
Considerations in the Accuracy of a Long-Path Transmissometer

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A recently developed long-path (≈ 15 km) transmissometer (LPT) was configured with a design criteria of measuring transmission independent of atmospheric turbulence accurately enough to determine ambient aerosol extinction coefficients with better than 10% error. To assess the ability of the LPT to measure atmospheric extinction accurately and to assess its response to atmospheric turbulence, a series of field programs was initiated to compare it to other measures of extinction as well as to itself using different path lengths. Relative accuracy of the transmissometer-derived extinction is calculated by comparing it to other measurements of extinction when it is expected that

those measurements would be unperturbed by meteorological conditions and/or relative humidity. For instance, integrating nephelometers can accurately measure near-Rayleigh extinction, and teleradiometer contrast measurements of artificial black targets under standard meteorological conditions eliminate the errors associated with the uncertain inherent contrast and nonuniform illumination. Turbulence effects were independently investigated by simultaneously operating two transmissometers over varying path lengths at Grand Canyon National Park from June 1986 to September 1986.

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 (Charlson et al., 1967) and teleradiometry using natural targets (Middleton, 1958; Malm and Molenaar, 1984). Both measurement techniques have serious shortcomings. On the one hand, the integrating nephelometer measures atmospheric scattering and not absorption, may modify (dry) particles that pass through its sampling chamber (Dzubay et al., 1982),

and properly measures scattering from only fine particles (Ensor and Waggoner, 1970; Quenzel et al., 1975). On the other hand, calculations of atmospheric extinction using teleradiometer measurements of natural target contrast 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 (Malm, 1987).

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 ($\geq 10\text{-}\mu\text{m}$) aerosols by a closed chamber inlet. However, transmissometers with path lengths greater than a

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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., Lowell, Mich. One transmissometer design criteria was to measure atmospheric extinction in near-Rayleigh atmospheres to an accuracy of better than 10%. A Rayleigh atmosphere refers to an atmosphere free of light scattering and absorbing aerosols. 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 using different path lengths and 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 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 arti-

ficial black target. By fabricating a target with $C_o = -1.0$, the errors associated with uncertain inherent contrast resulting from uneven illumination of the target or clouds behind the target are eliminated. However, some errors associated with clouds shading the sight path still remain (Malm and Tombach, 1986).

In each of the above-described experiments, and as part of a special study in the winter of 1987, 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 relative humidity (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 (Middleton, 1958). The equation governing the amount of radiant energy received at the observation point is

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

where $H(r)$ is irradiance at some distance, r , from the light source, I_o is radiant intensity, and b_{ext} is the atmospheric extinction coefficient. I_o/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, proposed by Hall and Riley (1975), utilizes measurements of $H(r)$

at two different distances. Measuring r_1 , r_2 , $H(r_1)$, and $H(r_2)$ and assuming the atmosphere is homogeneous over distances r_1 and r_2 allows for the calculation of I_0 . A third calibration technique, the one used in all field studies discussed in this paper, involves measuring $H(r)$ when the receiver and light source (transmitter) are placed within a few hundred feet of each other, and assumes $e^{-b_{\text{ext}}r} \approx 1$. Then $I_0 = H(r)r^2$, where r is the distance between the telera-diometer and transmitter.

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

$$b' = -\frac{1}{r} \left[\ln \frac{H(r)r^2}{I_0} + \ln f(r) \right], \quad (2)$$

where $b = -1/r \ln [H(r)r^2]/I_0$ is true extinction or extinction associated with only atmospheric aerosols and gases. Therefore, the difference in b' derived from transmissometer measurements over two path lengths of differing distances is

$$\Delta b' = \frac{1}{r_2} \ln f(r_2) - \frac{1}{r_1} \ln f(r_1). \quad (3)$$

r_1 and r_2 correspond to two different transmitter-receiver distances. For $\Delta b' = 0$ requires $1/r_1 \ln f(r_1) = 1/r_2 \ln f(r_2)$. Therefore, $1/r \ln f(r) = c$, where c is a constant and

$$f(r) = e^{cr}. \quad (4)$$

If $c = 0$, then $f(r) = 1$ and $\Delta b' = 0$. Under these circumstances, turbulence would not affect the measured irradiance, and true extinction is measured. If, however, $c \neq 0$ and the turbulence effect on measured irradiance takes on the functional form of Eq. 4, 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 the 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-Hz modulated signal. To maintain the lamp output constant to better than 1%, an optical feedback unit is used. Approximately 8% of the 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 diameter lens with a focal length of 629 mm mounted in a heavy walled aluminum tube. The transmitter (light source) image is focused on a photo diode detector with an interference filter placed directly in front of it. The interference filter has a band pass centered at 500 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 is shown in Figure 1a. The 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

