

DRI STANDARD OPERATING PROCEDURE

**Performance Audit of Radiance Research
Nephelometer, Model M903**

DRI SOP #4-115.1

**Desert Research Institute
Division of Atmospheric Sciences
2215 Raggio Parkway
Reno, NV 89512**

(775) 674-7044

Sept., 2002

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 Radiance Research Nephelometer, Model M903 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 Radiance Research Nephelometer, Model 903 continuously measures the particle scattering coefficient of particulate matter in the PM_{2.5} size fraction. After passing through the inlet and sample line, air with particles is brought into a chamber that is illuminated from the side with 530 nm light. The scattered light that is measured is related to the scattering coefficient. The flow rate through the chamber is critical and is controlled with a valve but not generally measured. The Nephelometer is calibrated to output the scattering coefficient by particles only, b_{sp} . The scattering coefficient data are collected by the site computer data acquisition system as one-minute averages.

The performance audit consists of measuring the flow rates at the inlet with the Nephelometer and other instruments attached and at the inlet to the Nephelometer alone, installing a zero particle filter on the inlet to the Nephelometer to check the no-particle condition, and introducing a large molecule gas, HFC-134a refrigerant, to measure its scattering coefficient. The response of the Nephelometer is compared to the known scattering coefficient of HFC-134a at the instrument pressure and temperature conditions. The pressure is measured with a portable altimeter. The temperature is measured with a portable thermocouple.

1.3 Method Interferences and Their Minimization

The expansion of HFC-134a during its introduction to the Nephelometer can lower the temperature of the gas inside the chamber and increase the measured scattering coefficient. The HFC-135a is entered at a low flow rate through a long tube so that the gas can equilibrate with the ambient temperature.

1.4 Ranges and Typical Values of Measurements

The scattering coefficient measured by the Nephelometer ranges from 0 to 1000 Mm^{-1} . The scattering coefficient of HFC-135a is approximately 85 Mm^{-1} .

1.5 Typical Lower Quantifiable Limits, Precision, and Accuracy

The HEPA filter removes 99.9% of the particles. The accuracy of the scattering coefficient for HFC-134a is $\pm 5\%$.

1.6 Audit Criteria

The audit criteria serves to notify the auditor and site operator of deviations from optimal operating conditions that may indicate potential problems. The flow rate for the Nephelometer should be within 1 to 2 l/min. The response of the Nephelometer to particle-free air should be $\pm 0.05 \text{ Mm}^{-1}$. Its response to HFC-134a refrigerant should be $\pm 5\%$.

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 STANDARD OPERATING PROCEDURE

Page: 3 of 19
Date: Sept., 2002
Number: 4-115.1
Revision: 2

Title: Performance Audit of Radiance Research
Nephelometer, Model M903

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

DuPont Suva HFC-134a refrigerant and dispenser
Whatman HEPA-Cap 75 disposable inline filter device
Thomas diaphragm pump
Audit flow meter: Gilibrator bubble meter, model S (0.1 – 6 lpm) and model H (2-30 lpm)
with printer
Audit pressure sensor: Thommen altimeter
Audit temperature sensor: Fluke Thermocouple Model 52 K/J
Inlet adapters: Flow adaptor to 1¼ inch OD pipe
Tubing to connect adapter to Gilibrator
Shade to cover Gilibrator to prevent stray light from activating sensor.

2.1.2 Maintenance

Regular maintenance for the Gilibrator includes:
Emptying bubble solution from reservoir after each day's use
Cleaning reservoir annually
Replacement of printer paper

2.1.3 Spare Parts and Supplies

DuPont Suva HFC-134a refrigerant, 12 oz can
Whatman HEPA-Cap 75 disposable inline filter device
Bubble solution, P/N 800450
Paper for printer, P/N A-400681

2.2 Forms and Paperwork

Audit form for the Nephelometer audit, paper copy, Figure 2-1.
Electronic copy of Nephelometer on portable computer that includes computation formulas.

