MEASUREMENT OF BLOWING SNOW PROPERTIES
USING OPTICAL ATTENUATION DEVICES

by

J.W. Pomeroy, T. Brown, D.H. Male

Division of Hydrology
University of Saskatchewan
Saskatoon, Saskatchewan
Canada

presented at

SNOW PROPERTY MEASUREMENTS WORKSHOP
Lake Louise, Alberta
1-3 April, 1985

TECHNICAL MEMORANDUM 140

Compiled By
P.R. Kry
NRCC 27594
SNOW PROPERTY MEASUREMENT WORKSHOP

April 1-3, 1985
Chateau Lake Louise
Alberta, Canada

Sponsored by
Snow and Ice Subcommittee
Associate Committee on Geotechnical Research

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TECHNICAL MEMORANDUM 140

April 1987
NRCC 27594
INTRODUCTION

Blowing or drifting snow can occur frequently over the winter in regions where sufficient snowcover and open terrain permit entrainment of the snowpack by the wind. In the North American prairies, the Arctic, Siberia and Antarctica, blowing snow causes widespread relocation of precipitation. Wind transport also enhances the rate of sublimation from the snowpack (Schmidt, 1982). Relocation of and sublimation from snow during wind transport make the phenomenon of importance to hydrology, agriculture, transportation, plant ecology and engineering design. However, there has been limited development of simple devices capable of continuous, rapid monitoring of blowing snow. This is due in part to the variability of blowing snow transport rates with height and windspeed and in part to the severe meteorological conditions under which blowing snow occurs.

The blowing snow measurement system described here simultaneously measures two optical indicators of blowing snow; the proportion of light extinguished while passing through a snow-air flux and the number of pulses caused by blowing snow particles interrupting a narrow beam of light. Using geometrical optics theory, the drifting mass density (drift density) and mean particle size can be determined from these two measurements. The system is relatively inexpensive and suitable for meteorological studies or continuous monitoring.

Properties of Blowing Snow

Blowing snow refers to frozen precipitation mechanically removed from the surface snowpack by the action of wind. It occurs in two modes of transport: saltation and suspension. Saltation involves regular contact and momentum exchange between the particle and the snowpack surface. Snow particles are ejected into the saltating layer by impact from other particles, aerodynamic lift and magnus effect forces (Kobayashi, 1972; Owen, 1964; White, 1982). The particles travel curved trajectories generally less than 0.1 m in height. When
vertical turbulent diffusion is sufficient to overcome gravitational and drag effects, the snow particle enters suspension. The suspended layer of snow transport can reach from 0.1 to over 300 m in height (Budd et al., 1965).

The drift density of snow increases logarithmically with height. A maximum of near 500 g/m$^3$ has been recorded in the saltation layer (Fig. 1). At a 2 m height, values from 0.1 to 10 g/m$^3$ are common. Transport rates up to 1 kg/sec through an area 1 m wide and 300 m high have been calculated for Antarctica (Budd et al., 1965).

Budd (1965) found that for blowing snow without snowfall, particle diameter distributions match a two-parameter gamma function distribution. The gamma frequency distribution for particle diameters, $P_d$, as given by Budd is;

$$f(P_d) = \frac{P_d^{(\alpha-1)}}{\beta^{\alpha} \Gamma(\alpha)} e^{-P_d/\beta} ,$$

where $\alpha$ and $\beta$ are the shape and scale parameters and $\Gamma(\alpha)$ is the gamma function (Haan, 1977). Note that $\beta = \bar{P_d}/\alpha$, where $\bar{P_d}$ is the mean particle diameter. This allows the description of the relative number of particles for any diameter class using two variables; the mean diameter and $\alpha$ from the gamma function. Schmidt (1981, 1984) has confirmed the validity of the gamma distribution for blowing snow and has shown that concurrent snowfall quickly metamorphoses into the expected particle diameter distribution during saltation. Schmidt (1982) has also found that blowing-snow particles are somewhat ellipsoid although they show no preferred orientation while suspended.

**EXTINCTION OF TRANSMITTED LIGHT BY BLOWING SNOW PARTICLES**

**Single Particle Extinction**

The effect of a single particle in extinguishing a narrow light beam is the basis for snow particle counters or detectors. These instruments are designed to measure the number and often size of particles by recording pulsed drops in
Figure 1. Drift density as a function of wind velocity for a range of heights (z) (after Budd et al., 1965).
beam transmittance. The pulses are caused by a moving particle interrupting the light beam. Geometrical optics approximations can accurately describe the effects of single and multiple particle light scattering and absorption for translucent particles in the size range of blowing snow particles (Ungut, et al, 1981). Geometrical optics theory is therefore used in these calculations.

For a single blowing snow particle, interrupting a uniform beam of parallel light, the transmittance $T$ is found from the expression (Zuev, 1970);

$$T = T_0 - \left(\frac{\pi P_r^2}{\pi B_r^2}\right) E_c$$  \hspace{1cm} (2)

$T_0$ is the transmittance before the beam is interrupted, $P_r$ is the radius of a circle of equivalent cross-sectional area to the particle, $B_r$ is the cross-sectional radius of the light beam and $E_c$ is the corrected extinction efficiency of the particle-light beam arrangement. Since blowing snow particles have no preferred orientation (Schmidt, 1984), $P_r$ can be considered the effective particle radius when large numbers of particles are examined.

For a specific light beam geometry and electromagnetic wavelength, the corrected extinction efficiency of a particle is the ratio of the light flux scattered and absorbed to the flux geometrically incident on the particle. $E_c$ is conceived as having four components; the extinction efficiency $E$, the diffraction correction $\Delta E_0$, the external reflectance correction $\Delta E_1$ and the refraction correction $\Delta E_2$. Where;

$$E_c = E - (\Delta E_0 + \Delta E_1 + \Delta E_2)$$  \hspace{1cm} (3)

For ice spheres from 20 to 500 $\mu$m diameter in visible to near-infrared light $E = 2.0$ (Seagraves, 1984). The extinction efficiency refers to light extinguished by both interception and diffraction by the particle (Van de Hulst, 1957).

