

# Evaluation Results and Discussion

Results of the evaluation are broken down into the respective criteria as detailed in the *Evaluation Criteria* section. Table 3 summarizes suitability, ease of use, and reliability results. Other than the statistical results for accuracy and comparison of identical instruments to each other, evaluation results are subjective, based on the authors' operational experience with the instruments and their opinions.

## Suitability

**Mass Concentration Range**—All of the continuous, real-time instruments evaluated can estimate mass concentration levels from 1,000  $\mu\text{g}/\text{m}^3$  and lower.

**Portability**—The MIE DataRam was the smallest and most portable of all the instruments, although none is really heavy or bulky. The DataRam comes with its own protective carrying case that measures 11 x 12 x 16 in. The Radiance Research nephelometer is lightweight, a little larger than the DataRam, and does not come with a carrying case. The other instruments are larger, heavier, and more cumbersome than the DataRam and Radiance nephelometer. One person can carry any one of the instruments without a problem.

**Power Consumption**—All the continuous real-time instruments are configured to run on standard 110- to 115-V ac

power. Except for the Andersen aethalometer, all the instruments consume very little power and can be configured to run on 6- or 12-V batteries. The MIE DataRam is the only instrument that has an internal, 6-V, 6.5-Ah battery supplying enough power to run the instrument for at least 24 h on a full charge. The DataRam's inlet heater requires an additional battery. The DataRam can also be configured to operate on an external 6-V power source. The Radiance nephelometer can be configured to run on a 12-V battery. It consumes about 4 W of power. More power is required if the inlet heater is attached. The Met One GT-640 can be operated with a 12-V battery. It draws about 2 A. The Optec NGN-3 requires a 13.8-V dc power source providing a minimum of 5 A. A large battery recharged by a solar panel could power most of these instruments.

**Weatherproof Enclosure**—These instruments contain sensitive electronic components that must be protected from harsh environmental conditions, especially rain. The Met One GT-640 is the only instrument that comes standard in a weatherproof enclosure. An optional weatherproof enclosure is available for the Andersen aethalometer. The manufacturers do not supply weatherproof enclosures for the Radiance Research and Optec NGN-3 nephelometers or for the MIE DataRam.

**Cost**—The cost for each instrument varies depending on the accessories. The least-expensive instrument was the Radiance Research nephelometer,

which costs \$4,795. The Met One GT-640 costs \$5,382, (including a tripod and  $\text{PM}_{2.5}$  cutoff device). The MIE DataRam costs \$11,005, (including the inlet heater,  $\text{PM}_{2.5}$  cutoff device, and ambient air-sampler inlet). The Optec NGN-3 costs \$12,900. The Andersen aethalometer costs \$16,645. Consult the manufacturer for current prices.

## Ease of Use

**Learning Curve**—Each instrument has its own peculiarities, but none is extremely difficult to learn to operate. Changing monitoring parameters such as log interval and times is easiest on the MIE DataRam and Met One GT-640. All the parameters can be modified by using the front panel keypads and following simple directions. Parameters for the Andersen aethalometer can be changed using its own keypad. A computer is needed when changing some of the operational parameters on the Radiance and Optec nephelometers.

**Setup**—All of the real-time continuous monitors are relatively easy to transport and set up. Once the monitors have been calibrated, all that has to be done is to take them to the desired location and turn them on. The only difficulty encountered was placing the Met One GT-640 on its tripod due to the awkward mounting brackets, the unit's weight, and the tripod's height.

Table 3—Summary of the evaluation criteria results for the real-time, continuous, particulate-monitoring instruments evaluated. Results are based on a scale of 1 to 10, with 1 being the lowest and 10 being the highest.

	Price (dollars)	Portability	Learning curve	Setup	Data collection	Data manipulation	Calibration	Reliability	Customer service
Met One GT-640	5,382	7.5	7.5	7	8.5	7.5	<sup>1</sup> 8	9	10
MIE DataRam	11,000	10	8.5	10	9	8.5	9.5	9	10
Radiance Research	4,795	9.5	7.5	9.5	8.5	8	7.5	8.5	8
Optec NGN-3	12,900	7.5	7	9.5	7.5	8.5	8	<sup>2</sup> NA.	10
Andersen aethalometer	16,645	8	8	9.5	9.5	8.5	<sup>3</sup> NA.	<sup>2</sup> NA.	10

<sup>1</sup> Results based on model tested. Newest model has simplified calibration.

<sup>2</sup> Insufficient data. Did not operate long enough to allow a good judgment.

<sup>3</sup> Received factory calibrated. Did not repeat factory calibration procedure.

**Data Collection**—A laptop computer using an RS-232 port and Microsoft Windows standard HyperTerminal interface was used to download the data from all of the instruments except the Optec NGN-3 and the Andersen aethalometer. A dedicated laptop using a communication package called ProComm Plus was used to log data from the Optec NGN-3. The Andersen aethalometer internally logs its data to a floppy disk.

**Data Manipulation**—Microsoft Excel spreadsheets were used to manipulate the data. All instruments provide mass concentration ( $\mu\text{g}/\text{m}^3$ ) except the Radiance nephelometer, which provides *Bscat*. *Bscat* can readily be converted to mass concentration within Excel. The Met One outputs data with a header at 40-minute intervals. The header must be removed and data points consolidated for graphing or averaging. The DataRam outputs data every other line in the spreadsheet. When opening the file, blank lines must be eliminated before graphing or averaging. Both the Met One and the DataRam offer optional software packages to eliminate these operations.

**Calibration**—The DataRam and Met One use internal calibration methods. The DataRam performs its zero calibration and completes a span check when a knob on the back panel is rotated to insert the calibration rod. The LCD panel prompts the user to perform the operations. The DataRam can also be gravimetrically calibrated for a particular aerosol. The mass concentration on its 37-mm membrane filter is compared to the optically derived concentration by computing the Time Weighted Average (TWA) using the Estimated Time (ET) and flow-rate values. The Met One's internal zero and span calibration is performed by turning a knob on the instrument's side panel. Zero and span can be adjusted by using a small flat-head screwdriver and turning two screws in the side panel (the latest

model of the GT-640 internally performs zero and span adjustments).

The Radiance Research nephelometer requires particle-free air (zero air or a HEPA filter) to perform the zero calibration and an external refrigerant gas, such as Freon,  $\text{SF}_2$  or  $\text{CO}_2$ , for the span constant. The constants on the panel display must be adjusted to match the zero and span readings. The Optec NGN-3 has an internal zero air filter. An external refrigerant gas (R-134) is used to obtain the measured scattered light value for the span calibration. Achieving a stabilized calibration for these instruments can take 20 minutes or longer. The Andersen aethalometer performs its calibration internally during each startup.

## Reliability

All instruments performed reliably with only minor problems. The manufacturers were prompt and helpful when needed.

**MIE DataRam:** The front panel keypad was not responding and was returned to the vendor and promptly fixed. The customer service was excellent.

**Radiance Research:** This instrument was considerably overestimating the *Bscat* reading. The vendor provided directions for cleaning the optics. Cleaning brought the nephelometer back into normal operating range. The vendor would have repaired the instrument if cleaning had failed. Radiance Research is a very small company. It took several days for the company to respond to the problem although they were very helpful once they responded.

**Met One:** The instrument was recalled for an upgrade and returned promptly. Service was excellent.

**Optec NGN-3:** No problems.

**Andersen Aethalometer:** No problems.

## Accuracy and Instrument Comparison Results

Accuracy and instrument comparison results are based on the two laboratory studies and the field tests. Accuracy was determined by comparing the average mass concentration to the gravimetric results for each test. The average mass concentration for an individual test was calculated by averaging the logged mass concentrations for the test duration. For instance, the MIE DataRam was programmed to average and log the mass concentration in 1-min intervals. For a 1-h test, the average mass concentration would be the average of the 60 logged values. The average test mass concentration for the gravimetric instruments was calculated by dividing the total accumulation of mass deposited on the filter by the total volume of air sampled. Instrument comparison results are determined by comparing the results from identical instruments.

Accuracy and instrument comparisons are broken down for each instrument. Comparison results were not available for the Optec NGN-3 and the Andersen aethalometer because only one of each instrument was available for testing.

Accuracy and instrument comparisons of each instrument type are judged by the least squares linear regression coefficients (slope and correlation coefficient  $R^2$ ) obtained for the number of samples ( $N$ ). The intercept was forced to be zero for clarity. Each figure will show the appropriate data points, slope equation, and the correlation coefficient. For comparison purposes, a line has been drawn at 45 degrees, indicating the best possible one-to-one relationship.

## Gravimetric Instruments

The two FRM instruments compared extremely well. Figure 11 shows that the FRM samplers located beside each other during the 2000 laboratory tests had a slope of 0.99 and an  $R^2$  value of 0.97 over a range of  $PM_{2.5}$  mass concentrations of 40 to 215  $\mu\text{g}/\text{m}^3$ . Results of the collocation studies of the Fire Sciences Laboratory's gravimetric sampler to the FRM during the 1998 and 2000 laboratory tests indicate that the Fire Sciences Laboratory's sampler measured about 10-percent lower than the FRM. Statistical results show a slope of 0.90 with an  $R^2$  value of 0.93 (figure 12). Based on this comparison, all Fire Sciences Laboratory sampler results used in the real-time continuous comparison were corrected by 1.11 ( $1/0.90$ ) to equalize their results with the FRM.

