

THE RELATIVE ACCURACY OF TRANSMISSOMETER DERIVED EXTINCTION COEFFICIENTS

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INTRODUCTION

Measurement of the extinction coefficient is essential to understanding how atmospheric aerosols affect the visibility of scenic vistas. However, accurate measurement of extinction in clean atmospheres and under all meteorological conditions poses a formidable problem. To date, the two methods routinely employed for estimating extinction are integrating nephelometry and teleradiometry using natural targets^{1,2}. Both measurement techniques have serious shortcomings. The integrating nephelometer measures atmospheric scattering and not absorption, may modify particles that pass through its sampling chamber and properly measures scattering from only fine particles. Calculations of atmospheric extinction using teleradiometer measurements of natural target contrast, on the other hand, are sensitive to both scattering and absorption, and measure effects of particles of all sizes in the ambient aerosol. However, the extinction calculation from the contrast measurement is sensitive to variations in inherent contrast and nonuniform illumination conditions, neither of which can be readily accounted for in normal measurements.³

A transmissometer operated without enclosing the light beam has the potential for measuring atmospheric extinction without perturbing the aerosols and without the inadvertent removal of large ($> 10\mu$) aerosols by a closed chamber inlet. However, transmissometers with path lengths greater than a few kilometers are required to achieve the sensitivity to measure extinctions near the Rayleigh limit. Operation of transmissometers over path lengths greater than 2-3 km can result in beam modification because of atmospheric turbulence effects. Beam 'spreading' results in a lower detected beam irradiance that is erroneously interpreted as atmospheric extinction.

Over the past three years the National Park Service (NPS) has carried out a number of tests on a long path transmissometer manufactured by OPTEC, Inc.⁴ One transmissometer design criteria was to measure atmospheric extinction in near Rayleigh atmospheres to an accuracy of better than 10%. Since standard atmospheres and/or gases cannot be introduced into open air long path instruments, a number of field programs were designed to intercompare the transmissometer with itself but with different path lengths and with other atmospheric extinction/scattering measurement techniques. Under certain limiting conditions various measurement techniques will accurately measure atmospheric scattering and/or extinction and consequently should compare favorably.

Intercomparisons included side by side operation of two transmissometers with path lengths of 5.79 km and 15.57 km. Unless the effect of atmospheric turbulence on derived extinction has a specific functional form, it is expected that as the path length is increased, the error due to turbulence on measured extinction will increase. Thus, the deviation between two extinction measurements made over different path lengths may yield some insight into the accuracy of the measurement or the functional form of the effect that turbulence is having on derived extinction.

A second field study compared transmissometer derived extinction with an extinction calculated from teleradiometer sky-target contrast measurements of an artificial black target. By fabricating a target with $C_0 = -1.0$, the error

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associated with uncertain inherent contrast resulting from uneven illumination of the target or clouds behind the target are eliminated. However, some error associated with clouds shading the sight path still remain.³

In each of the above described experiments and as part of a special winter 1986 study, the transmissometer was compared to integrating nephelometer measurements of the atmospheric scattering coefficient. Under near Rayleigh conditions or when the atmosphere is free of absorbing and large particles and the RH is less than approximately 60%, nephelometer scattering coefficient measurements should compare favorably to transmissometric derived atmospheric extinction.

INSTRUMENTATION

Transmissometry

Theory. Historically, transmissometry has been thought of as teleradiometric measurements of the intensity of a light source placed at some distance r from an observation point.⁵ The equation governing the amount of radiant energy received at the observation point is

$$H = \frac{I_0}{r^2} e^{-b_{\text{ext}} r} \quad 1)$$

where H is irradiance at some distance r from the light source, I_0 is radiant intensity and b_{ext} is the atmospheric extinction coefficient. I_0/r^2 is essentially a calibration term that can be determined by comparison of transmission measurements to other optical measurements such as teleradiometer measurements made under "standard" lighting conditions or to integrating nephelometer measurements made on days that are near the Rayleigh scattering limit. A second calibration technique utilizes measurement of a signal proportional to H at two different distances:

$$H_1 = \frac{I_0}{r_1^2} e^{-b_{\text{ext}} r_1} \quad 2)$$

$$H_2 = \frac{I_0}{r_2^2} e^{-b_{\text{ext}} r_2} \quad 3)$$

Measuring r_1 , r_2 , and a signal proportional to H_1 and H_2 , and assuming the atmosphere is homogeneous over distances r_1 and r_2 allows equations 2 and 3 to be solved for I_0 .⁶ A third calibration technique and the one used in all field studies involves measuring H when the receiver and light source (transmitter) are placed within a few hundred feet of each other and assuming $e^{-b_{\text{ext}} r} \approx 1$. Then $I_0 = Hr^2$ where r is the distance between the teleradiometer and transmitter.

Effect of Turbulence. If it is assumed that the effect of atmospheric turbulence on measurement of H is to modify equation 1 in a multiplicative way, and that it is some function of transmitter-receiver distance, then

$$\hat{b}_1 = -\frac{1}{r_1} \ln \frac{f(r_1)H_1 r_1^2}{I_0} = -\frac{1}{r_1} \left[\ln \frac{H_1 r_1^2}{I_0} + \ln f(r_1) \right] \quad 4)$$

and

$$\hat{b}_2 = -\frac{1}{r_2} \ln \frac{f(r_2)H_2 r_2^2}{I_0} = -\frac{1}{r_2} \left[\ln \frac{H_2 r_2^2}{I_0} + \ln f(r_2) \right] \quad 5)$$

Since $b = -\frac{1}{r_1} \ln \frac{H_1 r_1^2}{I_0} = -\frac{1}{r_2} \ln \frac{H_2 r_2^2}{I_0}$, subtracting equation 5 from 4 yields

$$\hat{b}_1 = \hat{b}_2 + a_0 \quad 6)$$

where

$$a_0 = \frac{1}{r_2} \ln f(r_2) - \frac{1}{r_1} \ln f(r_1) \quad 7)$$

a_0 is the difference between derived extinction associated with atmospheric turbulence for two transometric measurements over different path lengths.

In order for $\hat{b}_1 = \hat{b}_2$ requires $a_0 = 0$. a_0 is zero if $\frac{1}{r_2} \ln f(r_2) = \frac{1}{r_1} \ln f(r_1)$. $\frac{1}{r_2} \ln f(r_2) = \frac{1}{r_1} \ln f(r_1)$ requires that $\frac{1}{r} \ln f(r) = c$ where c is a constant. Therefore

$$f(r) = e^{cr}. \quad 8)$$

If $c = 0$ then $f(r) = 1$ and $\hat{b}_1 = \hat{b}_2 = b$. Under these circumstances, turbulence would not affect the measured irradiance and true extinction will be measured. If, however, $c \neq 0$ and the turbulence effect on measured irradiance takes on the functional form of equation 8, the effect of atmospheric turbulence would not be detected by comparing transmissometric measurements of different path lengths.

Design Considerations. To minimize the effect of background or ambient illumination, the transmitted light beam is modulated from on to off while the receiver electronics are designed to measure the difference between background radiance (transmitter off) and background plus transmitter radiance (transmitter on). The difference between the two signals is proportional to the irradiance associated with the radiant energy from the transmitter light source.

To achieve modulation of transmitter light source, a four blade "chopper" is mounted near a condenser lens and rotated at an exact speed of 19.53125 revolutions per second. This results in a 78.125 cycle per second modulated signal. To maintain the lamp output constant to better than 1%, an optical feedback unit is used. Approximately 8% of lamp output is optically diverted to a photo diode over which a narrow, 550 nm band pass interference filter has been placed. The output from this diode is used to control voltage applied to the transmitter lamp.