Title: Performance Audit of Radiance Research
Nephelometer, Model M903

Figure 2-1: Blank Worksheet for Nephelometer Audit

3.0 CALIBRATION STANDARDS

3.1 Preparation, Ranges, and Traceability of Standards

The scattering coefficient of DuPont Suva 134a refrigerant is stated in the Radiance Research manual for the Nephelometer.

The Gilibrator Bubble Flow Meter S-cell and H-cell are calibrated with a NIST-traceable Hastings Bubble flow meter, model HBM-1A using the 100 cm³ tube, S/N 1426, and the 1000 cm³ tube, S/N 1476, respectively.

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

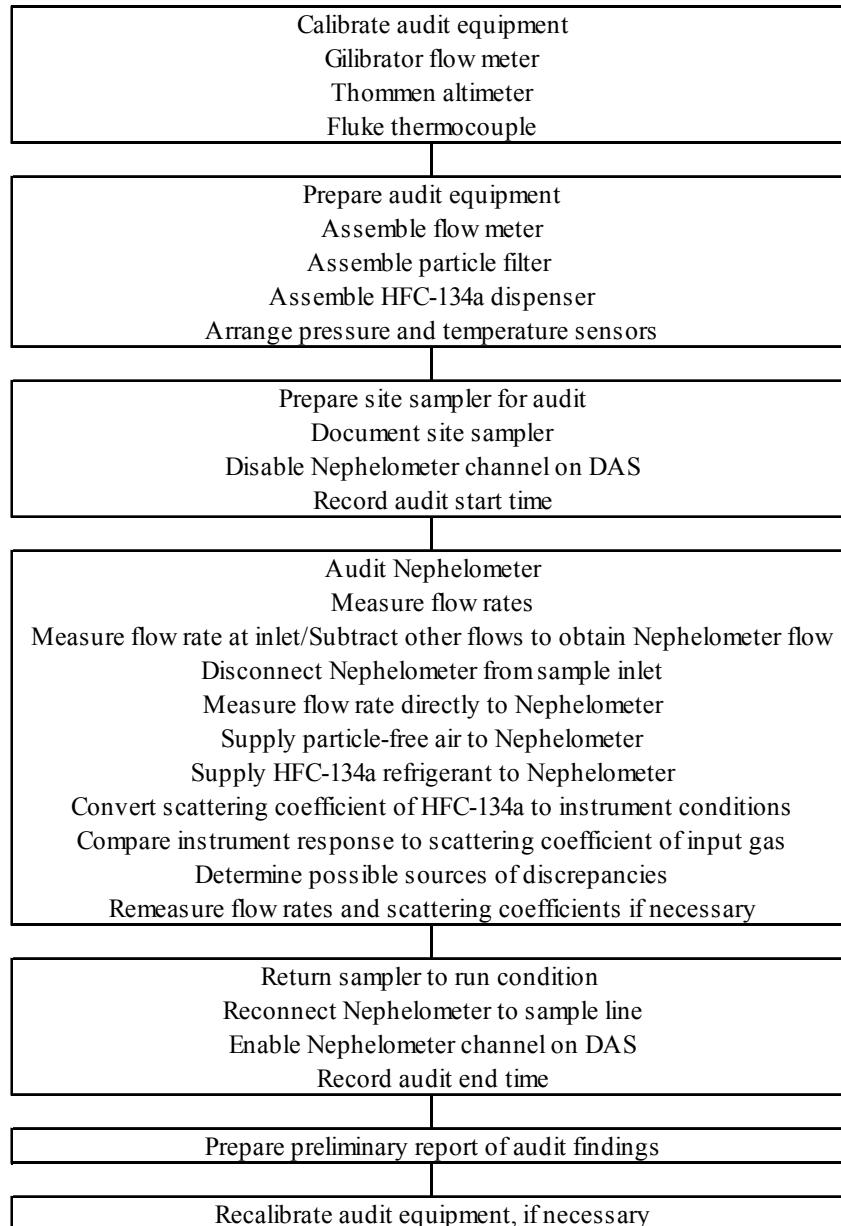
The accuracy of the scattering coefficient is $\pm 5\%$. The accuracy of the flow rates are $\pm 2\%$. The accuracy of the pressure standard is ± 1 mb. The accuracy of the temperature standard is ± 0.01 °C.

