Theoretical Analysis of the Response Characteristics of Optec NGN-2 and TSI 3563 Integrating Nephelometers

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Introduction

Two different integrating nephelometers were operated during SEAVS to measure fine aerosol scattering (bsp).; a single TSI 3563 three-wavelength 2.5 μm cut system and multiple Optec NGN-2 systems. The Optec systems consisted of one ambient open air, two ambient inlet no size cut, and two ambient inlet 2.5 μm size cut nephelometers. Examination of Optec bsp data indicates the Optec systems measured bsp to within 2-5% of each other for most of the SEAVS period Comparison of bsp data collected by the two different nephelometers during the entire study period indicates the TSI green bsp was approximately 70% of the Optec bsp. A more intensive review noted problems with the TSI data associated with drift in the calibration during a portion of the monitoring period that could not be resolved. Removing this data from the comparison improved the comparison, resulting in the TSI bsp to be 90% of the Optec bsp. Further analysis by EPRI resulted in the following conclusions:

- the TSI light scattering measurements appear to be consistent with theoretical expectations for red, green, and blue total and backscattering,
- the differences between the Optec and the TSI are primarily due to:

  (1) RH differences between the aerosols sampled,
  (2) differences in wavelength response of the detectors, and
  (3) drift in the calibration of the TSI during the latter portion of the study.

It was further hypothesized that the differences might be related to:

- differences in cyclone size selection efficiency, and
- different detector viewing angles (truncation errors).

This report presents a theoretical investigation of all the above effects.

Cyclone Efficiencies

During SEAVS the TSI nephelometer used a AIHL 2.1 cyclone and the Optec used a Bendix 240 cyclone as size selective inlets. Figure 1 is a plot of the penetration efficiencies of the cyclones, (ie. The ability of aerosols of a specific size to pass through the cyclone). There appears to be a significant difference in the cyclones. To test this difference a computer model was constructed that calculated the theoretical scattering that would be measured by a perfect integrating nephelometer operating with the cyclones and measuring aerosols of various lognormal size distributions. Figure 2 is an example of two specific size distributions superimposed on the cyclone efficiency plot. Nearly all the aerosols of the lognormal distribution with a mass mean diameter (mmd) of 0.4 μm will pass through both cyclones. However, there different numbers of aerosols with a mmd of 0.8 μm will pass through each cyclone, resulting in a different scattering measurement by a nephelometer. Figure 3 shows the results of the calculations for aerosol mmd from 0.1 to 2.5 μm. It is a plot of the scattering ratio measured by a perfect nephelometer with a AIHL 2.1 cyclone to one with a Bendix 240 cyclone, versus aerosol mmd and two different geometric standard deviations (1.5 and 2.0). The difference is less than 0.5% for mmd below 1.0 μm. Since SEAVS scattering is dominated by fine particles less than 1.0 μm, the observed b_{scat} differences between the TSI and Optec nephelometers does not appear to caused by the two different cyclones.

Truncation Error

A perfect integrating nephelometer will collect all scattered light from 0 - 180°. All real nephelometers must collect scattered light less than this 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 is known as truncation error. This 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.

The TSI has a manufactures' reported scattered light collection angle of 7-170° the Optec 5-175°. Figures1 and 2 show the calculated wavelength dependent truncation error associated with each instrument for varying aerosol 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 error associated with truncation angle. 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 for both instruments. Figure 3 is the scattering ratio of the TSI to Optec due to truncation error versus aerosol mmd. At 550 nm an a mmd equal to 0.5 μm the TSI will measure 1% less scattering, at mmd equal to 0.8 μm 2% less scattering compared to the Optec due to truncation error.

Spectral Response

Even though the TSI and Optec nephelometers have a stated central wavelength of 550 nm for green scattering measurements, the two instruments have quite different spectral response characteristics. Due to the strong wavelength dependence of scattering with size of scatterer, these spectral differences may result in large discrepancies between the scattering measurements of the two instruments. A computer model of the TSI, Optec and a theoretical photopic response system was created to investigate these effects. 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 and all filters used in the system. The signal output by a nephelometer is proportional to:

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

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 between the truncation angles of the instrument. Since the volume scattering function both of the calibrating gas and aerosol to be measured is a function both of wavelength and scattering angle, the measured scattering coefficient depends on the weighted average of the instrument response both for aerosol and Rayleigh calibration gas.

A thorough investigation of the TSI nephelometer has recently been published. (Anderson; et.al., 1996). The green spectral response of the TSI nephelometer was measured and presented in Figure 4a of that publication. This is the integrated response of the system including detector and filters, but not the lamp or any filters between the lamp and scattering chamber. The published figure was digitized and curve fit generating an analytical function to use in the computer model of the TSI system.

To date, no such measurements for the Optec nephelometer have been published. Therefor, spectral characteristics of detector, filters, and lamp were received from the manufacture of the Optec nephelometer. Analytical functions were also generated for each of the components and combined to create a response function for the Optec nephelometer.

Figure 7 presents the published response characteristics of the TSI nephelometer, the detector response of the Optec nephelometer, and the function used to simulate a photopic nephelometer. All curves have been normalized to the maximum response of each instrument. The Optec detector has a very wide response curve, however this is not the integrated response of the instrument.

Figure 8 presents the normalized response curves of the detector, lamp heat rejection filter (including acrylic opal diffuser), and lamp used in the Optec instrument. The source is a tungsten filament lamp that is best simulated by the CIE Source A curve. A similar lamp is used in the TSI nephelometer. These curves must be multiplied together to generate the total response of the Optec. In addition, the system response curves of the TSI and photopic instruments must be multiplied by the lamp output to produce he effective spectral response for each nephelometer. It is not necessary to use the heat rejection and diffuser curve on the TSI or photopic response nephelometers, since the detector response of these systems is only greater than zero in the range were the response of the heat rejection and diffuser curve is equal to 100%.

Figure 9 plots the normalized effective spectral response curves for the three systems. The peak response of each nephelometer is shifted to longer wavelengths due a combination of lamp output and width of detector response. The peak wavelengths are: 563 nm for the TSI, 605 nm for the Optec, and 570nm for a photopic system. However, due to the wide asymmetric bandpass of the instruments, the effective wavelength is not simple the peak wavelength, especially for the Optec nephelometer.

Figure 10 plots the wavelength dependence of scattering for a Rayleigh gas and lognormal aerosol size distributions with 4 different mass mean diameters (mmd).

Figure 11 is a plot of the expression in brackets in equation 1 as a function of wavelength for the TSI nephelometer, Figure 12 for the Optec nephelometer, and Figure 13 for an ideal photopic response nephelometer for a Rayleigh gas and several aerosol mmd. The function includes all spectral and truncation effects as well as the scattering effects shown in figure 10. The area under the curve is proportional to the output of the instruments.

Since the integrating nephelometer is calibrated by a Rayleigh gas, the ratio of the integrated response for any aerosol distribution to the integrated Rayleigh response results in a calculation of the relative error associated with each instrument. These ratios for the TSI and Optec nephelometers are plotted in figure 14 as function of aerosol mmd.

Figures 15 presents the percent difference between the TSI and Optec nephelometers responses by aerosol mmd. Figure 16 is a blow up of figure 15 to focus on mmd between 0.1 and 1.0 μm. The model predicts that the reported bsp of the TSI will be 2.5% higher at an aerosol mmd of 0.3 μm and 1.8% lower at an aerosol mmd of 0.8 μm than the Optec. This is the range of aerosol mmd seen in SEAVS

Conclusions

These analyses indicate:

- Since aerosol scattering during SEAVS is dominated by fine aerosols with a mass mean diameter typically below 0.8 μm, the differences in inlet efficiencies between the Bendix and AIHL cyclones should have a minimal effect, < 0.5%.;
- The differences in truncation angle between the Optec and TSI nephelometers by itself results in the TSI nephelometer response between 1 - 2% lower than the Optec even for fine aerosols;
- A model of the spectral responses of the nephelometers which includes truncation effects predicts that the output of TSI nephelometer will vary between 3% higher and 2% lower than the Optec response depending on aerosol mmd. The spectral differences between the two nephelometers overcomes and actually appears to compensate for the truncation angle effect.
- All these effects are lower than the typical calibration precision of 5-10% for nephelometers. Aerosol scattering comparisons between the multiple Optec nephelometers operated during SEAVS indicate that the Optec systems were self-consistent to within 2-5%. This implies that the Optec systems operated and were calibrated properly. Thus, the observed 10% (and at times greater) difference between the TSI and Optec nephelometer during SEAVS is probably related to unaccounted for heating of the aerosol and poor calibrations of the TSI nephelometer.

