DRI STANDARD OPERATING PROCEDURE

Performance Audit of Rupprecht & Patashnick
Partisol, Model 2025 Federal Reference Method $PM_{2.5}$ Sampler

DRI SOP #4-112.1

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1.0 GENERAL DISCUSSION

1.1 Purpose of Procedure

This standard operating procedure is intended to provide the procedures for conducting a performance audit of the Rupprecht & Patashnick Partisol Federal Reference Method (FRM) $PM_{2.5}$ sampler, model 2025 operated by Atmospheric Research and Analysis (ARA), Inc. at the Southeastern Aerosol Research Characterization (SEARCH) study sites.

This procedure will be followed by all audit personnel of the Division of Atmospheric Science of the Desert Research Institute.

1.2 Underlying Principles

The R & P Partisol, model 2025, $PM_{2.5}$ sampler is a sequential filter sampler designed to collect 24-hour integrated samples of particulate matter in the $PM_{2.5}$ size fraction within the guidelines of the Class 1 Federal Reference Method as give in EPA (1998). The sampler automatically switches up to 3 filters for multiple day operation. An impactor inlet of the $PM_{2.5}$ FRM is installed to remove particles with aerodynamic diameters greater than 10 µm. A WINS is installed downstream of the denuders to reduce the particle size to 2.5 µm. Ambient and sampler temperature and ambient pressure are measured. A mass flow controller controls the flow rate at a constant 16.7 lpm referenced to ambient temperature and pressure conditions.

The performance audit consists of flow rate measurements at the inlet of the $PM_{2.5}$ FRM. The audit and site flow rates at ambient conditions are compared. The ambient pressure is measured with a portable altimeter and compared to the site sensor. The ambient and internal temperatures are measured with a portable thermocouple and compared to the site sensors.

1.3 Method Interferences and Their Minimization

The audit flow meter has a pressure drop that may differ from the pressure drops in the sample line. The mass flow controller should be able to compensate for these differences. The air flow through a bubble type flow meter can have a slight reduction in temperature because of evaporation of water in the soap solution. In the humid Southeast, this reduction is slight. Temperature measurements can be affected by direct solar radiation. The thermometer and flow meter are shaded from direct insolation during the measurements.

1.4 Ranges and Typical Values of Measurements

The mass flow controllers maintain a flow rate of 16.7 sl/min. The ambient pressure ranges from 960 to 1020 mb at the SEARCH sites. The ambient temperature ranges from 10 to 40 °C.

1.5 Typical Lower Quantifiable Limits, Precision, and Accuracy

The accuracy of the audit flow meter is approximately ±2%. The accuracy of the pressure standard is ±2 mb. The accuracy of the temperature sensor is ±0.2 °C. The audit flow meter is checked with a NIST-traceable bubble flow meter. The pressure standard is compared to a Fortin-type mercury-in-glass barometer. The temperature standard is compared to a NIST-traceable mercury-in-glass thermometer in a water bath.

1.6 Personnel Responsibilities

The Field Auditors should read and understand the entire standard operating procedure prior to conducting a performance audit. Familiarity with the operation of the sampling equipment and the audit equipment is necessary for valid measurements. In addition the Field Auditor generates a preliminary report of the audit results at the time of the audit to be presented to the site operator.

It is the responsibility of the Audit Supervisor to ensure the audit procedures are properly followed, to examine and document all documentation, to arrange for maintenance and repair of audit equipment, to maintain the supplies necessary to insure uninterrupted measurements, and to generate a report summarizing the audit results.

1.7 Definitions

The following terms are used in this document:

Performance audit: Comparison of instrument response to audit standards.
Audit standards: Standards provided by auditor for comparison.

