Analysis of the Real World Performance of the Optec NGN-2 Ambient Nephelometer

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ABSTRACT

The Optec NGN-2 open air nephelometer was specifically designed to measure ambient scattering with as little modification of the aerosol as possible. Seventeen systems have been operated successfully since 1993 in a broad range of environmental conditions as an integral part of the Interagency Monitoring of Protected Visual Environments (IMPROVE) and United States Forest Service (USFS) long term baseline visibility monitoring networks. The NGN-2 has also been employed in a variety of intensive short term special studies including: Project MOHAVE, Mt. Zirkel Visibility Study, Dallas Winter Haze Study, Southeastern Aerosol Visibility Study, and Northern Front Range Air Quality Study. Insight into the performance characteristics of the NGN-2 has been gained from: (1) analyses of scattering and operational data collected in these routine and special monitoring programs, (2) closure experiments in which nephelometer measured and reconstructed scattering calculated from speciated and size resolved aerosol measurements are compared, and (3) several intensive laboratory and field studies. These special investigations have included side-by-side intercomparisons with other existing systems including the TSI 3563, Belfort 1590, and Radiance Research M903 integrating nephelometers. Results of these analyses, tests, and theoretical modeling of the response characteristics of the Optec NGN-2 indicate the robustness and delineate the challenges and uncertainties associated with measuring aerosol scattering under ambient conditions.

INTRODUCTION

To truly understand the optical properties of the ambient atmosphere it is necessary to measure, without modification, the atmospheric extinction coefficient and its components (the scattering and absorption coefficients). With the exception of transmissometry and radiance difference photometry , all current aerosol and optical measurement techniques modify the ambient atmosphere to some extent, thus confounding data analyses. Early integrating nephelometers modified the ambient aerosol to such a large degree that scattering measurements were difficult to properly interpret. The Optec NGN-2 integrating nephelometer was specifically designed for in-situ measurement of aerosol scattering. The instrument employs a unique open-air design that incorporates an unobstructed inlet, a low power lamp, and high flow rate. This design minimizes modification of ambient aerosol associated with a plumbed sampling inlet (unknown physical size cuts) and heating in the optical chamber. However, the requirement of ambient operation necessitated two significant compromises compared to earlier nephelometers. A photo diode light sensor is used instead of a photomultiplier tube (PMT) detector and a wider bandpass filter due to the decreased sensitivity of the photo diode compared to a PMT. The NGN-2's low power consumption, stable electronics, rugged compact design, easy installation and operation make it ideally suited for remote long term monitoring programs as well as intensive special studies. Insight into the performance characteristics of the NGN-2 has been gained from analyses of scattering and operational data collected since 1993 from the Interagency Monitoring of Protected Visual Environments (IMPROVE) and United States Forest Service (USFS) long term baseline visibility monitoring networks. In addition to these programs, closure experiments comparing nephelometer measured and reconstructed scattering calculated from speciated and sized aerosol measurements and several intensive laboratory/field studies have also been conducted. These have included side-by-side intercomparisons with other existing systems including the TSI 3563, Belfort 1590, and Radiance Research M903 integrating nephelometers. Results of these analyses, tests, and theoretical modeling of the response characteristics of the Optec NGN-2 indicate the robustness and delineate the challenges and uncertainties associated with measuring aerosol scattering under real-world conditions.

NEPHELOMETER DESIGN

Overview: Nephelometry is a mature science dating back 50 years with well understood design philosophies and inherent limitations[1]. However, earlier generation nephelometers and current versions of those systems were not specifically designed for ambient operation, thus they are not able to accurately measure true ambient scattering. The design and operational deficiencies of these nephelometers include:

- Significant heating of the sample air. Heating of the sample air is especially troublesome at high relative humidities when a large fraction of the ambient aerosol can be composed of hygroscopic or volatile particles.

- Ill-defined size cut caused by inlet, sample train, and optical chamber design.

- Non-linear drifts in calibrations caused by detector electronics when operated at ambient temperatures and humidities.

- Large truncation angle, affecting measurement of particles larger than a few microns in diameter.

The Optec NGN-2 was specifically designed to overcome these deficiencies. The key features of the NGN-2 that allow accurate measurement of ambient scattering include:

- An unobstructed inlet replaces complex sample trains and allows ambient air to directly enter the measurement chamber.

- The high flow rate (280 liters per minute) and specially designed chamber manifold wall ensure laminar flow through the measurement chamber and a minimum residence time of less than 0.25 seconds.

- The heat generated by the 25 watt quartz halogen lamp is drawn away from the measurement chamber with a 700 nm cut-off absorbing glass filter and heat sink in the sample fan chamber.

- The solid state detector and control electronics minimize temperature/humidity dependence, power consumption, and heat dissipation in the electronics chamber.

- A layer of insulation isolates the measurement chamber from heat generated in the electronics and sample fan chamber.

- The single-board computer controls all nephelometer functions, provides input and output via an RS-232 serial interface and analog lines, and allows for user-defined operational parameters (integration time, zero air interval, etc).

- Rugged physical design and solid state electronics in a sealed chamber allow the instrument to operate in ambient conditions over a broad temperature range (-20°C to 40°C) and relative humidity (0 to 100%) with no measurable temperature or humidity dependence.

- Highly reflective exterior white paint that minimizes solar heating.

Optical Design: The measurement chamber is illuminated by a near Lambertian flashed opal glass diffuser. The diffuser is illuminated by a low voltage (25 watt) tungsten filament quartz halogen lamp with a dichroic reflector through a heat absorbing glass filter that blocks all radiation longer than 700 nm. A telescope with a precisely defined field of view observes a 6 mm diameter, 260 mm long cylindrical volume of air slightly in front of the diffuser. A perfect nephelometer would measure scattering from 0 to 180°. The integration angles for the NGN-2 are 5° to 175° .

Electronic and Mechanical Design: P-N silicon photodiodes are used for the scattered and direct light detectors. Photodiodes are less sensitive than the photomultiplier tubes used in other currently available nephelometers, thus a wider band pass filter must be used to collect enough scattered light. However, photodiodes do not require a high voltage power supply and are not nearly as temperature or relative humidity dependent as photomultiplier tubes. The light source is chopped mechanically to allow extraction of the scattered light signal from noise (caused by ambient light in the measurement chamber) which is several orders of magnitude greater than the signal. The difference between the light-on signal and light-off signal is averaged over many hundreds of cycles. As a result, the minimum integration time for the NGN-2 is one minute. All signal processing and system control functions are handled by an integrated single board computer.

Operationally Required Design Enhancements: The Optec NGN-2 nephelometer operates in a wide range of ambient conditions, including extreme variations in temperature and humidity. During initial monitoring at sites ranging from Northern Minnesota to the Mohave Desert, several design, manufacturing, and operational problems were identified. The problems were most often associated with precipitation events and usually adversely affected zero air calibrations and ambient data collection. As each problem was encountered, a solution was developed, tested in the laboratory and field test facility; then implemented throughout the monitoring networks. Table 1 summarizes these modifications and enhancements that have improved the operational reliability of the Optec NGN-2. The design of the system has been essentially constant since mid-1995.

THEORETICAL ANALYSIS OF OPTEC NGN-2

Truncation Angle: A perfect integrating nephelometer will collect all scattered light from 0 - 180°. However, real nephelometers must collect scattered light less than this optimal range due physical limitations of detector size, the need to shield the light trap from direct illumination by the light source, and finite length of the scattering chamber. This effect, known as truncation error, is minimized to some extent by calibrating the instrument with a Rayleigh scattering gas. However, since aerosols have a different scattering phase function compared to gases, the truncation error will increase with aerosol size as more light is scattered in the forward (0°)and backward (180°) directions. Table 2 lists the integration angles for the types of nephelometers referred to in this paper. Figure 1 shows the calculated wavelength dependent truncation error associated with each instrument for varying aerosol mass mean diameters (mmd) with a geometric sigma of 1.75. The assumption here is that all other instrumental parameters (wavelength response, etc.) are the same for each instrument. This allows inspection of only the truncation error associated with the physical design of each instrument. The error is presented as the ratio of truncated measured scattering to measured scattering for a perfect integrating nephelometer (0-180°). The error increases rapidly with aerosol mmd greater than 1.0 μm for all instruments. The larger integration angle of the NGN-2 results in about a 10-20% lower truncation error than the other nephelometers at aerosol mmd greater than 0.8 μm.

Spectral Response: The spectral response, R(λ), of a nephelometer is obtained by multiplying the spectral energy distribution of the light source with the spectral sensitivity of the detector, filters and all optical components used in the system. The signal output by a nephelometer is proportional to:

$$2\pi \int_{\lambda} \int_{\varphi} B(\varphi,\lambda) \sin(\varphi)\, d\varphi\, R(\lambda)\, d\lambda \qquad (1)$$

where: $B(\varphi,\lambda)$ is the volume scattering function; integration over lambda is for all wavelengths the nephelometer is sensitive to; and integration over φ is over the integration angle of the instrument. The volume scattering function, both of the calibrating gas and aerosol to be measured, is a function of wavelength and scattering angle. Thus, the measured scattering coefficient depends on the weighted average of the instrument response of both the aerosol and Rayleigh calibration gas.

The spectral characteristics of detector, filters, and lamp were received from the manufacturer of the Optec nephelometer. Analytical functions were generated for each of the components and combined to create a response function for the system. The response of the TSI 3563 and Belfort 1590 nephelometers were generated from published measured response curves.[3,4] Information received from Radiance Research indicates that model M903 has the same spectral response as the Belfort 1590.[5] Figure 2 plots the normalized wavelength response for these integrating nephelometers. The peak response of each instrument is quite different. However, due to the varying bandwidths, the effective wavelength is not simply the peak wavelength, but rather is a function of the integrated response of the instrument, scattering coefficient at the calibration wavelength and scattering properties of the aerosol.