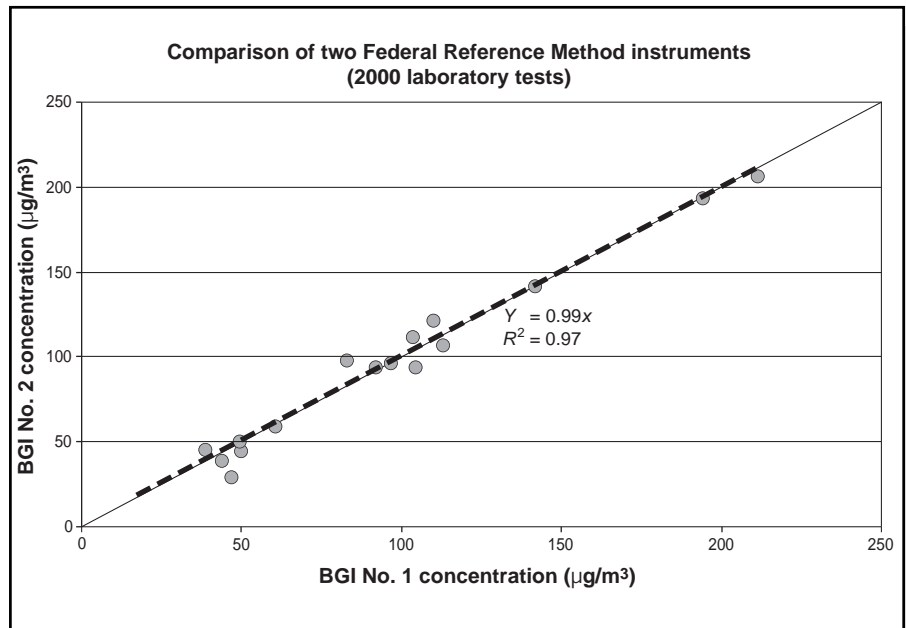


Figure 11—Comparison of the two BGI Federal Reference Method gravimetric samplers used in the 2000 laboratory tests.

## Real-Time Continuous Monitoring Results

### Met One GT-640

**1998 Laboratory Tests**—The Met One GT-640 was not available for these tests.

**Field Tests**—Only one GT-640 was available for the field tests. Results (figure 13) show the instrument over-estimated the mass concentrations by 10 percent in the field environment (slope = 1.10 when compared to the FRM). The  $R^2$  value was poor at 0.35 but only 12 data points were obtained.

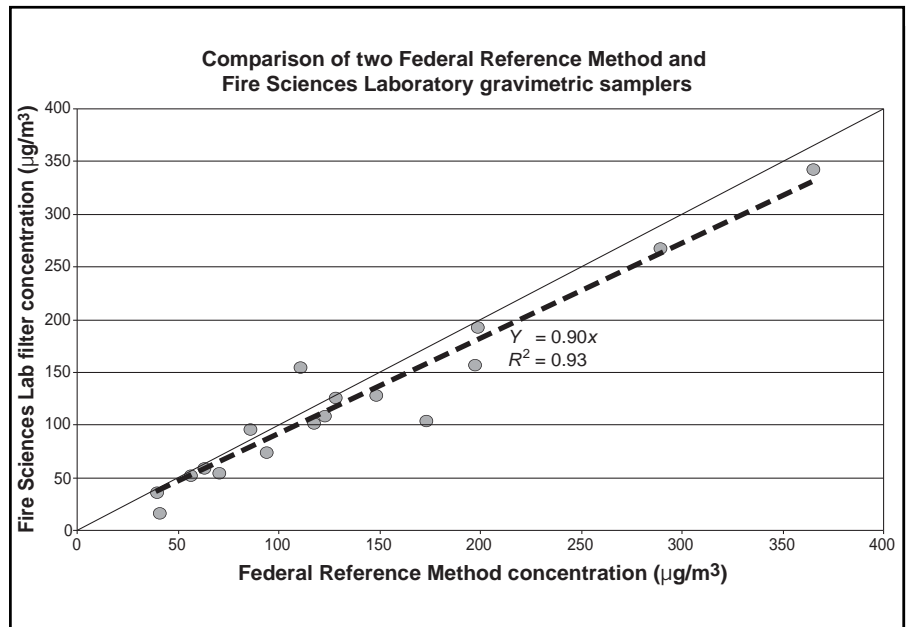


Figure 12—Regression results of the collocated Federal Reference Method and the Fire Sciences Laboratory gravimetric instrument from the 1998 and 2000 laboratory tests.

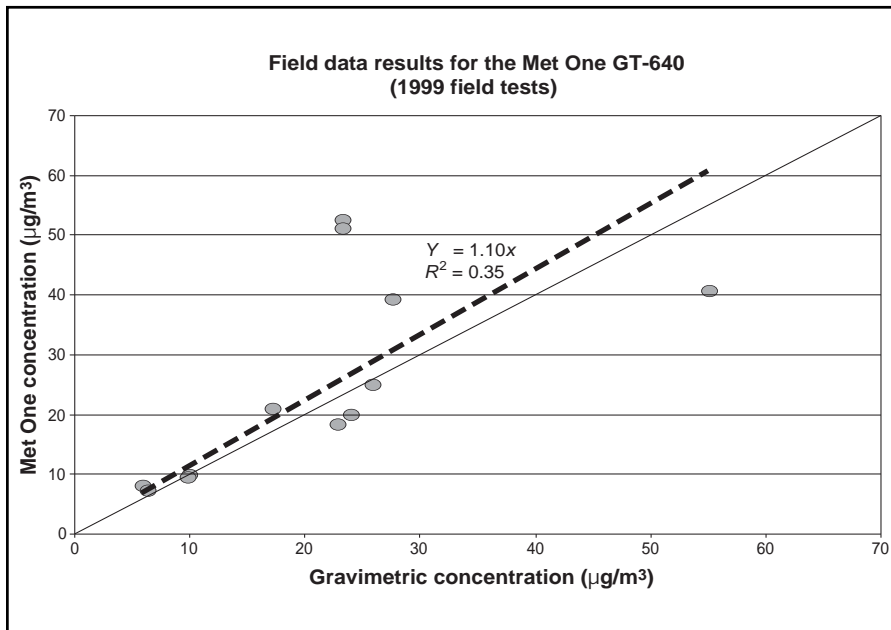


Figure 13—Comparison of the Met One GT-640 and gravimetric results from the 1999 field tests.

Met One instruments shows that the instrument with the inlet heater (Met One No. 2) read higher than the instrument without the heater (Met One No. 1) by 11 percent (slope = 1.11,  $R^2 = 0.98$ ).

**Discussion**—The concentrations measured by the Met One GT-640 did not correlate well with those measured by the Federal Reference Method sampler. This could be due to the small number of data points collected. The 2000 Laboratory tests show the instrument grossly underestimated the mass concentrations by 40 to 50 percent. Although all the real-time continuous instruments underestimated mass concentrations to some degree during the 2000 laboratory tests, the Met One showed the largest discrepancy. Correlation between the two Met One instruments was poor.

**2000 Laboratory Tests**—Two Met One GT-640's were available for the 2000 laboratory tests. Both underestimated the mass concentrations (figures 14 and 15) when compared to the FRM results. Met One No. 1 had a slope of 0.47 ( $R^2 = 0.73$ ). Met One No. 2 had a slope of 0.60 ( $R^2 = 0.78$ ). When the instruments were compared to one another, the No. 2 instrument was reading 26 percent higher than instrument No. 1 (slope = 1.26,  $R^2 = 0.79$ ).