The diffraction correction, $\Delta E_0$, is the reduction in extinction due to detection of diffracted light by the sensor. It can be significant for ice spheres in the sizes and wavelengths of interest and is found from the expression (Hodkinson and Greenleaves, 1963; corrections - Seagraves, 1984);
\[ \Delta E_0 = 1 - \left( J_0^2 \left( \frac{2\pi P_r}{\lambda} \sin \theta \right) \right) + J_1^2 \left( \frac{2\pi P_r}{\lambda} \sin \theta \right) \]  

where \( J_0 \) and \( J_1 \) are zeroth and first order Bessel functions of the first kind respectively, \( \lambda \) is the electromagnetic wavelength and \( \theta \) is the distance between the particle and beam sensor or detector. For parallel light, the beam radius is assumed equal to the active radius of the detector. Thus, the amount of light diffracted forward into the beam detector is a function of particle radius, light wavelength and the angle of the cone formed by the particle center and the detector perimeter.

The external reflectance correction, \( \Delta E_1 \), is the reduction in the extinction efficiency due to detection of externally reflected light. It is a function of the detector-particle geometry and the complex index of refraction, \( m \), for the particles. For ice, \( m = 1.302 \) (Liou, 1981). According to Hodkinson and Greenleaves (1963), \( \Delta E_1 \) reaches a maximum of 0.01 for possible detector-blowing snow particle geometries. Variation in \( m \) due to various light wavelengths or ice contamination has little effect on \( \Delta E_1 \) in this range. For most snow particle-detector geometries, \( \Delta E_1 \) is much less than 0.01. It will be ignored in this analysis.

The refraction correction, \( \Delta E_2 \), is the reduction in extinction due to collection of light transmitted from the source then refracted by the particle. It is a function of the particle-detector geometry and the complex index of refraction of the particle. Though often ignored in the analysis of light transmission through air-snow mixtures, \( \Delta E_2 \) can be as high as 0.45 for ice spheres. \( \Delta E_2 \) is calculated following Hodkinson and Greenleaves (1963);

\[ \Delta E_2 = 4 \left( \frac{-m}{m^2 - 1} \right)^4 \int_0^{\theta \left( \frac{m \cos \theta}{2} - 1 \right)} \left( \frac{m \cos \theta}{2} \right)^3 \left( 1 + \sec^4 \theta / 2 \right) \sin \theta \left( \cos \theta / 2 \right) \left( m^2 + 1 - 2m \cos \theta / 2 \right) d \theta , \]  

where \( \theta = \arcsin \left( \frac{B_r}{\theta} \right) \).
If the incident beam is not parallel, the corrected extinction efficiency will drop further, due to a change in the angle of light incident on the particle and the detector. $\Delta E_0$ and $\Delta E_2$ increase by an amount which cannot be readily determined. Approximately parallel beams are therefore necessary for precise theoretical calibrations of particle detectors and extinction meters.

A consequence of the dependence of $\Delta E_0$ and $\Delta E_2$ on $\arcsin(B_r/\lambda)$ is that for a given particle, the corrected extinction efficiency varies, dependent on the particle location along the light beam. As well, a single particle whose path does not entirely intercept the beam will cause a drop in transmittance corresponding to the intercepted area of the particle, not its true area. These two effects make theoretical calibration of a device which determines ice particle size from single-particle light extinction unreliable. The effects are enhanced when the light is not collimated and represent a major drawback of particle counters.

**Multiple Particle Extinction**

The effect of an ensemble of particles in extinguishing light transmittance is the basis for extinction or attenuation meters. These devices are designed to measure the drift density of a snow flux by recording the mean drop in light beam transmittance caused by interception with the particles. Geometrical optics are used to calculate this.

Following Winchester and Gimmestad (1983), for a number of uniformly dispersed blowing snow particles with extinction coefficient $\sigma_\lambda$ m$^{-1}$, located in an optical path of length $L$ m, the transmittance, $T$ for wavelength $\lambda$ m is:

$$T = \exp(-\sigma_\lambda \cdot L).$$

The extinction coefficient is a property independent of the length of light transmission, but is a function of the wavelength and particle-detector geometries. Seagraves (1984) notes that for the simplified case of a mono-sized
dispersion of snow particles in the atmosphere;

\[ \sigma_{\lambda} = N \pi \bar{P}_r^2 \bar{E}_c \]

(7)

where \( N(\#/m^3) \) is the number of particles per unit volume of atmosphere, \( P_r \) is the snow particle radius and \( \bar{E}_c \) is the mean corrected extinction efficiency.

Evaluation of \( \bar{E}_c \) is similar to \( E_c \) for the single particle extinction case except that the diffraction and refraction corrections are averaged over the beam length. Thus,

\[ \bar{E}_c = E - \frac{1}{L} \int_0^L (\Delta E_0 + \Delta E_2) dl \]

(8)

\( \Delta E_0 \) and \( \Delta E_2 \) are calculated using Eqs. 4 and 5 respectively.

Equation 7 can be expanded to fit snow particle dispersions of various sizes. For some particle radius distribution;

\[ \sigma_{\lambda} = \int_{P_r} n(P_r) \bar{E}_c \pi P_r^2 dP_r \]

(9)

where \( \int_{P_r} dP_r \) is the integral of \( P_r \) over the expected particle radius range, and \( n(P_r) \) is the number of particles of radius \( P_r \) per unit volume. Note that \( \bar{E}_c \) is a function of the particle radius.

