# Theoretical and Experimental Analysis of the Optec NGN Nephelometer

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## ABSTRACT

## INTRODUCTION

The integrating nephelometer is an instrument specifically designed to directly measure the scattering coefficient of atmospheric aerosols. Nephelometry is a mature science dating back 50 years, with well understood design philosophies and inherent limitations[1]. The Optec NGN integrating nephelometer was designed to operate in low power, low maintenance, ambient field conditions.[2] This required two main compromises in the optical design:

- The use of a photodiode rather than a photomultiplier tube (PMT) detector, and
- A wide band filter to compensate for the reduced sensitivity of the photodiode compared to a PMT.

The following is a theoretical examination of the effect of these design requirements on the measurement accuracy of the Optec NGN integrating nephelometer and an experimental determination of the measurement precision of the instrument. Included in the theoretical analysis are comparisons to three other currently available integrating nephelometers:

- TSI 3563: TSI, Inc., St. Paul, Minnesota
- Belfort 1590 : Belfort Instrument Company, Baltimore, Maryland
- Radiance Research M903: Radiance Research Inc., Seattle, Washington

## OPTEC NGN OPTICAL DESIGN

Figure 1 presents the basic optical layout of the Optec NGN nephelometer. Light enters the measurement chamber through a circular acrylic near Lambertian diffuser. The diffuser is illuminated by a low power (13.8 VDC, 25 watt) quartz halogen projection bulb with a dichroic reflector. A heat absorbing glass filter is between the lamp and diffuser. The diffuser and heat filter block all radiation less than 400 nm and longer than 700 nm. The light source is mechanically chopped at 10 Hz.

Two identical silicon photodiode detectors are used. One, the lamp brightness detector, directly views the diffuser. The signal from this detector is used to lock onto the chopped light signal and monitor the lamp output. The second, the scattered light detector, uses a small telescope to view a 6-mm diameter, 260-mm long, cylindrical volume of air parallel to and slightly in front of the diffuser terminating in a light trap. A small Fabry lens behind a field stop images the entrance pupil of the telescope objective lens onto the active area of the silicon photodiode detector. This allows all the light flux that passes through the field stop to be collected by the detector and reduces the effect of response differences across the detector's surface. A hemispheric field stop around the diffuser prevents light from directly illuminating the detector or light trap.

Identical P-N silicon photodiodes operating in the photovoltaic mode are used for the direct and scattered light detectors. Photodiodes are less sensitive than the photomultiplier tubes used in other currently available nephelometers, thus a wide band 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 output of the scattered light detector is normalized by the output of the direct light detector. This compensates for lamp brightness changes and precludes the need for some sort of lamp stabilization circuitry.

The light source is chopped mechanically at 10 Hz to allow extraction of the scattered light signal. In the absence of noise, the difference between the top of the signal level when the lamp is on ( passing through the chopper illuminating the measurement chamber) and the bottom of the signal when the lamp is off (blocked by the chopper) would give an accurate measurement of the scattered light. Since noise due to the detector and amplifier electronics is usually several orders of magnitude greater than the signal, the average difference must be calculated over many hundreds of cycles. An integrated single board computer handles all signal processing and system control functions. The computer integrates the scattered light signal for 14 seconds and then integrates the direct light signal for 1 second. This is repeated four times to compromise the basic one-minute reading of an Optec NGN nephelometer. The sensitivity of the detectors and gain of electrometer results in an output of 1 count approximately equal to 1 $Mm^{-1}$.

## THERORETICAL ANALYSIS OF OPTICAL DESIGN

To evaluate the theoretical effect of this variability on $\alpha_M$, the scattering efficiency, $Q_{scat}$, at 550 nm was computed using subroutines developed by Dave (1968) for all possible combinations of the parameters in the above ranges. Care was taken to use sufficiently small increments in all parameter ranges to satisfy the Dave criterion (Dave, 1969). It should be noted, this method of independent variation ignores the effect of correlations between parameters that may minimize the range of $\alpha_M$ for real particles, such as mineral particles (high density, transparent) in comparison to carbon particles (low density, absorbing). However, allowing the parameters to vary independently is a reasonable first step in the sensitivity analysis. It is also worth pointing out that, while in principal, Mie theory of scattering from polydispersions is applicable to only spherical particles**,** studies have indicated that it is a useful approximation to experimental measurements of fine particle scattering provided the size distribution is relatively broad (Mishchenko *et al.*, 1997).

### Truncation Angle

An ideal integrating nephelometer will collect all scattered light from $0^O$ – $180^O$ . Real nephelometers, however, must collect scattered light from 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. 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 ($0^O$) and backward ($180^O$) directions. Table 1 lists the integration angles for the various nephelometers referred to in this paper. Figure 2 shows the calculated wavelength dependent, Rayleigh gas corrected, truncation error associated with each instrument for varying aerosol mass mean diameters (mmd) with a geometric sigma of 1.75. The assumption 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 ($0^O$-$180^O$). The error increases rapidly with aerosol mmd greater than 1.0 μm for all instruments. The larger integration angle of the NGN 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, $R(\lambda)$, 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 $\varphi$ 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 the Optec NGN nephelometer detector, filters, and lamp were received from the manufacturer. Analytical functions were generated for each of the components and combined to create a response function for the system. Analytical functions for the system response of the TSI 3563 and Belfort 1590 nephelometers were generated from published measured curves.[3, 4] Information received from Radiance Research indicates that model M903 has the same spectral response as the Belfort 1590. Figure 3 plots the normalized wavelength response for these integrating nephelometers. The peak response of each instrument is quite different. Due to the varying bandwidths, however, 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, scattering phase function, and wavelength dependence of scattering coefficient of the aerosol. Figure 4 plots the wavelength dependence of Rayleigh scattering and scattering of lognormal aerosol size distributions with varying mmd. Figure 5 shows the modeled wavelength dependent response of the Optec NGN to the scattering functions in Figure 4. The output of the nephelometer will be equal to the area under each curve. 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 6 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.