References

Anderson, T.L.; et.al., 1996: " Performance Characteristics of a High-Sensitivity, Three-Wavelength, Total Scatter/Backscatter Nephelometer", Journal of Atmospheric and Oceanic Technology, **13**, 967-986

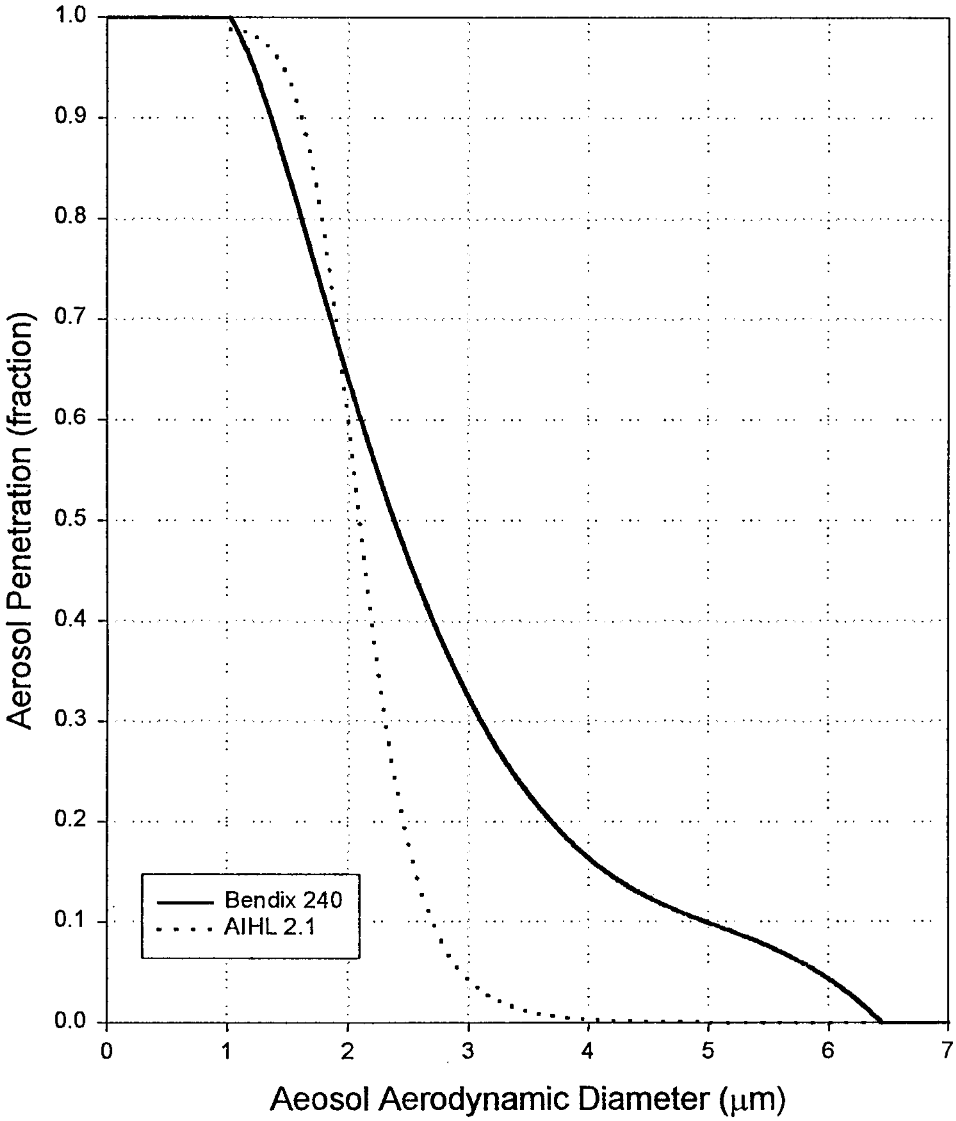


Figure 1: Cyclone Efficiencies

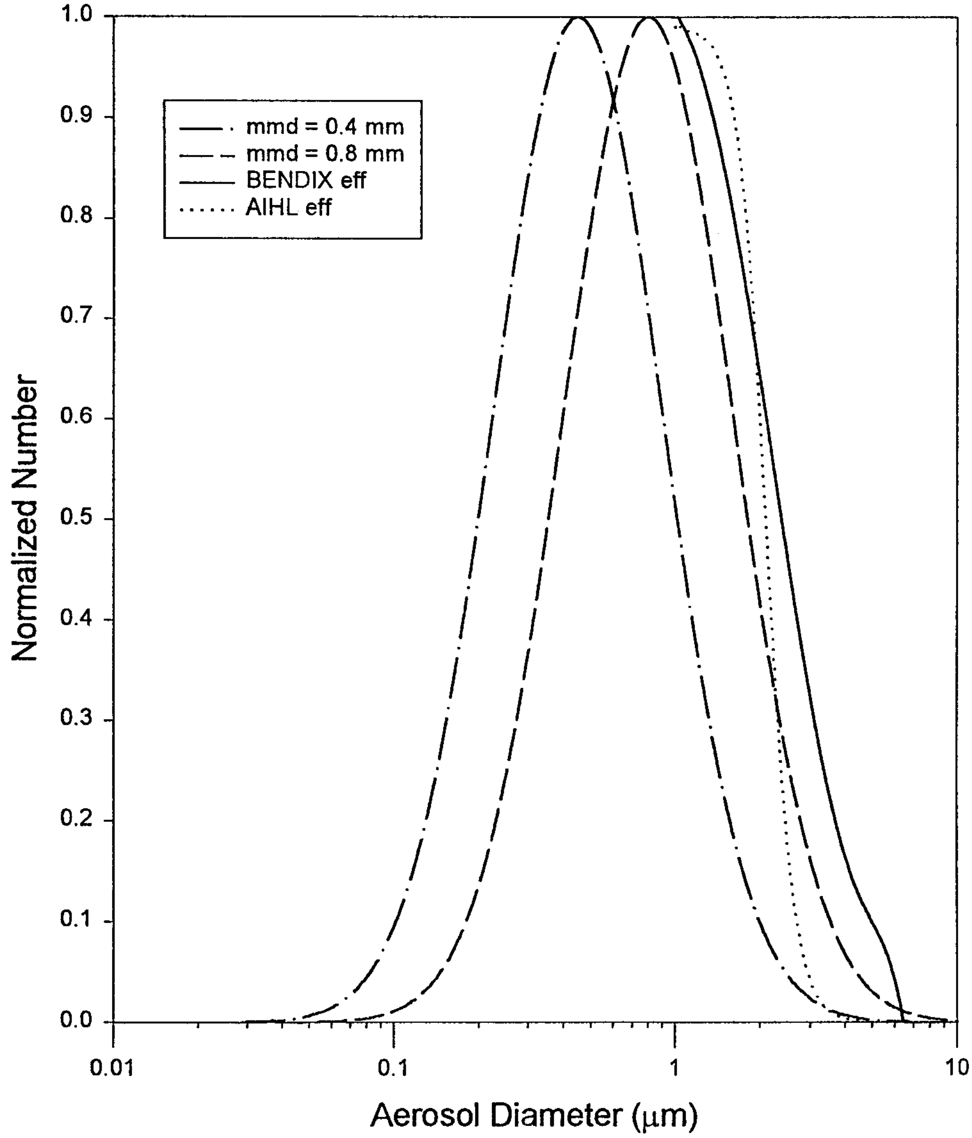


Figure 2: Lognormal size distributions & Bendix & AIHL Efficiencies

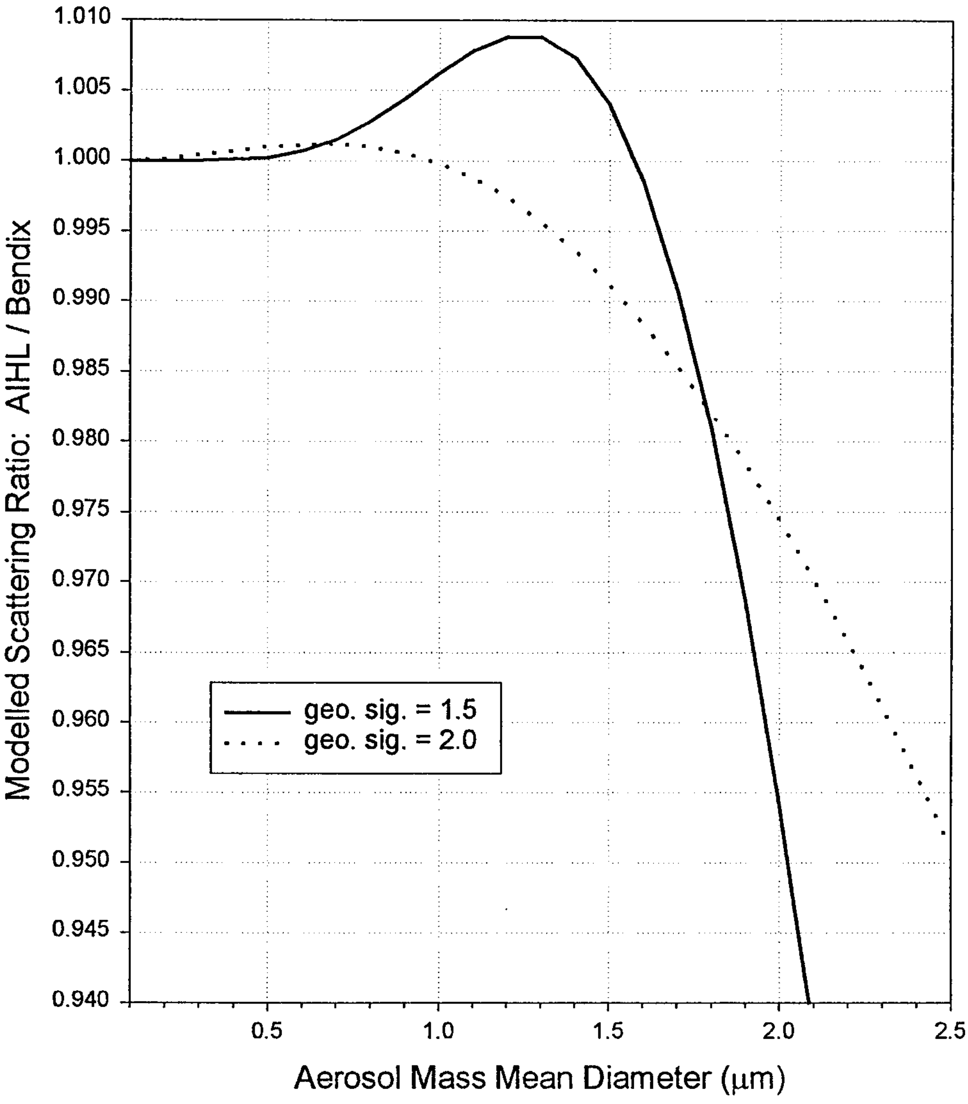


Figure 3: AIHL 2.1 / Bendix 240 scattering ratio
(0 - 180^{O} integration)