Figure 3 plots the wavelength dependence of Rayleigh scattering and scattering of lognormal aerosol size distributions with varying mmd. Since the integrating nephelometer is calibrated with a Rayleigh gas, the ratio of the integrated response for any aerosol distribution to the integrated Rayleigh response (when the scattering is equal at the effective wavelength), results in a calculation of the relative error associated with each instrument. Figure 4 is a plot of this modeled error as a function of aerosol mmd for the Optec, TSI, Belfort and Radiance Research nephelometers. This analysis includes all spectral and truncation effects as well as the wavelength dependence of scattering shown in Figure 3. The estimated error is less than 2% for all the nephelometers at mmd less than 0.5 µm. The predicted Optec error is less than 2% up to 2.0 µm, while the error of the other nephelometers increases to greater than 5% in the range 0.75 - 1.5 µm aerosol mmd which is near the upper end of mmd for fine particle distributions recently measured in SEAVS.[6]

NEPHELOMETER INTERCOMPARISON TESTS

Laboratory Constant-Density Environment Test: In 1994 an Optec NGN-2 and Radiance Research M903 were tested in a sealed (constant density) Lexan chamber filled with filtered particle-free air and then with SUVA134a gas and cycled over a wide range of temperatures. The tests were designed to investigate the stability of the nephelometers with temperature. In a constant-density environment, an ideal instrument would measure a constant scattering, regardless of temperature or pressure. The chamber was placed in a computer-controlled variable-temperature environmental test facility. The chamber was first filled with particle-free air (bscat = 10 Mm^{-1}) and cycled for 12 hours in the environmental chamber from -25°C to 40°C to -15°C to 25°C. The chamber was next filled with SUVA 134a gas (bscat = 72 Mm^{-1}) and cycled through the same range of temperatures. The nephelometers were operated normally (sample fans on, door open). The nephelometer analog outputs, temperature, and pressure sensor outputs were logged on a Campbell 21X datalogger placed outside of the temperature controlled environment. The Optec NGN-2 exhibited a range of ± 3 Mm^{-1} during the both the clean air and SUVA phase of the experiment. This results in a precision of 30% for the clean air value and 4% for the up scale measurement. The variation in measured bscat appeared random and generally unrelated to temperature or pressure variations during the test. The Radiance Research M903 exhibited a very non-linear response to the effects of temperature. The clean air range was ± 6 Mm^{-1} (representing a 60% variation) and the SUVA-134 span gas test resulted in ± 50 Mm^{-1} range (70% precision). The variations were strongly correlated with temperature, suggesting uncorrected PMT tube saturation and electronic drift of the instrument with increasing temperature. These results are very similar to the problems seen when operating Belfort 1590 nephelometers under ambient conditions.[2]

Controlled Intercomparisons: Intensive side by side nephelometer tests were performed in 1994 and repeated in 1996. The following nephelometers were included in the 1994 study:

- Optec Model NGN-2 (3 instruments)
- Belfort Model 1590 configured for ambient operation in a ventilated shelter.
- Radiance Research Model M903 configured for ambient operation

The three Optec NGN-2 nephelometers were mounted two meters above ground level under a precipitation and solar radiation shield with their inlets facing north. The Radiance Research M903 nephelometer is not designed to operate in ambient conditions without sheltering, thus, it was enclosed in a 40cm x 60cm x 60cm forced-ventilated enclosure with the nephelometer inlet and exhaust ported to the outside. The Belfort 1590 nephelometer was configured for near-ambient operation including a lamp cooling fan, sealed and dried PMT compartment and the complete instrument was housed in a high velocity forced air ventilated shelter[2]. The Belfort and Radiance Research inlets were also two meters above ground level. Thermocouples were placed in the inlet and exhaust near the measurement chamber of the Belfort and Radiance Research nephelometers to monitor temperature changes to the sample air. Five-minute average scattering, ambient and chamber temperature, and ambient relative humidity data were logged on Campbell Scientific 21XL dataloggers. The five-minute raw scattering data for all nephelometers were reduced to hourly averages and converted to aerosol scattering (bsp) based on the upscale and zero calibrations performed for all systems during the study. The Belfort and Radiance Research aerosol scattering data were converted from 525 nm to scattering at 550 nm. The intercomparison test was repeated in 1996 with an identical setup except that the Belfort 1590 nephelometer was not included, the Radiance Research nephelometer was an updated version with new internal software to address questions raised in the 1994 study. A 2.5 µm cut Optec NGN-2 was also included in the study. One of the ambient Optec nephelometers (#38) was the same instrument used in the 1994 test. All the various types of nephelometers in both studies had estimated measurement uncertainties of less than 15% in bsp (based on multiple zero air and SUVA 134a upscale calibrations) and also had an average chamber heating of less than 1.0°C.

Figure 5 contains the scatter plots for the six Optec NGN-2 ambient nephelometers that ran during the 1994 and 1996 studies. Table 3 lists the regression statistics for the paired data. Figure 6 is a plot of all paired measurements from the two study years. Figure 7 is a plot of the calculated mean precision of the paired measurements as a function of average bsp. The precision of each paired measurement is estimated by:

$$\text{precision (\%)} = 100 * [(x-y)] / [(x+y) / 2] \tag{2}$$

The data were sorted into average bsp bins and a mean precision with 99% confidence limits was calculated for each bin. The precision is better than 10% for all bsp > 10 $\mathrm{Mm^{-1}}$. As bsp decreases to the Rayleigh limit the precision increases to > 50% at bsp = 1 $\mathrm{Mm^{-1}}$.

Figure 8 contains scatter plots and Table 4 statistics of bsp measured by the Belfort 1590 in the 1994 test and the 2.5 µm cut Optec in the 1996 test versus the average of the three ambient Optecs that operated during each test period. The data is stratified by relative humidity range into three bins: rh < 70%, rh < 95% and all rh. The 2.5 µm cut Optec exhibits a high degree of correlation and precision when compared with the ambient Optecs. As expected, aerosol scattering is lower since the cut system is only monitoring fine aerosols. The precision decreases with data above 95% rh included due primarily to the ambient Optecs response to fogs.

The Belfort data is similar to earlier measurements obtained in 1991 when the Optec was first tested and the Belfort had been successfully modified for near-ambient operation.[2] It exhibits reasonable agreement with the Optec ambient systems, but has lower precision due mainly to noisy temperature and relative humidity response of the PMT detector and older electronics, even when they are in a partially sealed de-humidified chamber.

The Belfort was operated in 1994 for one reason: to compare it to the Radiance Research M903 nephelometer. Radiance Research stated that the M903 was essentially an updated Belfort 1590 with newer more reliable components, operating characteristics, and internal software to make a better bsp measurement under a wide variety of ambient conditions. Figure 9 and Table 5 present the Radiance Research M903 comparison to the ambient Optec measurements. The results of the 1994 test were disappointing, with the M903 displaying imprecise and quite noisy bsp data. These results were thought to be associated with the PMT and was verified by the constant density chamber laboratory test discussed previously. The instrument tested in 1996 was a newer version of the M903 with internal temperature and relative humidity sensors and updated software to account for the PMT response to temperature and rh. The results of the 1996 test are slightly better than the 1994 test. The Radiance Research M903 still exhibits a reduced bsp signal at high relative humidities. Figure 10 plots the ratio of hourly measured bsp by the M903 and Belfort 1590 to the average of the ambient Optecs as a function of relative humidity for both test periods. The large rapid fall off in the Radiance Research instrument at high relative humidity is readily apparent. The updated instrument used in 1996 shows a slight improvement compared to the 1994 instrument, but still has unacceptable response characteristics at ambient relative humidity above 80%. Thus, the Radiance Research M903 nephelometer still cannot not be used as an ambient instrument in high humidity environments.

Field Study Intercomparisons: The TSI 3563 nephelometer has recently been operated in conjunction with Optec systems in three recent field studies: 1994 Mt. Zirkel Visibility Study (MZVS), 1996 Southeastern Visibility and Aerosol Experiment (SEAVS) and 1996-97 Northern Front Range Air Quality Study (NFRAQS). Table 6 lists the regression statistics and Figure 11 has the scatterplots of the collocated Optec and TSI bsp data for these three studies. The TSI 3563 exhibited large heating of the aerosol in all three studies, 7.1 °C during MZVS, 4 °C during SEAVS, and 6.5 °C during NFRAQS. Thus, the TSI bsp data must also be carefully examined for heating effects when comparing to Optec data. Detailed discussions of this data have been presented elsewhere in these proceedings.[6,7,8]

REAL WORLD OPERATIONAL CHARACTERISTICS

Network Operations 1993-97: Seventeen Optec NGN-2 ambient nephelometers are currently operating in the IMPROVE and USFS visibility monitoring networks. The primary purpose of these systems is to compare measured ambient bsp with reconstructed bsp from collocated IMPROVE aerosol samplers. Ambient measured bsp is required to analyze and validate relative humidity growth curves used to generate reconstructed bsp, especially in high humidity environments. The nephelometers operate in a cycled mode making a two-minute integrated scattering measurement in every 5 minute period. Twelve periods are collected and reported as mean and standard deviation of bsp for each hour. High quality relative humidity (rh) data are collected at each site with an aspirated Rotronics temperature/rh sensor.

It is extremely important to make frequent and accurate clean air measurements with ambient nephelometers to account for changes in the wall scattering component of the collected scattered light. The wall scattering will change in unpredictable ways as the reflectivity of the interior of the nephelometer changes with precipitation or high concentrations of aerosols which adhere to the walls. The standard procedure in these networks is to make an automatic clean air measurement every six hours by closing the door, filtering the air in the optical chamber for fifteen minutes and calculating the clean air measurement from the average of the last ten minutes of the period. The validity of this clean air procedure was tested by operating an Optec nephelometer in continuous mode for 60 days during the winter of 1996/97. A 30 minute clean air period was initiated every hour and one-minute scattering data were collected. Figure 12 is a plot of the mean ratio of nephelometer output for each minute during a clean air cycle to the average of minutes 20-29 for the entire test period. The signal rapidly decreases from ambient levels to the clean air value. By minute 5 the signal has essentially reached the clean air value regardless of ambient scattering level. The precision of the clean air reference, estimated by the standard deviation of the ratios, is on the order of 4% for the IMPROVE protocol clean air period.

Since the Optec NGN-2 attempts to measure the ambient atmosphere, fog, rain, snow or ice crystals can enter the optical chamber resulting in a high and rapidly varying signal. Thus, all measurements are filtered to identify hourly bscat data that may be unduly influenced by weather events. If a data point fails any one or combination of the following criteria the hourly data is flagged as having possible weather (wx) induced effects:

- Relative humidity: rh > 90%
- Maximum: bscat > 5000 Mm^{-1}
- Rate of change: difference between hourly data > 50 Mm^{-1}
- sigma/mean: ratio of standard deviation/mean for hourly data > 10%
- Rayleigh: bscat < Rayleigh at location (9-12 Mm^{-1}) and
- any non-wx identified data point between two or more wx flagged points

Nephelometer data flagged as affected by meteorological interference are still considered valid, but require more sophisticated procedures when incorporated in additional analyses. Tables 7, 8 and 9 list operational statistics for the two networks. Overall, 85% of the collected data is considered to be valid. Approximately 38% of the valid data is identified as failing the above tests, thus having possible meteorological interference. Almost three quarters (72%) of these flags are associated with relative humidity above 90%. It is important to note the high median relative humidity experienced at the non-western sites. A non-ambient nephelometer would seriously underestimate the ambient aerosol scattering at these sites. With typical heating in the optical chamber of less than 1.0 °C, the Optec nephelometers are operating very near to ambient. Still, this slight heating must be properly accounted for when comparing reconstructed to measured scattering.