## EXPERIMENTAL TEST OF PRECISION

Intensive side by side nephelometer tests were performed in 1994 and repeated in 1996. Three Optec NGN nephelometers were mounted two meters above ground level under a precipitation and solar radiation shield with their inlets facing north (Figure 6). 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 ($b_{sp}$) based on the upscale and zero calibrations performed for all systems during the study. One of the ambient Optec nephelometers (#38) was used in both the 1994 and 1996 tests. All the nephelometers in both studies had estimated measurement uncertainties of less than 15% in $b_{sp}$ (based on multiple zero air and SUVA 134a upscale calibrations) and also had an average chamber heating of less than $1.0^{O}$C. Figure 7 contains the scatter plots for the six Optec NGN ambient nephelometers that ran during the 1994 and 1996 studies. Table 2 lists the regression statistics for the paired data. Figure 8 is a plot of all paired measurements from the two study periods. Figure 9 is a plot of the calculated mean precision of the paired measurements as a function of average $b_{sp}$. The precision of each paired measurement is estimated by:

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

The data were sorted into average $b_{sp}$ bins and a mean precision with 99% confidence limits was calculated for each bin. The precision is better than 10% for all $b_{sp} > 10$ $Mm^{-1}$. As particle scattering decreases to zero, the precision increases to nearly 100%. This is to be expected, since the minimum detectable increment for the Optec nephelometer is approximately 1 $Mm^{-1}$.

## CONCLUSIONS

The Optec NGN integrating nephelometer was designed to make aerosol scattering measurements under a wide variety of field and experimental conditions. The design requirements of low power, low maintenance, 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. Field tests of multiple Optec nephelometers show the precision of the instrument to be excellent.

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1. Table 1. Integration angles for various integrating nephelometers.

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

Table 2. Optec NGN nephelometer aerosol scattering ($Mm^{-1}$) intercomparison statistics for 1994 and 1996 studies (See Figure 7 for scatter plots)

