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Extinction coefficient measurement in falling snow with a forward scatter meter

Gary Koh

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A forward scatter meter designed to measure the visible extinction coefficient in fog has been tested in falling snow. The comparison of the extinction coefficients measured with a forward scatter meter and a transmissometer indicates that a forward scatter meter can be used to measure extinction coefficient in falling snow. The different calibrations required for snow and fog are partially explained by examining the effect of particle size on the angular distribution of scattered light.

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PREFACE

This report was prepared by Gary Koh, Research Physical Scientist, Geophysical Sciences Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory. Funding for this research was provided by DA Project 4A762730AT42, Design, Construction and Operations Technology for Cold Regions; Task Area FS, Fire Support; Work Unit 007, Battlefield Obscuration during Fog Concurrent with Snow.

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Gary Koh

INTRODUCTION

The military often requires detection of visible and infrared radiation emitted or reflected by distant targets. This involves the transfer of optical energy from one point in space to another. Therefore, the performance of electro-optical systems (systems employing sensors to convert optical energy into electrical signals) is in many cases limited by the optical properties of the atmosphere. To evaluate the performance of electro-optical systems under field conditions, a primary parameter of interest is the extinction coefficient. This is a measure of the attenuation of radiation as it propagates through the atmosphere.

Transmission measurements are frequently used to determine the extinction coefficient. A calibrated radiation source and a receiver are placed a known distance apart and the extinction along the transmission path is determined using the following equation:

$$B_{ext} = -\ln(T)/L \tag{1}$$

where B_{ext} is the extinction coefficient, T is the transmittance and L is the transmission path length. The relatively long path length required for transmission measurements makes this technique impractical for some applications. Light scattering measurements may also be used to determine the extinction coefficient. This approach is preferable over transmission measurement, particularly when space, weight, power and cost limitations exist. Instruments to measure light scattering can be miniaturized so that an entire instrument can be mounted on a single pedestal, assuring ease of handling and eliminating the need for field alignment of the optics.

A field test was conducted to investigate the feasibility of the light scattering technique for measuring the extinction coefficient in falling snow. This was accomplished by comparing simultaneous light scattering and transmission measurements. This paper presents a brief theory describing the light scattering approach. Experimental results are then presented to show that the light scattering technique can be used to measure the extinction coefficient in falling snow.

BACKGROUND

Measurement of the extinction coefficient by light scattering is based on the principle that the intensity of scattered light at certain angles is linearly related to the extinction coefficient. Mathematically, this relationship is expressed as

$$\frac{B_{ext}}{\int_{0}^{2\pi}\int_{\theta_1}^{\theta_2} B(\theta)\sin\theta d\theta d\phi} = \text{constant.} \tag{2}$$

The angular scattering coefficient, $B(\theta)$, is dependent on the chemical composition of the particles, their size and shape, and the wavelength of the incident beam. θ is defined such that 0° and 180° represent the forward and backward scatter angles respectively. Since detectors to measure the scattered light possess finite acceptance angles, $B(\theta)$ is measured over some range θ_1 to θ_2. If absorption is negligible, integration of $B(\theta)$ over all scattering angles yields the extinction coefficient, B_{ext}. The optimal range of angles for measuring the scattered light can be determined if the intensity of scattered light as a function of the scattering angle θ is known. The mathematical difficulties involved in solving light scattering by irregularly shaped particles limit the theoretical calculations of the optimal scattering angles to particles with a high degree of symmetry (i.e., spheres and spheroids).

Winstanely and Adams (1975) used the Mie theory to determine the angular light scattering properties for a broad distribution of fog droplets. These calculations indicated that the intensity of light scattering by fog in the range of 30-40° is proportional to the extinction coefficient. This theoretical finding has been supported by field tests of light scattering instruments against standard transmissometers. Forward scatter meters, operating on the basis of this theory, are commercially available to measure the extinction coefficient in fog.

The angular light scattering properties of irregularly shaped particles such as snow are not well known. Theoretical calculations to determine the optimal range of scattering angles to achieve a linear relationship between the intensity of scattered light and the extinction coefficient in falling snow are not possible. Empirical studies are therefore required.

Muench and Brown (1977) used a forward scatter meter to measure the integrated intensity of light scattered by snow particles at angles of 20-50° to determine extinction in falling snow. Comparing their results with a transmissometer, they concluded that the forward scatter meter measured the extinction coefficient as accurately in snow as in fog using the same calibration. This is somewhat surprising when the differences in size and shape between snow and fog particles are considered. Mill and Shettle (1983) also found a good relationship between the extinction coefficient measured in falling snow with a forward scatter meter and a transmissometer, but did not describe the calibration technique. The present work is an extension of the above-mentioned efforts, which may provide more insight into the use of light scattering techniques to measure the extinction coefficient in falling snow.

