Near-Infrared Extinction in Rain Measured Using a Single Detector System

F. J. NEDVIDEK, C. W. SCHNEIDER, Z. KUCEROVSKY AND E. BRANNEN

The Faculty of Engineering Science and the Department of Physics, The University of Western Ontario, London, Ontario, Canada

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ABSTRACT

The performance and operation of an optical device to accurately measure extinction due to rainfall over a 100 m sample path is described. A collimated beam from an infrared light-emitting diode operating at 0.94 μm is used as a sensing beam. A PIN diode detector receives reference and sample signals alternately in a switch arrangement using a beam splitter and mirrored chopper wheel. Demultiplexing and phase sensitive detection are used to separate and demodulate the sample and reference signals.

The experimental results are in agreement with theoretical predictions and theoretical results obtained for rainfall rates up to 90 mm h⁻¹. Extinction calculations based on the recent theoretical treatment of Ulbrich and Atlas produced a best fit to the experimental results.

1. Introduction

The power of a collimated electromagnetic beam is attenuated by liquid and solid phase particles in the form of rain, snow, and fog (Clay and Lenham, 1981). The correlation between signal attenuation and the density of hydrometeors in the sensing path (Atlas, 1953) can be used to measure precipitation. Microwave, infrared (Jessen et al., 1980) and visible wavelengths (Wang and Lawrence, 1981) have been used to measure precipitation rate; however, the dependence of near-infrared extinction of rainfall rate has not yet been extensively researched. In this paper an optical method is proposed to accurately measure atmospheric attenuation of a 0.94 μm incoherent signal in a 100 m sample path. Results show a strong correlation with readings from gauge instruments. The compact dimensions and battery-powered operation of the instrument offer increased mobility over conventional optical precipitation-sensing systems based on laser sources. The system lends itself to both remote ground-based placement and airborne installation. The use of a single-detector configuration eliminates drift problems encountered with two-detector systems.

Since raindrop diameters are very large compared to the wavelength of near-infrared light and water behaves as a low-loss dielectric in this region of the electromagnetic spectrum (Tomasz, 1979; Centeno, 1981), the geometrical optics approximation can be used to determine the power decrease of the sensing beam by reflection and refraction (Glatschning and Chen, 1981). The total extinction coefficient is a sum over all particles in the sample beam and is expressed in Eq. 1 as

\[ \beta = \int_{0}^{\infty} \pi Q(\kappa) r^2 dr, \]  

where \( \beta \) is the total extinction coefficient (dB km⁻¹), \( Q \) the extinction efficiency \( Q = 2 \), \( r \) the radius of each raindrop (mm), and \( N(\kappa) \) the raindrop-size distribution. Using Eq. (1), the attenuation of an optical signal due to hydrometeors can be calculated for particular particle densities and size distributions.

The water volume accumulation at the ground is a product of the particle volumes and the fall velocities. The total water accumulation is given by Eq. (2):

\[ R = 15.1 \times 10^{-2} \int_{0}^{\infty} N(\kappa) v(\kappa) r^3 dr, \]  

where \( R \) is the rainfall rate (mm h⁻¹), \( v(\kappa) \) the raindrop fall velocity, and \( r \) the particle radius (mm).

The rainfall rate and the sensing-beam intensity are related through the raindrop-size distribution \( N(\kappa) \). The size spectrum follows the general relation suggested by Deirmendjian (1965, 1975):

\[ N(D) = N_0 D^\gamma \exp(-\gamma D), \]  

where \( N_0, \gamma, \mu \) are parameters of the distribution, and \( D \) is the raindrop diameter (mm) and \( D = 2r \). Equation (3) allows simple expressions for rainfall integral relations and reduces to the simple case of an exponential distribution for \( \mu = 0 \) (Ulbrich, 1983). Variations in the distribution shape for variations in rain conditions (Waldvogel, 1974; Joss and Gori, 1970) can be accounted for by \( \mu \).