Results from the high-humidity tests (figures 16 and 17) show both instruments underestimated the mass concentrations. Instrument No. 1 without its inlet heater underestimated mass concentrations by 15 percent (slope = 0.85,  $R^2 = 0.63$ ). Instrument No. 2 with its inlet heater installed underestimated mass by 6 percent (slope = 0.94,  $R^2 = 0.61$ ). Comparison of the results of the two

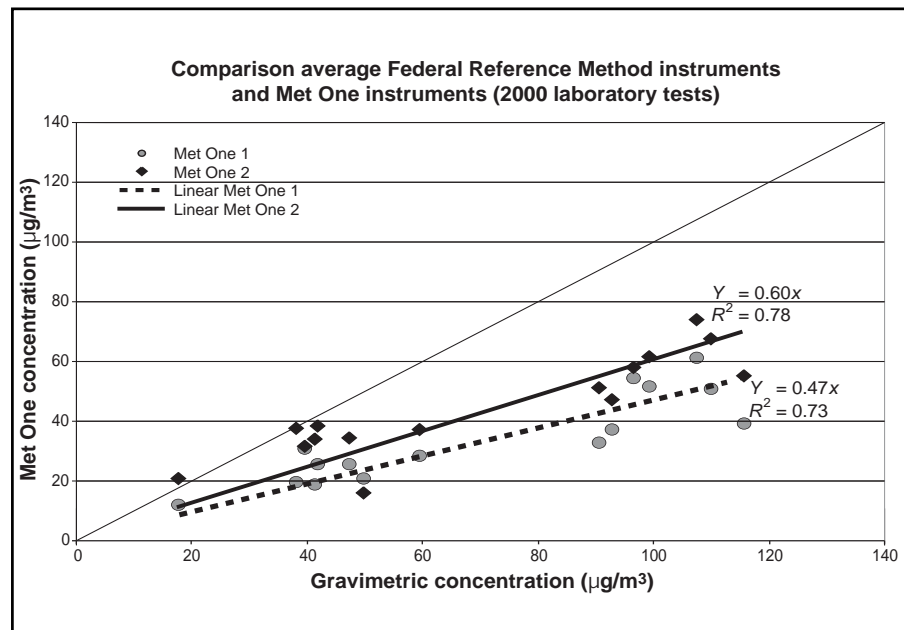


Figure 14—The 2000 laboratory results of the two Met One GT-640's and the gravimetric samplers. Gravimetric results are derived from the average of the two Federal Reference Method samplers.

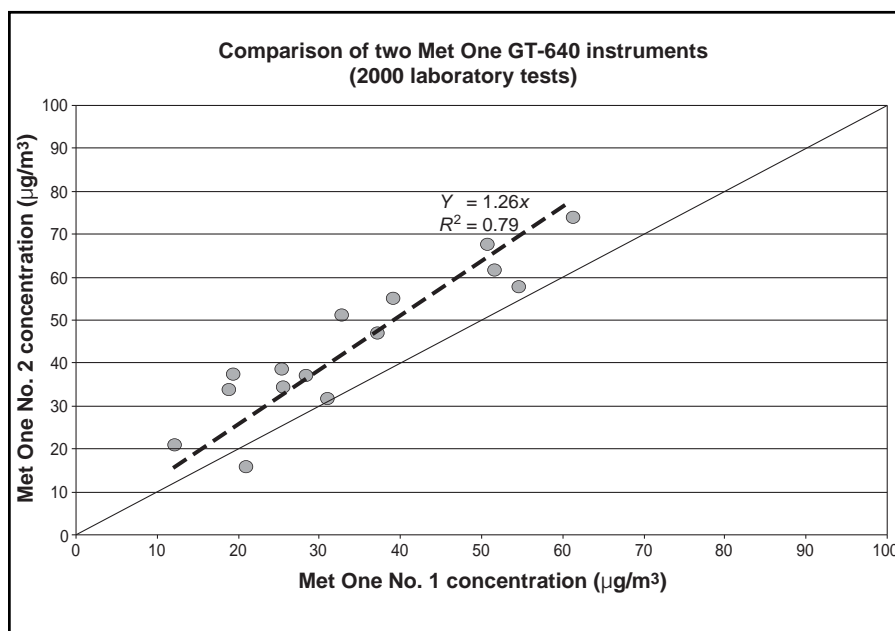


Figure 15—Comparison of the results from the two Met One GT-640 samplers during the 2000 laboratory tests.

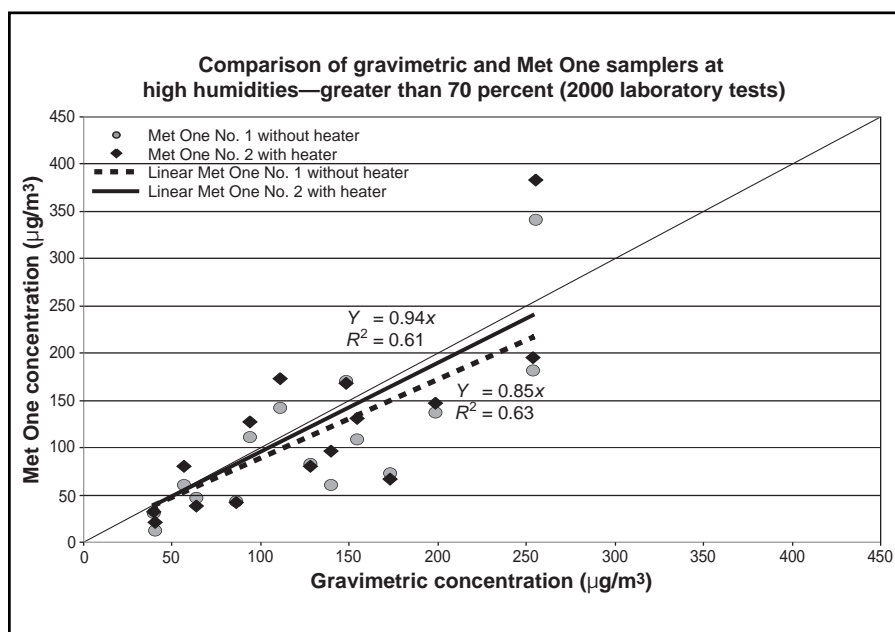


Figure 16—Results of the high-humidity laboratory tests. Instrument No. 1 did not have the inlet heater installed.

One instrument read 26 percent higher than the other. Met One has upgraded the GT-640 to improve the instrument's performance at low particulate concentrations. This may improve the consistency among identical instruments.

The high-humidity tests yielded positive results. In theory, the inlet heater should be drying the particulates as they enter the optical chamber, lowering the mass concentration estimate from the instrument. In this study, even though the instrument with the inlet heater was still reading higher than the one without the inlet heater, the difference between the two decreased (from 26 percent to 11 percent), indicating the heater was removing some moisture from the particulates.

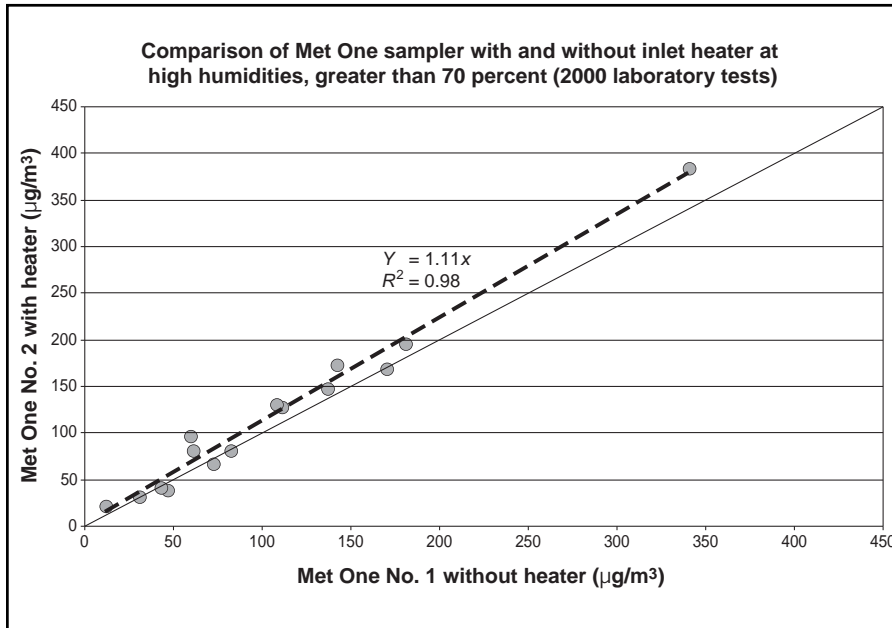


Figure 17—Comparison of the laboratory high-humidity results from two Met One GT-640 instruments.

## MIE DataRam

**1998 Laboratory Tests**—Two DataRams were used for the 1998 laboratory tests. Concentrations measured by the gravimetric sampler during the tests ranged from 20 to 450  $\mu\text{g}/\text{m}^3$ . Figures 18, 19, and 20 show the results. DataRam No. 1 had a slope of 1.93 with an  $R^2$  of 0.98, indicating that it overestimated the mass concentration results from the gravimetric sampler by 93 percent. DataRam No. 2 had a slope of 2.16 with an  $R^2$  of 0.97 when its results were compared to the gravimetric results. Comparison results between the two instruments indicate DataRam No. 2 read 13 percent higher than DataRam No. 1. The slope of the line for the instrument comparison was 1.13 with an  $R^2$  above 0.99, indicating excellent reliability but a need to calibrate each instrument.