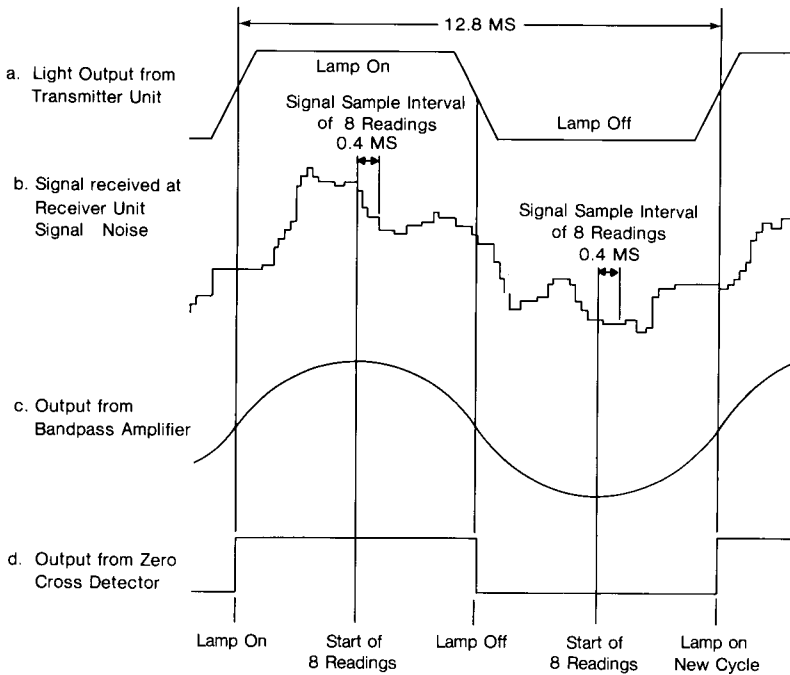


FIGURE 1. Receiver signal processing waveforms.

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 Hz 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, and the output from the zero cross detector is represented in Figure 1d. By knowing the time associated with the 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 are designed

to yield a 10-minute average transmitter irradiance signal. A 10-minute reading is the average of ten 1-minute readings. A 1-minute reading consists of ten 6-second sampling intervals where the initial second is used to establish the "phase" of the signal and the subsequent 5 seconds are used to obtain 6250 samples of the signal. The receiver electronics are 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 Eq. 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 (Malm, 1987). However, the traditional method of making teleradiometric extinction measurements involves measuring sky and natural target ra-

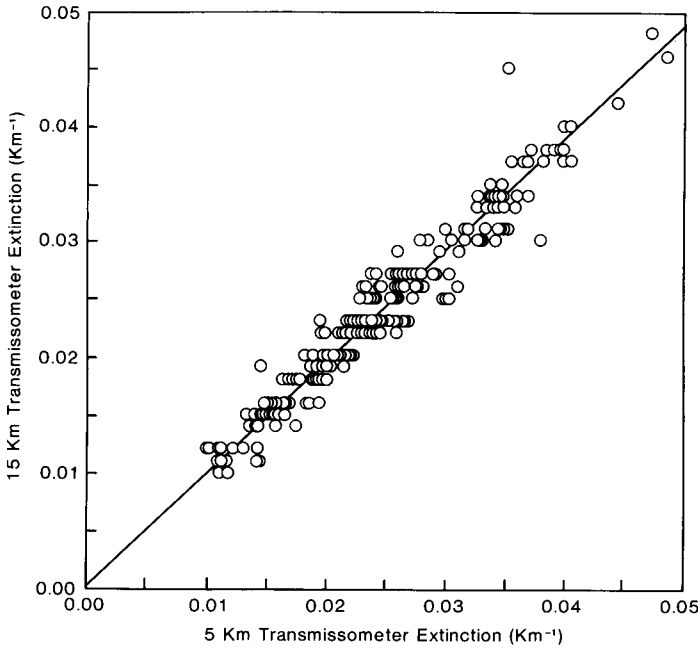


FIGURE 2. Comparison of extinction coefficients derived from transmissometers operated over two different path lengths.