The disadvantage of using Eq. (3) in Eq. (1) to calculate extinction is that the volume of the sample beam must be known to determine the number of intercepting particles. A general equation describing extinction can be obtained by normalizing the extinction integral of Eq. (2) to rainfall rate. The size distribution can be normalized to yield a percentage distribution,
Eq. (4). The number of particles having a particular radius is then determined by multiplying the normalized distribution by a weighting function that gives the number of particles in the rain sample:

$$n(r)_{\%} = \frac{N(r)}{\int_0^\infty N(r)dr},$$  \hspace{1cm} (4)

where $N(r)$ is the normalized particle-size distribution. The resulting Eq. (6) is similar to Eq. (2) scaled to rainfall rate:

$$V(r)_{\%} = \frac{15.1 \times 10^{-6} \pi r^3}{\int_0^\infty 15.1 \times 10^{-6} \pi r^3 dr},$$  \hspace{1cm} (5)

$$\beta = 0.434R \int_0^\infty \frac{\pi Qr^3}{15.1 \times 10^{-6} \pi r^3} dr,$$  \hspace{1cm} (6)

where $V(r)$ is the normalized percentage accumulation, and $\beta$ is the extinction coefficient ($\text{dB km}^{-1}$). Equation 6 is general and can be used to determine the attenuation of a sensing beam for arbitrary particle-size distributions that satisfy geometrical optics scattering.

The value of raindrop radius $r$ used in the above equations is assumed to be the average of the raindrop major and minor axes. Aerodynamic drag causes hydrometeors to deform oblately, especially at large particle diameters (Ramaswamy et al., 1980). This does not invalidate the spherical modeling of raindrops because the distortions do not significantly affect either the extinction efficiency (Asano and Yamamoto, 1975) or the volume of raindrops, as compared to a perfect sphere having the average radius $r$.

The empirical relation of Eq. (7) was initially proposed by Atlas (1953) to describe optical extinction in rain:

$$\beta = \alpha R^B$$  \hspace{1cm} (7)

where $\alpha$ and $B$ are coefficients. For exponential drop-size distributions as given in Eq. (3), Ulbrich and Atlas (1985) have shown that Eqs. (2) and (6) can be expressed as

$$\beta = \frac{0.682 \Gamma(3 + \mu)N_0}{\gamma^{(3+\mu)}},$$  \hspace{1cm} (8)

$$R = \frac{33.31 \Gamma(4.67 + \mu)N_0}{\gamma^{(4.67+\mu)}},$$  \hspace{1cm} (9)

where $\Gamma$ is the gamma distribution function. In the above relations, the particle fall velocity is assumed to be of the form given by Atlas and Ulbrich (1977) in Eq. (10):

$$v(D) = 17.67D^{0.67},$$  \hspace{1cm} (10)

Here $\gamma = 3.672/D$ for an exponential distribution (Ulbrich and Atlas, 1985).

The measurement of precipitation by the attenuation of an optical signal is attractive in situations where extinction from other airborne particulates is negligible. The method allows real-time measurement of precipitation rate integrated over the length of the sensing beam path (Atlas and Ulbrich, 1977), whereas gauge devices supply only total accumulation data at a single point location. Consequently, optical extinction measuring instruments can be used in applications where wind or localized variations in rainfall rate adversely affect the accuracy of gauge readings.

2. Apparatus

Since it is assumed that raindrops can be modeled as dielectric spheres, the size and number density of hydrometeors in the sample volume can be measured using an infrared sensing beam. The dependence of infrared extinction on rainfall is used to monitor the rainfall rate. The source of the sensing beam is an infrared light-emitting diode, and a matched PIN diode serves as a receiver. The output signal from the receiver is proportional to the infrared power falling upon the PIN diode.

An accurate method of detecting variations in the intensity of a sensing beam involves comparing the signal produced by the beam traversing the sample path to a well-defined reference signal (Schneider et al., 1982). In our system, a single detector compares the power of the sample beam to a reference beam with fixed transmission properties. Temporal variations in the characteristics of the transmitter and receiver due to changes in temperature, fluctuations in the supply voltage, or aging affect both the sample and the reference signals equally, thus avoiding the drift problems inherent in two detector systems (Kraus, 1966). Because a common receiver is used for both signals, an optical switching system is required to select the beam to be measured.

In a previous paper (Nedvidek et al., 1983), attenuation of a near-infrared signal propagating in rain and snow was measured using a two-detector system. In the two-detector system, the sensing radiation is divided into two beams, one of which remains within the apparatus and serves as a reference signal. The other portion of the emitted infrared signal traverses the sample path and experiences attenuation due to atmospheric particulates. The difference in the relative intensity of each beam as detected by the sample and reference receivers is used to determine atmospheric attenuation, and consequently, drift in the gain or sensitivity of the detectors introduces errors to the extinction measurements. Although the single-detector system is optically and electronically more complex, it provides greater accuracy and reliability when compared to the system employing two detectors.