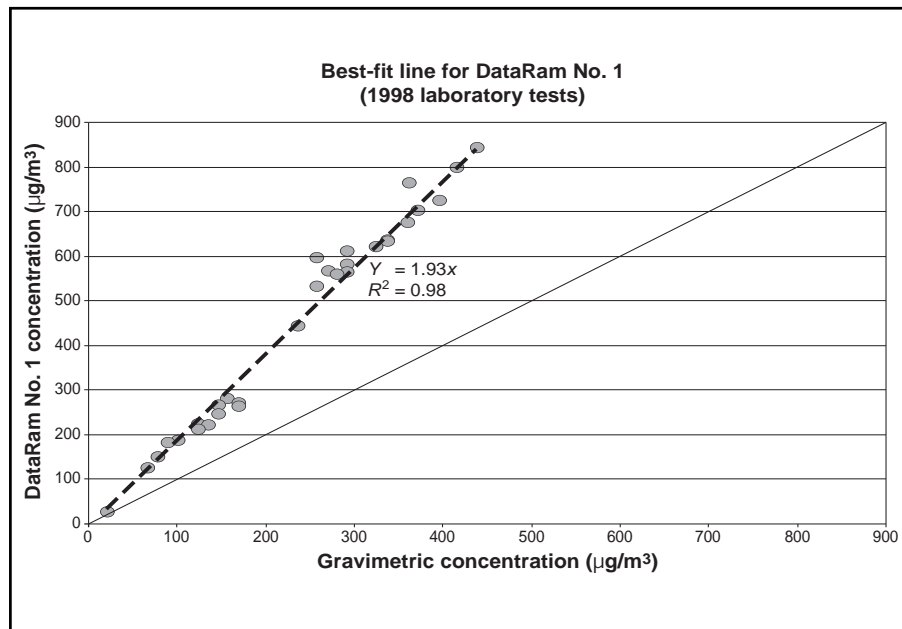


Figure 18—Comparison of the 1998 laboratory results from DataRam No. 1 and the gravimetric sampler. Gravimetric results are from the Fire Sciences Laboratory gravimetric sampler.

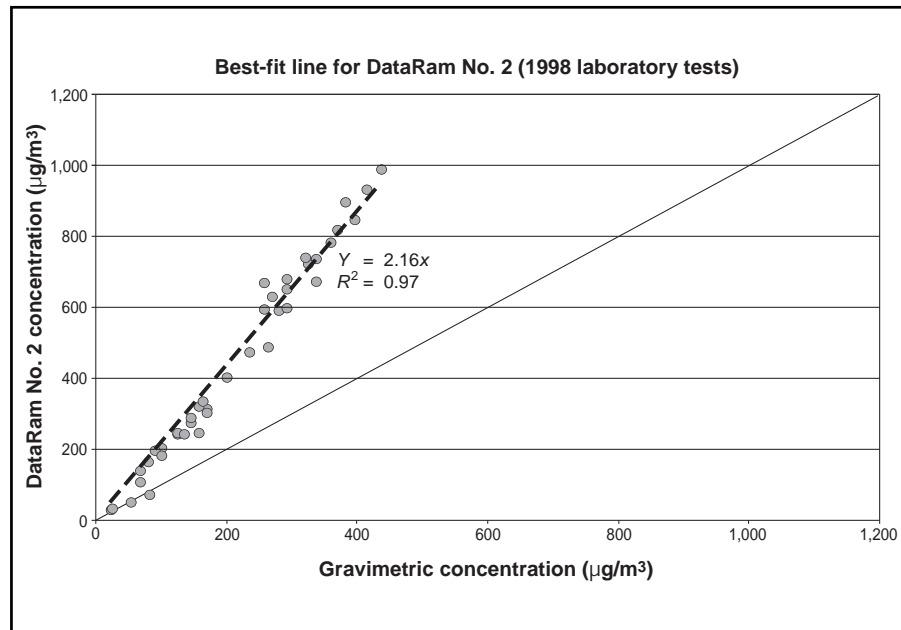


Figure 19—Comparison of the 1998 laboratory results from DataRam No. 1 and the Fire Sciences Laboratory gravimetric sampler.

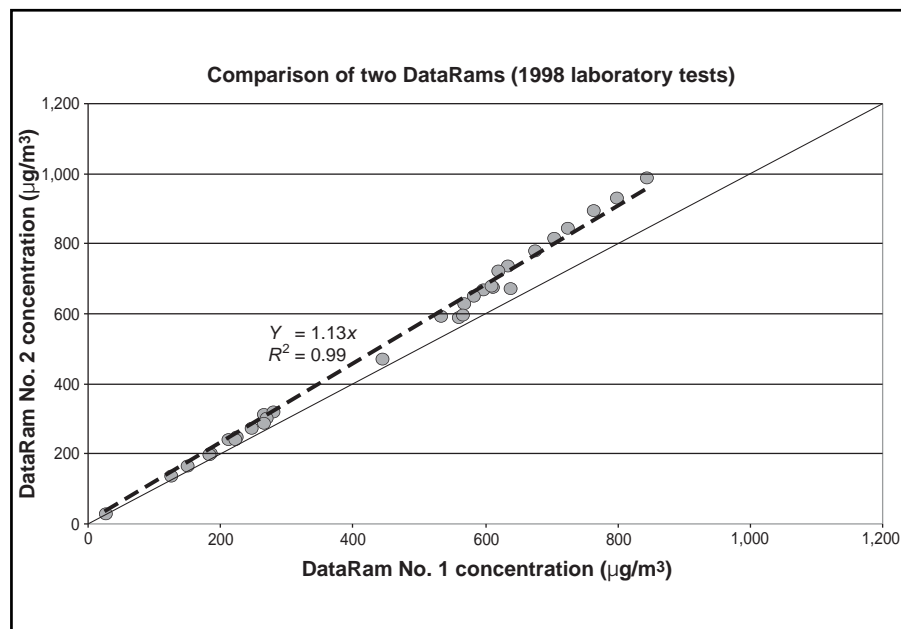


Figure 20—The 1998 laboratory results of the two DataRams plotted against each other.



**Field Results**—Figure 21 shows the DataRam results for the field collocation study. Field tests conducted in 1998 and 1999 show the DataRam overestimated the gravimetric results by 21 percent (slope = 1.21,  $R^2 = 0.89$ ,  $N = 20$ ).

**2000 Laboratory Tests**—Concentration ranges for the 2000 laboratory tests were intended to be lower than in the 1998 laboratory tests (similar to concentrations that would be seen in actual field use). The concentrations during the 2000 laboratory tests ranged from under  $20 \mu\text{g}/\text{m}^3$  to just under  $120 \mu\text{g}/\text{m}^3$  as measured by the FRM. Figure 22 shows the results of the two DataRams compared to results of the average of the two FRM samplers. Both DataRams underestimated the mass concentration. DataRam No. 1 had a slope of 0.70 ( $R^2 = 0.76$ ) while DataRam No. 2 had a slope of 0.80 ( $R^2 = 0.79$ ). Comparison of the two DataRams (figure 23) to each other indicates that DataRam No. 2 read 14 percent higher than DataRam No. 1 (slope = 1.14,  $R^2 = 0.99$ ,  $N = 15$ ). These instrument comparison results are remarkably similar to the 1998 laboratory results conducted at concentrations more than twice as great, showing instrument consistency and individuality.

High-humidity tests (relative humidity higher than 70 percent) were performed with DataRam No. 1 configured with no inlet heater and DataRam No. 2 with its inlet heater installed. Figures 24 and 25 show the results from those tests. As previously mentioned, at low relative humidities and with the inlet heater installed, DataRam No. 1 had a slope of 0.70 ( $R^2 = 0.76$ ). At high relative humidities without the inlet heater, the slope increased to 1.38 ( $R^2 = 0.73$ ). DataRam No. 2 had the inlet heater installed for both the low and high relative humidities tests.

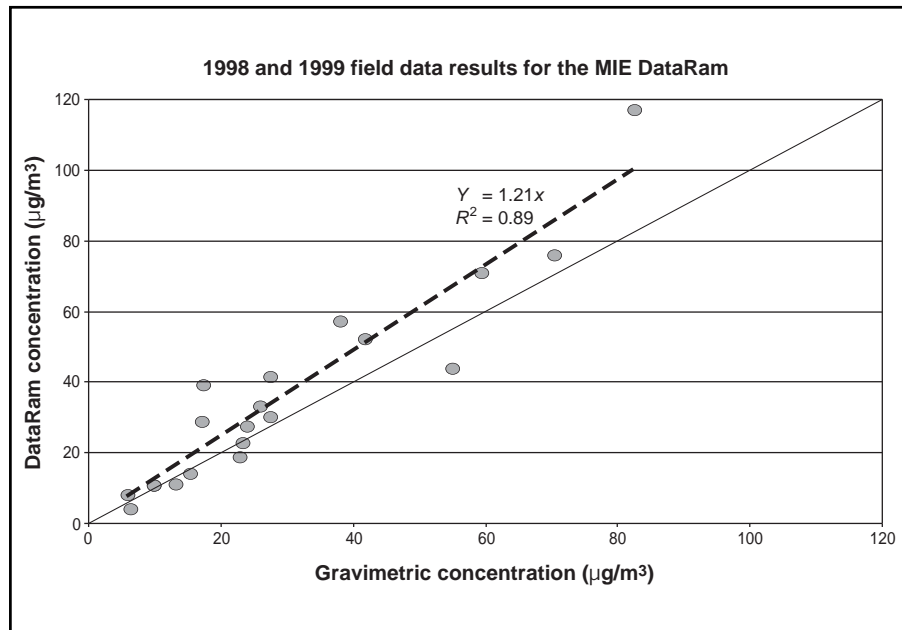


Figure 21—The 1998 and 1999 field results of the DataRam No. 1 plotted against the gravimetric results. Gravimetric results are from the Fire Sciences Laboratory and the Federal Reference Method samplers.