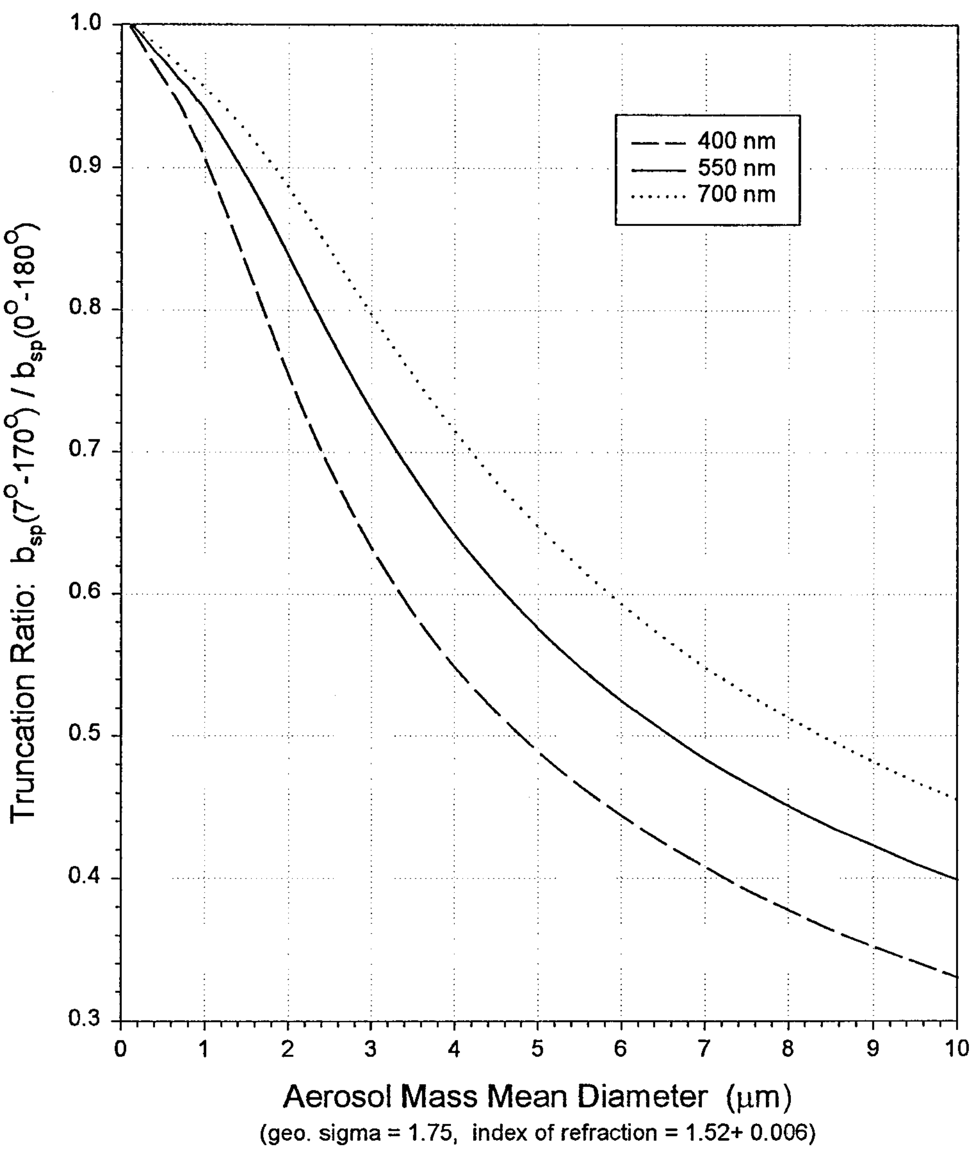


Figure 4: TSI 3563 Rayleigh gas adjusted aerosol truncation error

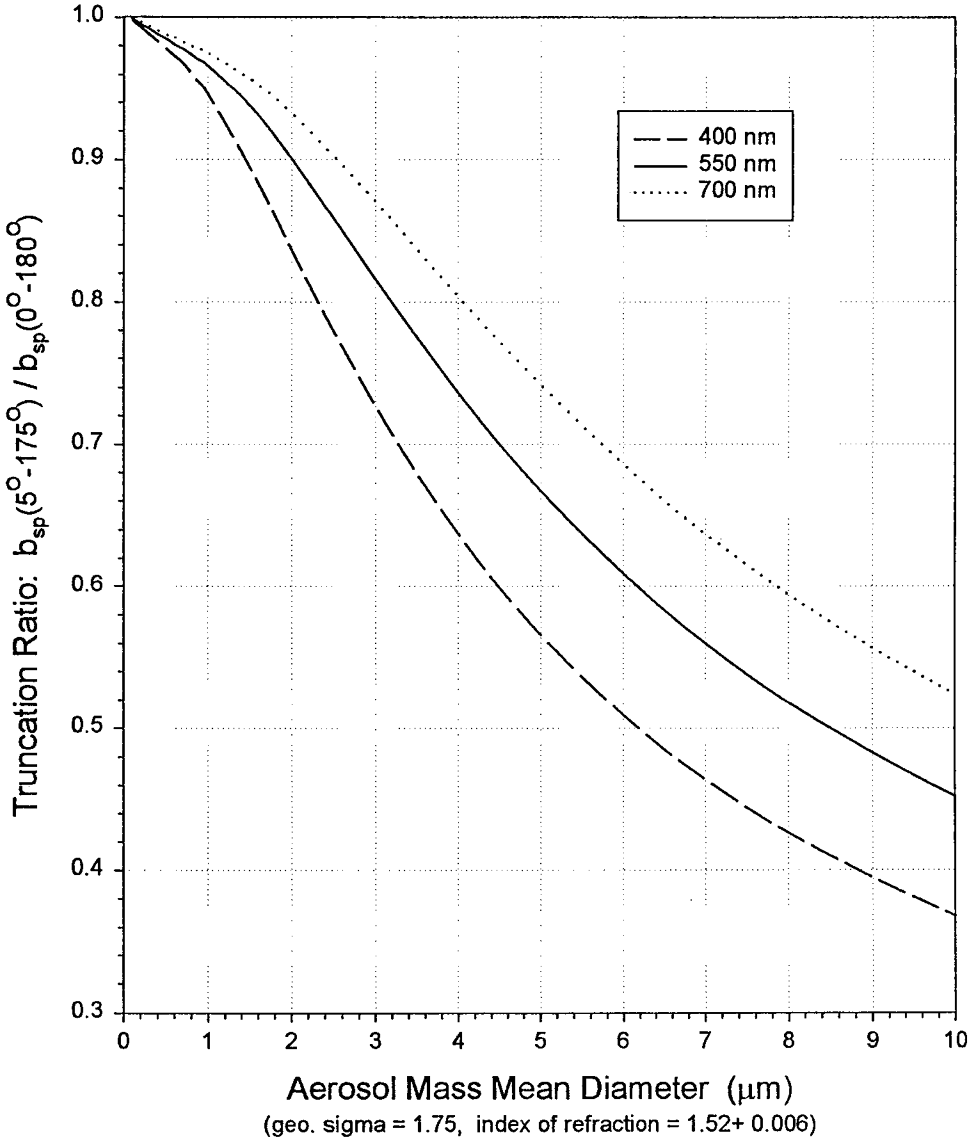


Figure 5: Optec NGN-2 Rayleigh gas adjusted aerosol truncation error

