

Extinction Coefficient Measurements in Rain and Snow Using a Forward Scatter Meter

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ABSTRACT

A forward scatter meter is a convenient and accurate method to measure the local visible extinction coefficient in fog and haze. A sample volume is illuminated and the intensity scattered in the angular range of 27 to 42 degrees is measured. The scattered intensity is well correlated to the extinction coefficient of fog regardless of the fog droplet size distribution. The forward scatter meter also gives meaningful measurements during rain and snowfall. A comparison of extinction measurements made with a narrow beam transmissometer show that during rain, the forward scatter meter extinction coefficient is from 25% to 50% greater than the transmissometer value. During snowfall the forward scatter meter extinction coefficient is about 10% to 40% less than that measured with the transmissometer. These results can be used to define correction factors so that the forward scatter meter can be used to estimate extinction during rain and snow as well as during fog.

INTRODUCTION

It is well known (Winstanley and Adams, 1975) that the amplitude of the scattering phase function of haze and fog droplets is insensitive to the aerosol size distribution for scattering angles between about 15° and 45°. In the visible and near IR, absorption is negligible so that the extinction coefficient α can be derived by measuring the intensity of light scattered in this range of angles from a calibrated source. Forward scatter meters that use this principle for the determination of α have several advantages over the more traditional transmissometer. A forward scatter meter is compact since it does not require separate source and receiver and it requires no alignment. Forward scatter meters are believed to be immune to multiple scattering effects that may be a problem for transmissometers at high extinction levels, especially in rain and snow (Hutt et. al. (1991a).

We have used two forward scatter meters (FSM) to measure atmospheric extinction. The instruments are both Model VR-301 manufactured by HSS Inc., Bedford Mass. The VR-301 measures forward scattered light between 27° and 42°. The source is a LED with peak emission at 0.88 μm . A schematic diagram of the VR-301 is shown in Fig. 1. We found that the apparent extinction measured during rain and snow is linearly related to the apparent extinction measured with a HeNe laser transmissometer operating at 0.63 μm . Figures 2a and 2b are scatter plots of extinction values obtained during a rain and a snow episode. Some of the scatter in Figs. 2a and 2b is due to the fact that the FSM provides a point measure while the transmissometer provides a path averaged measurement. The two FSMs were located within 10 m of the transmissometer receiver. The

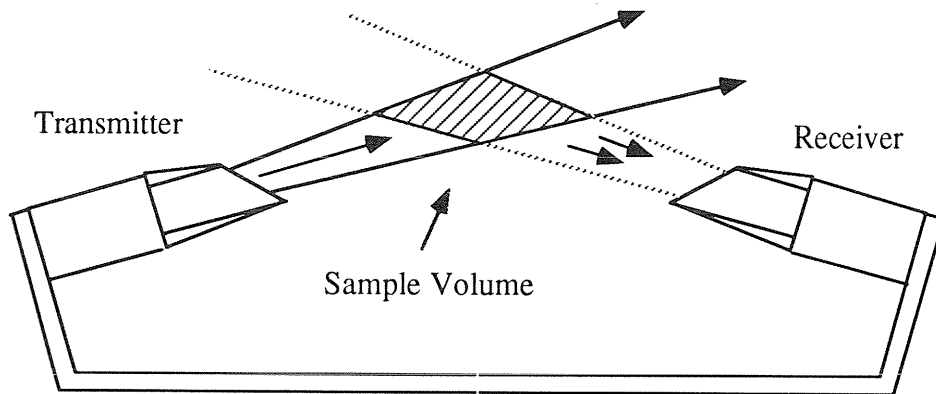


Fig. 1. Schematic diagram of the VR-301 forward scatter meter. The intensity of light scattered into the receiver is proportional to the visible extinction coefficient in haze and fog.

FSMs and the transmissometer each had 30 s integrating time constants and the extinction values were recorded every 20 s. Figure 3 is a histogram of ratios of FSM measured extinction to transmissometer measured extinction obtained during 20 rain and snow episodes. For rain, the FSM values are from about 25% to 50% more than the transmissometer values while for snow the FSM values are from 10% to 40% less than the transmissometer values. The results are similar to the findings of Koh (Koh, 1987a and 1987b).