The receiver optics consist of a 125 mm refractor lens with a focal length of 629 mm mounted in a heavy walled aluminum tube. The transmitter (light source) image is focussed on a photo diode detector with an interference filter placed directly in front of it. The interference filter has a band pass centered at 550 nm, a 10 nm band width and a peak transmission of 60%. Characteristics of the receiver interference filter are nearly identical to the one used in the transmitter optical feedback system.

The processing of the signal received at the transmitter is schematically shown in Figure 1. The transmitter signal at $t = 0$ is shown in Figure 1a. The "on - off" cycle time is 12.8 ms. Figure 1b, the output from the receiver 12 bit A/D converter, shows the effect of atmospheric turbulence and attenuation on the transmitted signal after the modulated light beam has transversed some path length r . To determine the difference between lamp on and off voltage, the receiving computer must accurately determine the time at which the transmitted signal is sampled. That is, the voltage must be extracted from the transmitted signal that corresponds to when the light is on and when it is off. This is achieved by using a phase-sensitive detection scheme. A high Q ($Q=32$) band pass amplifier centered at the chopper frequency 78.125 CPS allows the fundamental frequency of the chopped signal to be passed to a zero crossover detector. The output of the high Q band pass amplifier is shown in Figure 1c, while the output from the zero cross detector is represented in Figure 1d. By knowing the time associated with zero cross point, an algorithm can be used to determine the time at which the incoming signal is sampled. The signal is sampled for 0.4 ms and consists of eight separate readings.

If the effect of atmospheric turbulence on the signal is random, averaging many radiance difference measurements will yield a "true" value. Figure 2 shows an example of how the receiving electronics is designed to yield a 10 minute average transmitter irradiance signal. A ten minute reading is the average of ten one-minute readings. A one-minute reading consists of ten six-second sampling intervals where the initial second is used to establish the "phase" of the signal and the subsequent five seconds are used to obtain 6250 samples of the signal. The receiver electronics is designed to average over any time period selected by the operator. Once the receiver has been calibrated, the averaged signal can be used directly in equation 1 to calculate atmospheric extinction.

Teleradiometry of a Black Target

Teleradiometers measuring atmospheric radiance of sky and natural targets can be used in a number of ways to yield approximations of atmospheric extinction.³ However, the traditional method of making teleradiometric extinction measurements involves measuring sky and natural target radiance at some distance r and using:

$$C_r = C_o \frac{s_N o}{s_N r} e^{-\bar{b}_{ext} r} \quad 9)$$

to approximate b_{ext} ^{3,4}. C_r and C_o are the apparent and inherent target contrasts respectively, $s_N o$ and $s_N r$ are the sky radiance at the target and observer, while r is the distance to the target and b_{ext} is the average atmospheric extinction coefficient over path length r . If it is assumed that $s_N o / s_N r \approx 1$, then equation 1 can be solved for b_{ext} :

$$\bar{b}_{\text{ext}} = -\frac{1}{r} \ln [C_r/C_o] \quad 10)$$

When using a fabricated black target with $C_o = -1.0$, most errors associated with calculating extinction from contrast measurements under standard illumination conditions are removed. The only error associated with the extinction calculation is due to the uncertainty in sN_o/sN_r . For standard illumination conditions over the short path lengths ($r < 10$ km) required for use of artificial black targets, $sN_o/sN_r \approx 1$ and little error is associated with determining extinction.³ However, single teleradiometer contrast measurements of black targets are still subject to cloud shadowing of the sight path which results in $sN_o \neq sN_r$. Errors due to sight path shadowing can only be remedied by measuring sky radiance at the target (sN_o) and explicitly accounting for the ratio sN_o/sN_r .

In the field experiment using black targets the target teleradiometer distance was 3.3 km. A sensitivity analysis of path radiance as a function of target distance shows that the teleradiometer's accuracy and sensitivity must be extremely high. For a black target located 3.3 km distant from the teleradiometer, the path radiance on a Rayleigh day will be approximately 3.5% of the sky radiance. To measure Rayleigh extinction (0.01 km^{-1}) with an accuracy of near 10% requires a contrast measurement accuracy of less than 1/2%. Therefore, special care must be taken to carefully characterize teleradiometer flare characteristics. Measurements showed that teleradiometer flare was nearly 1% of background sky radiance. Therefore the path radiance readings were corrected for flare using:

$$tN_{3.3\text{km}} = \hat{t}N_{3.3\text{km}} - 0.01sN_{3.3\text{km}} \quad 11)$$

where $tN_{3.3\text{km}}$ is the measured path radiance, $sN_{3.3\text{km}}$ is the measured sky radiance at the observation point, and $\hat{t}N_{3.3\text{km}}$ is the corrected path radiance used to calculate the extinction coefficient. The subscript 3.3 km indicates that the artificial target was 3.3 km from the observation point.

Other considerations in using artificial black targets are the required target size as a function of target distance and the problem of maintaining teleradiometer alignment on the black portion of the target. For instance, the teleradiometer used in the field study was designed with a 0.017° angle of view. This corresponds to an approximate 1.0 m target at a path distance of 3.3 km. For purposes of maintaining alignment and reducing teleradiometer flare, the target was chosen to be twice as big or approximately 2.0 m in diameter.

When the teleradiometer is aligned so that it is centered on the black target, a shift in alignment of only 0.0085° moves the teleradiometer off target. Therefore, alignment was routinely checked to minimize drift in teleradiometer positioning.

Integrating Nephelometer

The integrating nephelometer differs conceptually from the methods discussed above in that it measures the light scattered from the aerosol, whereas the other methods measure a change in radiance or transmittance due to scattering and absorption. The geometry of the instrument is such (see, for example, the description in reference 1) that the signal is proportional to

the scattering portion of b_{ext} , namely b_{scat} . This is an advantage in clean environments, because a small quantity is measured directly rather than being derived from a difference or ratio of larger numbers and, in fact, commercially-available integrating nephelometers can reliably measure b_{scat} due to Rayleigh scattering from gases. On the other hand, the optical signal is so small that it has been measured most successfully in a totally dark, closed chamber, free of stray light.

The closed chamber and instrument geometry result in several considerations concerning the use of the instrument for determining atmospheric extinction:

- o The measurements are totally independent of meteorological conditions and illumination, and they directly measure one component of extinction independent of atmospheric lighting conditions.
- o The measurement is made at one point in space and thus can be compared unambiguously to particulate data that is also gathered at the same point.
- o The sample must be drawn through ducts into a chamber which, in practice, is a different environment from the ambient. This can result in modification of the aerosol due to impaction on surfaces and because of heating or cooling.
- o The commercially available instrument used in the field studies (MRI 1560) inadvertently heated the sample by approximately 10° F. However, heating can be minimized to about 1°-2° with special modifications of the instrument.
- o The commercially available instrument is unable to measure light scattering in the extreme forward and backward directions, typically within 8-10° of the axis. For particles larger than a few micrometers in diameter, a substantial fraction of the scattering is in the forward direction and is not detected by the nephelometer, which means that the instrument underestimates the scattering from larger particles.

The errors caused by the various factors noted above vary from location to location. Heating of the sample by the instrument, by even a few degrees Celsius, can cause errors approaching 100% at high humidities when the particles deliquesce.^{7,8} Forward angle truncation typically results in about 10% underestimates^{9,10} (after allowing for the fact that calibration of the instrument with a Rayleigh scattering gas compensates for some of the truncation error).

RESULTS

Comparison of the Two Transmissometers Operated Over Different Path Lengths.