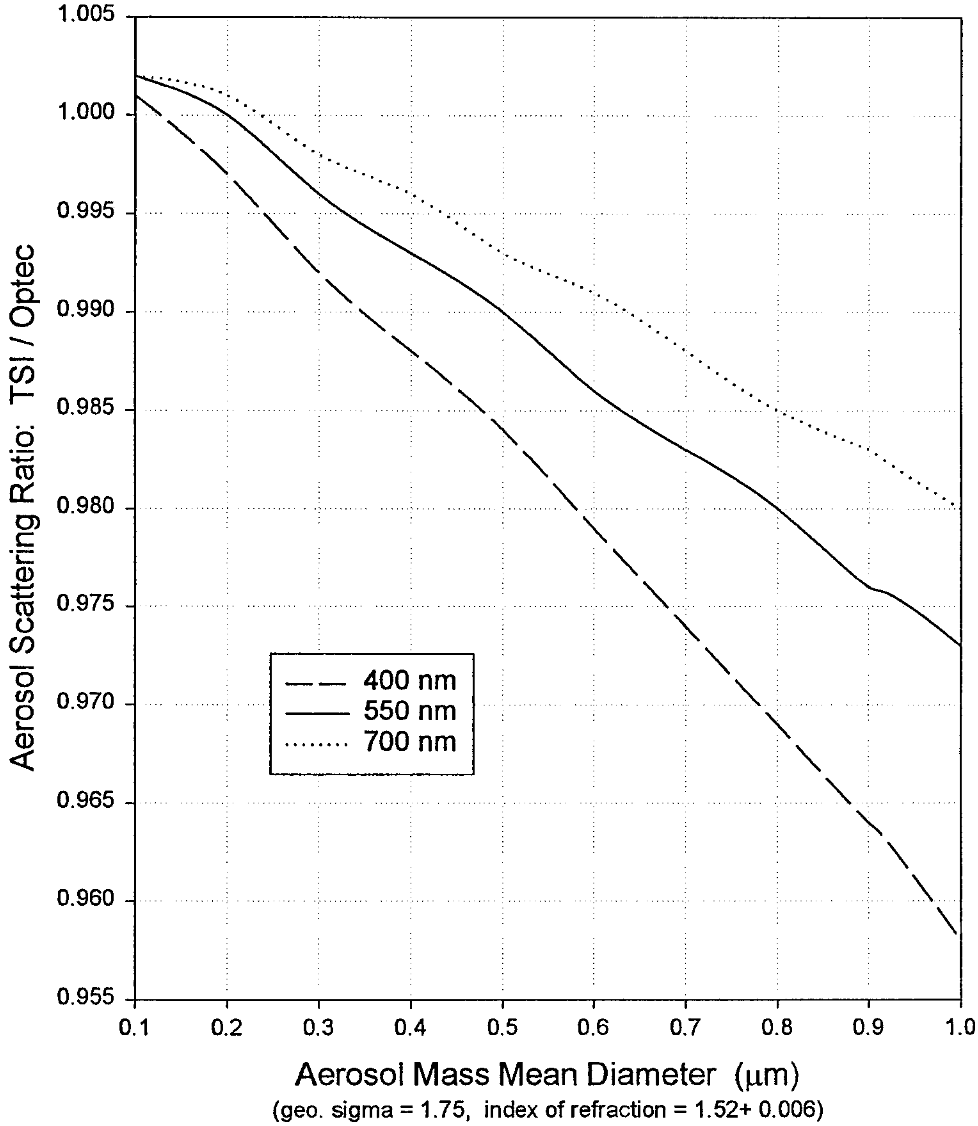


Figure 6: Scattering ratio due to Rayleigh gas adjusted aerosol truncation error

TSI (7°-170°) / Optec (5°-175°)

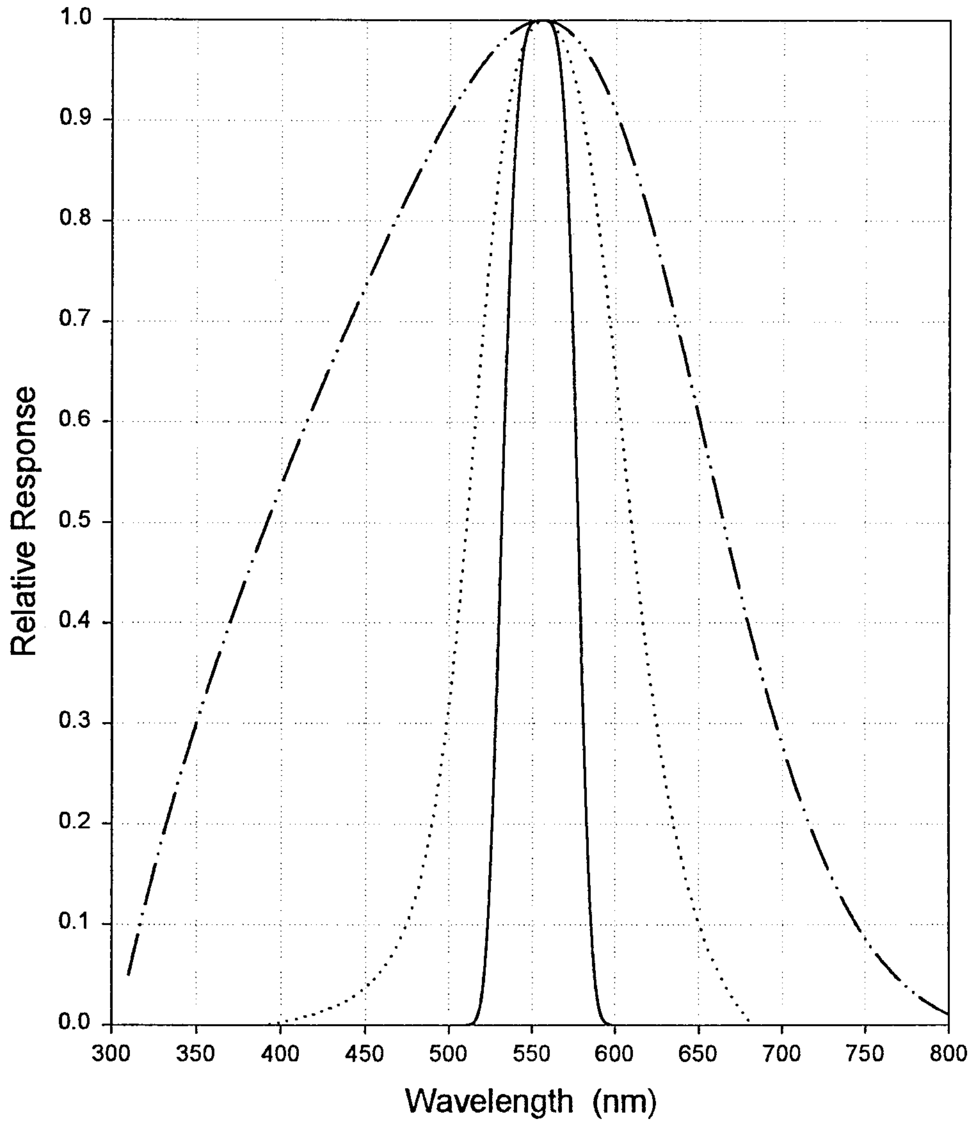
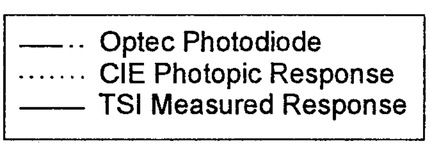


