

Ratnoze1 User Guide

Mountain Air Engineering
mtnaireng.com
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1 Features

The Ratnoze is a portable sampling system specialized for measuring solid fuel combustion emissions. It is appropriate for emission measurements of brick kilns, and other large and small scale industrial combustion sources with and without exhaust stacks. It is also appropriate for emission measurements of cookstoves with and without chimneys.

The Ratnoze is a dilution sampler, which is different from other conventional emission measurement equipment, because it conditions the exhaust sample with dilution air for representative measurement of condensible particulate matter and other semi-volatile species. It is intended to be used for determining

emission factors by the carbon balance method, but can also be used to determine undiluted exhaust concentrations and exhaust flow rate for many other emission metrics.

The Ratnoze is a complete kit that includes a sensor box, probe, carrying case, and all required accessories to conduct emission sampling. The sample train contains a PM2.5 size selective inlet and two parallel 47 mm filter holders that can be used for collecting filter samples for laboratory analysis. The following parameters in Table 1 are logged to an on-board SD card at a 1 second time base. The data can be viewed and plotted in real-time using the provided computer and software. The on-board lithium ion battery provides power for 14 hours of run time.

Table 1: Parameters measured and recorded by the Ratnoze1 sensor box

Parameter	Range	Measurement Method
CO	0-5000 ppm	electrochemical
CO background	0-5000 ppm	electrochemical
CO ₂	0 - 50000 ppm	NDIR
CO ₂ background	0 - 50000 ppm	NDIR
SO ₂	0-2000 ppm	electrochemical
SO ₂ background	0-2000 ppm	electrochemical
NO	0-250 ppm	electrochemical
NO ₂	0-20 ppm	electrochemical
O ₂	0-25 %	electrochemical
PM light scattering	0 - 500000 Mm ⁻¹	optical 635 nm
BC concentration	0 - 500000 ug/m ³	MicroAeth
MicroAeth filter attenuation	0 - 150 ATN	MicroAeth
MicroAeth flow	0 - 250 sccm	MicroAeth
Isokinetic bypass flow	0 - 4000 sccm	mass flow sensor
Filter 1 flow	0 - 4000 sccm	mass flow sensor
Filter 2 flow	0 - 4000 sccm	mass flow sensor
Gas sensor flow	0 - 4000 sccm	mass flow sensor
Dilution flow	0 - 4000 sccm	mass flow sensor
Sample relative humidity	5 - 95 %	capacitive
Sample temperature	0 - 150 °C	LM35
Probe nozzle temperature	0 - 1000 °C	Type K thermocouple
Auxiliary temperature	0 - 1000 °C	Type K thermocouple
Pitot tube differential pressure	-250 - 250 Pa	solid state transducer
Auxiliary differential pressure	-250 - 250 Pa	solid state transducer
Battery voltage	0 - 30 V	ADC
Stack velocity	0 - 20 m/s	calculated
Nozzle velocity	0 - 20 m/s	calculated
Dilution Ratio	0 - 20	calculated
PM mass on filter	0 - 1000000 ug	calculated

2 Components

The Ratnoze sampling kit consists of the sensor box, probe, accessories, and cases.

2.1 Sensor Box

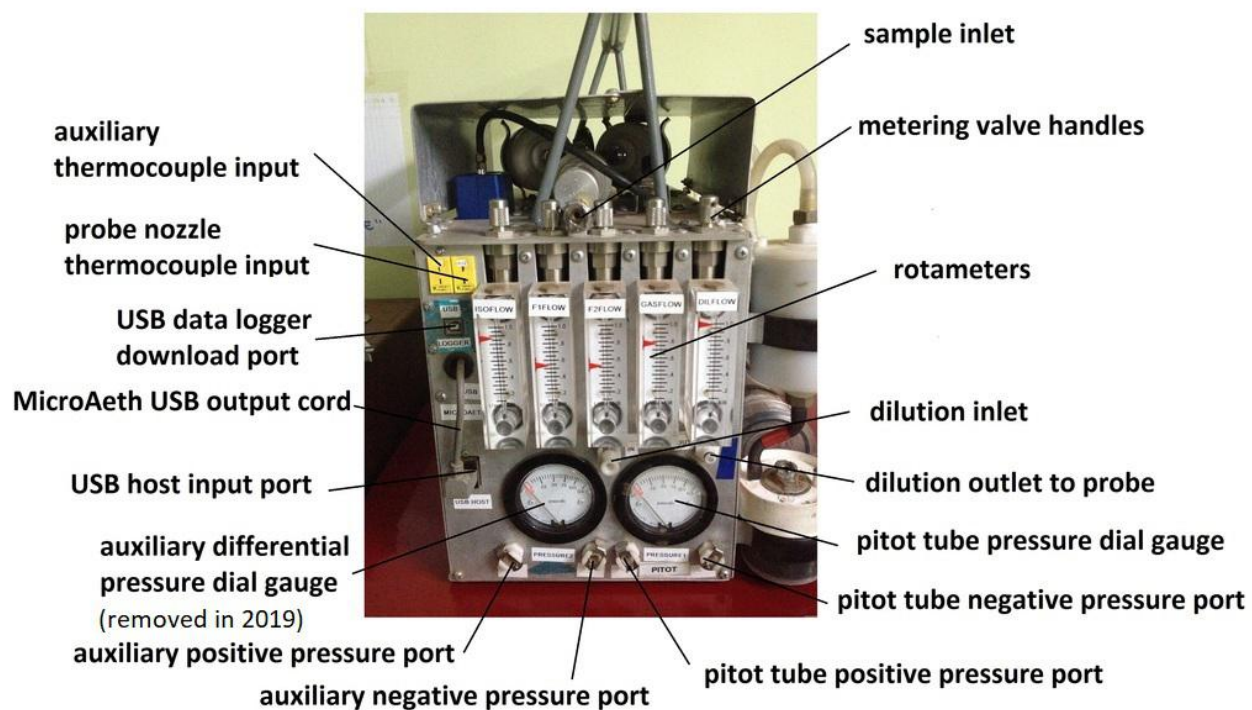


Figure 1: Front panel of sensor box



Figure 2: Side panel of sensor box

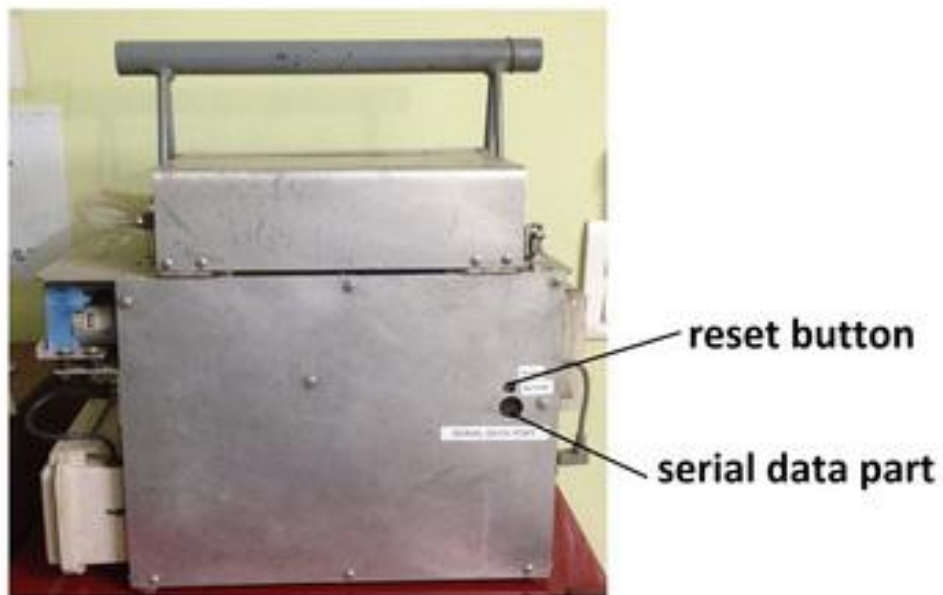


Figure 3: Other side panel of sensor box

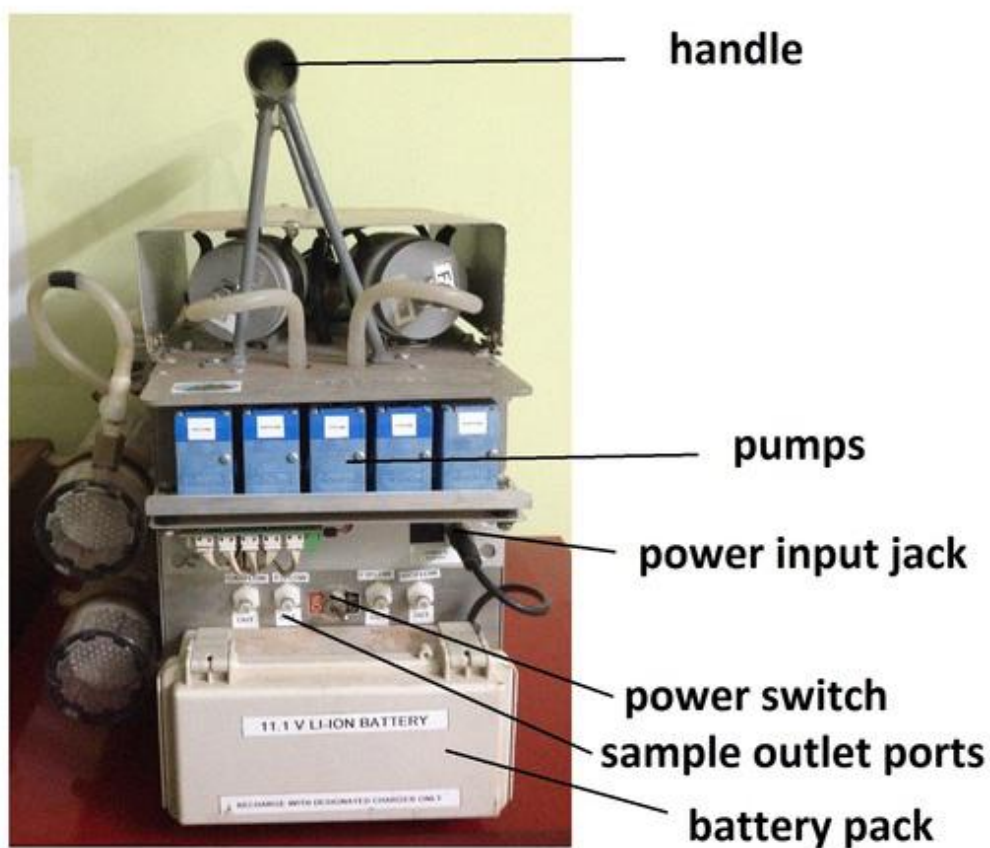


Figure 4: Rear end of sensor box



Figure 5: Top of sensor box

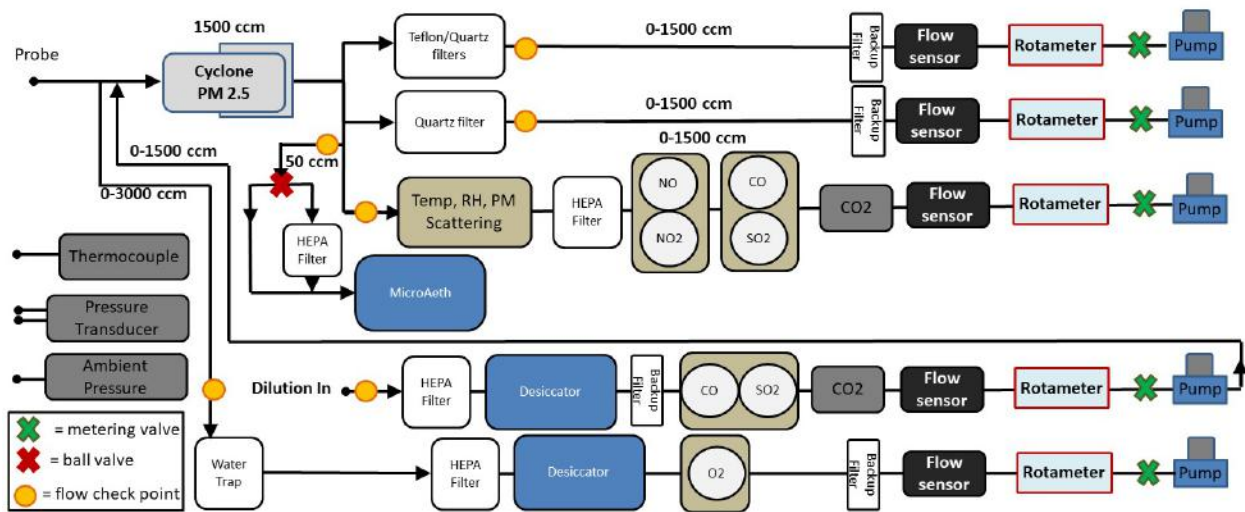


Figure 6: Sensor box flow schematic

2.2 Accessories

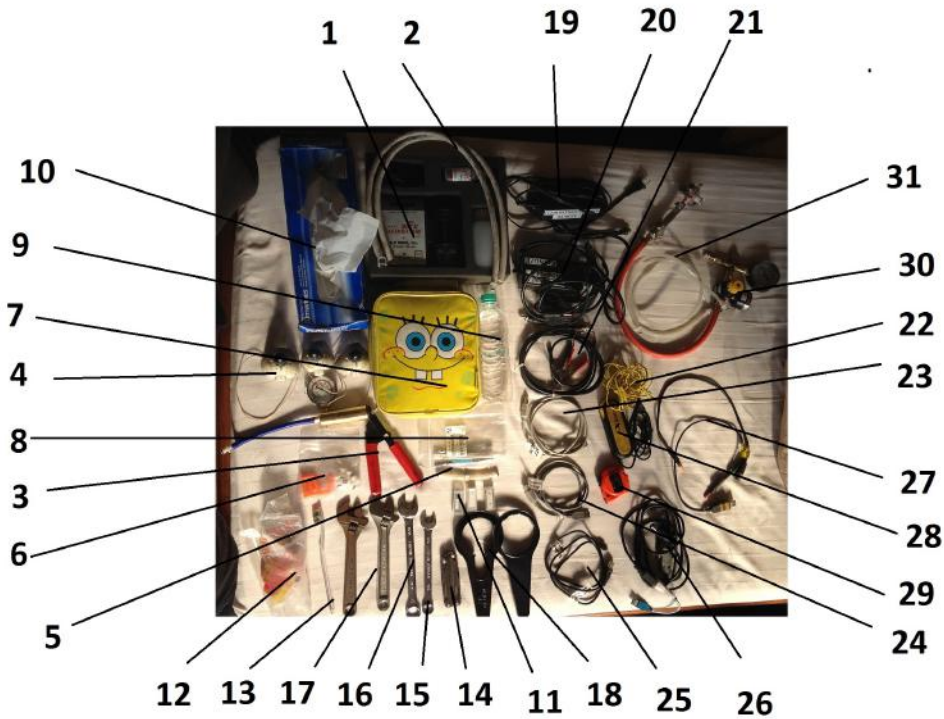


Figure 7: Accessories

Table 2: Accessories. Items marked with * are not supplied in the kit.

Number in Figure	Item	Purpose/Note
1	bubble meter (AP Buck flow calibrator)	for setting and checking flows
2	bubble meter tubes	for setting and checking flows
3	hand pump vacuum gauge	for leak testing
4	safety masks (x3)	for safety
5	pressure zeroing tube	for zeroing pressure sensor
6	caps and plugs	for sealing filter holders during transportation
7	SpongeBob insulated case	for transporting filters
8	tweezers	for handling filters
9	*acetone or similar solvent	for cleaning filter holders and probe
10	Kimwipes or similar low lint tissues	for cleaning filter holders and probe
11	*MicroAeth filters	source: Aethlabs, USA
12	baking soda	for cleaning probe
13	toothbrush	for cleaning probe and you teeth
14	multi-tool (pliers, knife, screwdriver)	
15	9/16" wrench	for assembling probe
16	11/16" wrench	for assembling probe
17	crescent wrench (x2)	for assembling probe
18	desiccant chamber tools	for replacing desiccant
19	battery charger (11.1 V Li-ion)	
20	AC power supply	DC converter
21	auxiliary battery cables	for connecting to back-up battery
22	thermocouple extension cord (yellow)	
23	USB data download cord	
24	USB MicroAeth extension cord	
25	USB firmware programming cord	
26	RS232-USB serial data cord	
27	serial-USB wireless transmitter pair	
28	Kestrel weather meter	for measuring ambient temp, pressure, and RH
29	*measuring tape	
30	probe back-purge hose and valve	for connecting to compressed air tank
31	gas sensor calibration tube	
not pictured	probe back-purge tank	for storing compressed air
not pictured	*rag	for stuffing in port to seal around probe
not pictured	*heat resistant gloves	for handling hot probe
not pictured	nitrile exam gloves	
not pictured	*47mm sample filters	for gravimetric and/or BC analysis
not pictured	HEPA filter	for cyclone inlet during background measurement
not pictured	light	
not pictured	*umbrella	for protecting sensor box from sun and rain also for the Mary Poppins stack dismount

2.3 Probe

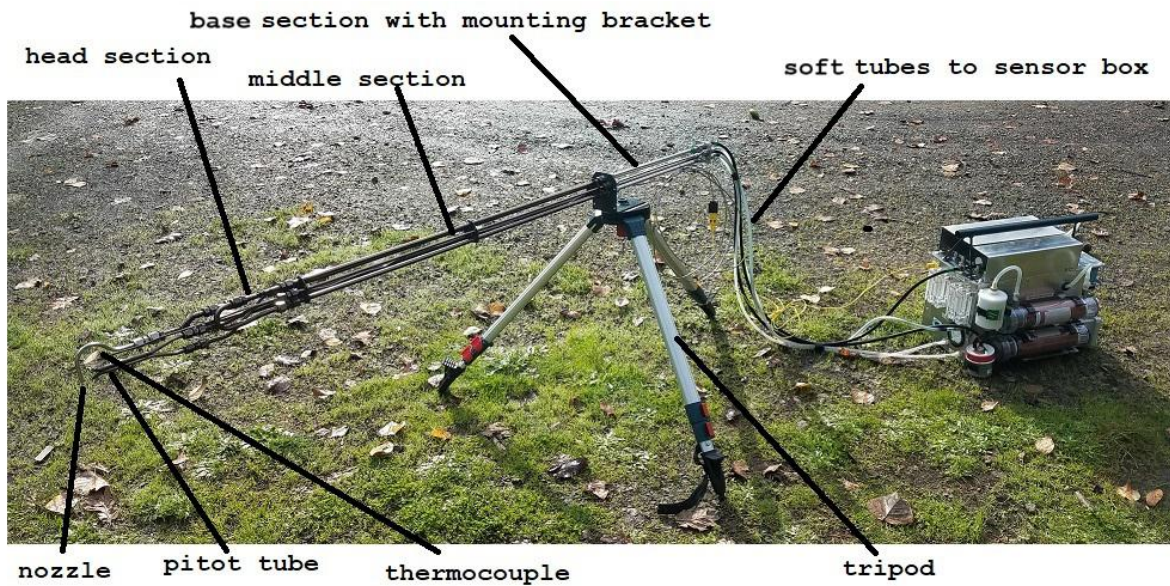


Figure 8: The probe can be mounted on the tripod for free-standing applications. The multi-point open-plume sampling nozzle and probe extension pieces are on the ground. The probe can be assembled to lengths of 1.23, 2.12, or 3.0 m. See Section 8 for more details.