The gamma distribution is the preferred frequency function for blowing snow particle sizes (Budd, 1966; Schmidt, 1984). \( n(P_r) \) can be related to the relative frequency of a particle radius, \( f(P_r) \), by;

\[ n(P_r) = N \cdot f(P_r) \]

(10)

Particle radius frequency is found using the two-parameter gamma distribution of the form

\[ f(P_r) = \frac{P_r^{(\alpha-1)}}{\beta^\alpha \Gamma(\alpha)} \cdot e^{-P_r/\beta} \]

(11)

where \( \alpha \) is the shape parameter and \( \beta \) is the scale parameter (Haan, 1977). Note
that $\beta = \overline{P_r}/\alpha$, where $\overline{P_r}$ is the mean particle radius. Substituting the gamma distribution into Eq. 9 yields:

$$\sigma_\lambda = \frac{N \pi}{\beta \alpha \Gamma (\alpha)} \overline{E_c} \int \frac{P_r^{\alpha+1} e^{-P_r/\beta}}{P_r} \, dP_r . \quad (12)$$

To find the extinction coefficient in terms of the drift density $C$ kg/m$^3$, the drift density must first be defined in terms of individual ice particle volumes and densities. For some distribution of $P_r$:

$$C = \int P_r n(P_r) \frac{4\pi \rho_i P_r^3}{3} \, dP_r , \quad (13)$$

where $\rho_i$ kg/m$^3$ is the density of ice. Substituting the gamma distribution yields,

$$C = \frac{4\pi \rho_i}{3 \beta \alpha \Gamma (\alpha)} \int \frac{P_r^{\alpha+2} e^{-P_r/\beta}}{P_r} \, dP_r . \quad (14)$$

Combining Eqs. 12 and 14 makes it possible to determine $\sigma_\lambda$ from the variables $L$, $\overline{P_r}$, $\alpha$ and $C$. Thus,

$$\sigma_\lambda = \frac{3C \int \frac{\overline{E_c} P_r^{\alpha+1} e^{-P_r/\beta}}{P_r} \, dP_r}{4 \rho_i \int \frac{P_r^{\alpha+2} e^{-P_r/\beta}}{P_r} \, dP_r} . \quad (15)$$

Equations 8 and 15 can be extremely useful in the development of calibration curves for blowing snow detection using light extinction meters. Similar geometrical optics equations used with laser transmissometer outputs have accurately predicted precipitation rate and particle size for falling snow (Seagraves, 1984).

**OPTICAL MEASUREMENT OF BLOWING SNOW**

**Extinction Meters**

Orlov (1961) described a gauge which responds to light extinction as snow blows between a collimated lamp and a photocell. Landon-Smith and Woodberry
(1965) describe in detail a similar system using a cadmium sulfide photoconductor detector and a broad-band source. To exclude the effects of ambient light the source and detector are housed in a black rectangular tube whose openings are exposed to the flux of blowing snow. The gauge was empirically calibrated against an anemometer and a mechanical snow trap. The gauge design resulted in incomplete exclusion of ambient light. This factor along with the constantly changing sensitivity of the system necessitated frequent reference measurements. For a reference measurement, incoming snow was blocked and the gauge output signal recorded. Landon-Smith and Woodberry report a systematic error caused by the non-linear relationship between gauge output and drift density. The output was averaged over 30 min. and the drift density calculated from the averaged signal. This error could have been reduced by shorter averaging times. The investigators recognize but make no attempt to correct errors in transmittance caused by varying particle size distribution parameters.

Wishart (1965) improved the electronics and mechanics of the Landon-Smith and Woodberry design. In his instrument light baffles and yellow light limiting filters reduce the effects of ambient light fluctuations. A reference photoconductor monitors fluctuations in the source intensity and photoconductor sensitivity. However significant signal drift still occurred and the tubing and baffles used to protect the detector from ambient light interfered with the snow-air flux.

Sommerfeld and Businger (1965) describe an extinction meter similar in design to Wishart's except that light baffles are not used. The authors did not report how ambient light effects were accounted for. The device was empirically calibrated in a cold room. The authors found its useful range limited due to low sensitivity and inadequate strength in construction of the support arms. At windspeeds below 10 m/s drift densities were too low to elicit an
adequate signal from the device. Above 15 m/s vibrations from the support arms introduced signal noise and the snow shielding on the detector housing became inadequate. Advantages of this instrument over other gauges are its rapid response time, large sampling area and reduced interference with the air stream (Hollung et al., 1966).

**Particle Counters**

Hollung et al. (1966) describe a gauge designed to detect individual blowing snow particles. This gauge employs two rectangular light beams separated by 1 mm and of cross-sectional dimensions 0.62 x 2.75 mm. The beams are arranged so that a snow particle crosses both beams perpendicular to the long dimension. The interruption of the beams by a particle causes a pulse in each beam's output. The velocity of the particle is calculated from the elapsed time between the particle's edge contacting the first beam and the second beam. Hollung et al. estimated the particle diameter from the elapsed time as the particle travels from the midpoint between the two beams to the point where its edge leaves the second beam. The estimate of diameter is dependent upon the accuracy of the velocity estimate.

Two fast response photo-duo-diodes were used as detectors, with a broadband lamp as the single source. Two rectangular windows in front of the photodiodes limit the area of light projected on the detectors. The length of the beams exposed to the snow flux is 25 mm. The structure supporting the source and detectors was designed for stability and interferes somewhat with the snow-air flux. The two photodiode signals are presented in opposite polarities, this allows electronic identification of the signal pulses. The signals are amplified twice, increasing voltage by a factor of 10,000. Signal distortion is not reported below particle counts of 60,000 per second. Signals from the device were recorded on magnetic tape and the transmittance record examined on a storage oscilloscope. Data on the extinction pulses were collected manually.
from the oscillogram.