The objective of operating two transmissometers side by side but with different path lengths was to investigate the effect of atmospheric turbulence on transmissometer-derived atmospheric extinction. The instruments were operated at Grand Canyon, Arizona from late May to the end of July 1986. One instrument was operated continuously over a 5.79 km path, while a second instrument, configured to make 10 minute average readings at the top of each hour, had a path length of 15.57 km. Both receivers were placed at Grand View Point with the transmitters located at Moran Point (5.79 km) and Desert View Watchtower (15.57 km). To minimize turbulence due to thermal gradients near the surface of the ground, instruments were placed next to cliff edges such that the light beam path was well above terrain features.

To examine the relationships between extinction derived from the two instruments, a scatterplot, shown in Figure 3, was made with the 15.57 km and 5.79 km path instruments plotted on the x and y axes, respectively. The continuous signal from the 5.79 km instrument was averaged to correspond to the 15.57 km instrument. Pertinent statistics associated with Figure 3 are presented in Table 1.

The two instruments compared quite favorably. It is clear that there is an approximate linear relationship between the two extinction coefficients. Correlations between $b_{ext,1}$ and $b_{ext,2}$ are equal to 0.97, and a perpendicular departure regression analysis indicates a straight line with nonsignificant intercept. Because there is error in both the independent and dependent variable, perpendicular departure regression analysis yields a more "physically" representative regression line.¹² Details of perpendicular regression are presented in Appendix A. 95% of the time b_1 is within 13% of b_2 , while relative error between b_1 and b_2 given by

$$RE = \frac{1}{n} \sum [|b_{1i} - b_{2i}| / (b_{1i} + b_{2i}) / 2] \quad (12)$$

averaged over all cases is 11.6%. That is, the discrepancy between the two transmissometers is 11.6% on the average. In fact, in 75% of the cases the discrepancy is less than or equal to 4.3%.

The rather exceptional agreement between the two instruments under a variety of turbulence conditions and during day and nighttime conditions suggests that either turbulence was not significantly affecting the transmissometer-derived extinction calculation and that the transmissometers were making very accurate measurements or that the effect of atmospheric turbulence on measured irradiance takes on the form of equation 8 and the effects of turbulence are not detected by this experiment.

Comparison of Transmissometer Extinction to Teleradiometer Black Target Extinction.

During October 1986 a special study was conducted near Meteor Crater, Arizona to intercompare a number of methods for measuring atmospheric extinction. As part of that experiment, a precision, low-flare teleradiometer was used to measure contrast of a prefabricated two meter diameter black target located 3.3 km from the observation point. All teleradiometers used in the black target experiment were calibrated to yield identical readings (millivolts) when measuring the radiant energy from a constant radiance light source. Relative radiance is defined to be teleradiometer voltage output. The actual radiance can be achieved by multiplying the teleradiometer voltage by an appropriate constant. However, for purposes of this experiment, absolute radiance is not necessary since the constant will cancel out when calculating contrast.

Figure 4 shows a plot of the October 9, 1985 "raw" teleradiometer readings associated with the artificial black target. The highest readings correspond to sky radiance, while the lower readings correspond to the path radiance between the observation point and black target. The "relative radiance" reading for the path radiance can be arrived at by dividing the y-axis scale in Figure 4 by a factor of 2. From the hours 0000 to 0600 and 1800 to 2400 the sun is down and the teleradiometer reads zero radiance. The effects of clouds on lighting conditions are reflected in teleradiometer

readings between 0600 and 1200 hours. From 1200 to 1400 hours there were intermittent showers with enough rain during 1200 to 1300 hours to make teleradiometer readings drop to near zero at certain times. These readings were eliminated from the data set. Afternoon readings correspond to nearly cloud-free conditions. Notice how the sky and path radiance varies smoothly in time. The increase in path radiance at 1600 hours corresponds to an increase in particulate matter which was also measured by the transmissometer and nephelometer. The teleradiometer relative radiance readings were converted to atmospheric extinction through the use of equation 10 after correcting for flare.

Adjacent to the black target instrumentation, a transmissometer was operated over a path length of 8 km. The instrument was calibrated by the same method as previously described. Figure 5 is a scatterplot comparing "black target" to transmissometer extinction for all data gathered during the study period. Slopes of the regression line comparing two measurements were carried out using "perpendicular" departure rather than conventional regression analysis since there is error in both dependent and independent variables.¹⁰

The slope of the regression line is equal to 1.07 ± 0.074 and the intercept (-0.003 ± 0.003) is not statistically different from zero. The correlation between the two measurements is 0.80 while the relative error is 15.0%. Given the potential error due to sight path shading by cloud cover, the agreement between the two instruments is surprisingly good.

Comparison of Transmissometer Extinction to Integrating Nephelometer Scattering.

In the field studies at Grand Canyon, Meteor Crater and Page, Arizona, the MRI 1560 integrating nephelometer was used. The instrument was operated according to standard procedures. The span of the instrument was set using freon 12, while the "zero" point was monitored at least every six hours by pumping clean air through the sampling chamber. Typical temperature differences between the nephelometer inlet and outlet were around 10°F.

At Grand Canyon, the nephelometer was operated at Hopi Point, a monitoring site which is approximately 18 kilometers from Grand View Point and 30 kilometers from Desert View. Figure 6 shows a scatterplot of hourly average nephelometer and 5.79 km transmissometer scattering/extinction measurements. Given the rather large physical separation of the two instruments and the fact that the operation logbook indicated some local control burn activity, the instruments compared favorably. The perpendicular regression line slope is 0.91 ± 0.27 , with a near zero intercept of 0.0068 ± 0.001 , while the correlation coefficient is 0.94. When the atmosphere is free of aerosols, both instruments should predict Rayleigh scattering of 0.01 km^{-1} . The regression equation can be used to estimate relative error (RE) by predicting b_{ext} when $b_{\text{scat}} = 0.01$. The RE is given by $(b_{\text{scat},R} - b_{\text{ext},R})/0.01$ where $b_{\text{scat},R}$ and $b_{\text{ext},R}$ are the nephelometer and transmissometer Rayleigh scattering coefficients. The RE for the Grand Canyon experiment was 9.9%. On the average, however, the nephelometer predicted scattering coefficient was approximately 10% lower than transmissometer extinction. The difference could be attributed to nephelometer underestimation of large particle scattering, absorption or drying of wet aerosols.

A similar comparison was done during the Meteor Crater study and results are shown in a scatterplot presented in Figure 7. The slope of the perpendicular regression line for this study was 0.53 ± 0.055 and the intercept again was near zero at 0.003 ± 0.006 . The correlation between the two measurements is near 0.80 while the relative error is 28.6% at Rayleigh conditions. A slope of 0.53 implies that on the average nephelometer scattering was approximately 50% lower than transmissometer-derived extinction.

A third comparison between a transmissometer and integrating nephelometer was carried out over the time period from January 7 to February 18, 1986-1987 as part of the Winter Haze Intensive Tracer Experiment (WHITEX) at Page, Arizona.¹¹ The transmissometer receiver and integrating nephelometer were placed on a 4,300 foot plateau that is located just north of Page and the Navajo Generating Station. The transmissometer transmitter was placed 11.18 km north of the receiver and nephelometer. Any local emissions from Page or the power plant could, under some meteorological conditions, be detected by the nephelometer before being uniformly mixed through the transmissometer receiver-transmitter path. This was most evident during early morning hours (5:00 a.m. - 8:00 a.m.) when wood smoke from Page could be seen (and smelled) passing over the monitoring station. The nephelometer responded with sharp spikes, while the transmissometer responded slower and over significantly longer time periods.