2.4 Cases

The entire kit is contained inside two durable cases for transportation and storage, one case for the sensor box and accessories, and one case for the probe. The cases are suitable for airline travel.



Figure 9: Sensor box case. Outside dimensions = 57 x 57 x 54 cm (L x W x H excluding wheels). The case has wheels that allow you to effortlessly roll through Customs. The wheels can be easily removed (unclipped) without hand tools. The wheels should be removed before airline travel. During sampling events, the case doubles as a work bench.



Figure 10: Probe case. Outside dimensions = 97 x 41 x 16 cm (L x W x H). The thermocouple and soft sample tubes fit inside the sensor box case.

2.5 Weight

Table 3: Weight

Sensor box (with batteries)	15.2	kg
Accessories	6.0	kg
Case	11.6	kg
<u>Case wheels</u>	<u>3.4</u>	<u>kg</u>
Total	36.2	kg
Probe	7.6	kg
<u>Probe case</u>	<u>7.7</u>	<u>kg</u>
Total	15.3	kg

3 Sampling Procedure

3.1 Preparation Before a Sampling Event

3.1.1 Charge batteries for:

sensor box
bubble meter
computer
camera

3.1.2 Change desiccant if necessary (see Section 9.4)

3.1.3 Load filters into filter holders (see Section 9.5)

3.2 Pre-sampling Setup

3.2.1 Assemble probe (see Section 8)

3.2.2 System leak check (see Section 9.1)

3.2.3 Connect the HEPA filter to the cyclone inlet to prevent background PM from accumulating on the sample filters.

3.2.4 Connect serial data output to computer using USB cord or wireless transmitter and run the Ratnoze software (see Section 4).

3.2.5 Power on the sensor box (the power switch is on the rear end of the sensor box).

3.2.6 Put in a new MicroAeth Filter, then open MicroAeth valve and power on the MicroAeth (see Section 7).

3.2.7 Check that clocks are synced for Ratnoze, computer, and camera.

3.2.8 Let the sensor box run for 10 minutes to warm up.

3.2.9 Zero the pitot pressure sensor (Pres1). Optional: Zero flow sensors and gas sensors if necessary.

3.2.10 Update the nozzle diameter in the Ratnoze calibration parameters. (Using the Ratnoze computer software, Select Utilities tab and then "update parameters". Read the current value of NozDiam and update if necessary.)

3.2.11 Set flows (See Section 9.2 for guidance determining the appropriate flow settings):

AethFlow = on/off (as desired)

IsoFlow = 0 sccm

F1Flow = 200 sccm (or desired flow)

F2Flow = 200 sccm (or desired flow)

GasFlow = ? (use bubble meter on cyclone inlet and adjust GasFlow so cyclone flow = 1500 ccm)

DilFlow = ? (adjust DilFlow to achieve the desired dilution ratio)

3.3 Sample Period

3.3.1 Take a pre-test background reading for at least 10 minutes.

3.3.2 Move the probe so the nozzle is in the center of the stack or plume and connect the tubes to the sensor box (remove the HEPA filter on the cyclone inlet).

3.3.3 During the sampling period:

Adjust the IsoFlow so $NozVel = StakVel$ for isokinetic sampling conditions

Watch the MicroAeth ATN value. Change the MicroAeth filter when ATN is greater than 60.

Watch the PMmass channel. End the sampling event if the filters get overloaded.

Back purge the probe at a regular frequency.

3.3.4 At the end of the sampling period:

Disconnect sensor box from probe and remove probe from the stack or plume.

Connect the HEPA filter to the cyclone inlet.

Let the sensor box run for at least 20 minutes to take a post-test background.

3.3.5 Power off the Ratnoze and MicroAeth.

3.4 Post-sampling Tasks

3.4.1 Remove filters from filter holders (see Section 9.5).

3.4.2 Download data from SD card (see Section 6) and inspect it using LiveGraph (see Section 4.2.2).

3.4.3 Delete MicroAeth Data (see Section 7).

3.4.4 Empty Water Trap

3.4.5 Clean probe, cyclone, and sensor box (see Section 9.3).

3.4.6 Charge batteries for:

sensor box

bubble meter

computer

camera

3.5 Sampling Procedure Checklist

Ratnoze Checklist

Date/Test Info:

Pre-Test	
☐	Check/Change Desiccant
☐	Load Filters
☐	Assemble Probe
☐	Cyclone (F1Flow, F2Flow, GasFlow) Leak Check
☐	DilFlow Leak Check
☐	IsoFlow Leak Check
☐	Probe Leak Check
☐	Computer Power On
☐	Ratnoze Power On
☐	MicroAeth Power On
☐	Clocks Synced
☐	Nozzle Diameter Updated
☐	Zero Pitot (Press1)
☐	Set/Check Flows (Order: F1Flow, F2Flow, Gasflow, DilFlow)
☐	Pre-Background
Test	
☐	Adjust IsoFlow so StakVel = Nozvel
☐	Change MicroAeth filter when AethATN > 60
☐	Monitor Fuel Consumption
☐	Collect Fuel Samples
☐	Take Photos
Post-Test	
☐	Post-Background
☐	Flow Checks
☐	Ratnoze Power Off
☐	MicroAeth Power Off
☐	Remove Filters
☐	Clean Filter Holders
☐	Download Ratnoze Data
☐	Inspect Ratnoze Data
☐	Erase MicroAeth Data
☐	Empty Water Trap
☐	Clean Cyclone
☐	Clean Probe
☐	Ratnoze Battery Charge
☐	Computer Battery Charge
☐	Bubble Meter Battery Charge
☐	Camara Battery Charge

4 Software

4.1 Ratnoze Plotter Software

The Ratnoze1 sensor box outputs UART serial data that can be read by serial port terminal software with the following settings:

baud: 9600
bits: 8
parity: none
stopbits: 1

Specialized Ratnoze plotter software exists that provides a user-friendly GUI for plotting real-time data, configuring parameters, and calibrating. The software is written in Python using the pyqt library. The most current version of the software can be downloaded from www.mtnaireng.com. This documentation is for software version: plotter 5.2.

4.1.1 Launching the Software

To start the plotter software, double click the **ratnoze** icon on the desktop of the Ratnoze computer and then select **execute**.



Figure 11: To launch the software, double click the **ratnoze** icon and select **execute**.

Once the software opens, select the serial port. The Ratnoze must first be connected to the computer with the USB wireless transmitter or the USB/RS-232 adapter. The serial port is usually `/dev/ttyUSB0`, but the port number will increment if the USB adapter is plugged into the computer multiple times during one session. Try `/dev/ttyUSB0` first, and if that doesn't work then try USB1, 2, 3, etc. You can also manually write a port name in the box instead of using the drop down menu. To determine the correct port number, plug in the USB device, then open a terminal by pressing `<ctrl><alt>t` and enter `dmesg` at the command line. This command shows driver messages for the operating system. The port name is printed in the last

line of the dmesg output:

```
[ 1619.392136] usb 1-2: FTDI USB Serial Device converter now attached to ttyUSB0.
```

4.1.2 Plot Mode

Once a serial port connection is established the plot screen will open. If there is no connection with the Ratnoze, or if the Ratnoze is powered off, then the plot screen will open like the following:

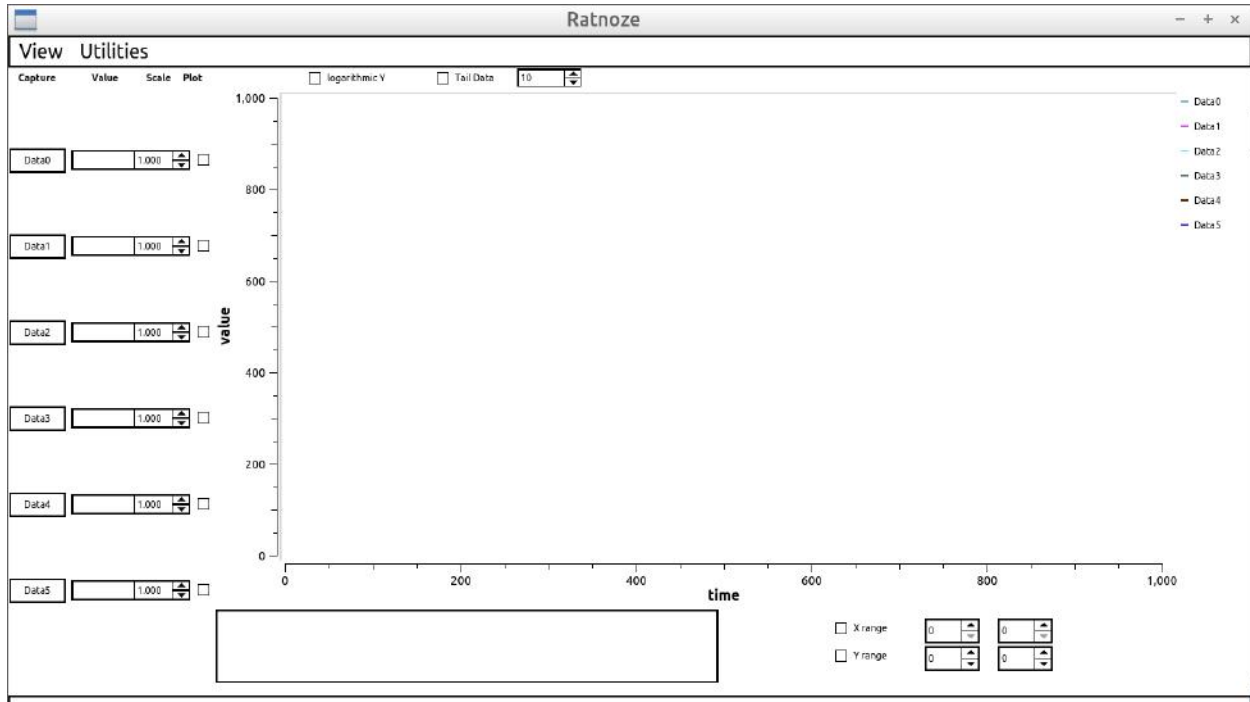


Figure 12: Default plot screen when no serial data connection is established.

If the above screen is displayed, turn on the Ratnoze and connect the serial data cord to the computer. If the Ratnoze is already on, the plot screen will populate with the data stream.

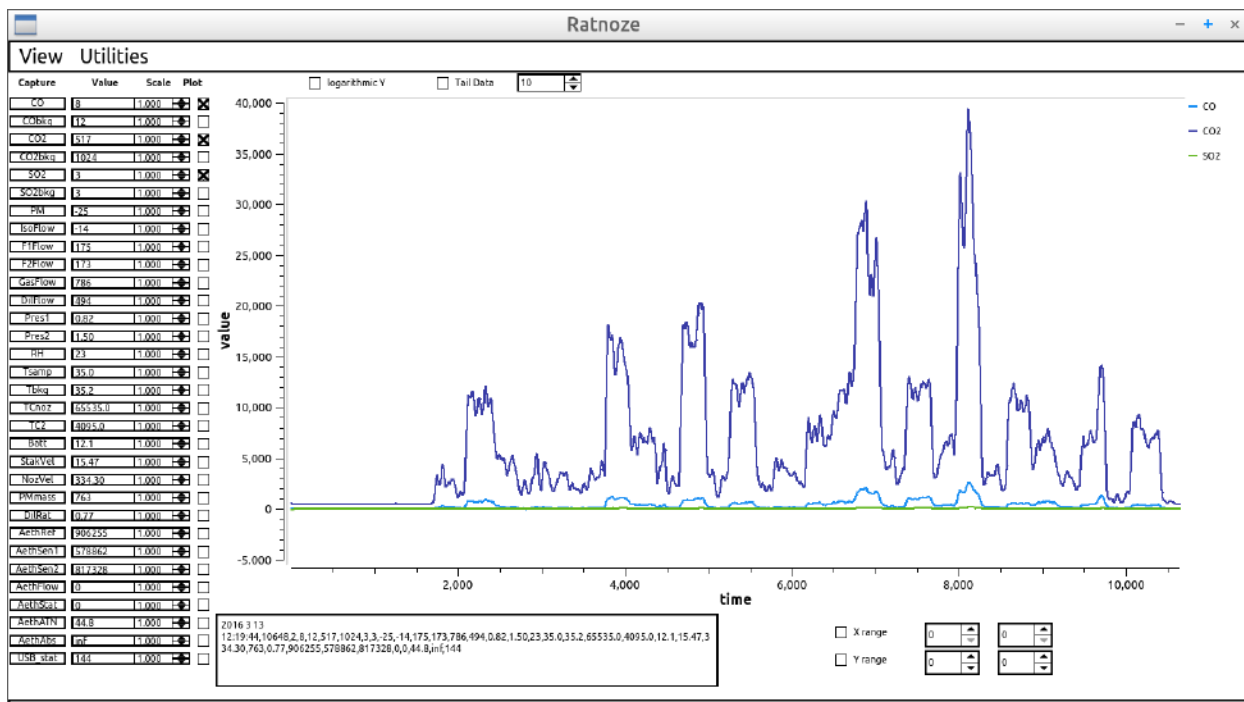


Figure 13: Plot screen. X axis is seconds elapsed since the Ratnoze was powered on or reset.

Incoming data channels are displayed on the left. The channels are listed as follows:

- CO: sample carbon monoxide [ppm]
- CObkg: background carbon monoxide measured in the dilution train [ppm]
- CO2: sample carbon dioxide [ppm]
- CO2bkg: background carbon dioxide measured in the dilution train [ppm]
- SO2: sample sulfur dioxide [ppm]
- SO2bkg: background carbon dioxide measured in the dilution train [ppm]
- NO: sample nitric oxide [ppm]
- NO2: sample nitrogen dioxide [ppm]
- O2: undiluted sample oxygen [%]
- PM: particulate matter optical scattering coefficient [Mm^{-1}]
- IsoFlow: Isokinetic bypass flow rate [scm]
- F1Flow: Filter 1 flow rate [scm]
- F2 Flow: Filter 2 flow rate [scm]
- GasFlow: gas sensor flow rate [scm]
- DilFlow: dilution flow rate [scm]
- Pres1: pitot tube differential pressure [Pa]
- Pamb: absolute ambient pressure [Pa]
- RH: relative humidity [%]
- Tsmp: sample temperature measured at gas sensors [C]
- Tbkg: background temperature measured at the background gas sensors [C]
- TCnoz: nozzle temperature [C]
- TC2: auxiliary thermocouple [C]
- Batt: battery voltage [V]
- StakVel: stack velocity [m/s]
- NozVel: nozzle inlet velocity [m/s]
- PMmass: integrated PM mass on F1 filter [ug]
- DilRat: dilution ratio (dilution flow/nozzle flow) [-]
- AethRef: MicroAeth reference signal [-]

AethSen1: MicroAeth sensor 1 signal [-]
AethSen2: MicroAeth sensor 2 signal [-]
AethFlow: MicroAeth flow rate [scm]
AethStat: MicroAeth status code [-]
AethATN: MicroAeth attenuation [-]
AethBC: PM black carbon mass concentration [ug/m³]
USB stat: USB host status code [-]

The **Capture** column displays the channel names. The **Value** column displays the channel values. Click a channel name in the **Capture** column to “capture” a reading. The value box will turn yellow and display the captured reading, which is a 10 second average. Click the channel name again to release the captured reading. The value box will turn back to white and resume displaying current values. The **Scale** column allows you to apply a scaling parameter to the plotted data channel. The **Plot** column has check boxes to select which channels are plotted.

The **logarithmic Y** check box will convert the Y axis to a logarithmic scale.

The **Tail Data** check box will set the X axis to plot the most recent points. Enter the tail data length in the adjacent box.

The **X range** and **Y range** check boxes in the bottom right set the X and Y axis to the minimum and maximum values defined in the adjacent two boxes.

The large box near the bottom of the screen shows the current raw data stream. If the USB connection is lost, the box will display “port in use”. If this happens, unplug the USB device, plug it in again, and restart the Ratnoze plotter software.

4.1.3 Terminal Mode

Terminal Mode replaces the plot window with a terminal that shows the raw data stream, which is used to send commands to the Ratnoze to update operating parameters. To enter Terminal Mode, select the **View** tab and check the **Terminal Mode** box. Place the cursor in the bottom box to send commands. Three line ending options are listed to the right of the box. **LF only** will add a line feed character to every command that is sent. This is the default option which is required to communicate with the Ratnoze. **RTN only** will add a carriage return character to the end of commands. This option is required to communicate directly with the CO2 sensors. **RTN and LF** adds a carriage return and line feed. This option is not needed. To exit out of Terminal Mode and return to Plot Mode, select the **View** tab and uncheck the **Terminal Mode** box.

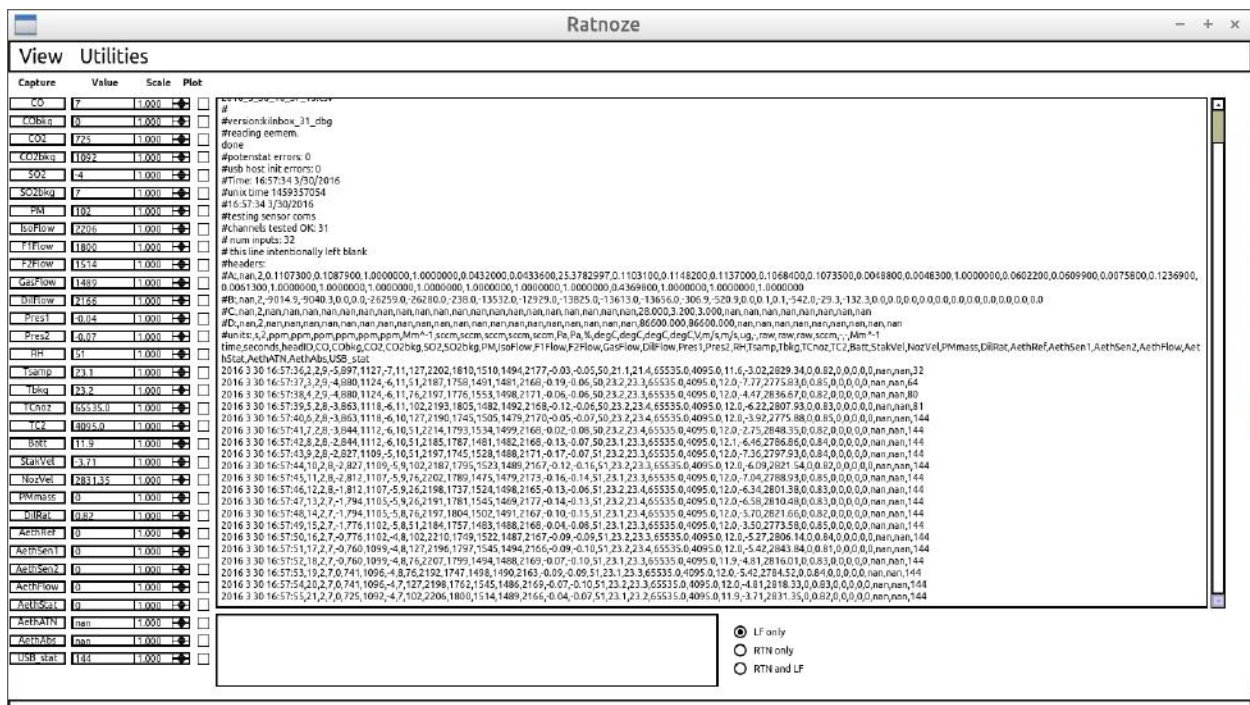


Figure 14: Terminal mode.