A problem with this system is that since snow particles are not perfect spheres, a random cross-section of a particle may not be representative of its volume. The pulse shapes shown on the oscillograms vary considerably and suggest that determination of the particle edge from the pulse edge is a subjective procedure. Diffraction effects by the particle edges are not discussed by the authors. Geometrical optics theory states that ideally, as much light diffracted by the edges of a small particle as is incident on the particle. The authors state that for the same size obstruction, the pulse size dropped as the light beams were interrupted further from the detectors. This indicates that non-parallel light was used which would distort the shadow of a particle with increasing distance from the detector. It is felt that these factors put in question the claims that this device does not require physical calibration.

Schmidt (1977) describes the development of a particle counter based on the design by Hollung et al. The source-detector geometry is almost identical to the Hollung et al. model. However the lamp and phototransister housings are redesigned to maximize stability and minimize interference with the snow-air flux. Amplifier design was improved, with low-impedence current to voltage converters permitting more rapid signal response times. Noise common to both phototransistors was filtered at this stage. The amplified signal is then sent to an analog tape recording unit or strip chart recorder. Schmidt (1984) describes a more recent analog to digital converter which feeds digital signals into a commercial microprocessor. The microprocessor can then dump directly into a desktop computer, which controls the system.

Schmidt (1977) altered the signal analysis procedure from that of Hollung et al. (1966). Particle velocity estimates are made using the time interval between the signal pulse from the first and second phototransister. An electronic time interval counter is triggered at a set voltage. When this voltage
threshold is crossed by a signal pulse the timer is triggered. A more recent version utilizes a signal peak detector (Schmidt, 1984) to measure peak amplitude. This technique is dependent on the pulse size and shapes being identical. Particle size estimates are made based on signal pulse amplitude. Schmidt found for his detector that a simple linear relationship between the square of particle radius and pulse amplitude is unworkable. Non-parallel light and non-uniform sensitivity across the detector areas are cited as reasons for this. The variation of extinction efficiency corrections with the distance from particle to detector, noted earlier in this paper, must also be a component of the problem. Schmidt (1984) notes that even if the light beams were perfectly parallel, only a part of some particles will cross the beam. This results in underestimated mean particle sizes and skewed particle size distributions calculated from such data. Schmidt therefore does not attempt an exact calibration of the pulse amplitude to particle sizes.

The calibration Schmidt develops is empirical and complex. From tests with lead shot, sieved sand and sieved snow the author finds a correspondence between particle size and the largest signal pulse it can generate. This pulse occurs when the particle path bisects the beam cross-sections and crosses the beams adjacent to the detector windows. Therefore only a small percentage of pulses (less than 1%) will be significantly related to the snow particle size (Schmidt, 1977). Pulses are classified based on their maximum amplitude. The number of particles in a diameter class is hypothesized to be related to the area under the signal amplitude frequency distribution contributed by that class size (Fig. 2), where

\[ n(P_d) = K A \Delta(n(A)) \quad . \]  

\( n(P_d) \) is the number of particles in a particle diameter class with midpoint \( P_d \), \( K \) is an empirical constant determined from sieved sand and snow tests and is a function of the pulse amplitude, \( A \) is the pulse amplitude and \( \Delta(n(A)) \) is the
Figure 2. Signal amplitude density distribution showing contributions of particle size classes as measured by Schmidt's particle counter (after Schmidt, 1977).
difference in the number of pulses per 10 mv between class limits at amplitude
A. Schmidt's (1977) plot of A against K for known particle diameters shows
considerable scatter.

While the type of information calculated from Schmidt's snow particle
counter is of scientific interest, its performance and empirical calibration
raise several questions. Calculation of particle size is based on less than 1%
of collected observations and on an empirical relationship developed primarily
using sand particles. Schmidt's (1977) examples of particle diameter distribu-
tions found using the snow particle counter vary significantly from the sieved
particle diameter distributions used to generate the signals. Actual mean
particle diameters vary from estimated means by up to 25%, while no example of
close correspondence between actual and estimated distributions is shown for
snow particles.

Particle velocity estimations are handicapped by problems similar to dia-
meter estimations. Tests with a spinning wire (Schmidt, 1977) show a 10% var-
ance in particle velocity estimates for various distances from the detector
window. This is due to the divergance of the sensitive beam area from the
detector windows to the source window. It should be noted that the spinning
wire is an ideal case. Actual particles will produce edge diffraction effects
which will vary due to irregular shape. Only the particle velocity component
perpendicular to the light beams is measured. This presents some problems when
compared to windspeeds estimated using cup anemometers. The author notes that
the snow particle counter is saturated in the saltation layer, as more than one
particle at a time is in the light beams.

Gubler (1981) designed a snow particle counter that uses an infra-red light
emitting diode (LED) source and a photodiode detector. The LED source is super-
ior to conventional incandescant sources because of its uniformity of intensity
across the beam width, stability with respect to time and low power consumption.
The length of the exposed beam is 0.02 m and the beam cross-section is 0.5 by 1.0 mm. Light is collimated by lenses in front of both the LED and photodiode and by 0.04 m of narrow tubing between each lens and the windows. The combination of the lens to straighten the light and tubing to exclude passage of stray light is apparently sufficient to collimate the beam.

Uniform collimated light simplifies the task of determining particle size from signal pulse amplitude. Gubler develops a linear relationship between signal pulse amplitude and area of the beam obstructed. He bases this relationship on tests with spinning wires of various diameters. However the expression is not presented in the text. An equation to find the mass snow flux, \( Q \, \text{kg m}^{-2}\text{s}^{-1} \), as a function of the total number of particles counted, \( N \), is given as:

\[
Q = N \frac{(1.42 \, \text{P}_{dl}^{1/2})^{3/4} / 3 \pi 918}{T \, n \, \text{TnF}},
\]

where \( \text{P}_{dl} \) is the smallest detectable particle diameter in metres, \( T \) is the period of time over which count \( N \) is taken in minutes, \( n \) is the number of samples per minute, \( \tau \) is the duration of one sample in seconds and \( F \) is the sensitive area of the beam in m\(^2\). Equation 17 is based on a "typical" particle size distribution (log-normal) recommended by Pope but unpublished and the results of the spinning wire pulse amplitude calibration.