Reconstructed versus Measured Scattering: The main purpose for going to the effort to make good ambient aerosol scattering measurements is to verify the algorithm used to reconstruct scattering from co-located speciated aerosol data. The IMPROVE and USFS visibility programs operate Optec ambient nephelometers in association with IMPROVE aerosol samplers for just this reason.[9] Typically, aerosol scattering is reconstructed using a model such as:

$$\begin{aligned} bsp = {} & b_{SO4}\, f(rh)_{SO4}\, [\text{Sulfate}] + b_{NO3}\, f(rh)_{NO3}\, [\text{Nitrate}] + \\ & b_{OC}\, f(rh)_{OC}\, [\text{Organic}] + b_{Soil}\, [\text{Soil}] + b_{CM}\, [\text{Coarse mass}] \end{aligned} \tag{3}$$

where, b_X is the dry scattering efficiency and $f(rh)_X$ is the hygroscopic growth function for the species X. The species concentrations in brackets are calculated from detailed chemistry of the collected aerosol samples.[10] Because certain aerosol species, such as sulfates and nitrates, have an affinity for water, their scattering characteristics change with relative humidity. Various growth functions have been proposed for the hygroscopic aerosols. Table 10 lists the constants used by IMPROVE and the constants recommended by the Grand Canyon Visibility Transport Commission (GCVTC) for use in Equation 3. Figures 13, 14, and 15 plot reconstructed aerosol scattering versus measured scattering for IMPROVE sites using a Dry, IMPROVE and GCVTC aerosol model respectively. Since the IMPROVE aerosol monitor collects a twenty four hour integrated sample, the hourly nephelometer and relative humidity data must be combined into a daily mean value. The figures include days where at least 12 non-wx interference hourly values were in the daily mean measured bsp, rh and f(rh). With this restriction there are still over 2000 days represented in the figures. It is obvious that "Dry" reconstructed bsp underestimates measured bsp by quite a large factor. The GCVTC recommended constants results in a significant overestimation of measured bsp. Using the IMPROVE constants results in the best fit to reconstructed data except on the cleanest and highest scattering days. Without ambient aerosol scattering measurements it would be impossible to judge which of the reconstruction algorithms are appropriate.

CONCLUSIONS

The Optec NGN-2 integrating nephelometer was designed to make ambient aerosol scattering measurements. Since first entering routine service in 1993, the instrument has been upgraded to improve its operating characteristics and field performance. With these modifications, the instrument has proven to be rugged, reliable, and fully capable of successfully operating under a wide range of extreme environmental conditions. However, the requirement of ambient operation necessitates certain compromises such as a solid state detector and wide band filter. Theoretical analysis of instrument response indicates that these compromises do not seriously affect the possible accuracy of scattering measurement by the Optec NGN-2. Instrument intercomparisons of multiple Optecs and laboratory tests show the precision of the instrument to be excellent. Intercomparisons with Belfort 1590, Radiance Research M903 and TSI 3563 integrating nephelometers show that these systems do not make ambient measurements. In addition, they exhibit poor to unacceptable performance when attempting to operate under ambient conditions. The final test of the rationale for attempting to make an ambient scattering measurement is to complete a closure analysis with reconstructed scattering from collocated aerosol measurements. Analysis of over 2000 days from the IMPROVE and USFS monitoring networks validates the need to properly handle relative humidity effects when calculating reconstructed scattering as well as the need for an ambient scattering measurement for closure. Without a true ambient measurement of aerosol scattering, the proper method for reconstructing bsp cannot be determined.

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Table 1. Optec NGN-2 Nephelometer operationally required design enhancements.

Problem	Solution
The original optical light trap collected water following precipitation events causing erratic data and calibrations.	New light trap with cone-shaped interior and an integrated wicked drain effectively keeps water from affecting the function of the light trap.
The original clean air filter collected and held moisture in wet environments. Mold and other contamination in the filter media adversely affected zero calibrations.	New filter assemblies allow the filter media to replaced on-site at two-week intervals.
The original precipitation sensor proved ineffective at closing the inlet door during precipitation events (particularly during freezing rain, rime ice, or blowing snow).	Optec-supplied retrofit kits improve the sensitivity of the precipitation sensor, and a rain/snow shield can be installed over the nephelometer to shed precipitation.
The aperture ring around the diffuser in the measurement chamber was attached to the manifold wall with epoxy and often fell off during operation or shipping.	The aperture ring is now attached with screws through the manifold wall.
The paint in the optical chamber often peeled or flaked off after field operation and caused erratic readings.	Optec has changed painting procedures and all instruments are carefully checked prior to use.
The span gas valves failed after about one year of operation. The failures manifested themselves as poor span calibrations.	Span gas valves are now routinely replaced during annual servicing and when an instrument is repaired. A new , more robust valve is being used.
The original door motors experienced regular failures.	The original motor is replaced with a more robust one at every yearly servicing.
The base plate of the nephelometer could be warped when the top was screwed on too tightly resulting in misalignment of the scattered light detector telescope.	Reinforcement bars have been attached to the base plate of all nephelometers.
Electronic components such as serial I/O, analog output, and the DC/DC converter were being damaged routinely due to near by lightning storms.	Transient voltage suppressers are now installed at all locations to lessen (but not completely remove) the occurrence of such damage.
The original lamp holder was cumbersome and allowed an operator to install the lamp incorrectly. Incorrectly installed lamps cause erratic zero calibrations and readings.	A new lamp assembly with external wire and removable tray allows the operator to replace the lamp without having the wires interfere with the lamp position.

Table 2. Integration angles for various types of nephelometers.

Nephelometer	Integration Angle (deg)
Optec NGN-2	5 to 175
TSI 3563	7 to 170
Belfort 1590	8 to 170
Radiance Research M903	10 to 165

Table 3. Optec NGN-2 nephelometer aerosol scattering (Mm^{-1}) intercomparison statistics for 1994 and 1996 studies (See Figure 5 for scatterplots)

Year	Nephelometers Compared		Range in	Regression Statistics (Y = Slope * X + Intercept)		
	X	Y	rh %	Slope	Intercept	R^2
1994	Optec NGN-2 #13	Optec NGN-2 #24	0 - 100%	1.03	0.9	0.991
1994	Optec NGN-2 #13	Optec NGN-2 #38	0 - 100%	0.98	3.2	0.987
1994	Optec NGN-2 #24	Optec NGN-2 #38	0 - 100%	0.94	2.4	0.988
1996	Optec NGN-2 #31	Optec NGN-2 #38	0 - 100%	1.07	0.1	0.991
1996	Optec NGN-2 #31	Optec NGN-2 #41	0 - 100%	1.04	-0.3	0.991
1996	Optec NGN-2 #38	Optec NGN-2 #41	0 - 100%	0.98	-0.5	0.988
	All paired 1994 and 1996 Measurements		0- 100%	1.01	0.9	0.987

Table 4. Optec NGN-2 nephelometer , Belfort 1590 and 2.5 µm cut Optec NGN-2 aerosol scattering (Mm^{-1}) intercomparison statistics for 1994 and 1996 studies in various relative humidity ranges (See Figure 8 for scatterplots).

Year	Nephelometers Compared		Range in	Regression Statistics (Y = Slope * X + Intercept)		
	X	Y	rh %	Slope	Intercept	R^2
1994	Avg. of Ambient Optecs*	Ambient Belfort 1590	0 - 100%	0.97	4.4	0.918
1994	Avg. of Ambient Optecs*	Ambient Belfort 1590	0 - 95%	1.05	2.9	0.949
1994	Avg. of Ambient Optecs*	Ambient Belfort 1590	0 - 70%	1.18	-0.2	0.949
1996	Avg. of Ambient Optecs*	2.5 µm Cut Optec	0 - 100%	0.73	2.6	0.935
1996	Avg. of Ambient Optecs*	2.5 µm Cut Optec	0 - 95%	0.91	-2.6	0.983
1996	Avg. of Ambient Optecs*	2.5 µm Cut Optec	0 - 70%	0.97	-4.2	0.985

* Average of three ambient Optec NGN-2 nephelometers run simultaneously

Table 5. Optec NGN-2 and Radiance Research M903 nephelometer aerosol scattering (Mm^{-1}) intercomparison statistics for 1994 and 1996 studies in various relative humidity ranges (See Figure 9 for scatterplots).

Year	Nephelometers Compared		Range in	Regression Statistics (Y = Slope * X + Intercept)		
	X	Y	rh %	Slope	Intercept	R^2
1994	Avg. of Ambient Optecs*	Radiance Research M903 ROM version 2.04	0 - 100%	0.56	7.6	0.890
1994	Avg. of Ambient Optecs*	Radiance Research M903 ROM version 2.04	0 - 95%	0.62	6.7	0.944
1994	Avg. of Ambient Optecs*	Radiance Research M903 ROM version 2.04	0 - 70%	0.86	2.7	0.901
1996	Avg. of Ambient Optecs*	Radiance Research M903 ROM version 2.37	0 - 100%	0.49	10.0	0.842
1996	Avg. of Ambient Optecs*	Radiance Research M903 ROM version 2.37	0 - 95%	0.67	4.9	0.912
1996	Avg. of Ambient Optecs*	Radiance Research M903 ROM version 2.37	0 - 70%	0.81	1.6	0.981

- Average of three ambient Optec NGN-2 nephelometers run simultaneously

Table 6. Optec NGN-2 and TSI 3563 green nephelometer aerosol scattering (Mm^{-1}) intercomparison statistics from various field studies (See Figure 11 for scatterplots).

Year & Study	Nephelometers Compared		Range in	Regression Statistics (Y = Slope * X + Intercept)		
	X	Y	rh %	Slope	Intercept	R^2
1995 MZVS	Ambient Optec NGN-2	2.5 µm cut TSI 3563 Green	0 - 90%	0.53	11.7	0.231
1996 SEAVS	Ambient Optec NGN-2	2.5 µm cut TSI 3563 Green	0 - 90%	0.62	15.1	0.592
1996 SEAVS	2.5 µm cut Optec NGN-2	2.5 µm cut TSI 3563 Green	0 - 90%	0.87	-2.2	0.871
1996/97 NFRAQS	Ambient Optec NGN-2	2.5 µm cut TSI 3563 Green	0 - 90%	0.34	4.8	0.787
1996/97 NFRAQS	2.5 µm cut Optec NGN-2	2.5 µm cut TSI 3563 Green	0 - 90%	0.57	3.6	0.826

Table 7. IMPROVE and USFS Optec NGN-2 nephelometer monitoring networks aerosol scattering statistics.