Title: Performance Audit of Radiance Research
Nephelometer, Model M903

4.0 PROCEDURES

4.1 General Flow Diagram

The typical flow of the audit procedures for the Nephelometer is given in the following:

Title: Performance Audit of Radiance Research
Nephelometer, Model M903

4.2 Audit Procedures

The following sections describe in detail the audit procedures for the Nephelometer. 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 cells 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 during the audit to convert the flow rate from the Gilibrator flow meter from ambient conditions to standard conditions. The altimeter can be placed nearby in a convenient location so that it can be read periodically. The probe of the temperature sensor should be placed inside the box covering the flow meter near the flow cell. The meter for the temperature sensor should be placed at a location that can be read.
- 9) An adapter that slips over the 1¼ inch inlet pipe and connects to a ¼ inch tube on the other connects the flow meter to the site instrument through one or more pieces of tubing depending on the location of the flow meter and the location of the measurement. Plastic couplers are used to connect the pieces of tubing together.

4.2.2 Site Instrument Inspection and Preparation

- 1) Start audit so that all flow measurements will be completed within the current hour so that only one hour of data will have to be discarded.
- 2) Prepare audit forms or audit notebook by entering site name and date of audit.
- 3) Inside the shelter, record instrument serial number. Note which instruments are connected to the sample inlet with the Nephelometer.
- 4) Step through screens by pushing the Display switch to Next. Record Zero setting, Span setting, gas coefficient, wall percentage, pressure setting, temperature setting, and cal gas to Rayleigh scattering ratio.
- 5) Record time that audit flow checks begin. Disable the Nephelometer channel on the site computer DAS.
- 6) At the inlet, record the serial numbers of the inlet.

4.2.3 Instrument Audit

Flow Rates

- 1) Remove inlet cyclone by lifting off of inlet pipe. Inspect the cyclone for cleanliness and foreign material
- 2) Attach adapter to inlet. Attach other end of the tube to the outlet of the flow meter. Be careful that the tubing does not become kinked, particularly by the shade box.
- 3) 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.

Title: Performance Audit of Radiance Research
Nephelometer, Model M903

- 4) 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.
- 5) Record instrument and measurement location on log sheet or in notebook.
- 6) Record pressure and temperature on log sheet or in notebook.
- 7) 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.
- 8) 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 8 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.
- 9) 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 pressure and temperature.
- 10) Record at least 2 more sets of 10 good flow measurements with pressure and temperature readings with each set. 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.
- 11) After each set of 10 good audit measurements, record and sum the flow rates of the instruments connected to the inlet with the Nephelometer. Subtract the sum from the

measured flow rate to get the flow rate for the Nephelometer. While the Nephelometer flow rate is not critical to the measurement, it should be in the 1 to 2 l/min range.

- 12) For pressures near 1 atm (1013.25 mb, 760 mm Hg) and temperatures near 25 °C, the actual flow rate measured by the Gilibrator flow meter approximately equals the standard flow rate and can be compared directly to the site flow rate for an initial comparison. An audit flow rate that differs from the inlet flow rate by more than ± 1 lpm indicates a possible problem in the sample train or with one of the instruments. For a more precise comparison, convert the audit flow rates to standard conditions before comparing flow rates.
- 13) Attach audit flow meter to tube directly into the Nephelometer. Repeat steps 6) through 11) to collect flow rates at through the instrument.

Particle-Free Air

- 1) Attach tubes from exhaust of Thomas pump to ball valve and from ball valve to inlet of Whatman HEPA-Cap filter. Attach third tube to outlet of filter. Check that flow rate is about 10 l/min with a rotameter.
- 2) Read and record ambient absorption coefficient reading on instrument and DAS.
- 3) Disconnect sample inlet and outlet tubes from Nephelometer. Plug the lower (outlet) port of the Nephelometer. Partially cover the upper (inlet) port of the Nephelometer with a piece of electrical tape. Remove cover from tap at rear of base of Nephelometer. Attach tube from pump/filter to tap and turn pump on. Allow the reading on Nephelometer to stabilize. Read and record at least three one-minute readings from the site DAS. Record the front panel readings at the same time. Measure and record the ambient pressure and temperature near the Nephelometer for each one-minute average.
- 4) Compare DAS and instrument readings to the ambient reading and to the expected value of 0 for the scattering coefficient due to particles, b_{sp} .
- 5) Remove pump/filter.