Figure 1 shows a block diagram of the infrared remote-sensing system. The output of the infrared light-emitting diode is collimated by two spherical lenses and directed into the beam path by the beam splitter.
S1. A motor-driven, butterfly-shaped, aluminum-coated chopper blade is used to direct the beam into the reference or the sample path. When the mirrored chopper blade intercepts the sensing beam, the beam is reflected back through beam splitter S1, focused by the spherical mirror into the receiver, and detected as the reference beam. When the transparent portion of the chopper blade is in this position, the transmitted beam travels across the sample path to the remotely positioned retroreflector. The sample beam retraces its path back to the receiver and is detected as the sample signal. A synchronous detector comprising an electronic multiplier and integrators is used to process the receiver signal. An electronic gating network connects the reference or the sample signal, whichever is being selected, to the multiplier. A square wave derived from the transmitter oscillator output forms a product with the input in the synchronous detector, with the output of the multiplier switched to the appropriate integrator channel. Using a common demodulator avoids the drift problems of a two-channel system. The output of the log-ratio amplifier is a measure of beam extinction in decibels.

In the optical section of the transmitter, a collimator is used to increase the radiant power density of the sensing beam. A corner retroreflector directs the sample beam back to the sensing system after it has traversed the sample space. A small, low-powered He–Ne visible laser can be used for initial alignment of the system optics and positioning of the retroreflector. All electronics can be operated from a ±12 V battery supply.

a. Transmitter

An integrated circuit timer delivers a 1.0 kHz, 50% duty cycle square-wave signal to a class C transistor amplifier, which drives an infrared light-emitting diode [Texas Instruments part number (TIL) 38]. Peak radiant power output is approximately 12 mW at 0.94 μm. The 1.0 kHz modulation frequency is above the frequency of fluctuations in beam intensity due to air turbulence and is also convenient for electronic processing and signal detection.

b. Receiver

A spherical gold-coated mirror focuses the incoming beam onto the infrared detector. An aperture positioned in front of the detector reduces the acceptance angle of the receiver and thereby reduces the reception of stray reflections and ambient interference. The infrared detector was a PIN diode (TIL 100) with a peak sensitivity at 0.94 μm to match the transmitter. The diode body is made of black infrared transmissive plastic to filter out unwanted visible wavelengths. The high saturation current and fast recovery time of this device enables the detection of both the sample beam and the relatively more intense reference beam without transient problems. The output voltage signal from the PIN diode is amplified 20 dB by a low-noise, integrated-circuit amplifier before the gated amplifier processing.

c. Gated amplifier

The optical switch consists of a stepping motor driving a butterfly-shaped pyrex glass wheel. The front surfaces of the two blades were coated with aluminum to reflect the reference beam. The chopper is a part of a servo feedback loop with reference frequencies derived from a crystal clock. The useful frequency range of the chopper extends from 0.1 Hz to 100 Hz.

The reference and sample signals are distributed to separate amplifiers by an electronic gating switch synchronized with the optical switch. The gate delay and time window are selectable. These controls are normally set to reject both signals when the chopper is in transition between passing and reflecting the sensing beam. In this way transient signals are ignored. Amplifier gains from 0.5 to 20× are available. The windowed signals are recombined before being passed to the multiplier.

d. Demodulator

A phase-sensitive demodulation consisting of a multiplier and two integrators is used to recover the 1.0 kHz signal of the reference and sample signals. The system employs electronic switching and allows the use of a single multiplier circuit to reduce the likelihood of phase drifts that could occur if separate units were used. A maximum sensitivity is achieved when phase differences are minimized (Blair et al., 1975). After multiplication the reference and sample signals are restored to their appropriate integrators.

The output of the multiplier is a product of the sample or the reference signal and a constant amplitude square wave from the transmitter oscillator. Phase shifts from 0°–360° are possible to allow null-quadrature calibration. A narrow-band filter centered at 1.0 kHz reduces the signal bandwidth before multiplication. The output of the sample and reference integrators is proportional to the power of the sample and reference beams. Integration time is variable between 0.1 and 60 s.

A log-ratio amplifier with gains variable from 1.0 to 20× compares the outputs of the sample and reference integrators. During measurements the integration times were maintained at least 20× the period of the chopping frequency to avoid noise at the output of the log-ratio amplifier.