4.1.4 Calibration Mode

Calibration Mode provides an interface for calibrating sensors. To enter Calibration Mode, select the **View** tab and toggle **Cal Mode**.

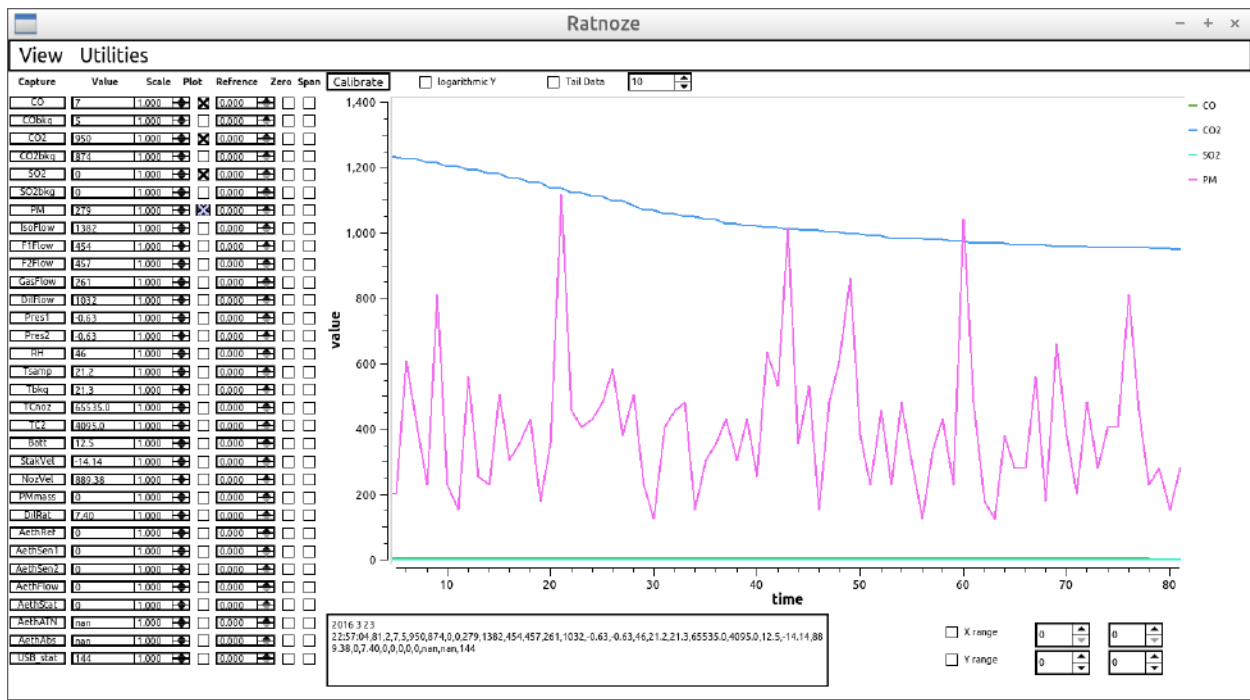


Figure 15: Calibration mode.

Calibration Mode adds three columns to the left of the plot window. The **Reference** column has boxes to enter reference values for performing calibrations of desired channels. The **Zero** column has check boxes to select a zero offset calibration for desired channels. The **Span** column has check boxes to select a span calibration for desired channels. The **Calibrate** button performs calibrations for each channel that has a zero or span box checked.

To "zero" a sensor, expose the sensor to a zero reference reading, capture a reading by clicking the channel name, select the Zero check box, and then press the Calibrate button. Once the calibration button is pressed, the program will switch to terminal mode and send a series of commands to update the zero offset (B parameter).

The sensor can be zeroed using a non-zero reference reading. For example, the CO2 sensor can be zeroed in ambient air at 400 ppm. To zero a sensor using a non-zero reference, just enter the reference reading in the **Reference** box.

To set the span of a sensor, expose the sensor to a span reference reading, enter the reference value in the **Reference** box, capture a reading by clicking the channel name, select the **Span** check box, and then press the **Calibrate** button. Once the calibration button is pressed, the program will switch to terminal mode and send a series of commands to update the span (A) parameter for the selected channels.

Multiple channels can be calibrated during one calibration.

It is not necessary to capture a reading to perform a calibration. If a reading is not captured before pressing the **Calibrate** button, then the most current reading from the sensor will be used to perform the calibration. Capturing a reading provides a more accurate calibration by using an average sensor reading to filter out signal noise.

To manually adjust the zero or span calibration for a sensor without actually taking a sensor reading, capture a reading, then manually enter a value in the **Value** box and **Reference** box.

4.1.5 Utilities

Select the **Utilities** menu item to see available utilities.

Clock Sync sets the Ratnoze clock to match the computer clock.

Set Parameters allows you to set parameters in the Ratnoze EEMEM that are used to calculate the output of the NozVel, StakVel, PMmass, And AethBC channels. When this utility is selected, the current parameter values will be read from the Ratnoze. A box will open that shows a list of parameters, the current values, and an entry box to update the values. To change a value, enter the new value, check the Update box, and click OK.

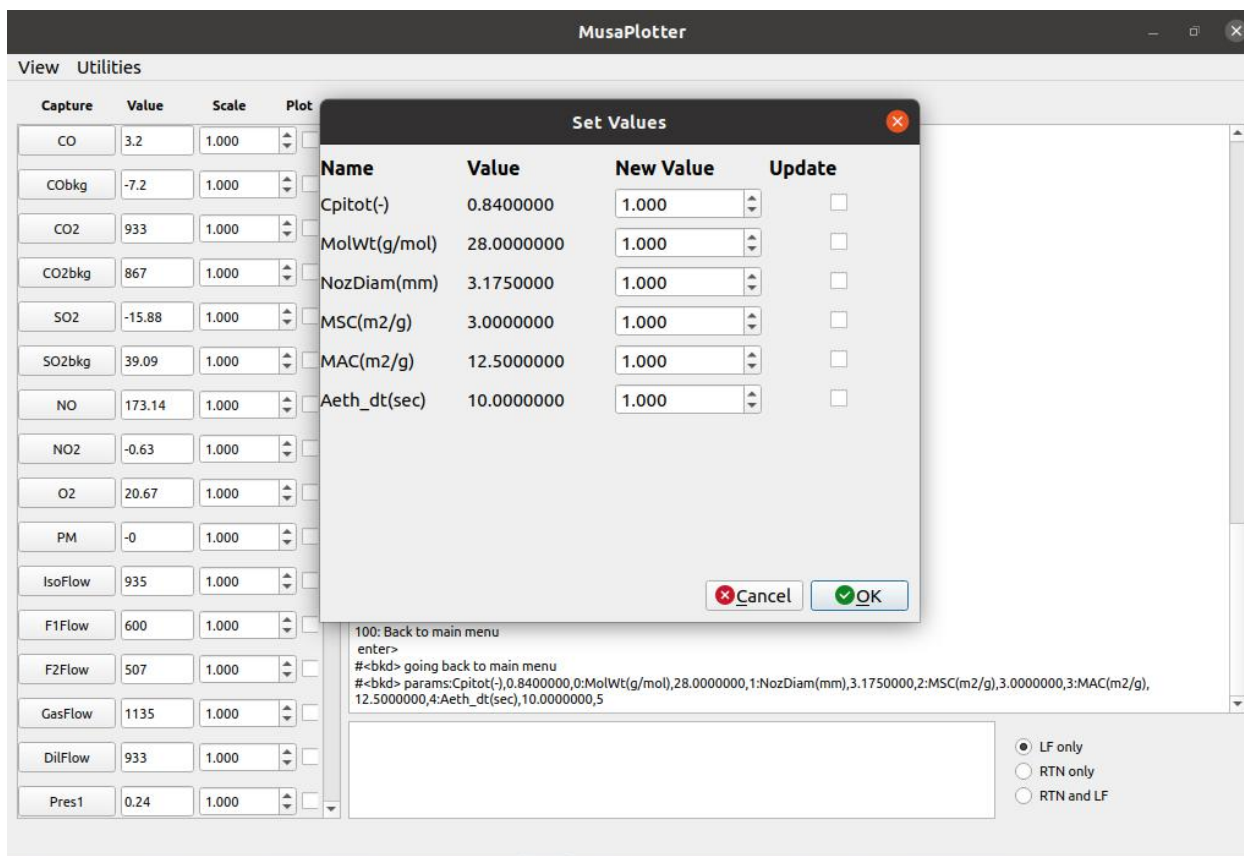


Figure 16: Set parameters utility shows the current parameter values and allows the user to update them. Cpilot is the pitot tube calibration constant. MolWt is the flue gas molecular weight. NozDiam is the probe nozzle diameter. MSC is the mass scattering cross-section used to estimate PM mass concentration from the optical scattering coefficient. MAC is the mass absorption cross-section used to estimate black carbon mass concentration from the optical absorption coefficient. Aeth_dt is the time step (sampling rate) of the MicroAeth used to calculate the absorption coefficient and BC concentration.

4.2 Other Software Tools

The Ratnoze computer contains other useful software in addition to the Ratnoze plotter.

4.2.1 Stack Sampling Calculator

The Stack Sampling Calculator.xls spreadsheet is located on the desktop of the Ratnoze computer. The spreadsheet has three tabs, one tab for pitot tube calculations (Figure 17) , one tab for determining the appropriate nozzle diameter (Figure 18), and one tab for converting flow measurements between actual and standard conditions (Figure 19). The active cells in each sheet are color coded. Green cells are input variables that should be updated for each calculation. Yellow cells are constants and intermediate variables that should not be modified. Orange cells are output variables.

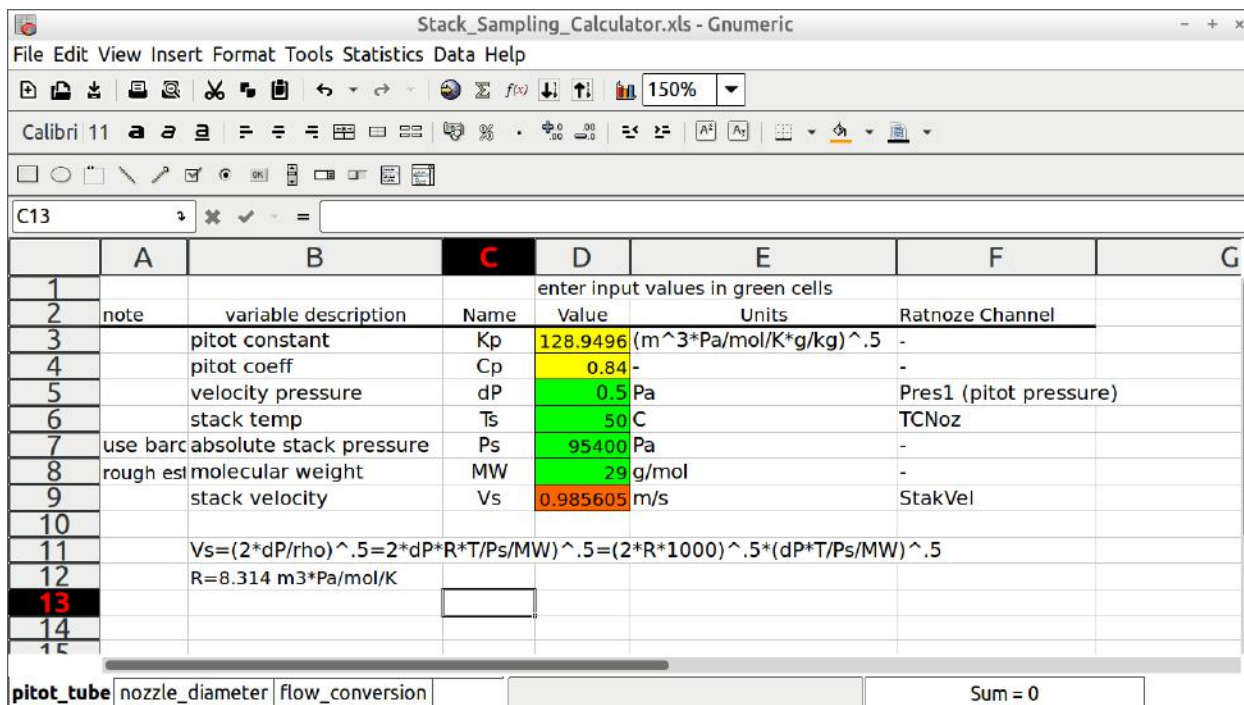


Figure 17: The pitot tube tab calculates the stack velocity using the theoretical pitot tube calculation.

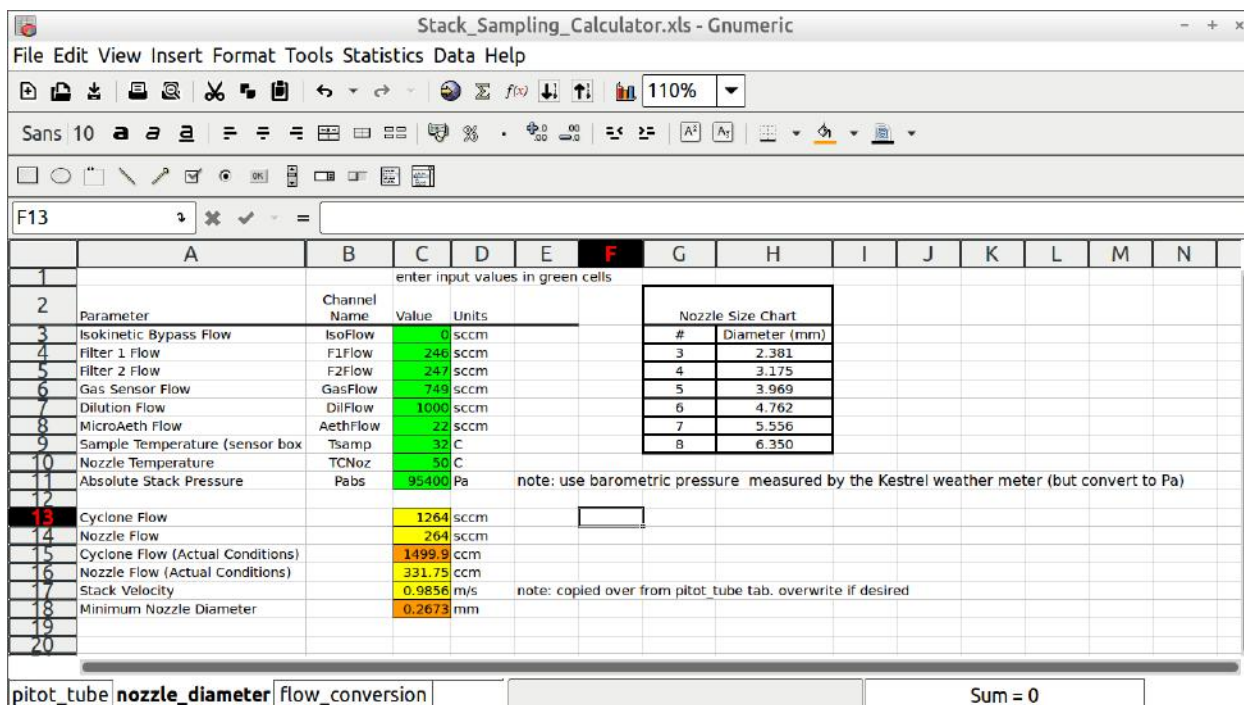


Figure 18: The nozzle diameter tab is used to determine the appropriate nozzle size. It calculates the minimum acceptable nozzle diameter for isokinetic sampling conditions and provides the nozzle size chart to choose the appropriate nozzle.

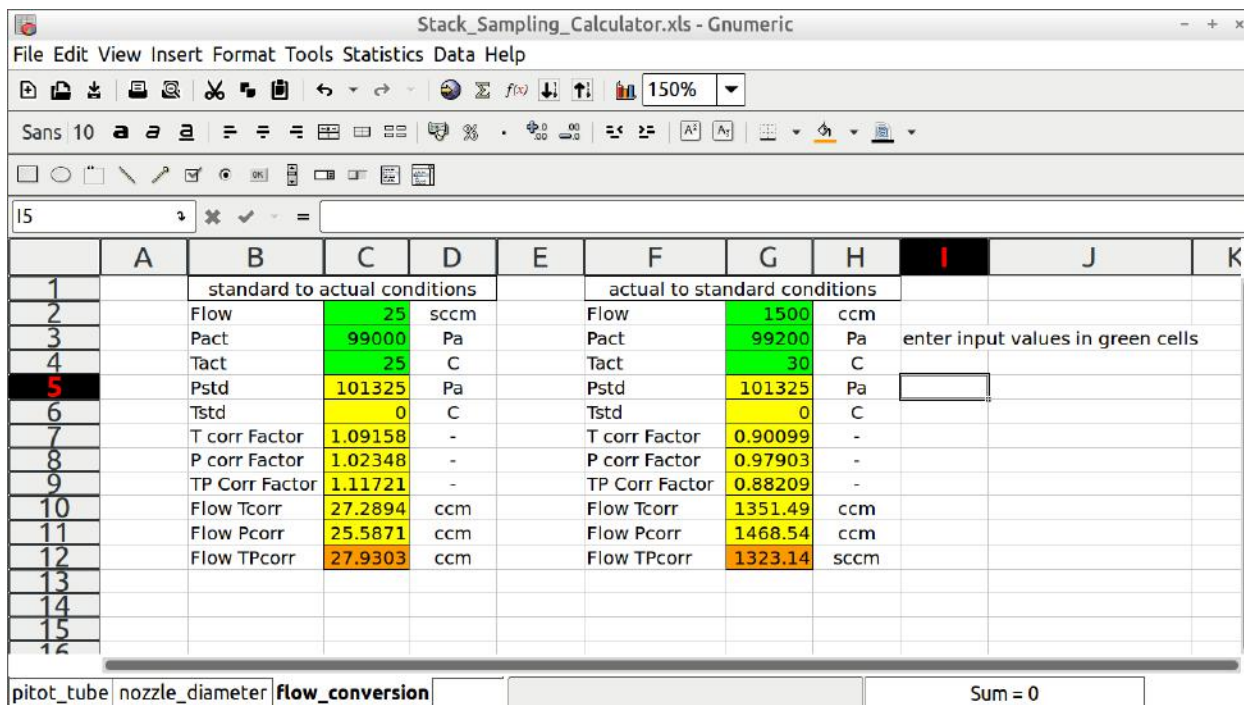


Figure 19: The flow conversion tab converts volumetric flow rates back and forth between actual conditions (ccm) and standard conditions (sccm) using ideal gas law temperature and pressure corrections.