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

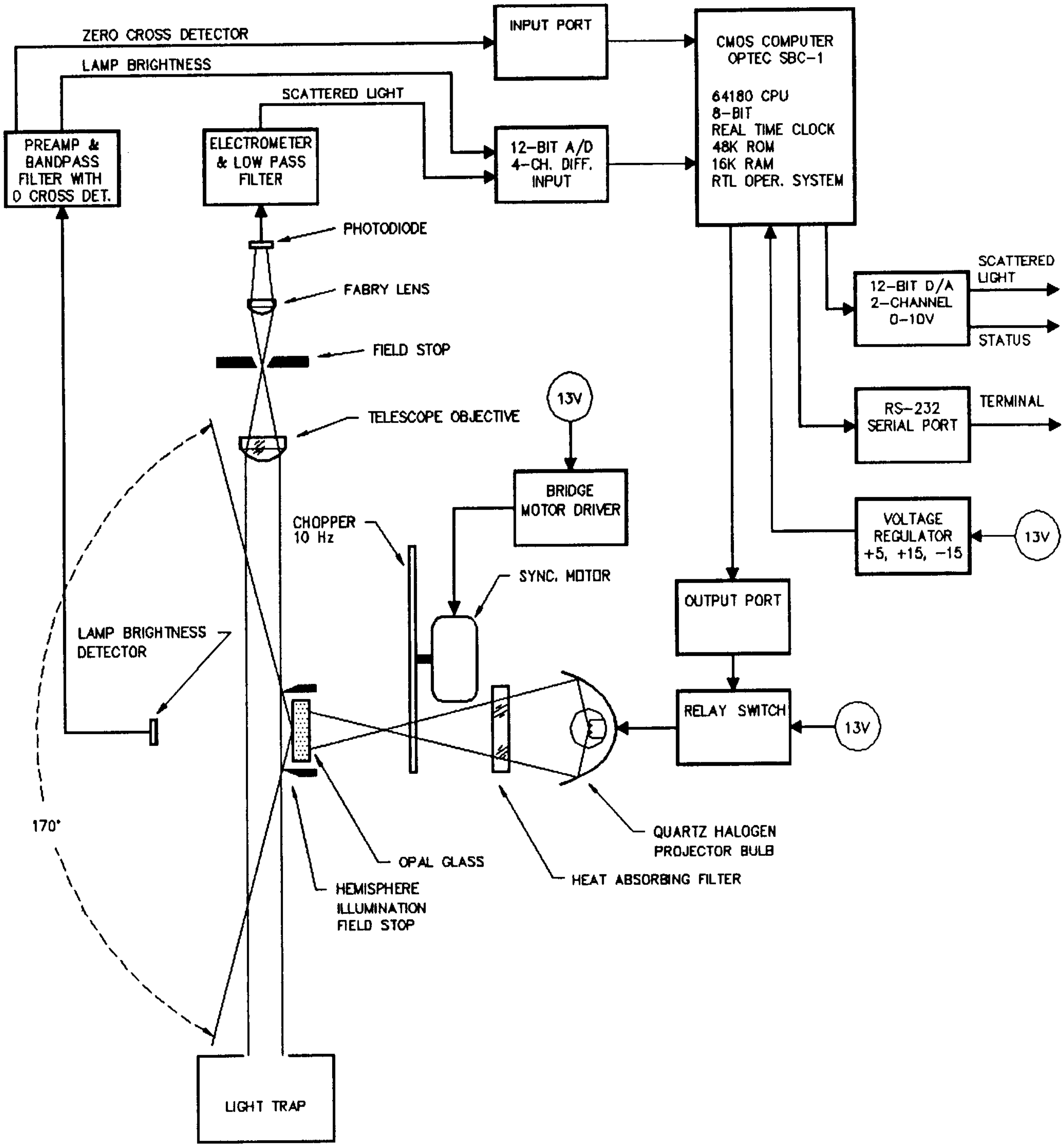


**Figure 1**. Optec NGN nephelometer optical design

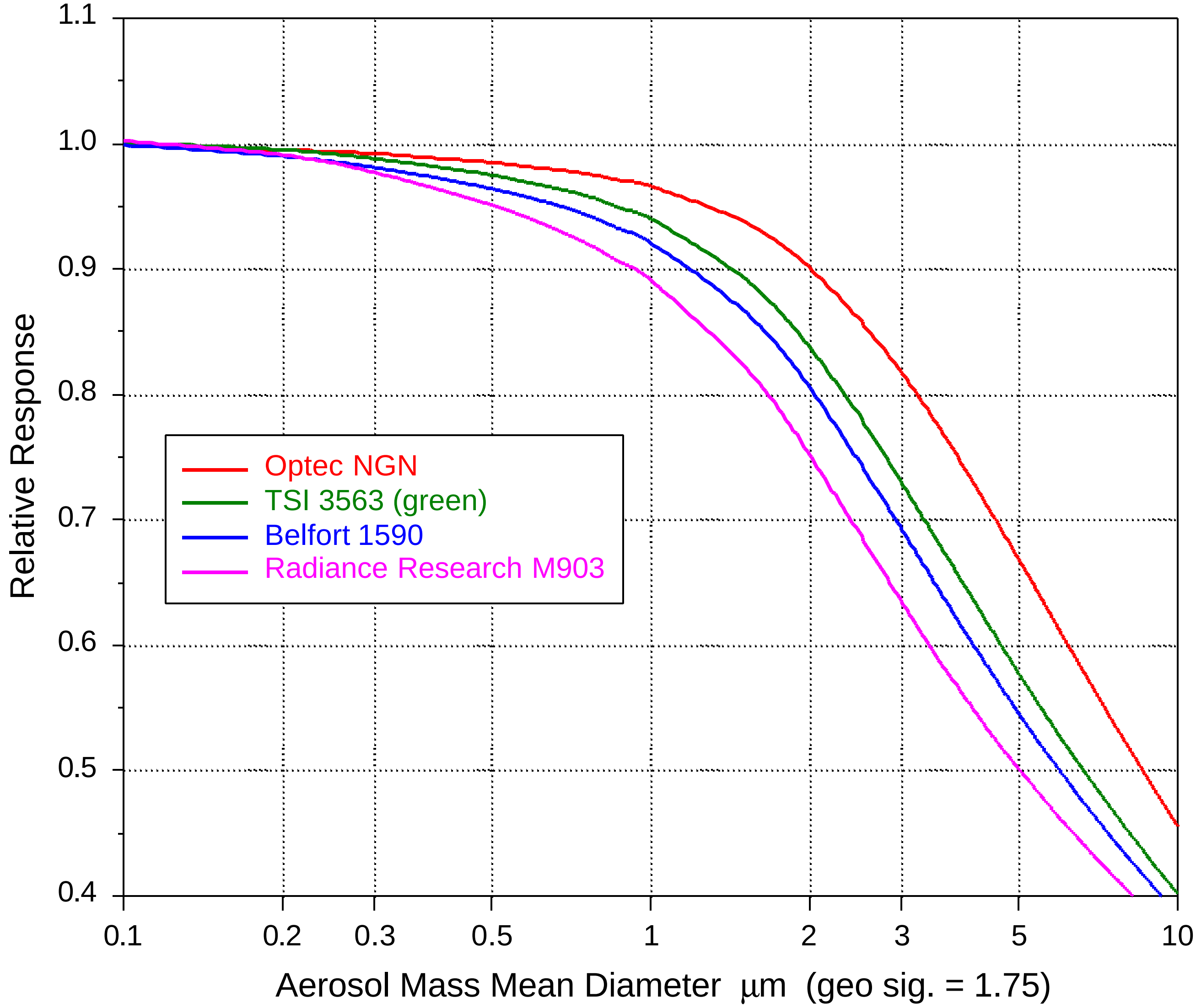


**Figure 2.** Modeled Rayleigh gas corrected truncation error of Optec NGN, TSI 3563 (green), Belfort 1590, and Radiance Research M903 integrating nephelometers.