MEASUREMENT OF EXTINCTION WITH A FORWARD SCATTER METER

The power scattered by a unit volume of aerosol particles in the angular range θ_1 to θ_2 is

$$P_m(\alpha, \theta_1, \theta_2) = I_0 \omega_0 \alpha 2\pi \int_{\theta_1}^{\theta_2} P(\theta, x) \sin\theta d\theta \quad [1]$$

where I_0 is the incident intensity, α is the extinction coefficient, ω_0 is the single scattering albedo and $P(\theta, x)$ is the phase function. We will restrict our discussion to the visible and near IR thus ω_0 can be taken to be one. In Eq. 1, x is the size parameter $2\pi r/\lambda$. The extinction coefficient is proportional to $P_m(\alpha, \theta_1, \theta_2)$ with the proportionality constant k given by,

$$k = 1 / \{ I_0 2\pi \int_{\theta_1}^{\theta_2} P(\theta, x) \sin\theta d\theta \} \quad [2]$$

Numerical integration of the phase functions of four representative fog droplet size distributions (Shettle and Fenn, 1979), between the angles 27° and 42° (the angular range of the HSS forward scatter meter) yields a mean of kI_0 of 0.130 with a standard deviation of 4%.

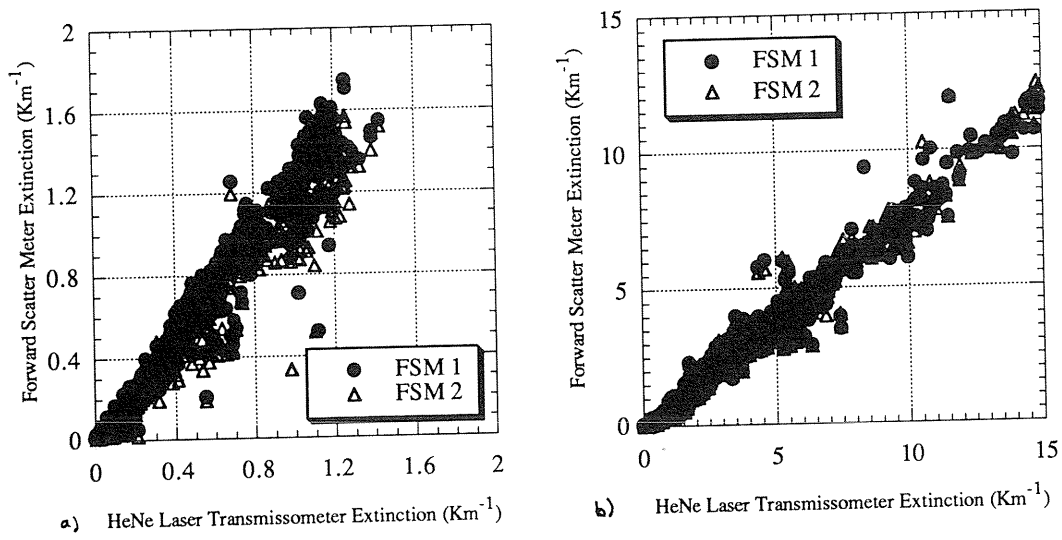


Fig. 2. Scatter plot of extinction measured with two forward scatter meters (FSM 1 and 2) versus extinction measured with a HeNe laser transmissometer during rainfall (a) and snowfall (b).

