

# OPTICAL EFFECTS IN FALLING SNOW

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## 1. INTRODUCTION

The effect of falling snow on the propagation of visible and IR radiation and on visibility is of great practical importance. During the past five years DREV has had a program to study propagation effects during snowfall. Measurements of transmission along a 530 m path have shown that transmission is sensitive to the wavelength and to the geometry of the transmissometer (Ref. 1). These results are a consequence of the fact that snowflakes are much larger than the wavelengths of visible or IR light and thus the angular scattering function of snow is dominated by a diffraction peak which tends to scatter light along the forward direction of the light beam. For transmission above 5% a simple model estimates the contribution of scattered light to the measured transmittance (Ref. 2). Besides the optical configuration of the transmissometer, the model requires only an estimate of the mean diameter of the snowflakes.

Measurements of the mass concentration of airborne snow have also been made using a device known as the ASCME (Airborne Snow Concentration Measuring Equipment) or cyclone snow sampler (Ref. 3 and 4). Combined with measurements of transmission or extinction the mass extinction coefficient of the snow may be calculated. This parameter is a measure of the obscuration ability of the snow and depends greatly on the type of snow crystals. The relationship between snow concentration and precipitation rate has also been measured (Ref. 5).

## 2. TRANSMITTANCE MEASUREMENTS

Visible transmittance through falling snow was measured with a transmissometer comprised of two transmitted beams detected by a common receiver. One source is a 10 mW HeNe laser with a wavelength of 0.633  $\mu\text{m}$  collimated to a diameter of 2.8 cm with a half-angle divergence of 0.05 mrad. The second source consists of a 200 W quartz halogen incandescent lamp collimated to a 25 cm diameter beam by a Cassegrain telescope with a half-angle divergence of 3 mrad. The collimators are separated by a distance of about 0.5 m. The common receiver has a f/0.8 Fresnel lens objective and photovoltaic silicon detector with a half-angle field-of-view (FOV) of 20 mrad. The two beams are modulated at different frequencies and are discriminated at the receiver using lock-in amplifiers. The transmission range is 540 m long so that at the receiver, the narrow beam reaches a diameter of about 10 cm and the wide beam, a diameter of about 3 m. The important distinction is that the receiver captures the entire narrow beam but only a fraction of the wide beam. This results in significant differences in the measured transmittances normalized to the clear-air values.

Figure 1 shows a good example of transmission measured with the wide and narrow beam visible transmissometers during a snow storm. A clear air period at the end of the snowfall is used to normalize the two channels. The transmittance measured with the wide beam is consistently higher than that measured for the narrow beam. Similar measurements were made in the 3-5  $\mu\text{m}$  and 8-12  $\mu\text{m}$  bands in the IR with similar results which are discussed in Ref. 1. Figure 2 shows the data of Fig. 1 plotted in terms of extinction coefficient. The apparent extinction coefficient  $\alpha_a$  was derived from the measured transmittance  $T_m$  using Beer's law:  $\alpha_a = \ln T_m / z$  where  $z$  is the propagation distance. The extinction values range from 0 to 10  $\text{km}^{-1}$  which corresponds to a heavy snowfall. Since the measurements were made at practically the same wavelength these results indicate the influence of the beam divergence on the apparent extinction. There is almost a linear relationship between the coefficients with a slope of 0.79. The wide-beam extinction values are less than those of the narrow-beam due to greater scattered contributions to the wide-beam transmittance. This is a result of the fact that the wide-beam illuminates a larger volume of falling snow thus more snowflakes may scatter a contribution to the receiver.

For transmittance values above about 5% the following relationship (Ref. 5) between the measured transmittance  $T_m$ , the unscattered transmittance  $T$  and the transmissometer characteristics was found to be valid:

$$T_m = T \left[ 1 - 2\pi w \ln T \int_0^{\delta'} \int_0^{\phi'} P_d(\delta+\phi) f(\delta) g(\phi) d\delta d\phi \right] . \quad [1]$$

