whether any small leaks exist on the calibration gas fittings, regulators, or lines, and to anticipate when cylinders will need to be changed. In accordance with NOAA GMD guidelines, do not use any calibration cylinders below 300 psig (20 atm) and return them to laboratory for post-calibration at this point.

AIRCOA Set-up/Tune-up Procedures for **5 Inlet Line** Unit

Unit ____________ Date _______________ Location: _____________

OPTIONAL: If Diagnostics suggests a leak, here's how to track it down:

Do a high pressure leak check
"o" to open all relays
Power up leak check valve (R12 on)
Open LT, Sample solenoid (R5, R6 on) for 30 sec (Pressure should go to ~ 20 kPa over ambient)
Close LT, leave sample solenoid open (R5 off)
When pressure stabilizes, note time and pressure ____________ @ ____:____:____
Wait 2 minutes and again note time and pressure _______ @ ____:____:_____
If pressures differ by more than 0.05 kPa/min, check fittings for potential leaks
Repeat if necessary. Repeat with Sample solenoid (R6) off to localize below or above gas selection manifold.

Low Pressure Leak Check
"o" to open all relays
Power up line 1 (R0), Guest Cal (R11) and Micropump (R13) to vent above regulator for 30 sec

Close Guest Cal (R11), power up leak check (R12) and note time and pressure
____________ @ ____:____:_____
After two minutes , note time and pressure ____________ @ ____:____:_____
Change should be less than 0.05 kPa/min or a cal solenoid needs repair/replacement

STANDARD:

Adjust inlet needle valves
"o" to open all relays. For first time tune, open all needle valves all the way
Power up Lines 2, 3, 4 and 5 (R1, R2, R3, R4 on) so all flush flow goes through Line 1
Line 1 Flow ________________V
Repeat for Lines 2, 3, 4 and 5
R0, R2, R3, R4 on. Line 2 Flow _________________V
R0, R1, R3, R4 on. Line 3 Flow _________________V
R0, R1, R2, R4 on. Line 4 Flow _________________V
R0, R1, R2, R3 on. Line 5 Flow _________________V
Adjust each inlet needle valve so that MFM reads the same as the lowest one (or 4.9, whichever is less) +/- 0.1.
Line 1 Flow ____________Line 2 Flow ____________V Line 3 Flow ______________V
Line 4 Flow ____________Line 5 Flow ____________V

Adjust all calibration cylinder regulators (not LT!) to 9 psig (initial set-up only)

Set Beswick regulator
"o" to open all relays
Watch Licor pressure till stable. Licor ambient pressure _______________kPa
Close leak check solenoid (R12 on), ensure pump is off (R13 off)
Open LS2 (R7 on)
Adjust regulator/check that Licor pressure is 30 +/- 2 kPa above ambient (Note: may need to open V12 if pressure goes above setpoint to allow pressure to vent back down).
Beswick regulator setting: _______________kPa @ 30 seconds after V7 on
Close LS2 (R7 off)

Set LT cylinder regulator
"o" to open all relays

Close Leak check solenoid (R12 on)
Open Sample solenoid (R6 on), open LT inlet solenoid (R5 on)
Adjust LT cylinder regulator to get Licor pressure 20 +/- 2 kPa over ambient after 30 sec
LT regulator setting: ________________kPa, regulator gauge _____________psi

Adjust Licor flow needle valve
“o” to open all relays
Open Line 1, Sample solenoid (R0, R6 on)
Turn on pump (R13 on)
Use Licor needle valve to set flow on Sample MFM to 100 sccm (~ 2.35 V).
Flow: _______________V, Licor Pressure: _____________kPa

Check calibration sampling pressures and flows
“o” to open all relays
LS2 solenoid open (R7 on)
LS2 Pressure: _____________kPa, Sample Flow V: __________________
Repeat for LS1 (R8), HS1 (R9) and HS2 (R10)
LS1 Pressure: _____________kPa, Sample Flow V: __________________
HS1 Pressure: _____________kPa, Sample Flow V: __________________
HS2 Pressure: _____________kPa, Sample Flow V: __________________

Adjust line purge needle valve

“o” to open all relays
Connect Sample MFM to outlet of line purge needle valve
Open Line 1 solenoid (R0)
Turn on pump (R13 on) to send Line 1 flow out purge valve
Adjust needle valve to 100 sccm (2.2-2.5 V)
Line purge flow: ________________

Cylinder High Side Pressures

HS2	
HS1	
LS1	
LS2	
LT	

Fine tune LT needle valve
“o” to open all relays
Open LT solenoid (R3 on)
Turn on pump (R13 on) to send LT flow out purge valve
Adjust needle valve to get flow equal to 100 sccm (2.2-2.5 V)
LT purge flow: _________________V
Return Sample MFM on outlet Nafion

Then check Line sampling pressures and flows
“o” to open all relays
Open Line 1, Sample solenoid (R0, R6 on)
Turn on pump (R13 on)
Line 1 pressure: _______________kPa, Line Flow V: ___________ Sample Flow V: ______________
R0 off, R1 on
Line 2 pres: _________________kPa, Line Flow V: ____________ Sample Flow V: _____________
R1 off, R2 on
Line 3 pres: _________________kPa, Line Flow V: ____________ Sample Flow V: _____________
R2 off, R3 on
Line 4 pres: _________________kPa, Line Flow V: ____________ Sample Flow V: _____________
R3 off, R4 on
Line 5 pres: _________________kPa, Line Flow V: ____________ Sample Flow V: _____________
R4 off, R5 on
LT pres: _________________kPa, Line Flow V: _______________ Sample Flow V: _____________

AIRCOA Set-up/Tune-up Procedures for **3 Inlet Line** Unit

Unit ____________ Date _______________ Location: _____________

OPTIONAL: If Diagnostics suggests a leak, here's how to track it down:

Do a high pressure leak check
"o" to open all relays
Power up leak check valve (R12 on)
Open LT, Sample solenoid (R3, R6 on) for 30 sec (Pressure should go to ~ 20 kPa over ambient)
Close LT, leave sample solenoid open (R3 off)
When pressure stabilizes, note time and pressure ____________ @ ____:____:____
Wait 2 minutes and again note time and pressure _______ @ ____:____:_____
If pressures differ by more than 0.05 kPa/min, check fittings for potential leaks
Repeat if necessary. Repeat with Sample solenoid (R6) off to localize below or above gas selection manifold.

Low Pressure Leak Check
"o" to open all relays
Power up line 1 (R0), Guest Cal (R11) and Micropump (R13) to vent above regulator for 30 sec

Close Guest Cal (R11), power up leak check (R12) and note time and pressure
____________ @ ____:____:_____
After two minutes , note time and pressure ____________ @ ____:____:_____
Change should be less than 0.05 kPa/min or a cal solenoid needs repair/replacement

STANDARD:

Adjust inlet needle valves
"o" to open all relays. For first time tune, open all needle valves all the way
Open Lines 2 and 3 (R1, R2 on) so all flush flow goes through Line 1
Line 1 Flow ________________V
Repeat for Lines 2 and 3
R0, R2 on. Line 2 Flow _________________V
R0, R1 on. Line 3 Flow _________________V
Adjust each inlet needle valve so that MFM reads the same as the lowest one (or 4.9, whichever is less) +/- 0.1.
Line 1 Flow ____________Line 2 Flow ____________V Line 3 Flow ______________V

Adjust all calibration cylinder regulators (not LT!) to 9 psig (initial set-up only)

Set Beswick regulator
"o" to open all relays
Watch Licor pressure till stable. Licor ambient pressure _______________kPa
Close leak check solenoid (R12 on), ensure pump is off (R13 off)
Open LS2 (R7 on)
Adjust regulator/check that Licor pressure is 30 +/- 2 kPa above ambient (Note: may need to open V12 if pressure goes above setpoint to allow pressure to vent back down).
Beswick regulator setting: _______________kPa @ 30 seconds after V7 on
Close LS2 (R7 off)

Set LT cylinder regulator

"o" to open all relays
Close Leak check solenoid (R12 on)
Open Sample solenoid (R6 on), open LT inlet solenoid (R3 on)
Adjust LT cylinder regulator to get Licor pressure 20 +/- 2 kPa over ambient after 30 sec
LT regulator setting: _______________kPa, regulator gauge ____________psi

Adjust Licor flow needle valve

"o" to open all relays
Open Line 1, Sample solenoid (R0, R6 on)
Turn on pump (R13 on)
Use Licor needle valve to set flow on Sample MFM to 100 sccm (~ 2.35 V).
Flow: ______________V, Licor Pressure: ____________kPa

Check calibration sampling pressures and flows

"o" to open all relays
LS2 solenoid open (R7 on)
LS2 Pressure: ____________kPa, Sample Flow V: _________________
Repeat for LS1 (R8), HS1 (R9) and HS2 (R10)
LS1 Pressure: ____________kPa, Sample Flow V: _________________
HS1 Pressure: ____________kPa, Sample Flow V: _________________
HS2 Pressure: ____________kPa, Sample Flow V: _________________

Adjust line purge needle valve

"o" to open all relays
Connect Sample MFM to outlet of line purge needle valve
Open Line 1 solenoid (R0)
Turn on pump (R13 on) to send Line 1 flow out purge valve
Adjust needle valve to 100 sccm (2.2-2.5 V)
Line purge flow: _______________

Cylinder High Side Pressures

HS2	
HS1	
LS1	
LS2	
LT	

Fine tune LT needle valve

"o" to open all relays
Open LT solenoid (R3 on)
Turn on pump (R13 on) to send LT flow out purge valve
Adjust needle valve to get flow equal to 100 sccm (2.2-2.5 V)
LT purge flow: ________________V
Return Sample MFM on outlet Nafion

Then check Line sampling pressures and flows

"o" to open all relays
Open Line 1, Sample solenoid (R0, R6 on)
Turn on pump (R13 on)
Line 1 pressure: ______________kPa, Line Flow V: __________ Sample Flow V: _____________
R0 off, R1 on
Line 2 pres: ________________kPa, Line Flow V: ___________ Sample Flow V: ____________
R1 off, R2 on
Line 3 pres: ________________kPa, Line Flow V: ___________ Sample Flow V: ____________
R2 off, R3 on
LT pres: ________________kPa, Line Flow V: ______________ Sample Flow V: ____________

B. AWM3300 mass-flow meter lookup chart

sccm	volts	sccm	volts
0	1.00	500	4.13
25	1.39	525	4.20
50	1.72	550	4.28
75	2.01	575	4.35
100	2.26	600	4.42
125	2.47	625	4.49
150	2.66	650	4.55
175	2.82	675	4.60
200	2.97	700	4.65
225	3.10	725	4.70
250	3.22	750	4.73
275	3.33	775	4.77
300	3.43	800	4.80
325	3.52	825	4.82
350	3.62	850	4.84
375	3.71	875	4.86
400	3.79	900	4.87
425	3.88	925	4.89
450	3.96	950	4.92
475	4.04	975	4.95
500	4.13	1000	5.00

C. Li-820 calibration

The AIRCOA does not rely on the Li-820 CO_2 sensor calibration but does perform better if the Li-820 is reasonably well calibrated because its internal pressure correction functions are more accurate then. We recommend recalibrating the Li-820 whenever its internal calibration has drifted by more than 20 ppm as determined by comparing to one of the known calibration gas concentrations. The Li-820 PC interface software that is required to do this can be downloaded from:

ftp://ftp.licor.com/perm/env/LI-820/Software/LI820_win-1.0.0.exe

The Li-820 manual is provided as a supporting document to this manual (see Appendix F) and can also be downloaded from:

http://ftp.licor.com/env/LI-820/Manual/LI-820_Manual.pdf

Most of the Li-820 drift is in the zero or constant offset component, but unfortunately the Li-820 software does not allow adjustment of the zero to match an ambient concentration reference gas. Therefore, you will need a source of zero CO_2 gas to perform this calibration. We recommend using N_2 as opposed to air that has been scrubbed of CO_2 to avoid getting any of the scrubbing agent inside the instrument and we recommend using 99.999 % N_2 or better to reduce the amount of CO_2 in the gas. Note: the CO_2 readings from the instrument will be biased for up to several hours after running N_2 through the instrument as the Nafions and other plastic surfaces come back into equilibrium with ambient CO_2 levels. To introduce the N_2 to the instrument, you can connect to the guest-cal bulkhead fitting on the outside of the instrument and use the manual relay control program to select this line. The Li-820 span also drifts and after zeroing the instrument you should introduce HS2 calibration gas to the sensor and use its value to set the span.

D. Drying system

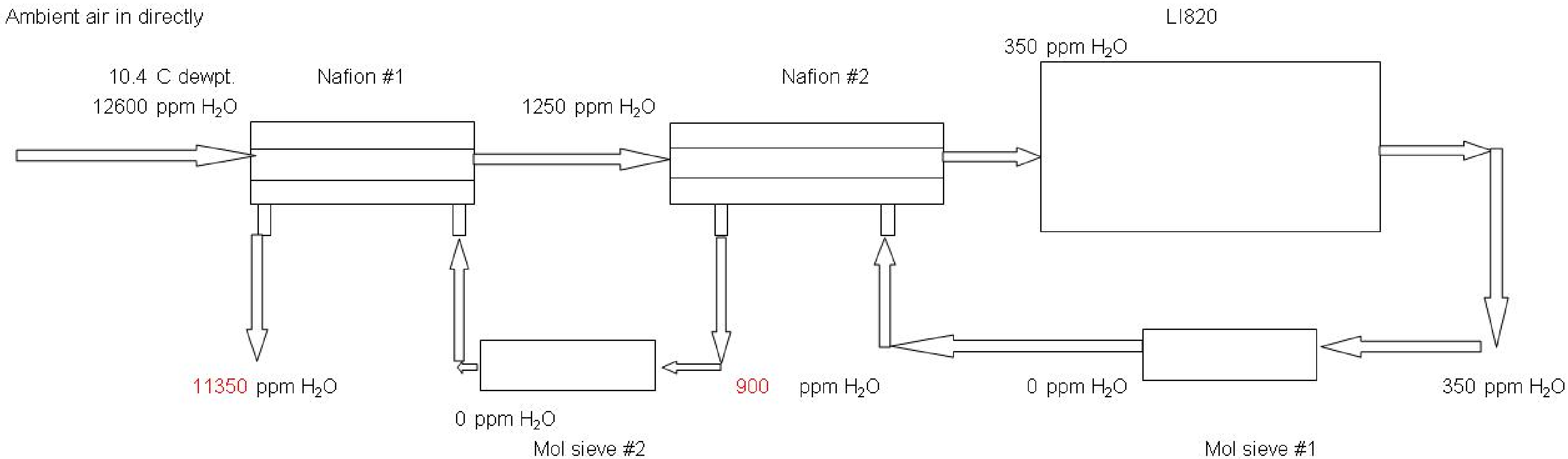
The AIRCOA drying system consists of a combination of Nafion drying tubes (www.permapure.com) and mole sieve moisture traps. Water in the sample air is transported by the Nafion from the inner sample tube to the outer purge tube as a result of the humidity difference. The air entering the outer purge tube has been dried by the mole sieve traps so enters with no water and carries away most of the water that entered in the inner sample tube. The first Nafion tube dries the sample gas to 1000-3000 ppm H_2O and the second Nafion tube further dries the sample gas and humidifies the calibration gases to 300-700 ppm H_2O. A difference in humidity between the sample and calibration gases of 300 ppm would result in a dilution bias in the CO_2 measurement of 0.1 ppm. The response time of the Nafion tubes to changes in input humidity is many hours. Therefore, they are very good at matching humidity between the calibration and sample gases to within a few ppm. Note: their response time to a change in ambient temperature is very rapid, with a 1 C change in ambient temperature resulting in a 1 C change in output dew point. The AIRCOA mole sieve driers contain 200 ml of mole sieve (13X with 4A indicating). For systems intended for high-altitude operations, only one 200 ml drier is used in the second position, but for systems intended for sea-level operations, two 200 ml driers in series are used in this position to increase the time between required replacement.