Figure 7: Detector Spectral Characteristics



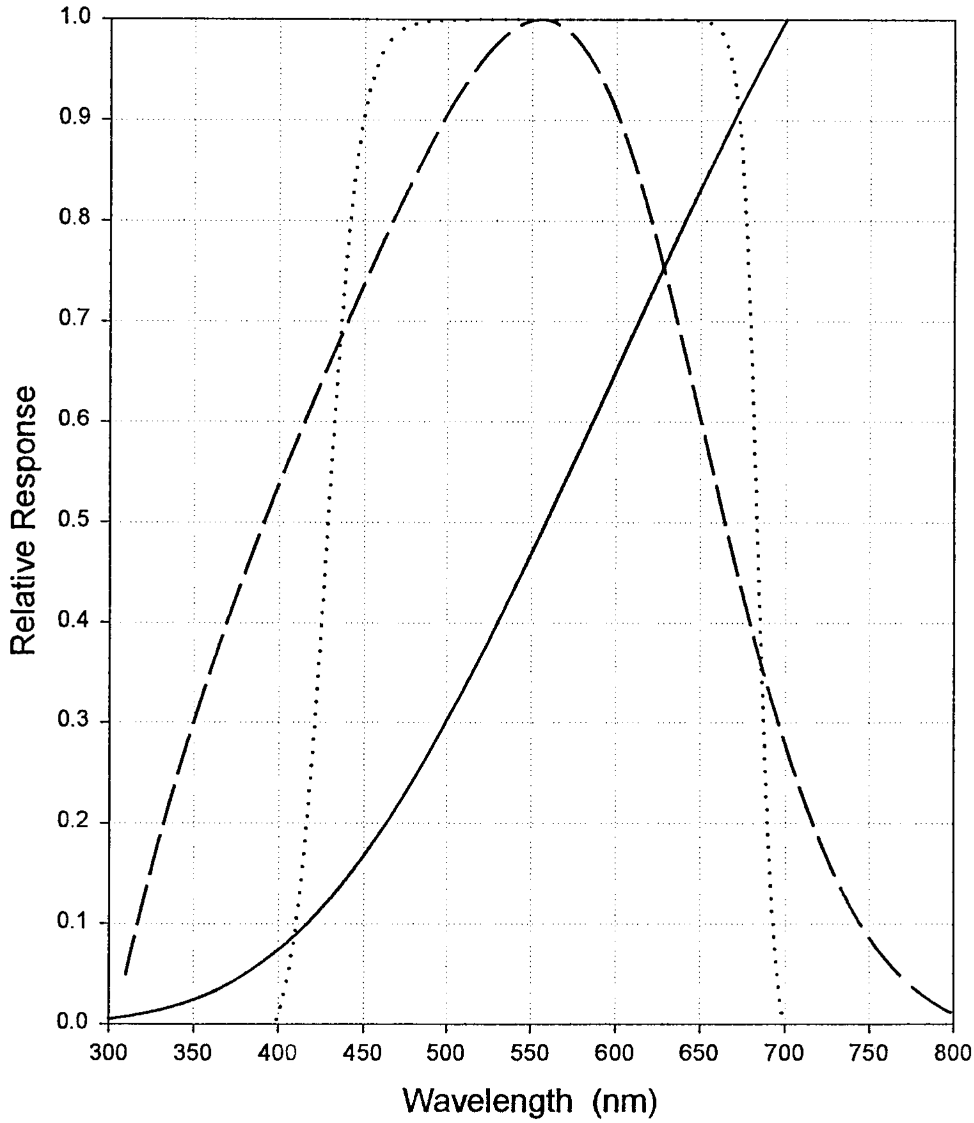


Figure 8: Optec NGN-2 Spectral Characteristics

——	CIE Source A
·····	Heat Filter x Acrylic Diffuser
—— -	Photodiode

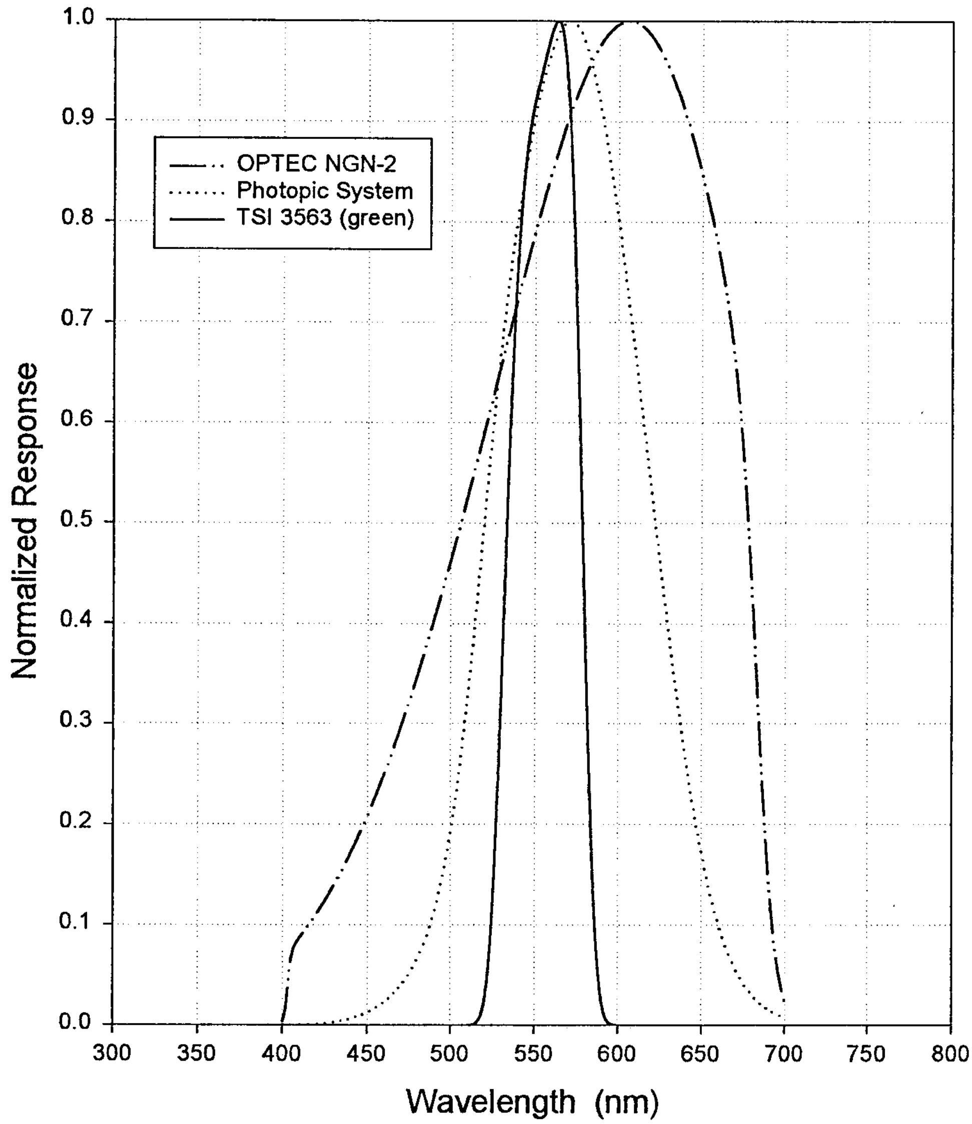


Figure 9: Nephelometer Effective Spectral Response
(detector x all filters x lamp output)