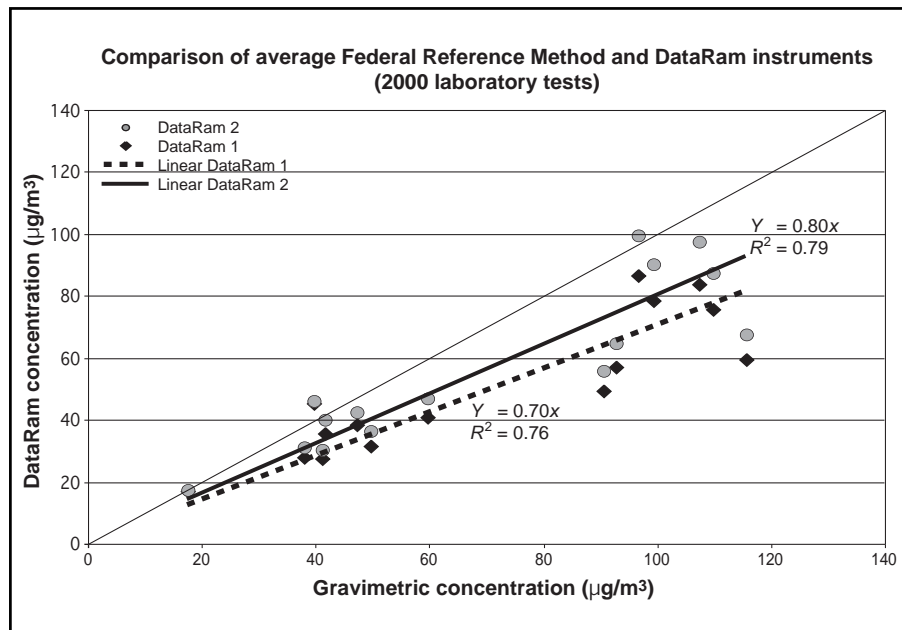


Figure 22—Results of the two DataRams used in the 2000 laboratory tests compared to the gravimetric results. Gravimetric results are derived from the average of the two Federal Reference Method samplers used during the tests.



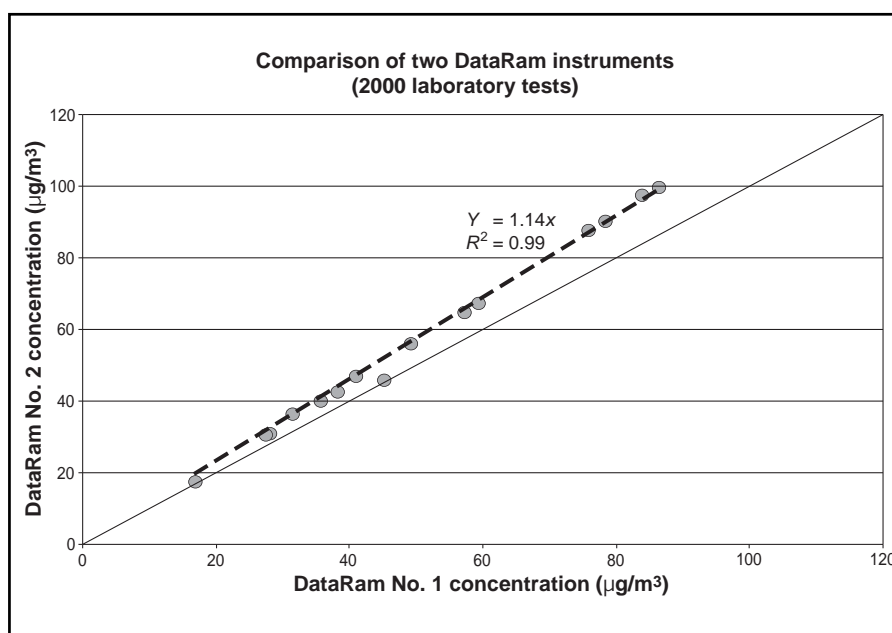


Figure 23—Comparison of the two DataRams used in the 2000 laboratory tests.

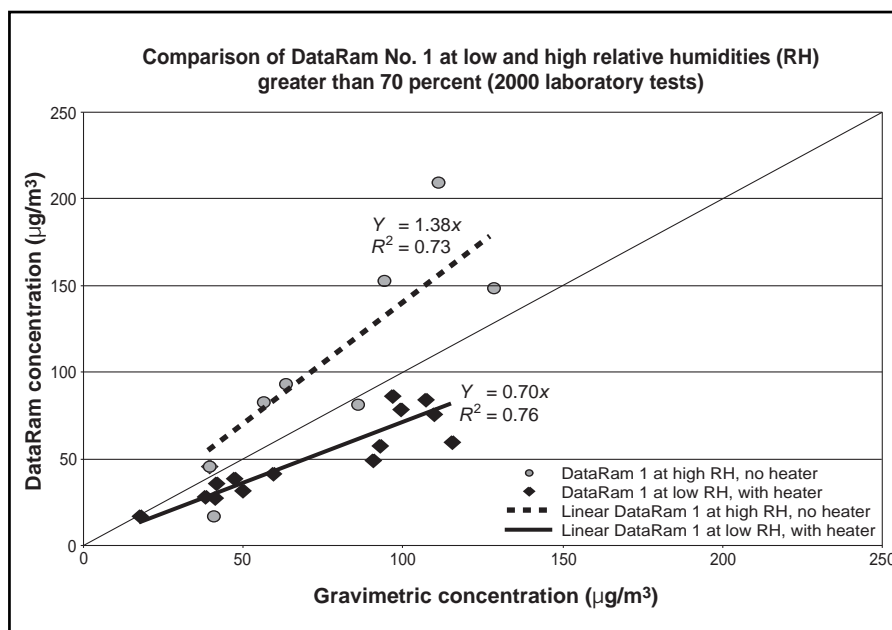


Figure 24—Comparison of DataRam No. 1 at low (less than 40 percent) and high (more than 70 percent) relative humidities during the 2000 laboratory tests. The inlet heater was installed for the low-humidity tests. The inlet heater was removed for the high-humidity tests. Gravimetric results are from the Federal Reference Method sampler.

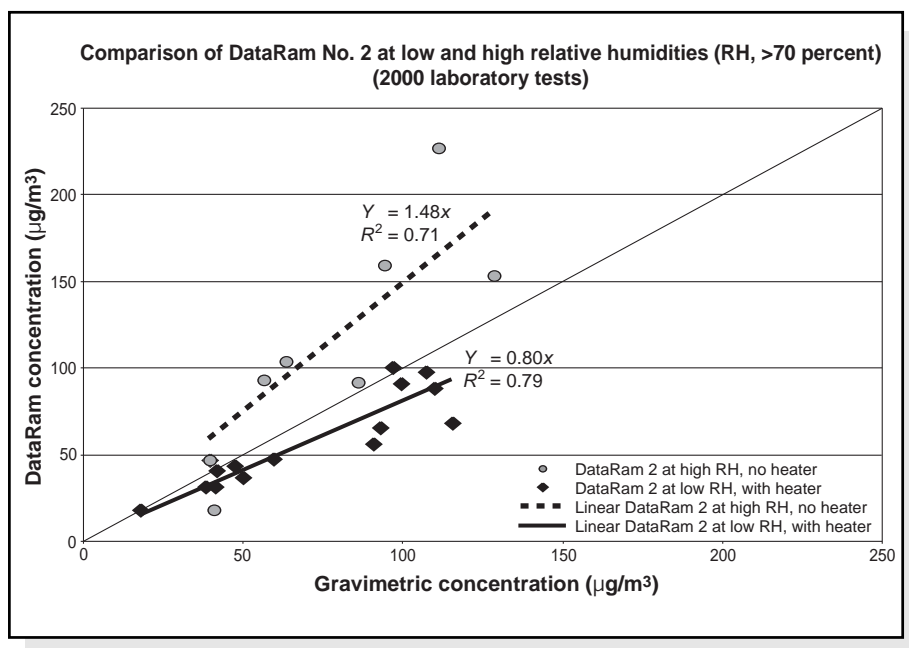


Figure 25—Comparison of DataRam No. 2 at low (less than 40 percent) and high (more than 70 percent) relative humidities during the 2000 laboratory tests. The inlet heater was installed for both the high- and low-humidity tests. Gravimetric results are from the Federal Reference Method sampler.

The slope went from 0.80 ( $R^2 = 0.79$ ) at low relative humidities to 1.48 ( $R^2 = 0.71$ ) at high relative humidities.

**Discussion**—During the 1998 tests when the instruments were exposed to higher particulate concentrations, the DataRam overestimated concentrations by about 93 percent. During the 2000 laboratory tests the DataRam underestimated lower mass concentrations by 20 to 30 percent. Field tests sampling low concentrations (similar to the 2000 laboratory tests) showed that the DataRam overestimated mass concentrations, but not as much as during the high-concentration 1998 laboratory tests. The differences in the laboratory results may be attributed to the different amount of needles being burned. This caused different flaming and smoldering conditions within the fire and may have generated particulates with different optical properties.