The last two pages in this section show the results of laboratory tests of the drying system during which the humidity at multiple points in the system was measured. The two tests correspond to sampling air with a dew point of 10 C and a dew point of 26 C. These tests indicate that the driers in the second position will last between 5.5 and 14.5 months depending on ambient humidity conditions. The drier in the first position should last between 10 and 18 months but we recommend replacing it at the same time as the other driers. When a drier becomes saturated, the RH measurement in the instrument will begin a steady climb, indicating that servicing is required. Saturated mole sieve can be regenerated by heating at 250 C for several hours in a shallow pan.

It is also possible that during extreme precipitation events the instrument may ingest liquid water. If liquid water comes in contact with the Nafion tubes they will no longer work. The following note is from the Permapure FAQ web page:

> Introduction of liquid water into the dryer causes failure by an unexpected mechanism. Ordinarily Nafion dryers remove water vapor from the sample and perevaporate it into the surrounding medium. There is no net phase change, and no energy is consumed. If liquid water enters the dryer, it is still absorbed then perevaporated as water vapor. Since energy is thereby consumed, the dryer begins to cool. As it cools, it condenses more water, causing more cooling. There is a cascade failure in which the dryer becomes progressively colder and wetter until it is completely soaked and nonfunctional.
>
> In most instances, when the dryer becomes physically wet, the process can be reversed by simply discontinuing sample flow and permitting the purge gas to dry out the device. The dryer then recovers its normal performance. Unfortunately, in some instances the sample may contain ionic compounds in the gas phase. If present, these ionic compounds will dissolve in the liquid water accumulating within the dryer. Once present in solution, the ions can participate in ion exchange with the Nafion tubing, converting the tubing to another form that is much less water absorptive. Should this occur, it will be necessary to regenerate the Nafion tubing by treatment with acid before it fully recovers its normal performance.

Note that in the AIRCOA system it is not possible to stop the sample flow while keeping the purge flow going, as the two are linked. If water does enter one of the Nafion tubes, we recommend removing both tubes from the instrument as soon as possible and purging them with dry air or nitrogen for several days. Also, if the inner Nafion tube still appears kinked or collapsed, soaking all but the end fittings in methanol can restore its shape. It is also possible in this case that liquid water will have entered the Li-820. We recommend also purging the Li-820 with dry air or nitrogen. If the Li-820 calibration seems significantly affected, follow the Li-Cor procedures for cleaning the optical bench and then perform a recalibration.



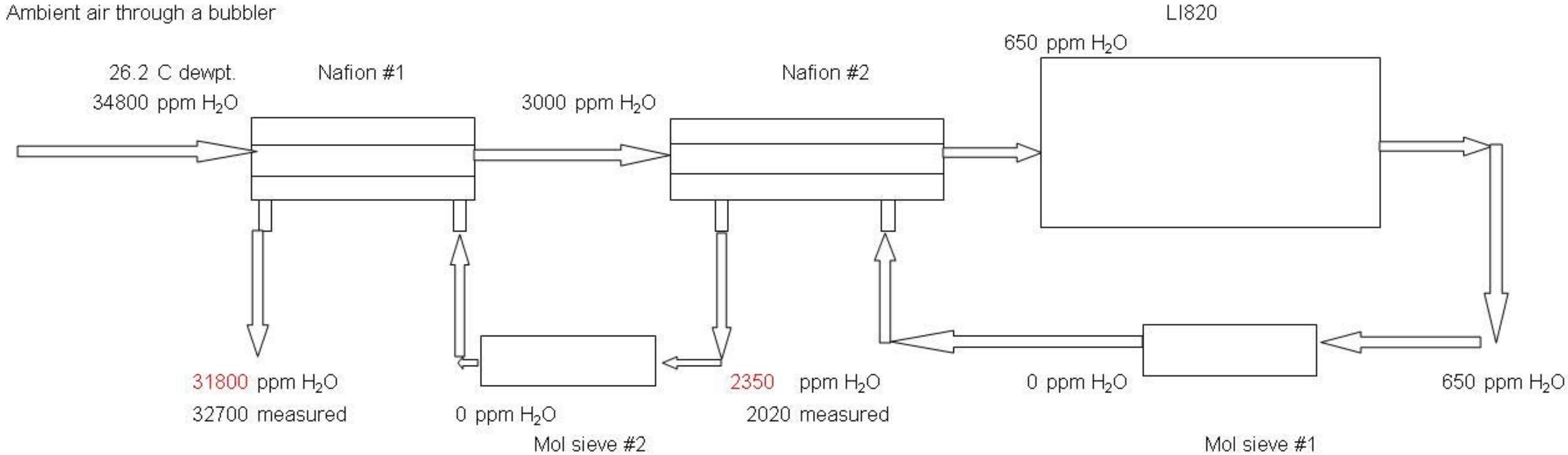
Red values are calculated

Second mol sieve removes

	900	ppm H_2O	=umol/mol
Flow rate	100	mL/min	
Ideal gas	22.4	mL/mmol air	
mol. Weight	18	ug H2O/umol	
	1000	mmol/mol	
Molar flow rate	4.46	mmol air/min	
Part that is H2O	4.02	umol H2O/min	
	72.32	ug H2O/min	
	104.14	mg H2O/day	
Trap size	400.00	mL	
Bulk density, mol sieve	0.64	g/mL	
Wt. mol sieve	256.00	g	
g H2O/g mol sieve	0.18		
Total water it can hold	46.08	g	
Time before full	442.47	days	

First mol sieve removes

	350	ppm H_2O	=umol/mol
Flow rate	100	mL/min	
Ideal gas	22.4	mL/mmol air	
mol. Weight	18	ug H2O/umol	
	1000	mmol/mol	
Molar flow rate	4.46	mmol air/min	
Part that is H2O	1.56	umol H2O/min	
	28.13	ug H2O/min	
	40.50	mg H2O/day	
Trap size	200.00	mL	
Bulk density, mol sieve	0.64	g/mL	
Wt. mol sieve	128.00	g	
g H2O/g mol sieve	0.18		
Total water it can hold	23.04	g	
Time before full	568.89	days	



Red values are calculated

	Second mol sieve removes		First mol sieve removes	
	2350	ppm H_2O =umol/mol	650	ppm H_2O =umol/mol
Flow rate	100	mL/min	100	mL/min
Ideal gas	22.4	mL/mmol air	22.4	mL/mmol air
mol. Weight	18	ug H2O/umol	18	ug H2O/umol
	1000	mmol/mol	1000	mmol/mol
Molar flow rate	4.46	mmol air/min	4.46	mmol air/min
Part that is H2O	10.49	umol H2O/min	2.90	umol H2O/min
	188.84	ug H2O/min	52.23	ug H2O/min
	271.93	mg H2O/day	75.21	mg H2O/day
Trap size	400.00	mL	200.00	mL
Bulk density, mol sieve	0.64	g/mL	0.64	g/mL
Wt. mol sieve	256.00	g	128.00	g
g H2O/g mol sieve	0.18		0.18	
Total water it can hold	46.08	g	23.04	g
Time before full	169.46	days	306.32	days

4. Instrument Computer Configuration

A. Basic setup

The instrument computer is contained in a PC104 stack that includes, from bottom to top, a custom interconnect board (Appendix E) that supplies power and receives signals from all of the diagnostic sensors, a relay board with 20 relays, a power supply board, and a Prometheus 486 computer board. Also, the Prometheus board has a 32 MB flash module mounted to it which contains the BusyBox Linux operating system (http://www.busybox.net) and custom C programs for controlling and interacting with the instrument. These C programs control relays for the valves and micropump, record serial data from the CO_2 sensor, and log analog signals from the mass flow, temperature, and humidity sensors.

Connect to the instrument using either the COM 2 or ethernet interfaces as described in Section 2. The computer can be rebooted either by powering the instrument down and up, or by using the command:

```
~ # reboot
```

The initialization file /etc/rc.sysinit configures much of the system at startup and by default it contains:

```
#!/bin/sh

# Required to allow spawning of persistant processes from this script.
trap "" SIGHUP

PATH=/bin:/sbin:/usr/bin:/usr/sbin:/usr/local/bin:/usr/local/sbin:.
export PATH

export TERM=vt100

/sbin/fsck.ext3 /dev/hda1

/bin/hostname aircoan  # or other aircoa unit name
/bin/mount -t proc /proc /proc
/bin/mount -n -o remount,rw,noatime /

# read hardware clock
/sbin/insmod rtc && /sbin/hwclock --hctosys

# ramfs
mount /var/tmp
mkdir /var/tmp/run
mkdir /var/tmp/log
touch /var/tmp/log/messages
touch /var/tmp/log/isff.log
touch /var/tmp/log/lastlog      # used by sshd (doesn't grow)
```

```
/sbin/ifconfig lo 127.0.0.1 netmask 255.0.0.0

# fixed ip address (use this for field operation)
#/sbin/ifconfig eth0 198.11.18.44 netmask 255.255.255.0 # edit
addresses and uncomment

# gateway (if needed)
#/sbin/route add default gw 198.11.18.1

# dhcp (use this if needed for lab testing)
mkdir /var/tmp/dhcpcd
/sbin/dhcpcd -L /var/tmp/dhcpcd -d -n -h `hostname` -R eth0

# set up network time sync
cp /etc/ntp/drift /var/run/ntp.drift
/sbin/portmap
/sbin/syslogd -m 0
/usr/sbin/ntpdate 192.43.244.18 && /sbin/hwclock --systohc # NCARs NIST
ntp server
/usr/sbin/ntpd -P 50

/usr/bin/setupsshkeys.sh && /usr/sbin/sshd &

/sbin/insmod /lib/modules/misc/dscudkp.o

# set up serial ports
/bin/setserial /dev/ttyS0 port 0x3f8 irq 4 uart 16550A
/bin/setserial /dev/ttyS1 port 0x2f8 irq 3 uart 16550A
/bin/setserial /dev/ttyS2 port 0x3e8 irq 5 uart 16850
/bin/setserial /dev/ttyS3 port 0x2e8 irq 15 uart 16850

# mount USB pen drive
mount /data && ([ -d /data/aircoa ] || mkdir /data/aircoa)

# start aircoa program
/home/isff/aircoa.sh 2>&1 | /usr/bin/logger -p local4.info &

# start daily data zipping program
#/home/isff/dailyzip.sh &
```

This file also automatically starts the aircoa instrument control program ‘aircoa’ by calling the shell script /home/isff/aircoa.sh.

B. Ethernet setup

By default the Prometheus attempts to obtain an IP address on start-up using DHCP. You will need to convert to using a specified IP address in the field and may need to do so in laboratory as well. To do this, use the vi terminal editor to edit rc.sysinit and comment out the 2 DHCP lines:

```
#mkdir /var/tmp/dhcpcd
#/sbin/dhcpcd -L /var/tmp/dhcpcd -d -n -h `hostname` -R eth0
```

Next comment in the line:

```
/sbin/ifconfig eth0 198.11.18.44 netmask 255.255.255.0
```

and edit the eth0 address and netmask to correspond to your network environment. If you need to specify a gateway, do so by uncommenting the line:

```
/sbin/route add default gw 198.11.18.1
```

and editing the gateway address to correspond to your gateway.

C. USB drive

The data are stored on a 512 MB USB drive attached to the Prometheus via one of the USB connectors. This drive is configured in the file /etc/fstab with the line:

```
/dev/sda1       /data vfat   defaults,noatime,noauto 0 0
```

and mounted as /data during start up by the line in /etc/rc.sysinit:

```
mount /data && ([ -d /data/aircoa ] || mkdir /data/aircoa)
```

This command also creates the directory /data/aircoa. IMPORTANT: This USB drive can not be 'hot-swapped' as it could on a Windows or Mac system and disconnecting it before unmounting it could result in corrupted data or damage to the drive. In normal operation using remote data transfer (see Section 5) you should not have to disconnect this drive. If you do need to disconnect this drive, first stop the aircoa program by starting the manual relay control program (see Section 2D above) and typing 'Q' then unmount the drive using the command:

```
~ # umount /data
```

after reconnecting it, you must mount it using the command:

```
~ # mount /data
```

and ensure that the directory /data/aircoa exists before restarting the aircoa program with the command:

```
~ # /home/isff/aircoa.sh 2>&1 | /usr/bin/logger -p local4.info &
```

D. Network time synchronization

The Prometheus is configured to synchronize its clock with GMT time using the NCAR NIST ntp server. To do this, it must be connected to the internet. If it is not connected or the ntp program is not configured properly, the Prometheus time will drift by around 30 seconds per week and will require manual resetting. The ntp program is configured in two places. First, in rc.sysinit with the lines:

```
cp /etc/ntp/drift /var/run/ntp.drift
/usr/sbin/ntpdate 192.43.244.18 && /sbin/hwclock –systohc
/usr/sbin/ntpd -P 50
```

and second, in the file /etc/ntp.conf with the line:

```
server 192.43.244.18
```

If you wish to use a different ntp server, you must set its IP address in BOTH of these files.

