

Field Test Results of the Optec NGN-3 PM_{2.5} Size-cut Nephelometer

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ABSTRACT

The Optec NGN-3 size-cut and heated nephelometer was specifically designed to measure continuous dry PM_{2.5} aerosol scattering which can be used as a surrogate for PM_{2.5} mass. The NGN-3 integrates the original optics from the widely-accepted NGN-2 ambient nephelometer with a well-characterized PM_{2.5} size-cut inlet, an inline sample heater, and a controlled 7 LPM sample flow rate.

In order to test its performance against an EPA Federal Reference Method (FRM) for PM_{2.5} sampling, as well as other continuous and filter-based mass samplers, and to investigate the effectiveness of its size-cut inlet, the NGN-3 has operated in studies at Bakersfield, California (December 1998 – January 1999), Fort Collins, Colorado (March – April 1999), and Phoenix, Arizona (November 1999 – February 2000). Results from these studies indicate that over a broad range of pollution conditions, the Optec NGN-3 size-cut nephelometer effectively and accurately measures continuous dry PM_{2.5} scattering and mass.

INTRODUCTION

The Optec NGN-3 size-cut and heated nephelometer was specifically designed as a surrogate for PM_{2.5} mass sampling and has been involved in three studies over the past year to test its performance against other types of continuous and filter-based mass sampling instruments. This paper summarizes the results from those studies.

The NGN-3 integrates the optical design of the original NGN-2 ambient nephelometer with a 2.5 μm size-cut device and an inline sample heater to measure the dry scattering of fine mass. The sample flow is held at 7 LPM to ensure the proper cut point by maintaining the pressure of the

pump exhaust through a critical orifice. Feedback from a pressure sensor located before the orifice in the exhaust stream controls the variable speed pump. The NGN-3 continuously outputs both a particle scattering and a fine mass measurement with a minimum integration time of 2 minutes. Conversion of the particle scattering to mass is accomplished with a constant user-defined mass scattering efficiency:

$$\text{Fine Mass } [\mu\text{g}/\text{m}^3] = \text{Particle Scattering } [\text{Mm}^{-1}] / \text{Mass Scattering Efficiency } [\text{m}^2/\text{g}].$$

In reality the mass scattering efficiency is determined by the aerosol size distribution, density, and refractive index. Based on published studies of the natural variability of these parameters for fine mass, Molenaar¹ has generated a frequency distribution of possible mass scattering efficiencies with a geometric mean of 2.8 m²/g, and 95% confidence limits of 1.3 to 6.2 m²/g. During the studies reported here, the user-defined mass scattering efficiency was set to 3.0 m²/g. This choice yielded good agreement between NGN-3 and other mass measurements at Bakersfield and Fort Collins. Analysis of the data collected at Phoenix indicated that, on average, the NGN-3 mass measurements were 59% of the filter mass measurements, implying that a choice of 1.8 m²/g for the mass scattering efficiency at this location during winter is appropriate.

BAKERSFIELD STUDY RESULTS

The California Air Resources Board (CARB) sponsored a comprehensive instrument intercomparison study of over 25 sampling instruments in Bakersfield, California, during Winter 1999 (December 1998 through January 1999). All sampler inlets resided on the roof of a one story building located within a 10 m by 40 m area. Daily 24-hr average PM_{2.5} mass concentrations during the study ranged from 5 to 130 μg/m³, with hourly events extending above 160 μg/m³.

The standard reference for PM_{2.5} mass concentration during the study was a CARB-operated Andersen Sequential sampler (EPA FRM for PM_{2.5} sampling). Regression analysis of 24-hr averages of NGN-3 PM_{2.5} mass against the standard, shown in Figure 1, yielded a slope of 1.02, an intercept of -6.17 μg/m³, and an R² of 0.99. Precision of the NGN-3, as measured against a second, collocated NGN-3 which operated for a portion of the study yielded a slope of 1.01, an intercept of -1.64 μg/m³, and an R² of 0.99.²

The NGN-3 inlet was collocated with an Optec NGN-2 ambient nephelometer during the study. Intakes for both nephelometers were approximately 2 m above roof level and 1 meter apart. The ambient nephelometer is an open-air design with no size-cut device or sample air heater. As such, the NGN-2 measures particle scattering (b_{sp}) of all airborne aerosols, including hygroscopic particles whose scattering increases with relative humidity (RH). The measured ambient b_{sp} was almost always higher than the dry, size-cut b_{sp} measured with the NGN-3. Figure 2 shows a comparison of NGN-2 ambient b_{sp} and NGN-3 dry size-cut b_{sp} for periods when the ambient RH was less than 70%. The NGN-3 size-cut particle scattering was, on average, 61% of the ambient particle scattering with an R² of 0.98.