To minimize the effect of inhomogeneous aerosol distributions, the transmissometer and nephelometer data were averaged over a six hour period. Six hours was chosen to correspond to the length of particulate sampling intervals, since an ultimate goal of WHITEX was to relate aerosol mass concentration to atmospheric extinction. A scatterplot of the 6 hour averaged nephelometer-transmitter readings are shown in Figure 8, while pertinent statistics for both 10 minute and 6 hour averaged data are given in Table 1. The slope and intercept and their associated errors are approximately the same for 10 minute or six hour data. However, the R^2 are 0.57 and 0.71 for the 10 minute and 6 hour data, respectively. The slope of the perpendicular regression line shown in Figure 6 is 2.4 ± 0.112 , while the intercept is statistically different from zero at -0.027 ± 0.003 .

Examination of Figure 8 suggests that the regression line may be disproportionately driven by a few high extinction values. The extinction-scattering numbers that are less than 0.03 km^{-1} appear to be closer to the 1:1 line than those values above 0.03 km^{-1} . An examination of those transmissometer extinction points greater than $\approx 0.03 \text{ km}^{-1}$ show that they mostly occurred during one episode from 2/6-2/13, 1987 when the relative humidity routinely exceeded 60%. The data were further segregated by relative humidity. Figure 9 shows a scatterplot for those 6 hour averaged data points below $\text{RH} = 60\%$, and Figure 10 corresponds to 6 hour averaged data gathered at $\text{RH} \geq 60\%$. For $\text{RH} < 60\%$, the slope is 1.2 ± 0.084 and the intercept is again near zero (-0.003 ± 0.002). The average relative error between the two measurements under Rayleigh conditions is 9.0%. For RH less than 60%, the nephelometer measured scattering was approximately 20% lower than transmissometer extinction. However, the slope of the regression line for $\text{RH} \geq 60\%$ is 2.7 ± 0.19 with an intercept of -0.035 ± 0.005 . For $\text{RH} \geq 60\%$, the nephelometer, on the average, is underpredicting extinction by 60%, assuming the transmissometer is accurately measuring true ambient extinction.

It should be pointed out that the slope of the transmissometer extinction versus nephelometer scattering was nearly the same for either 6 hour or for 10

minute averaged data. The one data set where slopes did not compare was for $RH < 60\%$. Examination of the 10 minute scatterplot showed that the regression line was being overly responsive to a few outlying data points where the nephelometer was impacted by local smoke before it passed uniformly into the transmissometer light path.

To further investigate the response of the two instruments to aerosols under a variety of RH conditions, the ratio of 10 minute ratio b_{tran}/b_{neph} was plotted as a function of RH for the time period 2/6-2/13. This plot is shown in Figure 11. Notice that below $RH \approx 60\%$ the ratio of b_{tran}/b_{neph} varies around 1, while for $RH > 60\%$ the ratio is much larger than one. For $RH \approx 95\%$, the ratio exceeds 3.5, indicating the nephelometer is drying the aerosol sufficiently to underpredict true scattering by nearly 80%.

CONCLUSION

Three separate field studies were conducted to examine the ability of the OPTEC, Inc. transmissometer to measure atmospheric extinction. One study sought to investigate the effect of atmospheric turbulence by operating two identical transmissometers over two path lengths. If turbulence is causing the measured irradiance to be erroneously low, the effect should manifest itself more for longer than shorter paths. A second study compared transmissometer extinction to teleradiometer black target contrast derived extinction. Using a truly black target eliminates all the error associated with uncertainty in inherent contrast. Finally, the transmissometer extinction was compared to nephelometer scattering. It is expected under some circumstances that nephelometer scattering and transmissometer extinction should compare favorably. For instance, in clean atmospheres both instruments should measure the Rayleigh scattering coefficient. All of the above measurements suggest that the transmissometer is accurately measuring the true unperturbed ambient extinction coefficient. Specifically:

- o Two transmissometers operating under a variety of turbulence conditions, both day and night but over different path lengths, yielded almost identical extinction, indicating the turbulence did not affect the measurements or that turbulence effects on measured irradiance is a very simple exponential function of the path length r . The average relative error between the two instruments was 11.6%
- o The transmissometer and black target extinctions correlated very well and there was little apparent bias between the two instruments. The linear regression line between the two variables was not statistically different from one. The average relative error was 15.0%
- o In each of the studies, nephelometer scattering was systematically lower than transmissometer extinction by as little as 10% and in some cases by as much as 80% under others. However, the intercept of the regression line comparing the two instruments had an intercept (except for $RH > 60\%$ at Page, AZ), which was not substantially different from zero, indicating atmospheric turbulence was not affecting the transmissometer measurements. If the transmissometer readings are being biased toward higher extinctions because of atmospheric turbulence, it would be expected that this bias would be apparent on Rayleigh as well as high extinction periods. The average relative error between the transmissometer and nephelometer measured Rayleigh

scattering was 9.9%, 28.6% and 9.0% at Grand Canyon, Meteor Crater and Page, respectively.

Appendix A

For intercomparison of data derived from two measurement methods, the usual least squares regression is often not appropriate. This is due to the fact that data obtained from both measurement methods are contaminated with measurement errors. The more appropriate approach is to use the so called 'errors in variables regression model'. There is a vast amount of literature on this subject, but an adequate background for applications can be obtained from a paper by Mandel.¹²

Let (X_i, Y_i) $i=1, 2, \dots, n$ denote the data obtained from two measurement methods where X_i denote readings from instrument A and Y_i from instrument B. Suppose that the true values being measured are denoted by w_i . If both instruments have a zero shift and a bias, then:

$$X_i = \alpha_1 + \beta_1 w_i + v_i \quad \text{A1)}$$

and

$$Y_i = \alpha_2 + \beta_2 w_i + \epsilon_i \quad \text{A2)}$$

where v_i , ϵ_i denote random errors. Eliminating w_i between the above two equations, the relationship between Y_i and X can be written in the form

$$y_i = \alpha + \beta x_i \quad \text{A3)}$$

where

$$Y_i = y_i + \epsilon_i \quad \text{A4)}$$

and

$$X_i = x_i + v_i \quad \text{A5)}$$

Here y_i and x_i denote the readings from instrument A and instrument B respectively in the absence of random errors. The coefficients α and β stand for the relative zero shift and the relative bias respectively. If the two instruments agree on the average, then α should be zero and β should be 1.

Suppose that the random error ϵ_i associated with the Y_i has mean zero and variance σ_ϵ^2 and the random error v_i associated with X_i has mean zero and variance σ_v^2 . Let the ratio $\sigma_\epsilon^2/\sigma_v^2$ be represented by λ . We assume that this ratio can be experimentally determined and hence, for all practical purposes, known. The formulas for calculating estimates a and b of α and β respectively along with their standard errors are shown below. The formulas for the standard errors are approximate and exact formulas are not available.

$$b = \frac{(SYY - \lambda SXX) + \{(SYY - \lambda SXX)^2 + 4 \lambda SXY^2\}^{1/2}}{2 SXY} \quad \text{A6)}$$

$$a = \bar{Y} - b\bar{X}$$

where

$$SYY = \sum (Y_i - \bar{Y})^2$$

$$SXX = \sum (X_i - \bar{X})^2$$

$$SXY = \sum (X_i - \bar{X})(Y_i - \bar{Y}) \quad \text{A7)}$$

\bar{X} = the mean of X_1, \dots, X_n

and

\bar{Y} = the mean of Y_1, \dots, Y_n .