In Eq. 1  $w$  is the single-scattering albedo,  $f(\delta)$  the receiver FOV sensitivity function,  $g(\phi)$  the angular beam intensity function and  $P_d(\theta)$  a function that approximates the forward diffraction peak of the phase function. For  $P_d(\theta)$  the following function was used:

$$P_d(\theta) = \frac{\chi^2}{4\pi} \left[ \frac{2J_1(\chi \sin \theta)}{\chi \sin \theta} \right]^2 \quad \text{for } \sin \theta_1 < 0.610 \frac{\lambda}{r} , \quad [2]$$

where  $J_i$  is the  $i^{\text{th}}$ -order Bessel function of the first kind,  $\chi$  is the particle size parameter  $2\pi r/\lambda$  and  $\theta_1$  is the angle corresponding to the first zero of  $J_1$ . Only the scattering contribution of the diffraction peak is considered in the calculation so  $P_d(\theta)$  is taken to be zero for  $\theta > \theta_1$ . For wavelengths on the order of microns and snowflake effective diameters on the order of millimeters the angular width of the forward scattering peak is on the order of milliradians. Since the beam divergence and receiver FOV of the transmissometers are also on the order of milliradians the integrand in Eq. 1 can have a large value with the result that forward scattering may have a great effect on  $T_m$ . Note that Eq. 1 is transcendental and must be solved iteratively for  $T$ .

The snowflake effective radius used to solve Eq. 1 was 500  $\mu\text{m}$ . This value for  $r$  was determined empirically by calculating values of  $T_m$  for the different transmissometer configurations based on a given value of  $T$  and choosing the value of  $r$  that gave the best agreement with the measurements of  $T_m$  made simultaneously with the wide and narrow beam transmissometers. The estimated mean radius of snow crystals observed during the snowfalls studied was often about 500  $\mu\text{m}$ . The results of these studies are discussed in detail in Ref. 1.

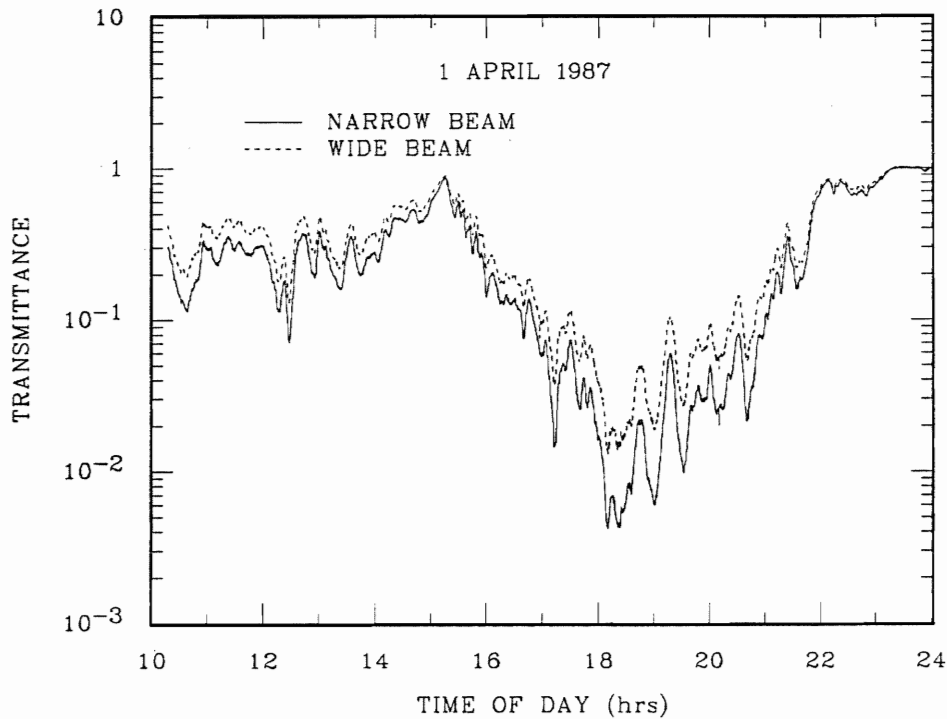


Fig. 1 Visible transmittance as a function of time during snowfall for a narrow (0.05 mrad) beam and a wide (6 mrad) beam. The two light beams were coaxial with a pathlength of 530 m. The transmittance values are normalized to the clear air value.