FIELD MEASUREMENT

An HSS Forward Scatter Meter (FSM) designed to integrate all the light scattered between 27 and 42° is shown in Figure 1. The sample volume, defined by the intersection of the transmitted beam and the field of view of the receiver, is approximately 400 cm^3. An infrared emitting diode with peak emission at 0.88 μm is the radiation source, and a silicon hybrid detector-amplifier records the intensity of scattered light. The real and imaginary components of the complex refractive index of ice at 0.88 μm are 1.33 and 3.92×10^{-7} respectively (Warren 1984), which allows absorption to be ignored so that the scattering coefficient is equivalent to the extinction coefficient. Individual snow particles scatter light to the receiver at random intervals, and these pulses are integrated over 30 seconds to provide an analog voltage output. The output voltage is converted to an extinction coefficient based on a calibration provided by the manufacturer.

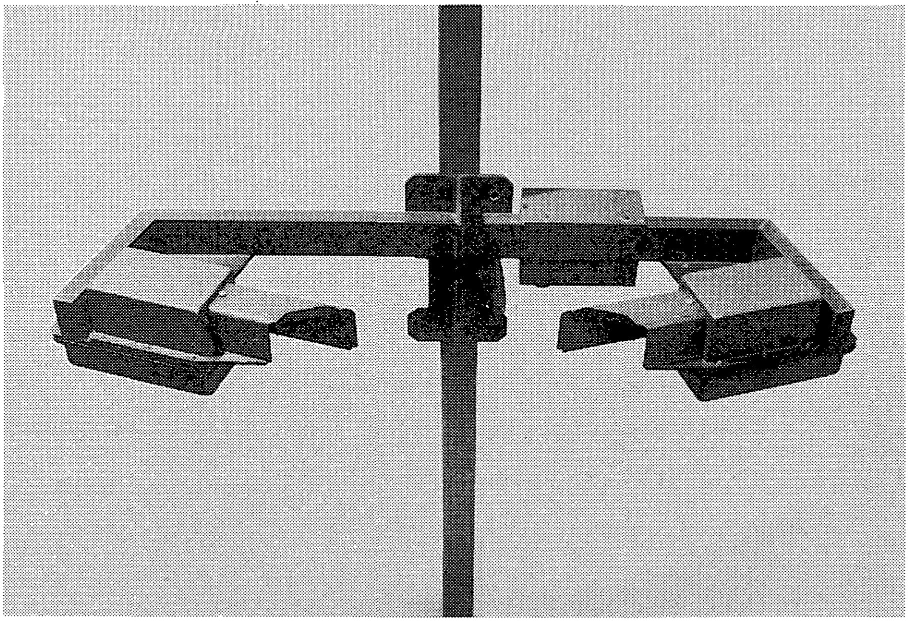


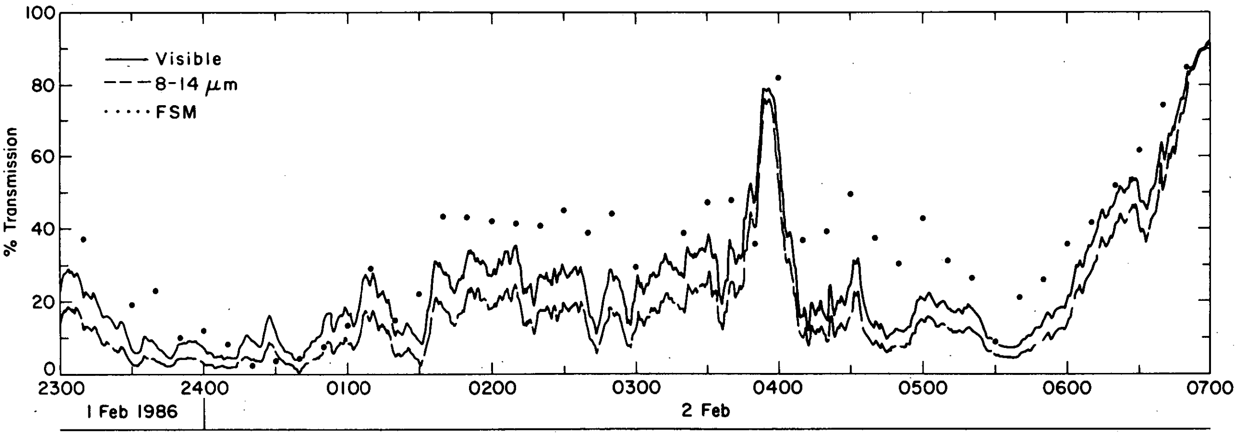
Figure 1. Forward scatter meter designed to measure angular light scattering from 27 to 42°.