To compute the standard errors of these coefficients, it is convenient to first calculate the following intermediate quantities.

$$SUU = SXX + 2 b SXY + b^2 SYY \quad A8)$$

$$SVV = SYY - 2 b SXY + b^2 SXX$$

and

$$s_e = [SVV / (n-2)]^{1/2} . \quad A9)$$

We then have

$$s.e.(a) = s_e \left[\frac{1}{n} + \frac{\bar{X}^2(1+b^2)^2}{SUU} \right]^{1/2} \quad A10)$$

and

$$s.e.(b) = s_e \left[(1+b^2)^2 / SUU \right]^{1/2} . \quad A11)$$

Approximate 95% confidence intervals on α and β can be obtained in the usual manner by computing the limits as estimate plus two standard errors and estimate minus two standard errors.

For calculations in this paper it was assumed that $\lambda = 1$ (that is, the measurement error variances for the different measuring methods are roughly equal). The calculation of a and b then reduces to computing the estimates of α and β by minimizing the sum of squares of the perpendicular distances from the data points to the fitted line. We can also compute a figure of merit for the degree of agreement between the two instruments. For the case $\lambda = 1$, this can be done as follows: Calculate the sum of squares of the perpendicular distances from the data points to the line of best fit defined in (A6). Let this quantity be denoted by SPD1. Also calculate the sum of squares of the perpendicular distances from the data points to the line $Y = X$. Let this be denoted by SPD2. Let R denote the ratio SPD1 / SPD2. The value of R is always between 0 and 1. If the line of best fit is not too different from the line $Y = X$ (which corresponds to perfect agreement between the two instruments apart from random errors) then the ratio R should be very close to 1.

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Table 1. Pertinent statistics for comparing the transmissometer derived extinction to other measures of extinction/scattering.

	<u>Slope</u>	<u>Intercept</u>	<u>SE of Slope</u>	<u>SE of Intercept</u>	<u>R</u>
Transmissometer 1 vs Transmissometer 2 (Summer 1986)	0.97	0.0002	0.016	0.000	0.98
Transmissometer vs Black Box	1.07	-0.0030	0.074	0.003	0.80
Transmissometer vs Nephelometer (Grand Canyon)	0.91	0.0007	0.027	0.001	0.94
Transmissometer vs Nephelometer (Meteor Crater)	0.53	0.0060	0.055	0.002	0.79
Transmissometer vs Nephelometer (Page - 10 minute)	2.30	-0.0230	0.064	0.002	0.75
Transmissometer vs Nephelometer (Page - 6 hour)	2.40	-0.0270	0.011	0.003	0.84
Transmissometer vs Nephelometer ($\geq 60\%$ 10 minute)	2.64	-0.0320	0.101	0.003	0.81
Transmissometer vs Nephelometer ($\geq 60\%$ 6 hour)	2.70	-0.0350	0.190	0.005	0.85
Transmissometer vs Nephelometer ($< 60\%$ 10 minute)	0.82	0.0060	0.036	0.001	0.66
Transmissometer vs Nephelometer ($< 60\%$ 6 hour)	1.21	-0.0030	0.084	0.002	0.80

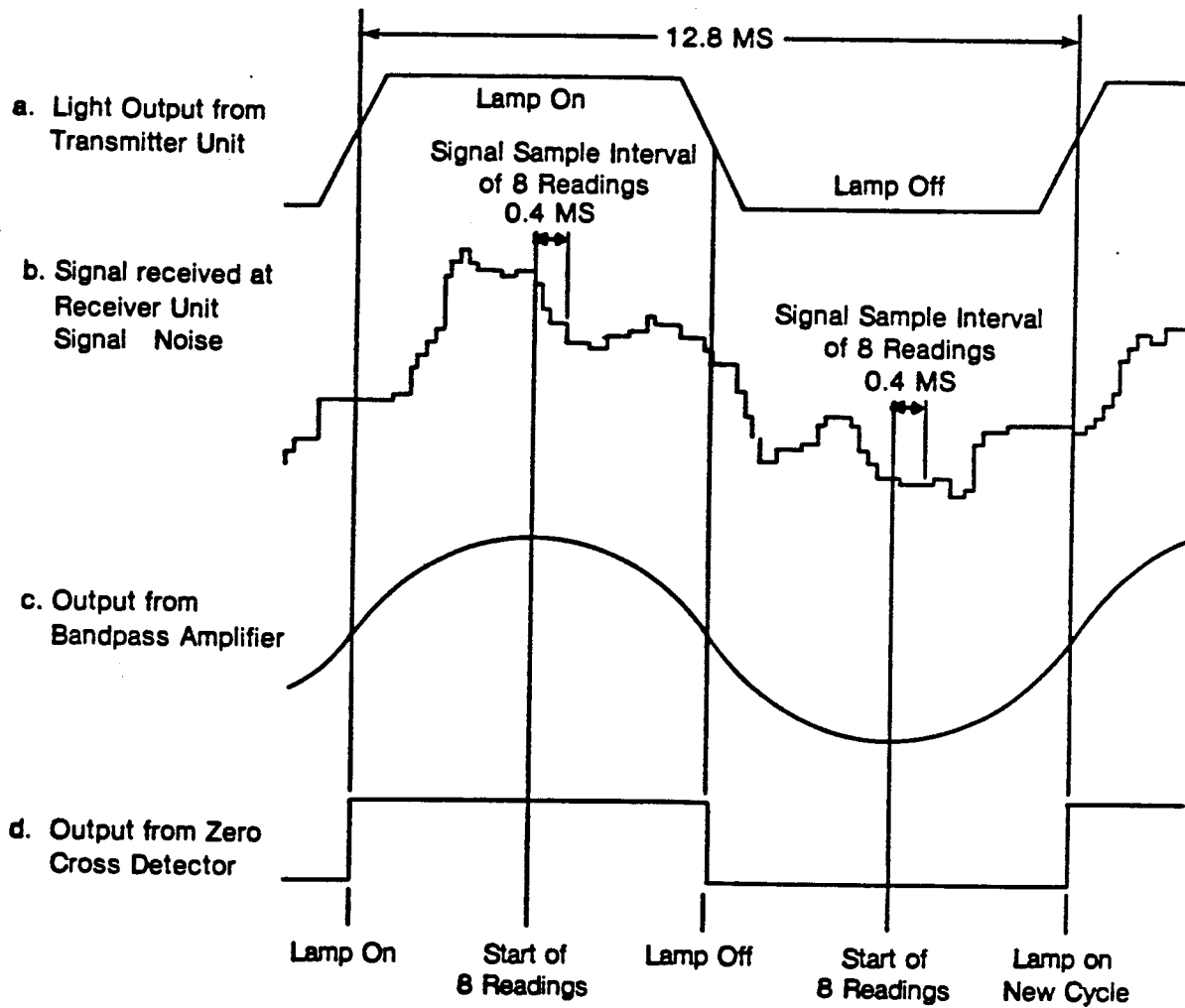


Figure 1. Receiver signal processing waveforms.