The two DataRams compared similarly during previous tests but accuracy was poor. DataRam No. 2 read about 14 percent higher than DataRam No. 1 throughout the tests. The high-humidity tests indicate that the inlet heater is not entirely effective in reducing the moisture content of the particulate. The instruments continue to overestimate mass concentrations. DataRam No. 1’s mass concentration estimates increased by 97 percent when relative humidities were above 70 percent and the inlet heater was not installed. DataRam No. 2’s mass-concentration estimates increased by 85 percent when relative humidities were above 70 percent, even when the inlet heater was installed.

## Radiance Research Nephelometer

**1998 Laboratory Tests**—The Radiance Research nephelometers overestimated the mass-concentration results by 1.90 for sampler No. 1 and 1.81 times for sampler No. 2 (figures 26 and 27). The  $R^2$  values were 0.97 and 0.92, respectively. For the 12 samples when two Radiance nephelometers were collocated, Radiance No. 2 underestimated the mass-concentration estimate of Radiance No. 1 by 5.5-percent (slope = 0.95,  $R^2 = 0.99$ ). Concentration ranges for the tests varied between 20  $\mu\text{g}/\text{m}^3$  and 450  $\mu\text{g}/\text{m}^3$  as measured by the gravimetric sampler.

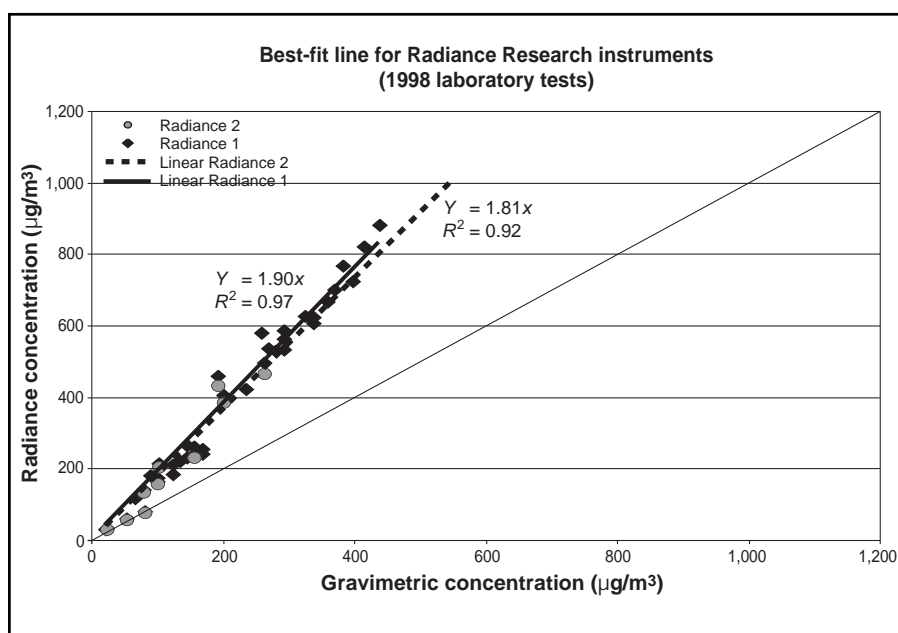


Figure 26—The 1998 laboratory results of the two Radiance Research nephelometers and the gravimetric sampler. Gravimetric results are from the Fire Science Laboratory gravimetric sampler.

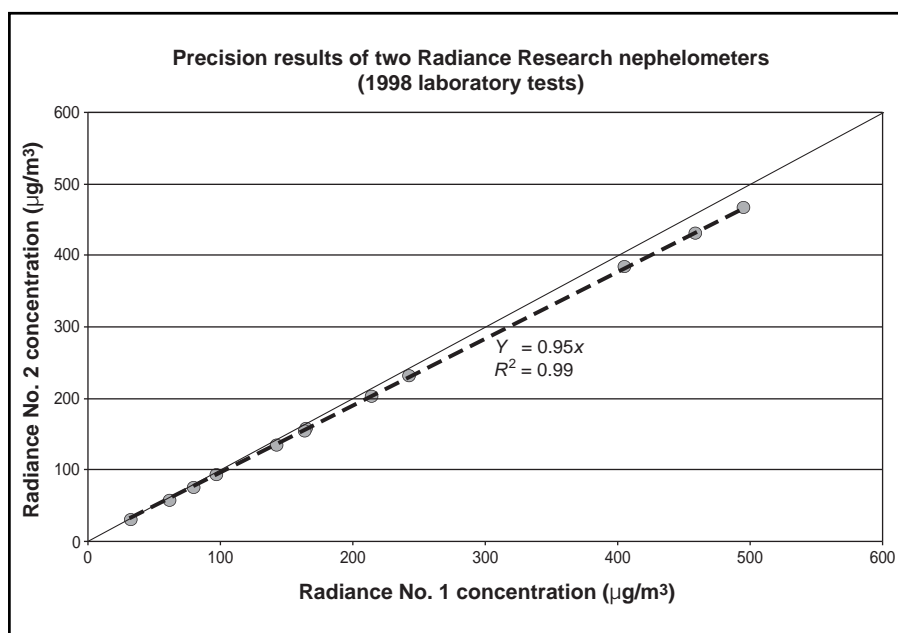


Figure 27—The 1998 laboratory results of the two Radiance Research nephelometers compared to one another.

**Field Tests**—Results from the field tests (figures 28 and 29) show both the Radiance Research nephelometers overestimated the mass concentration results of the FRM samples. Radiance No. 1 overestimated the concentrations by 27 percent (slope = 1.27,  $R^2 = 0.78$ ,  $N = 22$ ). Radiance No. 2 overestimated the concentrations by 57 percent (slope = 1.57,  $R^2 = 0.90$ ,  $N = 14$ ). Radiance No. 2 was not used for all the field tests. For this reason, different slopes were obtained for the two nephelometers. Comparing the results when both of the Radiance nephelometers were available shows that they estimate essentially the same mass concentration for the field tests (slope = 1.00,  $R^2 = 0.97$ ,  $N = 14$ ).

**2000 Laboratory Tests**—The 2000 laboratory test results (figures 30 and 31) show that both Radiance Research nephelometers overestimated mass concentrations when compared to the average results of the two FRM's. Radiance No. 1 overestimated concentrations by 12 percent (slope = 1.12,  $R^2 = 0.90$ ,  $N = 13$ ) while Radiance No. 2 overestimated the concentrations by 14 percent (slope = 1.14,  $R^2 = 0.90$ ,  $N = 14$ ). The Radiance nephelometers estimated total suspended particulate while the other instruments estimated  $PM_{2.5}$  and smaller.

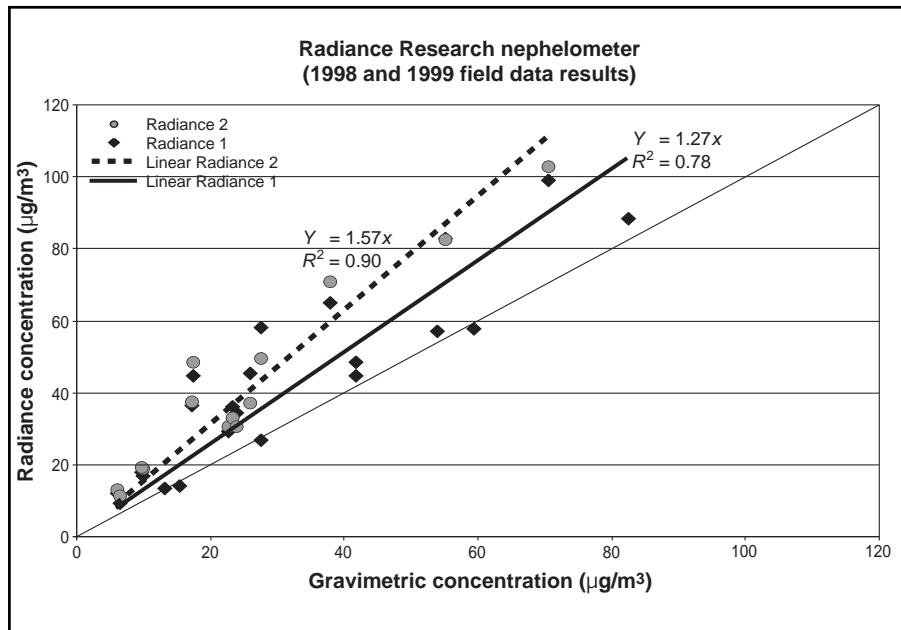


Figure 28—The 1998 and 1999 field results of the two Radiance Research nephelometers and the gravimetric samplers. Gravimetric results are from both the Fire Sciences Laboratory and Federal Reference Method samplers.