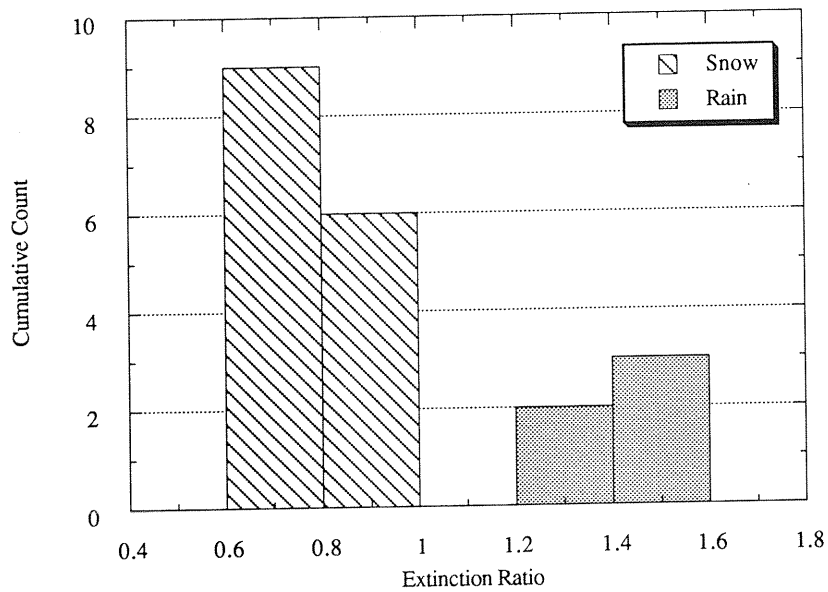


Fig. 3. Histogram of the slopes of scatter plots such as the ones shown in Figs. 2a and 2b for 20 different rain and snow episodes.

PERFORMANCE OF FORWARD SCATTER METER IN RAIN AND SNOW

It is reasonable to assume that rain droplets up to a radius of about 1000 μm are spherical (Ramaswamy and Chylek, 1979) and therefore their phase function can be derived from Mie theory. Phase functions were calculated for four rain droplet size distributions based on the model of Marshall and Palmer (Marshall and Palmer, 1948) with assumed rain rates between 10 and 125 mm/hr. The mean value of kI_0 for rain evaluated at a wavelength of 0.8 μm was 0.109 with a standard deviation of 2%. The values of the rain phase functions are thus lower than those of fog in the range 27° to 42° . The reason for this is that the scatterers are large compared to the wavelength of light and thus scatter more energy in a narrow diffraction lobe in the forward direction. This energy is scattered at the expense of larger angles. This means that for a given extinction coefficient, rain scatters less energy toward the FSM sensor than fog. From the calculated values of kI_0 , we would expect that a FSM calibrated to measure fog extinction would under estimate the extinction coefficient of rain, giving about 85% of the correct value. We cannot estimate kI_0 for the case of snow because the complete phase function of snowflakes is not known to sufficient accuracy despite many efforts to measure it (St. Germain, 1987). The most we can say qualitatively, is that since snowflakes are much larger than the wavelengths of visible light, scattering by snowflakes must be characterized by a prominent diffraction peak. It follows that the amplitude of the phase function of snow in the region 27° to 42° is probably lower than that of fog because more energy is scattered in the near forward direction and less energy is available to be scattered at larger angles.

EXTINCTION MEASUREMENTS WITH A TRANSMISSOMETER

Our transmissometer consists of a 10 mW HeHe laser operating at 0.633 μm collimated to a diameter of 2.8 cm with half angle divergence 0.05 mrad. The transmissometer path length is 538 m. The source is chopped and the transmissometer signal demodulated with a lock-in amplifier. The receiver has a 25 cm diameter $f/0.8$ Fresnel lens objective and PIN photodiode detector. The collection efficiency of the Fresnel lens is considerably less near the edge compared to the center. The effective diameter of the lens is about 12 cm. Transmission measurements were made with the laser beam striking the center of the lens. At the receiver, the laser beam diameter is about 6 cm and is thus entirely captured by the receiver. The half angle field of view (FOV) of the receiver is 20 mrad. The extinction coefficient α was derived from the transmission measurements τ using Beer's law; $\alpha = -\ln(\tau)/R$ where R is the transmissometer path length.

Effect of Molecular Absorption

The contribution of molecular absorption to the measured extinction was calculated using FASCOD2 (Ridgway et. al., 1982). The following conditions were assumed for the calculations: range = 540 m; temperature = 20° ; relative humidity = 100%; atmospheric pressure = 1000 mb and sea level altitude. These meteorological conditions would result in maximum molecular extinction that would have been encountered during our measurements. The results depend on the exact wavelength of the laser and its spectral bandwidth. However, for a laser operating near 0.633 μm the maximum calculated molecular extinction coefficient was

$7 \times 10^{-3} \text{ km}^{-1}$ which is totally negligible compared to typical measured extinctions on the order of 1 km^{-1} . The molecular extinction coefficient would be even less for lower temperatures thus we conclude that the effect of molecular extinction does not need to be taken into account in determining the aerosol extinction coefficient from the transmissometer measurements.