	Start Date	% Valid bsp data	% of Valid bsp that is non-wx coded	Cumulative Frequency Non-wx aerosol bsp (Mm^{-1})			Cumulative Frequency All aerosol bsp (Mm^{-1})		
				10%	50%	90%	10%	50%	90%
IMPROVE									
Acadia NP, Maine	6-11-93	90	67	6	18	55	7	35	162
Boundary Waters W, Minnesota	5-5-93	85	69	5	16	56	5	21	115
Dolly Sods W, West Virginia	5-12-93	82	49	10	36	136	14	79	539
Great Smoky Mts. NP, Tennessee	4-28-93	87	69	12	45	190	14	63	296
Jarbidge W, Nevada	4-7-93	90	85	1	5	18	1	7	22
Mammoth Cave NP, Kentucky	3-9-93	80	50	16	44	123	21	82	445
Mount Rainier NP, Washington	2-8-93	94	34	7	20	47	8	29	94
Okefenokee NWR, Georgia	2-10-93	91	56	16	42	97	20	63	243
Upper Buffalo W, Arkansas	2-26-93	79	61	11	38	127	13	62	388
USFS									
Columbia River Gorge NSA, Washington	9-1-93	87	83	4	16	59	4	18	95
Gila W, New Mexico	4-12-94	94	81	1	9	24	1	10	37
Great Gulf W, New Hampshire	6-6-95	66	48	4	22	81	5	36	189
Lone Peak W, Utah	11-16-93	94	80	2	11	29	2	12	46
Mount Zirkel W, Colorado	8-9-94	91	63	1	7	22	1	11	111
Shining Rock W, Virginia	6-7-94	53	49	2	21	99	5	59	4763
Snoqualmie Pass (Alpine lakes W), Washington	9-1-93	78	48	5	16	40	6	24	165
Three Sisters W, Oregon	9-1-93	87	59	5	15	37	4	16	52

NP = National Park, W = Wilderness, NWR = National Wildlife Refuge, NSA= National Scenic Area

Table 8. IMPROVE and USFS Optec NGN-2 nephelometer monitoring networks precision, optical chamber heating and relative humidity statistics

	Estimated Calibration Precision %	**Aerosol Heating Chamber - Ambient °C**		**Cumulative Frequency Relative Humidity %**			**Cum. Frequency f(rh) Tang's Ammonium Sulfate Curve**		
		Mean	**Sigma**	**10%**	**50%**	**90%**	**10%**	**50%**	**90%**
IMPROVE									
Acadia NP, Maine	40	0.5	0.9	48	79	99	1.26	2.63	6.52
Boundary Waters W, Minnesota	23	0.8	2.6	46	79	97	1.20	2.63	6.52
Dolly Sods W, Virginia	18	0.3	2.1	40	83	99	1.06	2.98	6.52
Great Smoky Mts. NP, Tennessee	21	-0.4	2.6	47	77	100	1.24	2.53	6.52
Jarbidge W, Nevada	13	0.6	0.8	22	56	84	1.00	1.52	3.04
Mammoth Cave NP, Kentucky	14	0.9	1.7	49	86	100	1.29	3.19	6.52
Mount Rainier NP, Washington	11	0.7	1.2	56	94	100	1.52	5.93	6.52
Okefenokee NWR, Georgia	14	0.5	2.9	48	85	100	1.26	3.13	6.52
Upper Buffalo W, Arkansas	21	0.3	1.5	43	76	98	1.14	2.44	6.52
USFS									
Columbia River Gorge NSA, Oregon	20	0.1	1.6	31	62	88	1.00	1.76	3.56
Gila W, New Mexico	15	1.2	1.5	13	43	90	1.00	1.14	3.88
Great Gulf W, New Hampshire	13	1.2	1.5	47	84	99	1.24	3.05	6.52
Lone Peak W, Utah	12	1.0	1.5	23	53	91	1.00	1.42	4.05
Mount Zirkel W, Colorado	11	0.5	1.9	34	75	95	1.00	2.38	6.44
Shining Rock W, Virginia	23	0.4	2.0	37	86	100	1.02	3.23	6.52
Snoqualmie Pass (Alpine lakes W), Washington	12	0.5	0.9	53	92	100	1.40	4.39	6.52
Three Sisters W, Oregon	18	0.7	1.4	39	86	100	1.05	3.22	6.52

NP = National Park, W = Wilderness, NWR = National Wildlife Refuge, NSA= National Scenic Area

Table 9. Collection statistics and WX interference codes for IMPROVE and USFS nephelometer networks

	Number	%
Total possible hourly bsp data	469,517	100
Total valid hourly bsp data collected (% of possible)	400,584	85.3
Total bsp without wx effects (% of valid)	249,168	62.2
Total bsp with possible wx affects (% of valid)	151,416	37.8

Analysis of WX Interference Codes	Number	% of Valid bscat data
bscat < Rayleigh	8,866	2.2
rh > 90% (RH)	57,271	14.3
bscat > 5000 Mm^{-1} (MAX)	709	0.18
rate of change > 50 Mm^{-1}/hour (ROC)	5,803	1.5
sigma/mean > 10% (SIGMA)	12,538	3.1
RH + MAX	3,279	0.82
RH + SIGMA	18,333	4.6
RH + ROC	14,901	3.7
RH + SIGMA + ROC	18,841	4.7
RH + MAX + ROC	1,193	0.30
RH + MAX + SIGMA	1	0.0
RH + MAX + ROC + SIGMA	228	0.06
MAX + ROC	261	0.07
MAX + SIGMA	361	0.09
MAX + ROC + SIGMA	845	0.21
SIGAMA + ROC	4,600	1.2
data point between WX code	3,386	0.85

Total WX codes with rh>90% = 109,047 this is 72% of WX identified interference data and 27% of total valid bscat data

Table 10. Constants used in reconstructing dry, IMPROVE, and GCVTC aerosol scattering from IMPROVE speciated aerosol data.

	DRY	IMPROVE	GCVTC
Dry scattering/mass coefficient			
Sulfate	3.0	3.0	3.0
Nitrate	3.0	3.0	3.0
Organic	4.0	4.0	4.0
Soil	1.0	1.0	2.0
Course Mass	0.6	0.6	0.6
Relative humidity growth function	none	Tang's [9]	0.7/(1.0-rh)
Percent of organic aerosol that is hygroscopic	0%	0%	50%

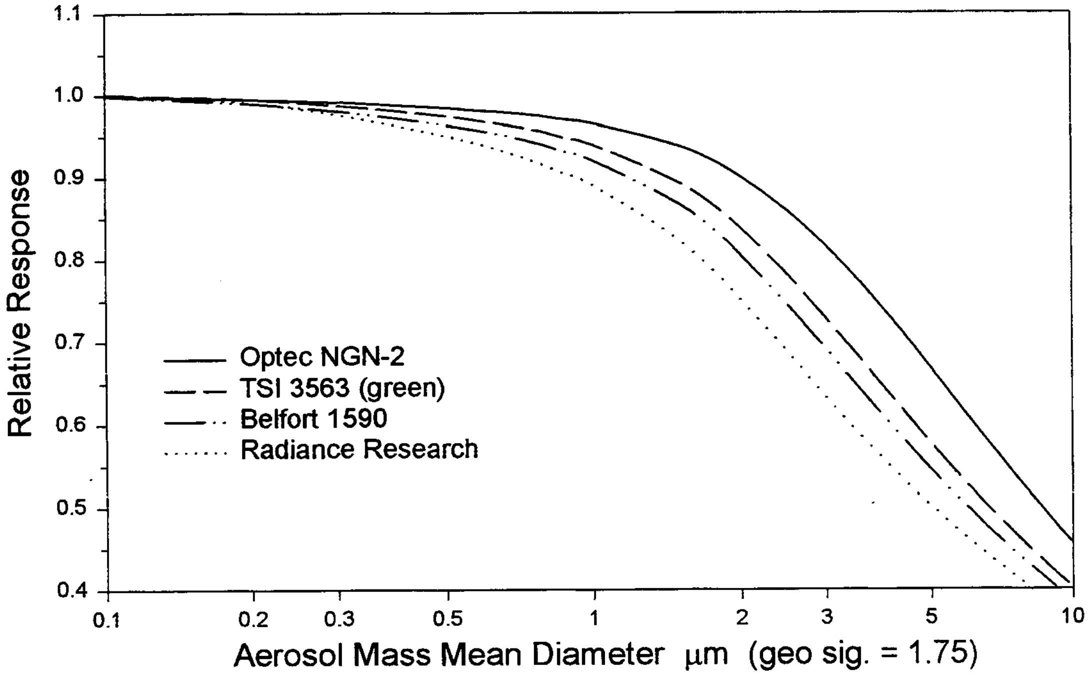

Figure 1: Modeled Rayleigh gas corrected truncation error of Optec NGN-2, TSI 3563 (green), Belfort 1590 and Radiance Research M903 integrating nephelometers.

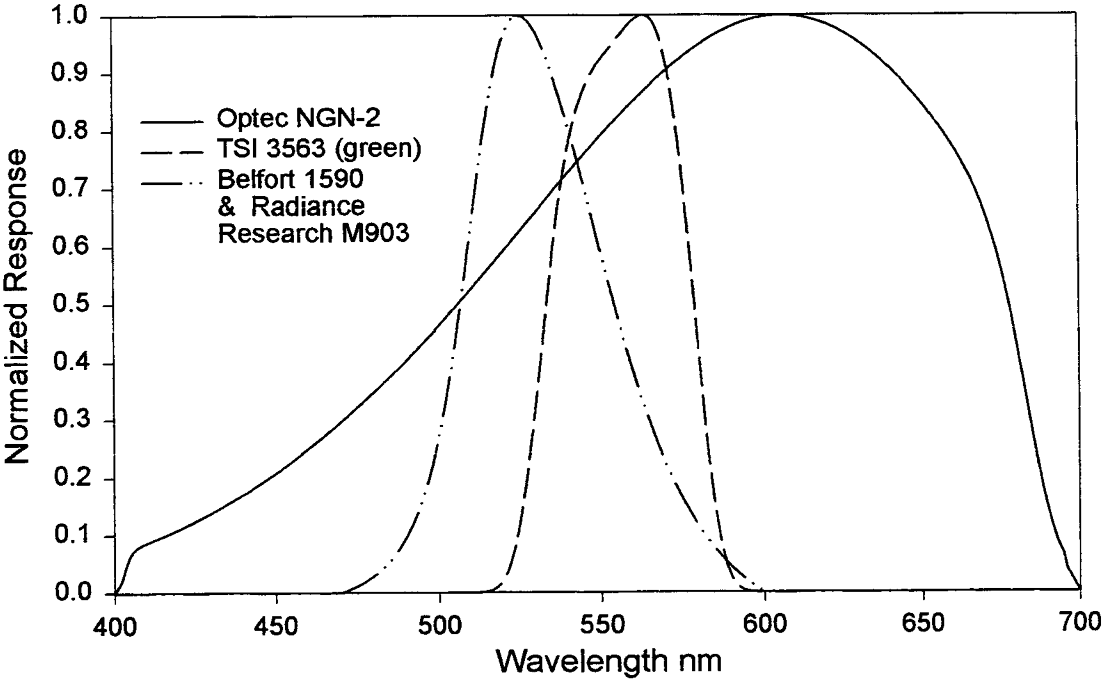

Figure 2: Normalized wavelength dependent response of Optec NGN-2, TSI 3563 (green), Belfort 1590 and Radiance Research M903 integrating nephelometers.