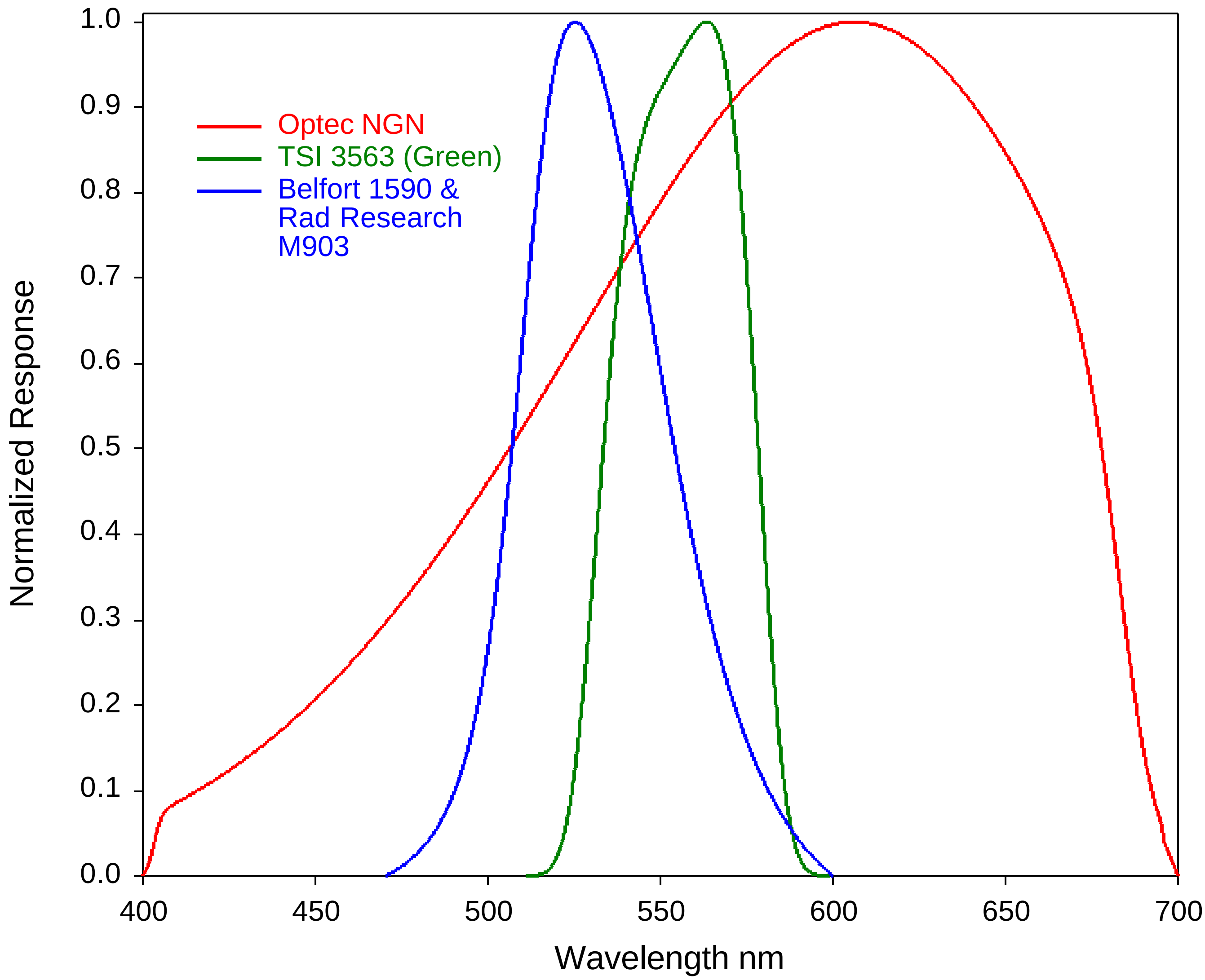


**Figure 3.** Normalized wavelength dependent response of Optec NGN, TSI 3563 (green), Belfort 1590, and Radiance Research M903 integrating nephelometers.