Figure 1. Comparison of Optec NGN-3 and Andersen FRM PM_{2.5} mass, Bakersfield, California, Winter 1999.

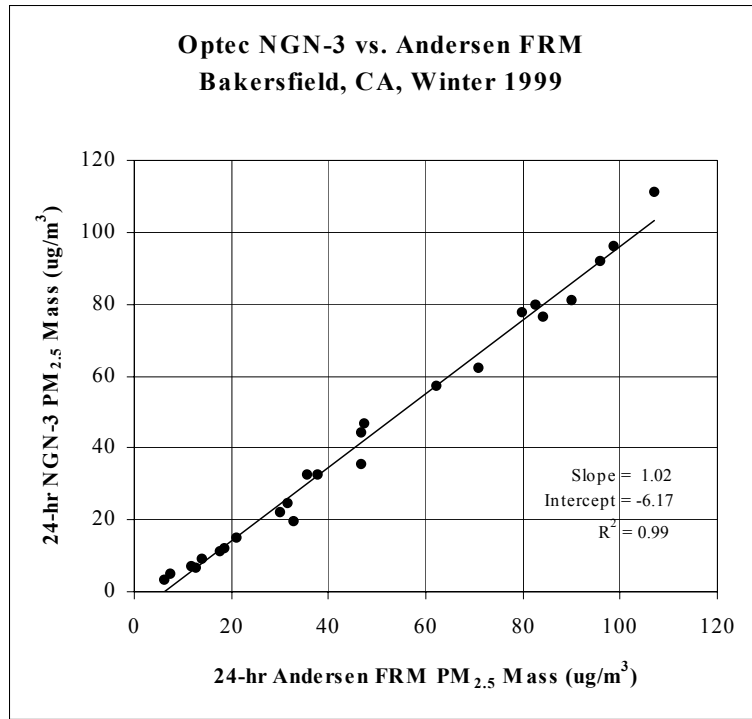
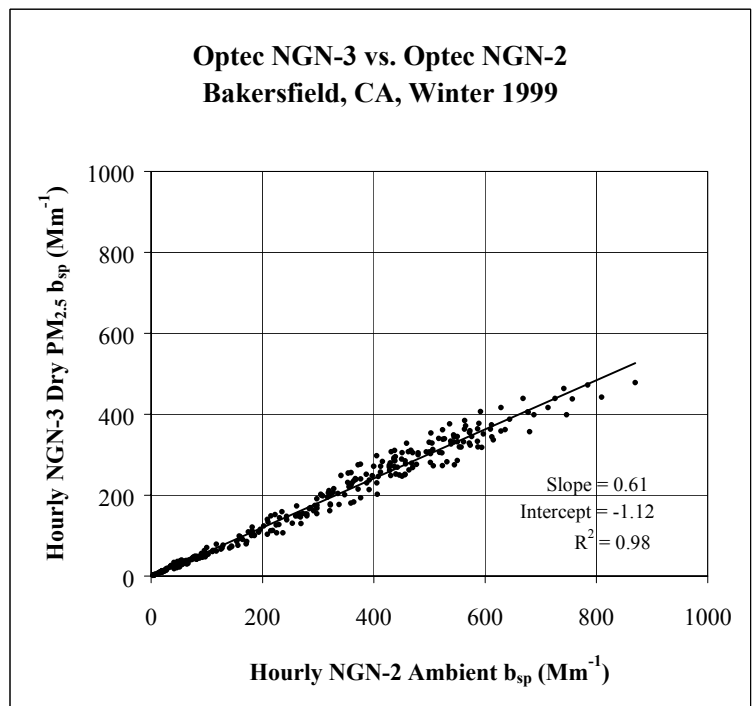


Figure 2. Comparison of Optec NGN-3 and Optec NGN-2 particle scattering (b_{sp}) for periods when the RH was less than 70%, Bakersfield, California, Winter 1999.