Gubler notes that non-spherical particle shapes, deviations in the actual particle size distribution, effects from particles just grazing the beam and LED intensity changes with temperature all contribute significant deviations to calculated mass flux using Eq. 17. However even if these effects were compensated for, errors in using an extended linear object (spinning wire) instead of spheroids (snow particles) put the validity of the initial calibration in question. A linear object will have a different edge perimeter than a sphere of the same area and therefore a different diffraction effect. It is felt
that the author's estimated accuracy in the mass flux measurement of \( \pm 50\% \) is conservative.

Schmidt et al. (1984) tested four snow particle counters against small filter fabric bag snow traps as described by Takeuchi (1980). Tested are his initial analog system (Schmidt, 1977), his digital system (Schmidt, 1984), a new system similar to the digital system but including particle speed in the flux calculation and Gubler's (1981) particle counter system. Filter fabric bag traps are reasonably accurate and efficient blowing snow traps when emptied frequently. Plots of the mass flux measured by the filter bags and those calculated by the snow particle counting systems show an almost random scatter (Fig. 3). The collection efficiencies of filter bags are not known to change erratically with either drift density or windspeed, and can be compensated for using wind tunnel tests to determine the aerodynamic efficiency of the bags (Takeuchi, 1980). It is therefore most probable that the scatter in the plots is due to inaccuracies in output from the snow particle counters.

It is apparent that after nearly 20 years of development, snow particle detectors are unable to provide reliable estimates of blowing snow mass flux and therefore the parameters of blowing snow transport that determine the mass flux. Factors that still impede the development of accurate snow particle counters are the variation in single snow particle extinction efficiency with distance from the detector, non-representative pulse amplitudes when a particle only grazes the beam, the large number of particles that must be sampled to describe a snow flux with confidence and the small amplitude of the individual pulses created by particles interrupting the detection beam. In both Schmidt's and Gubler's particle counters, pulses are often near the electronic noise level. These factors suggest that pending improvements in opto-electronic technology and optical theory, snow particle counters may not be suitable for use in measuring particle diameters and velocities in blowing snow.
Figure 3. Comparison of the mass flux estimated by Schmidt's (1984) and Gubler's (1981) particle counters with that trapped by a fabric bag snow trap. The dashed line represents a 1:1 correlation (after Schmidt et al., 1984).
BLOWING SNOW DETECTION SYSTEM

Based on the experiences of previous researchers and considering the implications of geometrical optics theory for snow particles, it was decided that a gauge measuring multiple particle extinction in combination with a gauge measuring the number of single particle light extinction pulses would compose a reliable blowing snow detection system. Advances in opto-electronics since the 1960's have made the development of an accurate light extinction meter possible, however the reduction in transmittance measured by these meters is a function of the drift density and particle size distribution. Single particle detectors can accurately count particles, the number of particles counted can be related to the number density of blowing snow particles. Assuming a particle size distribution shape parameter, output from an extinction meter and particle detector can be used to find the drift density and mean particle radius of blowing snow. It will be shown that variation in $\alpha$ over its range in blowing snow leads to only minor variations in the results.

Infrared Extinction Meter

Desired attributes of a light extinction meter are; capability to detect incoming light accurately, negligible interference with the air-snow flux, capability to compensate for ambient light levels, stable light source intensity and spectral range, stable detector responsivity and signal output, low power consumption and inexpensive components. The gauge described here is an attempt to meet these criteria.

The extinction meter consists of an LED source and a photodiode detector, mounted 0.15 m apart on two supporting arms (Fig. 4). The LED (Motorola MLED 930) is approximately collimated by a convex lens. Beam divergence is less than $10^\circ$ for irradiances greater than 90% of the maximum irradiance (Technical Information Centre, 1983). The spectral output of the LED reaches a maximum at a wavelength of 900 nm, in the near-infrared range of the spectrum (Fig. 5).
Figure 4. Infrared extinction meter.
Figure 5. Spectral distributions of the relative photodiode responsivity and LED power output for the extinction meter and particle detector.
Relative power of the LED increases as the temperature decreases, at -32° C output is twice that at 25° C (Technical Information Centre, 1983). The LED is circular with a radius of 1750 μm.

The photodiode (Silicon Detector Corporation SD-100-11-11-021) is operated in the photovoltaic mode, with peak responsivity at a wavelength of 900 nm. Solar radiation is reduced by water vapour absorption in this spectral range (Oke, 1978), resulting in less intense ambient light than levels found in the visible range. The detector is limited in its visible range by a visible light reducing filter (Kodak 87C). The responsivity of the detector with filter across the spectral range is well matched to the LED output (Fig. 5). The optimal frequency response of the photovoltaic detector for an 80% step in received radiation is 100 MHz. Typical response is somewhat slower. The detector is circular, with no optics and has an active detector surface radius of 1270 μm.

To compensate for the level of ambient light detected, the LED is switched. An ambient light reading is taken with the LED off and an ambient plus LED light reading is taken with the LED on. The current output from the detector is fed to an amplifier, which amplifies and converts the current signal to a voltage (Fig. 6). The voltage signal is then sent to an analog to digital converter (A/D converter), which integrates the signal over 33.3 ms, and digitizes the result. To maintain the input voltage for the A/D converter within its acceptable range (+ 2V), an opposing "offset" current to offset ambient light is applied to the photodiode signal current before it reaches the amplifier. The magnitude of the offset current is adjusted until the analog signal voltage is within the A/D converters operating range. The offset current is selected on the first reading (LED off).