diance at some distance, r , and using

$$C_r = C_o \frac{{}_s N_o}{{}_s N_r} e^{-\bar{b}_{ext} r} \tag{5}$$

to approximate b_{ext} (Middleton, 1958). $C_r = ({}_t N_r - {}_s N_r) / {}_s N_r$ and $C_o = ({}_t N_o - {}_s N_o) / {}_s N_o$ are the apparent and inherent target contrasts, respectively, ${}_t N_r$ and ${}_t N_o$ are the target radiances at the target and observer, while ${}_s N_r$ and ${}_s N_o$ are sky radiances at the target and observer. r is the distance to the target and \bar{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 Eq. 1 can be solved for \bar{b}_{ext} :

$$\bar{b}_{ext} = -\frac{1}{r} \ln [C_r / C_o]. \tag{6}$$

When using a fabricated black target with $C_o \equiv -1.0$, 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 ${}_s N_o / {}_s N_r$. For uniform illumination conditions over the short path lengths ($r < 10$ km) required for use of artificial black targets, ${}_s N_o / {}_s N_r \approx 1$ and little error is associated with determining extinction (Malm, 1986). However, single telera-dimeter contrast measurements of black targets are still subject to cloud shadowing of the sight path, which results in ${}_s N_o \neq {}_s N_r$. Errors due to sight path shadowing can only be remedied by measuring sky radiance at the target (${}_s N_o$) and explicitly accounting for the ratio ${}_s N_o / {}_s N_r$.

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 Charlson et al., 1967) 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} owing 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 of the commercially available nephelometers result in inadvertent heating and drying of aerosols (Dzubay et al., 1982), restriction of large particles from entering the sampling chambers and underestimation of large particle scattering because of truncation errors (Ensor and Waggoner, 1970).

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, Ariz.

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 2, was made with the 15.57- 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 2 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 $b_{\text{ext},1}$ and $b_{\text{ext},2}$ 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, perpen-

TABLE 1. Pertinent Statistics for Comparing the Transmissometer-Derived Extinction to Other Measures of Extinction/Scattering

	Slope	Intercept	SE of Slope	SE of Intercept	R
Transmissometer 1 vs. Transmissometer 2 (Grand Canyon, Arizona; Summer 1986)	0.97	0.0002	0.016	0.000	0.98
Transmissometer vs. Black Box (Meteor Crater, Arizona; Fall 1985)	1.07	-0.0030	0.074	0.003	0.80
Transmissometer vs. Nephelometer (Grand Canyon, Arizona; Summer 1986)	0.91	0.0007	0.027	0.001	0.94
Transmissometer vs. Nephelometer with 2.5 μm Inlet (Meteor Crater, Arizona; Fall 1985)	0.60	0.001	0.06	0.002	0.79
Transmissometer vs. Nephelometer (<60% 6 hour average; Page, Arizona; Winter 1987)	0.82	0.002	0.059	0.001	0.78

dicular departure regression analysis yields a more "physically" representative regression line (Mandel, 1984). It was found that 95% of the time b'_1 is within 13% of b'_2 , while relative error (RE) between b'_1 and b'_2 , given by

$$RE = \frac{1}{n} \left[\frac{|b_{1i} - b_{2i}|}{(b_{1i} + b_{2i})/2} \right] \quad (7)$$

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 Eq. 4 and the effects of turbulence are not detected by this experiment.

Comparison of Transmissometer Extinction to Teleradiometer Black Target Extinction

A consortium of industrial and governmental agencies, the Subregional Cooperative Electric Utility, Department of Defense, National Park Service, and Environmental Protection Agency Study, or SCENES (McDade and Tombach, 1987), was formed to investigate chemical and physical properties of hazes on the Colorado Plateau. As part of SCENES, a special study was conducted near Meteor Crater, Ariz. to intercompare a number of methods for measuring atmospheric extinction (Malm et al., 1987). As part of that study a teleradiometer was used to measure contrast of a prefabricated black target located 3.3 km from the observation point. 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.

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 0.5%. Therefore, special care must be taken to carefully characterize the amount of flare or extraneous light entering the teleradiometer.

The flare of the precision teleradiometer was estimated by measuring the radiance of a small nearby light trap or nearly perfectly black target. The geometry of the measurement was chosen such that the target was twice as big as the area "seen" by the teleradiometer. For all sun angles and illumination conditions the measurements showed that teleradiometer flare was nearly 1% of background sky radiance. Therefore, the path radiance readings were corrected for flare using

$${}_t N_{3.3 \text{ km}} = {}_t N'_{3.3 \text{ km}} - 0.01 {}_s N_{3.3 \text{ km}}, \quad (8)$$

where ${}_t N'_{3.3 \text{ km}}$ is the measured path radiance, ${}_s N_{3.3 \text{ km}}$ is the measured sky radiance at the observation point, and ${}_t N_{3.3 \text{ km}}$ 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.