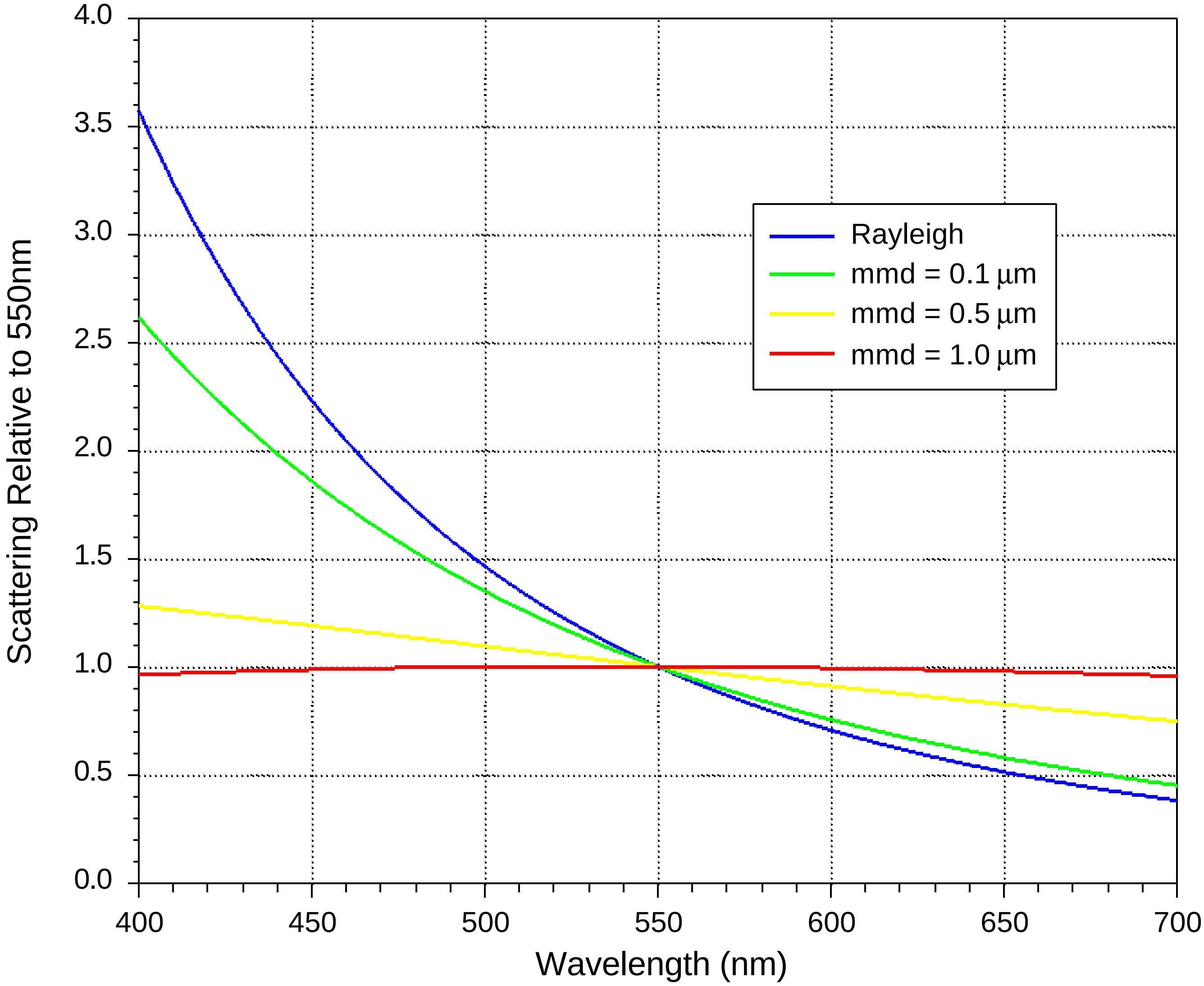


**Figure 4.** Modeled wavelength dependence of scattering of a Rayleigh gas and lognormal aerosol size distributions with varying mass mean diameters (mmd), constant geometric sigma (1.75) and index of refraction (1.52 ± 0.006*i*). Scattering normalized to 1.0 at 550 nm.

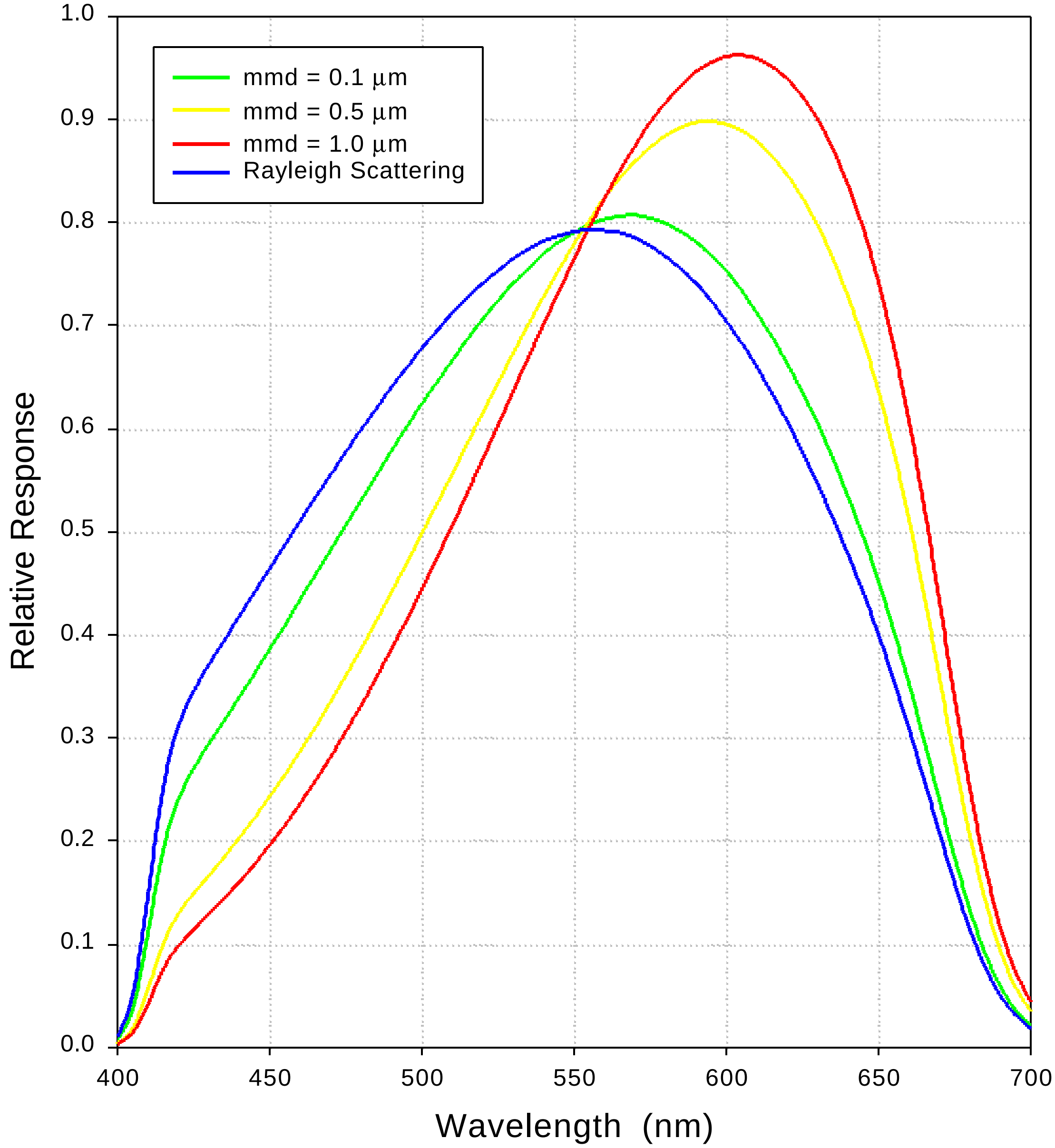


**Figure 5.** Modeled wavelength dependent response of Optec nephelometer to: Unit scattering by a Rayleigh gas and the lognormal aerosol size distributions in Figure 3. Output of nephelometer will be equal to area under each curve.