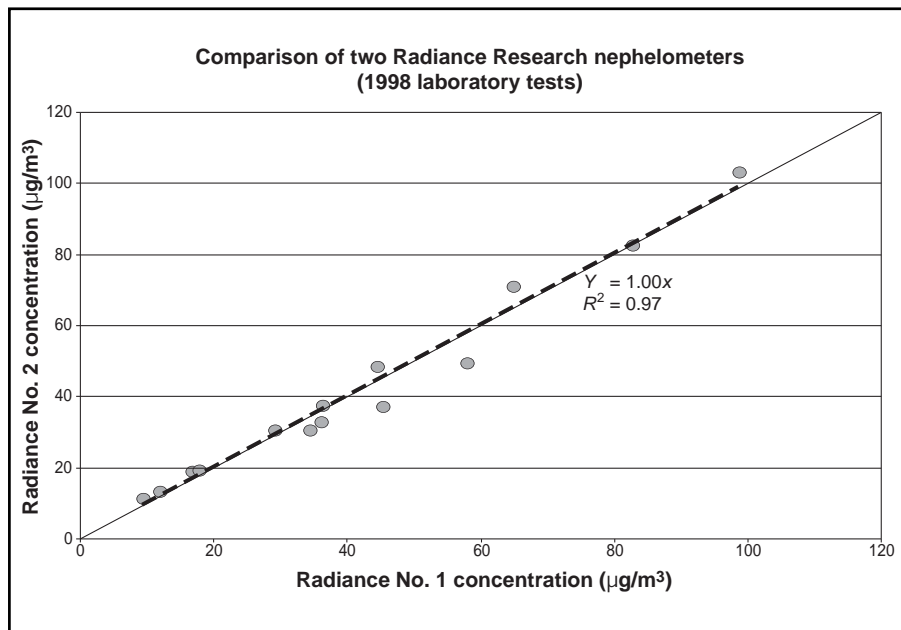


Figure 29—Comparison of the two Radiance Research nephelometers used in the field tests.

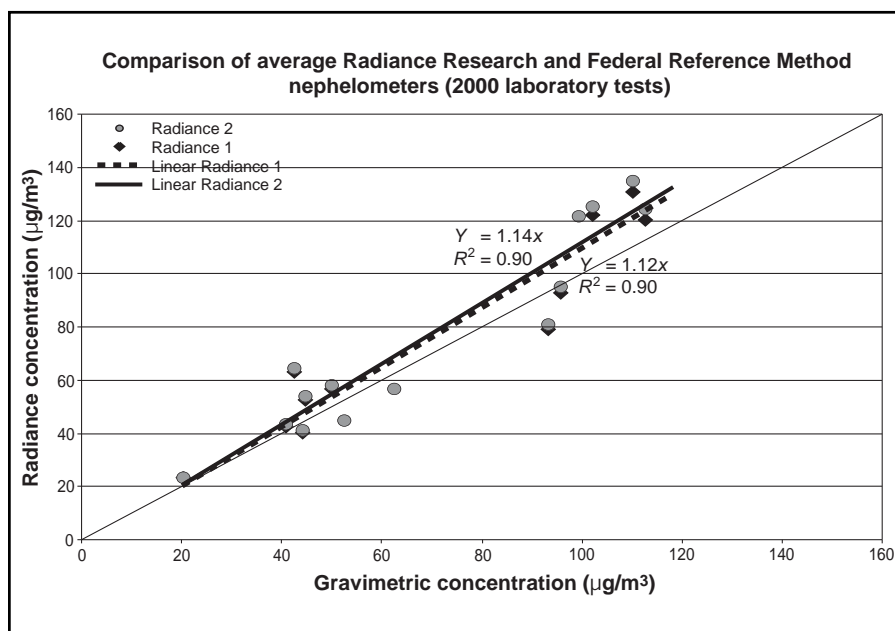


Figure 30—The 2000 laboratory results of the two Radiance Research nephelometers compared to the average result from the Federal Reference Method gravimetric samplers used in the tests.

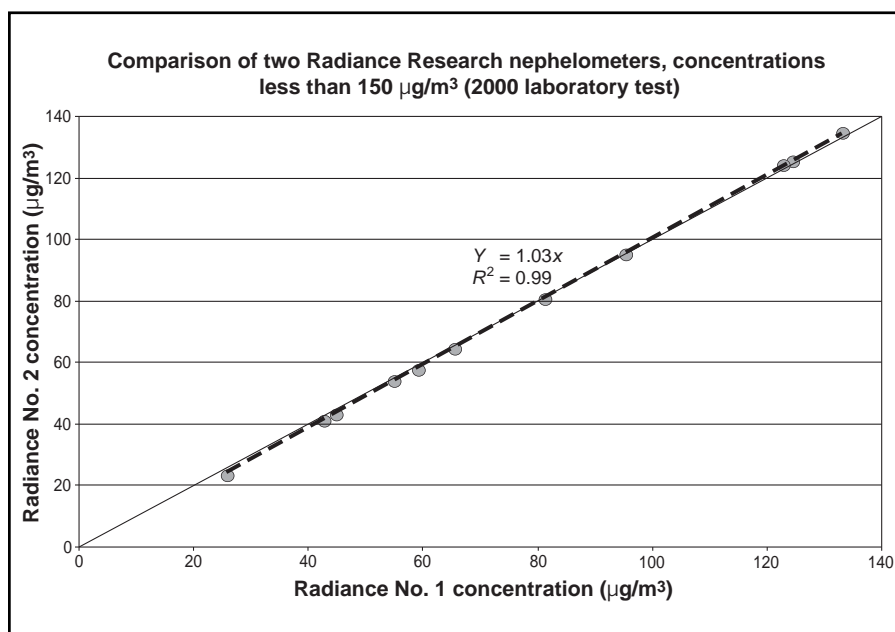


Figure 31—Comparison of the results from the two Radiance Research nephelometers in the 2000 laboratory tests.

At high humidities (higher than 70 percent), the Radiance nephelometers overestimated the mass concentrations by 51 percent (with inlet heater) and 64 percent (without inlet heater, figures 32 and 33). The Radiance nephelometer with the inlet heater had a slope of 1.51 and an  $R^2$  value of 0.87. The nephelometer without the inlet heater had a slope of 1.65 and an  $R^2$  value of 0.84. The Radiance nephelometer with the inlet heater read 9 percent lower than the nephelometer without the heater (slope = 0.91,  $R^2 = 0.98$ ,  $N = 14$ ).

**Discussion**—The Radiance Research nephelometer performed much like the DataRam. It overestimated mass concentrations by 80 to 90 percent during the 1998 laboratory tests. The overestimate was 10 percent during the 2000 laboratory tests. The field test overestimates were between the 1998 and 2000 laboratory overestimates. The difference in the laboratory results may be attributable to differences in the amount of needles burned during the tests.

The Radiance nephelometers showed excellent consistency when compared against each other. The instruments consistently read within 5 percent of each other with very high correlations.

The high-humidity tests indicated that the inlet heater does affect the mass concentration estimations. The nephelometer with the inlet heater had readings 9 percent lower than the one without.

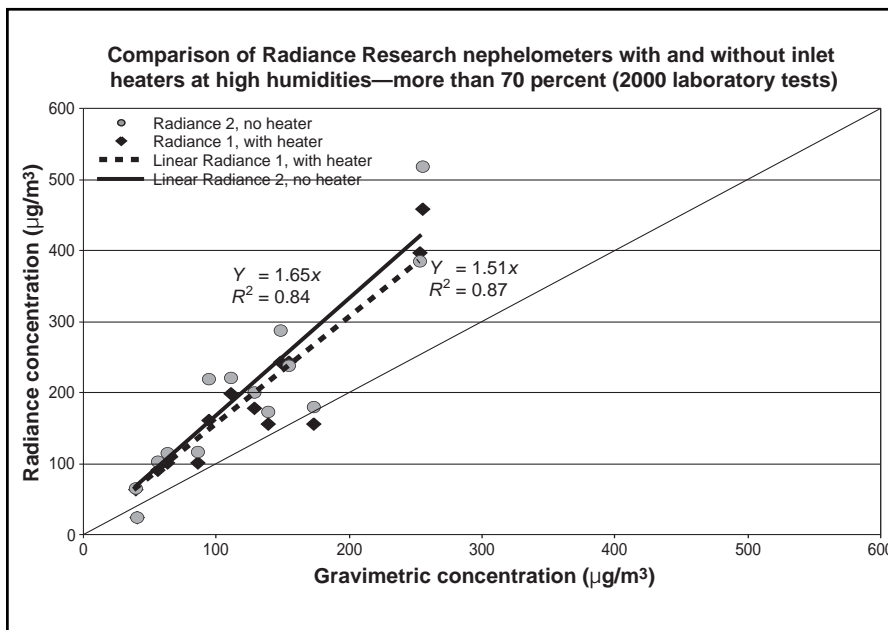


Figure 32—Comparison of the results from the Radiance Research nephelometers and the gravimetric sampler. Radiance No. 1 had an inlet heater while Radiance No. 2 did not. Gravimetric results are from the Federal Reference Method sampler.