FORT COLLINS STUDY RESULTS

Two NGN-3 size-cut nephelometers and one IMPROVE stage A aerosol sampler with a PM_{2.5} inlet were operated together during Spring 1999 (March through April, 1999), in Fort Collins, Colorado. All sample inlets were approximately 4.5 m above ground level, and the nephelometer and aerosol sampler inlets were 4.5 m apart. Daily 24-hr average PM_{2.5} mass concentrations during the study ranged from 3 to 16 µg/m³, with hourly events extending above 30 µg/m³.

Regression analysis of 24-hr averages of NGN-3 PM_{2.5} mass against the IMPROVE sampler mass, shown in Figure 3, yielded a slope of 0.99, an intercept of -1.34 µg/m³, and an R² of 0.81. (This regression analysis was performed without the two outliers noted on the plot. It is strongly suspected that the filter mass reported for that day is erroneous.) Precision calculations between the two NGN-3 nephelometers, summarized in Figure 4, show the average difference between the paired hourly averages to be 0.2 µg/m³ with a standard deviation of 0.4 µg/m³. Regression analysis between data from the two nephelometers yielded an R² of 1.00.³

It was determined during the Fort Collins study that the size-cut inlet impaction surface needed to be lightly greased to reduce the occurrence of coarse particles penetrating the inlet. This problem was particularly noticeable on windy days. The application of Apiezon M grease in the size-cut inlet was adopted as part of the instrument's operating protocol.

Figure 3. Comparison of Optec NGN-3 and IMPROVE Stage A PM_{2.5} mass, Fort Collins, Colorado, Spring 1999. The best fit line does not include the two outlying data points noted on the graph.

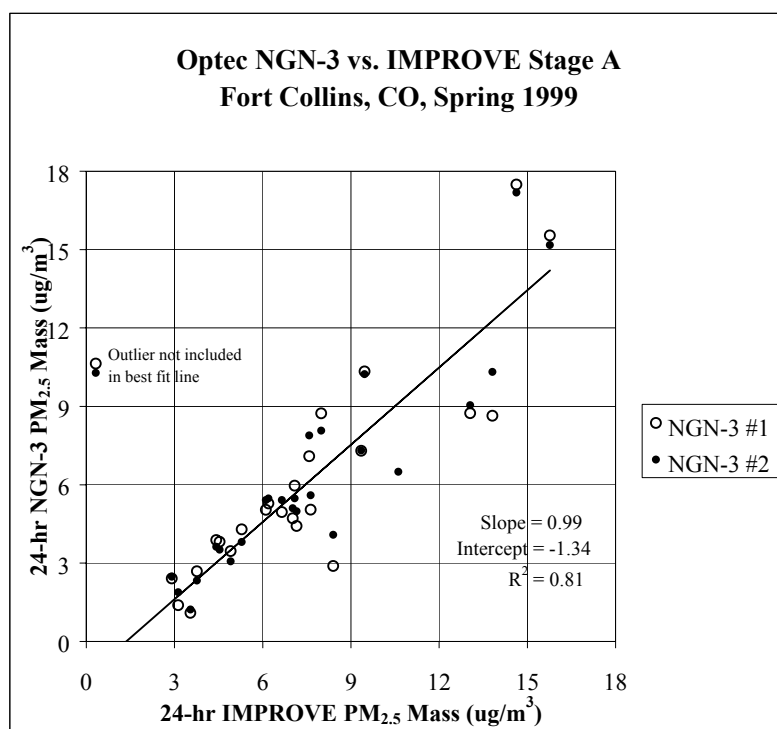
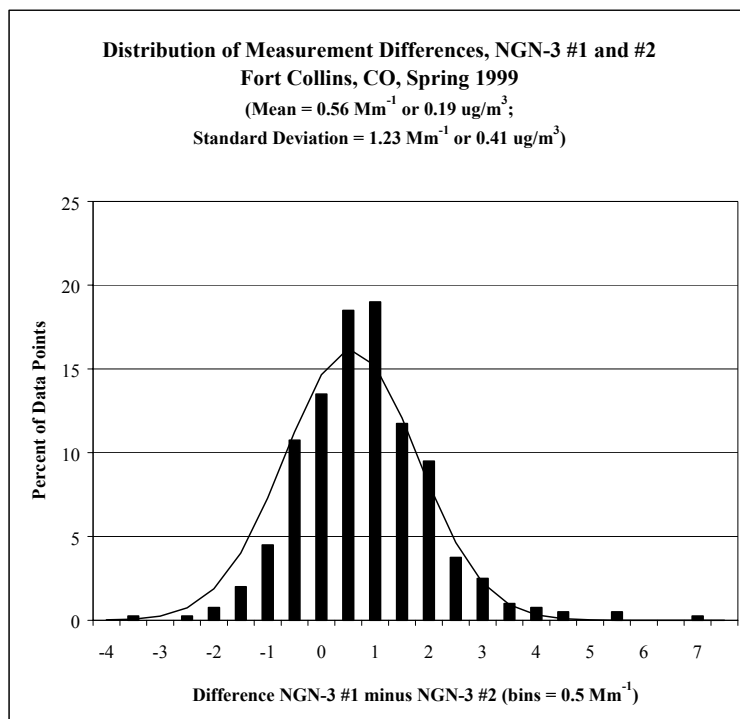