E. Instrument control program

The instrument control program ‘aircoa’ and the manual relay control program reside in the directory /usr/local/bin. The aircoa program is started from the script /home/isff/aircoa.sh, which is called by /etc/rc.sysinit on system start up. The script aircoa.sh is set to attempt to start the aircoa program every 30 seconds until successful. It contains:

```
#!/bin/sh

cd /home/isff/aircoa

PATH=/usr/local/bin:$PATH

# aircoa arguments:
#  -r relay_program_file relay_program_name:  file and program to run
#  -x xml_init_file    :   file of XML to send to LI820 on startup
#  -t serial output port:
#  -R samples per second:
#  -a archive file_directory name_format interval_in_seconds:

args="-r relays5.txt relays5 -x li820.xml -t /dev/ttyS2 -R 1 -a
/data/aircoa af_%y%m%d_%H%M%S.dat 28800"

while true; do
  # exit loop if successful exit from aircoa
  aircoa $args && break
  sleep 30
done

echo "$0 exiting"
```

where the first 2 letters of the output file correspond to the specific AIRCOA unit. Also, a 3 inlet line unit will call the file relays3.txt and the program relays3 instead of relays5.txt and relays5 as shown. The output file interval (third input to argument -a) is currently set to 28800 seconds (3 files per day) but can be adjusted. The output rate (input to argument -R) is currently set to 1 Hz but can be adjusted to minimize data file size as long as the Li-820 filter is adjusted accordingly (see below). The file /home/isff/aircoa/li820.xml configures the Li-820 sensor and contains:

```
<LI820>
  <CFG>
    <OUTRATE>0</OUTRATE>
    <HEATER>TRUE</HEATER>
    <PCOMP>TRUE</PCOMP>
    <BENCH>14</BENCH>
    <SPAN>1000</SPAN>
    <FILTER>2</FILTER>
  </CFG>
  <RS232>
    <CO2ABS>FALSE</CO2ABS>
    <IVOLT>FALSE</IVOLT>
    <RAW>FALSE</RAW>
  </RS232>
</LI820>
```

Refer to the Li-820 manual (Appendix F or http://ftp.licor.com/env/LI-820/Manual/LI-820_Manual.pdf) for details on these commands. The raw data rate of the Li-820 is 2 Hz. Setting the filter to 2 causes the sensor to apply a 2 second digital smoother to the measurements which ensures that our 1 Hz sampling rate does not undersample the measurements. If the sampling rate is reduced to 0.5 Hz, this filter should be increased to 4 seconds.

The program file /home/isff/aircoa/relays5.txt specifies the schedule of relay switches for the 5 inlet line units and contains:

```
include sequences5.txt

program relays5
  #        name     repeat
  sequence baseloop 3
  sequence zerocal1 1

  sequence baseloop 2
  sequence zerocal2 1

  sequence baseloop 2
  sequence zerocal3 1

  sequence baseloop 2
  sequence bloopno1 1
  sequence zerocal4 1
```

```
  sequence baseloop 2
  sequence zerocal1 1

  sequence baseloop 2
  sequence zerocal2 1

  sequence baseloop 3

  sequence fullcal1 1

  sequence baseloop 3
  sequence zerocal3 1

  sequence baseloop 2
  sequence zerocal4 1

  sequence baseloop 2
  sequence zerocal1 1

  sequence baseloop 2
  sequence bloopno1 1
  sequence zerocal2 1

  sequence baseloop 2
  sequence zerocal3 1

  sequence baseloop 2
  sequence zerocal4 1

  sequence baseloop 3

  sequence fullcal2 1

end program
```

which defines the program 'relays5' and includes the file /home/isff/aircoa/sequences5.txt. This file defines the sequences named in the program relays5 as:

```
include settings5.txt

sequence baseloop
  # setting     seconds
  line5         150
  line4         150
  line3         150
  line2         150
  line1         150
end sequence

sequence bloopno1
  # setting     seconds
  line5         150
  line4         150
  line3         150
```

```
  line2         150
end sequence

sequence zerocal1
  # setting     seconds
  cal1          150
end sequence

sequence zerocal2
  # setting     seconds
  cal2          150
end sequence

sequence zerocal3
  # setting     seconds
  cal3          150
end sequence

sequence zerocal4
  # setting     seconds
  cal4          150
end sequence

sequence fullcal1
  # setting     seconds
  cal1          150
  cal2          150
  cal3          150
  cal4          150
  ventall       30
  loleakcheck   120
  lt            150
end sequence

sequence fullcal2
  # setting     seconds
  cal4          150
  cal3          150
  cal2          150
  cal1          150
  ventall       30
  loleakcheck   120
  pressurize    30
  hileakcheck   120
end sequence
```

and further includes the file /home/isff/aircoa/settings5.txt which specifies what relays to turn on in each of the named settings:

```
#  spare pump lkchk guest HS2  HS1  LS1  LS2 air lt  l5 l4 l3 l2 l1
#    14   13   12    11   10    9    8    7   6   5   4  3  2  1  0
#
settings
#               14 13 12 11 10  9  8  7  6  5  4  3  2  1  0
  line1         0  1  0  0  0   0  0  0  1  0  0  0  0  0  1
  line2         0  1  0  0  0   0  0  0  1  0  0  0  0  1  0
```

```
  line3          0  1  0  0  0   0  0  0  1  0  0  0  1  0  0
  line4          0  1  0  0  0   0  0  0  1  0  0  1  0  0  0
  line5          0  1  0  0  0   0  0  0  1  0  1  0  0  0  0
  lt             0  1  0  0  0   0  0  0  1  1  0  0  0  0  0

  cal1           0  1  0  0  0   0  0  1  0  0  0  0  0  0  1
  cal2           0  1  0  0  0   0  1  0  0  0  0  0  0  0  1
  cal3           0  1  0  0  0   1  0  0  0  0  0  0  0  0  1
  cal4           0  1  0  0  1   0  0  0  0  0  0  0  0  0  1

  ventall        0  1  0  1  0   0  0  0  0  0  0  0  0  0  1
  pressurize     0  0  1  0  0   0  0  0  1  1  0  0  0  0  0
  loleakcheck    0  1  1  0  0   0  0  0  0  0  0  0  0  0  1
  hileakcheck    0  0  1  0  0   0  0  0  1  0  0  0  0  0  0
end settings
```

Collectively, these three files in /home/isff/aircoa (relays5.txt, sequences5.txt, and settings5.txt) define the valves sequences shown in Appendix B. The three files relays3.txt, sequences3.txt, and settings3.txt are somewhat simpler but perform a similar function for the 3 inlet line units. If necessary, these files can be edited to change the default relay sequences.

One more file in this directory, /home/isff/aircoa/aircoa_config.txt, is used to configure the analogue input channels on the Prometheus. For the 5 inlet line units this file contains:

```
T 108 -1.25 1.25
RH 100 -1.25 1.25
flow0 111 -5 5
flow1 104 -5 5
flow2 101 -5 5
flow3 103 -5 5
flow4 110 -5 5
flow5 102 -5 5
flow6 109 -5 5
```

The first column is the variable name, the second column specifies the analog Prometheus channel (Vin0 to Vin11) to use, and the third and fourth columns specify the voltage range. See the Prometheus manual (Appendix F) for details on the allowable range settings. The row order in this file specifies the column order in the output to COM port 3, the manual relay control program, and the output data files. Note: because the Humitter RH signals are very small (~ 20 mV) at the operational dried humidity levels of a few percent, the nature of the Prometheus multiplexing results in a sensitivity of around 0.05 mV to large changes (~ 2 V) in the measured previously signal. Therefore, we sample RH on channel 100 immediately after sampling flow0 (sample flow) on channel 111, which is fairly constant at around 2.35 V, instead of after one of the other flow signals which typically vary by over 3 V.

The aircoa program can be quit by starting the manual relay control program (see Section 2D above) and typing ‘Q’. To trouble shoot problems in starting the aircoa program, start it from the command line directly using the following commands:

```
cd /home/isff/aircoa
PATH=/usr/local/bin:$PATH
aircoa -r relays5.txt relays5 -x li820.xml -t /dev/ttyS2 -R 1 -a
/data/aircoa af_%y%m%d_%H%M%S.dat 28800
```

where the first two letters of the output file format correspond to the specific AIRCOA unit. Standard and error messages will then show up on screen.

5. Transferring Data

A. Storage and manual transfer

The files stored in /data/aircoa on the USB drive take up approximately 9 MB/day for a 3 inlet unit running at 1 Hz and 10 MB/day for a 5 inlet unit. Without zipping, a 512 MB USB drive will fill in approximately 50 days. Connect or log into the system and delete old files every month to prevent the USB drive from filling. If it does fill, the program will no longer log data. To fix this, connect or log in to the computer and delete old files, then restart the aircoa program or reboot the computer.

The script /home/isff/dailyzip.sh can be run to automatically zip previous days' data and this script can be enabled by uncommenting the line in /etc/rc.sysinit:

```
/home/isff/dailyzip.sh &
```

These zipped files are approximately 5 times smaller than the unzipped versions.

Files can be transferred using the linux secure copy command 'scp' or using 'rsync' configured to use ssh. To do this, use the command:

```
> rsync -ae 'ssh' root@123.45.67.89:/data/aircoa/\* .
```

after substituting in the IP address of the specific AIRCOA unit, and enter the root password when prompted.

B. Automated data transfer

To automate this process, it is necessary to set up password-less ssh to the Prometheus computer. To do this, on your home machine enter the command:

```
> ssh-keygen -t dsa
```

You will be prompted for a destination for the key file. Put it in .ssh/aircoa_id_dsa in your home directory. Then enter a carriage return for the passphrase twice. This will create two files in your .ssh directory:

```
aircoa_id_dsa
```

and

```
aircoa_id_dsa.pub
```

Copy the *.pub file to the Prometheus into root's .ssh directory using the command:

```
> scp .ssh/aircoa_id_dsa.pub root@123.45.67.89:/root/.ssh
```

after substituting in the IP address of the specific AIRCOA unit. Then, connect or log in to the Prometheus and cd to the .ssh directory:

```
~ # cd .ssh
```

Next, append the *.pub file to a file called 'authorized_keys' using the command:

```
~/.ssh # cat aircoa_id_dsa.pub >> authorized_keys
```

which will create authorized_keys if it doesn't exist. The permissions on this file must not allow read/write to anybody but root, so next enter the command:

```
~/.ssh # chmod 600 authorized_keys
```

Finally, back on your home system try to ssh into the Prometheus using the command:

```
> ssh -i ~/.ssh/aircoa_id_dsa root@123.45.67.89
```

after substituting in the IP address of the specific AIRCOA unit and replacing the ~ with your explicit home directory path. If it connects without asking for a password it is properly set up. Now, you can modify the rsync command to be:

```
> rsync -ae 'ssh –i ~/.ssh/aircoa_id_dsa'
root@123.45.67.89:/data/aircoa/\* .
```

all on one line and substituting in the IP address of the specific AIRCOA unit and replacing the ~ with your explicit home directory path. This command can then be put into a shell script that is called automatically by a cronjob.

6. Processing Data

The aircoa program stores files of normally 1-Hz data that can then be transferred to a home computer via the internet. Automated Linux scripts and functions written in R (http://www.r-project.org/) are available to process these files to produce diagnostic plots and calibrated data. You will need to download and install R on a Unix or Linux machine. There is also a Windows version of R but the AIRCOA scripts would have to be modified to work in Windows. Once installed the R scripts can be sourced from within the R environment or run using automated batch files from the Unix/Linux environment.

This section contains a description of the R functions, scripts, and batch files. See Section 7 for instructions on obtaining the source files themselves. This code is not fully tested and comes with absolutely no warranties. We will strive to keep anyone who downloads the files appraised of future revisions or corrections, but please also check back often for new versions. The format used to list these files below is:

R source code file name **[executable function name]** (options=defaults)

A. Daily diagnostics and 1-Hz to 2.5-min averaging

aircoa_raw_day.r **[acrawday]** (loc='NWR', unit='A', day='050901', outflag='', njog=150, skip=50, ntrd=50, ico=0.0, eco=1.0, png=F)

This function calls the external data_dump procedure to convert AIRCOA output files (*.dat) with binary time stamps into temporary ascii files. It then reads in data from these ascii files, filters and averages to get 2.5 minute processed data, outputs a processed data file (e.g. NWR_050901.out), a log file (e.g. NWR_050901.log), and daily diagnostic plots.

Parameter	Type	Description
loc	text3	Site code corresponding to data to be processed
unit	text1	AIRCOA unit in use at that site
day	text6	Day of output to be processed
outflag	text1	Optional flag to attach to output files - use to process different parts of one day separately
njog	integer	Data values in measurement period
skip	integer	Data values to skip at start of measurement period

ntrd	integer	Data values to use at start and end of averaging period for slope calculations
ico	real	Fraction of day before which data will be cut off
eco	real	Fraction of day after which data will be cut off
png	logic	Whether png graphs should be generated directly, which is only possible from within the R environment, or via the bitmap command, which works using BATCH files

B. Monthly diagnostics and calibrated data

aircoa_conc_days.r **[acconcdays]** (loc='NWR',unit='A', startchr='050901', endchr='050907' ,inflag='', outflag='', pcor=T, tcor=T, fcor=F, ltmpco=0.5, sflco=70, ico=0.0, eco=1.0, png=F, daily=T)

This function reads in one or more output files (*.out) from acrawday. It also reads in the aircoa_cylrec.txt file and calls a lookup routine (cflkup.r, not shown here) to find assigned calibration gas values. It calculates pressure and temperature smoothers and applies 4-hourly quadratic and 30-minute zero-offset calibrations. It also reads in the aircoa_timeoff.txt file and makes any necessary clock-drift corrections and reads in the aircoa_inlet.txt file and calculates and applies time lags. It interpolates data to 15-minute intervals. It outputs a concentration processing file (e.g. NWR_050901_050907.con), a calibrated measurements file (e.g. NWR_050901_050907.mes), an interpolated measurements file (e.g. NWR_050901_050907.int), a dump file (e.g. NWR_050901_050907.dmp), a log file (e.g. NWR_050901_050907.log), and daily timeseries and profile plots, weekly timeseries plots, a monthly timeseries plot, a monthly diurnal cycle and variability plot, and monthly diagnostic plots. Furthermore, it reads in concentration processing output files from previous months and outputs a full concentration processing file (e.g. NWR_050901_061106.lco), full calibrated measurements file (e.g. NWR_050901_061106.lme), a full interpolated measurements file (e.g. NWR_050901_061106.lin), and full timeseries plots. It also reads in the aircoa_hiside.txt file and outputs a timeseries plot of cylinder pressures.