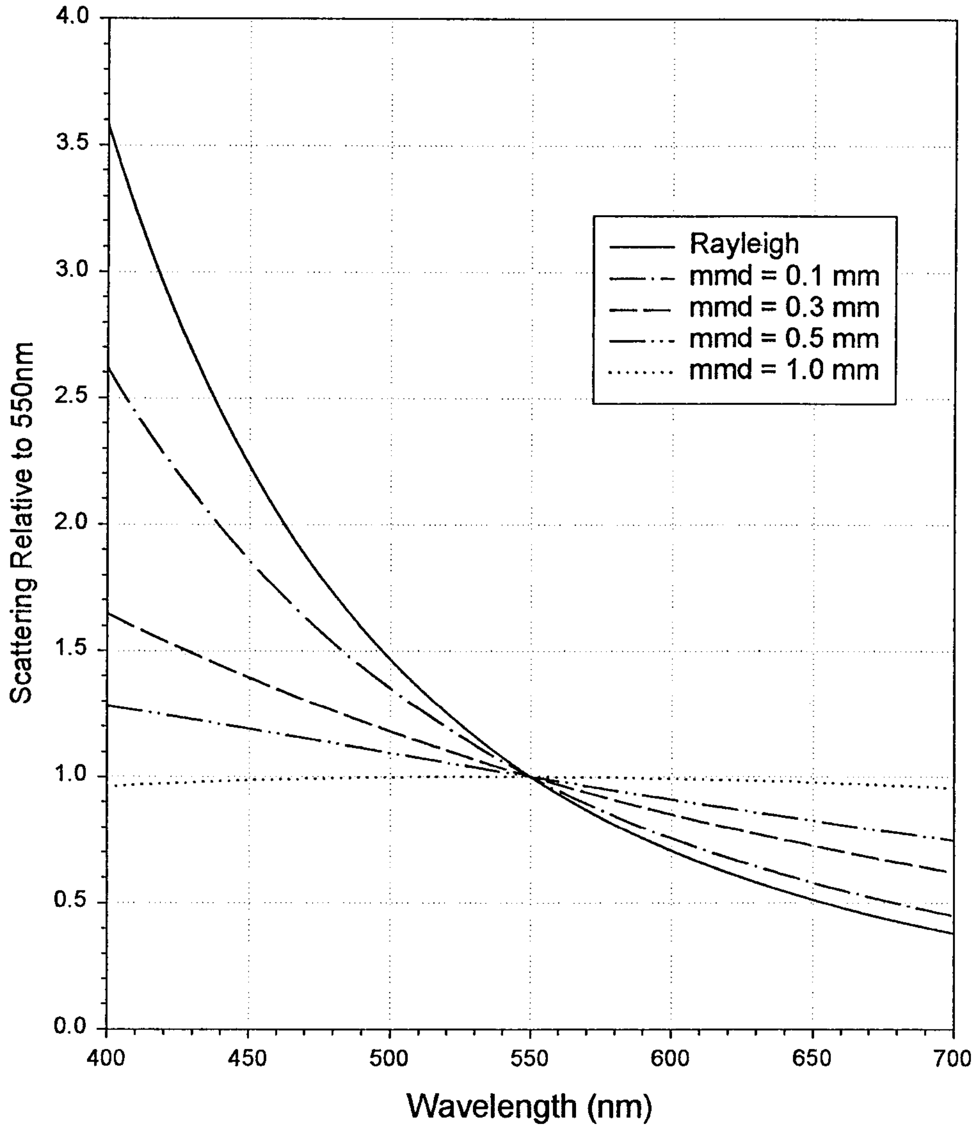


Figure 10: MIE Modeled Wavelength Dependence of Scattering
(geo. sigma = 1.75 and n = 1.52 $\pm$ 0.006*i*)

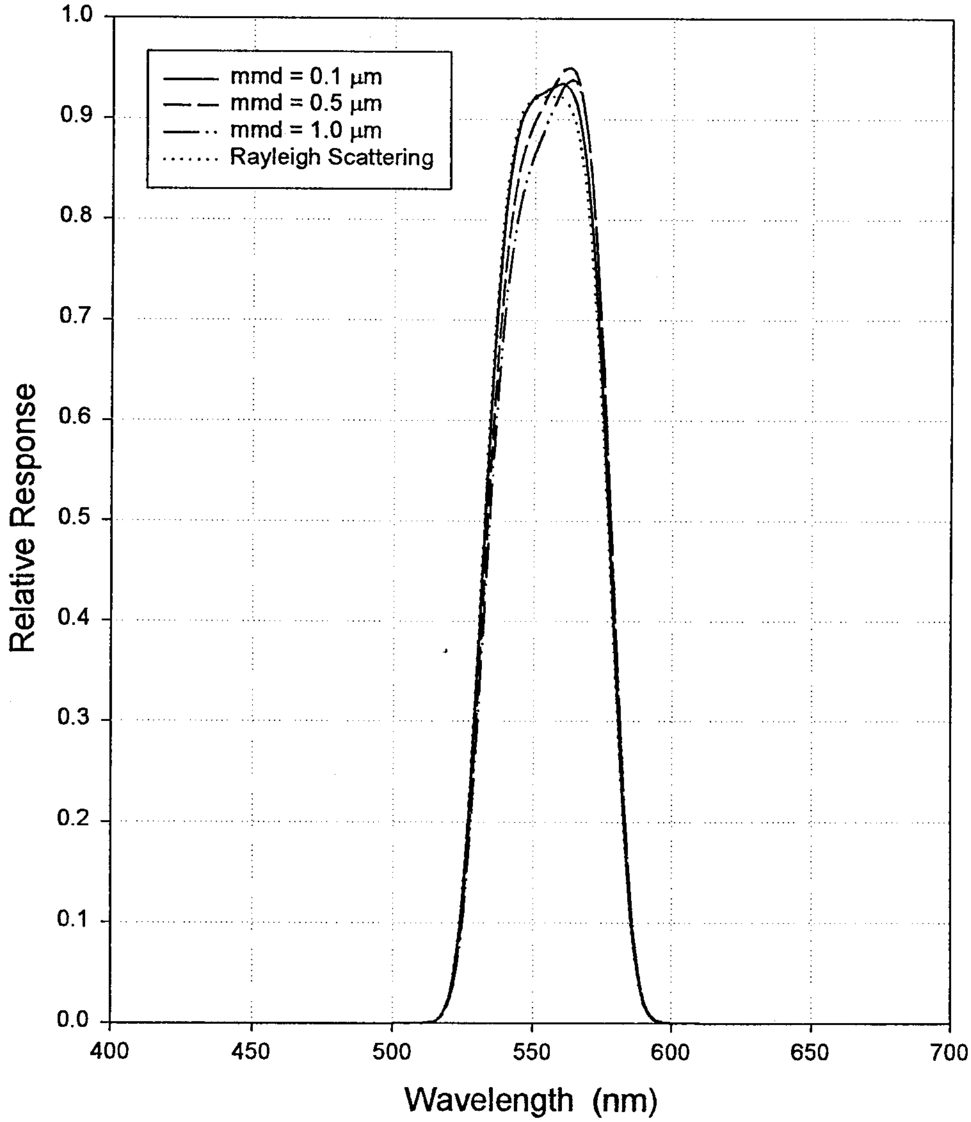


Figure 11: TSI 3563 green spectral response including truncation effects for Rayleigh scattering and various lognormal aerosol size distributions (all with: geo.sigma = 1.75 and n= 1.52 ± 0.006*i*)