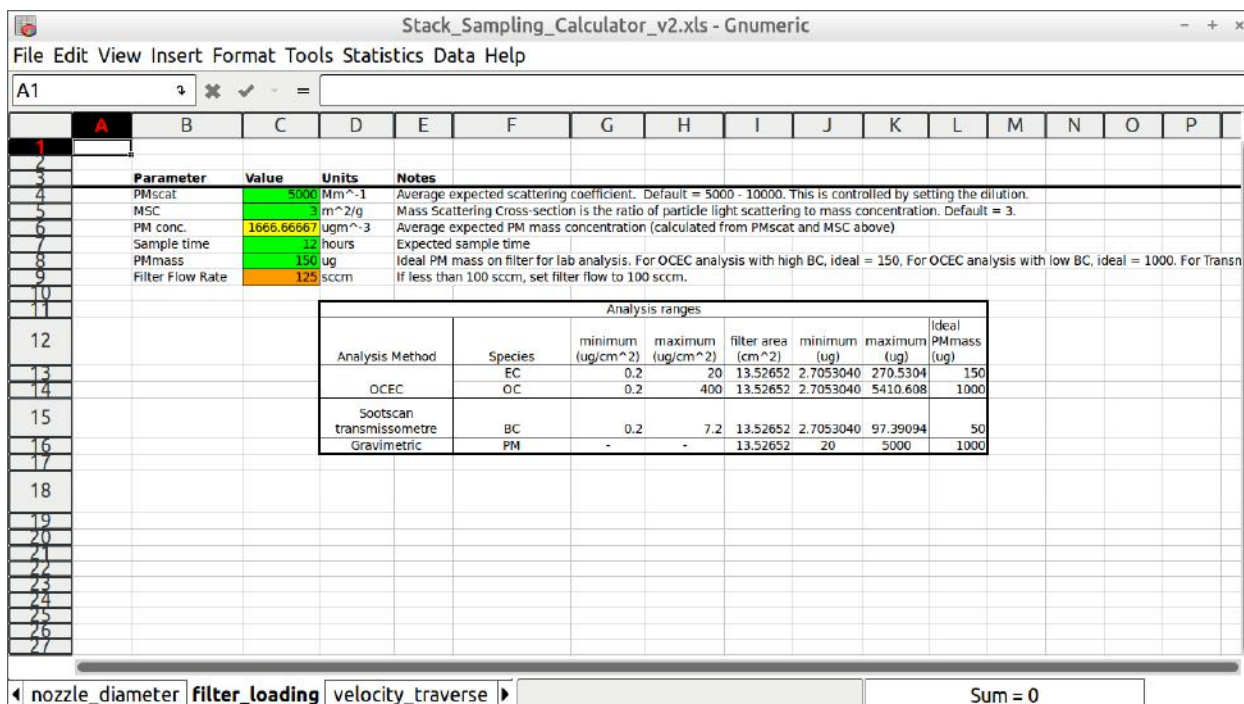


Figure 20: The filter loading tab provides a calculation to estimate the ideal filter flow rate for your particular sampling application.

Stack_Sampling_Calculator_v2.xls - Gnumeric

File Edit View Insert Format Tools Statistics Data Help

A1

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1		Number of traverse points on a diameter													see Method 1 for more info					
2	Traverse Point Number	2	4	6	8	10	12	14	16	18	20	22	24							
3	1	14.6	6.7	4.4	3.2	2.6	2.1	1.8	1.6	1.4	1.3	1.1	1.1							
4	2	85.4	25	14.6	10.5	8.2	6.7	5.7	4.9	4.4	3.9	3.5	3.2							
5	3		75	29.6	19.4	14.6	11.8	9.9	8.5	7.5	6.7	6	5.5							
6	4		93.3	70.4	32.3	22.6	17.7	14.6	12.5	10.9	9.7	8.7	7.9							
7	5			85.4	67.7	34.2	25	20.1	16.9	14.6	12.9	11.6	10.5							
8	6			95.6	80.6	65.8	35.6	26.9	22	18.8	16.5	14.6	13.2							
9	7				89.5	77.4	64.4	36.6	28.3	23.6	20.4	18	16.1							
10	8				96.8	85.4	75	63.4	37.5	29.6	25	21.8	19.4							
11	9					91.8	82.3	73.1	62.5	38.2	30.6	26.2	23							
12	10					97.4	88.2	79.9	71.7	61.8	38.8	31.5	27.2							
13	11						93.3	85.4	78	70.4	61.2	39.3	32.3							
14	12							90.1	83.1	76.4	69.4	60.7	39.8							
15	13							97.9												
16	14								94.3	87.5	81.2	75	68.5	60.2						
17	15								98.2	91.5	85.4	79.6	73.8	67.7						
18	16									95.1	89.1	83.5	78.2	72.8						
19	17									98.4	92.5	87.1	82	77						
20	18										95.6	90.3	85.4	80.6						
21	19										98.6	93.3	88.4	83.9						
22	20											96.1	91.3	86.8						
23	21											98.7	94	89.5						
24	22												96.5	92.1						
25	23												98.9	94.5						
26	24													96.8						
27														99.9						
28																				
29																				
30																				

nozzle_diameter filter_loading velocity_traverse Sum = 0

Figure 21: The velocity traverse tab provides a table of EPA traverse points as a percentage of the diameter.

4.2.2 LiveGraph

LiveGraph is Java based, open source, data graphing software that is very useful for quickly graphing and exploring data files. To open LiveGraph, double click the desktop icon and select **Execute**.



Figure 22: To launch LiveGraph, double click the **livegraph** desktop icon and select **execute**.

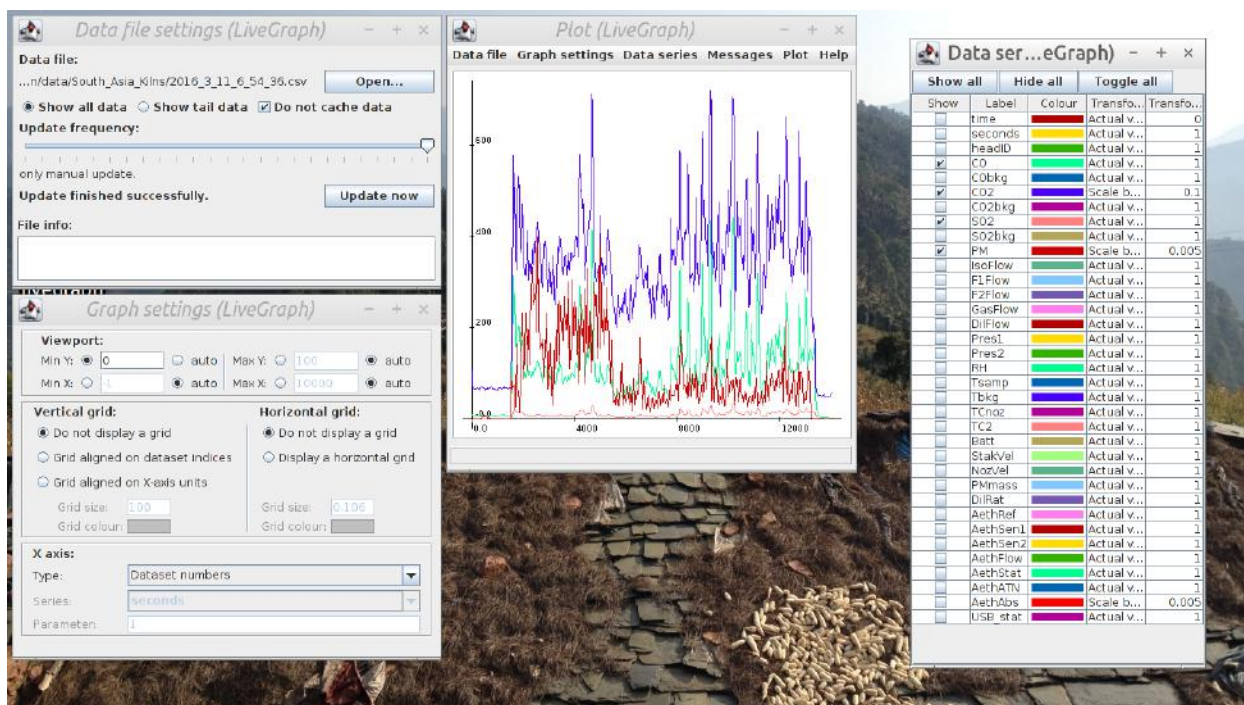


Figure 23: LiveGraph software.

LiveGraph has four windows:

Window 1: Data file settings

0.84,-0,-3.35,916012,850537,663765,22,0,7.4,579,144

Lines 1 - 8 are diagnostic information for startup and initialization

Line 1: firmware version

Line 2: indicates that calibration parameters were read from memory

Line 3: result of the potenstat chip initialization for CO and SO2 sensors

Line 4: result of the USB host test

Line 5-6: Result of communication test with all sensors

Line 7: Result of input count

Line 8: Indicates that data file headers will follow

Line 9: A parameters stored for each channel

Line 10: B parameters stored for each channel

Line 11: C parameters: List of parameter names used in firmware calculations

Line 12: D parameters: List of parameter values used in firmware calculations

Line 13: Physical units of each channel output

Line 14: Channel names

Line 15: First line of data in the logging loop

Line 16: Second line of data in the logging loop

Line 17: Third line of data in the logging loop.

The logging loop will continue once per second until the Ratnoze is powered off or the cal command is sent. The data columns in the logging loop are as follows:

1. time: date and time [yyyymmdd hh:mm:ss]
2. seconds: seconds elapsed since logging loop started [sec]
3. headID: header ID code [-] for software to identify the data stream without seeing the header
4. CO: sample carbon monoxide [ppm]
5. CObkg: background carbon monoxide measured in the dilution train [ppm]
6. CO2: sample carbon dioxide [ppm]
7. CO2bkg: background carbon dioxide measured in the dilution train [ppm]
8. SO2: sample sulfur dioxide [ppm]
9. SO2bkg: background carbon dioxide measured in the dilution train [ppm]
10. NO: sample nitric oxide [ppm]
11. NO2: sample nitrogen dioxide [ppm]
12. O2: undiluted sample oxygen [%]
13. PM: particulate matter optical scattering coefficient [Mm^{-1}]
14. IsoFlow: Isokinetic bypass flow rate [sccm]
15. F1Flow: Filter 1 flow rate [sccm]
16. F2 Flow: Filter 2 flow rate [sccm]
17. GasFlow: gas sensor flow rate [sccm]
18. DilFlow: dilution flow rate [sccm]
19. Pres1: pitot tube differential pressure [Pa]
20. Pamb: absolute ambient pressure [Pa]
21. RH: relative humidity [%]
22. Tsamp: sample temperature measured at gas sensors [C]
23. Tbkg: background temperature measured at the background gas sensors [C]
24. TCnoz: nozzle temperature [C]
25. TC2: auxiliary thermocouple [C]
26. Batt: battery voltage [V]
27. StakVel: stack velocity [m/s]
28. NozVel: nozzle inlet velocity [m/s]
29. PMmass: integrated PM mass on F1 filter [ug]
30. DilRat: dilution ratio (dilution flow/nozzle flow) [-]
31. AethRef: MicroAeth reference signal [-]

- 32. AethSen1: MicroAeth sensor 1 signal [-]
- 33. AethSen2: MicroAeth sensor 2 signal [-]
- 34. AethFlow: MicroAeth flow rate [sccm]
- 35. AethStat: MicroAeth status code [-]
- 36. AethATN: MicroAeth attenuation [-]
- 37. AethBC: PM black carbon mass concentraion [$\mu\text{g}/\text{m}^3$]
- 38. USB_stat: USB host status code [-]

5.2 Setup Mode (**cal** Command)

At any time during the sampling loop, the user can send the **cal** command to the sensor box to pause sampling and print the setup menu. All serial communication sent to the Ratnoze must have LF (line feed) endings.

entering calmode

```
1: A
2: B
3: C
4: D
5: Time
6: CO2 com
7: CO2bkg com
8: .Digits
9: Header ID
10: Save
11: Reset
enter>
```

The setup menu gives 11 options. Enter a menu item number to continue.

5.2.1 A Parameters

Menu item 1 returns a list of A parameters for each channel. See Appendix B to see how the parameters are used in the output calculations.

A Entry

```
0: CO 0.1107300
1: CObkg 0.1087900
2: CO2 1.0000000
3: CO2bkg 1.0000000
4: SO2 0.0432000
5: SO2bkg 0.0433600
6: NO 0.0071900
7: NO2 -0.0102000
8: O2 0.0417600
9: PM 25.3782997
10: IsoFlow 0.1103100
11: F1Flow 0.1148200
12: F2Flow 0.1137000
13: GasFlow 0.1068400
14: DilFlow 0.1073500
15: Pres1 0.0048800
```

```

16: Pres2 0.0048300
17: RH 1.0000000
18: Tsamp 0.0602200
19: Tbkg 0.0609900
20: TCnoz 0.0075800
21: TC2 0.1236900
22: Batt 0.0061300
23: StakVel 1.0000000
24: NozVel 1.0000000
25: PMmass 1.0000000
26: DilRat 1.0000000
27: AethRef 1.0000000
28: AethSen1 1.0000000
29: AethSen2 1.0000000
30: AethFlow 0.4369800
31: AethStat 1.0000000
32: AethATN 1.0000000
33: AethBC 1.0000000
100: back to main menu
enter>

```

Enter a channel number to change the parameter value. Then enter the new value when prompted. Enter **100** or **<RTN>** to return to the main menu. If any parameter values are changed, the changes will be temporary until they are saved to EEMEM. To do this, you must select **10. Save** from the main setup menu before exiting setup mode.

5.2.2 B Parameters

Menu item 2 returns a list of B parameters for each channel. Use the same procedure as for the A parameters to view and change parameter values.

5.2.3 C Parameters

Menu item 3 returns a list of names of constant parameters. This list can not be edited.

5.2.4 D Parameters

Menu item 4 returns a list of D parameters for each channel. Use the same procedure as for the A parameters to view and change parameter values.

5.2.5 Time

Menu item 5 is used to set the clock time of the Ratnoze real-time clock. The current time is printed. Enter **y** to change the time or **n** to return to the main setup menu.

Time set

Current time: 06:19:18 03/27/16 (h:m:s d/m/y) Change? (y/n)>

To change the time, you are prompted to enter a new time string:

Enter time string (YYYYMMDD HH:MM:SS)>

After a new time is entered in the correct format, it is read back:

Read back:

Sec: 08
Mins: 21
Hour: 6
Day of month: 27
Month: 3
Year: 16
Times set to: 06:21:08 27/3/16 (h:m:s d/m/y)

5.2.6 CO2 com

Menu item 6 establishes a direct serial communication channel with the CO2 sensor. The CO2 sensor has its own internal microcontroller, and its own set of commands for calibration and temperature and pressure corrections. See documentation for the Vaisala GM111 for more information. The CO2 sensor communication requires <RTN>(carriage return) line endings. Sending  will stop CO2 sensor communication and return to the main setup menu.

5.2.7 CO2bkg com

Menu item 7 establishes a direct serial communication channel with the CO2bkg sensor. See menu item 6 above for more information.

5.2.8 .Digits

Menu item 8 returns a list of digit parameters for each channel. The digit parameter defines the number of digits to the right of the decimal when a channel output is printed in the data logging loop. It is used to set the resolution of each channel. Use the same procedure as for the A parameters to view and change parameter values.

5.2.9 Header ID

Menu item 9 is used to define the Header ID, which is a unique ID number for the header format. This ID allows the Ratnoze software to identify which machine it is connected to, and the channel names, without actually receiving the data stream header. Do not change this parameter.

5.2.10 Save

Menu item 10 saves the current parameter values to EEMEM. This action must be performed if any parameters were changed, otherwise the changes will be lost. It takes about 30 seconds for the action to complete before printing "done" and returning to the main setup menu.

5.2.11 Reset

Menu item 11 resets the data acquisition system to begin a new sampling session.

6 On-board Data Logger

An on-board SD card logger records all data that is output from the Ratnoze sensor box. The SD card is not accessible from the outside of the sensor box. The data files can be accessed and downloaded from a mass storage device USB port (square type B) on the front panel (see Figure 1). The logger has two modes: data logging mode and read mode. When the logger is in logging mode, the data files cannot be accessed for viewing and downloading. When the logger is in read mode, the logger will not log data.

6.1 Data Logging Mode

The logger is normally in data logging mode as long as the USB cord is disconnected. A new data file is created every time the Ratnoze is powered on. The name of the file is a time stamp: "yyyy_mm_dd_hh_mm_ss.csv".

6.2 Read Mode

The logger switches to read mode when the Ratnoze is powered on while the USB cord is connected to a computer. The computer will detect the logger as a mass storage device, and the data files can be accessed and downloaded through the computer's file system browser. To return to data logging mode, remove the USB cord and power cycle the Ratnoze. If the USB cord is connected, the logger will remain in read mode, and it will not be able to log data. In this case, the Ratnoze will output the following error:

Read mode: SD USB connected to computer.

Conversely, if the USB cord is connected when the Ratnoze is already powered on, the logger will already be in data logging mode and will not switch to read mode. Always copy data files to the computer before opening them. Data files on the SD card can get corrupted if the USB cord is disconnected while the files are open in a computer browser. If it appears that files are corrupted or missing, try connecting to the logger with a Linux computer as opposed to a Windows computer. Large files may take a minute to open.

6.3 SD Card

The logger supports FAT16 micro SD cards. The SD card is located inside the sensor box behind the logger USB port. The SD card can be accessed by removing the side panel of the Ratnoze. Unlatch the card by sliding the metal holder, then hinging open.

7 MicroAeth

The MicroAeth is a stand-alone instrument manufactured by AethLabs for measuring real-time black carbon by filter based light absorption method. The MicroAeth manual is located on the Ratnoze computer in the Ratnoze folder. The MicroAeth sample inlet is connected to the Ratnoze sample train. The MicroAeth outputs raw data through a USB port. The Ratnoze has a USB host to read the MicroAeth data stream. The Ratnoze firmware interprets the raw data stream and uses the Beer-Lambert law to calculate the optical absorption coefficient and BC concentration. Separate MicroAeth computer software must be used to configure the MicroAeth flow rate and sampling rate. The Ratnoze configuration parameters **MAC** and **Aeth_dt** must be set correctly to match the MicroAeth configuration settings in order to correctly calculate the BC concentration (see Figure 16).