Figure 4. Histogram showing the distribution of differences between hourly average NGN-3 #1 and #2 particle scattering and mass measurements collected in Fort Collins, Colorado, Spring 1999.



PHOENIX STUDY RESULTS

One NGN-3 size-cut nephelometer operated at the Arizona Department of Environmental Quality (ADEQ) Supersite located in Phoenix, Arizona, during Winter 2000 (November 1999 through February 2000). ADEQ operates numerous particulate and criteria pollutant samplers at the Phoenix Supersite, but those of interest to this study are the Andersen Sequential sampler (EPA FRM for 24-hr PM_{2.5} sampling, samples collected daily), the Andersen Dichotomous (Dichot) sampler (24-hr PM₁₀ and PM_{2.5} filter samples collected every six days), the Rupprecht & Patashnick (R&P) Tapered Element Oscillating Microbalance (TEOM) continuous sampler (hourly PM₁₀ measurements), and the Optec NGN-2 Ambient Nephelometer (5-minute ambient particle scattering measurements). All sample inlets were approximately 5 m above ground level, and located within a 3 m by 6 m area. Daily 24-hr average PM_{2.5} mass concentrations during the study ranged from 6 to 32 µg/m³, with hourly events extending above 90 µg/m³. Daily 24-hr average PM₁₀ mass concentrations ranged from 16 to 77 µg/m³, with hourly events extending well above 300 µg/m³.

The standard reference for PM_{2.5} mass concentration during the study was the Andersen PM_{2.5} FRM sampler. Valid data from all filter-based samplers were available for November and December, 1999, only. Regression analysis of 24-hr averages of NGN-3 PM_{2.5} mass against the standard, shown in Figure 5, yielded a slope of 0.59, an intercept of -0.86 µg/m³, and an R² of 0.95. Also shown in Figure 5 is a regression of 24-hr Dichot PM_{2.5} mass against the standard for

all samples taken in November and December (slope of 0.90, intercept of 1.09 $\mu\text{g}/\text{m}^3$, and R^2 of 0.99). This analysis indicates that the choice of a mass scattering efficiency of 1.8 m^2/g is appropriate for this location during winter rather than the value of 3.0 m^2/g used during the study. All NGN-3 mass data were recalculated using this mass scattering efficiency. Regression analysis of the corrected NGN-3 $\text{PM}_{2.5}$ against the standard, shown in Figure 6, yielded a slope of 0.98, an intercept of $-1.44 \mu\text{g}/\text{m}^3$, and an R^2 of 0.95.

As expected (for the reasons stated above) the ambient b_{sp} measured with the NGN-2 was almost always higher than the dry, size-cut b_{sp} measured with the NGN-3. A comparison of hourly NGN-2 and NGN-3 b_{sp} data when the RH was less than 70% is presented in Figure 7. The NGN-3 size-cut particle scattering was, on average, 54% of the ambient particle scattering with an R^2 of 0.95.