The pair of digitized voltages are read by a microprocessor which subtracts the voltage corresponding to ambient light from the voltage corresponding to ambient and LED light. The resultant voltage is a linear function of the
Figure 6. Extinction meter signal processing (shown for several gauges).
radiant power received from the LED. A pair of readings is taken in sequence for each extinction meter in use (presently 8). Each meter is sampled every 56.25 sec. At the end of 7 1/2 min. the eight readings are averaged.

The extinction meter output is calibrated theoretically using geometrical optics theory. When extraneous factors affecting detector output are compensated for and the assumptions of geometrical optics theory met, theoretical calibrations of multiple snow particle light extinction gauges can be extremely accurate (Landon-Smith and Woodberry, 1965; Seagraves and Ebersole, 1983; Seagraves, 1984 and Winchester and Gimmestad, 1983). A major requirement of geometrical optics predictions is the use of approximately parallel light. While the extinction meter optics are not perfectly collimated, the maximum deviation of the active beam is only 0.18°. This deviation does not significantly affect the corrections to the extinction efficiency ($\Delta E_0$, $\Delta E_2$).

Equations 6 and 15 are used to calibrate the extinction meter output. In terms of gauge output, transmittance is defined as the ratio of the present output to the unattenuated output. To calibrate the gauge in terms of transmittance the inputs are: $\lambda = 900 \cdot 10^{-3}$ m, $B_r = 1.27 \cdot 10^{-3}$ m, $m = 1.302$, $L = 0.15$ m, $\rho_i = 930$ kg/m$^3$. Equation 15 is solved for $\sigma$ using an array of the variables $C$ kg/m$^3$, $P_r$ m and $\alpha$. Equation 6 is then solved for transmittance, using the extinction coefficient. The variation of transmittance with drift density for $\alpha = 10$ and a wide range of mean particle radii is shown in Fig. 7. Figure 7 demonstrates that for this gauge, a means of estimating the mean particle radius is necessary for precise determination of the drift density from transmittance. Figure 8 shows the variation of transmittance with drift density for a common mean particle radius and a range of shape parameters of the particle radius distribution ($\alpha$). The effect of $\alpha$ on the drift transmittance for a drift density is limited for most of the range of $\alpha$. 
Figure 7. Theoretical extinction meter performance for particle radius distribution parameter, ω = 10 and various mean particle radii.
Factors other than infrared extinction in blowing snow that might affect the gauge output are; temperature variations, frost accumulation on the LED and photodiode, changes in ambient light intensity that are faster than a pair of gauge readings (66 ms) and other light attenuating atmospheric phenomena. Since blowing snow is accompanied by a strong degree of atmospheric surface layer mixing, phenomena associated with temperature inversions such as fog and ice crystals are usually not concomitant with blowing snow. Any levels of ambient light not subtracted from the signal will be gaussian in magnitude and will tend to average out. Operator maintenance and the small quantity of heat produced by the LED can control frost and snow accumulation on the gauge during light winds. High winds tend to clear snow and ice crystals from the detector and source windows. Variation with temperature of the LED radiant power, photodiode responsivity and system voltage changes the gauge output. Use of a reference gauge, shielded from blowing snow or a calibration of output against gauge temperature during periods of no blowing can compensate for this effect.

**Particle Detector**

The particle detector is inspired by Gubler's (1981) model, however it is designed to simply count particles. Construction is similar to the infrared extinction meter, with an LED source and photodiode detector mounted 0.02 m apart on two supporting arms (Fig. 9). The LED (Motorola MLED 930) is identical to that in the extinction meter. However, to insure a light beam of constant cross-sectional area along its length, the LED beam is shone through a 500 μm diameter hole. The hole is precision drilled in a brass shim plate. The light leaving this hole is well collimated.

The photodiode is a smaller version of that used in the infrared extinction meter (Silicon Detector Corp. 50-020-11-11-011), with identical relative responsivity over its spectral range. Ambient light reception is limited by a filter identical to that on the extinction meter. The optimal frequency response of
Figure 8. Theoretical extinction meter performance for mean particle radius = 60 μm and various gamma distribution shape parameters.
Figure 10 Particle detector signal processing.
the photovoltaic detector for an 80% step in received radiation is 143 MHz. The active detector surface radius is 254 μm, identical to that of the light exit window of the LED.

When a particle interrupts the light beam, there is a momentary drop in the photodiode output signal. Current from the photodiode is fed to a high gain amplifier which converts the current signal to a voltage signal. This signal is filtered to eliminate low frequency noise (ambient light, AC). The voltage signal is sent to a threshold detector, which produces an output for each pulse whose amplitude is greater than a threshold voltage. This signal is sent to a pulse counter (Fig. 10).

A typical pulse amplitude from a blowing snow particle is in the range of microvolts and therefore difficult to detect electronically. The problem is compounded by the nature of the pulse, it is not with respect to the ground but rides on top of a high level signal caused by the ambient light and the LED output. In practice, the threshold amplitude of detection is determined by the responsivity of the detector, level of electronic noise, limits of the amplifier, speed of response and resolution of the threshold detector. Only those particles eliciting a pulse amplitude above the threshold can be counted.

The pulse amplitude is a function of the particle radius, crossing position between the source and detector, cross-sectional trajectory through the beam, particle velocity, and the electronic system frequency response and electronic noise level at the time of detection. The projected area of the particle in the beam is a function of the cross-sectional area and trajectory of the particle in the beam. The effective radius of the particle is the radius of a circle of equivalent area to the projected area of the particle. The influence of the effective radius and distance from the particle to the detector on the drop in transmittance can be calculated using Eq. 2 and is shown in Fig. 11. The effective radius of the particle \( E_r \), is substituted for \( P_r \) in the calculation. The
Figure 9. Particle detector.
Figure 11. Single particle infrared extinction for several effective particle radii in the particle detector.
small transmittance drop for smaller particles makes it evident that not all particles can be counted.