Since it is a stand-alone instrument, the MicroAeth must be powered on and off separately from the Ratnoze. The MicroAeth filter strips must be changed periodically during sampling. See the MicroAeth manual for instructions on using the MicroAeth and changing the filter strips. The following instructions explain how to use the MicroAeth when it is connected to the Ratnoze.

The MicroAeth is sensitive to ambient light. For this reason, the Ratnoze hood should be kept closed to shield the MicroAeth from ambient light.

7.1 MicroAeth Valve

The Ratnoze has a three-way valve that controls the flow to the MicroAeth (Figure 24). When the MicroAeth is off, the MicroAeth valve should be in the CLOSED position to prevent dilution air from being drawn through the MicroAeth into the Ratnoze. Before the MicroAeth is turned on, the MicroAeth valve must be

in the OPEN position. When the valve is turned to the FILTER CHANGE position, the MicroAeth sample is diverted through a HEPA filter to protect the MicroAeth from PM during filter strip changes.

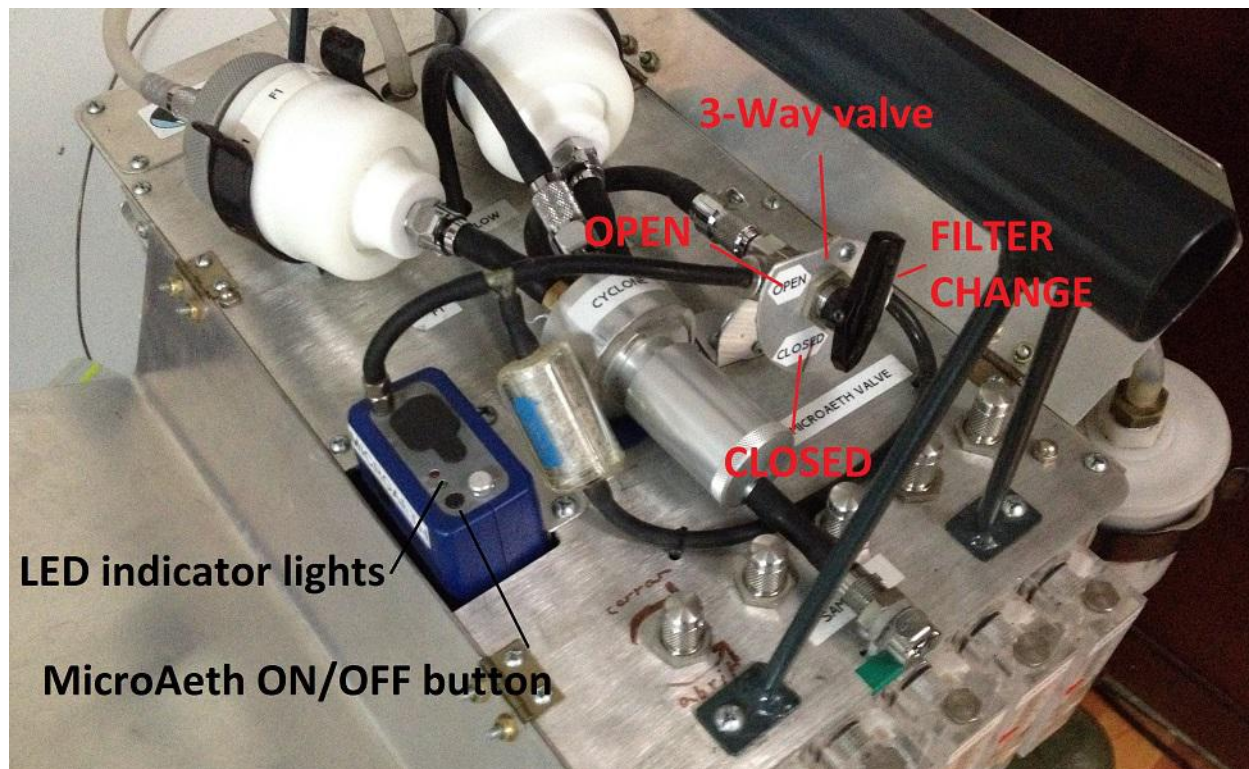


Figure 24: MicroAeth valve in the CLOSED position.

7.2 Powering On

The MicroAeth can be powered on before, during, or after the Ratnoze is powered on. Before turning on the MicroAeth, the MicroAeth valve must be in the OPEN position (Figure 24). To turn on the MicroAeth, press and hold the MicroAeth power button until it beeps. Once the MicroAeth is powered on, it will remain idle up for up to one minute before it starts sending data.

7.3 Powering Off

To turn off the MicroAeth, hold the power button for a few seconds until the MicroAeth beeps. Once the MicroAeth is off, turn the MicroAeth valve to the closed position (Fig 24).

7.4 Data Stream

The MicroAeth data is columns 28-33 of the Ratnoze data stream (see 5.1 Data Stream). If the MicroAeth is off, the Ratnoze data stream will print "0"s for the MicroAeth raw data "nan" for the absorption coefficient. During sampling, the MicroAeth data stream should be monitored periodically.

The AethStat channel prints the MicroAeth error codes. This channel should be 0 to indicate there are no errors. If there is an error, then the error code should be looked up in the MicroAeth manual and resolved. Error code 2 may indicate that the MicroAeth valve was left closed. Error code 4 may indicate that the filter strip needs to be changed, or that the filter strip was installed upside down.

The AethATN channel is the light attenuation through the MicroAeth filter. If AethATN is larger than

60, then the filter should be changed (see 7.5 below).

The MicroAeth has LED indicator lights that are also an indicator of operation status (Figure 24). Under normal operation, the green indicator light should blink. If the red indicator light blinks, then there is an error (Note: The red indicator light will also blink during startup. This is normal). If the MicroAeth is on, but it is not outputting data, and the red indicator light is blinking, then the MicroAeth flash memory might be full, and it must be cleared (see 7.6 below).

7.5 Changing Filter Strips

If AethATN is greater than 60, then the MicroAeth filter strip should be changed. To do this:

7.5.1 Open the Ratnoze hood

7.5.2 Turn the MicroAeth valve to the FILTER CHANGE position

7.5.3 Remove the used filter (see MicroAeth Operating Manual)

7.5.4 Insert new filter (see MicroAeth Operating Manual)

7.5.5 Turn the MicroAeth valve to the OPEN position

7.5.6 Close the Ratnoze hood

7.6 Downloading Data and Clearing Flash Memory

The BC concentration output by the Ratnoze AethBC channel is an approximation calculated in real-time from the raw MicroAeth data stream. For data analysis and reporting, the most accurate value of the BC concentration should be used, which is calculated by the MicroAeth computer software when the MicroAeth data is downloaded after an emission test.

The MicroAeth stops sending data when it's internal memory is full. To avoid this from happening during sampling, the MicroAeth memory should be cleared after the data is downloaded. To download and clear the MicroAeth memory, connect to the MicroAeth using AethLabs software. To do this:

7.6.1 Disconnect the MicroAeth USB cord from the Ratnoze USB host and use the USB extension cord to connect the MicroAeth to the a computer with AethLabs software.

7.6.2 Then open the MicroAeth software and turn on the MicroAeth. Follow the procedure to download the data.

7.6.3 To clear the MicroAeth memory, click “Erase all data” button in the MicroAeth software window. The software will indicate when it finished. Then turn off the MicroAeth and turn it back on again. Look at the data stream to make sure the MicroAeth is working properly.

7.7 Flow Calibration

The MicroAeth has its own internal pump and feedback controller to maintain a constant flow. To adjust the flow rate of the MicroAeth, use the MicroAeth flow calibration software.

To calibrate the flow rate (meaning to calibrate the flow reading, not change the flow rate), follow the procedure described in Section 10.2 to set the span of AethFlow. Do not try to zero AethFlow, because the zero offset is not enabled for AethFlow.

8 Probe

8.1 Probe Components

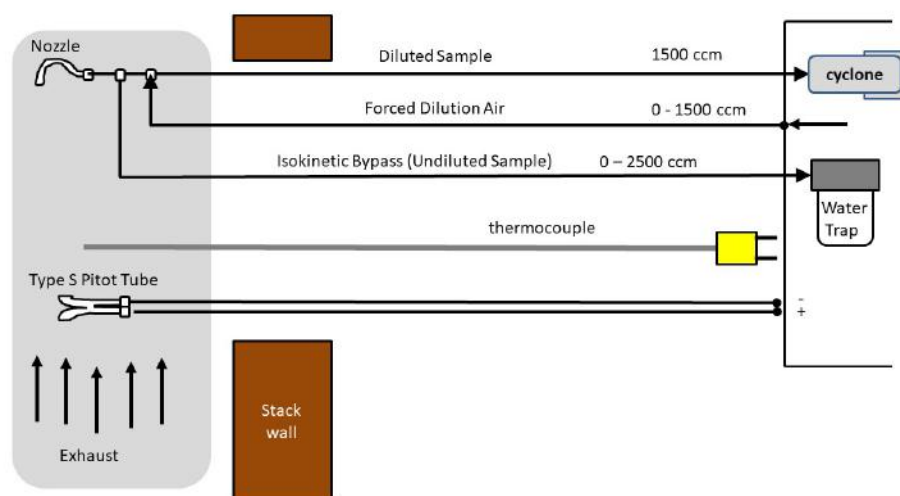


Figure 25: Probe flow schematic.

8.2 Probe Assembly

The probe is made of stainless steel tubing and the sections are assembled together with Swagelok compression fittings. The fittings must be tightened with wrenches in order to seal. The main parts of the probe include the base section (with mounting bracket and connections to soft tubing), one to four probe sections, the head, nozzle, pitot tube, thermocouple, and soft tubing to connect the probe to the sensor box. The shortest probe configuration (with 1 short section) is 0.8 m. With one long section, the probe is 1.25 m long, with two long sections it is 2.12 m long, and with three long sections it is 3.0 m long.

Table 4: Probe kit parts.

Number	Item	Purpose/Note
1	probe nozzle set	ID=3/32", 1/8", 3/16", 1/4"
2	multi-point array nozzle	for open-plume sampling
3	Type S pitot tube	with connectors
4	Probe head	joins nozzle, dilution, and isokinetic tubes
5	long section 1	
6	long section 2	
7	long section 3	
8	short section	
9	base section	mounting bracket and soft tube connections
10	unions	for connecting probe sections
11	spare union	
12	spare Tee	for special probe configurations
13	nozzle caps	
14	3/8"-1/4" reducer	for connecting 1/4" nozzles
15	thermocouple probe	
16	soft tubing for pitot tube	blue
17	soft tubing for dilution	blue
18	soft tubing for sample	black, conductive
19	soft tubing for Isokinetic bypass	black, conductive
20	spare tubing	for special probe configurations
21	wrench set	for probe assembly
22	brushes	probe cleaning kit
23	push rod kit	probe cleaning kit
24	pipe cleaners	probe cleaning kit
25	pull cord	probe cleaning kit
not pictured	tripod	

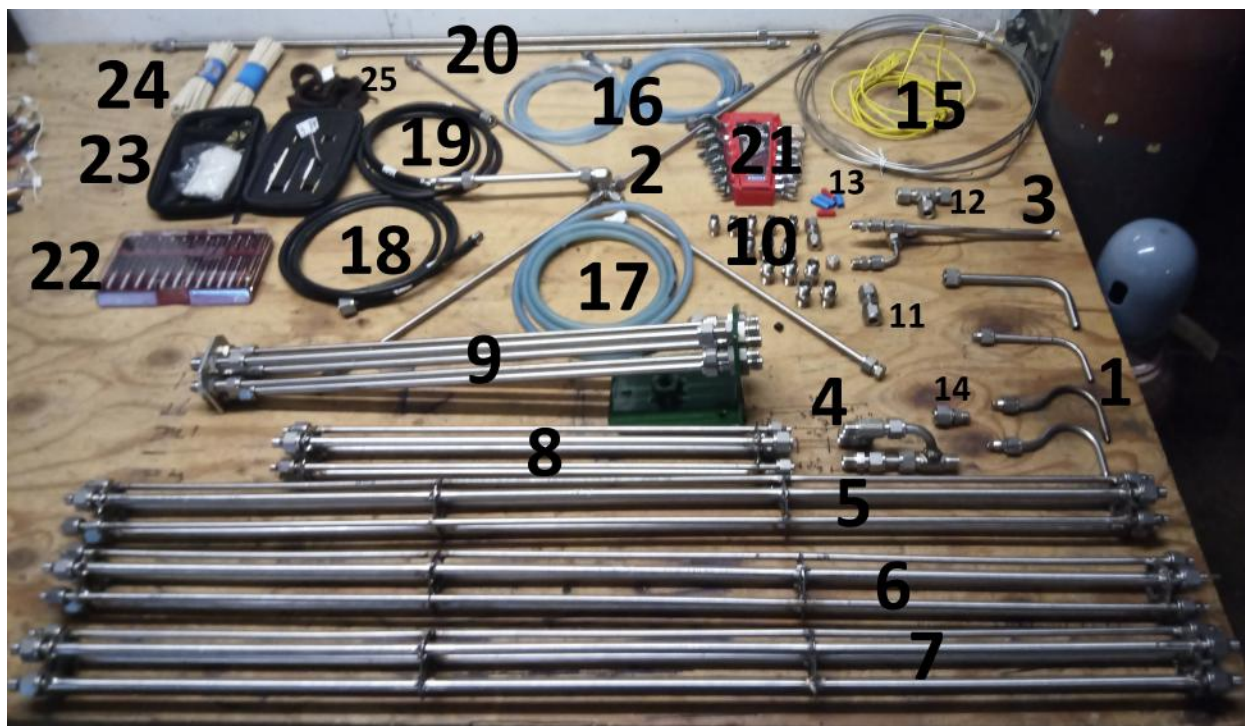


Figure 26: Probe kit parts.

Connect the base section to the tripod. A bolt on the tripod screws into the mounting bracket on the base section.

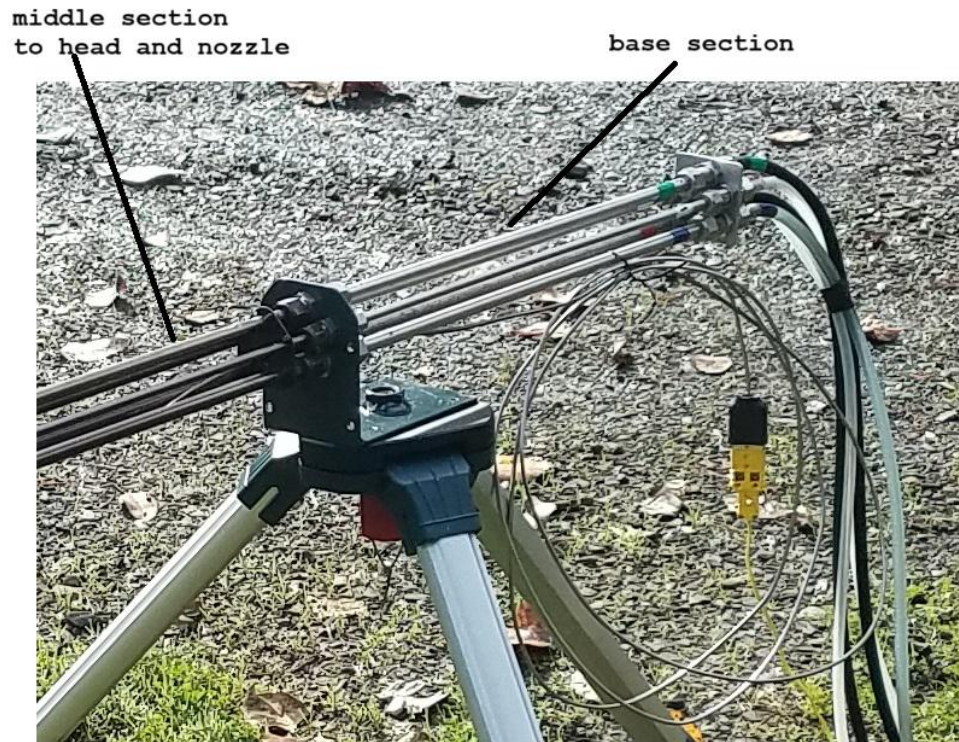


Figure 27: Base section connected to tripod.

Connect one or more probe sections to the base section, starting at the tripod bracket. The tubes are labeled at each joint:

S: sample tube

I: Isokinetic bypass tube

D: dilution tube

+: pitot positive pressure

-: pitot negative pressure

Connect the probe head to the end of the probe section. Then connect the nozzle and pitot tube. Feed the thermocouple through the center holes in the spacer plates.

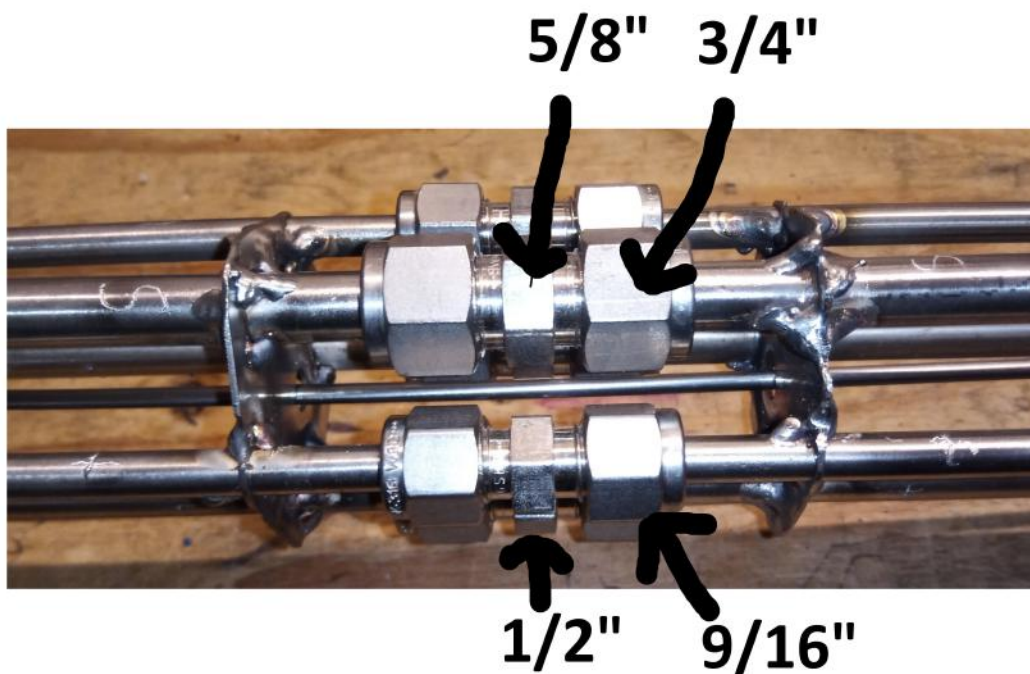


Figure 28: Probe section joint. To tighten the unions, put the 5/8" wrench on the union, and the 11/16" wrench on the nuts at the end of the tubes. For the 1/4" tubes, put the 1/2" wrench on the union and the 9/16" wrench on the nuts at the end of the tubes.