HFC-134a Scattering Coefficient

- 1) Attach can of HFC-134a to dispenser. Close regulator valve on dispenser. Puncture top of HFC-134a can. Connect one piece of refrigerator tubing to dispenser and to inlet of 10 l/min rotameter. Connect second piece of refrigerator tubing to outlet of rotameter and attach refrigerator connector to hose barb adapter to free end
- 2) Disconnect sample inlet and outlet tubes from Nephelometer. Check plug the lower (outlet) port and partial cover on the upper (inlet) port of the Nephelometer
- 3) Connect HFC-134a tubing to calibration tap at rear of Nephelometer with small piece of Tygon tubing

- 4) Open valve on HFC-134a dispenser to give a rotameter flow rate of about 5 l/min. Check that HFC-134a is flowing out of top port of Nephelometer by looking for distortion in the air near the port.
- 5) Allow the Nephelometer to equilibrate for several minutes. Record at least three one-minute averages on the site DAS (b_{sp} -low and b_{sp} -high). Record the front panel readings at the same time. Measure and record the ambient pressure and temperature near the Nephelometer for each one-minute average.
- 6) Compare the DAS and instrument readings to the scattering coefficient for HFC-134a at the pressure and temperature conditions of the instrument.

4.2.4 Return Site Instrument to Sampling Mode

- 1) Plug calibration tap.
- 2) Reconnect inlet and outlet tubing to Nephelometer.
- 3) Replace inlet cyclone.
- 4) Enable the Nephelometer channel on the site computer DAS.
- 5) Record time that Nephelometer was returned to operational status.

4.2.5 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) Disassemble particle-free air device and HFC-134a dispenser.
- 4) Enter the average flow rates for at least 3 sets of audit flow rates and the associated pressure and temperatures and the site standard flow rates for each of the Nephelometer measurements into the electronic form. Calculate the average audit flow rates for the audit and site standard flow rates and calculate the differences and averages. Check that the flow rate for the Nephelometer is approximately 1.5 l/min.
- 5) Enter the Nephelometer responses for particle-free air and for HFC-134a and the associated pressures and temperatures into the electronic form. Calculate the average responses and compare to the scattering coefficients for particle-free air and HFC-134a. Compare the results to the audit criteria for the response to particle-free air of $\pm 0.5 \text{ Mm}^{-1}$ and for the response to HFC-134a of 5%.
- 6) Generate a preliminary report of audit findings that includes the differences between the audit and site standard flow rates. Problems should be identified.

4.3 Abbreviated Operational Checklist

- 1) Prepare audit equipment
 - a) Assemble flow meter
 - b) Assemble particle-free air system
 - c) Assemble HFC-134a refrigerant dispenser
 - d) Arrange pressure and temperature sensors

Title: Performance Audit of Radiance Research
Nephelometer, Model M903

- 2) Prepare site sampler for audit
 - a) Document site sampler
 - b) Note time at start of audit
 - c) Disable Nephelometer channel on DAS
- 3) Measure flow rates
 - a) Measure flow at inlet
 - b) Compare total flow rate to the stated sum of flow rates of the instruments connected to the sample inlet.
 - c) Disconnect Nephelometer from sample line and measure flow directly into instrument.
 - d) Compare audit and site flow rates.
 - e) Determine possible sources of discrepancies and fix if possible
 - f) Remeasure flow rates if necessary
- 4) Response to particle-free air
 - a) Disconnect Nephelometer inlet and outlet, plug outlet and partially plug inlet.
 - b) Introduce particle-free air to tap at base of Nephelometer.
 - c) Record 3 one-minute readings from DAS and front display after readings stabilize.
 - d) Compare instrument response to audit criteria of $\pm 0.5 \text{ Mm}^{-1}$.
- 5) Response to HFC-134a refrigerant
 - a) Introduce HFC-134a refrigerant to calibration tap at base of Nephelometer.
 - b) Record 3 one-minute readings from DAS and front display after readings stabilize. Record pressure and temperature near Nephelometer for each one-minute reading.
 - c) Compute scattering coefficient for HFC-134a at instrument conditions and compare to the instrument responses. Compare to audit criteria of $\pm 5\%$.
- 6) Return sampler to run condition
 - a) Plug calibration tap.
 - b) Reconnect inlet and outlet tubing for Nephelometer.
 - c) Replace inlet cyclone
 - d) Enable Nephelometer channel on DAS
 - e) Note time at end of audit