1.8 Related Procedures

DRI SOP #4-208.1: Calibration of Gilibrator Bubble Flow Meter
DRI SOP #4-209.1: Calibration of Pressure Transfer Standard
DRI SOP #4-210.1: Calibration of Temperature Transfer Standard

2.0 APPARATUS, INSTRUMENTATION, REAGENTS, AND FORMS

2.1 Apparatus and Instrumentation

2.1.1 Description

Audit flow meter: Gilibrator bubble meter, model H (2-30 lpm) with printer
Audit pressure sensor: Thommen altimeter
Audit temperature sensor: Fluke Thermocouple Model 52 K/J
Audit psychrometer: Psychrodyne with mercury-in-glass wet- and dry-bulb thermometers
Inlet adapters: Flow adaptor to 1¼ inch OD pipe
Tubing to connect adapter to Gilibrator
Audit filter packs for $PM_{2.5}$ FRM if available
Shade to cover Gilibrator to prevent stray light from activating sensor.

2.1.2 Instrument Characterization

2.1.3 Maintenance

Regular maintenance for the Gilibrator includes:

- Emptying bubble solution from reservoir after each day's use
- Cleaning reservoir annually
- Replacement of printer paper

2.1.4 Spare Parts and Supplies

Bubble solution, P/N 800450
Paper for printer, P/N A-400681
Distilled water to wet wick of wet-bulb thermometer

2.3 Forms and Paperwork

Audit form for the $PM_{2.5}$ FRM audit, paper copy, Figure 2-1.
Electronic copy of $PM_{2.5}$ FRM on portable computer that includes computation formulas.

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$PM_{2.5}$ FRM SAMPLER AUDIT RECORD

REV 08/01

Sampling Network: ______ Site Name: ______ Date: ______
Auditor: ______ Site ID: ______ Start Time: ______ ___ST
Operator: ______ AIRS #: ______ End: ______ ___ST

Site Instrument Data:
Reference Method: NA

	Manufacturer	Model Number	Serial Number
Control Box:			
Sampler Inlet:			

Audit Instrument Information:

	Manufacturer	Model Number	Serial Number	Cert. Date
Audit Flow Meter:				
Barometer:				
Thermometer:				
Audit Dry				
Audit Wet				

Flw Mtr	Slope:	Intercept:	Corr Coef:
Aud Dry	Slope:	Intercept:	
Aud Wet	Slope:	Intercept:	

CorrRead = (Read-Int)/Slope

Audit Results

Time Site: ______ ___ST Difference
Audit: ______ ___ST ________ ___ST ________ min

T/P/RH

Filter T ______
FilComp T ______
Amb T ______
Amb P ______
Amb Rh ______

Audit Values
Amb T ______ Difference ________ C
Amb P ______ mb ________ mm Hg ________ mm Hg
In box: Aud Dry ______ RH ________ ________ %
Aud Wet ______

Flow

---- Audit Flow ----		--- Site Flow ---		Difference	
Qind LPM	Qcorr LPM	Qset LPM	Qind LPM	Qact Diff	% Diff

Average		
Std Dev.		

Leak Check

External check Results: ____

Internal check Results: ____

Comments: ____

Figure 2-1: Blank Worksheet for $PM_{2.5}$ FRM Audit

3.0 CALIBRATION STANDARDS

3.1 Preparation, Ranges, and Traceability of Standards

The Gilibrator Bubble Flow Meter is calibrated with a Hastings Bubble flow meter, model HBM-1A, 1000 cm^3 tube, S/N 1476, that is NIST-traceable.

The Thommen altimeter is checked with a Fortin-type mercury-in-glass barometer. The barometer reading is corrected for temperature and altitude using corrections provided by the Smithsonian Meteorological Tables (List, 1951).

The Fluke thermocouple is calibrated at approximately 0 and 30 °C in a water bath using a Brooklyn Thermometer (29 – 31 °C) S/N 10772 NIST-traceable.

3.2 Use of Standards

The audit equipment are calibrated prior to the field audit. If questions arise as to audit results, the audit equipment are calibrated after the audit.

3.3 Typical Accuracy of Calibration Standards

The accuracy of the flow rates are ±2%. The accuracy of the pressure standard is ±1 mb. The accuracy of the temperature standard is ±0.01 °C.