One of the benefits to operating a continuous monitor is the resolution of short-term events. The only instrument at the Phoenix Supersite to collect continuous $\text{PM}_{2.5}$ data during the study period was the NGN-3. However, an R&P TEOM collected hourly PM_{10} data. A timeline of the corrected hourly NGN-3 $\text{PM}_{2.5}$ mass and TEOM PM_{10} mass data is shown in Figure 8. Both instruments simultaneously tracked short-term events. In addition, the ratio of $\text{PM}_{2.5}$ to PM_{10} was investigated for the months of November and December, 1999 (the only two months of the study for which Dichot data are fully validated). The average ratio obtained from 9 valid Dichot $\text{PM}_{2.5}$ and PM_{10} samples was 0.32 with a standard deviation of 0.09. The average ratio obtained from 26 full days of valid NGN-3 $\text{PM}_{2.5}$ and TEOM PM_{10} was 0.34 with a standard deviation of 0.14.

Figure 5. Comparison of Optec NGN-3, Andersen Dichot, and Andersen FRM $\text{PM}_{2.5}$ mass, Phoenix, Arizona, Winter 2000. The NGN-3 used a mass scattering efficiency of 3.0 m^2/g . Based on an analysis of this data the average mass scattering efficiency of the sampled aerosols was approximately 1.8 m^2/g .

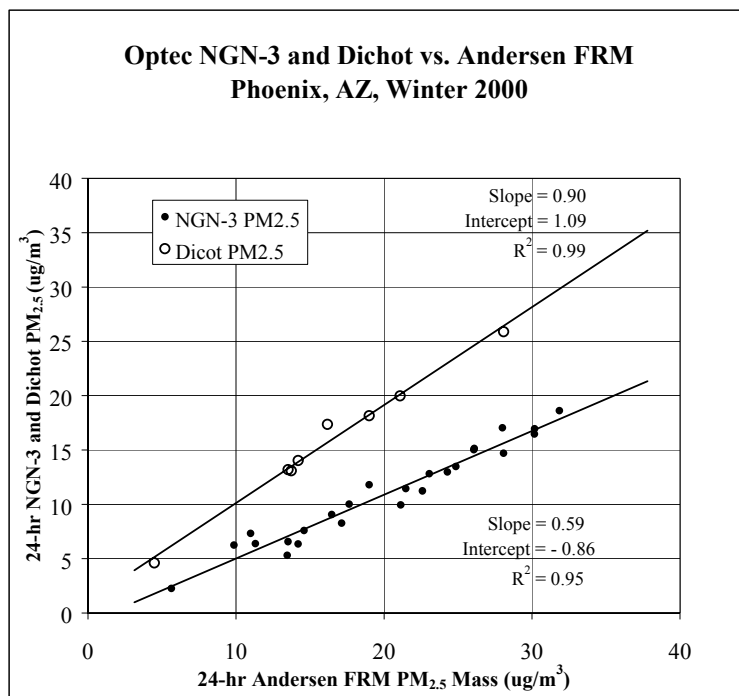


Figure 6. Comparison of Corrected Optec NGN-3 and Andersen FRM PM_{2.5} mass, Phoenix, Arizona, Winter 2000, using a mass scattering efficiency of 1.8 m²/g.