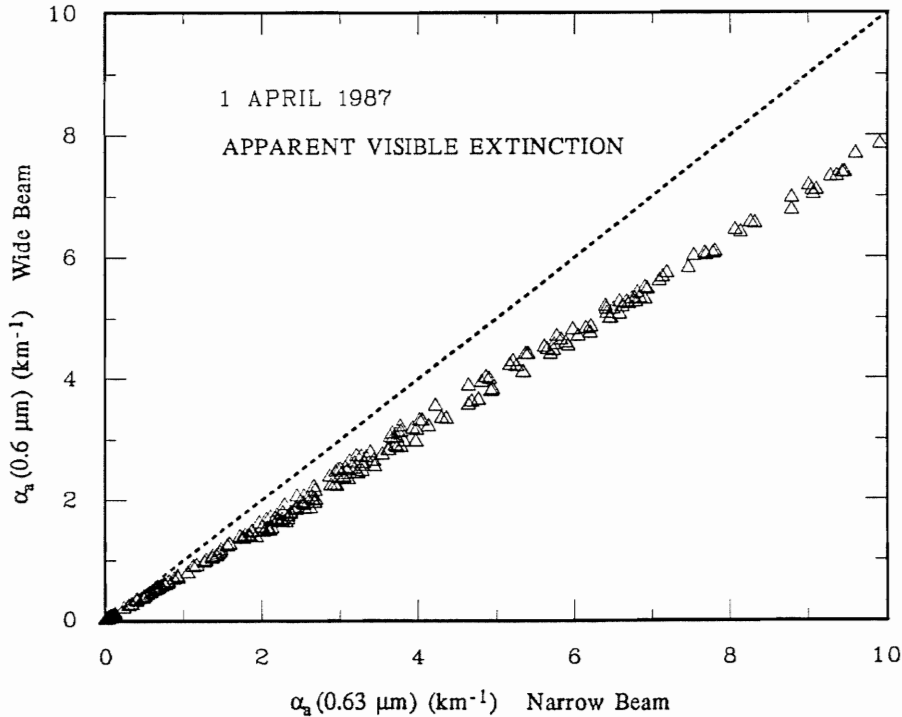


Fig. 2 The transmission data of Fig. 1 was converted to extinction coefficient  $\alpha_a$  using Beer's law ( $\alpha_a = -\ln T_m / z$ ) where  $z$  is the pathlength and  $T_m$  is the measured transmittance. The extinction measured with the wide beam is consistently lower than that of the narrow beam.

### 3. MASS CONCENTRATION AND PRECIPITATION RATE

The mass concentration of airborne snow was measured using a device known as the ASCME (Airborne Snow Concentration Measuring Equipment) or cyclone snow sampler which is fully described in Refs. 3 and 4. Once calibrated, the device measures the mass of snowflakes in a unit volume of air usually specified in units of  $\text{mg}/\text{m}^3$ . The mass extinction coefficient of the snow may be determined by dividing the visible extinction coefficient by the mass concentration. The mass extinction coefficient is a measure of the effectiveness of snow in attenuating visible light. Figure 3 shows a scatter plot of visible extinction versus mass concentration for two different snow episodes. The mass extinction coefficient is the slope of the best fit line through the data. The large aggregates have a much higher extinction for a given mass concentration than do the dendrites. Similar results were observed in the 3-5  $\mu\text{m}$  and 8-12  $\mu\text{m}$  bands.

The mass concentration  $M_c$  has also been correlated with precipitation rate  $R_s$ . An example scatter plot is shown in Fig. 4. In the absence of wind, the mass concentration and precipitation rate are linearly related. In Ref. 5 an analysis of 18 snow episodes showed that  $M_c = 0.36R_s$  on average. For dense types of snow such as ice pellets, columns and rimed crystals the relationship was  $M_c = 0.30R_s$  and for light snow types such as spatial dendrites and aggregates the relationship was  $M_c = 0.47R_s$ .

### 4. SUMMARY

Measurements of visible transmittance through falling snow using a wide beam transmissometer were found to be consistently higher than measurements made using a narrow beam. This is a result of forward scattering of the light by the snowflakes due to diffraction. For transmittance values greater than about 5% Eq. 1 was found to be a good description of the effect of forward scattering on the measured transmittance.

Measurements of airborne snow mass concentration enabled the mass extinction coefficient to be determined as well as the proportionality between the mass concentration and precipitation rate. Both of these quantities depend greatly on the type of snow crystals present.