Effect of Multiple Scattering

We showed previously (Hutt and Oman, 1991b) that for geometry of our transmissometer where the transmitted beam is smaller than the receiving optics, the effect of forward scattering on the measured transmittance is negligible. Although forward scattering does reduce the apparent extinction coefficient derived from the transmission measurements, this effect should be less than 3% for our transmissometer, for rain rates up to 125 mm/hr. The effect of multiple scattering is about the same as the measurement accuracy of the transmissometer which is estimated to be about 3%.

If the effects of multiple scattering and molecular extinction on the laser transmissometer are negligible, then the fact that FSM extinction in snow is always less than transmissometer extinction is easy to understand if we assume that the phase function of snow is lower than that of fog in the region 27° to 42° . Since the laser transmissometer measures essentially the correct extinction, the ratio of FSM extinction to transmissometer extinction should be less than one. This is exactly what our measurements have shown: the ratio $\alpha_{\text{FSM}}/\alpha_{\text{trans}}$ in snow varied from 0.66 to 0.95 for 15 different snow episodes.

We showed above that in the 27° to 42° region, the scattering intensity of rain is about 85% that of fog and is independent of rain rate assuming Marshall and Palmer rain size distributions. Thus, we would expect that a FSM calibrated to measure fog extinction would give about 85% of the value measured by the transmissometer during rainfall. Yet the ratio $\alpha_{\text{FSM}}/\alpha_{\text{trans}}$ measured in rain is from 1.25 to 1.55, not 0.85 as we have predicted. We estimated the maximum rain rate, RR(mm/hr), during the measurements from the transmissometer extinction using the relation $\alpha = 0.204\text{RR}^{0.68}$ (Ulbrich and Atlas, 1985). The maximum observed rain rate was about 110 mm/hr. Multiple scattering reduces the extinction coefficient measured by the laser transmissometer by only about 3% at a rain rate of 125 mm/hr (Hutt and Oman, 1991b) which is insufficient to explain the high extinction ratios measured in rain.

CONCLUSIONS

Measurements have shown that under conditions of rain or snow, the output of a FSM (forward scatter meter) is linearly related to the path averaged extinction coefficient measured with a narrow beam HeNe laser transmissometer. The laser beam is entirely captured by the receiver and analysis of this unusual transmissometer geometry shows that it is insensitive to the effect of multiple scattering for rain rates up to at least 125 mm/hr (Hutt and Oman, 1991b). The extinction values measured with the transmissometer should be accurate to about 3% and thus can be used to provide a correction for the FSM, enabling it to be used to estimate extinction during rain and snowfall even though it is only designed to measure the extinction in haze and fog. Based on measurements during five rain episodes and fifteen snow episodes we propose the following correction formulas:

$$\alpha_{\text{RAIN}} = (0.73 \pm 0.06)\alpha_{\text{FSM}} \quad [3]$$

$$\alpha_{\text{SNOW}} = (1.31 \pm 0.16)\alpha_{\text{FSM}} \quad [4]$$

In Eqs. 3 and 4, α_{FSM} is the extinction coefficient indicated by the FSM when it is correctly calibrated to measure fog extinction. The coefficients in Eqs. 3 and 4 are determined from the averages of the slopes of scatter plots such as those shown in Figs. 2a and 2b. The error given for each coefficient is the standard deviation of the measured slopes. Obviously the above formulas serve only as a means to estimate extinction during rain or snow given the FSM output. Eqs 3 and 4 are valid for the HSS model VR-301 although similar relations would be expected for other FSM sensors. Nonetheless these formulas are useful because a FSM is much more convenient to use than a transmissometer .

Qualitatively, the fact that the FSM indicates lower extinction than the transmissometer during snowfall can be understood if the scattering phase function of snow is lower in the region 27° to 42° than the phase function of fog or haze. This is quite possible because the intense forward diffraction peak of snowflakes must take scattered energy away from other regions of the phase function. However, this cannot be confirmed because sufficiently accurate measurements of the phase function of snow are not available. In the case of rain, numerical integration of the phase functions of Marshall and Palmer rain droplet size distributions results in a value about 15% lower in the region 27° to 42° compared to the phase function of fog. This implies that a FSM calibrated to measure fog extinction would give a reading about 15% less than the correct value during rainfall. However, our measurements show that the extinction indicated by the FSM is 25% to 55% higher than that measured by the transmissometer during rain. Further analysis is required to understand the behavior of the transmissometer and FSM during rainfall.

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