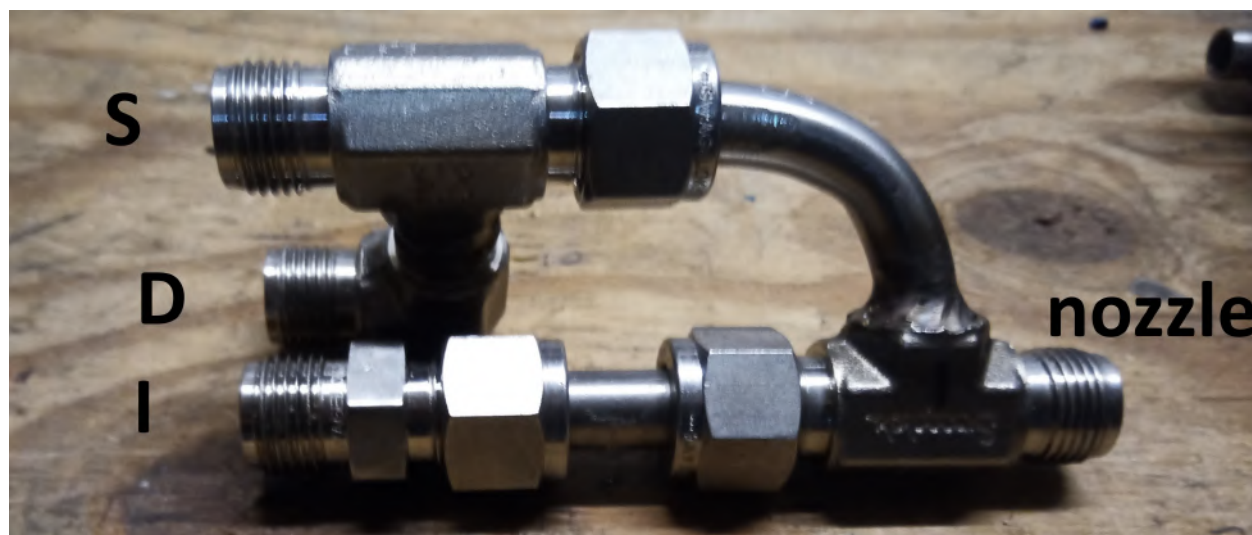


Figure 29: Probe head, showing connections for sample, dilution, isokinetic, and nozzle.



Figure 30: Probe head with nozzle and pitot tube. Positive (+) pitot port opens downward into the flow and negative (-) opens upward towards the sky. Match the + and - marks at the joints.

To attach the multi-point array nozzle for open plume sampling, first connect the four arms to the cross. Point the holes towards the flat side of the cross (away from the elbow). Then attach the elbow to the head section.



Figure 31: When assembling the multi-point array nozzle, point the holes towards the flat side of the cross (away from the elbow), so they point down when installed on the probe.



Figure 32: A multi-point nozzle for cookstoves was added in 2025 with 8 arms of 1/4" tubing, with a total diameter of 12".



Figure 33: Connect the soft tubing to the end of the base section.

8.3 Disassembling the Probe

Disassemble the probe in the reverse order that it was assembled.

9 Routine Procedures

9.1 Leak Check

Leak checks should be performed every sampling event as a quality control measure. Leaks in the sample train can cause erroneous emission measurements by diluting the measured concentrations and causing incorrect flow rates. To leak test the system, a vacuum gauge is used to apply a vacuum pressure (a pressure lower than atmospheric) to the sample train to see if the pressure holds. If the pressure remains constant, then there are no leaks, and the system passes the vacuum test. If the pressure drifts towards atmospheric pressure, then a leak exists, and it must be located and sealed.

In the Ratnoze sensor box, the sample train, dilution train, and isokinetic bypass train can be leak-tested separately. The pumps have a backflow prevention valve and are located at the downstream end of each flow train. Therefore the vacuum gauge can be connected to the inlet of each sample train to test for leaks. However, if the pump backflow valves do not seal, orange caps need to be placed on the outlet ports on the back side of the sensor box in order to perform the leak test. Perform the leak test with the Ratnoze off.

To leak test the sample train, connect the hand-pump vacuum gauge to the sample inlet (cyclone inlet). The MicroAeth does not have a backflow preventer, so the MicroAeth shutoff valve must be closed for the sample train to seal. Pump a vacuum pressure of at least 5 in. Hg. If the needle of the dial gauge remains steady, and does not drop back towards 0, the leak test passes. If the needle of the dial gauge does not remain steady then separate portions of the sample train should be isolated and tested until the leak is identified and fixed.

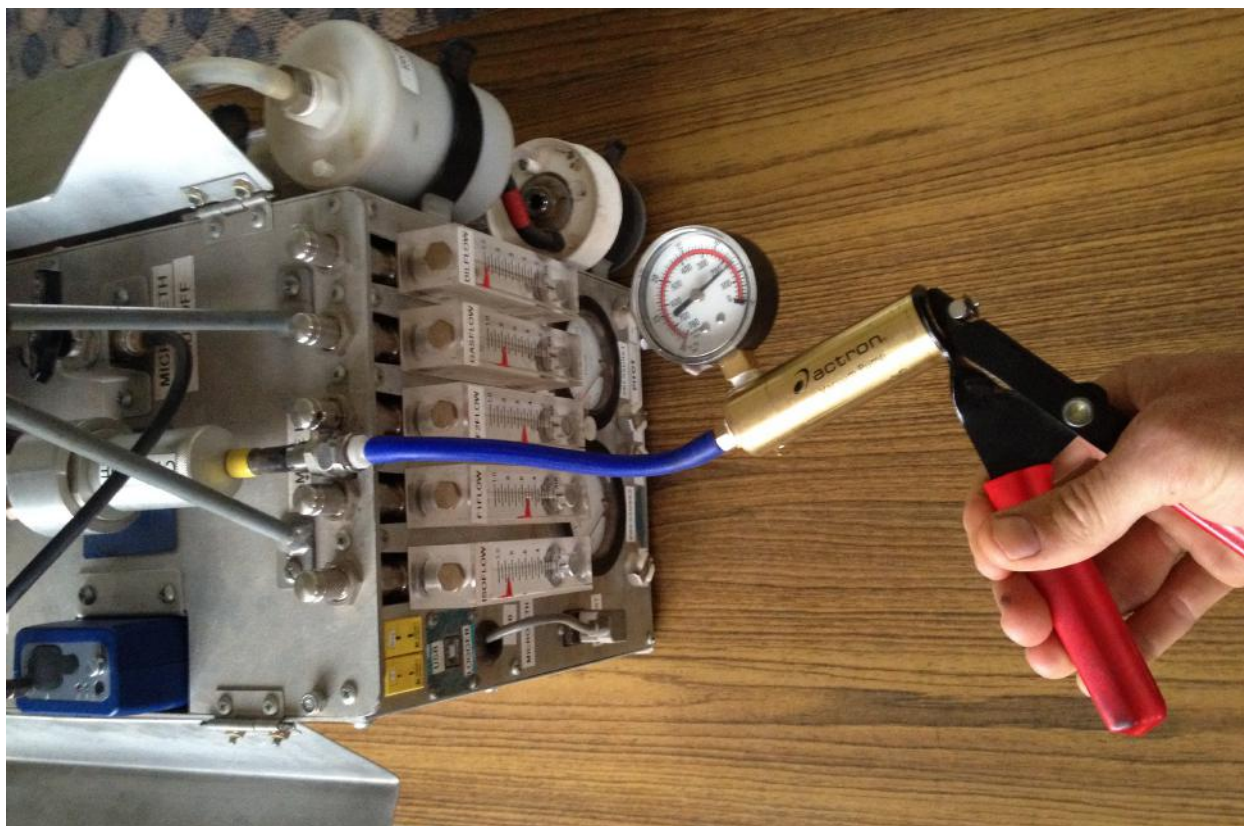


Figure 34: Leak testing the sample train.

To leak test the dilution train connect the hand-pump vacuum gauge to the dilution inlet and repeat the above procedure. Remember to remove the dilution inlet plug before starting, and replace it again when done.



Figure 35: Leak testing the dilution train.

To leak test the isokinetic bypass train connect the hand-pump gauge to the isokinetic bypass inlet and repeat the above procedure.



Figure 36: Leak testing the isokinetic bypass train.

The sample probe and connection tubes should also be leak tested every sampling event. To do this, fully assemble the probe, connect the dilution tube to the isokinetic bypass tube, cap the quick connect fitting of the sample tube (using the orange quick-connect cap), and connect the hand-pump vacuum gauge to the probe nozzle inlet using one of the white bubble meter tubes.



Figure 37: Leak testing the sample probe.

To leak test the pitot tube pressure lines on the probe, start with the positive pressure line and connect the hand-pump vacuum gauge to the pitot tube inlet using one of the white bubble meter tubes. Cap the other end of the line with an orange quick connect cap. Repeat the procedure for the negative pressure line. Do not leak test the pitot line when it is connected to the Ratnoze sensor box because the high vacuum pressure may damage the pressure transducer.



Figure 38: Leak testing the pitot tube lines.

There is a fast and simple way to vacuum test the entire system including the sample train, dilution train, isokinetic bypass train, and sample probe all at once. To do this, connect the probe to the sensor box as you normally would to begin sampling (Figure 8). Then connect the hand-pump vacuum gauge to the probe nozzle inlet using the white bubble meter tube. Turn on the sensor box momentarily to draw a vacuum on the system, then turn off the sensor box and check the needle on the dial gauge of the hand pump. It is also possible to use the hand pump to draw a vacuum pressure on the entire system but it may take a while.

9.2 Setting Flows

The Ratnoze kit has three types of flow measurement devices: rotameters, mass flow sensors, and bubble meter.

9.2.1 Rotameters

The rotameters on the front panel of the sensor box are not very accurate. They provide a visual quality control check that flows are approximately correct. The rotameters have sliding pointer flags that can be

used as reference marks for flow settings.

9.2.2 Mass Flow Sensors

The mass flow sensors inside the sensor box provide a real-time measurement of volumetric flow at standard conditions (20 C, 101325 Pa).

9.2.3 Bubble Meter

The bubble meter is a primary flow calibrator that measures the volumetric flow rate at actual conditions by measuring the time it takes for a soap bubble film to move up through the column. The bubble meter is manufactured by AP Buck, and is supplied with a charger and extra soap. The bubble meter is sensitive to sunlight, and it will usually malfunction in direct sunlight or around other high temperature heat sources.



Figure 39: The bubble meter is not working!

To use the bubble meter:

1. Remove the bubble meter port caps and put them somewhere safe where you won't lose them.
2. Connect the white bubble meter tubes to the bubble meter ports. The flow should go up through the bubble meter column, so the tube with male quick connect fitting should go on the top port, and the tube with the female quick connect should go on the bottom port.

3. Connect the bubble meter tubes to the flow source to create a flow through the bubble meter.
4. The bubble meter won't work correctly until the column walls are wet with a soap film. Depress the dipper repeatedly to create bubbles until the bubbles travel to the top of the column without breaking.
5. Once the column is wet, press the ON button to turn on the bubble meter. Depress the dipper to take a measurement. A bubble will travel up the column and the bubble meter will display the flow reading.
6. If multiple measurements are taken in series, the bubble meter will display a running average of all measurements. Press the ON button to clear the running average in order to take one reading at a time.
7. When done, turn off the bubble meter.
8. When putting the bubble meter away, replace the port caps to prevent soap water from leaking out and evaporating and to prevent dirt and debris from getting inside the column.

Troubleshooting the bubble meter: The bubble meter must contain just the right amount of soap to make a thin pool about 1 mm thick in the bottom of the reservoir. If there is too little soap, bubbles will not form when the dipper is pressed. If there is too much soap, many bubbles will form when the dipper is pressed. This is a problem because excess soap bubbles will get drawn into the Ratnoze sensor box. If the bubble meter seems to be giving inconsistent or incorrect readings, or no readings at all, watch the bubble travel up the column. If no bubbles are forming, the meter may be low on soap, and more should be added. If a uniform bubble forms and travels up the column but does not trip the photosensors, or if the photosensors trip without a bubble passing, then the battery may be low, or there may be interfering sources of infrared radiation nearby. If the bubbles are foamy and numerous then there is probably too much soap, and some soap should be poured out.

9.2.4 Flow Basics

A simplified flow diagram is shown below in Figure 40.

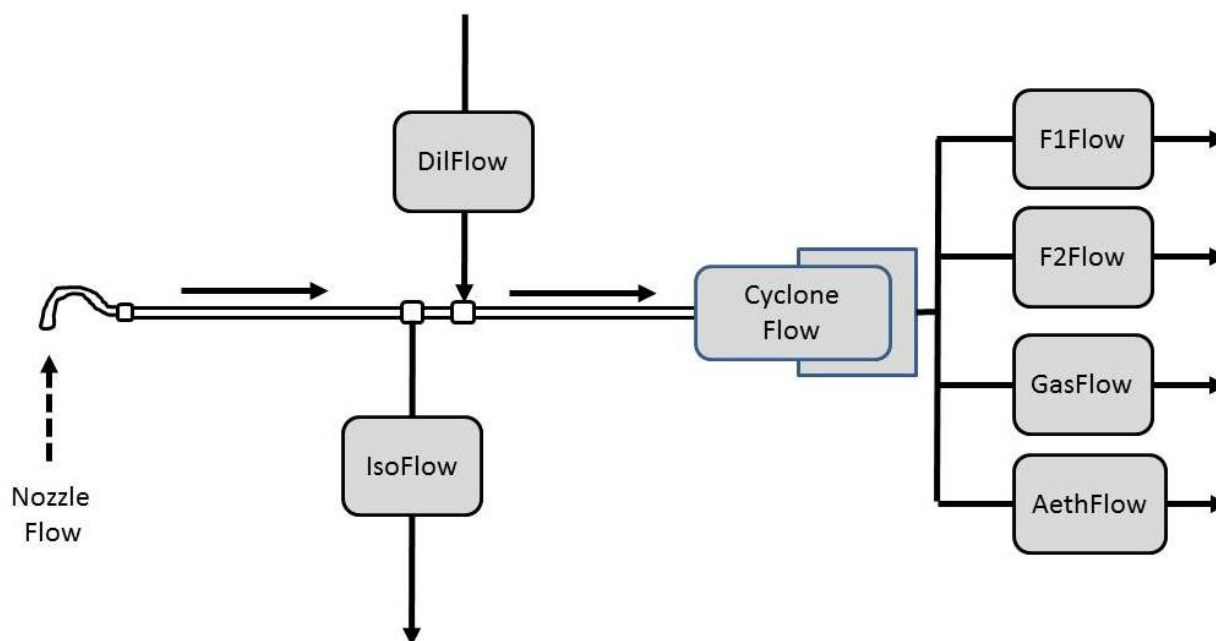


Figure 40: Simplified flow diagram.

$$CycloneFlow = F1Flow + F2Flow + GasFlow + AethFlow \quad (1)$$

$$NozzleFlow = CycloneFlow + IsoFlow - DilFlow \quad (2)$$

$$DilutionRatio = DilFlow / (CycloneFlow - DilFlow) \quad (3)$$

The cyclone flow must be 1500 ccm at actual conditions for a PM2.5 cutpoint. If the cyclone flow differs from 1500 ccm, the cutpoint will change according to the following relationship:

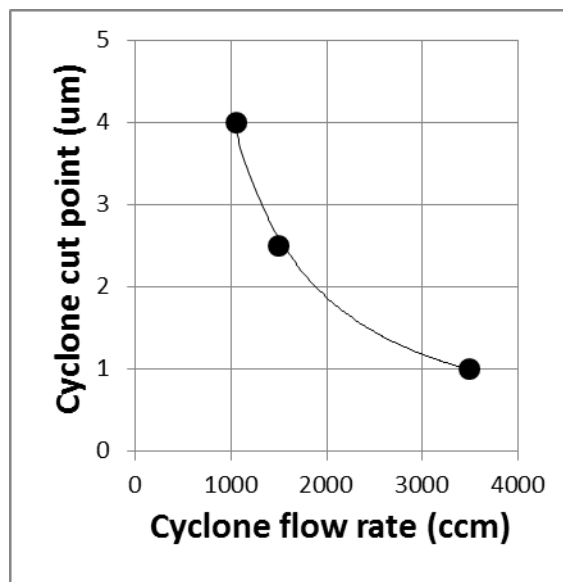


Figure 41: Cyclone cutpoint vs. flow rate. Data points are taken from BGI Triplex cyclone documentation.

Note that the dilution flow (DilFlow) and isokinetic bypass flow (IsoFlow) have no effect on the cyclone flow rate.

9.2.5 Procedure to Set Flows

With the exception of the MicroAeth, all flows are set by adjusting the metering valves (see Figure 1). Set the flows in the following order:

1. MicroAeth Flow (AethFlow): This flow does not need to be set before a sampling event. The MicroAeth automatically maintains a constant flow rate at a pre-programmed set point. If the MicroAeth is going to be used during sampling, then it must be turned on to set the other system flows, otherwise it should remain off with the shutoff valve closed.
2. Filter Flows: The filter flows F1Flow and F2Flow should be set to collect an appropriate amount of PM on the filter for the specific type of filter sample analysis that will be performed. The ideal filter flow rate is a function of the desired PM mass on the filter, the expected average PM concentration, and the sample time. To determine the ideal filter flow rate, use the filter loading calculator on the filter_loading tab of the Stack Sampling Calculator spreadsheet. The sum of F1Flow and F2Flow must be less than 1000 sccm.
3. Gas Sensor Flow (GasFlow): The GasFlow must be set between 500 and 1500 sccm. To set the GasFlow, connect the bubble meter to the cyclone inlet and adjust the GasFlow until the cyclone flow = 1500 ccm. If it is not possible to use the bubble meter, then convert the target cyclone flow of 1500 ccm from actual conditions (actual temp and pressure) to standard conditions (20 C, 101325 Pa) using the Stack Sampling Calculator spreadsheet (Figure 19). Then use equation 1 above to determine the target GasFlow (in sccm) and adjust the GasFlow metering valve accordingly.

4. Dilution Flow (DilFlow): Decide on an appropriate dilution ratio(dilution/sample) between 1 and 20. A value between 10 and 15 is appropriate for most solid fuel combustion sources. Watch the dilution ratio (DilRat channel) and adjust DilFlow until DilRat matches the desired value. If you don't know what the dilution ratio should be, choose a dilution flow that satisfies the following criteria:

$$PM_{scat} < 10000 Mm^{-1}$$

$$SO_2 < 50 ppm$$

$$CO < 500 ppm$$

$$RH < 50\%$$

$$CO_2 > 2000 ppm$$

5. Isokinetic Bypass Flow (IsoFlow): This flow only controls the probe nozzle flow rate and has no effect on the cyclone flow or the dilution ratio. Start the sampling event with IsoFlow off (0 ccm). Once the pitot tube is in place in the stack and the nozzle thermocouple is connected to get a stack velocity measurement, increase IsoFlow until the probe nozzle velocity (NozVel) = stack velocity (StakVel).