### 5. REFERENCES

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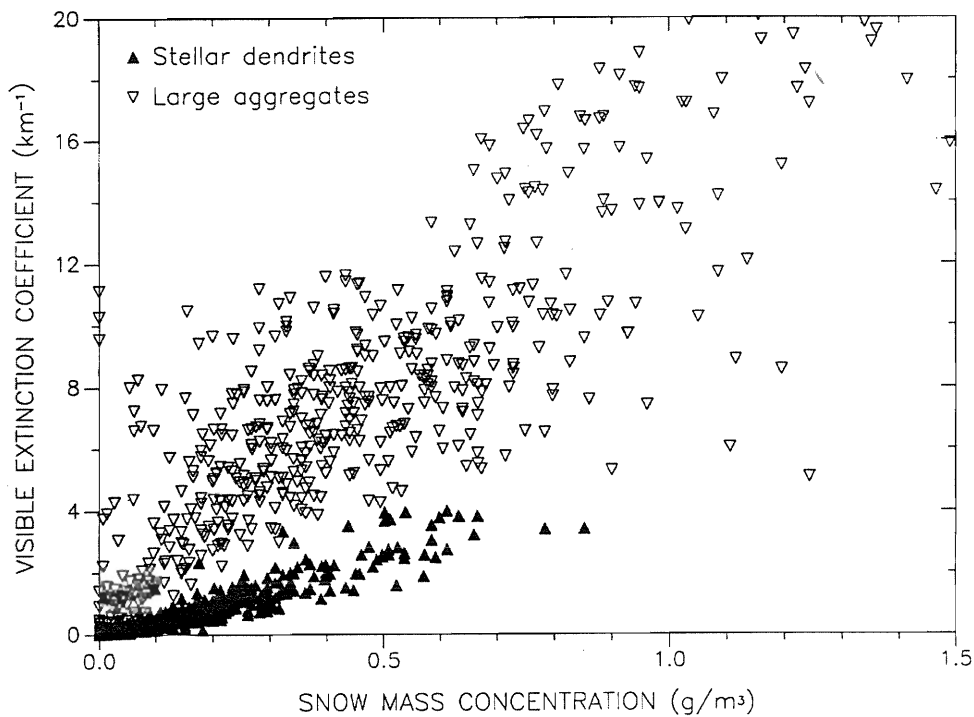


Fig. 3 The visible extinction coefficient versus airborne snow concentration for two different types of snow. For a given mass concentration the large aggregates create greater extinction (and lower visibility) than the dendrites which are a more compact crystal type. The linear relationship is also evident during conditions of high wind.

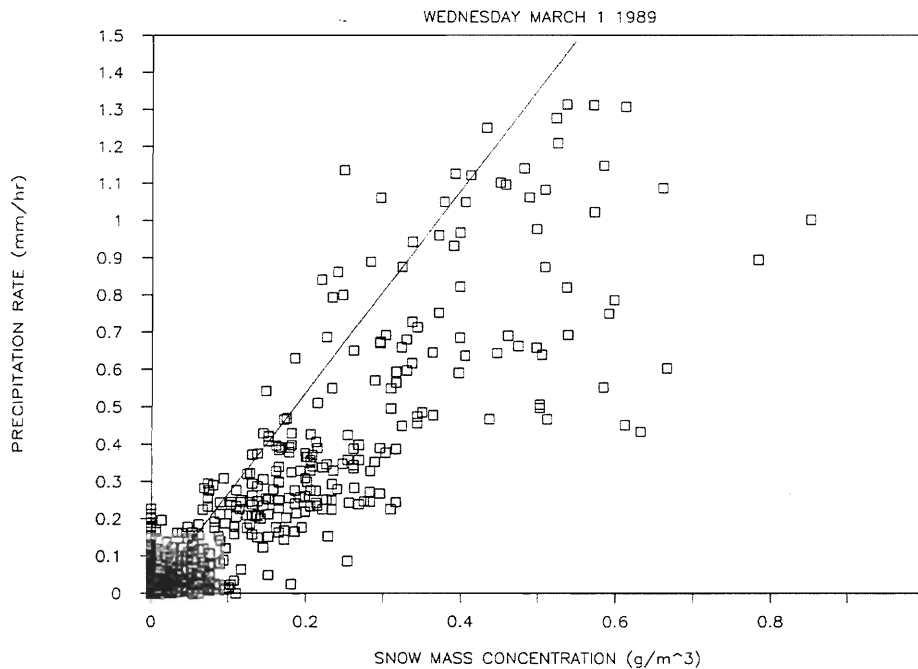


Fig. 4 Precipitation rate plotted as a function of airborne snow concentration. The solid line indicates the average slope measured for 18 different snow events (Ref. 4). The slope depends on the type of snow crystals. During conditions of high winds with blowing snow there is little correlation between precipitation rate and snow concentration.