For a given pulse threshold and frequency response and assuming particle speed and the electronic noise level are constant, a threshold transmittance can be defined. This is the transmittance associated with the smallest detectable pulse. Using Eq. 2, this level of transmittance can be related to the effective radius of a particle. The threshold effective radius $E_{tr}$, is the radius resulting in a transmittance at the threshold of detection. For a threshold effective radius and some particle radius greater than $E_{tr}$, there will be a maximum distance from particle centre to beam centre such that the threshold effective radius is exceeded. This distance above and below the beam centre is the vertical component of the detector sampling area, referred to as the sampling height of the detector for that particle radius and velocity.

The sampling height of the beam for a particle size and velocity is found using the geometry of the particle and beam cross-sections. The threshold transmittance (a function of the particle velocity) $T_c$, can be used to find the threshold effective radius $E_{tr}$, where:

$$E_{tr} = B_r \sqrt{(T_o - T_c)/E_c}$$  \hspace{1cm} (18)

The projected area of the particle in the beam $A_p$, is

$$A_p = \pi E_{tr}^2$$  \hspace{1cm} (19)

The distance $C$, from the particle centre to the beam centre, must be calculated using two different procedures. For case 1, where $A_p/\pi r^2 < \frac{1}{2}$, the projected area is the shaded area of intersection of the beam and particle shown in Fig. 12. This area is calculated using the geometry of the beam and particle cross-sections. Thus,

$$P_r^2X + B_r^2Y - P_r^2 \sin(2X) \bar{B}_r^2 \sin(2Y) = A_p$$  \hspace{1cm} (20)
Figure 12. Particle-beam cross-sectional geometry for the particle detector. Shaded areas denote the projected area of the particle, $P_r$ is the particle radius, $B_r$ is the beam radius and $G$ is the distance from the beam centre to the particle centre.
where: \[ X = \arccos \left( \frac{G^2 + P^2 - B^2}{2GP} \right) \]

\[ Y = \arccos \left( \frac{G^2 + B^2 - P^2}{2GB} \right) \]

G can be found from Eq. 20 using a trial and error procedure. For case 2 where \[ \frac{A^2}{\pi P^2} > \frac{4}{3} \], the projected area is calculated using the somewhat different geometry of the beam and particle as shown by the shaded area in Fig. 12.

Thus,

\[ \pi P^2 + B^2 Y - P^2 \left[ 1.571 - X \right] - B \sin(2Y) + P \sin[2(1.571 - X)] = A_p \] (21)

Again G can be found using a trial and error procedure. The sampling height \( H_s \) is twice the distance between the beam centre and the particle centre, when that particle is projecting an area possessing the threshold effective radius and the particle is at the closest point to the beam centre in its trajectory.

To find a representative sampling height across the beam length, changes in the corrected extinction efficiency with distance from the detector should be taken into account. For this particle detector the variation is not large and a simple averaging procedure is used. Thus,

\[ \overline{E_{tr}} = B_p \int_{0}^{L} \frac{\sqrt{(T_o - T_t)/E_c}}{d} \, dl \] (22)

\( \overline{E_{tr}} \) is the mean threshold effective radius of the detection width. When \( \overline{E_{tr}} \) is used to calculate G, twice G is \( \overline{H_s}(P_r, U) \), the mean sampling height for a particle radius and velocity U. The sampling area \( A_s \) is

\[ A_s(P_r, U) = \overline{H_s}(P_r, U)L \] (23)

When numbers of particles are considered in blowing snow conditions, the horizontal wind velocity can be considered equivalent to the horizontal particle velocity.
The number density of blowing snow particles can now be calculated from the number of particles counted per unit time and the windspeed. For a monosized particle distribution with constant windspeed and $P_r > E_{tr}$

$$N = \frac{\phi}{u A_s}$$

where $N$ is the number density of particles in $#/m^3$, $\phi$ is the number of particles counted per second by the particle detector in $#/s$, $u$ is the windspeed in m/s and $A_s$ is the sampling area perpendicular to the snow flux, in $m^2$. For a gamma density function distribution of particle radii and a windspeed $u$ for which there is a threshold particle radius $P_{tr}$, $N$ is found by dividing the number density of particles greater than $P_{tr}$ by the cumulative frequency of particles greater than $P_{tr}$. $P_{tr}$ is defined as the particle radius for which $A_s = 0$, and is a function of the windspeed. For a constant windspeed $u$, $N$ is found by

$$N = \frac{\int_{P_{tr}}^{\infty} \eta(P_r)/A_s(P_r) \, dP_r}{u \int_{P_{tr}}^{\infty} f(P_r) \, dP_r}$$

where $\eta(P_r)$ is the number of particles of radius $P_r$ counted per second. Note that $P_{tr}$ is a function of the windspeed $u$. The output of the particle detector, $\phi$ is the number of particles per second integrated over the interval from $P_{tr}$ to infinity, not $\eta(P_r)$.