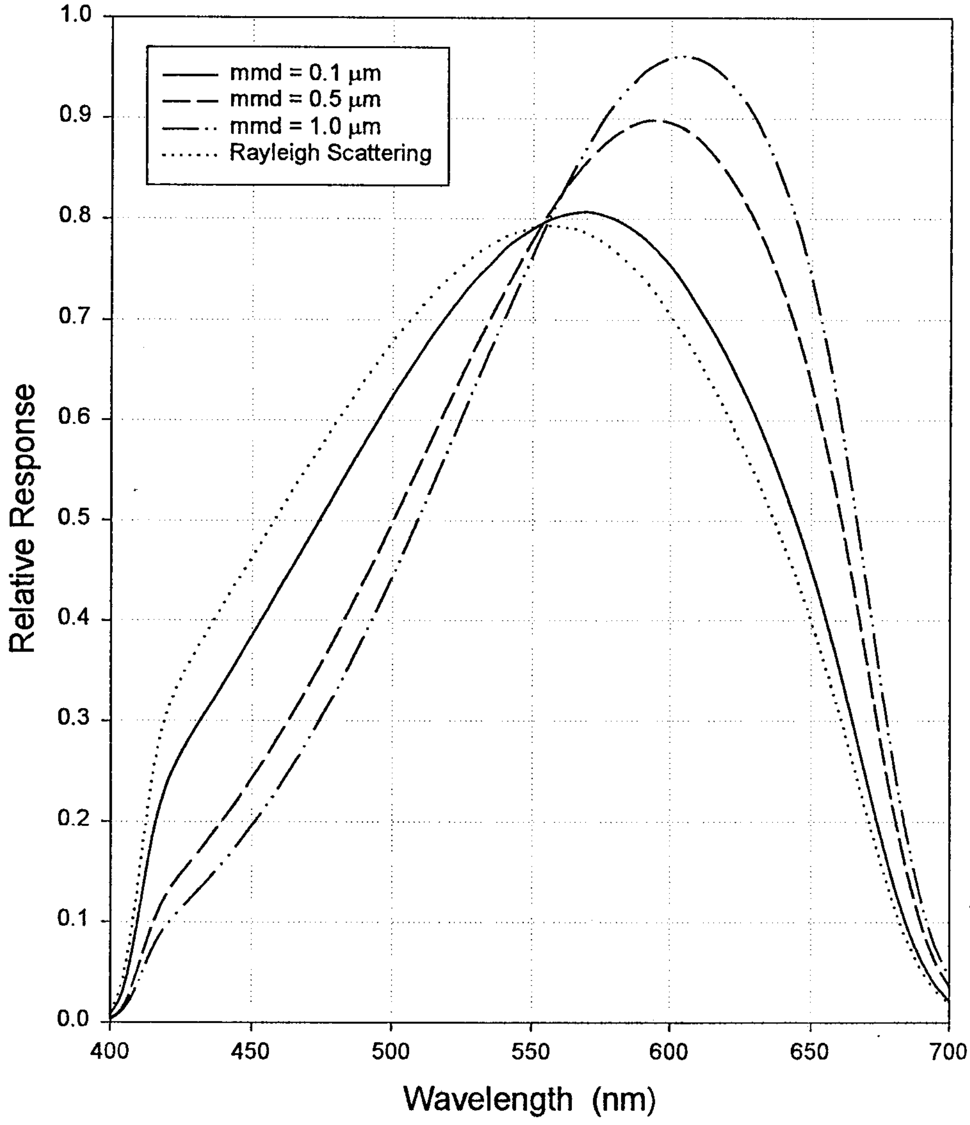


Figure 12: Optec NGN-2 green spectral response including truncation effects for Rayleigh scattering and various lognormal aerosol size distributions
(all with: geo.sigma = 1.75 and n= 1.52 ± 0.006*i*)

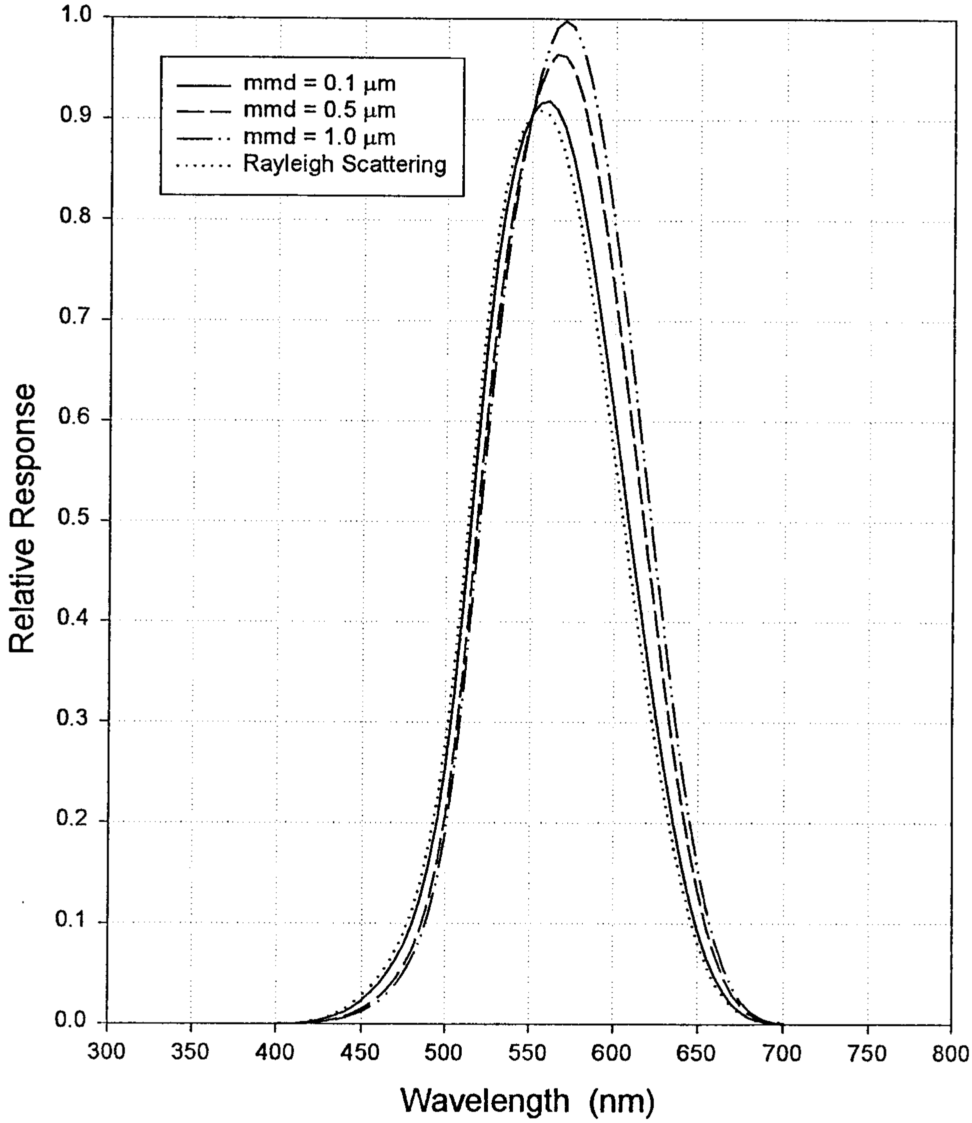


Figure 13: Ideal photopic spectral response without truncation effects for Rayleigh scattering and various lognormal aerosol size distributions
(all with: geo.sigma = 1.75 and n= 1.52 ± 0.006*i*)