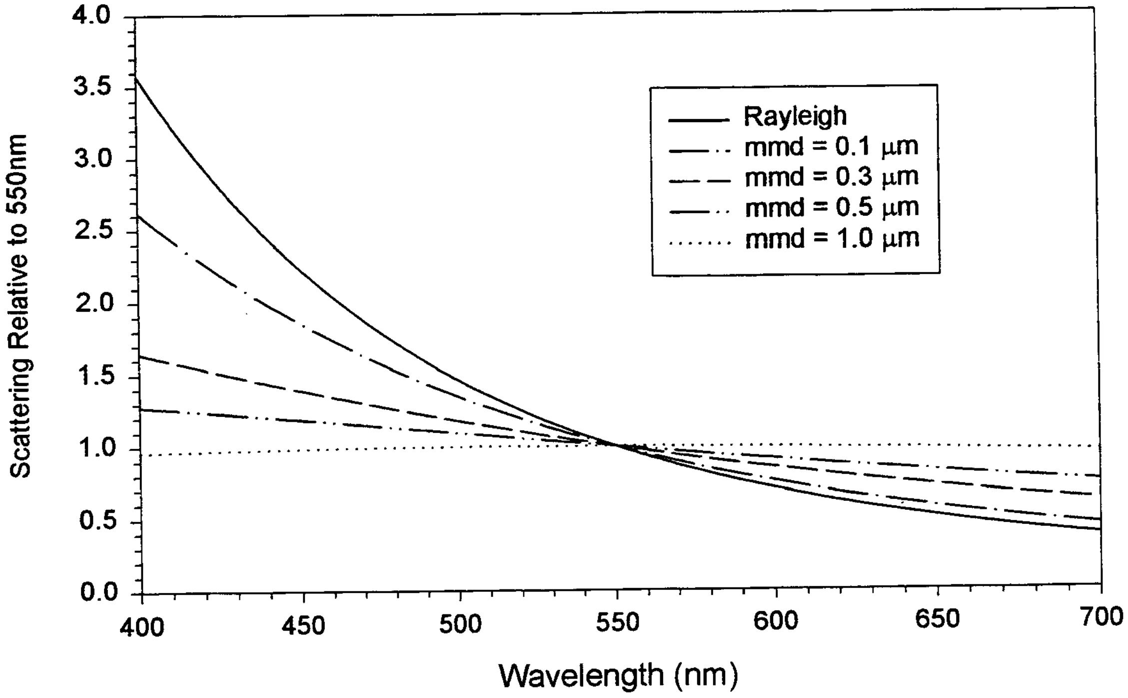

Figure 3: Modeled wavelength dependence of scattering of a Rayleigh gas and lognormal aerosol size distributions with varying mass mean diameters (mmd), constant geo. sigma (1.75) and index of refraction (1.52 ± 0.006*i*). Scattering normalized to 1.0 at 550 nm.

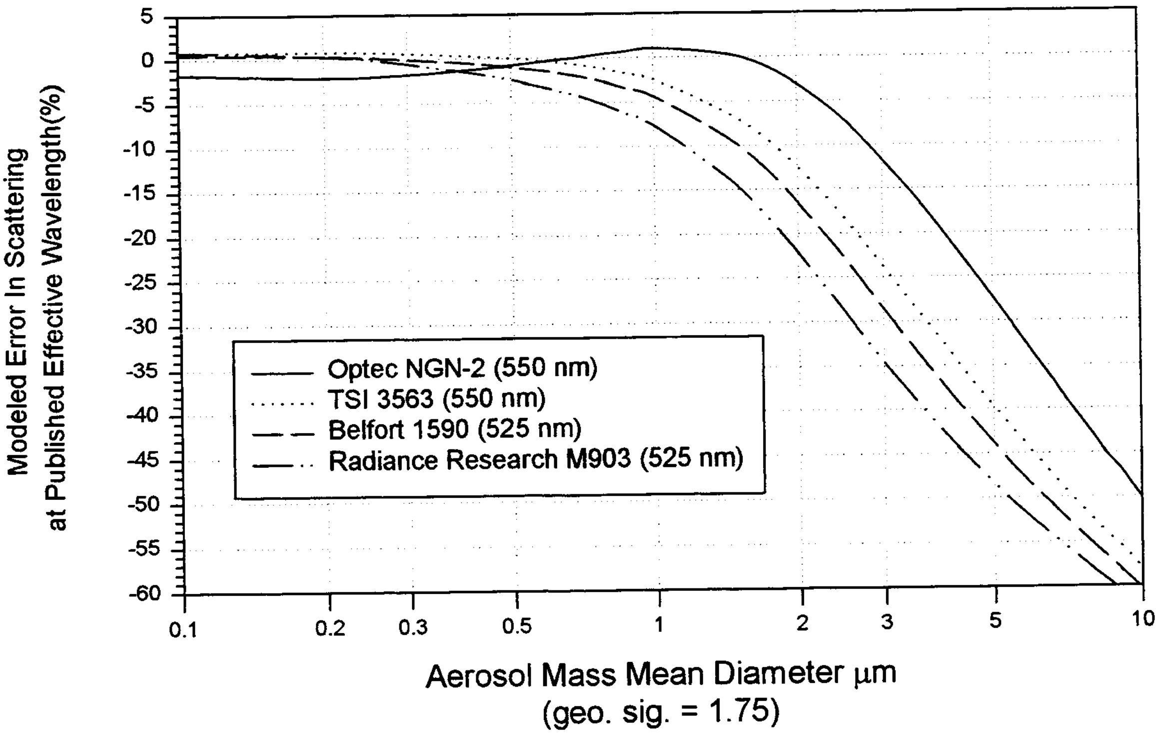

Figure 4: Estimated error in measured scattering at published effective wavelength for Optec NGN-2, TSI 3563 (green), Belfort 1590 and Radiance Research M903 integrating nephelometers as a function of aerosol mass mean diameter, including spectral response and truncation error.

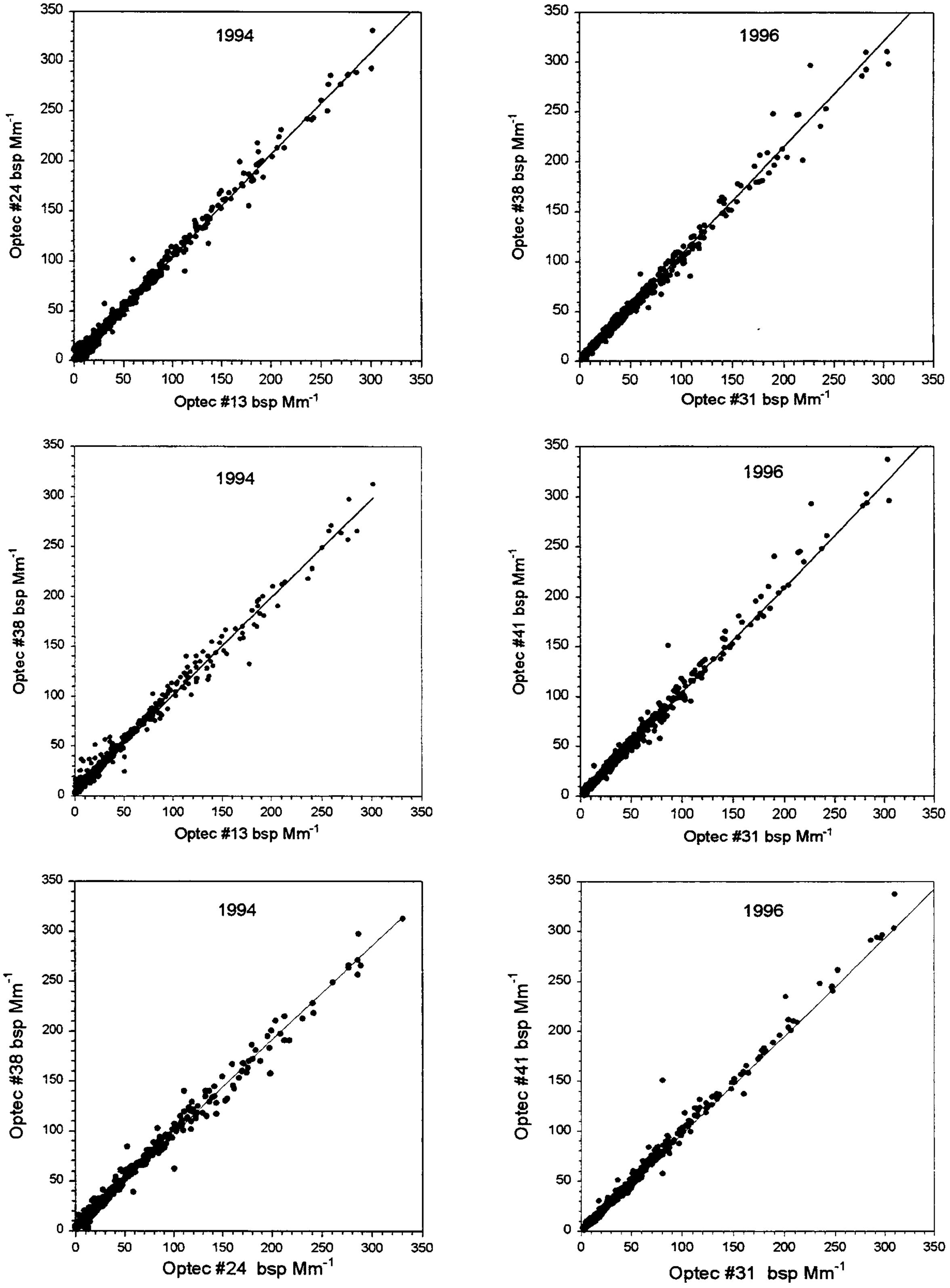

Figure 5: 1994 and 1996 Optec NGN-2 nephelometer intercomparisons of hourly average aerosol scattering, all relative humidities (0-100%) (regression statistics are listed in Table 3)