9.3 Cleaning

The following components should be cleaned after every sampling event. The Ratnoze kit includes several cleaning supplies such as Kimwipes, organic solvent, baking soda, toothbrush, pipe cleaners, and gun cleaning kit (push rod with brushes). There are two sets of push rods in the probe case. One is a small diameter for 1/4" OD tubing, and one is a large diameter for 3/8" OD tubing. A variety of brushes and cleaning tips are in a small white box inside the probe case.

9.3.1 Probe Cleaning

Protective gloves should be worn when handling the probe to protect your skin from soot and hazardous compounds such as sulfuric acid. First wipe the outside of the probe down with a rag wetted with a baking soda solution or acetone (other organic solvents are also acceptable).



Figure 42: Cleaning the outside of the probe. You can use a tea cup from your hotel to mix the baking soda. The toothbrush will get nasty, so borrow your friend's instead of using your own.

Disassemble the probe into sections (See Section 8). Blow the soft tubing out with compressed air. **DO NOT PUT ACETONE ON THE SOFT TUBING.** Rinse the inside of each metal tube with acetone by squirting acetone into the tube with a squirt bottle. Follow with the pull cord (Boresnake) or use the push rod with a brush. Then blow the tube out with compressed air. The dilution and pitot tube lines should not need to be cleaned, but they can be blown out with compressed air. To clean the probe head, nozzle, and pitot tube tip, rinse all tubes with acetone, then use a brush, then blow out with compressed air.

9.3.2 Sample Train Cleaning

After removing the sample filters from the filter holders, wipe the inside of the filter holders with a Kimwipe and acetone. Do not get acetone on the o-ring. Once the filter holders are removed, slide apart the cyclone. Do not use organic solvent on the cyclone, only water.



Figure 43: Slide the cyclone body apart from the inlet cap.

Wipe the inside of cyclone inlet cap with a damp Kimwipe (Figure 44). Unscrew the cyclone pot and clean it out with a damp Q-tip or twisted Kimwipe. Unscrew the next piece and wipe all surfaces with Kimwipe where particles have accumulated. Use a very soft brush or pipe cleaner to clean the inlet hole. Then reassemble the cyclone.

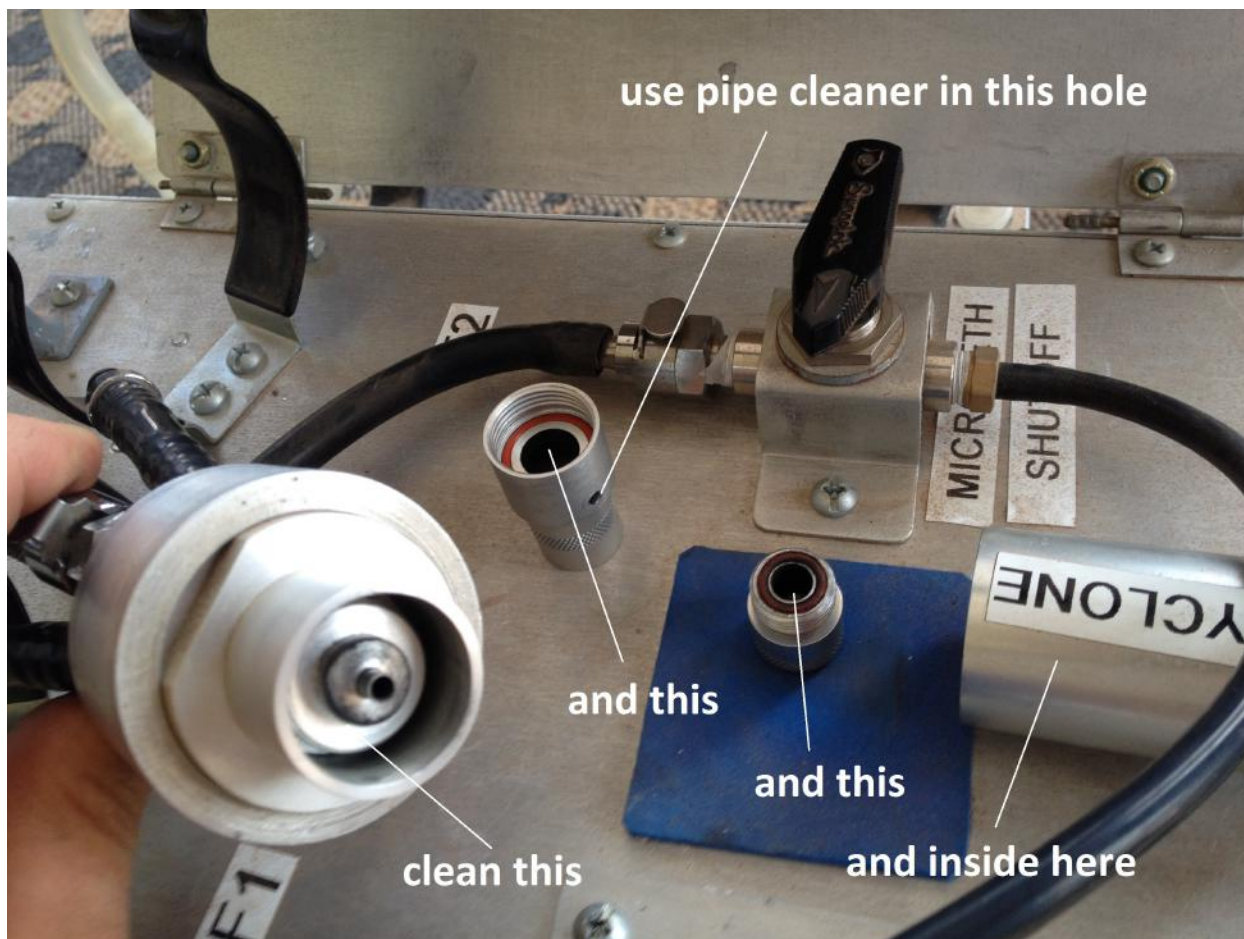


Figure 44: Unscrew the pot, then that other piece, and wipe everything down.

After heavy use the cyclone outlet cap can be removed and blown out with compressed air (Figure 45). The MicroAeth tube can be disconnected from the MicroAeth and also blown out with compressed air. Do not blow compressed air into the GasFlow tube unless it is disconnected from inside the sensor box.



Figure 45: The cyclone outlet cap can be removed from the cyclone. Be aware of the alignment and tube connections when putting it back together.

9.3.3 Isokinetic Bypass Train Cleaning

Pull the water trap out of the holder clips, unscrew the lid, and dump the water. Wipe out the water trap with a Kimwipe. After heavy use, disconnect the black tube that connects to the HEPA filter and blow the tube out with compressed air.



Figure 46: Dump the water trap.

9.4 Changing Desiccant

The desiccant material is color-changing silica gel. It is orange when dry, and blueish green when saturated. When a desiccant chamber is fully saturated, remove the chamber from the holder clips and disconnect the quick-connect fittings.



Figure 47: Removing the desiccant chamber.

Open the desiccant chamber lid. There are special tools for this in the accessory kit if the lid is too tight to remove with your bare hands. Remove the spring and plate. Dump out the old desiccant and refill the chamber to the same height with new desiccant. Then replace the spring and plate. Regenerate the old desiccant in an oven at 100 C. When reconnecting the dilution desiccant chamber, make sure the rear tube does not kink when the chamber is mounted into the holders.



Figure 48: Removing the desiccant.

9.5 Loading Filters

Follow your own desired protocol for handling filters. The kit includes tweezers.

10 Calibration

All Ratnoze sensors have a linear output which can be calibrated with a 2 point (zero and span) calibration.

10.1 Gas Sensor Calibration

The gas sensors should be calibrated before and after a set of emission measurements. The CO₂ sensors are NDIR and have an internal reference detector correction. They are expected to exhibit relatively low drift. The electrochemical sensors (CO, SO₂, NO, NO₂, O₂) are known to fade over time as a function of ppm-hours of exposure to the target gas as well as other interfering gases. They must be recalibrated on a regular basis to correct for this drift, and as a quality control check to ensure the sensors are functioning properly.

Recommended calibration gases:

Zero gas: Ultra-pure zero air (with 0 ppm of CO, CO₂, SO₂, NO, NO₂).

CO₂ span gas: 20000 ppm CO₂, balance air.

CO span gas: 500 ppm CO, balance air.
SO₂ span gas: 100 ppm SO₂, balance air.
NO span gas: 50 ppm NO, balance N₂.
NO₂ span gas: 15 ppm NO₂, balance air.
O₂ span gas: ambient air.

The balance gas in each gas mixture should be air (N₂ and O₂) as opposed to pure N₂, except for the NO span gas, which requires a balance gas of N₂ for stability.

All recommended span gases (except CO₂ span gas) are hazardous and/or toxic to health. The calibration must be performed with the sensor box placed in a fume hood that safely vents all exhaust gases out of the working area to a harmless location.

All sensors exhibit cross-sensitivity to gases other than the target gas. Therefore, it is recommended to use span gases that contain only one target gas, and to calibrate one sensor at a time, in order to observe the cross-sensitivity of each target gas on all sensors. By measuring cross-sensitivities in this way, a formula can be developed for each sensor to correct for interfering gases.

Some electrochemical sensors exhibit cross-sensitivity to moisture (typically 1 ppm or less). This effect can be observed as a baseline shift when the sensors are exposed to ambient air and then switched to dry zero air. For most accurate results, the sensors can be calibrated with the dry calibration gases specified above, and then later zeroed in ambient air (which contains moisture).

The gas sensors have a T90 response time of 30 - 120 seconds. However, the response time of the sensors installed in the Ratnoze system is longer due to the residence time of sample train. It is recommended to expose the sensors to calibration gas for 5 - 10 minutes to ensure a full response when calibrating. Each sensor calibration should consume 10 - 20 liters (at standard conditions) of each calibration gas.

10.1.1 Calibration Preparation:

1. Place the Ratnoze sensor box in a well ventilated fume hood.
2. Perform a leak test on the sample train and dilution train.
3. Power on the sensor box, connect to the computer, and warm up for at least 15 minutes.
4. Set the following flows:

GasFlow: 1000 ccm
DilFlow: 1000 ccm
IsoFlow: 1000 ccm
F1Flow and F2Flow are not used during the calibration.

5. Connect the Ratnoze gas calibrate tube:

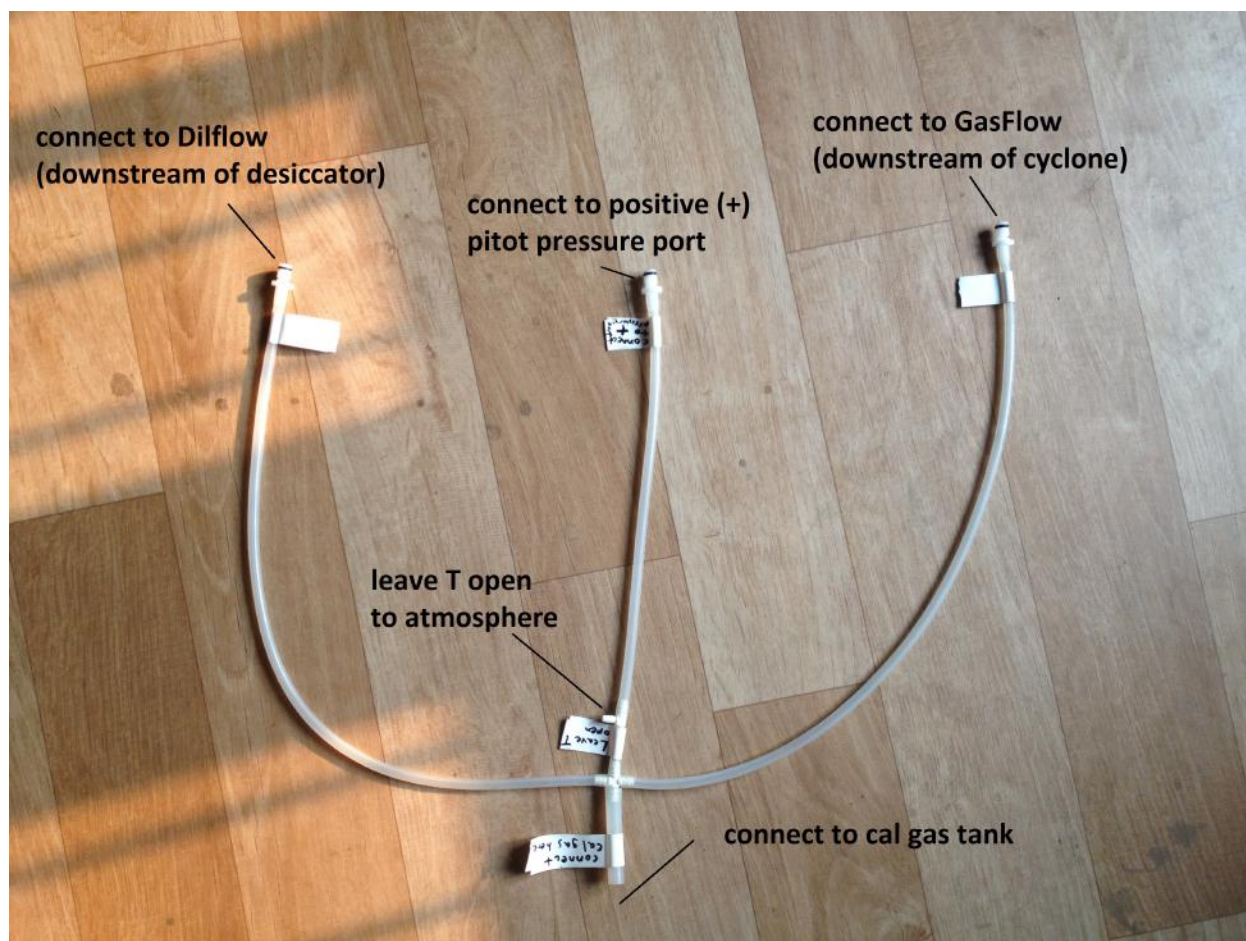


Figure 49: Gas calibration tube.

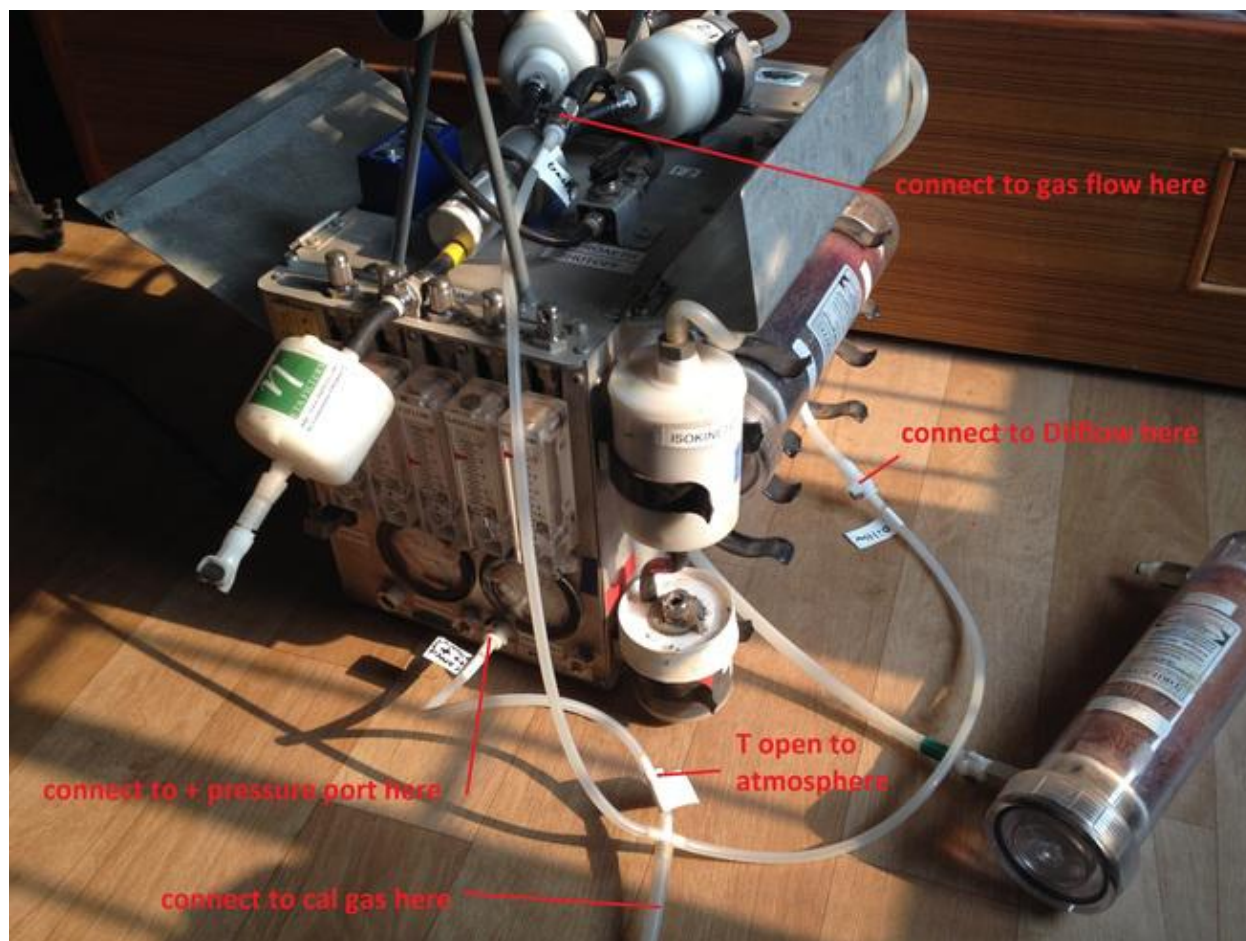


Figure 50: Gas calibration tube connection for CO₂, CO, and SO₂ calibration. The gas calibration tube has three branches. One branch has a T open to the atmosphere. Connect this branch to the pitot + port. Connect the other branches to the GasFlow flow checkpoint (between the filter holders) and to the dilution train just downstream of the dilution desiccator (first remove the dilution desiccator).

10.1.2 Zero Point Calibration for CO₂, CO, and SO₂

1. Connect the Ratnoze gas calibration tube to the calibration gas when the calibration gas flow is 0 (off). The sensor box will be drawing 2000 ccm in from the T that is open to ambient. The pressure gauge will read slightly negative.
2. Turn the zero gas flow on to about 2500 ccm. The GasFlow will be drawing 1000 ccm, the Dilflow will be drawing 1000 ccm, and about 500 ccm excess cal gas will exhaust out the T open to atmosphere. Make sure the pressure gauge is slightly positive to ensure that no ambient air is drawn in the T.
3. Sample zero gas for 10-15 minutes or until the sensor concentrations are stable.
4. Perform a zero point calibration for the background and sample sensors using the Ratnoze plotter software (See Section 4.1). Capture a reading, select the bkg and sample channels to zero, then click calibrate.
5. When the parameters have been updated, turn off the cal gas.