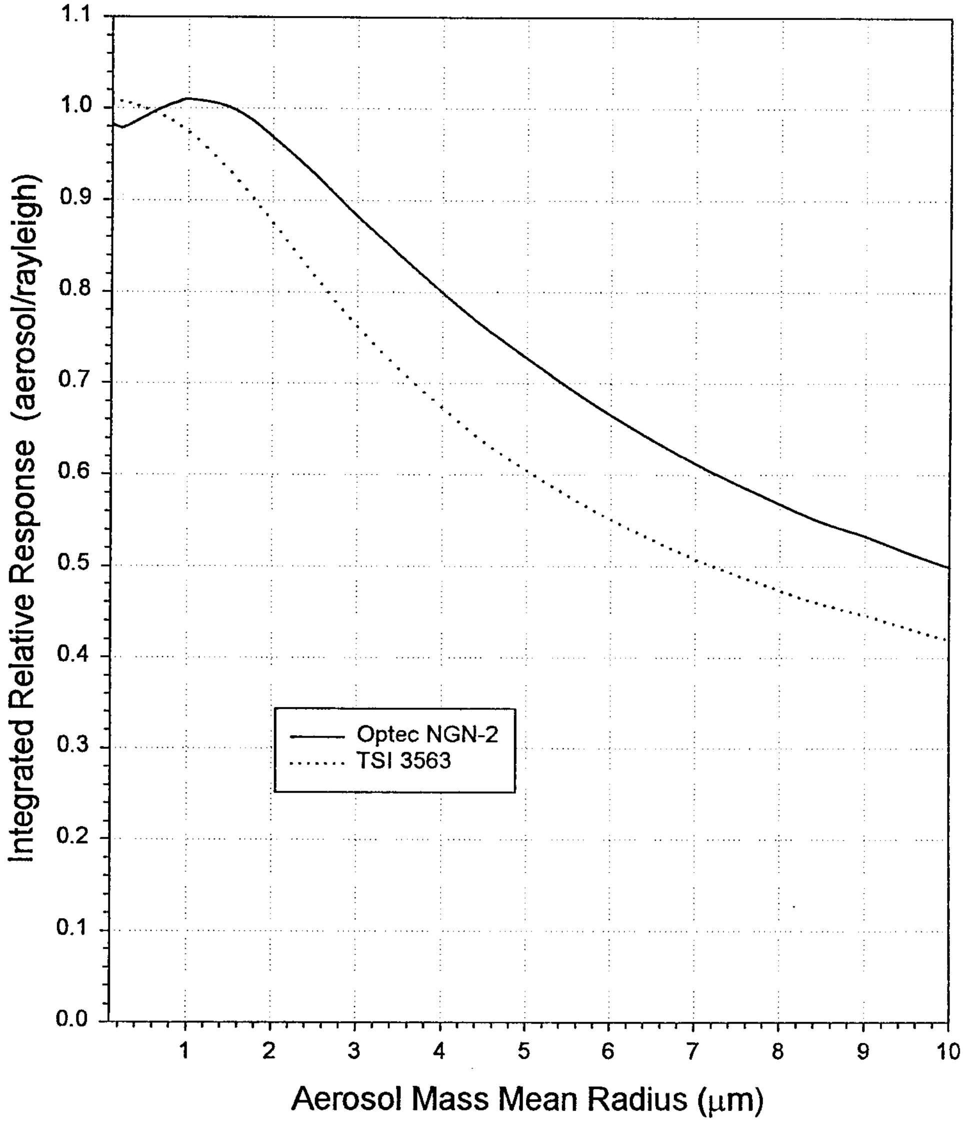


Figure 14: Ratio integrated responses (aerosol/Rayleigh) for Optec and TSI nephelometers as function of aerosol mass mean radius, including spectral responses and truncation effects.

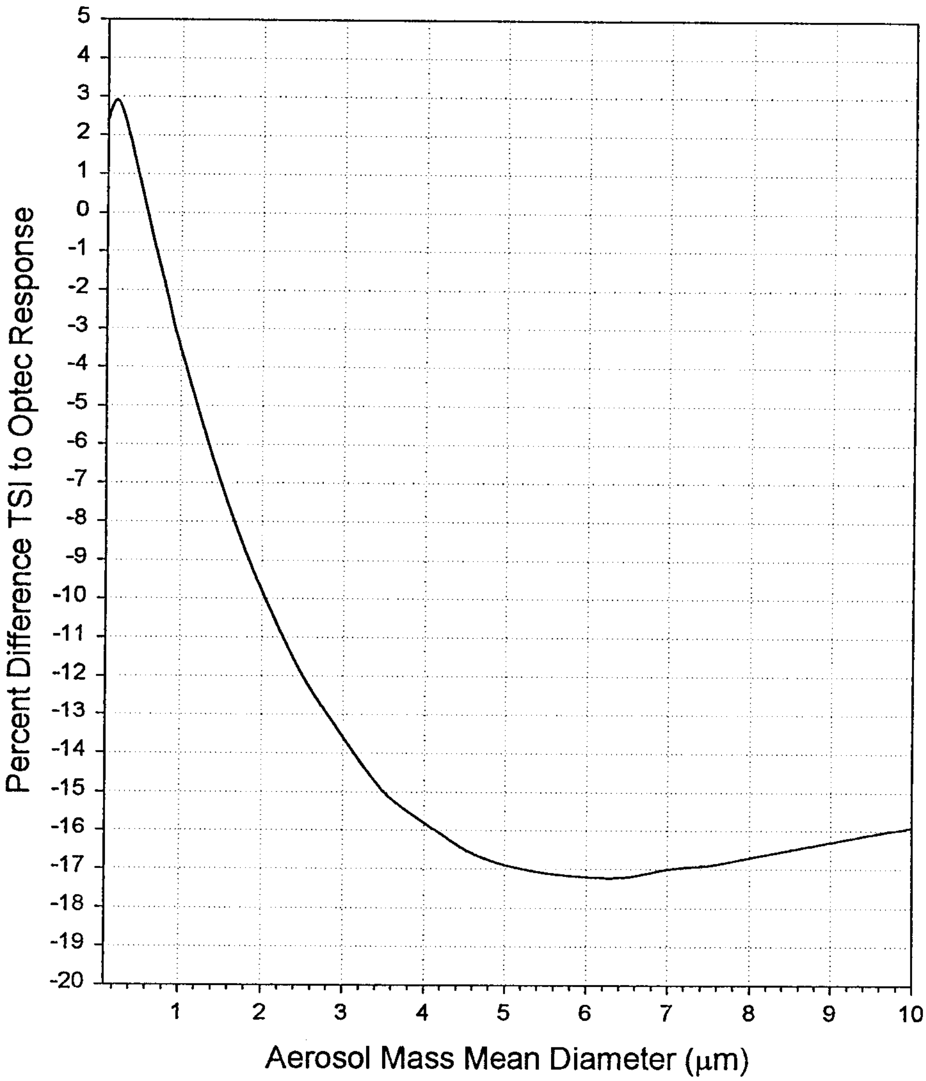


Figure 15: Percent difference in TSI to Optec green integrated response including spectral responses and truncation effects as a function of aerosol mass mean diameter: 0.1 - 10.0 μm (geo. sigma = 1.75 and n = 1.52 ± 0.006*i*)

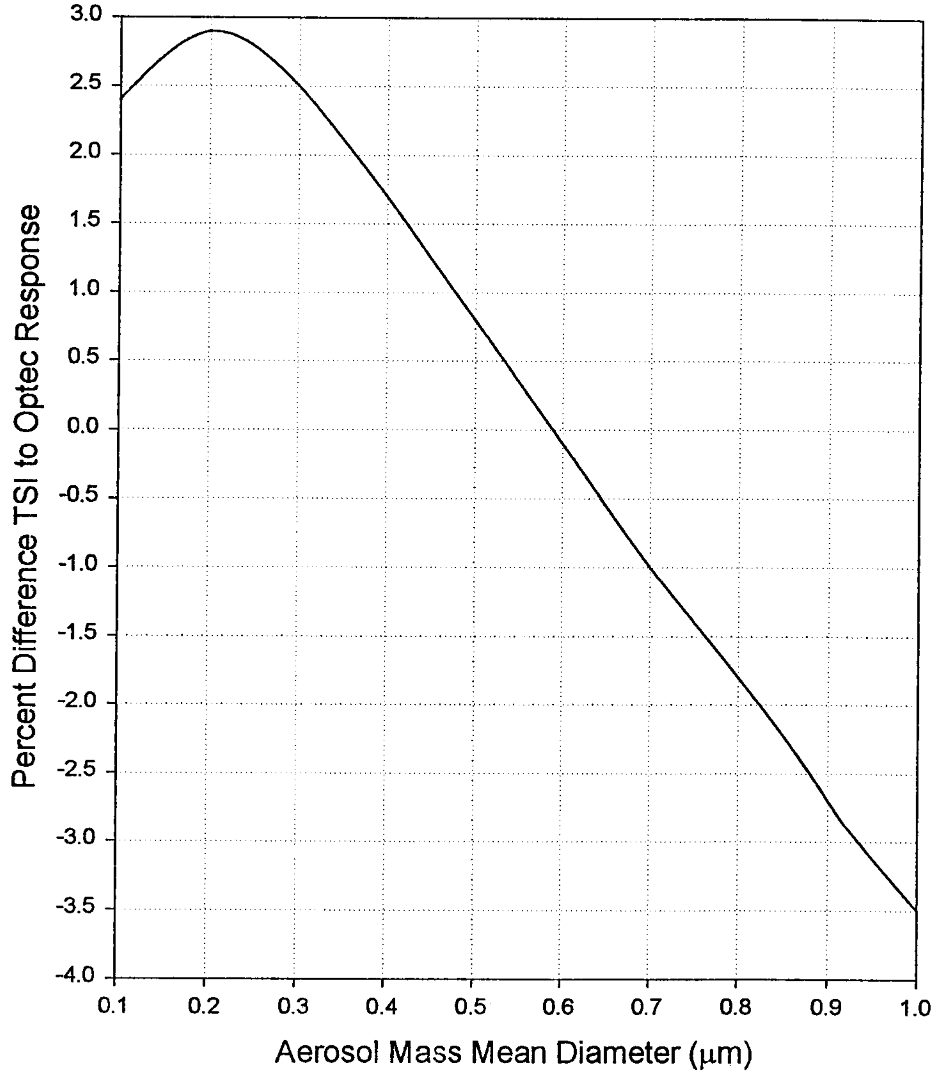


Figure 16: Percent difference in TSI to Optec green integrated response including spectral responses and truncation effects as a function of aerosol mass mean diameter: 0.1 - 1.0 μm (geo. sigma = 1.75 and n = 1.52 ± 0.006*i*)