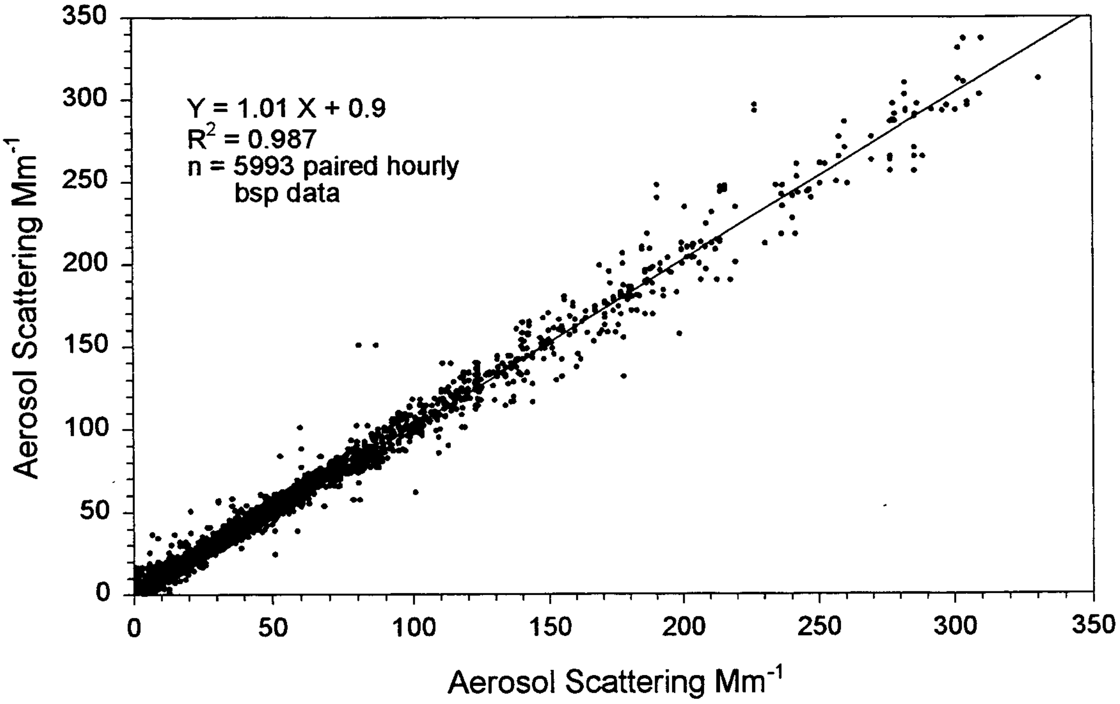

Figure 6: All Optec NGN-2 paired aerosol scattering data from 1994 and 1996 intercomparison studies at all relative humidities (0-100%)

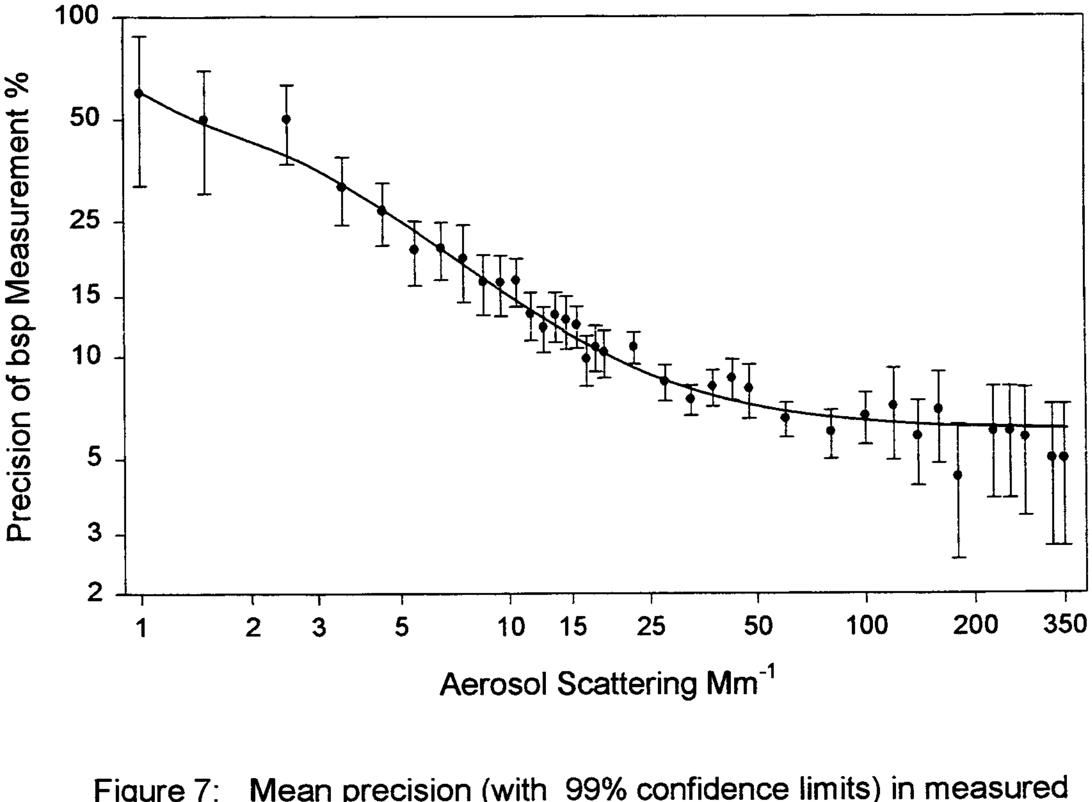

Figure 7: Mean precision (with 99% confidence limits) in measured aerosol scattering for all 1994 and 1996 paired hourly Optec NGN-2 measurements as a function of bsp.

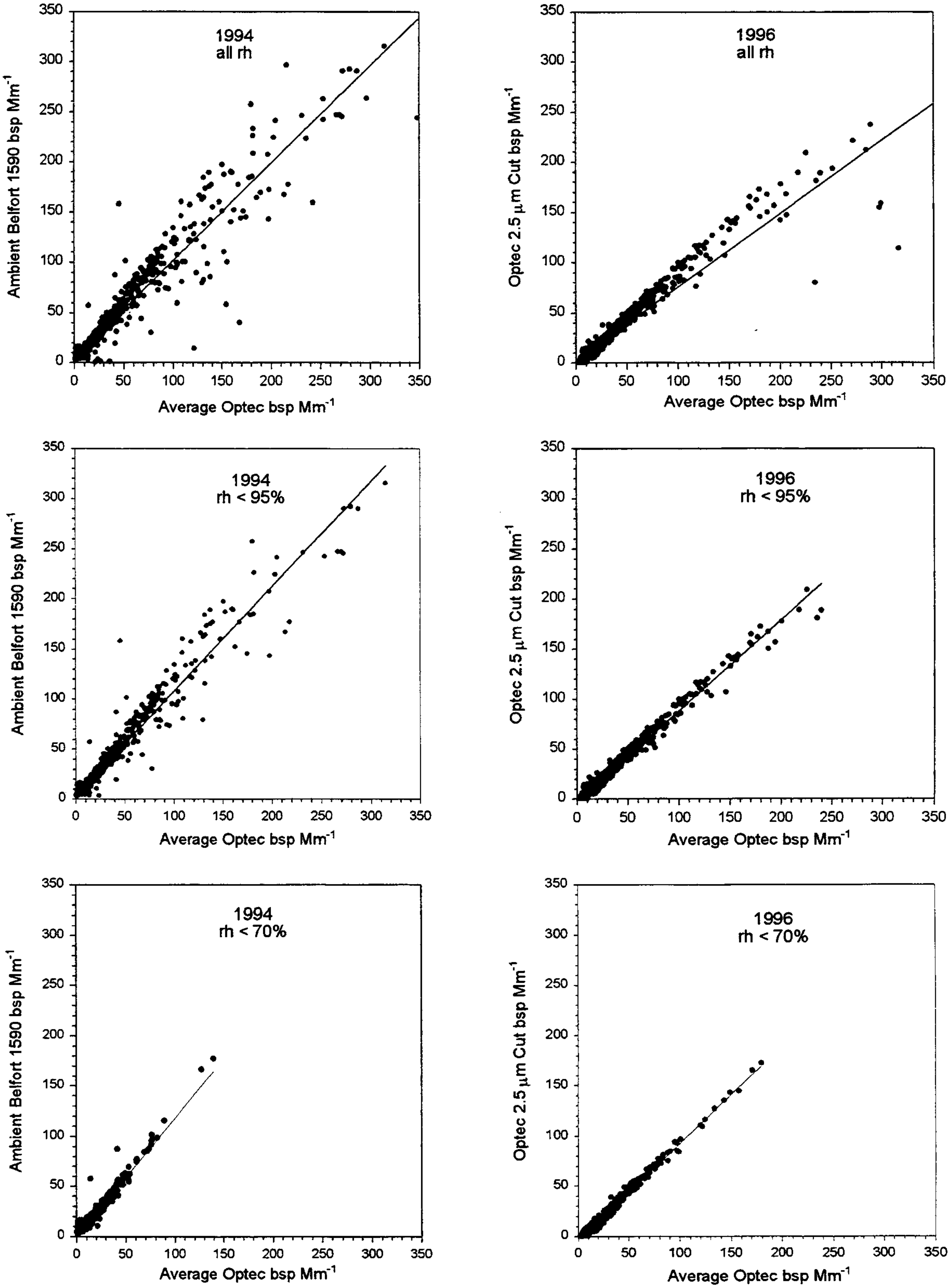

Figure 8: 1994 Ambient Belfort 1590 vs. Average Optec NGN-2 and 1996 Optec NGN-2 2.5 µm cut vs Average Optec NGN-2 hourly average aerosol scattering in various relative humidity ranges (regression statistics are listed in Table 4)