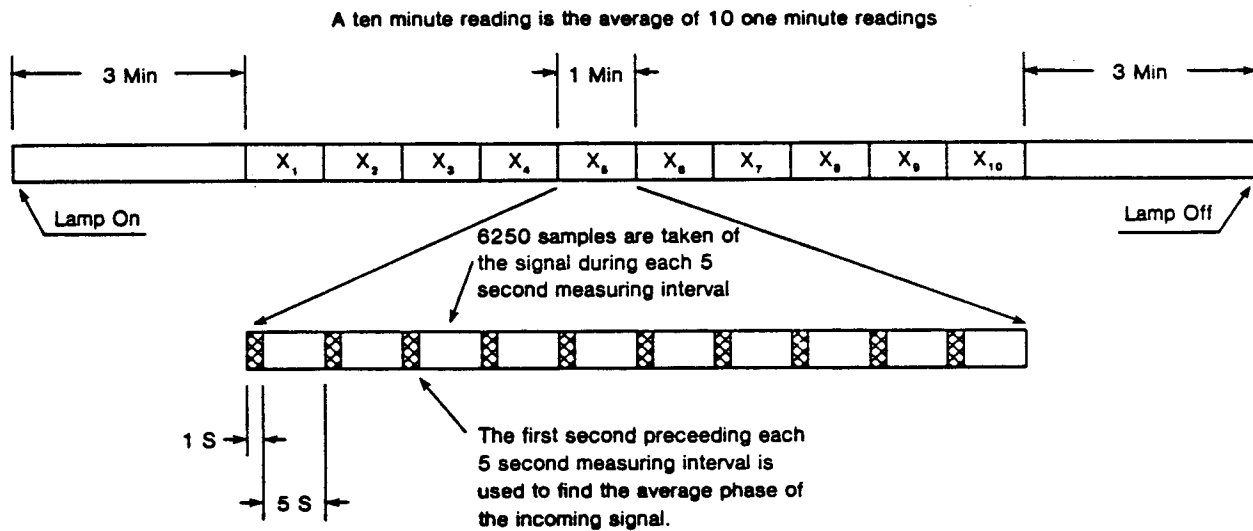


Figure 2. Example of a ten minute integration.

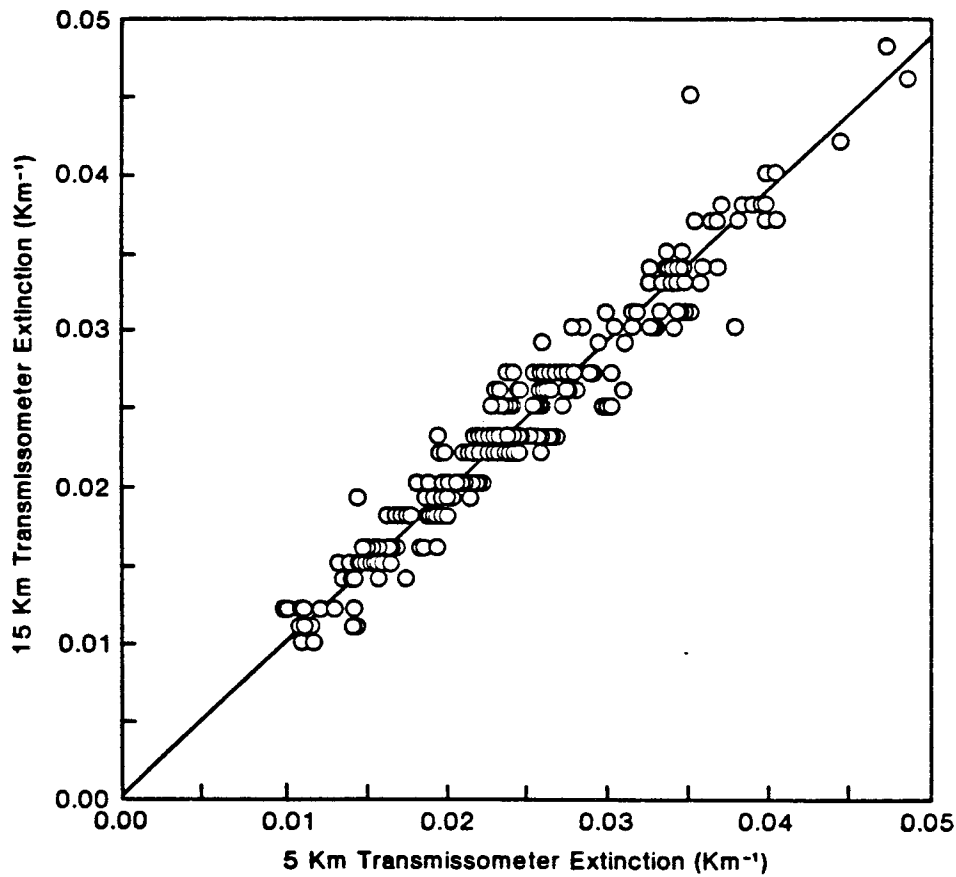


Figure 3. Comparison of extinction coefficients derived from transmissometers operated over two different path lengths.

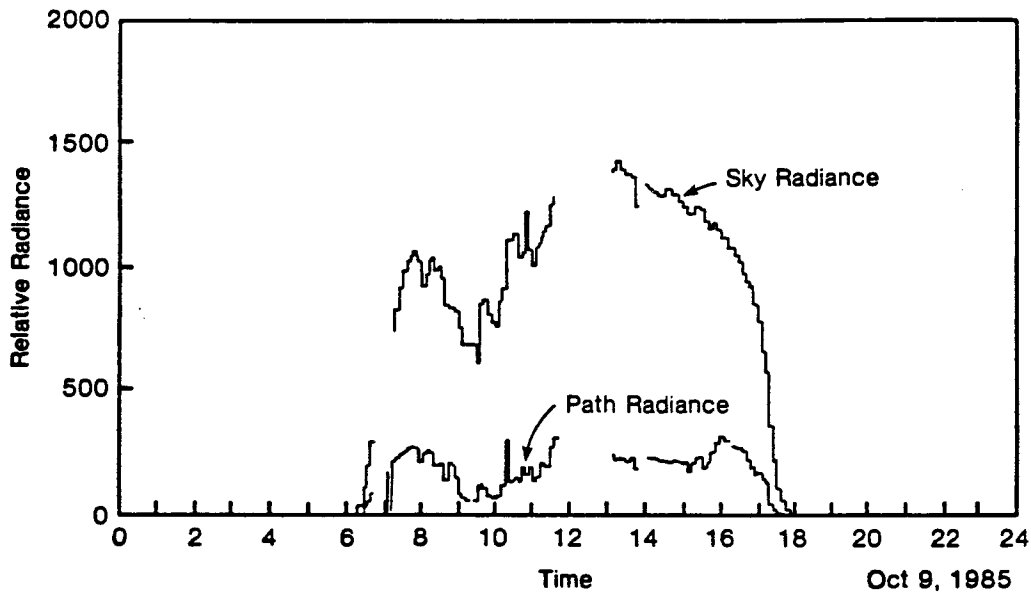


Figure 4. Relative sky and path radiance for the black target experiment plotted as a function of time for October 9, 1985. Relative path radiance is equal to the y-axis relative radiance values divided by two.