5.0 QUANTIFICATION

5.1 Calibration procedures

5.1.1 Gilibrator bubble flow meter

The Gilibrator Bubble Flow Meter S-cell and H-cell are calibrated with a NIST-traceable Hastings Bubble flow meter, model HBM-1A using the 100 cm³ tube, S/N 1426, and the 1000 cm³ tube, S/N 1476, respectively. Procedures are the same for each cell.

- 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 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 cm³. 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 $Q_{\text{Hast}} = V_{\text{Hast}}/t$, 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

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

where $Q_{\text{Gil-cvp}}$ 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):

$$p_v = (1.0007 + 3.46 \times 10^{-6} p) 6.1121 \exp\left(\frac{17.502 T}{240.97 + T}\right)$$

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

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

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

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

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.

Title: Performance Audit of Radiance Research
Nephelometer, Model M903

- 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 = $0.0000184 \text{ m/m}^\circ\text{C}$,
 T_S is standard temperature for brass expansion = 0°C ,
 M is coefficient of expansion for mercury volume = $0.0001818 \text{ m}^3/\text{m}^3^\circ\text{C}$,
 T_M is standard temperature for mercury expansion = 0°C .

Altitude correction for gravity:

$$g_a = g - [3.085462 \times 10^{-4} + 2.27 \times 10^{-7} \cos(2\phi)] Z \\ + [7.254 \times 10^{-11} + 10 \times 10^{-18} \cos(2\phi)] Z^2 \\ - [1.517 \times 10^{-17} + 6 \times 10^{-20} \cos(2\phi)] Z^3$$

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

Latitude correction for pressure:

$$C_G = p_L - p_T = p_T \left\{ \frac{g_a}{980.665} [1 - 2.6373 \times 10^{-3} \cos(2\phi) + 5.9 \times 10^{-6} \cos(2\phi)] - 1 \right\}$$

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

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. 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 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 into water.
- 5) Hold Brooklyn thermometer and Fluke probe side-by-side with the end of the Fluke probe near the end of the bulb of the Brooklyn thermometer.
- 6) Gently stir water so that it is well-mixed. Be careful not to hit the side of the vacuum bottle with the thermometer.
- 7) Raise 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 reading 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 Brooklyn thermometer readings near 0 °C and near 30 °C. Add differences to 0 and 30 °C, respectively, to obtain Fluke probe responses to temperatures at 0 and 30 °C. Generate a linear fit to the Fluke and Brooklyn readings to obtain the following expression for the corrected Fluke reading:

$$CorrFluke = \frac{30}{(30 + \Delta_{30} - \Delta_0)} (Fluke - \Delta_{30})$$

where CorrFluke represents the corrected Fluke temperature reading in °C,
Fluke represents the Fluke temperature reading in °C,
 Δ_{30} is the difference between the Fluke and Brooklyn readings near 30 °C,

Title: Performance Audit of Radiance Research
Nephelometer, Model M903

Δ_0 is the difference between the Fluke and Brooklyn readings near 0 °C.