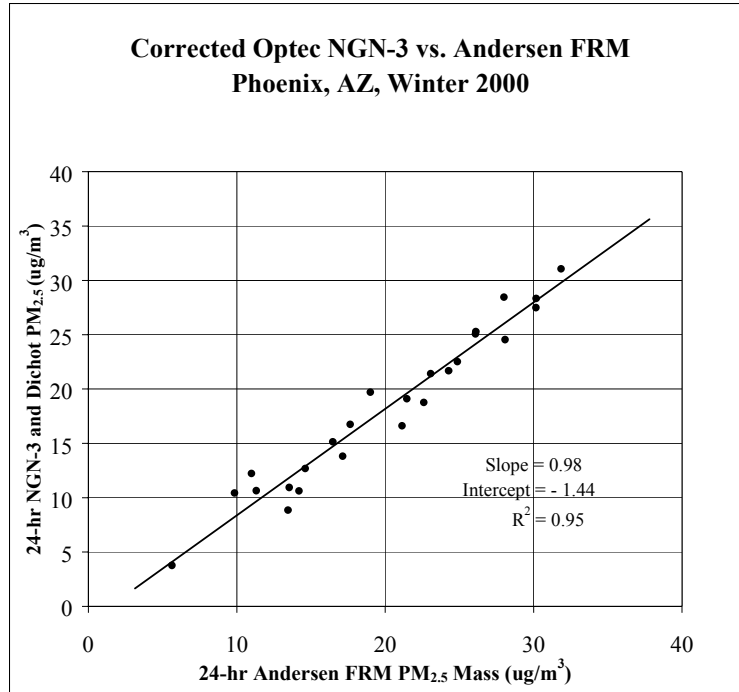


Figure 7. Comparison of Optec NGN-3 and Optec NGN-2 particle scattering (b_{sp}) for periods when the RH was less than 70%, Phoenix, Arizona, Winter 2000.

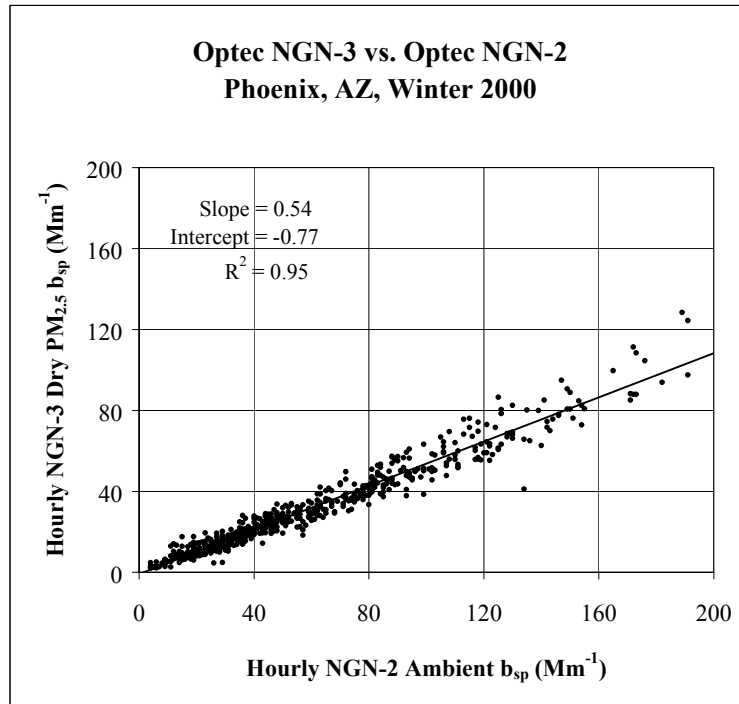
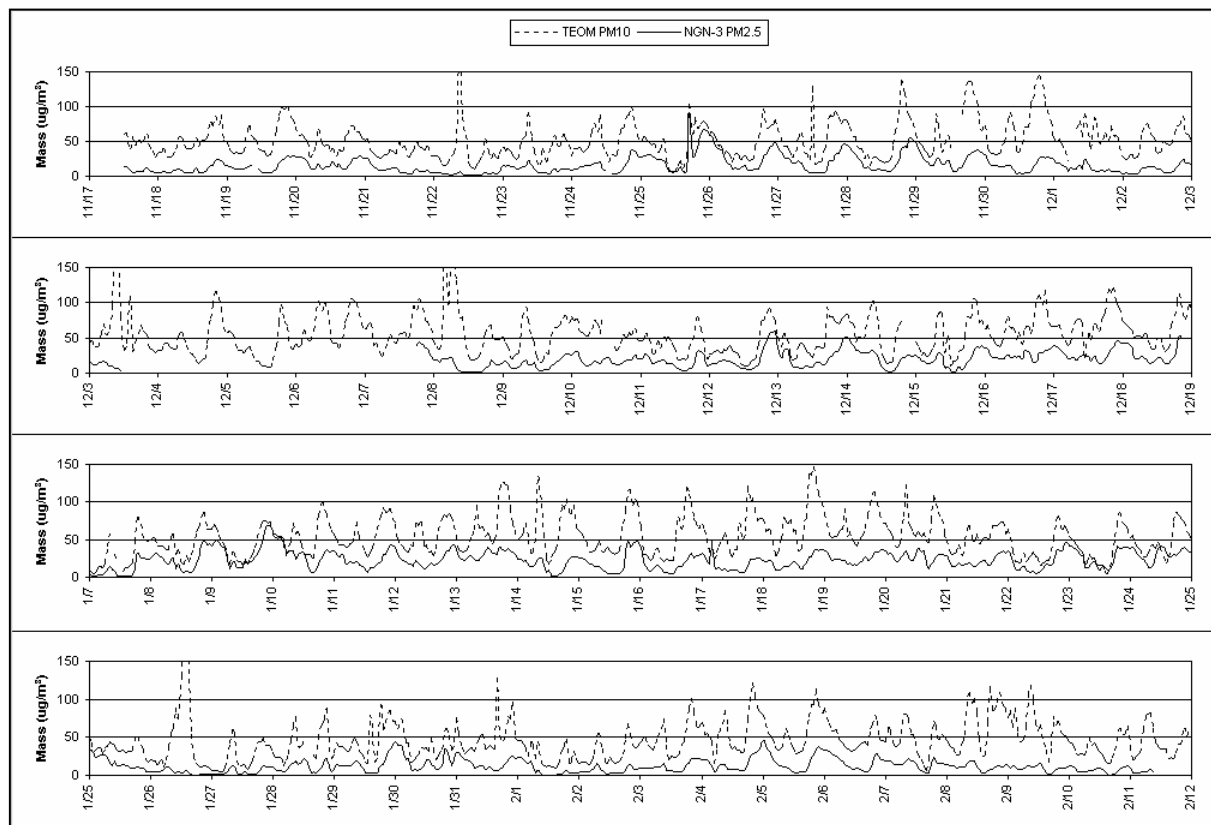