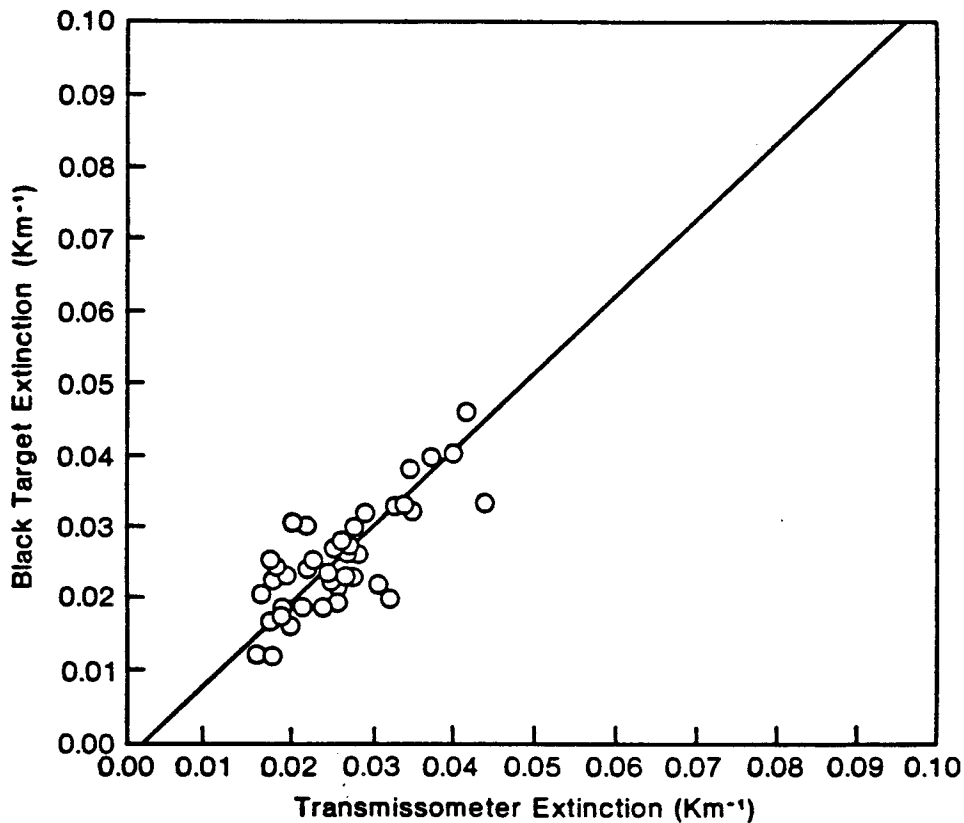


Figure 5. Scatterplot of black target and transmissometer atmospheric extinction. The slope of the perpendicular regression line is equal to 1.07 ± 0.074 and the intercept is equal to -0.003 ± 0.003 .

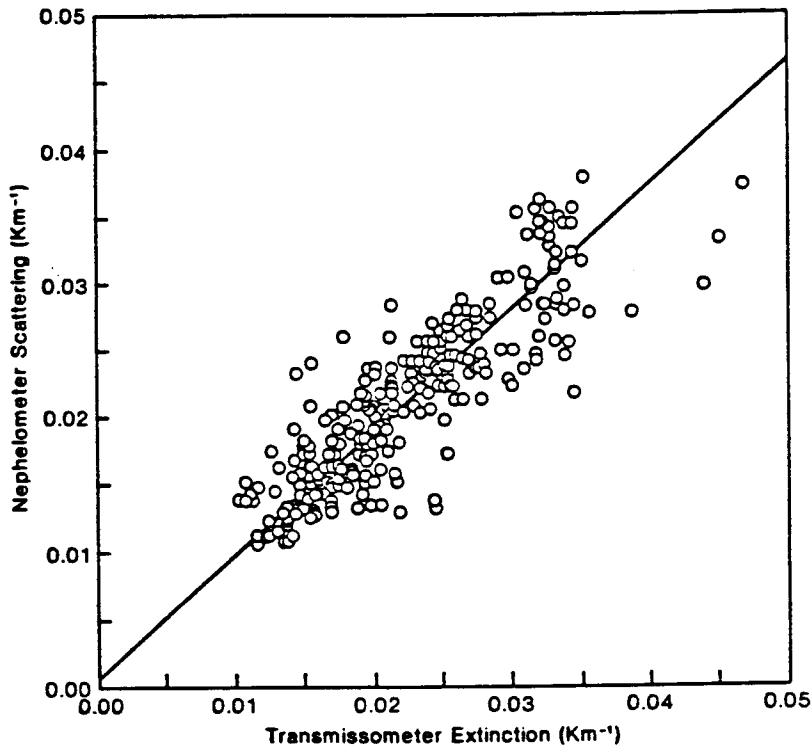


Figure 6. Scatterplot of hourly averaged nephelometer scattering and transmissometer extinction for the Grand Canyon intercomparison study. The slope of the perpendicular regression line is equal to 0.91 ± 0.027 and the intercept is equal to 0.0007 ± 0.001 .

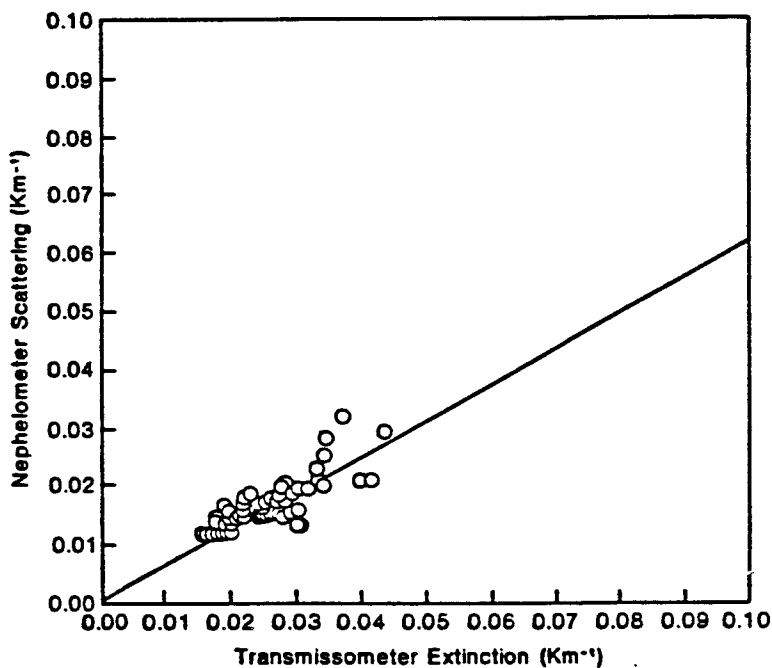


Figure 7. Scatterplot of "daytime" hourly averaged integrating nephelometer scattering and transmissometer extinction for the Meteor Crater study. The slope of the perpendicular regression line is 0.53 ± 0.055 and the intercept is equal to 0.003 ± 0.006 .

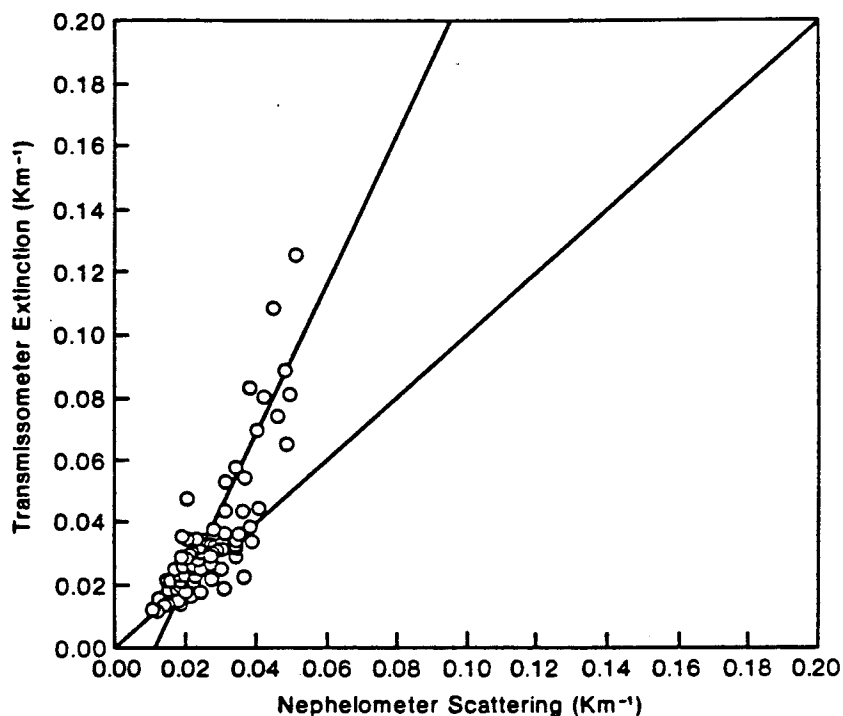


Figure 8. Scatterplot of the 6 hour averaged transmissometer extinction and nephelometer scattering for the WHITEX study. The slope of the perpendicular regression line is 2.4 ± 0.011 and the intercept is -0.027 ± 0.003 . For comparison, the scatterplot also shows the 1:1 line.