4.0 PROCEDURES

4.1 General Flow Diagram

Following is the typical flow of the audit procedures for the $PM_{2.5}$ FRM:

Calibrate audit equipment
Gilibrator flow meter
Thommen altimeter
Fluke thermocouple
Psychrodyne thermometers

Prepare audit equipment
Assemble flow meter
Arrange pressure and temperature sensors

Prepare site sampler for audit
Document site sampler serial numbers and time
Turn sampler off and record time
Replace site filter holders with audit filter holders
Place sampler in Audit mode
Perform external leak check
Observe operator perform internal leak check

Audit Flow Rate, Pressure, Temperature, RH
Measure flow rate at inlet
Measure ambient pressure
Measure ambient temperature
Measure temperature in enclosure
Measure relative humidity in enclosure
Compare audit and instrument quantities
Determine possible sources of discrepancies
Remeasure audit quantities if necessary

Return sampler to run condition
Turn sampler off
Replace audit filters with site filters
Turn sampler on and record time

Prepare preliminary report of audit findings

Recalibrate audit equipment, if necessary

4.2 Audit Procedures

The following sections describe in detail the audit procedures for the $PM_{2.5}$ FRM. This section must be read and understood in its entirety before beginning audit. When all aspects of the analysis procedure are understood, the abbreviated checklist appearing in Section 4.3 may be used for reference.

4.2.1 Audit Equipment Preparation

1) Unpack Gilibrator size H flow cell and control unit.
2) Attach flow cell to control unit. Twist flow cell by turning base of cell, not top. Attach connector from control unit to back of flow cell.
3) The flow meter can operate on batteries for several hours. For longer periods of use, the control unit will have to be plugged into 110 VAC power with the transformer. The batteries should be kept charged when the flow meter is not in use, as the batteries will not charge sufficiently to operate if the batteries have been completely discharged. For long periods of use, the flow meter should be plugged into 110 VAC power. While the flow meter is not in use, the flow meter should be plugged into 110 VAC power with its power switch turned off.
4) Fill the reservoir of the flow cell with bubble solution by introducing the solution in the small solution bottle into the lower opening of the flow cell. The cell should be filled so that when the plunger ring is depressed, it comes in contact with the solution. The solution should not be as high as the opening to the base of the flow cell.
5) Before the flow meter can be used, the insides of the cell need to be wetted with bubble solution. An efficient way to do this is to attach a piece of ¼ inch Tygon tubing to the lower opening of the flow cell, i.e., the inlet, and blow gently into the tube while periodically depressing the plunger to release soap bubbles into the flow tube. Continue doing this until the bubbles reach the top of the flow cell. The flow tube may need to be wetted again if there is a long pause between measurements. Flow from the site instrument can also be used to wet the tube sides. In this case, the tube is attached to the upper opening of the flow cell, i.e., the outlet, and ambient air is pulled through the flow meter in the same way as it normally operates with repeated depressions of the plunger until soap bubbles reach the top of the flow cell.
6) When the Gilibrator flow meter is used out doors in direct sun light, the sensors on the flow cell cannot distinguish the passing of the bubble and so need to be protected from the light. A small card board box can be used to shade the flow meter. It should cover the flow cell and have one opening to access the plunger and a second opening to view the bubble. The box also serves as a shield to direct solar radiation that might change the temperature of the flow cell.

7) Plug the printer ribbon strip into the control box. The printer obtains its power from the control box. It also has its own power switch.
8) It is also necessary to measure the ambient pressure and temperature and temperature and humidity inside the sampler enclosure. The altimeter is placed near the sampler where it can be read. The ambient temperature is measured with the sensor of the Fluke placed in the radiation shield on the side of the instrument. The internal temperature is measured with the Fluke temperature sensor by placing the sensor near the filter magazines and closing the enclosure door with the Fluke electronics outside. The humidity inside the enclosure is measured by placing the operating psychrometer inside the enclosure, allowing the thermometers to equilibrate, and quickly reading the temperatures.
9) An adapter is used to connect a ¼ inch tube to the 1¼ inch inlet tube of the $PM_{2.5}$ FRM instruments. The flow meter and cover can be placed on top of the instrument next to the inlet.