Figure 8. Timeline of hourly R&P TEOM PM₁₀ and hourly Optec NGN-3 PM_{2.5} data, Phoenix, Arizona, Winter 2000.



CONCLUSIONS

Results from the Bakersfield, Fort Collins, and Phoenix studies indicate that over a broad range of pollution conditions, the Optec NGN-3 size-cut nephelometer effectively and accurately measures the dry scattering of fine mass and can be used as a surrogate for continuous PM_{2.5} mass.

The accuracy of the NGN-3 dry PM_{2.5} mass measurement (assuming a mass scattering efficiency of 3.0 m²/g) at Bakersfield was determined with a linear regression between data sets from the NGN-3 and an EPA PM_{2.5} Federal Reference Method sampler. Over a range of 24-hr samples from 5 to 130 µg/m³, the regression yielded a slope of 1.02 and an R² of 0.99.

The accuracy of the NGN-3 dry PM_{2.5} mass measurement (assuming a mass scattering efficiency of 3.0 m²/g) at Fort Collins was determined with a linear regression between data sets from the NGN-3 and an IMPROVE Stage A PM_{2.5} sampler. Over a range of 24-hr samples from 3 to 16 µg/m³, the regression yielded a slope of 0.99 and an R² of 0.81.

Precision between two independent instruments in both the Bakersfield and Fort Collins studies were excellent. A linear regression of the data from Bakersfield yielded a slope of 1.01 and an R² of 0.99. An analysis of the differences between each instrument at Fort Collins yielded an average mass measurement difference of 0.2 µg/m³ with a standard deviation of 0.4 µg/m³.

The accuracy of the NGN-3 dry PM_{2.5} mass measurement (assuming a mass scattering efficiency of 1.8 m²/g) at Phoenix was determined with a linear regression between data sets from the NGN-3 and an EPA PM_{2.5} Federal Reference Method sampler. Over a range of 24-hr samples from 6 to 32 µg/m³, the regression yielded a slope of 0.98 and an R² of 0.95.

The ratio of PM_{2.5} to PM₁₀ was investigated in the Phoenix data set for the months of November and December, 1999. An average ratio based on 24-hr Dichot PM_{2.5} and PM₁₀ samples was 0.32. An average ratio based on 24-hr NGN-3 PM_{2.5} and TEOM PM₁₀ data was 0.34.

REFERENCES

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KEY WORDS

Nephelometer

Optec

NGN-3

Particle

Scattering

PM_{2.5}

Fine

Mass

Surrogate

Sampler