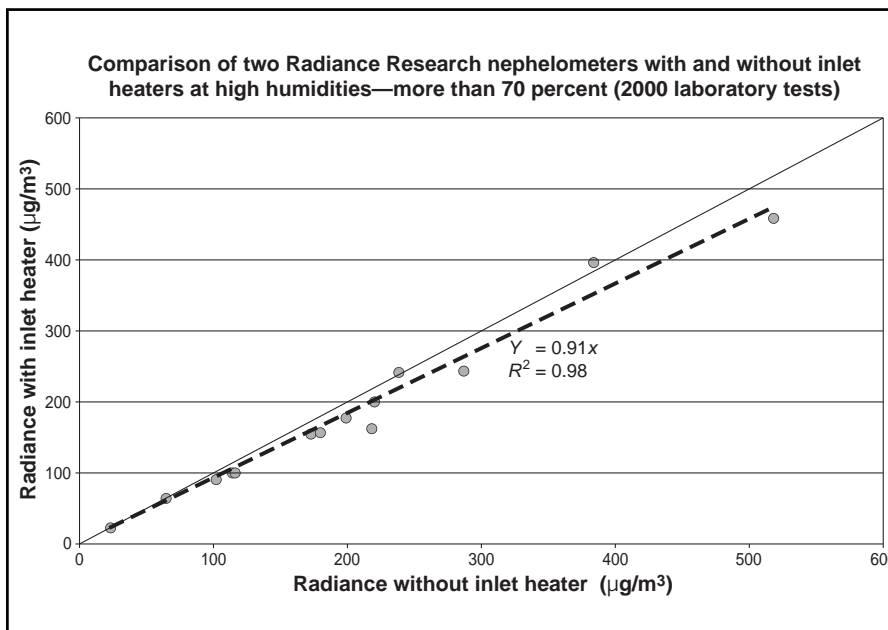


Figure 33—Comparison of the two Radiance Research nephelometers used during the high-humidity tests.

## Optec NGN-3 Nephelometer

The Optec NGN-3 was not available for the 1998 laboratory or field tests.

**2000 Laboratory Tests**—The Optec NGN-3 underestimated the mass concentrations by 33 percent (slope = 0.68,  $R^2 = 0.81$ ,  $N = 14$ ) when compared to the average results from the two FRM samplers (figure 34). The results for the tests were presented using a conversion factor of 3.0 from *Bscat* to mass concentration, the factory preset value. At high humidities, the NGN-3 with the correction factor set at 3.0 underestimated the mass concentrations by 6 percent (slope = 0.94,  $R^2 = 0.84$ , figure 35).

**Discussion**—The Optec NGN-3 is a new instrument and was not available for all the tests. The 2000 laboratory results were consistent with the other real-time continuous instruments. No instrument comparison results are available because only one instrument was included in the study.

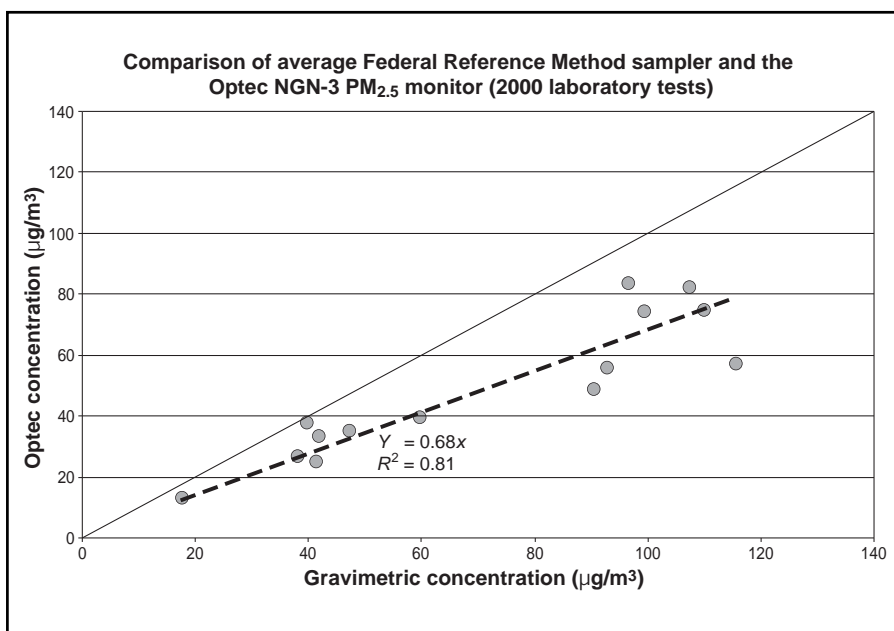


Figure 34—The 2000 laboratory results of the Optec NGN-3 nephelometer and the average of the two Federal Reference Method gravimetric samplers.

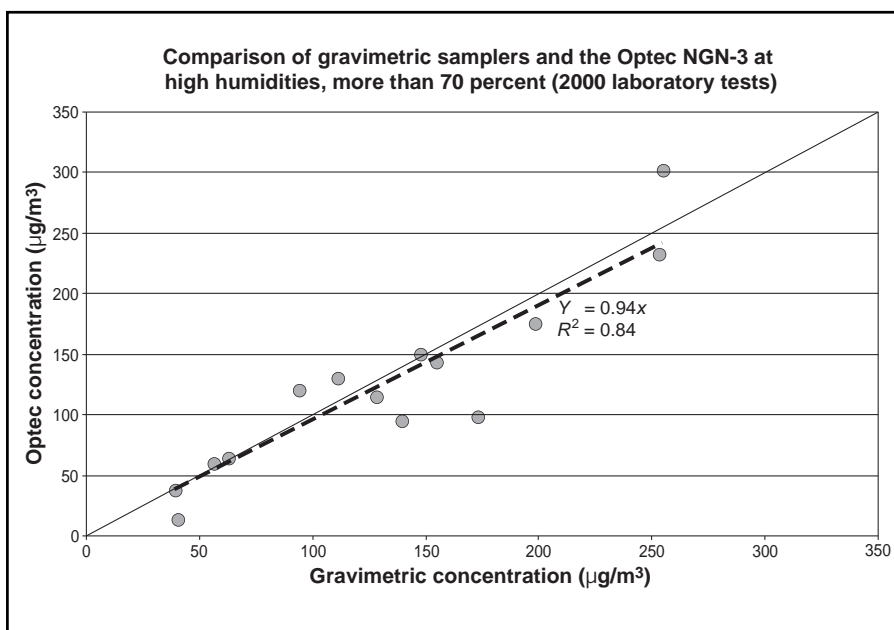


Figure 35—Results of the high-humidity tests for the Optec NGN-3 nephelometer compared to the gravimetric results. Gravimetric results are from a Federal Reference Method sampler.



## Andersen Aethalometer

The aethalometer was not available for the 1998 laboratory tests and was available only for part of the field tests. No data are available for the 2000 lab tests because of a configuration problem with a PM<sub>2.5</sub> cutoff inlet. The problem was found after testing was complete, voiding the test results.

**Field Tests**—For the few field tests in which the Andersen aethalometer was used, it overestimated the mass concentration. Figure 36 shows the best-fit line with a slope of 11.99, an intercept of 90  $\mu\text{g}/\text{m}^3$ , and an  $R^2$  value of 0.92.

**Discussion**—Results for the Andersen aethalometer are very limited and should be considered preliminary.

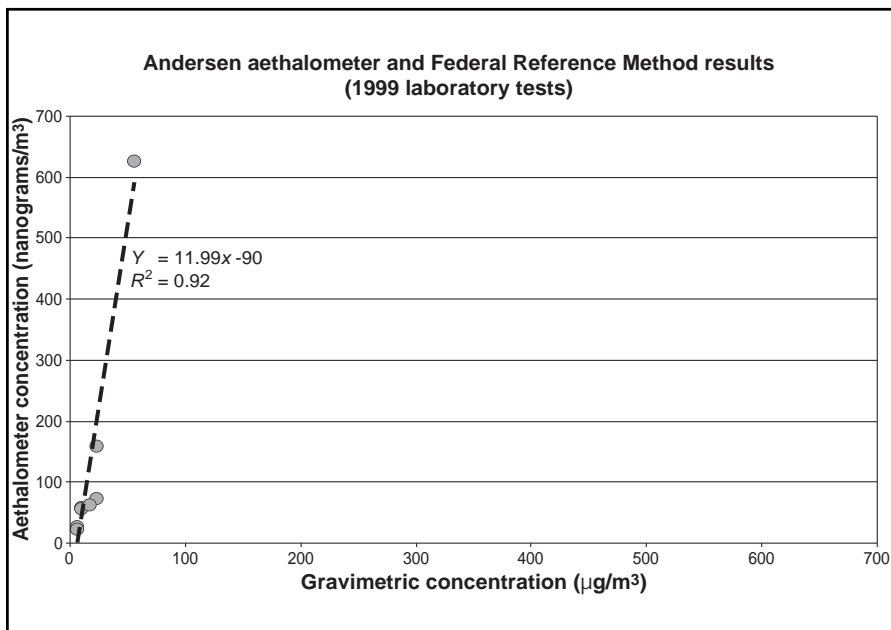


Figure 36—The 1999 laboratory results of the Andersen aethalometer compared to the results of a Federal Reference Method sampler.