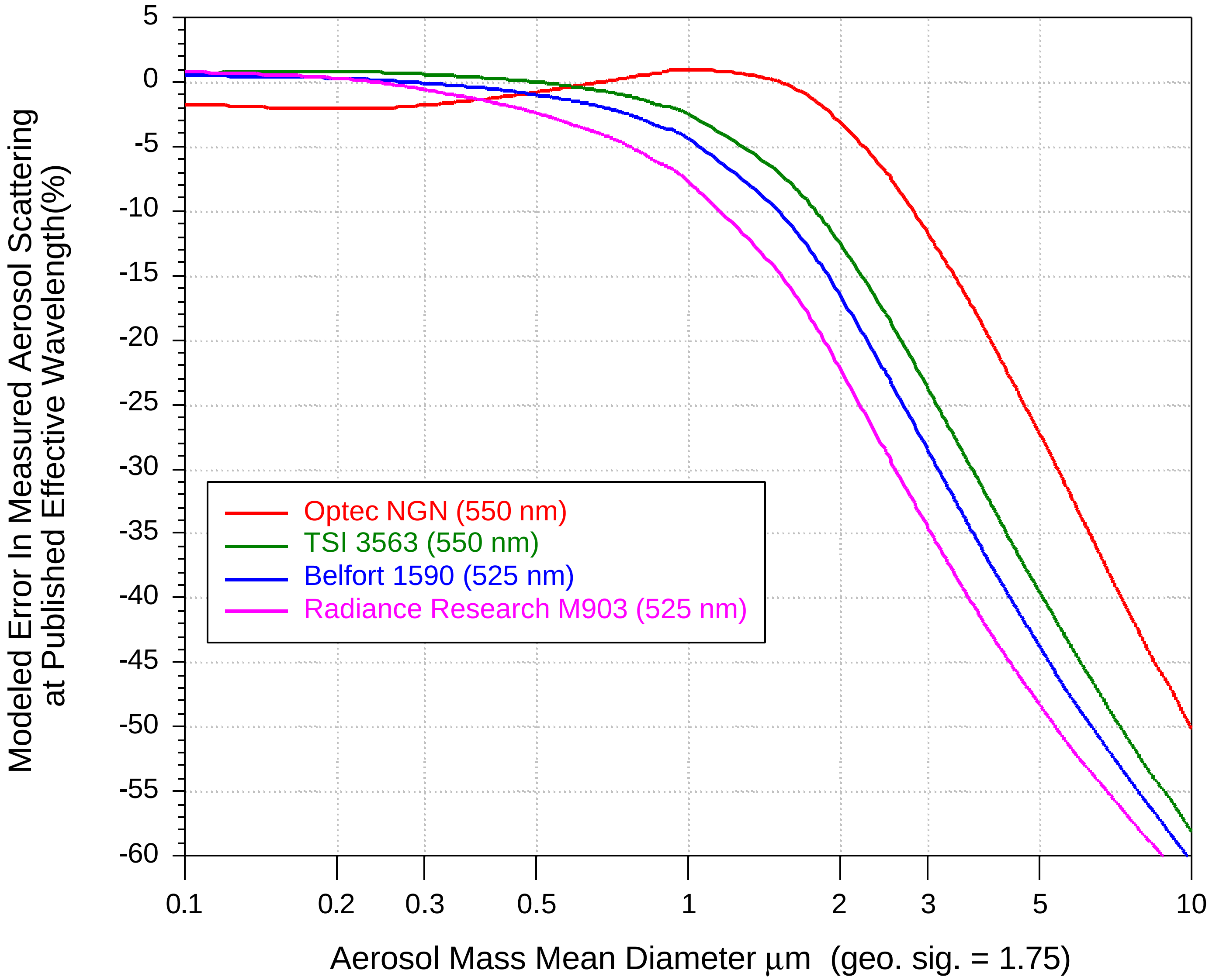


**Figure 6.** Estimated error in measured scattering at published effective wavelength for Optec NGN, TSI 3563 (green), Belfort 1590, and Radiance Research M903 integrating nephelometers as a function of aerosol mass mean diameter, including spectral response and truncation error.