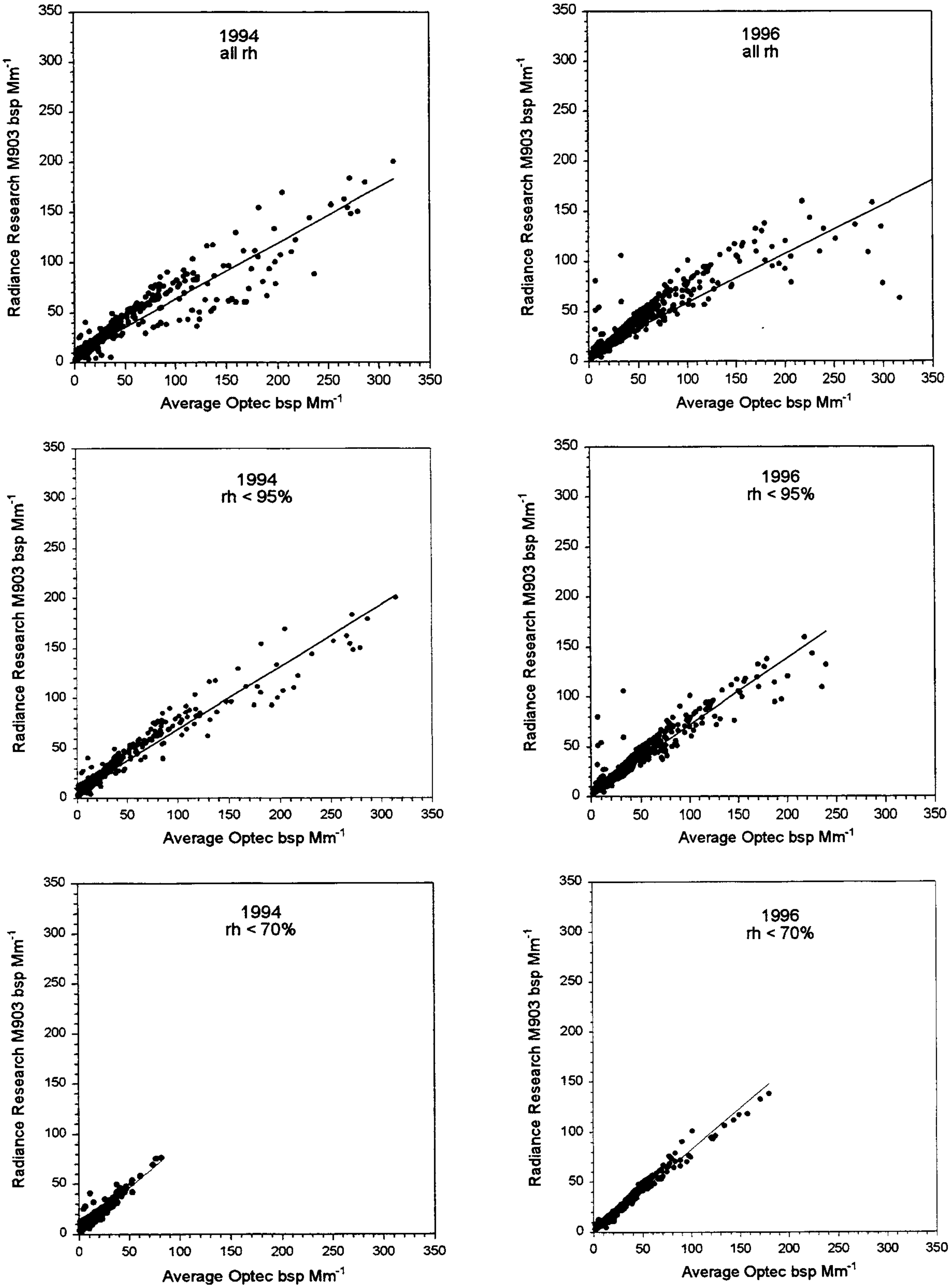

Figure 9: 1994 and 1996 Radiance Research M903 vs. Average Optec NGN-2 hourly average aerosol scattering in various relative humidity ranges (regression statistics are listed in Table 5)

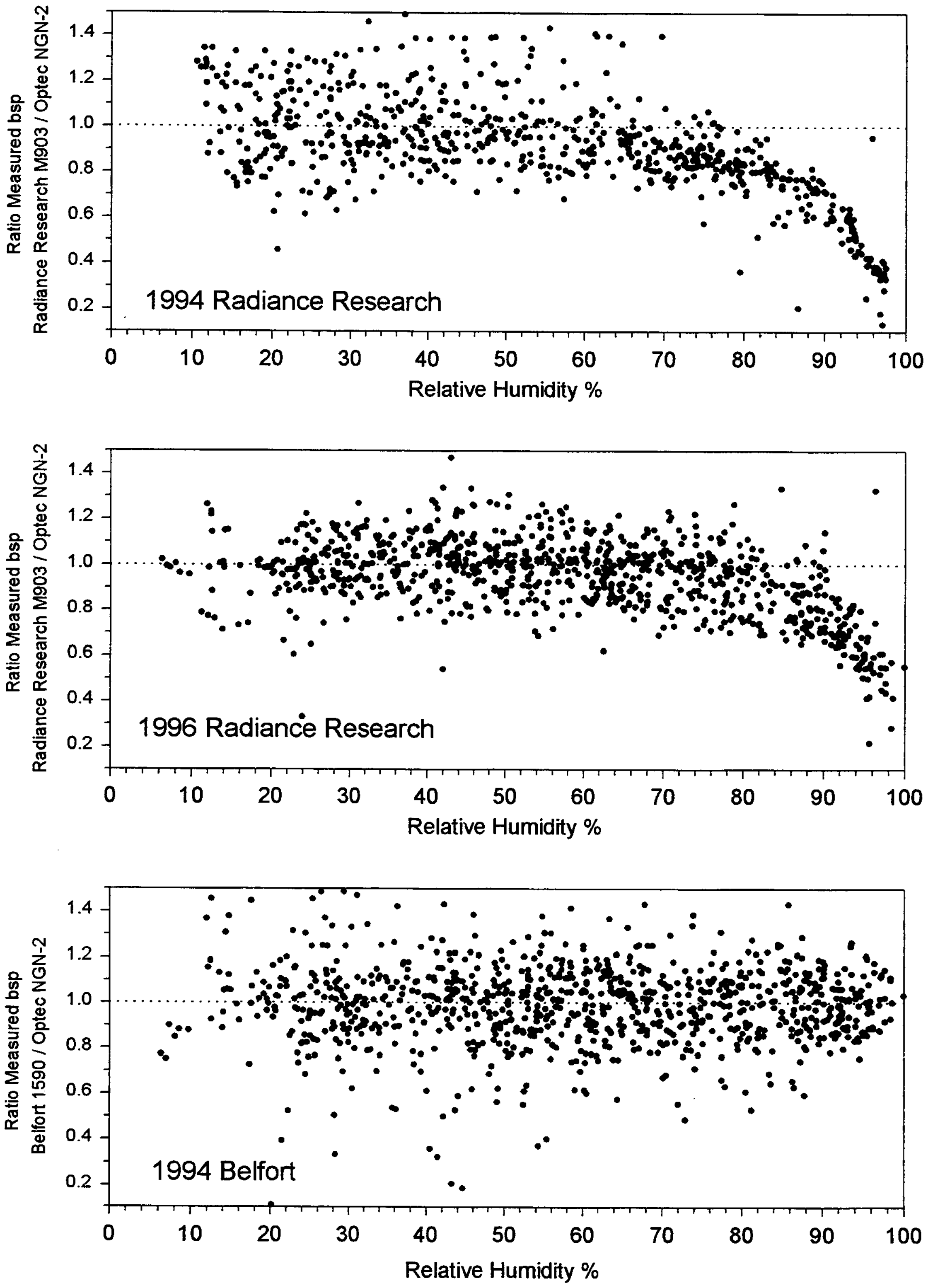

Figure 10: Ratio of measured bsp by Radiance Research M903 (1994 top, 1996 middle), and Belfort 1590 (1994 bottom) to average of ambient Optec NGN-2 by relative humidity. Ratios are normalized to mean ratio for entire test

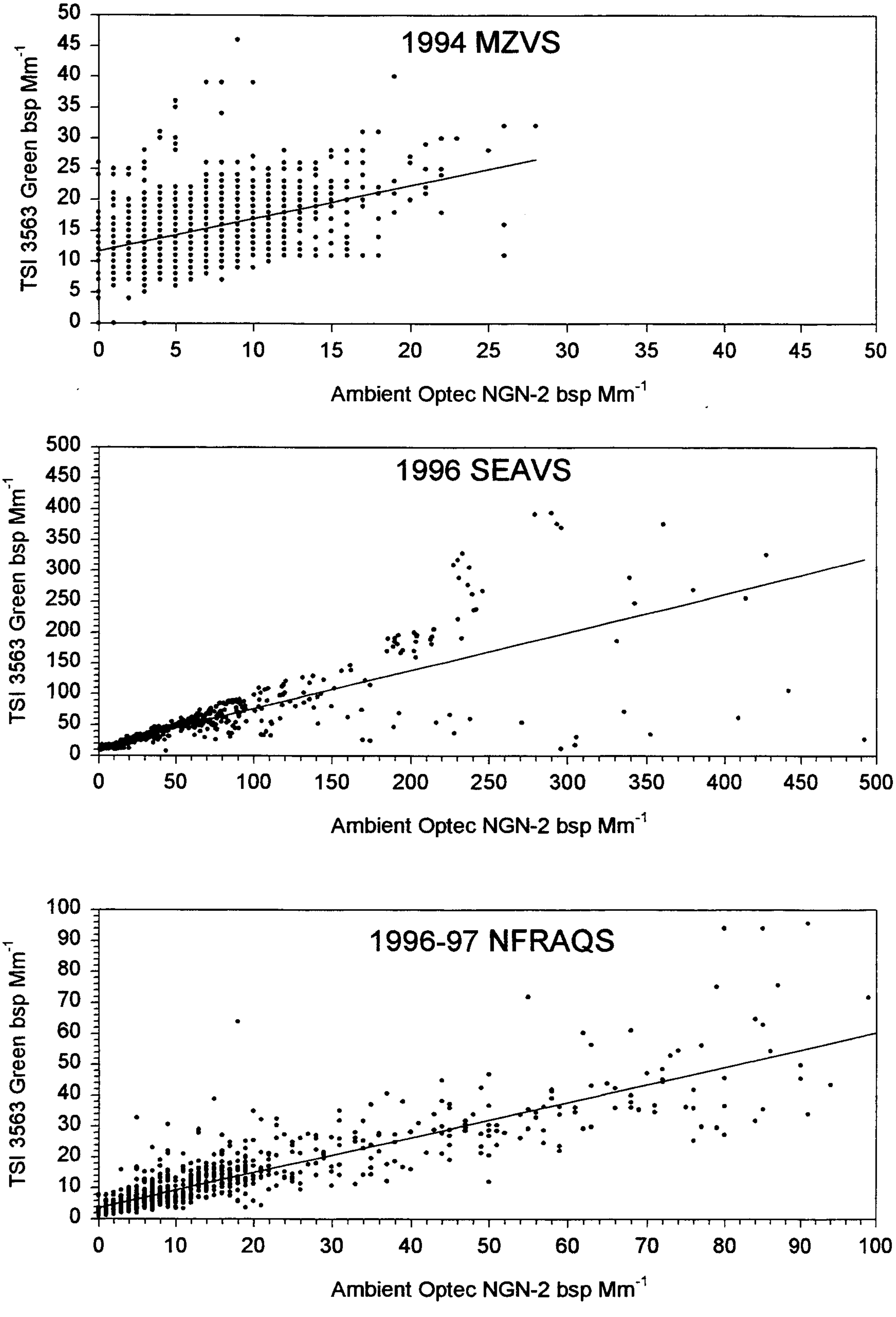

Figure 11: TSI 3563 vs Optec NGN-2 aerosol bsp comparisons
from three recent field studies:
1994 Mt. Zirkel Visibility Study (MZVS),
1996 Southeastern Visibility Aerosol Study (SEAVS)
1996-97 Northern Front Range Air Quality Stusy (NFRAQS)