Another consideration in using artificial black targets is maintaining teleradiometer alignment on the black portion of the target. 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

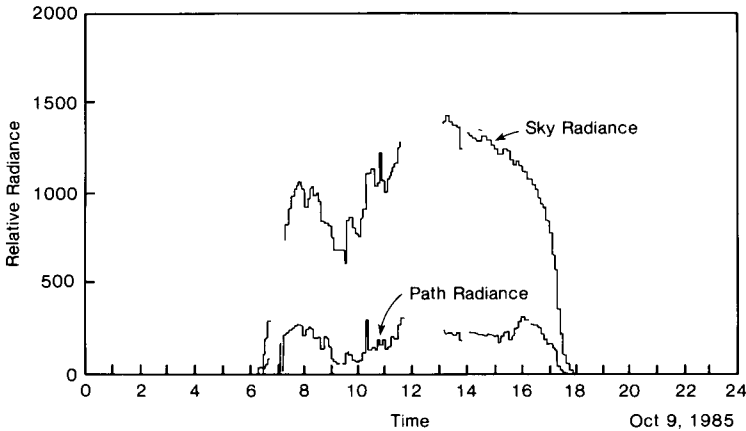


FIGURE 3. Relative sky and path radiance for the black target experiment plotted as a function of time for October 9, 1985. Relative path radiance is equal to the y -axis relative radiance values divided by two.

was routinely checked to minimize drift in teleradiometer positioning.

Figure 3 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. The teleradiometer relative radiance readings were converted to atmospheric extinction through the use of Eq. 6 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 4 is a scatterplot compar-

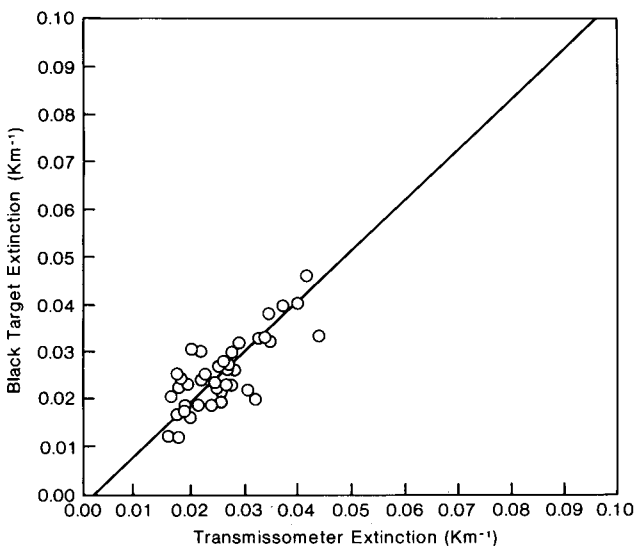


FIGURE 4. Scatterplot of black target and transmissometer atmospheric extinction. The slope of the perpendicular regression line is equal to 1.07 ± 0.074 and the intercept is equal to -0.003 ± 0.003 .

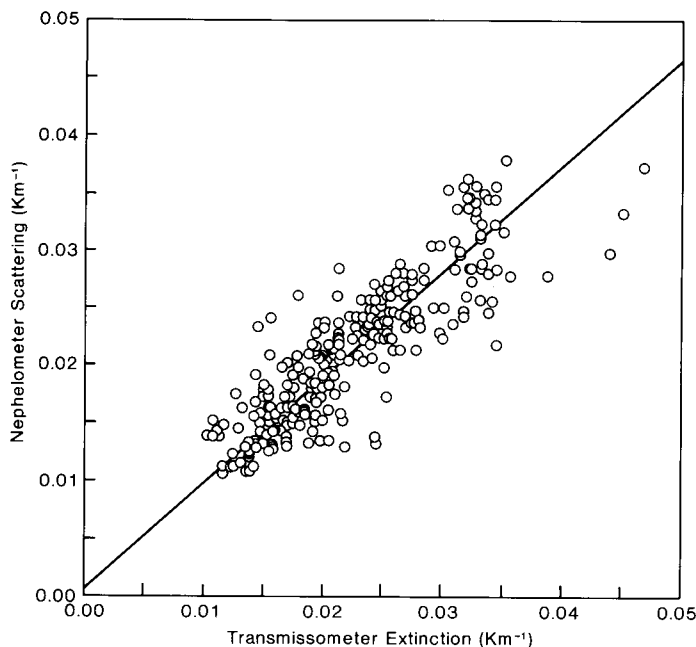


FIGURE 5. Scatterplot of hourly averaged nephelometer scattering and transmissometer extinction for the Grand Canyon intercomparison study. The slope of the perpendicular regression line is equal to 0.91 ± 0.027 and the intercept is equal to 0.0007 ± 0.001 .

ing “black target” to transmissometer extinction for all data gathered during the study period.