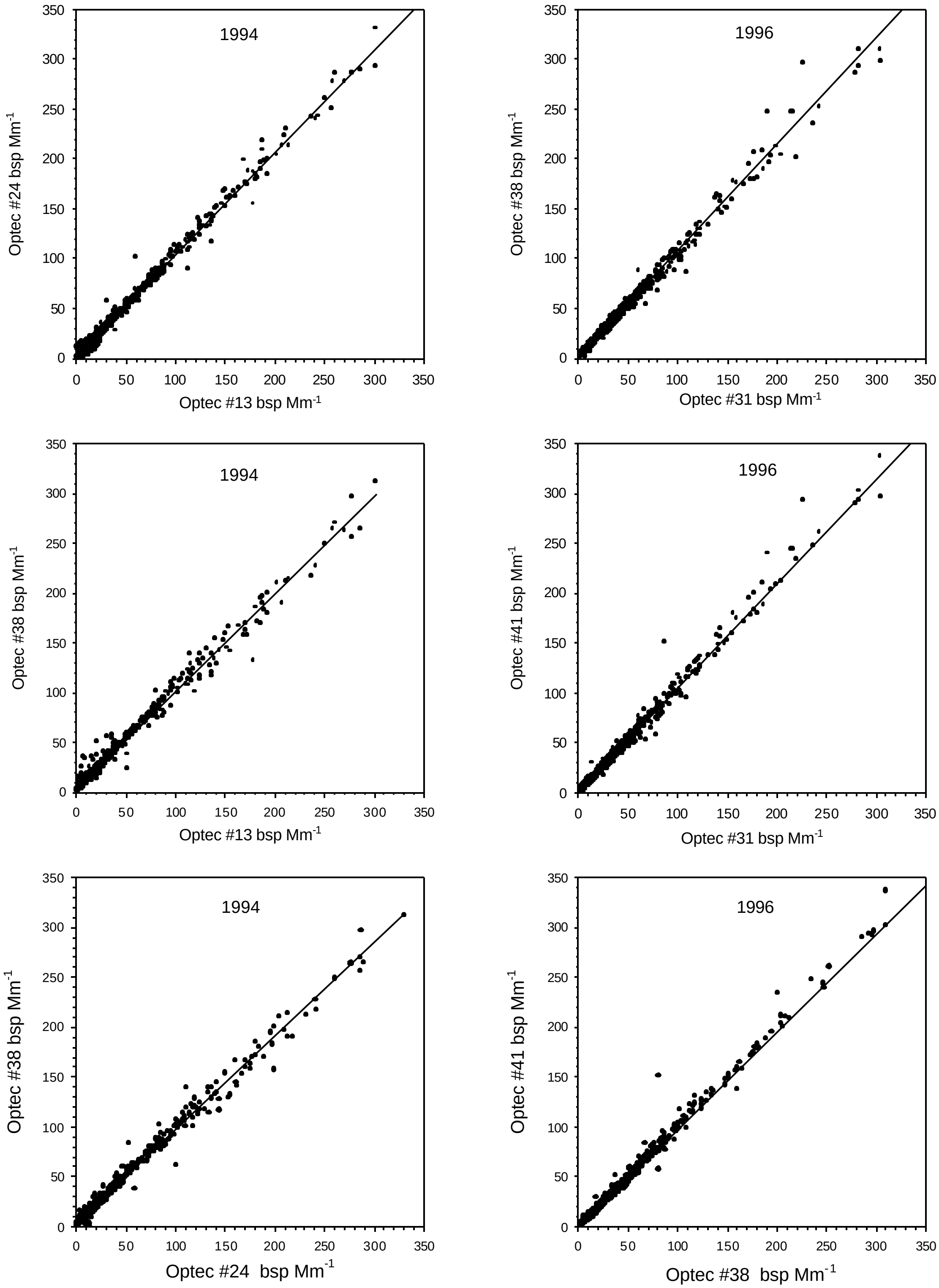


**Figure 7.** 1994 and 1996 Optec NGN nephelometer intercomparisons of hourly average aerosol scattering (regression statistics are listed in Table 2).