For the cumulative frequency of particles greater than some threshold, $P_{tr}$ is given by the cumulative frequency of all particles less the cumulative frequency of particles with radii below the threshold (Haan, 1977). If $\alpha$ is an integer, the cumulative frequency of $P_r$ greater than $P_{tr}$, where $j$ is an integer (Haan, 1977), is:

$$\int_{P_{tr}}^{\infty} f(P_r) \, dP_r = e^{-P_{tr}/\beta} \sum_{j=0}^{\alpha-1} \frac{(P_{tr}/\beta)^j}{j!}$$
To find \( \eta(p_r) \) for any \( p_r \), \( \phi \) is multiplied by the frequency of \( p_r \) as given by the gamma density function distribution of particle radii. Thus

\[
\eta(p_r) = \frac{\phi p_r^{\alpha-1} e^{-p_r/\beta}}{\beta^\alpha \Gamma(\alpha)}
\]

(27)

Thus, \( N \), as found from the particle detector output \( \phi \) is therefore;

\[
N = \frac{\phi}{\int_{p_{tr}}^{\infty} p_r^{\alpha-1} e^{-p_r/\beta} \frac{1}{\Lambda_s(p_r, u)} dp_r}
\]

(28)

\[
\int_{p_{tr}}^{\infty} \frac{1}{\Lambda_s(p_r, u)} dp_r
\]

where the threshold particle radius and size and shape parameters of the gamma distribution are known. Confidence in \( N \) as obtained from this equation depends on the value of \( p_{tr} \) in comparison with the distribution of particle radii. If \( p_{tr} \) is large with respect to the radius distribution, \( N \) will be based on very few observations. However, if \( p_{tr} \) is small, the number density of snow particles can be calculated with a high degree of confidence. For a given detector performance level, \( p_{tr} \) is a function of windspeed, therefore the accuracy of Eq. 28 will decrease as \( u \) increases. The sensitivity of the electronic detection system is therefore an important factor in determining the range of conditions in which a particle detector is useful.

**Operation of the Blowing Snow Detection System**

The infrared extinction meter, particle detector and an anemometer compose the instruments necessary to determine the mass flux and particle radius distribution of blowing snow. Both the extinction meter and particle detector are sensitive to the particle size distribution, and their separate outputs require knowledge of \( \alpha \) and \( \beta \) for correct interpretation. When the outputs of both gauges are used to solve for \( N \), the number density
of particles, only $\alpha$ need be assumed. The errors involved in incorrectly characterizing $\alpha$ are small (Fig. 8). A snow particle photography system is presently being used to find characteristic $\alpha$'s for blowing snow conditions in Western Canada. By solving for $N$ by using the outputs of both gauges, $B$ becomes the only unknown.

Recall Eq. 12 which is now solved for $N$:

$$N = \frac{\sigma^\alpha \beta^\alpha r(\alpha)}{\pi \int_0^\infty E_c p_r (\alpha-1) e^{-p_r/\beta} p_r^2 \, dp_r} \quad (29)$$

This is equated to Eq. 28, which is also solved for $N$. Using trial and error solutions for $N$, $B$ can be found. With $\alpha$ estimated, the mean particle radius is:

$$\bar{p}_r = \alpha \beta \quad (30)$$

Equation 14 is then solved for the drift density, $C$, using the particle radius distribution and the extinction coefficient. Where:

$$C = \frac{4 \sigma^\alpha \beta \int p_r (\alpha+2) e^{-p_r/\beta} \, dp_r}{3 \int p_r E_c p_r (\alpha+1) e^{-p_r/\beta} \, dp_r} \quad (31)$$

The drift flux is found by multiplying the drift density by the windspeed:

$$q = C u \quad (32)$$

Where $q$ is the drift flux in kg $m^{-2} s^{-1}$. Other values that can be calculated from the gauge outputs include the frequency distributions of particle diameters, masses and surface areas. These variables are useful in determining fall velocities and sublimation rates for the snow particles.
As shown in Eqs. 6, 15 and 30, the transmittance for a particular drift density responds to changes in \( \overline{P}_r \) when \( \alpha \) is held constant. The wide range of transmittances caused by variation in \( \overline{P}_r \) with \( \alpha \) held constant is shown in Fig. 7. When compared to the narrow range of transmittances caused by variation in \( \alpha \) with \( \overline{P}_r \) held constant (Fig. 8), it is evident that most of the uncertainty in calculating \( C \) from the extinction meter output is due to \( \beta \). Solving for \( \beta \) by using the particle detector output with the extinction meter output (Eqs. 28 & 29) allows more precise interpretation of the extinction meter output.

At this time a calibration curve between particle velocity and the threshold effective particle radius is being developed for the particle detectors. It is expected that a separate relationship will be developed for each gauge, as their response varies somewhat. These relationships will allow calculation of the sampling areas of the particle detectors for various particle velocities. This is the only empirical calibration required for interpreting the gauge outputs. A complete test of the detection system involves comparing the particle radius distribution as calculated from the extinction meter, particle detector and anemometer outputs to that measured by photographic techniques. Such a test will be completed in the near future.

**CONCLUSION**

The blowing snow detection system and data analysis procedure described here are capable, in principle, of giving precise estimates of blowing snow parameters. Such systems depend on the optical properties and the extinction capabilities of small spheres, but the analysis of the optical effects of blowing snow is not straightforward. Using geometrical optics approximations, it has been demonstrated that theoretical calibrations of multiple particle light
extinction meters and single particle counters are possible when the optical characteristics of the measuring system are known. Thus, "black box" calibrations are not required. The gauges incorporate improvements in opto-electronic and signal processing design over previous gauges. These improvements lead to enhanced sensitivity, response time, stability and data retrieval characteristics. In addition the resulting gauges are amenable to theoretical calibration.

Potential problems with the system may result from the estimation of particle velocities from wind velocity. This may limit the effectiveness of the present analysis procedure for data collected from the lower saltation layer. At the top of the saltation layer and in the suspended layer, horizontal particle velocities tend to approximate horizontal wind velocities (White, 1982). Of importance to the operation of the system is keeping the smallest detectable particle size for the particle detector low. This is necessary to maintain the accuracy of the calculation of the particle radius distribution.

Because of its minimal interference in the windstream, continuous monitoring capability and detailed data collection it is felt that this blowing snow detection system will increase our understanding of the blowing snow phenomena.

REFERENCES