4.2.2 Site Instrument Inspection and Leak Check

1) Prepare audit forms or audit notebook by entering site name and date of audit.
2) Record serial numbers of instrument and size-selective inlet.
3) Record and compare time on $PM_{2.5}$ FRM and the official audit time (referenced to NIST WWV radio).
4) If audit test filters are used, press F2 (Audit) from the Service Menu to stop current sample. Record time. Press F4 (FiltAdv) to advance filters to receiver magazine. Check and record filter ID of filter that is currently being exposed.
5) Install audit filter and advance to sample position. Start sampler. Record site flow rate. Remove inlet impactor. Inspect the impactor for cleanliness and foreign material as well as can be done without disassembling.
6) Attach 1¼ inch adapter to inlet tube and close valve. Press F5 (LeakChk) and then Start. Follow instructions on screen. A Pass or Fail message will appear at the end of the test. Repeat the external leak check if the Fail message appears. When the leak test is completed, slowly open the valve on the inlet tube to release the vacuum on the system.
7) The site operator should perform an internal leak test in the presence of the auditor.

4.2.3 Instrument Flow Rate Audit

1) Place audit flow meter on instrument next to inlet tube. Attach ¼ inch tube to inlet adapter and to outlet of the audit flow meter. Be careful that the tubing does not become kinked, particularly by the shade box.

2) With audit or site filters in place, enter Audit Mode to start sampler. Before turning the flow meter on, depress the plunger to see that the inside of the flow tube is wet. If not, depress the plunger several times until the inside is wet. Do not press the plunger too fast as this will generate multiple bubbles in the solution reservoir that interfere with the generation of single bubbles.

3) Turn on power switches on printer and control box. A header of 4 lines will be generated on the printer paper. The site, instrument, channel, measurement location and date should be noted on the printer paper.

4) Bubbles are generated by pushing the plunger down. Bubbles may also be generated when the plunger is released. If this happens too fast, there will be 2 bubbles in the chamber at a time. The proper practice is to generate the first bubble by pushing the plunger down and holding until that bubble reaches the top of the cell, the shape of the bubble is determined to be good, and the flow rate is near the expected value and then to generate the next bubble by releasing the plunger. As the amount of solution in the reservoir decreases, releasing the plunger will not always generate a bubble and so the generation of the second bubble needs to be confirmed. The state of the bubble also needs to be checked for each measurement. Sometimes multiple bubbles are generated if the solution reservoir is too full. Other times bubbles will form in the solution chamber and give odd shaped bubbles in the flow tube. Odd bubbles generally result in flow rates that are significantly different from the rest. These flow rates can be deleted from the calculation of the average flow rate by pressing the Delete key on the control unit before the next bubble is generated.

5) Depress and hold down plunger to generate the first bubble. There should be a single bubble and it should progress all the way to the top of the flow chamber. If the measurement is correct, a flow rate will be printed out that is approximately 16.7 lpm. Sometimes the first few bubbles do not work correctly and several bubbles are necessary before operations are correct. If necessary, reset the control unit output by pressing the Reset button or turning the power switch on the control unit off and on to start a new header and average flow measurement.

6) Generate 10 good flow measurements. Visually inspect the printer record of the 10 flow rate measurements. They should be within ±0.1 lpm of each other. If any of the measurements differ by more, the set of 10 measurements should be generated again. Record the average flow rate. Press Reset on the control unit to start the next average flow measurement. Record the instrument flow rate. Record at least 2 more sets of 10 good audit flow measurements and instrument readings. The flows measured with the Gilibrator flow meter tend to decrease 0.1 to 0.2 lpm from their initial value as more flow measurements are made. It may require 2 or 3 sets of 10 measurements before the flow rates equilibrate. The decrease in flow rate may be due to a decrease in the temperature inside the flow meter as the soap solution evaporates. In the humid Southeast, the evaporation effect should only be slight.

4.2.4 Pressure Audit

1) Place audit altimeter near $PM_{2.5}$ FRM. Tap gently and read and record altimeter.
2) Display Main menu on instrument panel. Record displayed pressure.
3) Convert audit and instrument pressures to same units, if necessary, and compare.
4) If time permits, repeat the pressure comparison at different times throughout the audit period to obtain a range of readings.