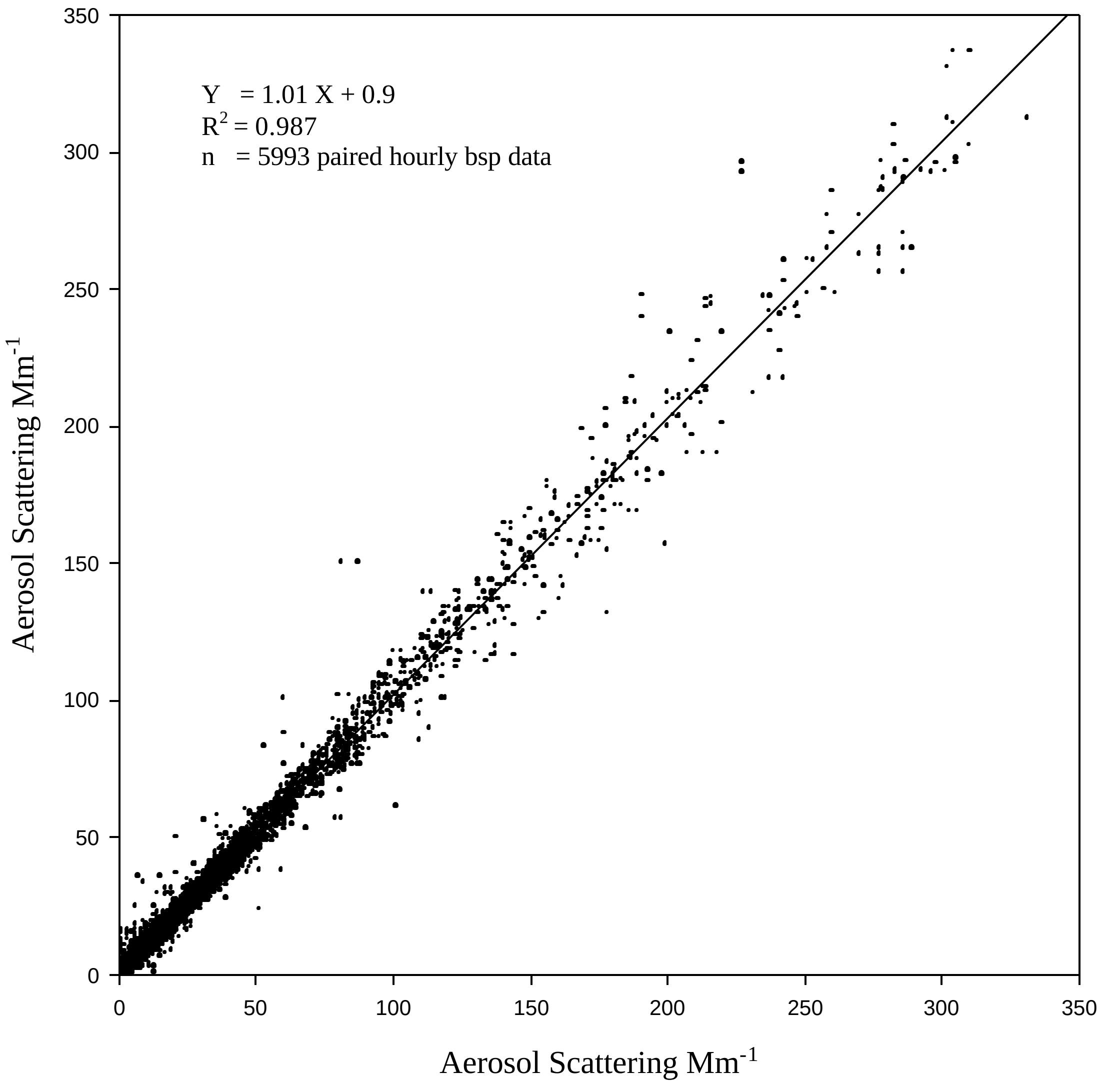


**Figure 8.** All Optec NGN paired aerosol scattering data from 1994 and 1996 tests.

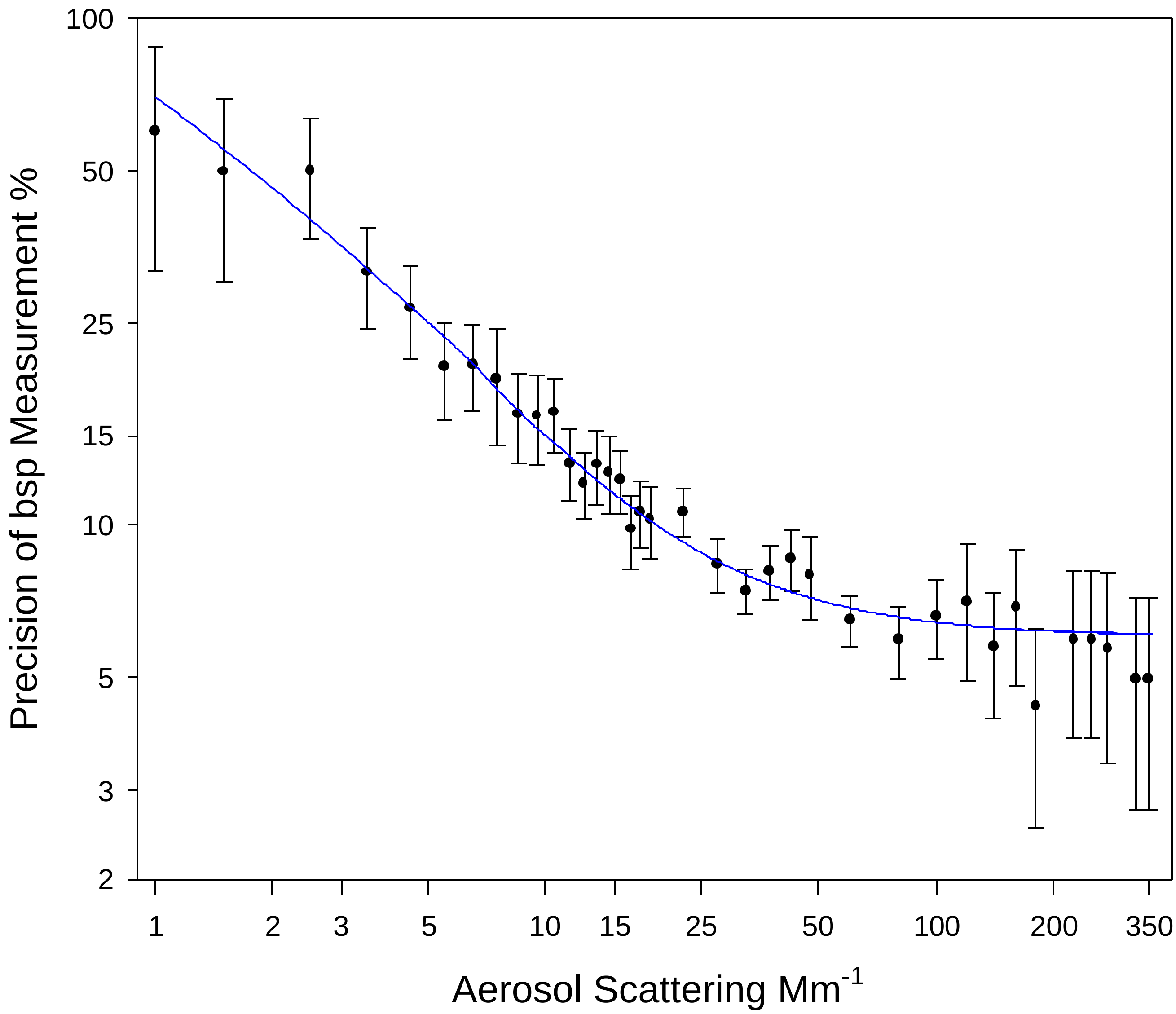


**Figure 9.** Mean precision (with 99% confidence limits) in measured aerosol scattering for all 1994 and 1996 paired hourly Optec NGN measurements as a function of $b_{sp}$.