10.1.3 Span Point Calibration for CO₂, CO, and SO₂

Repeat the above procedure in 10.1.2 with span gas instead of zero gas and perform the span calibration using the Ratnoze plotter software. Capture a reading, select the bkg and sample channels to calibrate, enter the reference value in the appropriate boxes, and then click calibrate. When the parameters have been updated, turn off the cal gas.

Repeat the zero and span calibration procedure (10.1.2 and 10.1.3) for each gas sensor (CO₂, CO, and SO₂).

10.1.4 Zero Point Calibration for NO and NO₂

This procedure is similar to 10.1.2, except the calibration gas is exposed to only the sample sensors, and not the background sensors. Disconnect the calibration gas tube from the dilution sample train, and put an orange cap to block the flow of the dilution branch of the gas calibration tube.

1. Connect the Ratnoze gas calibration tube to the calibration gas when the calibration gas flow is 0 (off). The sensor box will be drawing 1000 ccm in from the T that is open to ambient. The pressure gauge will read slightly negative.
2. Turn the zero gas flow on to about 1500 ccm. The GasFlow will be drawing 1000 ccm, and about 500 ccm excess cal gas will exhaust out the T open to atmosphere. Make sure the pressure gauge is slightly positive to ensure that no ambient air is drawn in the T.
3. Sample zero gas for 10-15 minutes or until the sensor concentrations are stable.
4. Perform a zero point calibration for the sensor using the Ratnoze plotter software (See Section 4.1). Capture a reading, select the channel to zero, then click calibrate.
5. When the parameters have been updated, turn off the cal gas.

10.1.5 Span Point Calibration for NO and NO₂

Repeat the above procedure in 10.1.4 with span gas instead of zero gas and perform the span calibration using the Ratnoze plotter software. Capture a reading, select the channel to calibrate, enter the reference value in the appropriate box, and then click calibrate. When the parameters have been updated, turn off the cal gas.

Perform the zero and span calibration procedure (10.1.4 and 10.1.5) for NO and NO₂.

10.1.6 Zero Point Calibration for O₂

The O₂ sensor does not require a zero point calibration, only a span calibration.

10.1.7 Span Point Calibration for O₂

Ambient air (approximately 21% O₂) can be used as a span gas to calibrate the O₂ sensor. The gas calibration tube is not needed.

1. Sample ambient air for 10-15 minutes.
2. Perform a span point calibration for the O₂ sensor using the Ratnoze plotter software (See Section 4.1). Capture a reading, enter 21 in the reference box, check the span box for the O₂ channel, then click calibrate.

When the calibration is finished, let the sensor run for at least 15 minutes to clear the sample train of calibration gas before powering off.

10.2 Flow Sensor Calibration

The flow sensor calibration should be performed before and after a set of emission measurements. The calibration is done using the bubble meter with Stack Sampling Calculator spreadsheet.

10.2.1 Zero Calibration:

1. Do the calibration in a clean indoor environment.
2. Perform a leak test on the sample train and dilution train.
3. Power on the sensor box, connect to the computer, and warm up for at least 15 minutes.
4. Use the Kestrel weather meter to measure the ambient barometric pressure and record the value.
5. Set all flows to 0 sccm by closing the metering valve for each flow (IsoFlow, F1Flow, F2Flow, GasFlow, DilFlow).
6. Perform a zero point calibration for these five flow sensors using the Ratnoze plotter software (See Section 4.1). Capture a reading, select the five channels to zero, then click calibrate.

10.2.2 Span Calibration:

1. Adjust the metering valves to set the flows to the following approximate flow rates:

Isoflow: 500 sccm
F1Flow: 500 sccm
F2Flow: 500 sccm
GasFlow: 1000 sccm
DilFlow: 1000 sccm

2. Start with IsoFlow: Connect the bubble meter to the IsoFlow inlet (water trap). Read the flow with the bubble meter. Take an average of a few readings.
3. Capture an IsoFlow reading with the plotter software to lock a reading. The Value box will turn yellow.
4. The bubble meter measures volumetric flow at actual conditions. This reading must be converted to volumetric flow at standard conditions using the Stack Sampling Calculator. Use the flow_conversion tab and use the column titled "actual to standard conditions". Enter the bubble meter reading in the **Flow** cell. Enter the barometric pressure in the **Pact** cell (remember to enter it in units of Pa and not hPa). Enter the sample temperature in the **Tact** cell. Make sure Pstd is 101325 and Tstd is 20. The corrected flow is in the orange cell called **Flow TPcorr** (Cell G12).

Stack_Sampling_Calculator.xls - Gnumeric

File Edit View Insert Format Tools Statistics Data Help

Sans 10

F15

	A	B	C	D	E	F	G	H	I	J	K
1		standard to actual conditions				actual to standard conditions					
2		Flow	25	sccm		Flow	487	ccm			
3		Pact	87300	Pa		Pact	99200	Pa	enter input values in green cells		
4		Tact	25	C		Tact	30	C			
5		Pstd	101325	Pa		Pstd	101325	Pa			
6		Tstd	20	C		Tstd	20	C			
7		T corr Factor	1.01706	-		T corr Factor	0.96700	-			
8		P corr Factor	1.16065	-		P corr Factor	0.97903	-			
9		TP Corr Factor	1.18046	-		TP Corr Factor	0.94672	-			
10		Flow Tcorr	25.4266	ccm		Flow Tcorr	470.927	ccm			
11		Flow Pcorr	29.0163	ccm		Flow Pcorr	476.787	ccm			
12		Flow TPCorr	29.5115	ccm		Flow TPCorr	461.051	sccm			
13											
14											
15											
16											

traverse points flow_conversion Sum = 0

Figure 51: Convert the bubble meter reading (ccm) to standard conditions (sccm).

- Go back to the Ratnoze plotter software and enter the corrected flow value (in sccm) into the IsoFlow Reference reading box. Check the span calibration but do not click calibrate yet. Wait until the values are set for all flow sensors before clicking the calibrate button.
- Repeat steps 2-4 for the other flow sensors. For F1Flow and F2Flow, the bubble meter should be connected inline to the flow train on the filter outlets. For GasFlow, the bubble meter should be connected at the cyclone outlet. For Dilflow the bubble meter should be connected to the dilution inlet (remove the inlet cap).
- The MicroAeth flow (AethFlow) does not need to be calibrated on a regular basis, but it can be span calibrated following this same procedure in steps 2-4. Connect the bubble meter inline at the AethFlow check point next to the shutoff valve.
- Once a reference value is entered in the Reference box and the span calibration box is checked for each flow, click the calibrate button.

10.3 PM Sensor Calibration

The PM sensor should not need to be calibrated on a regular basis. If desired, the PM sensor can be zeroed on-site before a sampling event. To zero the PM sensor, connect the HEPA filter to the sample inlet of the sensor box and zero the sensor using the Ratnoze plotter software. The span calibration is performed by sampling a constant concentration of smoke with the Ratnoze and a reference meter at the same time.

10.4 Thermocouple Calibration

The thermocouple does not need to be calibrated on a regular basis. A zero point calibration can be performed by placing the thermocouple in an ice bath. A span point calibration can be performed by placing the thermocouple in boiling water.

10.5 Sample and Background Temperature Calibration

The sample and background temperature sensors do not need to be calibrated on a regular bases. They are located inside the sensor box in the gas sensor chamber. Contact Mountain Air Engineering for instructions for accessing and calibrating the temperature sensors.

10.6 Humidity Sensor Calibration

The humidity sensor should not need to be calibrated on a regular basis. The sensor is located in the PM sensor chamber in the GasFlow sample train. The calibration can be checked by sampling dry desiccated air and steam. Dry air should read about 10 %RH and steam should read at least 80 % RH. The sensor will take few minutes for a full response.

10.7 Differential Pressure Sensor Calibration (Pitot)

The differential pressure sensor should be zeroed on-site prior to every sampling event. The span calibration annually.

10.7.1 Zero Calibration

To zero the sensor, connect the special zeroing tube to the pressure ports to equalize the pressure. Then perform the zero point calibration using the Ratnoze plotter software.



Figure 52: Connect this tube to equalize the pressure ports before zeroing.

10.7.2 Span Calibration

Calibrate the span against a standard reference manometer of the same range (0 - 250 Pa = 0 - 1 inches H₂O).

10.8 Ambient Pressure Sensor Calibration (Pamb)

The ambient pressure sensor calibration is recommended annually. The calibration is performed by comparing the sensor output to a reference sensor (Kestrel weather meter supplied in the accessory kit) at two pressure points that approximate the minimum and maximum range of operating conditions. There are two methods to obtaining a high and low pressure measurement.

One method is to physically transport the Ratnoze to low and high elevation and take a pressure reading with the Ratnoze and Kestrel at the same time. The low elevation location should be at or near sea level. The high elevation location should be at the highest mountain top that it is practical to travel to.

Another method is to simulate high and low ambient pressure in the laboratory. The Kestrel reference meter can be put inside a sealed pressure chamber, and this chamber can be connected to the ambient pressure port inside the Ratnoze. The pressure in the chamber can be varied using a vacuum pump. Contact Mountain Air Engineering for more detailed instructions about the experimental setup, and how to calculate A and B calibration constants.

A Appendix: Example Data Sheet

Ratnoze Kiln Data Sheet

Date		
Time		
Technician		
Computer		
Site		
Event		
Probe		
Nozzle #		
Nozzle Diam. (mm)		
Fuel		

Holder #		Filter ID
	F1	Stage 1
		Stage 2
	F2	Stage 1
		Stage 2

Initial Conditions							
	AethFlow	IsoFlow	F1Flow	F2Flow	GasFlow	DilFlow	Cyclone
Sensor (sccm)							
Bubble (ccm)							
Dilution Ratio		Ambient Temperature (C)				Ambient RH (%)	
Stack Velocity (m/s)		Ambient Pressure (hPa)					

Final Conditions							
	AethFlow	IsoFlow	F1Flow	F2Flow	GasFlow	DiIFlow	Cyclone
Sensor (sccm)							
Bubble (ccm)							
Dilution Ratio		Ambient Temperature (C)				Ambient RH (%)	
Stack Velocity (m/s)		Ambient Pressure (hPa)					

Time	Pre-background		Sample Period		Post-background	
	start	stop	start	stop	start	stop

[illegible]

Make dimensional drawing of stack cross-section and sample points on back side

B Appendix: Firmware Calculations

These calculations are for firmware version: ratnoze1.46.ino. In the following calculations, the variable x_{raw} represents the raw sensor reading for channel x . The variables A_x and B_x represent the A and B constant parameters for channel x which are stored in the EEMEM and printed in the file header. A_x is the span calibration parameter for channel x . B_x is the offset calibration parameter for channel x . Four additional constants (Cpitot, MolWt, NozDiam, MSC, MAC, Aeth_dt) are also stored in the EEMEM and printed in the file header, which are used to calculate the StakVel, NozVel, PMmass, and AethBC channels).

1. time: date and time [yyyymmdd hh:mm:ss]
2. seconds: seconds elapsed since logging loop started [sec]
3. headID: header ID code [-] for software to identify the data stream without seeing the header
4. CO: sample carbon monoxide [ppm]

$$CO = A_{CO} * (CO_{raw} + B_{CO}) \quad (4)$$

5. CObkg: background carbon monoxide measured in the dilution train [ppm]

$$CO_{bkg} = A_{CO_{bkg}} * (CO_{bkg_{raw}} + B_{CO_{bkg}}) \quad (5)$$

6. CO2: sample carbon dioxide [ppm]

$$CO_2 = A_{CO_2} * (CO_{2_{raw}} + B_{CO_2}) \quad (6)$$

7. CO2bkg: background carbon dioxide measured in the dilution train [ppm]

$$SO_2 = A_{SO_2} * (SO_{2_{raw}} + B_{SO_2}) \quad (7)$$

8. SO2: sample sulfur dioxide [ppm]

$$SO_2 = A_{SO_2} * (SO_{2_{raw}} + B_{SO_2}) \quad (8)$$

9. SO2bkg: background sulfur dioxide measured in the dilution train [ppm]

$$SO_{2bkg} = A_{SO_{2bkg}} * (SO_{2bkg_{raw}} + B_{SO_{2bkg}}) \quad (9)$$

10. NO: sample nitric oxide [ppm]

$$NO = A_{NO} * (NO_{raw} + B_{NO}) \quad (10)$$

11. NO2: sample nitrogen dioxide [ppm]

$$NO_2 = A_{NO_2} * (NO_{2_{raw}} + B_{NO_2}) \quad (11)$$

12. O2: oxygen measured in the undiluted sample train [ppm]

$$O_2 = A_{O_2} * (O_{2_{raw}} + B_{O_2}) \quad (12)$$

13. PM: particulate matter optical scattering coefficient [Mm^{-1}]

$$PM = A_{PM} * (PM_{raw} + B_{PM}) \quad (13)$$

14. IsoFlow: Isokinetic bypass flow rate [sccm]

$$IsoFlow = A_{IsoFlow} * (IsoFlow_{raw} + B_{IsoFlow}) \quad (14)$$

15. F1Flow: Filter 1 flow rate [sccm]

$$F1Flow = A_{F1Flow} * (F1Flow_{raw} + B_{F1Flow}) \quad (15)$$

16. F2Flow: Filter 2 flow rate [sccm]

$$F2Flow = A_{F2Flow} * (F2Flow_{raw} + B_{F2Flow}) \quad (16)$$

17. GasFlow: gas sensor flow rate [sccm]

$$GasFlow = A_{GasFlow} * (GasFlow_{raw} + B_{GasFlow}) \quad (17)$$

18. DilFlow: dilution flow rate [sccm]

$$DilFlow = A_{DilFlow} * (DilFlow_{raw} + B_{DilFlow}) \quad (18)$$

19. Pres1: pitot tube differential pressure [Pa]

$$Pres1 = A_{Pres1} * (Pres1_{raw} + B_{Pres1}) \quad (19)$$

20. Pamb: absolute ambient pressure [Pa]

$$Pamb = A_{Pamb} * (Pamb_{raw} + B_{Pamb}) \quad (20)$$

21. RH: relative humidity [%]

$$RH = A_{RH} * (RH_{raw} + B_{RH}) \quad (21)$$

22. Tsamp: sample temperature measured at gas sensors [C]

$$Tsamp = A_{Tsamp} * (Tsamp_{raw} + B_{Tsamp}) \quad (22)$$

23. Tbk: background temperature measured at the background gas sensors [C]

$$Tbk = A_{Tbk} * (Tbk_{raw} + B_{Tbk}) \quad (23)$$

24. TCnoz: nozzle temperature [C]

$$TCnoz = A_{TCnoz} * (TCnoz_{raw} + B_{TCnoz}) \quad (24)$$

25. TC2: auxiliary thermocouple [C]

$$TC2 = A_{TC2} * (TC2_{raw} + B_{TC2}) \quad (25)$$

26. Batt: battery voltage [V]

$$Batt = A_{Batt} * (Batt_{raw} + B_{Batt}) \quad (26)$$

27. StakVel: stack velocity [m/s]

$$StakVel = C_{pitot} * K_p * \sqrt{\frac{Pres1 * TCnoz}{Pamb * MolWt}} \quad (27)$$

C_{pitot} = pitot tube calibration coefficient [-]

K_p = pitot constant = $\sqrt{2 * 8.314 * 1000} = 129 [(\frac{m^3 * Pa * g}{mol * K * kg})^{\frac{1}{2}}]$

$MolWt$ = stack gas molecular weight [$\frac{g}{mol}$]

28. NozVel: nozzle inlet velocity [m/s]

$$NozVel = \frac{(F1Flow + F2Flow + GasFlow + AethFlow + IsoFlow - DilFlow) * \frac{101325}{Pamb} * \frac{TCnoz + 273}{293}}{60 * \frac{\pi * NozDiam^2}{4}} \quad (28)$$

$NozDiam$ = nozzle diameter [mm]

29. PMmass: integrated PM mass on F1 filter [ug]

$$PMmass = \frac{PM * F1Flow}{MSC * 60000000} + PMmass_{previous} \quad (29)$$

MSC = mass scattering cross section [$\frac{m^2}{g}$]

60000000 = conversion factor [$\frac{cm^3 * sec}{m^3 * min}$]

30. DilRat: dilution ratio [-]

$$DilRat = \frac{DilFlow}{F1Flow + F2Flow + GasFlow + AethFlow - DilFlow} \quad (30)$$

31. AethRef: MicroAeth reference signal [-]

32. AethSen1: MicroAeth sensor 1 signal [-]

33. AethSen2: MicroAeth sensor 2 signal [-]

34. AethFlow: MicroAeth flow rate [sccm]

$$AethFlow = A_{AethFlow} * AethFlow_{raw} \quad (31)$$

$AethFlow_{raw}$ = MicroAeth flow signal [sccm]

35. AethStat: MicroAeth status code [-]

36. AethATN: MicroAeth attenuation [-]

$$AethATN = 100 * \ln \frac{AethRef}{AethSen1} \quad (32)$$

37. AethBC: PM black carbon concentration [ug/m³]

$$AethBC = -\ln\left(\frac{AethSen1_{current} * AethRef_{previous}}{AethSen1_{previous} * AethRef_{current}}\right) * \frac{424115008}{AethFlow_{current} * Aeth_dt * MAC} \quad (33)$$

424115008 = $A_{spot}[m^2] * 60[\frac{sec}{min}] * 10^6[\frac{cm^3}{m^3}] * 10^6[\frac{m}{Mm}]$

A_{spot} = spot size = $\frac{\pi * 0.003^2}{4} = 7.06858 * 10^{-6}[m^2]$

Aeth_dt = time step (MicroAeth sampling rate) [sec]

MAC = mass absorption cross-section [m^2/g]

38. USB_stat: USB host status code [-]

C Appendix: Data Processing

The CO2 sensor calibration is pressure dependent. If the sensor is used at a different pressure than it was calibrated, then a pressure correction is required to the CO2 data when post-processing the data.

$$CO2_{corr} = CO2 * \frac{P_{cal}}{P_{amb}} \quad (34)$$

$CO2_{corr}$ = pressure-corrected CO2 concentration

$CO2$ = measured CO2 concentration

P_{cal} = atmospheric pressure during calibration = 87000 Pa for factory calibration

P_{amb} = atmospheric pressure during emission test measured by Pamb channel

The SO2 sensor has a cross-sensitivity to CO. The SO2 data should be corrected for this cross-sensitivity

when post-processing the data. A cross-sensitivity correction factor can be measured during gas sensor calibration.

$$SO2_{corr} = SO2 - CO * CF_{SO2-CO} \quad (35)$$

$SO2_{corr}$ = corrected SO2 concentration

$SO2$ = measured SO2 concentration

CO = measured CO concentration

CF_{SO2-CO} = cross-sensitivity correction factor of SO2 from CO = 0.10 from factory calibration, meaning the SO2 sensor has a 10% response to CO