4.2.5 Temperature Audits

1) Ambient temperature
   a) Insert the Fluke temperature probe in the radiation shield on the side of the $PM_{2.5}$ FRM and secure with tape.
   b) Display Main menu on instrument panel. Record displayed ambient temperature and compare to the audit temperature.
   c) If time permits, repeat the ambient temperature comparison at different times throughout the audit period to obtain a range of readings.
2) Filter Temperature
   a) Place Fluke temperature probe inside $PM_{2.5}$ FRM enclosure near the filter magazines with probe electronics outside enclosure.
   b) Gently close enclosure door and allow Fluke probe to equilibrate with the inside temperature.
   c) Record Fluke temperature and quickly open enclosure door and read and record the displayed Filter and FiltComp temperatures.
   d) If time permits, repeat the filter temperature comparison at different times throughout the audit period to obtain a range of readings.

4.2.6 Humidity Audit

1) Prepare audit psychrometer by wetting wet-bulb wick with distilled water and turn fan on.
2) Place psychrometer inside $PM_{2.5}$ FRM enclosure and close door.
3) Allow psychrometer to operate for about 3 minutes with door closed.
4) Quickly open door, read and record wet- and dry-bulb thermometers, and replace psychrometer for an additional minute.
5) Quickly read and record thermometers again to see if the wet-bulb has reached its lowest value. If there is only a small difference between the two readings, record the wet- and dry-bulb temperatures and the displayed instrument humidity.

6) Compute the audit humidity from the wet- and dry-bulb temperatures and the pressure and compare to the instrument humidity.
7) If time permits, repeat the humidity comparison at different times throughout the audit period to obtain a range of readings.

4.2.7 Return Site Instrument to Sampling Mode

1) Remove inlet adapter and replace size selective inlet.
2) If audit filter is used, turn sampler pump off. Advance audit filter to receiver magazine. Reinstall sampler magazine and advance the proper filter to the sampling position. Start sampling and close enclosure door.
3) Record time that $PM_{2.5}$ FRM sampler is returned to operational status.

4.2.8 Final Audit Procedures

1) Remove printer tape with flow rates for the audit from printer, fold, and place in envelop to save.
2) If no more flow measurements are to be made, disconnect printer from control unit and place in case. Disconnect cable from back of flow cell. Remove flow cell from control unit by twisting 90 degrees while holding onto base of cell. Pour bubble solution out of Gilibrator reservoir into large bubble solution bottle. Connect piece of tube between inlet and outlet of flow cell. Place flow cell and control unit in case.
3) Enter the average flow rates for at least 3 sets of audit and the associated $PM_{2.5}$ FRM sampler flow rates at ambient conditions. Calculate the average audit and $PM_{2.5}$ FRM flow rates for the audit and calculate the differences and averages. Compare the differences of the flow rates to the audit criteria of ±5%.
4) Generate a preliminary report of audit findings that includes the differences between the audit and site standard flow rates. Problems should be identified.

4.2.9 Abbreviated Operational Checklist

1) Prepare audit equipment
   a) Assemble flow meter
   b) Arrange pressure and temperature sensors
2) Prepare site sampler for audit
   a) Document site sampler serial numbers and time
   b) Turn sampler off and record time.
   c) Replace site filter with audit filter (optional)
   d) Place sampler in Audit mode
   e) Install adapter to inlet and perform external leak check
   f) Observe site operator perform internal leak check
3) Audit flow rate, pressure, temperatures, and humidity
   a) Measure and record audit flow at inlet and record sampler flow rate
   b) Measure and record ambient temperature in radiation shield and record sampler ambient temperature.
   c) Measure and record temperature inside enclosure and record sampler filter and filtcomp temperature
   d) Measure and record wet- and dry-bulb temperatures inside enclosure and record sampler relative humidity. Compute audit relative humidity from the wet- and dry-bulb temperatures and the pressure.
   e) Compare audit and sampler flow rates, pressures, temperatures, and relative humidities.
   f) Determine possible sources of discrepancies and fix if possible
   g) Remeasure audit quantities if necessary
4) Return sampler to run condition
   a) Turn sampler off
   b) Replace audit filters with site filters
   c) Turn sampler on and record time

5.0 QUANTIFICATION

5.1 Calibration procedures

5.1.1 Gilibrator bubble flow meter

The Gilibrator Bubble Flow Meter is calibrated with a Hastings Bubble flow meter, model HBM-1A, 1000 cm^3 tube, S/N 1476, that is NIST-traceable.