Concurrent with the FSM measurements, transmission measurements were made over a 400-m path in the visible and infrared (8-14 μm) wavelengths. The transmission system included a transmitter van containing a blackbody source (1000°C) and a receiver van housing detectors and a computer-controlled data acquisition system. Both the transmitter and receiver systems were equipped with 0.9-m optics. The field of view of the receiver was 2.5 mrad. The extinction coefficients measured by the two techniques are compared for two snowstorms that occurred on 1-2 and 4-5 February 1986 in southern Maine.

The results from the snowstorms are shown in Figure 2. The measured transmittance in the visible spectrum is represented by the continuous line, and the dashed line represents the transmittance in the infrared region. The slightly higher transmittance in the visible region is in part due to the increase in forward scattering as the ratio of particle size to wavelength dimension increases. A portion of this forward scattered light is measured by the receiver.

To compare the transmittance measurements with the FSM observations, eq 1 was expressed as

$$T = \exp\,(-B_{ext} \cdot L)$$



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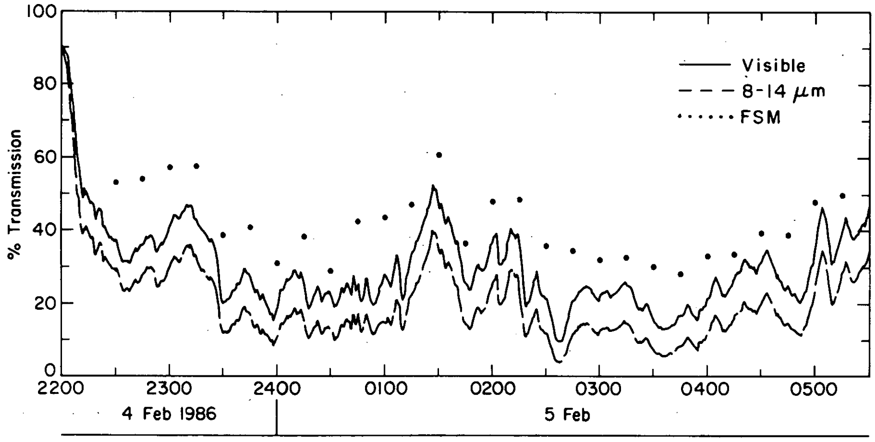

b. 4-5 February 1986.

Figure 2. Comparison of the transmission results obtained with a transmissometer and a forward scatter meter. Circles represent the transmission calculated from forward scatter meter data based on calibration for fog. This shows that calibration for fog underpredicts extinction in falling snow.

to convert the extinction coefficient measured by FSM to transmittance. The extinction coefficient measured by FSM using the calibration for fog given by the manufacturer is

$$B_{ext} = 10\ (V - 0.01)$$

where V is the output voltage from the FSM. The circles in Figure 2 represent the calculated transmittance. The figure illustrates that the calibration for fog underpredicts extinction in falling snow. A more appropriate calibration for falling snow based on these observations is

$$B_{ext} = 18\ (V - 0.01)\ .$$

This relationship was determined by correlating the data from the transmissometer and FSM. Although changes in snow crystal type will affect the calibration, no attempt was made to segregate the data according to the snow crystal type.

DISCUSSION AND CONCLUSIONS

The preliminary results confirm previous findings that a light scattering technique can be used to determine the extinction coefficient in falling snow. The calibration for fog is not appropriate in snow, contrary to the findings of Muench and Brown (1977), underpredicting the extinction coefficient in falling snow. This is probably due to the differences in the size and shape between snow and fog particles. The effect of particle shape on the properties of scattered light is not known; however, it appears that the observed results can be partially explained by examining the effect of particle size on the angular distribution of scattered light.

Phase function, $\rho(\theta)$, which describes the intensity of scattered light as a function of scattering angle θ, is expressed as

$$\rho(\theta) = \frac{1}{C_{sca}} \frac{dC_{sca}}{d\Omega} \qquad (3)$$

where C_{sca} is the scattering cross section and $dC_{sca}/d\Omega$, the differential scattering cross section, is the amount of light scattered into a unit solid angle about a given direction. Equation 3 is normalized so that

$$\int_{4\pi} \rho(\theta)\, d\Omega = 1.$$

The phase functions for light (0.88 μm) incident on 10-μm-radius and 100-μm-radius ice spheres calculated using a computer program for Mie scattering, AGAUS 82 (Miller 1983), are shown in Figure 3. As the particle-size-to-wavelength ratio increases, scattering is dominated by a sharp diffraction lobe in the near-forward direction. This forward scattering occurs at the expense of lateral and back scatter angles. This is evident in Figure 3 where the phase function of the 100-μm-radius ice sphere is greater than that of the 10-μm-radius ice sphere at the near-forward scattering angle, but it is less at the lateral and backscatter angles.