Parameter	Type	Description
loc	text3	Site code corresponding to data to be processed
unit	text1	AIRCOA unit in use at that site
startchr	text6	First day of output to be processed
endchr	text6	Last day of output to be processed

inflag	text1	Optional flag used to read in flagged output from acrawday
outflag	text1	Optional flag to attach to output files
pcor	logic	Whether a pressure smoother should be applied
tcor	logic	Whether a temperature smoother should be applied
fcor	logic	Whether a flushing correction should be applied
ltmpco	real	LiCor 840 temperature (degC) anomaly above which data will be cut off
sflco	real	Sample flow (sccm) below which data will be cut off
ico	real	Fraction of day before which data will be cut off on first day processed
eco	real	Fraction of day after which data will be cut off on last day processed
png	logic	Whether png graphs should be generated directly, which is only possible from within the R environment, or via the bitmap command, which works using BATCH files
daily	logic	Whether daily calibrated timeseries and profile plots should be produced

C. Comparisons between sites and units

aircoa_comp.r [accomp] (start='050902', end='050907', locs=c('NWR','FEF','SPL'), outflag='', ico=0.0, eco=1.0, png=F)

This function reads in the full output files (*.lco) from acconcdays for two or more units and compares their concentrations. It outputs a combined concentration file (e.g. comp_050226_050304.out), a results file (e.g. comp_050226_050304.res), a log file (e.g. comp_050226_050304.log), and comparison plots.

Parameter	Type	Description
start	text6	First day of output to be processed
end	text6	Last day of output to be processed
locs	vector of	Site codes corresponding to data to be processed

	text3	
outflag	text1	Optional flag to attach to output files
ico	real	Fraction of day before which data will be cut off on first day processed
eco	real	Fraction of day after which data will be cut off on last day processed
png	logic	Whether png graphs should be generated directly, which is only possible from within the R environment, or via the bitmap command, which works using BATCH files

D. Generation of organizing html pages

aircoa_make_html.r [acmkhtml] (loc='NWR',unit='A', start='050901', end='050907', procday=T, procconc=F, proccomp=F, outflag='', netdir='/net/www/docs/homes/stephens/RACCOON/', remold=T, remall=F)

This function makes daily diagnostic, multi-day (calibrated) diagnostic, and comparison html pages to organize png and log files from acrawday, acconcdays, and accomp. It removes old output in the network directory and moves new output and html files into the network directory.

Parameter	Type	Description
loc	text3	Site code corresponding to data to be processed (needed if procday or procconc = T)
unit	text1	AIRCOA unit in use at that site (needed if procday or procconc = T)
start	text6	First day of acconcdays or accomp output to be organized (needed if procconc or proccomp = T)
end	text6	Day of acrawday output to be organized, or last day of acconcdays or accomp output to be organized
procday	logic	Whether to organize output of an acrawday run
procconc	logic	Whether to organize output of an acconcdays run
proccomp	logic	Whether to organize output of an accomp run
outflag	text1	Optional flag used to organize flagged output from acrawday, acconcday, or accomp

netdir	text	Directory to move output and html
remold	logic	Whether to remove old output from netdir for same loc and day of acrawday output or same loc and starting day of acconcdays or accomp output
remall	logic	Whether to remove all old output from netdir for same loc

E. Example input files

The above described functions require a number of input files. Note: these input files are assumed to be 2 directories above the directory where the functions are being run.

../../aircoa_cylrec.txt

This file contains information on the cylinder IDs and installation dates and times (GMT) of all calibration cylinders.

```
LOC UNIT DATE TIME HS2 HS1 LS1 LS2 LT
NWR A 050825 0000 JJ21201 JJ8550  JJ13623 JJ8588  JJ19017
FEF C 050825 0000 CC60235 CC42692 CC28157 CC12938 CC29083
SPL D 050901 0000 JJ13615 JJ8174  JJ1348  JJ1378  FA02340
LB5 H 060207 2400 JJ21174 JJ23191 JJ12502 JJ22398 CC71620
SPL D 060303 0247 JJ8852  JJ8578  JJ9020  JJ8485  FA02340
NWR A 060405 1600 JJ9008  JJ8906  JJ482   JJ635   JJ19017
HDP E 060419 0000 JJ651   JJ31255 JJ20269 JJ12491 JJ8510
FEF C 060525 1730 FA02360 CC42692 CC28157 CC12938 CC29083
FEF C 060720 1615 JJ21174 JJ23191 JJ12502 JJ22398 CC29083
CE1 M 060621 0000 CC29040 CC56491 CC28553 CC66785 CC71620
SPL D 060817 1800 JJ8852  JJ8578  JJ9020  JJ8485  JJ18942
CE2 N 060901 0000 CC29040 CC56491 CC28553 CC66785 CC71620
LB6 I 060919 0000 CC29040 CC56491 CC28553 CC66785 CC71620
CE3 O 060929 0000 CC29040 CC56491 CC28553 CC66785 CC71620
CE4 L 060929 0000 CC29040 CC56491 CC28553 CC66785 CC71620
CE5 K 061020 0000 CC29040 CC56491 CC28553 CC66785 CC71620
LB6 I 061024 0000 CC29040 CC56491 CC71620 CC28553 FA02361
CE4 L 061024 0000 CC29040 CC56491 CC71620 CC28553 FA02361
CE5 K 061024 0000 CC29040 CC56491 CC71620 CC28553 FA02361
```

../../**aircoa_inlets.txt**

This file contains information on the installation dates and times (GMT) and tubing inlet heights and lengths in meters. The total inlet lengths are calculated by summing the inlet height and any extra tubing runs or inlet volumes. This file also allows specifying that more than one unit is sampling from the same line (e.g. during an intercomparison) to account for the faster flush flow. Note: this version only allows 3 inlet lines, but modifications are planned to allow 5 inlet lines.

```
LOC UNIT DATE SECONDS L1HEIGHT L2HEIGHT L3HEIGHT HZRUN1 HZRUN2 HZRUN3
  UNITSPERLINE
SPL D 050901 00000.0 2.5 5.8 9.1 149 147.3 164.1 1
FEF C 050829 00000.0 2.6 9.5 17.8 91.5 91.5 91.5 1
NWR A 050825 00000.0 1.3 3.5 2.3 3.3 3.3 4.3 1
NWR A 050910 77400.0 1.3 2.3 3.5 3.3 4.3 3.3 1
NWR A 051012 69000.0 1.3 3.5 5.1 3.3 3.3 5.9 1
LB5 H 060131 00000.0 1 1 1 0 0 0 1
HDP E 060419 00000.0 -999.99 17.1 17.7 -999.99 21.9 17.1 1
CE1 M 060621 00000.0 1 1 1 0 0 0 1
CE2 N 060901 00000.0 1 1 1 0 0 0 1
LB6 I 060919 00000.0 1 1 1 0 0 0 1
CE3 O 060929 00000.0 1 1 1 0 0 0 1
CE4 L 060929 00000.0 1 1 1 0 0 0 1
CE5 K 061020 00000.0 1 1 1 0 0 0 1
```

../../**aircoa_hiside.txt**

This file contains manual readings of the high side regulator gauges on the calibration cylinders. The times in this file must be consistent with the times in aircoa_cylrec.txt. For example, a cylinder swap out must be recorded in aircoa_cylrec.txt with a time after the old high side pressure and before the new high side pressure is recorded here.

```
LOC UNIT DATE GMT HS2P HS1P LS1P LS2P LTP
NWR A 050826 1400 1370 1390 1360 1270 1290
FEF C 050829 1653  780 1060  960 1110 1300
SPL D 050831 1646 1330 1510 1560  910 1120
FEF C 050901 1800  770 1050  960 1100 1300
FEF C 050908 1400  760 1040  930 1090 1300
NWR A 050909 1600 1280 1310 1280 1200 1270
NWR A 050916 1730 1250 1270 1240 1160 1260
NWR A 050922 1800 1200 1240 1210 1130 1260
NWR A 050929 1620 1170 1190 1160 1060 1250
NWR A 051008 2100 1110 1170 1120 1030 1210
FEF C 051013 1800  690  950  890 1000 1300
SPL D 051014 1000 1040 1200 1580  920  970
FEF C 051025 1200  660  940  860 1000 1300
NWR A 051026 1200 1010 1040 1010  910 1190
NWR A 051102 1200  950  990  980  860 1185
NWR A 051123 1200  850  920  890  770 1140
FEF C 051128 1200  600  870  790  920 1260
FEF C 051219 1200  570  840  770  900 1270
NWR A 060112 1200  630  680  660  550 1080
SPL D 060201 1200  440  600  650  510  730
```

../../**aircoa_timeoff.txt**

This file contains information on any clock-drifts. Initially ntp on the Prometheus computers was not configured properly and the computer clocks were drifting.

They no longer drift, but it would be important to maintain this file if the AIRCOA were deployed without internet access.

```
LOC UNIT DATE(YYMMDD) TIMEMEASURED(UNIT) OFFSET(UNIT-UTC in SEC)
NWR A 050824 00:00:00 0
NWR A 051026 18:55:45 -315
NWR A 051028 17:12:59 -316
NWR A 051028 17:13:00 -3  (rebooted)
NWR A 051221 20:45:00 -3
NWR A 060120 01:05:00 0
NWR A 060404 18:00:00 0
NWR A 060426 16:36:29 -53
NWR A 060426 16:36:30 0  (rebooted)
NWR A 060620 15:32:54 -173
NWR A 060620 15:32:55 0  (rebooted)
NWR A 060719 23:19:30 0  (fixed ntp.conf and rebooted)
FEF C 050829 00:00:00 0
FEF C 051026 19:00:00 0
FEF C 051221 20:45:19 199
FEF C 051221 20:45:20 0
FEF C 060120 01:11:51 248
FEF C 060120 01:11:52 0
FEF C 060319 01:18:54 212
FEF C 060319 01:21:00 0  (rebooted)
FEF C 060426 16:48:28 178
FEF C 060426 16:48:29 0
FEF C 060620 15:30:00 0
FEF C 060711 22:56:39 186
FEF C 060711 22:56:40 0  (fixed ntp.conf and rebooted)
```

netdir/CE1_notes.txt

The aircoa_make_html.r function also creates a link to a text file of notes that resides in the specified netdir. Create this file, replacing ‘CE1’ with your location code, and enter in records of field visits or other maintenance.

cflkup.out

The aircoa_conc_days.r function currently calls another R function to look up CO_2 concentrations measured in the NCAR O_2 CO_2 Calibration Facility for a given cylinder. Note: this portion of the code needs to be rewritten to accept a text file of manually entered concentrations. Note also: this code is being edited to account for assumed linear drifts between pre- and post- deployment calibration cylinder determinations.

F. Example batch files and scripts

To be edited.

7. Accessing Operation and Processing Code

Note: the C code for the instrument control programs and the R code described above will be made available through a public web page. Accessing this web page will require the acceptance of the following software license.

R CODE FOR PROCESSING, and C CODE FOR OPERATING, AIRCOA DATA

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Appendix A. WMO/IAEA Experts Meeting Report on AIRCOA

The following short paper briefly describes the AIRCOA instrument and approach. It can be cited as:

Stephens, B., A. Watt, and G. Maclean, An Autonomous Inexpensive Robust CO_2 Analyzer (AIRCOA). 13th WMO/IAEA Meeting of Experts on Carbon Dioxide Concentration and Related Tracers Measurement Techniques, WMO TD in press, 2006.

?.? An Autonomous Inexpensive Robust CO_2 Analyzer (AIRCOA)

Britton Stephens, Andrew Watt, Gordon Maclean

?.?.1 Introduction

We present our design of a new autonomous, inexpensive, and robust CO_2 analyzer (AIRCOA), a description of our quality control procedures, and data examples from ongoing deployments. Our AIRCOA units require less than $10K (USD) in components, can be assembled and tested in 4 weeks or less, show intercomparability of 0.1 ppm or better during laboratory and field tests, and run autonomously for months at a time.

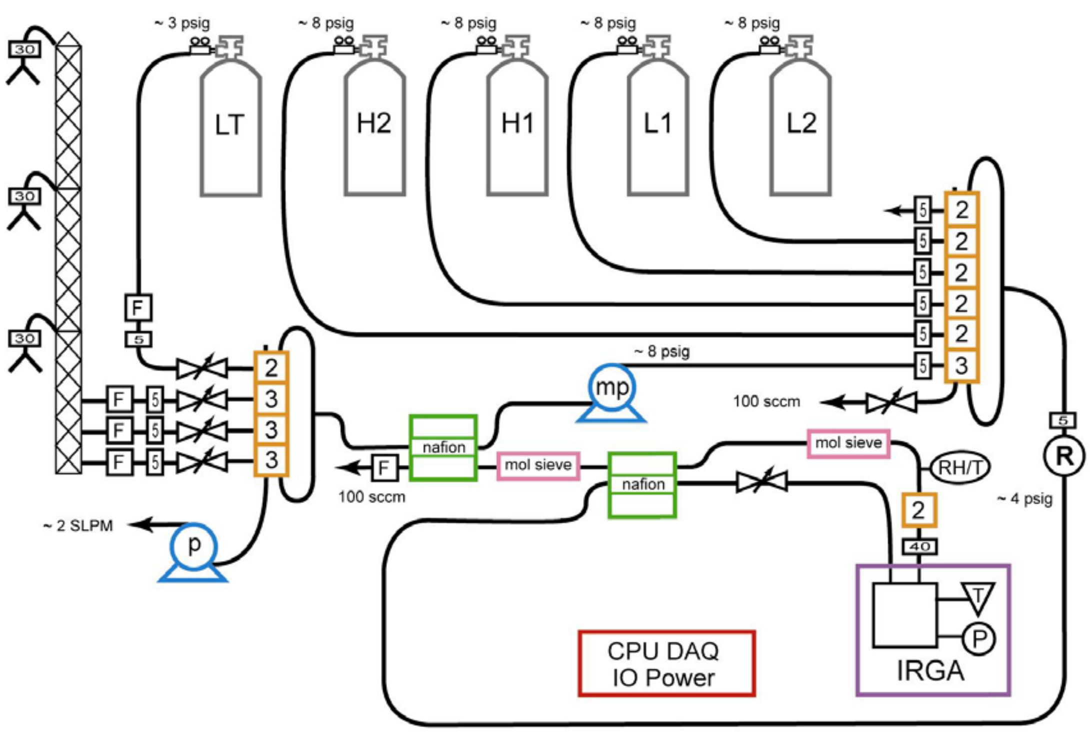


Figure 1: Schematic showing the AIRCOA design. Components include three sample air intakes with rain shields and 30 µm filters (30), mass-flow meters (F), 5 µm filters (5), manual needle valves, three-way (3) and two-way (2) solenoid valves and manifolds, Nafion driers, molecular sieve driers, a sample micropump (mp) and purge pump (p), four reference cylinders, one surveillance cylinder, two-stage pressure regulators, a single-stage pressure

regulator (R), a humidity and temperature sensor (RH/T), a PC104 computer running Linux, PC104 relay and A/D boards, a power supply, and a LiCor 820 single-cell IRGA.