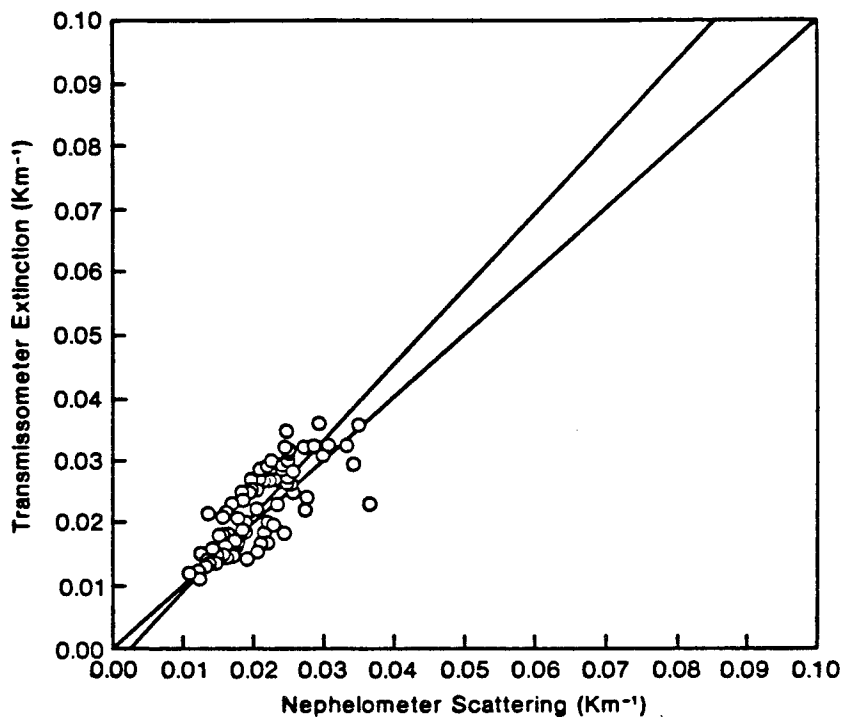


Figure 9. Scatterplot of the 6 hour averaged transmissometer extinction and nephelometer scattering for the WHITEX study but with $\text{RH} < 60\%$. The slope of the perpendicular regression line is 1.21 ± 0.084 and the intercept is -0.003 ± 0.002 . The 1:1 line is also shown.

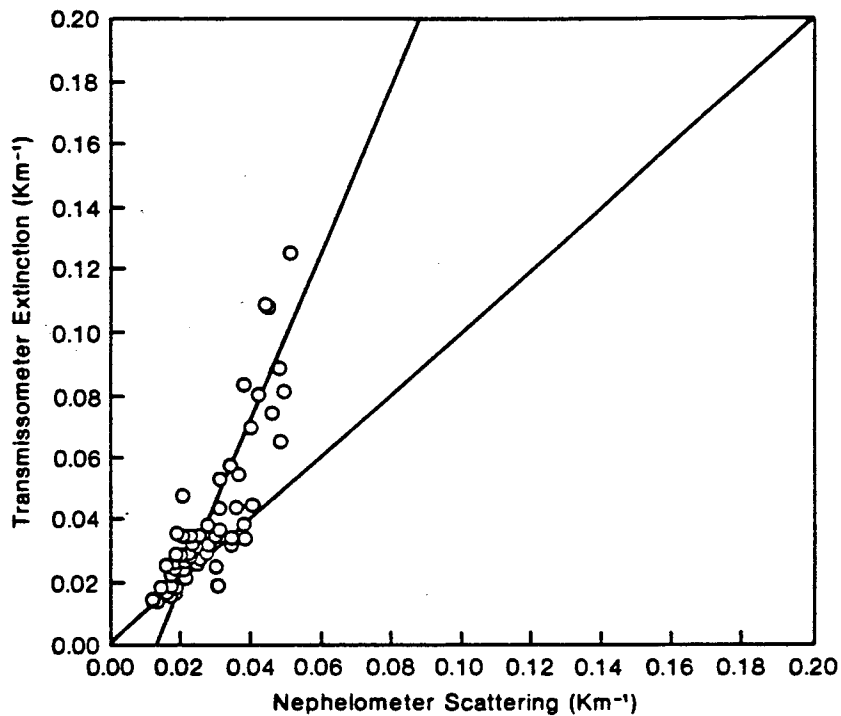


Figure 10. Scatterplot of the 6 hour averaged transmissometer extinction and nephelometer scattering for the WHITEX study but with $\text{RH} \geq 60\%$. The slope of the perpendicular regression line is 2.70 ± 0.19 and the intercept is -0.035 ± 0.005 .

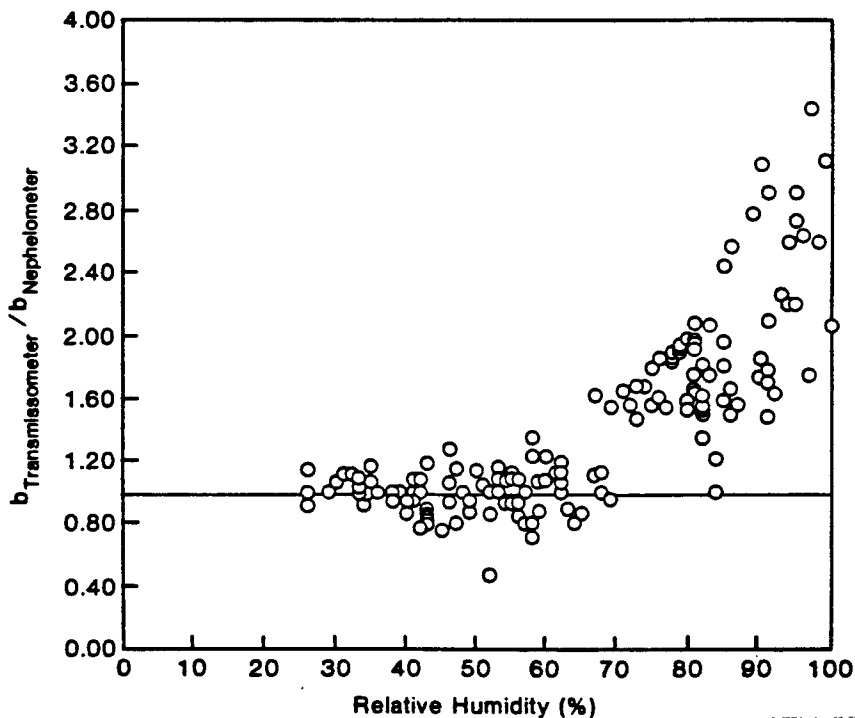


Figure 11. Ratios of the 10 minute transmissometer extinction to nephelometer scattering is plotted as a function of relative humidity for the time period of 2/6-2/13. Data is from the WHITEX study. The horizontal line corresponds to transmissometer extinction/nephelometer scattering = 1.0.