The amount of light scattered between angles θ_1 and θ_2 is expressed as

$$C_{sca} \int_0^{2\pi} \int_{\theta_1}^{\theta_2} \rho(\theta) \sin\theta\, d\theta\, d\phi.$$

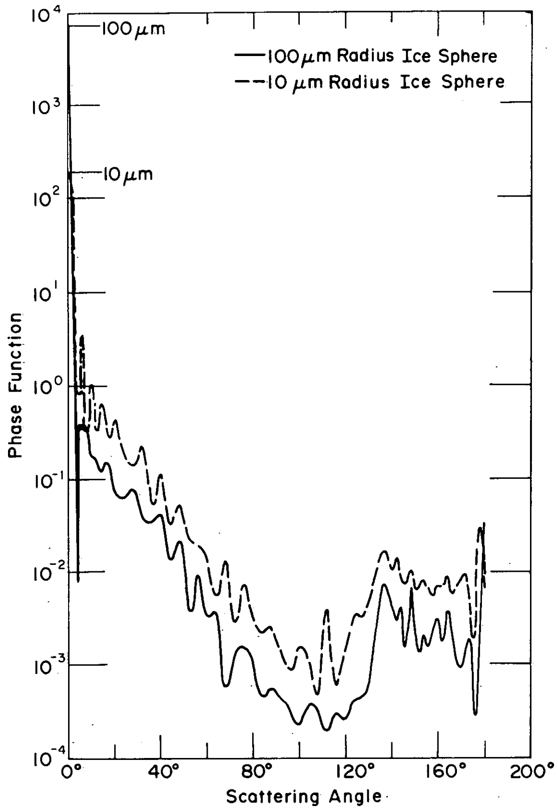

Figure 3. Phase functions for 10- and 100-μm-radius ice spheres at 0.88-μm wavelength. Note the larger peak in the near-forward direction for the 100-μm ice sphere.

The ratio of the scattering cross section to the amount of light scattered between θ_1 and θ_2 is:

$$\frac{C_{sca}}{C_{sca} \int_0^{2\pi} \int_{\theta_1}^{\theta_2} \rho(\theta)\sin\theta d\theta d\phi} .$$

If θ_1 and θ_2 represent 27 and 42°, respectively, the following relationship can be seen from Figure 3:

$$\frac{C_{sca}\ (10\mu m)}{C_{sca}\ (10\mu m) \int_0^{2\pi} \int_{\theta_1}^{\theta_2} \rho(\theta)\sin\theta d\theta d\phi} < \frac{C_{sca}\ (100\mu m)}{C_{sca}\ (100\mu m) \int_0^{2\pi} \int_{\theta_1}^{\theta_2} \rho(\theta)\sin\theta d\theta d\phi} . \quad (4)$$

The extinction coefficient is the sum of the scattering cross section per unit volume; therefore eq 4 can be changed to

$$\frac{B_{ext}\ (10\mu m)}{\int_0^{2\pi}\int_{\theta_1}^{\theta_2} B(\theta)\sin\theta d\theta d\phi} < \frac{B_{ext}\ (100\mu m)}{\int_0^{2\pi}\int_{\theta_1}^{\theta_2} B(\theta)\sin\theta d\theta d\phi} \quad . \tag{5}$$

This indicates that the ratio of the extinction coefficient to the angular scattering coefficient measured between 27 and 42° is less for the smaller particle.

The light scattering properties of snow cannot be represented by ice spheres. However, snow particles are much larger than fog droplets, and therefore the snow phase function will be greater than the fog phase function in the near-forward direction. Assuming that the snow phase function does not have a secondary maximum between 27 and 42°, one can use the same argument demonstrated for the ice spheres to show that

$$\frac{B_{ext}\ (\text{fog})}{\int_0^{2\pi}\int_{\theta_1}^{\theta_2} B(\theta)\sin\theta d\theta d\phi} < \frac{B_{ext}\ (\text{snow})}{\int_0^{2\pi}\int_{\theta_1}^{\theta_2} B(\theta)\sin\theta d\theta d\phi} \quad . \tag{6}$$

This relationship offers a possible explanation for the experimental results where the FSM calibrated for operation in fog underpredicts the extinction coefficient of falling snow.

The feasibility of using a forward scatter meter to measure the extinction coefficient in falling snow has been demonstrated. The different calibrations required for snow and fog have been partially explained by examining the phase functions for spherical particles of different sizes. To conduct a more quantitative analysis, the detailed measurements of snow phase function as a function of snow size and shape are required.

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