1) Prepare Gilibrator for operations.
2) Connect outlet of Gilibrator to vacuum source (pump or laboratory vacuum) with valve between flow meter and vacuum.
3) Invert Hastings 1000 cm^3 tube and secure chain clamp to ring stand. Connect tube from tapered end of Hastings tube to inlet of Gilibrator. Tubing of different sizes will be necessary with reducing unions between. Place bubble solution in a small dish that is wider than the inlet to the Hastings. Bubbles are generated in the Hastings by quickly touching the bubble solution to the inlet of the inverted Hastings tube to pull a bubble into the tube.
4) Turn vacuum on and wet inside of the Hastings tube and the Gilibrator.
5) Set valve so that flow rate is approximately 24 lpm on the Gilibrator. Record ambient temperature and pressure. Generate bubble in the Hastings tube and measure time required to pass by several lines. The bubble may not be stable for the lowest line or two and may break before reaching the top line. A typical volume is 700 cm^3. Record time and volume. Repeat four times. Generate three sets of ten Gilibrator readings and record average values.
6) Repeat step 5) at flow rates near 20, 16, 12, and 8 lpm.
7) Calculate Hastings flow rates using $Q_{Hast} = V_{Hast}t$, where V_{Hast} is volume of time bubbles in liters and t is time in minutes. The Hastings flow rates do not need correction for water vapor pressure because the air entering the tube is at ambient conditions. The air entering the Gilibrator does need to be corrected for the water vapor added by the Hastings. The Gilibrator flow rate is corrected for water vapor by

$$Q_{Gil-cvp} = Q_{Gil}\left(\frac{p + p_v}{p}\right)$$

where $Q_{Gil\text{-}cvp}$ is average Gilibrator flow rate in lpm corrected for vapor pressure,
Q_{Gil} is average Gilibrator flow rate in lpm,
p is ambient pressure in mb or mm Hg, and
p_v is saturation vapor pressure in same units as p.

The saturation vapor pressure is found from the following expression given by Buck (1981):

$$p_v = \left(1.0007 + 3.46x10^{-6}\, p\right) 6.1121\, \mathbf{exp}\left(\frac{17.502\, T}{240.97 + T}\right)$$

where p_v is saturation vapor pressure in mb,
p is ambient pressure in mb, and
T is ambient temperature in °C.

8) Generate a linear least squares fit using the Hastings flow rates as the x variable and the Gilibrator flow rates as the y variable to obtain

$$Q_{Gil-cvp} = MQ_{Hast} + B$$

where M and B are the slope and intercept from the least squares fit.

The corrected Gilibrator flow rate relative to the Hastings bubble meter is given by

$$Q_{Gil-corr} = \frac{\left(Q_{Gil-cvp} - B\right)}{M}$$

5.1.2 Thommen altimeter

The Thommen altimeter is checked with a Princo Fortin-type mercury-in-glass barometer. The barometer reading is corrected for temperature and altitude using corrections provided by the Smithsonian Meteorological Tables.

1) Place altimeter near Princo barometer. Gently tap altimeter and record reading.
2) Turn cistern adjustment screw at bottom of Princo barometer until white zero pointer in cistern just touches top of mercury.
3) Raise vernier above top of mercury meniscus and lower slowly until the front and back bottom edges of the vernier just appear to touch the top of the meniscus.
4) Read the millibar scale indicated by the vernier. The 1's, 10's and 100's places are given by the first line on the scale below the bottom of the vernier. The tenth's digit is given by the line on the vernier that aligns most closely with a scale line.
5) Read and record the temperature on the mercury-in-glass thermometer attached to the front of the Princo barometer.
6) Repeat steps 1) – 5) three times.
7) In Excel spreadsheet, "BARRCORR.XLS", for the next calibration, enter the Princo barometer and temperature readings and the altimeter reading. Duplicate calculations from previous calibrations to determine corrected barometer reading and difference between altimeter and Princo barometer.