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, Ariz., 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 6 hours by pumping clean air through the sampling chamber. Typical temperature differences between the nephelometer inlet and outlet were around 10°C .

At Grand Canyon, the nephelometer was operated at Hopi Point, a monitoring site which is approximately 18 km from Grand View Point and 30 km from Desert View. Figure 5 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 0.0007 ± 0.001 , while the correlation coefficient is 0.94. When the atmosphere is free of aerosols, both instruments

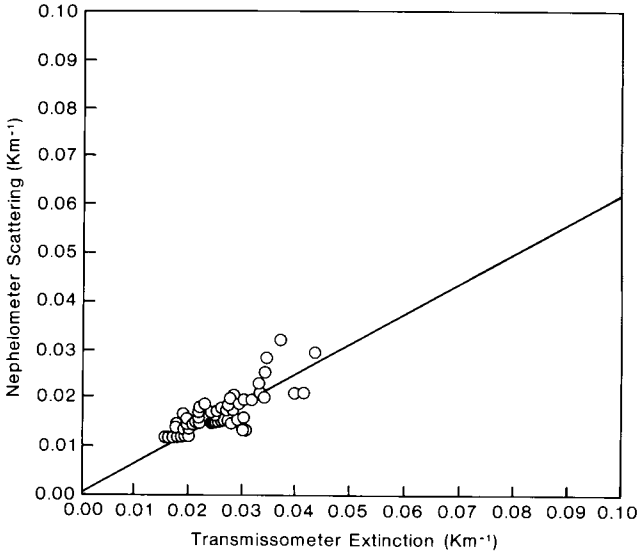


FIGURE 6. Scatterplot of "daytime" hourly averaged integrating nephelometer scattering and transmissometer extinction for the Meteor Crater study. The nephelometer was operated with a 2.5- μm cyclone in front of the inlet. The slope of the perpendicular regression line is 0.60 ± 0.06 and the intercept is equal to 0.001 ± 0.002 .

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 $b_{\text{scat}} = 0.01 \text{ km}^{-1}$. The RE is given by $|b_{\text{scat,R}} - b_{\text{ext,R}}| / 0.01 \text{ km}^{-1}$ 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 approximately 2%. 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 6. In this comparison, the nephelometer was operated with a cyclone which has a 2.5- μm "cutpoint," thus only particles with diameters of 2.5 μm or less were admitted to the nephelometer sampling chamber. The slope of the perpendicular regression line for this study was 0.60 ± 0.06 , and the intercept again was near zero at 0.001 ± 0.002 . The correlation between the two measurements is near 0.80, while the relative error is 30% at

Rayleigh conditions. A slope of 0.60 implies that, on the average, nephelometer scattering was approximately 50% lower than transmissometer-derived extinction. Since the nephelometer was operated with a 2.5- μm cyclone, it is not surprising that b_{scat} is substantially lower than b_{ext} .

A third comparison between a transmissometer and integrating nephelometer was carried out over the time period from January 7 to February 18, 1987 as part of the Winter Haze Intensive Tracer Experiment (WHITEX) at Page, Ariz. (Malm et al., 1989). The transmissometer receiver and integrating nephelometer were placed on a 4300-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. to 8:00 a.m.) when wood smoke from Page could be seen (and smelled) passing over the monitoring station. The nephelometer responded