There is a strong motivation to improve atmospheric carbon flux constraints from continental scales (~10,000 km) to regional scales (~1000 km) so that they can be better related to the underlying ecosystem processes, land-use histories, and climate forcing. This requires a considerable increase in the temporal and spatial density of accurate atmospheric CO_2 observations, which would be significantly aided by lowered costs and improved reliability of continuous CO_2 analysis systems. As part of the Carbon in the Mountains Experiment (CME), we developed AIRCOA for the purpose of observing local scale CO_2 gradients across a network of towers at the Niwot Ridge carbon flux site, and have since begun deploying the same system in a regional CO_2 observing network.

Making accurate CO_2 measurements requires careful attention to gas handling, numerous automated quality control diagnostics, and a suite of reference cylinders closely linked to the WMO CO_2 calibration scale. Our approach builds on those of Zhao et al. (1997) and Trivett and Köhler (1999), but with considerable changes (see Figure 1). AIRCOA is based on a single-cell infrared gas analyzer (IRGA), which dramatically lowers the cost but increases the short-term noise and instrument drift rate. We overcome the short-term noise with signal averaging and instrument drift with frequent calibrations. Additional potential sources of CO_2 measurement bias that we address with automated diagnostics include: incomplete flushing of the sample cell and dead volumes, incomplete drying of the sample air, IRGA sensitivity to pressure broadening, IRGA sensitivity to temperature, leaks to ambient air, leaks of calibration gas through solenoid valves, and modification of CO_2 concentrations by the drying system or plastic components (see Table 1).

?.?.2 Instrument Design

As shown in Figure 1, we sample air from three heights on a tower, using inlets consisting of rain shields, and quartz wool and 30 μm polypropylene filters. The instrument box is generally indoors in an environment with moderate temperature variability, but in principle it could also be outdoors. Each inlet stream passes through a mass-flow meter (Honeywell, AWM3000V), and a 5 μm metal filter and needle valve (Beswick Engineering, CF and MLS series) before reaching a manifold of solenoid valves (Numatech, TM10 series). A brushless DC diaphragm pump (KNF Neuberger, N89) flushes the sample lines at 500 to 1000 ml min^{-1} STP when they are not being analyzed. The one gas selected by these valves exits through both ends of the manifold and then passes through the first of two 2.44 m by 2.8 mm ID Nafion driers (Permapure, MD series). A smaller brushless DC diaphragm pump (KNF Neuberger, NMP015B) then compresses this gas to approximately 55 kPa above ambient at which point it passes through a second 5 μm metal filter and enters a second solenoid valve manifold.

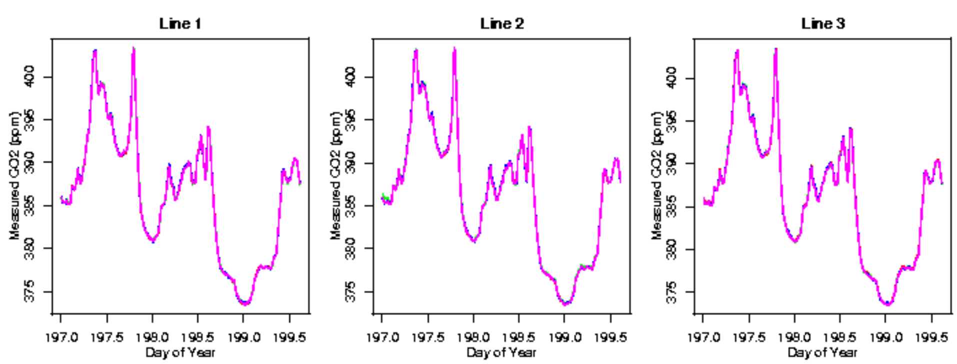
Table 1: Potential sources of measurement error and AIRCOA solutions.

Measurement Concern	Solution
Short-term IRGA noise	Average for 100 seconds to get 0.1 ppm precision
Incomplete drying of air	Slow flow; two 2.44 m Nafion driers; downstream humidity sensor to verify
Incomplete flushing of cell	Sufficient flow; alternate calibration sequence low-to-high / high-to-low
Drift in IRGA sensitivity	4-hourly 4-point calibrations and 30-minute 1-point calibrations
Inadequate IRGA pressure calibration	Automated 4-hourly pressure sensitivity measurements
Leaks through fittings and valves	Automated 8-hourly positive pressure and 4-hourly ambient pressure checks
Temperature sensitivity of IRGA	Empirical temperature sensitivity smoother from 30-minute 1-point calibrations
Drying system affecting CO_2	Constant flows, pressures, and humidity in Nafions
Other plastics affecting CO_2	Minimize changes in pressure drop at inlet

Different sensitivity with and without Ar	Use calibration gases made with real air
Fossil CO_2 in calibration gases	Comparisons to laboratory Siemens Ultramat 6F limit ^{13}C effect to 0.05 ppm
Regulator temperature effects	Laboratory tests show effect to be negligible; monitor for anomalous regulators
System diagnostics and verification	8-hourly analyses of surveillance gas run through entire inlet/drying system
Links to WMO scale	Laboratory calibration transfer facility; comparison to GMD flasks at NWR
Development of problems in the field	Near real-time data retrieval, processing, diagnostic checking, and display

This second manifold selects either a sample gas or a calibration gas to be analyzed. When the sample gas is not being analyzed it exits the valve manifold through a needle valve set to maintain constant pressure in the upstream Nafion drier. The four calibration gases typically span the range 340 to 480 ppm and are stored in high-pressure aluminum cylinders with Ceodeux valves (Scott Marrin Inc.) and two-stage brass regulators (Scott Specialty, model 14). These regulators are set to match the pressure in the sample line. We use 10 L high-pressure cylinders which last 12 months at our flows and calibration frequency. A fifth calibrated high-pressure cylinder stores a long-term surveillance gas which we run through the entire inlet system and treat as an unknown during analysis. The regulator on this cylinder is set to approximately 20 kPa above ambient and a needle valve is used to match sample pressures in the first Nafion drier.

The sample or calibration gas selected for analysis next passes through another 5 μm filter and a miniature pressure regulator (Beswick Engineering, PRD series) with an output of approximately 30 kPa above ambient. The gas is then dried by a second Nafion drier and reduced in pressure by a needle-valve (Swagelok, S series) before reaching a single-cell IRGA (LiCor, Li820). We adjust this needle valve to set the sample flow to 100 ml min^{-1} STP. After leaving the IRGA, the gas passes through a 40 μm metal filter, a normally-open needle valve used for leak checking purposes, and a humidity and temperature sensor (Vaisala, HUMITTER 50Y) used to verify drier performance. We then completely dry the gas once with 13X molecular sieve to use it as the purge gas on the second Nafion drier, and dry it a second time to use it as the purge gas on the first Nafion drier. Most of the moisture in the ambient air exits the first Nafion without ever reaching the mole sieve driers. We use 200 ml molecular sieve driers which last 6 to 12 months depending on outside humidity. The gas passes through a final mass-flow meter before exhausting to the room. There is little flow impedance between the Li820 cell and this exhaust such that sample and calibration measurements are both closely matched to ambient pressure.



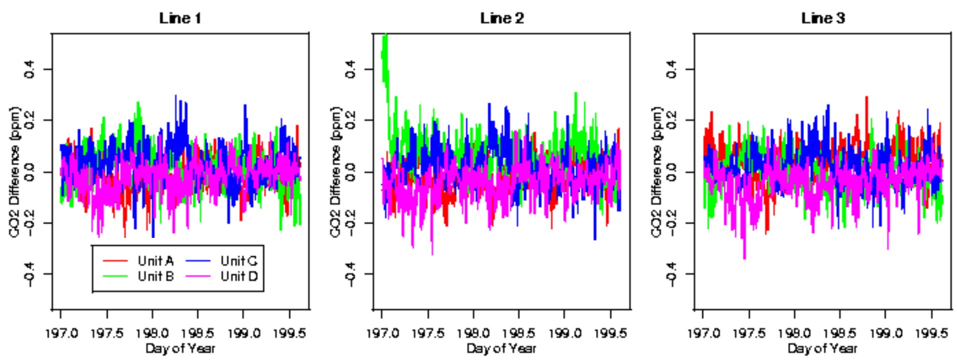


Figure 2: Measurements (top panels) made by 4 AIRCOA units on 3 days in Broomfield, CO during July 2005. These units were all in a laboratory with their inlet lines connected to a common manifold sampling outside air and common calibration cylinders. Comparison of measurements made by each unit during this period (bottom panels) shown as differences from the 4-unit median value at each sample time. The means (and 1-sigma standard deviations) for the 6 pair-wise differences were 0.05 (0.13) ppm or better.

The Li820 measures the pressure, temperature, and CO_2 concentration of the gas. It actively and precisely controls the optical bench to 50 ˚C and has excellent stability with respect to ambient temperature of around 0.05 ppm/C, which is a factor of 10 better than more expensive LiCor analyzers. We set the Li820 to use a 0.5 Hz digital filter and report values at 1 Hz. These filtered values have a 1-sigma rms noise of 0.6 ppm which averages to 0.1 ppm over 100 seconds. We switch the gas being analyzed every 150 seconds and ignore the first 50 seconds after each switch to allow for flushing of gases through the system. We then cycle between the three inlet lines on a 7.5 minute schedule. We make a calculation based on measured flows of how long the measured gas takes to get from the inlet to the sample cell and adjust the times of our reported measurements accordingly. Every 30 minutes we analyze one of the 4 calibration gases to estimate drift in the Li820 zero offset, while every 4 hours we measure all four calibration gases to estimate linear and 2^{nd}-order calibration coefficients for the Li820. We alternate the sequence of these 4 gases to look for problems associated with incomplete flushing of the sample cell and any dead volumes. Every 8 hours we analyze the long-term surveillance gas.

Every 4 hours we also perform automated system checks to determine the Li820 pressure sensitivity and to measure system leak rates to ambient at positive pressure and from the solenoid valves at ambient pressure. We make considerable efforts to minimize and monitor system leaks. Because of silicone seals in the Li820, plastic fittings on the Nafion driers, viton seals in the solenoid valves, Nafion driers, and manifolds, and plastic and viton seals in the micropump it is not practical to completely eliminate them. A leak of calibration gas with a 100 ppm difference from sample air through the solenoid valves at a rate of 0.1 ml min^{-1} would result in a 0.1 ppm bias in our measurements. We set an operational target of 0.015 ml min^{-1} for the total of all solenoid valve leaks and an absolute data-rejection cutoff of 0.03 ml min^{-1}. It is more difficult to estimate the effect of positive-pressure leaks to ambient, but because of the potential for diffusion against flow they are not negligible. We test at 5 kPa overpressure and use similar target and cutoff rates as for the ambient leak-up test.

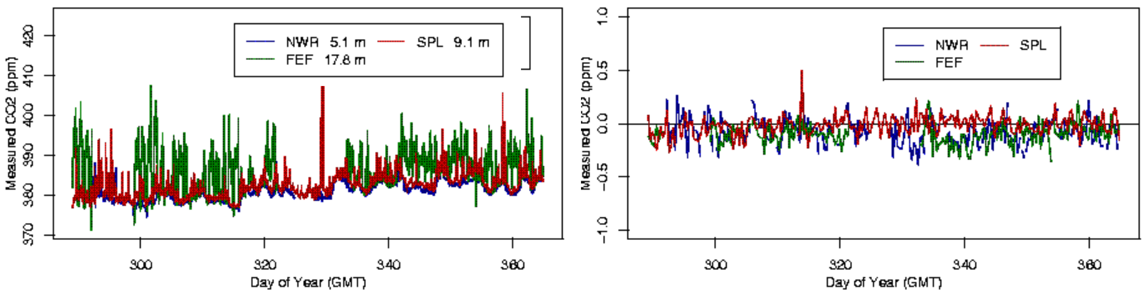


Figure 3: Measurements (left) made by 3 AIRCOA units from October 16 through December 30, 2005 in the field in Colorado: at Niwot Ridge (NWR), at Fraser Experimental Forest (FEF), and at Storm Peak Laboratory (SPL). Only values from the highest intake lines at these sites are shown. Comparison of surveillance cylinder measurements (right) made by each unit during this period, shown as differences from their laboratory assigned values. The means (and 1-sigma standard deviations) of these differences were -0.08 (0.13), 0.10 (0.10), and -0.01 (0.10) ppm respectively.

A PC104-based computer running Linux performs automated data acquisition and valve control. We access this system through a dedicated internet connection and retrieve, process, and display data and system diagnostics in near real time. If any of the automated diagnostics suggest a problem, we are then able to perform more detailed troubleshooting interactively. We cannot overstress the value of this direct connectivity and rapid processing for maintaining the systems and producing high-quality CO_2 measurements.

?.?.3 Results

In a week-long laboratory intercomparison between 4 AIRCOA units all sampling outside air from a common mixing volume and using common reference cylinders, unit-to-unit differences on coincident measurements showed 1-sigma variability of 0.13 ppm and systematic biases of 0.05 ppm or less (see Figure 2). During isolated field operation comparability is more difficult to assess, but we use 8-hourly analyses of surveillance tanks to estimate performance. We installed three AIRCOA systems in the field at the start of September 2005. Despite the added complexity of different sets of calibration gases and larger temperature variations in comparison to the laboratory tests, the units still perform very well. While periods of systematic bias of up to 0.2 ppm are evident, averaged over a period of 2.5 months the 1-sigma variability for these three units ranged from 0.10 to 0.13 ppm and the systematic bias ranged from 0.01 to 0.10 ppm (see Figure 3). This figure also illustrates that the systems have been operating with relatively few data gaps during their initial deployments. We are working closely with other investigators developing and deploying similar single-cell IRGA based systems, as well as investigators deploying longer-established but more expensive technologies, in an effort to improve the intercomparability between independent observing networks.

References

Trivett, N., and A. Köhler (1999), Guide on sampling and analysis techniques for chemical constituents and physical properties in air and precipitation as applied at stations of the Global Atmosphere Watch. Part 1: Carbon Dioxide, WMO TD No. 980.

Zhao, C.L., P.S. Bakwin, and P.P. Tans (1997), A design for unattended monitoring of carbon dioxide on a very tall tower, J. Atm. Oc. Tech., 14, 1139-1145.