5.2 Calculations

5.2.1 Standard 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 audit flow meter measures flow rate at ambient conditions while the flow rate through the instrument is maintained by a valve with the mass flow rate measured at standard conditions of pressure at 1 atm and temperature at 298.15 °K (25 °C). The audit flow rates are converted to standard conditions for comparison to the site flows. The conversion of flow rate at ambient condition, Q_{Act} , to flow rate at standard conditions, Q_{Std} , follows the ideal gas law:

$$Q_{Std} = Q_{Amb} \left(\frac{p_{Amb}}{p_{Std}} \right) \left(\frac{T_{Std}}{T_{Amb}} \right)$$

where Q_{Act} is the flow rate measured by the audit flow meter in l/min,
 Q_{Std} is the audit flow rate at standard conditions in sl/min,
 p_{Amb} is the ambient pressure in the same units as p_{Std} ,
 T_{Amb} is the ambient temperature in °K (°K = °C + 273.15),
 p_{Std} is the standard pressure (1 atm, 1013.25 mb, 760 mm Hg), and
 T_{Std} is the standard temperature, 293.15 °K (20 °C).

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:

$$\begin{aligned} \text{Difference} &= \text{Instrument} - \text{Audit} \\ \% \text{ Difference} &= \left(\frac{\text{Instrument} - \text{Audit}}{\text{Audit}} \right) 100 \end{aligned}$$

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.

5.2.3 Scattering Coefficient at Instrumental Conditions

The Radiance Research Nephelometer is normally setup to measure the component of the scattering coefficient that is due to particles alone. The instrument zero is set to zero when the chamber is filled with particle-free air to remove the component of the scattering coefficient due to air. The scattering coefficient of the calibration gas, HFC-134a, is adjusted to remove the air component. The Nephelometer manual gives a value of 7.35 for the ratio of the scattering coefficients for HFC-134a to air. With the instrument set to zero for particle-free air, the ratio of HFC-134a to air is 6.35. The listed scattering coefficients (minus air) for HFC-134a are 90.6 Mm^{-1} at a pressure of 1 atm and a temperature of $273.15 \text{ }^\circ\text{K}$ ($0 \text{ }^\circ\text{C}$) and 84.4 Mm^{-1} at a pressure of 1 atm and a temperature of $293.15 \text{ }^\circ\text{K}$ (20°C).

At other pressure and temperature conditions, the scattering coefficient of HFC-134a is calculated using the ideal gas law, as follows:

$$b_{sp-corr} = b_{sp-std} \left(\frac{p_{inst}}{p_{std}} \right) \left(\frac{T_{std}}{T_{inst}} \right)$$

where $b_{sp-corr}$ is the scattering coefficient of HFC-134a minus the effect of air at the pressure and temperature conditions of the instrument,

b_{sp-std} is the scattering coefficient of HFC-134a minus the effect of air at the standard pressure and temperature conditions (90.6 Mm^{-1} for $0 \text{ }^\circ\text{C}$ or 84.4 Mm^{-1} for $20 \text{ }^\circ\text{C}$),

p_{inst} is the pressure at the instrument in the same units as p_{std} ,

T_{inst} is the temperature at the instrument in $^\circ\text{K}$,

p_{std} is the pressure at standard conditions 1 atm (760 mmHg, 1013.25 mb), and

T_{std} is the temperature at standard conditions, $273.15 \text{ }^\circ\text{K}$ ($0 \text{ }^\circ\text{C}$) or $293.15 \text{ }^\circ\text{K}$ ($20 \text{ }^\circ\text{C}$).

5.3 Data Acquisition

Data acquisition is done manually by entering the scattering coefficient for HFC-134a refrigerant, audit flow rates, instrument pressure and temperature, instrument responses, and site flow rates on log sheets or in a notebook. The average of audit flow rates for the

Title: Performance Audit of Radiance Research
Nephelometer, Model M903

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

- Buck, A.L. (1981). New equations for computing vapor pressure and enhancement factor. *J. Appl. Meteor.*, **20**, 1527-1532.
- List, Robert .J. (1951). "Smithsonian Meteorological Tables 6th Revised Edition." Vol. 114, Smithsonian Institution, Washington, DC, 527 pp.
- Radiance Research (1999). "Operation Procedures-M903 Nephelometer." Radiance Research, 535 N.W. 163 St, Seattle, WA 98177.