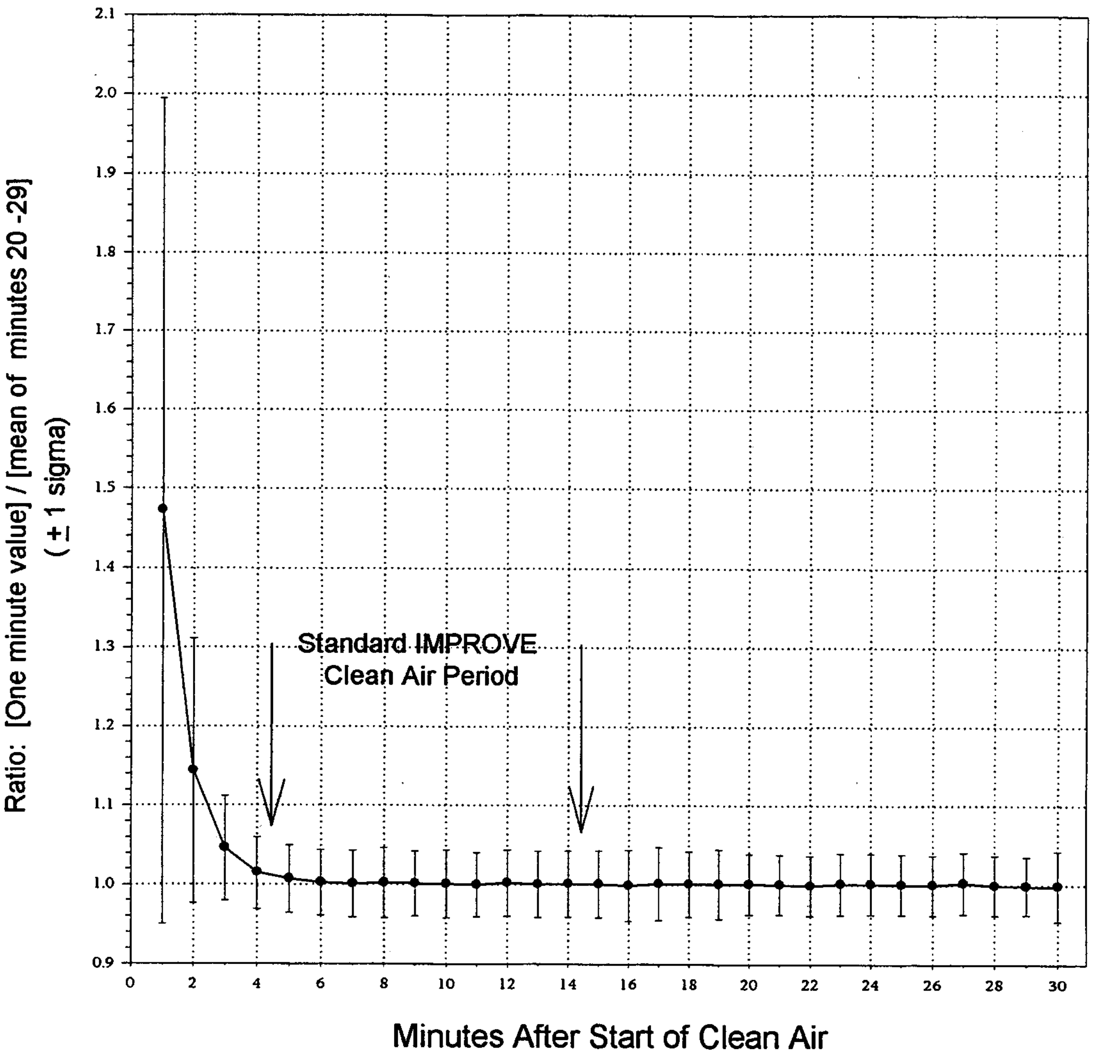

Figure 12: Average and standard deviation of the ratio of one-minute reading to average of minutes 20-29 for ambient Optec NGN-2 during clean air cycle. (1440 clean air cycles)

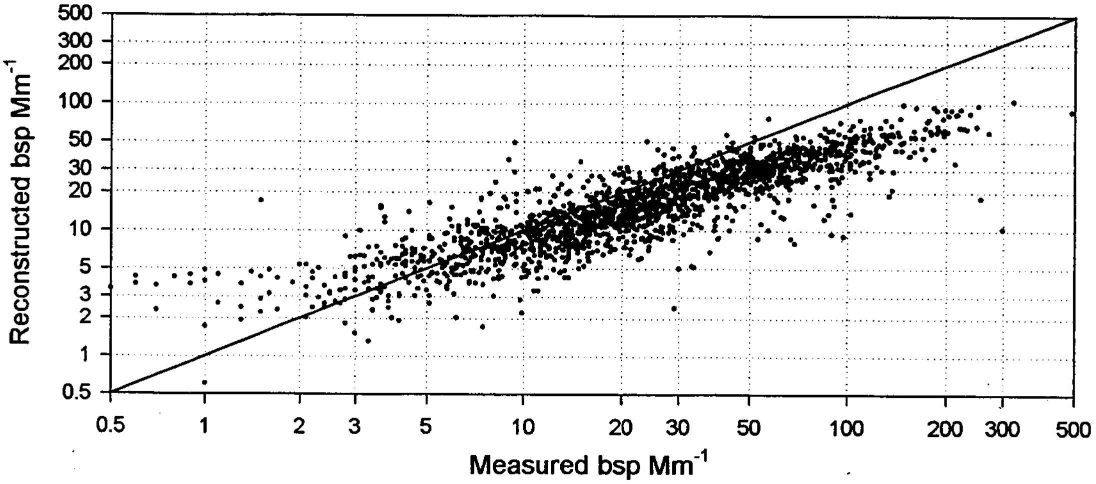

Figure 13: Dry reconstructed vs. measured daily aerosol scattering. (minimum 12 hourly measured bsp data in daily average)

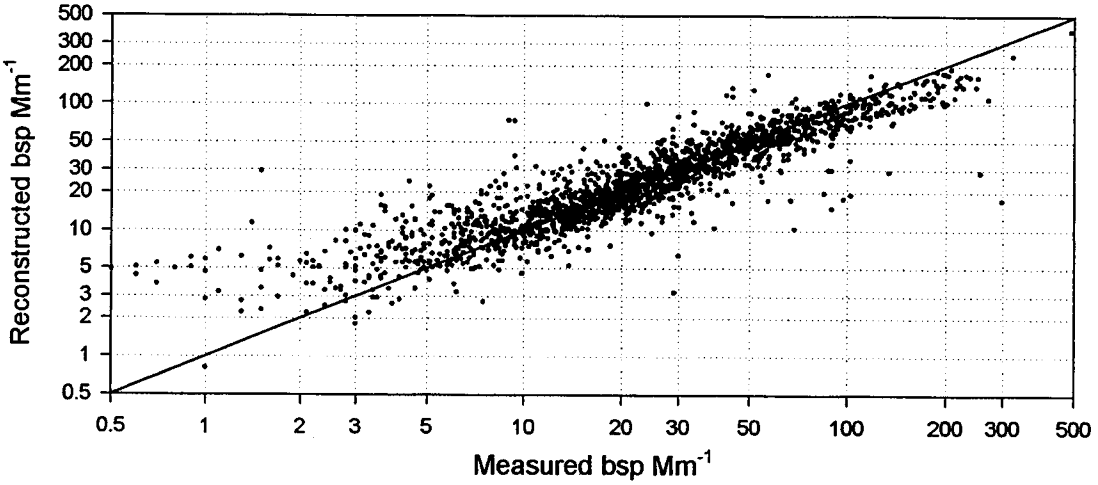

Figure 14: IMPROVE reconstructed vs. measured daily aerosol scattering. (minimum 12 hourly measured bsp data in daily average)

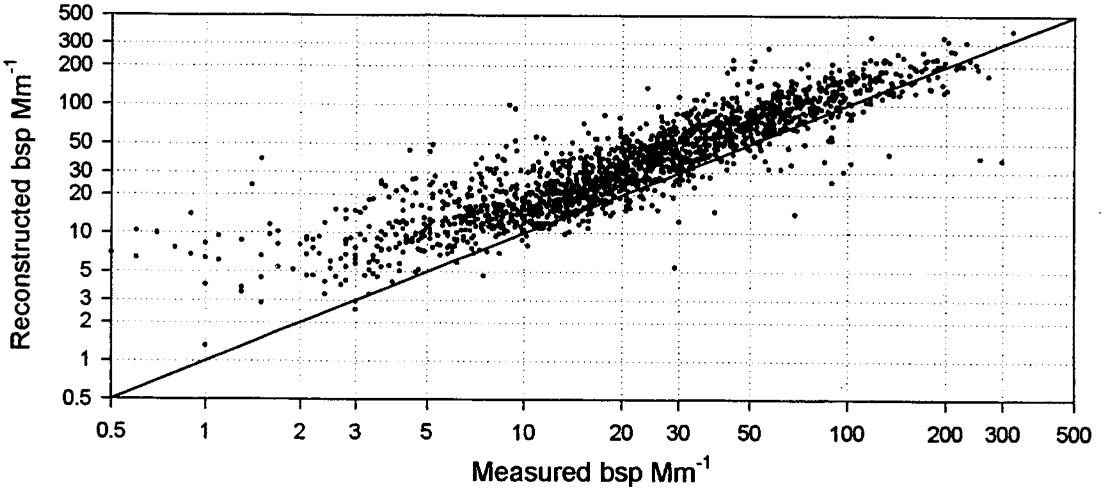

Figure 15: GCVTC reconstructed vs. measured daily aerosol scattering. (minimum 12 hourly measured bsp data in daily average)

IMPLICATIONS

Correct determination of the in-situ ambient aerosol scattering coefficient is required to fully characterize visual air quality effects associated with varying aerosol chemistry, concentrations, and physical properties. The Optec NGN-2 ambient nephelometer is examined theoretically, operationally, and compared with other existing integrating nephelometers with this as the primary goal. The NGN-2 is found to be the only currently available nephelometer that meets the challenging and at times contradictory requirements for an ambient scattering measurement.

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