Appendix B. Valve Switching Sequence

The following pages contain information on the default 3 inlet and 5 inlet valve switching schedules. These schedules are selected in the file /home/isff/aircoa.sh by using one of these two lines:

```
args="-r relays3.txt relays3 -x li820.xml -t /dev/ttyS2 -R 1 -a
/data/aircoa ai_%y%m%d_%H%M%S.dat 28800"
```

```
args="-r relays5.txt relays5 -x li820.xml -t /dev/ttyS2 -R 1 -a
/data/aircoa ai_%y%m%d_%H%M%S.dat 28800"
```

The file /home/isff/aircoa/relays*.txt sets the broad schedule and calls the file /home/isff/aircoa/sequences*.txt for details on the individual sequences. This file in turn calls the file /home/isff/aircoa/settings*.txt for the relay configuration under each setting (see Section 4 above). The last column of hexadecimal values in the component tables correspond to those reported by the program and can be converted into a binary number indicating which relays are turned on. For example, hexadecimal 2044 equals binary 10000001000100 indicating that relays 13, 6, and 2 are turned on.

3 inlet line schedule:

COMPONENT	ITERATIONS	DURATION (min)	START TIME		
BASE LOOP	4	30	0:00:00	8:00:00	16:00:00
ZERO CAL1	1	2.5	0:30:00	8:30:00	16:30:00
BASE LOOP	4	30	0:32:30	8:32:30	16:32:30
ZERO CAL2	1	2.5	1:02:30	9:02:30	17:02:30
BASE LOOP	4	30	1:05:00	9:05:00	17:05:00
ZERO CAL3	1	2.5	1:35:00	9:35:00	17:35:00
BASE LOOP	4	30	1:37:30	9:37:30	17:37:30
ZERO CAL4	1	2.5	2:07:30	10:07:30	18:07:30
BASE LOOP	4	30	2:10:00	10:10:00	18:10:00
ZERO CAL1	1	2.5	2:40:00	10:40:00	18:40:00
BASE LOOP	4	30	2:42:30	10:42:30	18:42:30
ZERO CAL2	1	2.5	3:12:30	11:12:30	19:12:30
BASE LOOP	4	30	3:15:00	11:15:00	19:15:00
FULL CAL1	1	15	3:45:00	11:45:00	19:45:00
BASE LOOP	4	30	4:00:00	12:00:00	20:00:00
ZERO CAL3	1	2.5	4:30:00	12:30:00	20:30:00
BASE LOOP	4	30	4:32:30	12:32:30	20:32:30
ZERO CAL4	1	2.5	5:02:30	13:02:30	21:02:30
BASE LOOP	4	30	5:05:00	13:05:00	21:05:00
ZERO CAL1	1	2.5	5:35:00	13:35:00	21:35:00
BASE LOOP	4	30	5:37:30	13:37:30	21:37:30
ZERO CAL2	1	2.5	6:07:30	14:07:30	22:07:30
BASE LOOP	4	30	6:10:00	14:10:00	22:10:00
ZERO CAL3	1	2.5	6:40:00	14:40:00	22:40:00
BASE LOOP	4	30	6:42:30	14:42:30	22:42:30
ZERO CAL4	1	2.5	7:12:30	15:12:30	23:12:30
BASE LOOP	4	30	7:15:00	15:15:00	23:15:00
FULL CAL2	1	15	7:45:00	15:45:00	23:45:00

3 inlet line schedule components:

		LEVEL/TANK/VALVE	line 1	line 2	line 3	LT	Air	LS2	LS1	HS1	HS2	Guest Cal	Leak Check	Micro Pump	
		RELAY NUMBER	0	1	2	3	6	7	8	9	10	11	12	13	HEX
		DURATION (sec)													
BASE LOOP	3 x 2.5-min.	150	off	off	**ON**	off	**ON**	off	off	off	off	off	off	**ON**	2044
	measurements	150	off	**ON**	off	off	**ON**	off	off	off	off	off	off	**ON**	2042
		150	**ON**	off	off	off	**ON**	off	off	off	off	off	off	**ON**	2041
ZERO CAL1	2.5-min. LS2 cal.	150	**ON**	off	off	off	off	**ON**	off	off	off	off	off	**ON**	2081
ZERO CAL2	2.5-min. LS1 cal.	150	**ON**	off	off	off	off	off	**ON**	off	off	off	off	**ON**	2101
ZERO CAL3	2.5-min. HS1 cal.	150	**ON**	off	off	off	off	off	off	**ON**	off	off	off	**ON**	2201
ZERO CAL4	2.5-min. HS2 cal.	150	**ON**	off	off	off	off	off	off	off	**ON**	off	off	**ON**	2401
FULL CAL1	4 x 2.5-min. cal.	150	**ON**	off	off	off	off	**ON**	off	off	off	off	off	**ON**	2081
	(10 min. total)	150	**ON**	off	off	off	off	off	**ON**	off	off	off	off	**ON**	2101
		150	**ON**	off	off	off	off	off	off	**ON**	off	off	off	**ON**	2201
		150	**ON**	off	off	off	off	off	off	off	**ON**	off	off	**ON**	2401
	Low P Leakcheck	30	**ON**	off	off	off	off	off	off	off	off	**ON**	off	**ON**	2801
	(2.5 min)	120	**ON**	off	off	off	off	off	off	off	off	off	**ON**	**ON**	3001
	2.5-min. LT meas.	150	off	off	off	**ON**	**ON**	off	off	off	off	off	off	**ON**	2048
FULL CAL2	4 x 2.5-min. cal.	150	**ON**	off	off	off	off	off	off	off	**ON**	off	off	**ON**	2401
	(10 min. total)	150	**ON**	off	off	off	off	off	off	**ON**	off	off	off	**ON**	2201
		150	**ON**	off	off	off	off	off	**ON**	off	off	off	off	**ON**	2101
		150	**ON**	off	off	off	off	**ON**	off	off	off	off	off	**ON**	2081
	Low P Leakcheck	30	**ON**	off	off	off	off	off	off	off	off	**ON**	off	**ON**	2801
	(2.5 min)	120	**ON**	off	off	off	off	off	off	off	off	off	**ON**	**ON**	3001
	High P Leakcheck	30	off	off	off	**ON**	**ON**	off	off	off	off	off	**ON**	off	1048
	(2.5 min)	120	off	off	off	off	**ON**	off	off	off	off	off	**ON**	off	1040

5 inlet line schedule:

COMPONENT	ITERATIONS	DURATION (min)	START TIME		
BASE LOOP	3	37.5	0:00:00	8:00:00	16:00:00
ZERO CAL1	1	2.5	0:37:30	8:37:30	16:37:30
BASE LOOP	2	25	0:40:00	8:40:00	16:40:00
ZERO CAL2	1	2.5	1:05:00	9:05:00	17:05:00
BASE LOOP	2	25	1:07:30	9:07:30	17:07:30
ZERO CAL3	1	2.5	1:32:30	9:32:30	17:32:30
BASE LOOP	2	25	1:35:00	9:35:00	17:35:00
B. LOOP NO 1	1	10	2:00:00	10:00:00	18:00:00
ZERO CAL4	1	2.5	2:10:00	10:10:00	18:10:00
BASE LOOP	2	25	2:12:30	10:12:30	18:12:30
ZERO CAL1	1	2.5	2:37:30	10:37:30	18:37:30
BASE LOOP	2	25	2:40:00	10:40:00	18:40:00
ZERO CAL2	1	2.5	3:05:00	11:05:00	19:05:00
BASE LOOP	3	37.5	3:07:30	11:07:30	19:07:30
FULL CAL1	1	15	3:45:00	11:45:00	19:45:00
BASE LOOP	3	37.5	4:00:00	12:00:00	20:00:00
ZERO CAL3	1	2.5	4:37:30	12:37:30	20:37:30
BASE LOOP	2	25	4:40:00	12:40:00	20:40:00
ZERO CAL4	1	2.5	5:05:00	13:05:00	21:05:00
BASE LOOP	2	25	5:07:30	13:07:30	21:07:30
ZERO CAL1	1	2.5	5:32:30	13:32:30	21:32:30
BASE LOOP	2	25	5:35:00	13:35:00	21:35:00
B. LOOP NO 1	1	10	6:00:00	14:00:00	22:00:00
ZERO CAL2	1	2.5	6:10:00	14:10:00	22:10:00
BASE LOOP	2	25	6:12:30	14:12:30	22:12:30
ZERO CAL3	1	2.5	6:37:30	14:37:30	22:37:30
BASE LOOP	2	25	6:40:00	14:40:00	22:40:00
ZERO CAL4	1	2.5	7:05:00	15:05:00	23:05:00
BASE LOOP	3	37.5	7:07:30	15:07:30	23:07:30
FULL CAL2	1	15	7:45:00	15:45:00	23:45:00

5 inlet line schedule components:

		LEVEL/TANK/VALVE	In 1	In 2	In 3	In 4	In 5	LT	Air	LS2	LS1	HS1	HS2	Guest Cal	Leak Check	Micro Pump	
		RELAY NUMBER	0	1	2	3	4	5	6	7	8	9	10	11	12	13	HEX
		DURATION (sec)															
BASE LOOP	5 x 2.5-min.	150	off	off	off	off	**ON**	off	**ON**	off	off	off	off	off	off	**ON**	2050
	measurements	150	off	off	off	**ON**	off	off	**ON**	off	off	off	off	off	off	**ON**	2048
		150	off	off	**ON**	off	off	off	**ON**	off	off	off	off	off	off	**ON**	2044
		150	off	**ON**	off	off	off	off	**ON**	off	off	off	off	off	off	**ON**	2042
		150	**ON**	off	off	off	off	off	**ON**	off	off	off	off	off	off	**ON**	2041
ZERO CAL1	2.5-min. LS2 cal.	150	**ON**	off	off	off	off	off	off	**ON**	off	off	off	off	off	**ON**	2081
ZERO CAL2	2.5-min. LS1 cal.	150	**ON**	off	off	off	off	off	off	off	**ON**	off	off	off	off	**ON**	2101
ZERO CAL3	2.5-min. HS1 cal.	150	**ON**	off	off	off	off	off	off	off	off	**ON**	off	off	off	**ON**	2201
ZERO CAL4	2.5-min. HS2 cal.	150	**ON**	off	off	off	off	off	off	off	off	off	**ON**	off	off	**ON**	2401
FULL CAL1	4 x 2.5-min. cal.	150	**ON**	off	off	off	off	off	off	**ON**	off	off	off	off	off	**ON**	2081
	(10 min. total)	150	**ON**	off	off	off	off	off	off	off	**ON**	off	off	off	off	**ON**	2101
		150	**ON**	off	off	off	off	off	off	off	off	**ON**	off	off	off	**ON**	2201
		150	**ON**	off	off	off	off	off	off	off	off	off	**ON**	off	off	**ON**	2401
	Low P Leakcheck	30	**ON**	off	off	off	off	off	off	off	off	off	off	**ON**	off	**ON**	2801
	(2.5 min)	120	**ON**	off	off	off	off	off	off	off	off	off	off	off	**ON**	**ON**	3001
	2.5-min. LT meas.	150	off	off	off	off	off	**ON**	**ON**	off	off	off	off	off	off	**ON**	2060
FULL CAL2	4 x 2.5-min. cal.	150	**ON**	off	off	off	off	off	off	off	off	off	**ON**	off	off	**ON**	2401
	(10 min. total)	150	**ON**	off	off	off	off	off	off	off	off	**ON**	off	off	off	**ON**	2201
		150	**ON**	off	off	off	off	off	off	off	**ON**	off	off	off	off	**ON**	2101
		150	**ON**	off	off	off	off	off	off	**ON**	off	off	off	off	off	**ON**	2081
	Low P Leakcheck	30	**ON**	off	off	off	off	off	off	off	off	off	off	**ON**	off	**ON**	2801
	(2.5 min)	120	**ON**	off	off	off	off	off	off	off	off	off	off	off	**ON**	**ON**	3001
	High P Leakcheck	30	off	off	off	off	off	**ON**	**ON**	off	off	off	off	off	**ON**	off	1060
	(2.5 min)	120	off	off	off	off	off	off	**ON**	off	off	off	off	off	**ON**	off	1040
B. LOOP NO 1	4 x 2.5-min.	150	off	off	off	off	**ON**	off	**ON**	off	off	off	off	off	off	**ON**	2050
	measurements	150	off	off	off	**ON**	off	off	**ON**	off	off	off	off	off	off	**ON**	2048
		150	off	off	**ON**	off	off	off	**ON**	off	off	off	off	off	off	**ON**	2044
		150	off	**ON**	off	off	off	off	**ON**	off	off	off	off	off	off	**ON**	2042

Appendix C. AIRCOA Parts Lists

General:

Item	Manufacturer/Vendor	Part number	Description	Qty	Price	Total	Web Page
1	Air Liquide	Cat # 1001	Model 14 Regulator, 2 stage, 0-10 psi, no CGA, qty. 25 volume discount	6	$ 250.00	$ 1,500	http://www.airliquide.com/en/business/industry/laboratories/equipment/equipment.asp
2	Scott Marrin, Inc.	05-NIP-50B-56	Brass CGA-590 nipple	6	$ 4.00	$ 24	http://www.scottmarrin.com/
3	Scott Marrin, Inc.	05-NUT-590B	Brass CGA 590 nut	6	$ 3.00	$ 18	http://www.scottmarrin.com/
4	LiCor, Inc.	LI-820	CO_2 Analyzer (qty. 3-5 3% discount)	1	$3,014.94	$ 3,015	http://www.licor.com/env/Products
5	Advantec MFS, Inc.	Cat # A-06623-22	In-line 47mm filter holder, polypro.	5	$ 25.97	$ 130	http://www.coleparmer.com/
6	Millipore	Cat # AN3H04700	Polypro. prefilters, 30 um x 47 mm dia.	0.05	$ 53.05	$ 3	http://www.millipore.com/
7	Hardware store		Funnel to fit Item 6, filter holder	5	$ 0.89	$ 4	
8	Valco	TSS285	1/8" o.d., 0.085" i.d. stainless tubing	10	$ 2.75	$ 28	http://www.vici.com/tube/cust_met.htm
9	KNF	N89 KNDC B	Tower intake pump – brushless DC	1	$ 302.00	$ 302	http://www.knf.com/pdfs/nmp010.pdf
10	KNF	NMP015B	Sample pump	1	$ 234.00	$ 234	http://www.knf.com/pdfs/n84_89.pdf
11	Numatics	TM101V12C2	Solonoid valves	13	$ 18.00	$ 234	http://www.numatech.com
12	Numatics	51030106	Solonoid manifold, 6 station	2	$ 43.67	$ 87	http://www.numatech.com
13	Numatics	62030002	24" leads for valves	13	$ 2.05	$ 27	http://www.numatech.com
14	Numatics	51030101	Solonoid manifold, 1 station leak check	1	$ 11.22	$ 11	http://www.numatech.com
15	Beswick	PRD-3N1-0-VIX	Miniature regulator	1	$ 68.05	$ 68	http://www/beswick.com
16	Perma Pure	MD-110-96F-4	Nafion Driers	2	$ 299.50	$ 599	http://www.permapure.com
17	Honeywell	AWM3300V	Mass flow meter, 0-1000 mL/min	7	$ 87.94	$ 616	http://catalog.sensing.honeywell.com
18	ExpressPCB	Custom	Interconnect Board	1	$ 46.88	$ 47	http://www.expresspcb.com/
19	Vaisala	HMP50 YAB1A1A	Humidity/temperature sensor	1	$ 290.00	$ 290	http://vaisala.com
20	Jameco	123334	12 V, 60 W power supply	1	$ 53.95	$ 54	http://www.jameco.com
21	Diamond Systems	PR-Z32-EA-ST	Prometheus PC/104 CPU	1	$ 700.00	$ 700	http://www.diamondsystems.com/
22	Diamond Systems	IR104	IR104 relay, optoislated inputs	1	$ 270.00	$ 270	http://www.diamondsystems.com/
23	Diamond Systems	Jupiter-MM-LP	25 watt, +5 volt output	1	$ 100.00	$ 100	http://www.diamondsystems.com/
24	Diamond Systems	C-PRZ-01	Cable Assy, PR-Z32 Breakout	1	$ 15.00	$ 15	http://www.diamondsystems.com/
25	Diamond Systems	C-PRZ-02	Cable Assy, PR-Z32 Ethernet	1	$ 15.00	$ 15	http://www.diamondsystems.com/
26	Diamond Systems	698012	Cable, USB Dual to 10-pin header	1	$ 15.00	$ 15	http://www.diamondsystems.com/
27	Diamond Systems	FD-32-XT	Flashdisk Module	1	$ 65.00	$ 65	http://www.diamondsystems.com/
28	Diamond Systems	SPC104	PC104 spacers	18	$ 0.40	$ 7	http://www.diamondsystems.com/
29	e.g., Memorex		USB memory stick, 512 Mb	1	$ 60.00	$ 60	
30	Scott Specialty	16053-44R-22	Mol Sieve Moisture Trap, 13X w/ 4A indicator, 200 mL, 1/8" fittings	3	$ 129.00	$ 387	http://www.scottgas.com/
31	Vynckier	RVJ1614HWPL2	Enclosure -- Fiberglass, w/ back panel	1	$ 115.00	$ 115	http://www.enclosuresonline.com
32	Custom		Mounting panels	3		$ 153	
33	McMaster-Carr		Tower pump vibration isolators	4	$ 3.77	$ 15	
34	McMaster-Carr		Micropump vibration isolators	2	$ 3.59	$ 7	
35	McMaster-Carr		4-40 bolts and nuts	100	$ 0.06	$ 6	
36			Fittings from other sheet			$ 610	
37			Electrical from other sheet			$ 162	
Total						$ 9,993	

Fittings:

description	part number	qty	supplier	$/each	Total	Location
1/8" x 1/4" reducer	SS-400-R-2	1	DV&F	$ 9.30	$ 9.30	From LT regulator into 1/4" bhf
1/4" female NPT x 1/4" sw. female elbow	B-400-8-4	5	DV&F	$ 5.30	$ 26.50	Top of tower
1/4" bulkhead fittings, stainless	SS-400-61	6	DV&F	$ 12.50	$ 75.00	into housing
1/4" bulkhead retainer,ss	S-402-61F	6	DV&F	$ 0.70	$ 4.20	For tower entry bulkheads
MFM o-rings	2-106 VITON-7	12	Rocket Seals	$ 0.41	$ 4.92	for MFMs
1/8" x 1/4" reducer	B-400-R-2	6	DV&F	$ 2.40	$ 14.40	out of mfm
1/8" x 10-32 compression fitting	MCB-1018-V	6	Beswick	$ 1.68	$ 10.08	into needle valve
10-32 5 micron filter	CF-1010-05-V	6	Beswick	$ 2.63	$ 15.78	into needle valve
1/8" needle valves	MLS-MV-1010-K-V	7	Beswick	$ 14.50	$ 101.50	to adjust sample flow and purge flow
10-32 hex extension	MEB-1010-1-V	6	Beswick	$ 1.08	$ 6.48	into sample manifold
10-32 plug	MSP-1000-V	1	Beswick	$ 0.66	$ 0.66	to plug sample manifold
1/8" tubing to 10-32 thr. Elbow	MCBL-1018-TALL-V	3	Beswick	$ 5.38	$ 16.14	in and out of sample manifold
1/8" male NPT x 1/8" sw. male elbow	B-200-2-2	1	DV&F	$ 4.00	$ 4.00	in to tower pump
1/8" male NPT x 1/4" tubing	B-4-TA-1-2	1	DV&F	$ 1.60	$ 1.60	out of tower pump
union tee, 1/8"	B-200-3	1	DV&F	$ 6.50	$ 6.50	from either side of the manifold to 1st Nafion
reducer, 1/8" x 1/4"	B-200-R-4	2	DV&F	$ 2.30	$ 4.60	into and out of 1st Nafion
insert for 1/4" plastic tubing	B-405-2	2	DV&F	$ 0.60	$ 1.20	in and out of micropump
reducing union, 1/4" x 1/8"	B-400-6-2	2	DV&F	$ 2.80	$ 5.60	in and out of micropump
1/8" male NPT x 1/8" sw. male connector, ss	SS-200-1-2	4	DV&F	$ 5.70	$ 22.80	Out of cal tank regulators
1/8" bulkhead,ss	SS-200-61	5	DV&F	$ 17.20	$ 86.00	For cal tanks
1/8" bulkhead retainer,ss	S-202-61F	5	DV&F	$ 0.70	$ 3.50	For cal tanks
1/8" plug	NY-200-P	1	DV&F	$ 2.40	$ 2.40	To plug guest cal bhf
1/8" tubing to 10-32 thr. Elbow	MCBL-1018-TALL-V	8	Beswick	$ 5.38	$ 43.04	into and out of cal valve manifold
10-32 5 micron filter	CF-1010-05-V	7	Beswick	$ 2.63	$ 18.41	into cal valve manifold and regulator
10-32 plug	MSP-1000-V	1	Beswick	$ 0.66	$ 0.66	to plug cal manifold
1/8" needle valve	MLS-MV-1010-K-V	1	Beswick	$ 14.50	$ 14.50	to adjust sample bypass flow
1/8" x 10-32 compression fitting	MCB-1018-V	1	Beswick	$ 1.68	$ 1.68	out of needle valve
union tee, 1/8"	B-200-3	1	DV&F	$ 6.50	$ 6.50	from either side of the manifold to regulator
1/8" tubing to 10-32 thr. Elbow	MCBL-1018-TALL-V	1	Beswick	$ 5.38	$ 5.38	into regulator
1/8" x 10-32 compression fitting	MCB-1018-V	1	Beswick	$ 1.68	$ 1.68	out of regulator
reducer, 1/8" x 1/4"	B-200-R-4	2	DV&F	$ 2.40	$ 4.80	into and out of 2nd Nafion
1/8" needle valves, S series	B-SS2	1	DV&F	$ 46.30	$ 46.30	Licor flow adjustment
1/8" port connnector	B-201-PC	1	DV&F	$ 1.30	$ 1.30	into Licor
insert for 1/4" plastic tubing	B-405-2	2	DV&F	$ 0.60	$ 1.20	in and out of Licor
reducing union, 1/4" x 1/8"	B-400-6-2	2	DV&F	$ 2.80	$ 5.60	into Licor
1/8" tubing to 10-32 thr. Elbow	MCBL-1018-TALL-V	2	Beswick	$ 5.38	$ 10.76	in and out of leak check valve
10-32 plug	MSP-1000-V	3	Beswick	$ 0.66	$ 1.98	plugs for leak check manifold
reducer, 1/8" x 1/2"	B-200-R-8	2	DV&F	$ 7.20	$ 14.40	to increase and reduce for HUMITTER
1/2" union tee	B-810-3	1	DV&F	$ 11.10	$ 11.10	for HUMITTER
arbor, 1/2" teflon ferrules	TFE-810-Sets-10	0.1	DV&F	$ 3.05	$ 0.31	for HUMITTER
reducer, 1/8" x 1/4"	B-200-R-4	2	DV&F	$ 2.30	$ 4.60	into and out of 2nd Nafion purge
reducer, 1/8" x 1/4"	B-200-R-4	1	DV&F	$ 2.30	$ 2.30	into and out of 1st Nafion purge
				TOTAL	$ 610.36	

Electrical:

Item #	Vendor	Manufacturer	Part number	Description	Qty	Price	Total
1	Newark	Molex	38C9955	Connection header, 2 position	22	$ 0.55	$ 12.01
2	Newark	Molex	38C9956	Connection header, 3 position	7	$ 0.81	$ 5.64
3	Newark	Molex	38C9957	Connection header, 4 position	1	$ 0.90	$ 0.90
4	Newark	Molex	50F2064	Connection header, 10 position	1	$ 1.78	$ 1.78
5	Digi-Key	Molex	A26304-ND	Connection header, 16 position	1	$ 2.33	$ 2.33
6	Newark	Molex	50F2067	Connection header, 20 position	1	$ 5.87	$ 5.87
7	Newark	Molex	38C9863	Connection housing, 2 position	18	$ 0.58	$ 10.39
8	Newark	Molex	38C9864	Connection housing, 3 position	14	$ 0.40	$ 5.57
9	Newark	Molex	25C5453	Connection housing, 4 position	1	$ 0.56	$ 0.56
10	Newark	Molex	35C5018	Pins for above	75	$ 0.09	$ 6.90
11	Newark	Molex	90F4757	Connection housing, 10 position	1	$ 1.71	$ 1.71
12	Newark	Molex	90F4759	Connection housing, 16 position	1	$ 1.54	$ 1.54
13	Newark	Molex	90F4760	Connection housing, 20 position	1	$ 1.76	$ 1.76
14	Newark	Amp	90F4539	Connection housing, 50 position	1	$ 4.51	$ 4.51
15	Newark	Amp	90F4138	Pins for above	56	$ 0.27	$ 14.90
16	Newark		27F592	Fuse holder	1	$ 2.17	$ 2.17
17	Newark		27F882	5 A fuse for above	1	$ 0.44	$ 0.44
18	Newark		07F7478	5 V voltage regulator, LM7805	2	$ 0.59	$ 1.19
19	Newark		09F3574	Diode, 1N4001	20	$ 0.03	$ 0.54
20	Newark		33C4436	Capacitor, CK05BX104K	2	$ 0.22	$ 0.43
21	Newark	Amphenol	89F1466	D-sub 9 pin connector, socket contacts	1	$ 1.58	$ 1.58
22	Newark	Amp	48F1669	9-pin CPC, square flanged	2	$ 2.55	$ 5.09
23	Newark	Amp	92F7919	Pins for above	4	$ 0.44	$ 1.76
24	Newark	Amp	44F8388	9-pin CPC, plug	1	$ 2.40	$ 2.40
25	Newark	Amp	95F1798	Heat shrinkable boot for above	1	$ 7.10	$ 7.10
26	Newark	Amp	96F7920	Sockets for above	4	$ 0.52	$ 2.10
27	Newark	Amp	46F1142	3-pin CPC, square flanged	1	$ 2.35	$ 2.35
28	Newark	Amp	92F4851	Pins for above	3	$ 7.14	$ 21.42
29	Newark	Amp	46F1144	3-pin CPC, plug	1	$ 2.99	$ 2.99
30	Newark	Amp	50F516	Heat shrinkable boot for above	1	$ 6.98	$ 6.98
31	Newark	Amp	90F7240	Sockets for above	3	$ 7.77	$ 23.31
32	Digi-Key		Q123-ND	Line cords	1	$ 3.26	$ 3.26
33	Newark	Alpha Wire	92F9994	White hook up wire, 22 ga	20	$ 0.02	$ 0.30
34	Newark	Alpha Wire	92F9983	Black hook up wire, 22 ga	20	$ 0.02	$ 0.30
35	Newark	Alpha Wire	92F9329	Red hook up wire, 22 ga	20	$ 0.02	$ 0.30
						TOTAL	$ 162.36

Appendix D. Recommended Field Equipment

For initial deployment

AIRCOA unit
stand
Cal and LT cylinders
Regulators
1/8" stainless tubing
Power cable and
  Extension cord
Ethernet cable
Hub (if needed)
Laptop/palmtop and serial
  cable
Tool box
Funnels
Filter holder, with fitting
Filter paper
Synflex
Cable ties
Hard soled shoes
Climbing rope and harness
1.5' 2 x 4's
Lag bolts
Drill and bit, lag pilot and
  tubing penetration
Cylinder straps
I-bolts
Surge protector
Ethernet surge protector
Hose clamps for grounding
Sign for door
Box of wood screws
10' extension cord