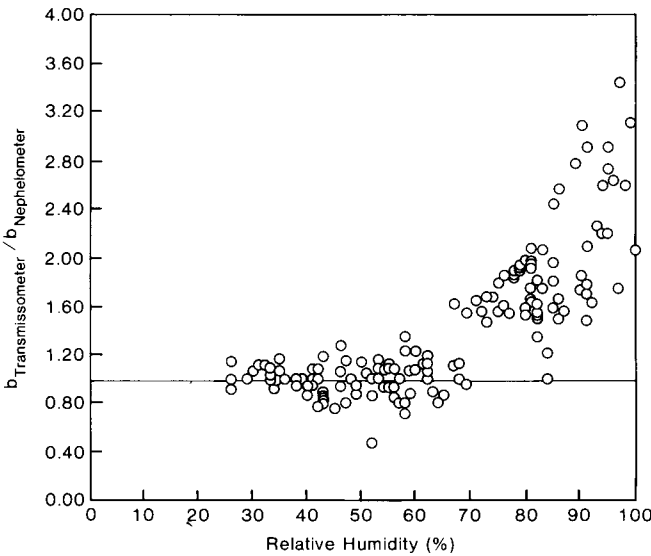


FIGURE 7. Ratios of the 10-minute transmissometer extinction to nephelometer scattering is plotted as a function of relative humidity for the time period of February 6–13. Data are from the WHITEX study. The horizontal line corresponds to transmissometer extinction/nephelometer scattering = 1.0.

with sharp spikes, whereas the transmissometer responded more slowly and over significantly longer time periods.

To minimize the effect of inhomogeneous aerosol distributions, the transmissometer and nephelometer data were averaged over a 6-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.

Relative humidity often exceeded 60% and 70% during the course of the study. Therefore, since the sampling chamber of the nephelometer was known to heat the air by about 10°C, the relative response of the nephelometer and transmissometer as a function of RH was explored. The 10-minute ratio $b_{\text{tran}}/b_{\text{neph}}$ was plotted as a function of RH for the time period February 6–13. This plot is shown in Figure 7. Notice that below $\text{RH} \approx 60\%$ the ratio of $b_{\text{tran}}/b_{\text{neph}}$ varies around 1, while for $\text{RH} > 60\%$ the ratio is much larger than one. For $\text{RH} \approx 95\%$, the ratio exceeds 3.5, indicating the

nephelometer is drying the aerosol sufficiently to underpredict true scattering by nearly 80%.

Since the relationship between the nephelometer and transmissometer is very non-linear above 60% RH because of inadvertent heating within the nephelometer sampling chamber, only those data values corresponding to RH below 60% are used in the analysis. Figure 8 shows a scatterplot for those 6-hour averaged data points below $\text{RH} = 60\%$. The slope is 0.82 ± 0.059 and the intercept is again near zero, 0.002 ± 0.001 . 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.

CONCLUSION

Three separate field studies were conducted to examine the ability of the OPTEC, Inc. transmissometer to measure atmospheric ex-

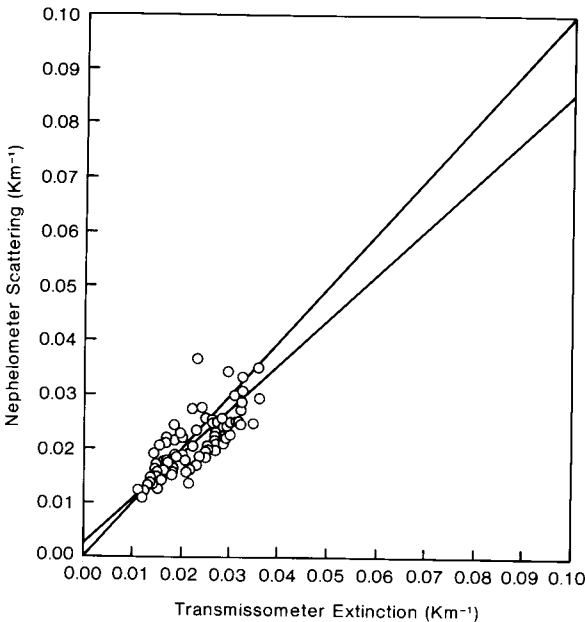


FIGURE 8. Scatterplot of the 6-hour averaged transmissometer extinction and nephelometer scattering for the WHITEX study, but with $RH < 60\%$. The slope of the perpendicular regression line is 0.82 ± 0.059 and the intercept is 0.002 ± 0.001 . The 1:1 line is also shown.

tion. 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 teloradiometer 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:

1. 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%.

2. The transmissometer and black target extinctions correlated very well and there was little apparent bias between the two measurements. The linear regression line between the two variables was not statistically different from 1. The average relative error was 15.0%.
3. 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 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 errors between the transmissometer- and nephelometer-measured Rayleigh scattering were 2%, 30%, and 9.0% at Grand Canyon, Meteor Crater, and Page, respectively.

The assumptions, findings conclusions, judgments, and views presented herein are those of the authors and should not be interpreted as necessarily representing official National Park Service policies.

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Received October 11, 1988; accepted December 3, 1990.