8) If the altimeter reading differs from the corrected Princo barometer by more than ±3 mb, the altimeter should be adjusted. There is an adjustment small screw on the back side of the altimeter behind a small slider. Adjust and recheck against Princo barometer.
9) The following corrections are applied to the Princo barometer readings to correct for temperature, latitude, and altitude:

Temperature correction:

$$C_T = p_T - p_R = p_R\left(\frac{1 + L(T - T_S)}{1 + M(T - T_M)} - 1\right)$$

where C_T is temperature correction,
p_T is pressure in mb corrected for temperature,
p_R is barometer pressure reading in mb,
L is coefficient of expansion for brass scale = 0.0000184 m/m°C,
T_S is standard temperature for brass expansion = 0 °C,
M is coefficient of expansion for mercury volume = 0.0001818 m^3/m^3°C,
T_M is standard temperature for mercury expansion = 0°C.

Altitude correction for gravity:

$$\begin{aligned} g_a = g &- [3.085462x10^{-4} + 2.27x10^{-7}\cos(2\varphi)]\,Z \\ &+ [7.254x10^{-11} + 10x10^{-18}\cos(2\varphi)]\,Z^2 \\ &- [1.517x10^{-17} + 6x10^{-20}\cos(2\varphi)]\,Z^3 \end{aligned}$$

where g is gravity at a latitude of 45° and elevation of 0 meters (= 980.616 $cm\text{-}s^{-2}$),
φ is latitude, and
Z is altitude above sea level in meters.

Latitude correction for pressure:

$$C_G = p_L - p_T = p_T\left\{\frac{g_a}{980.665}\left[1 - 2.6373x10^{-3}\cos(2\varphi) + 5.9x10^{-6}\cos(2\varphi)\right] - 1\right\}$$

where C_G is correction for latitude,
p_L is pressure in mb corrected for latitude, altitude, and temperature,
p_T is pressure in mb corrected for temperature, and
980.665 is gravity for which correction tables were developed.

Final corrected barometer reading:

$$p_L = p_R + C_T + C_G$$

5.1.3 Fluke thermocouple and Psychrometer thermometers

The Fluke thermocouple and the wet- and dry-bulb thermometers from the Psychrodyne psychrometer are calibrated at approximately 0 and 30 °C in a water bath using a Brooklyn Thermometer (29 – 31 °C) S/N 10772 NIST-traceable. The water bath can be in a small vacuum bottle for a single thermometer or in a temperature controlled bath if more thermometers are calibrated at the same time.

1) Fill bottle with cold water and chipped ice. Stir vigorously with a stirring rod – not with the Brooklyn thermometer. Check temperature of bath with the Fluke probe.
2) As the temperature approaches 0 °C, place Brooklyn thermometer in the bath. Continue stirring of the bath but at a reduced intensity. The height of the mercury in the Brooklyn will eventually decrease to the point that it be in the near zero scale of the thermometer. The thermometer should be at the 6 inch immersion depth during the stirring but needs to be lifted out of the water to read the near zero scale. Read and record the Brooklyn thermometer values to 0.01 °C and Fluke and psychrometer thermometer readings to 0.1 °C.
3) If the Fluke and Brooklyn thermometer readings differ by more than ±0.2 °C, turn the Fluke adjust screw to bring the readings into agreement. Both channels of the Fluke should be checked with either the same probe or with a second probes if available.
4) Fill the vacuum bottle with water that is near 31 °C. Place Brooklyn thermometer and Fluke probe and psychrometer thermometer into water.
5) Hold Brooklyn thermometer, Fluke probe, and psychrometer thermometers side-by-side with the end of the Fluke probe near the end of the bulbs of the thermometers.
6) Gently stir water so that it is well-mixed. Be careful not to hit the side of the vacuum bottle with the thermometers.
7) Raise the Brooklyn thermometer until the 6 inch immersion line is at top of water and read and record thermometer value to 0.01 °C and read and record Fluke and psychrometer thermometers readings to 0.1 °C.
8) Repeat stirring and reading values for at least 3 sets of readings as the temperature of the water in the vacuum bottle gradually decreases.
9) Average the differences between the Fluke probe and the psychrometer thermometers and Brooklyn thermometer readings near 0 °C and near 30 °C. Add differences to 0 and 30 °C, respectively, to obtain Fluke probe and psychrometer thermometers responses to temperatures at 0 and 30 °C. Generate linear fits to the Fluke and pyschrometer and Brooklyn readings to obtain the following expression for the corrected Fluke and psychrometer thermometer readings:

$$CorrAuditTemp = \frac{30}{(30 + \Delta_{30} - \Delta_0)}\left(AuditTemp - \Delta_{30}\right)$$

where CorrAuditTemp represents the corrected Fluke, wet-bulb or dry-bulb temperature readings in °C,
AuditTemp represents the Fluke, wet-bulb, or dry-bulb readings in °C,
Δ_{30} is the difference between the Fluke, wet-bulb, or dry-bulb and Brooklyn readings near 30 °C,
Δ_0 is the difference between the Fluke, wet-bulb, or dry-bulb and Brooklyn readings near 0 °C.

5.2 Calculations

5.2.1 Audit Flow Rate Calculations

During the operation of the Gilibrator flow meter, ambient air is pulled into the flow meter where it passes over the solution of water and soap. Water vapor is added to the air as evaporation occurs in the vicinity of the solution. This water vapor slightly increases the volume passing through the Gilibrator to the mass flow controller. Since the Gilibrator and the mass flow meter both are exposed to the same water vapor-laden volume, the volume measured by the Gilibrator does not have to be corrected for the additional volume.

The flow rate maintained by the $PM_{2.5}$ FRM is referenced to actual conditions as is the audit flow rate. The audit flow rate is not corrected standard conditions for the $PM_{2.5}$ FRM audit.

5.2.2 Differences between Instrument and Audit Measurements

The results of the audit are quantified by comparing the displayed instrument values to the audit measurements for those quantities. The comparison includes the computation of the difference and the percent difference between the instrument values and the audit values. The difference and percent differences are computed from the following expressions:

$$Difference = Instrument - Audit$$

$$\%\ Difference = \left(\frac{Instrument - Audit}{Audit}\right)100$$

where Instrument represents the value of the audited quantity displayed by the instrument or DAS and
Audit represents the measurement of the audited quantity with the audit equipment.

5.2.2 Relative Humidity Calculations

The relative humidity in percent is defined as 100 times the ratio of the vapor pressure of the air, e(T), to the saturation vapor pressure of the air, $e_s(T)$ at temperature T:

$$RH = 100\left(\frac{e(T)}{e_s(T)}\right)$$

where $e_s(T)$ is given by

$$e_s(T) = (1.0007 + 3.46x10^{-6}\, p)\, 6.1121\, \mathbf{exp}\left(\frac{17.502\, T}{240.97 + T}\right)$$

The vapor pressure of the air at temperature T is calculated from the psychrometric equation (List, 1951) using the wet- and dry-bulb temperatures, the pressure, and the vapor pressure at the wet-bulb temperature (Buck,1981):

$$e(T) = e_s(T_w) - 0.00066\, p(T - T_w)(1 + 0.00115 T_w)$$

where e(T) is the vapor pressure of the ambient air in mb,
T is the ambient (dry-bulb) temperature in °C,
T_W is the wet-bulb temperature in °C,
p is the pressure in mb, and
$e_s(T_W)$ is the saturation vapor pressure at the wet-bulb temperature in mb and is given by

$$e_s(T_w) = (1.0007 + 3.46x10^{-6}\, p)\, 6.1121\, \mathbf{exp}\left(\frac{17.502\, T_w}{240.97 + T_w}\right)$$

5.3 Data Acquisition

Data acquisition is done manually by entering audit flow rates, ambient pressures, ambient temperatures, and site flow rates on log sheets or in a notebook. The average of audit flow rates for the individual measurements is computed by the Gilibrator control unit and printed as the data are collected. Processing of the audit and site data is done in an Excel spreadsheet.

6.0 QUALITY CONTROL

Quality control is maintained by periodic calibration of audit transfer standards with laboratory standards that are traceable to the National Institute of Standards and Technology. Calibrations are performed on at least an annual basis and before a major audit trip. Calibrations may also be performed following an audit trip if major discrepancies arose between the audit standards and the audited equipment.

7.0 REFERENCES

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