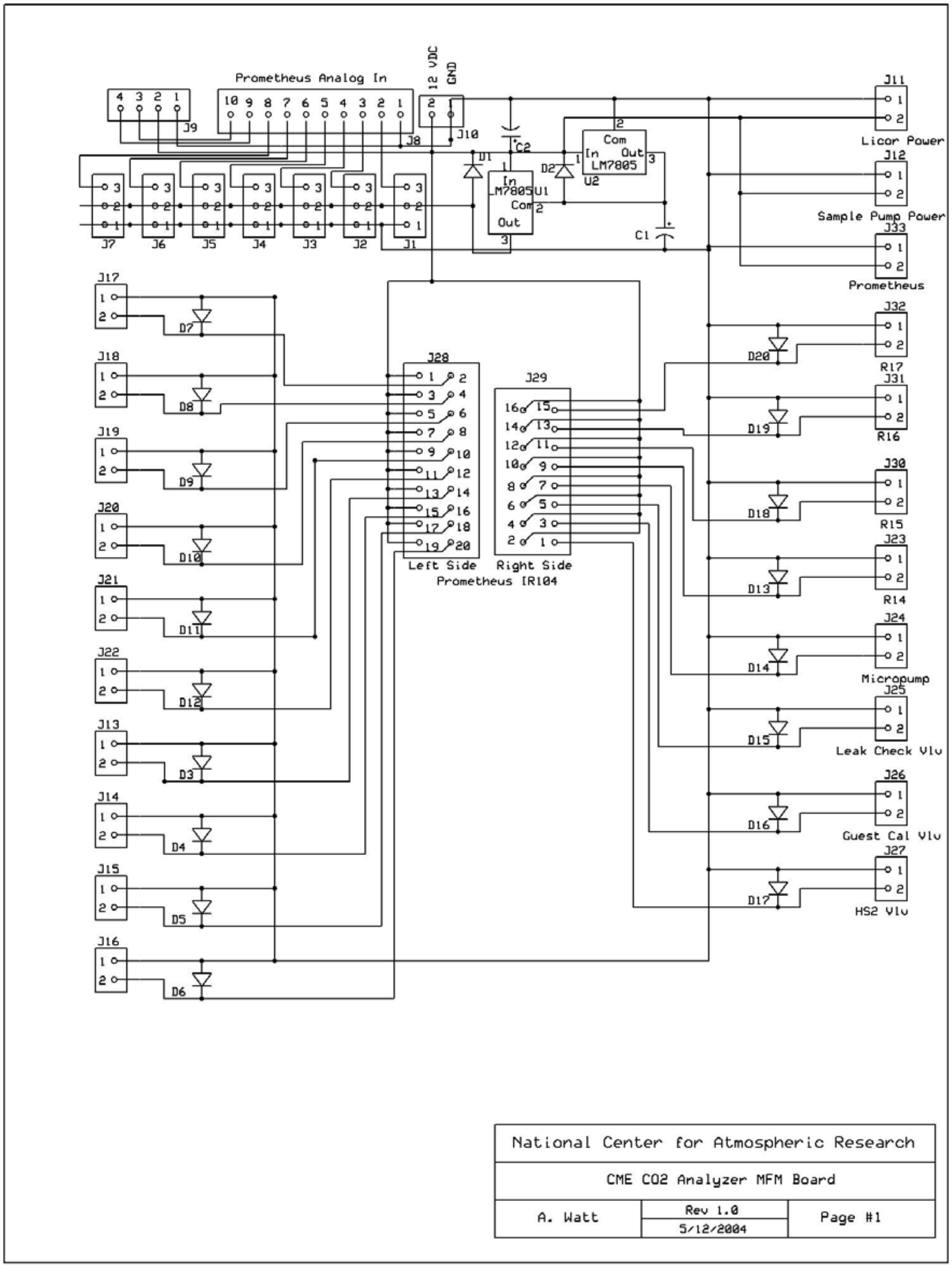
For tool box

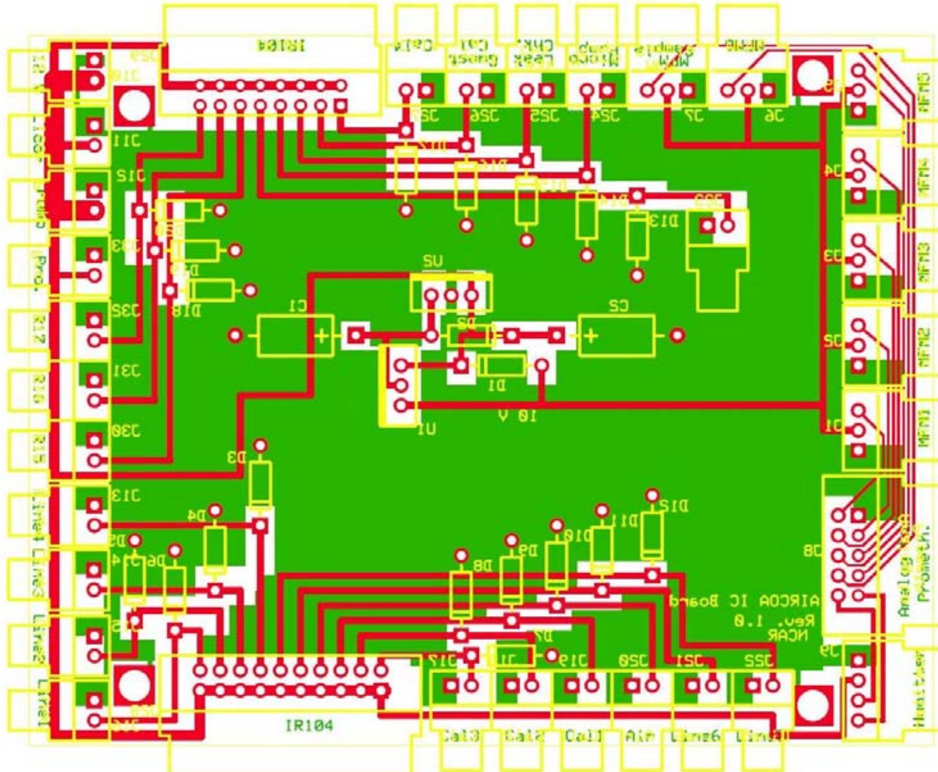
Leatherman
Needlenose pliers
Wire strippers
Soldering Iron and solder
Wrenches, 1/4, 5/16, 3/8,
  7/16 x 21, 1/2 x 2, 9/16,
  5/8, 11/16
Adjustable wrenches x 2
Cylinder wrench
Cylinder valve wrench
Misc slotted screwdrivers
Misc Phillips screwdrivers
Set allen wrenches
Synflex tubing cutter
Stainless tubing cutter
Tubing reamers
Flashlight
Tape measure
Mirror
Scalpel
Awl
Socket set, 1/4"
Misc. small files
Chapman set
Voltmeter
7/16"nut driver
Shovel for burying tubing
Caulk and gun
Purge flow adjust jig
Tune-up worksheets
Snoop
Crimpers and extra crimp
  pins
LI820 Cleaning Kit
Pens
Sharpies
Pump for leak checks
Teflon tape
Crimpers for RJ-45
Camera
Camera batteries
Serial cable
Colored tape
Gender benders DB9

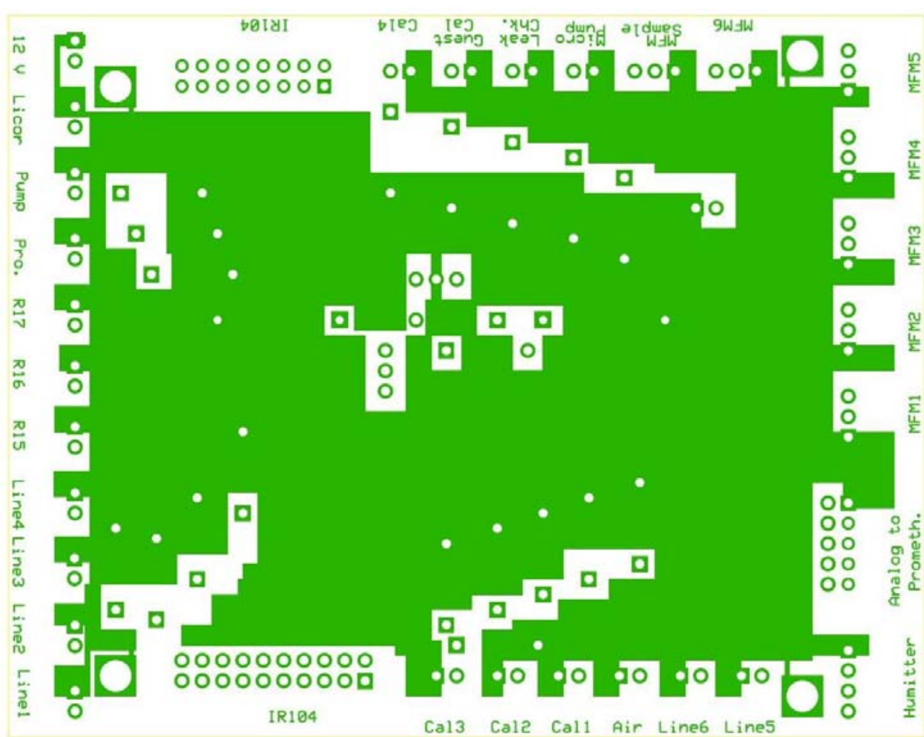
Spare parts

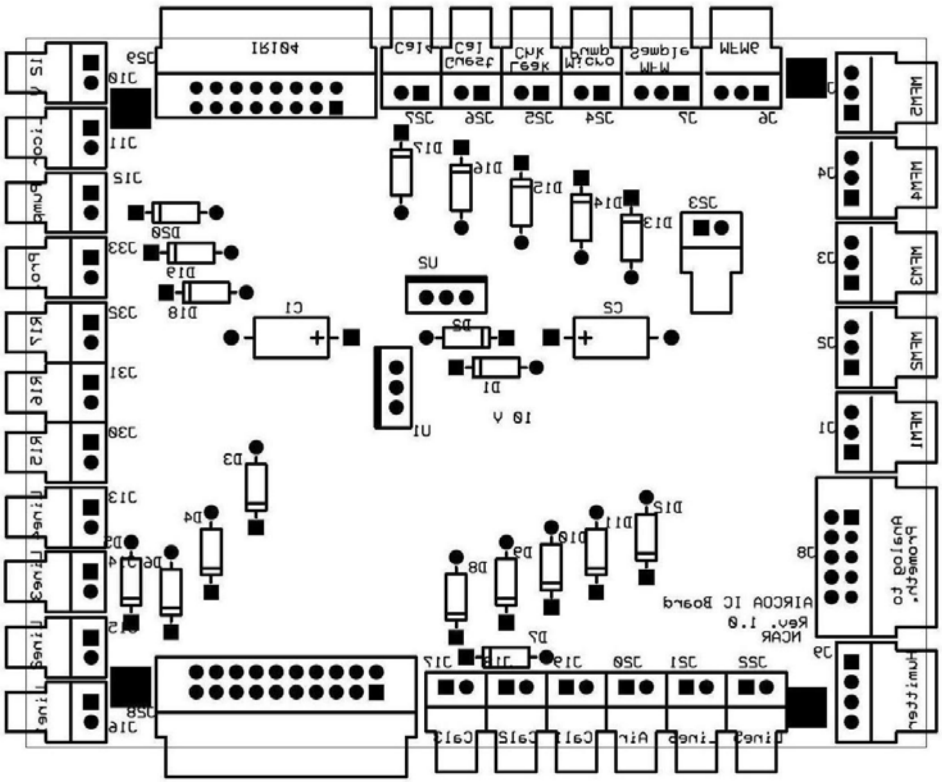
1/4" Synflex (~2')
1/8" tubing x 2
Honeywell AWM3300 x 3
N89 KNDC brushless
  sample pump
NMP015B micropump
Prometheus
Humitter
Numatech solenoid x 4
Numatech blank-off kit
Beswick filter and needle
  valve
Beswick plugs
Selection of Swagelok
  fittings and ferrules,
  including tees
Selection of Beswick
  fittings and ferrules
Brass insert for
  compression fittings
Heat shrink tubing
Beswick regulator
MFM o-rings x 2
Labbook
5 A fuses x 4
Pins for Amphenol
  connectors
Pins for Amp connnectors
Pins for Molex
  connnectors
Humitter pin-outs
Interconnect board
  schematic
Cal sheet for AWM's
RJ-45 plugs
Nafion x 2
Nafion caps x 8
Glass wool
Length of bev-a-line
Power supply
1/4" ultratorr fittings for
  bypass
LI-840 for humidity
  problems
Isolation mounts for both
  pumps
Spare pen drive
Spare ultra torr o-rings

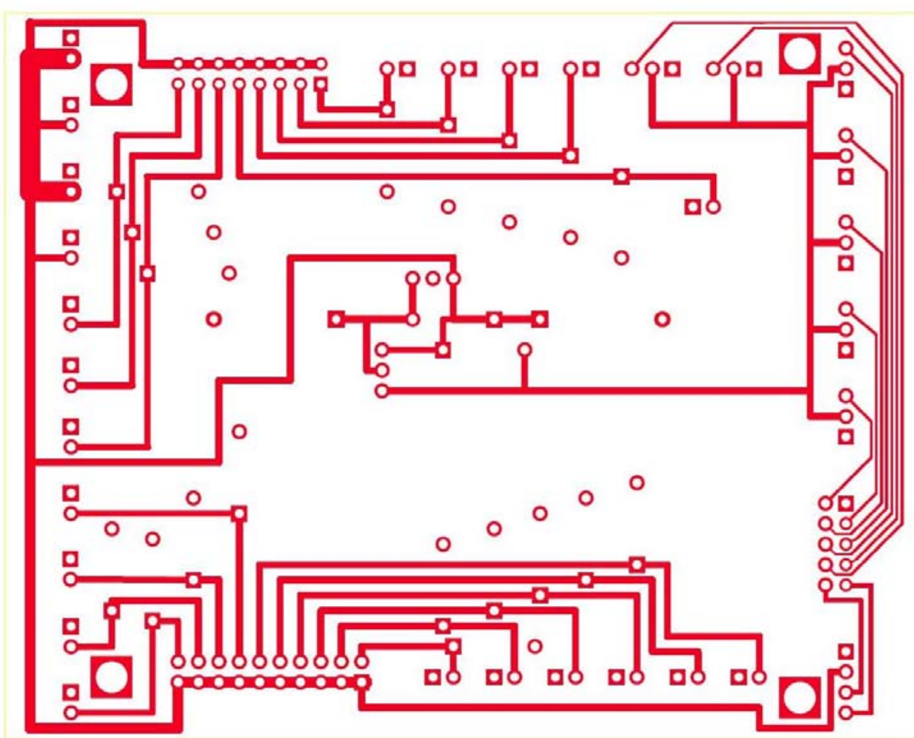
Appendix E. Interconnect Board Schematics




AIRCOA IC Board
Rev. 1.0
NCAR
IR104
Cal3
Cal2
Cal1
Air
Line6
Line5
U1
C1
C2
D1
10 V


12 V
Licor
Pump
Pro.
R17
R16
R15
Line4
Line3
Line2
Line1
IR104
Cal3
Cal2
Cal1
Air
Line6
Line5
MFM5
MFM4
MFM3
MFM2
MFM1
Analog to Prometh.
Humitter





Appendix F. List of Additional Technical Documents

The following documents are provided separately as reference material on individual components of the AIRCOA system:

1) HMP50 Manual - 2004 Dec.pdf (Honeywell documentation on RH/T sensor)
2) KNF N84_89.pdf (KNF documentation on N89 tower pump)
3) KNF NMP015.pdf (KNF documentation on sample pump)
4) KNF NMP850.pdf (KNF documentation on N850 low-power tower pump)
5) Meanwell Power Supply.PDF (documentation on 12 V DC power supply)
6) numatech TM.pdf (schematics of TM10 solenoid valves)
7) IR104Manual.pdf (manual for relay board)
8) Prometheus Manual, v1.44.pdf (Diamond Systems manual for instrument computer)
9) LI820Manual.pdf (Li-Cor manual for CO_2 sensor)