A log-ratio amplifier with gain variable between 1 and 20× compares the output of the reference and sample integrators and generates the natural logarithm. The circuit is designed around an integrated circuit logarithm-function analog processor. A hard copy of beam attenuations is available from the chart recorder.
e. Optical elements

All optical components are mounted in a cage made of 7/8 in. diameter bars connected by 1 in. square cross-members. The chopper, receiver, mirrors, and beam splitters are held in place by the cross-members. A photograph of the optical cage is shown in Fig. 2. The transmitter and collimating optics are secured by a smaller precision cage supported within the larger cage. It utilizes 1/2 in. aluminum bars to guide the lens and mirror mounts. The rails are clamped by set screws into 1 in. thick end flanges. The design allows for ample flexibility while providing precise optical alignment. The detector and emitter are mounted inside of brass headshells that can be clamped into the cage mounts. A small entrance pupil in the receiver headshell shields the detector from all radiation except the sensing beam. Sockets at the rear of the headshells accept coupling to aluminum die cast boxes that house the transmitter and receiver circuitry.

Except for the 48% transmittance beam splitter B1 (gold on quartz), all other mirrors are deposited with aluminum. Two short focal-length lenses, L1 and L2, comprise the collimator. A beam diameter of 2.5 cm was used. The retroreflector employs three front surface mirrors and has a working diameter of 8 cm. The retroreflector is mounted inside an aluminum container to prevent the mirrors from being fouled by water and dust. The ensemble is attached to a tripod for convenient positioning.

3. Experiment

The retroreflector was placed at a distance of 50 m from the exit aperture of the infrared remote-sensing system; the effective atmospheric sensing path was thus 100 m. The gauge used for calibration was located 10 m from the instrument, directly beneath the sensing path. A continuous record of the reference beam intensity, sample beam intensity, and the output of the
log-ratio amplifier was made using chart recorders. The water accumulation in the gauge was recorded at 60 s intervals.

A switching frequency of 11 Hz was used in all experiments. This frequency was chosen because it is not a factor of 60 Hz line frequency or the 1.0 kHz modulation frequency that could cause harmonic modulations to be superimposed on the output data. At this chopping rate, approximately 70 cycles of the sample and reference signals were passed after truncation by the gating amplifier. The gate-delay and gate-on times were adjusted to produce a time window that rejected the transients associated with the chopper blade transitions.

In experiments during daylight hours it was found that ambient light entering the receiver with the reference beam produced an additional dc component on the sample signal. To prevent overloading of the multiplier, ac coupling of the gating amplifier was necessary. Stability tests showed that the output voltage from the log-ratio amplifier drifted a maximum of 6 mV, while the maximum noise voltage of 5 mV was measured. Signal levels varied between 50 and 150 mV for rainfall rates from 90 to 0 mm h⁻¹, respectively.

The gain of the reference channel of the gating amplifier was set to 0.5× and that of the sample channel set to 20×. Integration times of 5 s were selected for both integrator channels. The phase sensitive demodulator was calibrated by first adjusting the phase of the oscillator signal to produce a null output. An additional 90° phase shift was then added to give a maximum output.

Uncertainties were estimated for gauge data and beam extinctions. The rainfall rate predicted for each device was averaged over data values at earlier and later times, similar to the running average method used by Gertzman and Atlas (1977). Values for the standard deviation for different time windows are shown in Table 1. Running averages were taken over 5 and 10 min intervals to provide a reasonable temporal resolution of rainfall rate. The number of bins used in each time window was also varied.

4. Results

The calibration curve for the near-infrared sensing instrument is shown in Fig. 3. The curve was fitted to the Gaussian mean of the actual data points. The solid curve represents the current experimental results, while the dashed curve is the calibration result previously obtained for the two-detector system (Nedvidek et al., 1983). The largest discrepancy occurs for rainfall rates of 90 mm h⁻¹, where the single-detector calibration curve lies approximately 2 dB above that of the two-detector system. The single-detector curve follows the power law relation given in Eq. (15) to within ±15%:

\[
\beta = 0.92 R^{0.63},
\]

where \( R \) is the rainfall rate (mm h⁻¹) and \( \beta \) is the extinction in dB km⁻¹.

Figure 4 compares the experimental result to the plots obtained from theoretical calculations. The lower dashed curve was computed by numerically integrating Eq. (6) over the range of particle sizes and particle fall velocities. A normalized Gaussian size distribution, applied to the results of Laws and Parsons (1943) and employed by Rensch and Long (1970), given in Eq. (14) was used in conjunction with the velocity distribution of Eq. (15) given by Goldstein (Kerr, 1951). The upper dashed curve was computed using the size distribution derived by Markowitz (1976) in Eq. (13) and the velocity distribution of Best (1950) as per equation (12). The lower dotted curve was calculated using the velocity distribution of Best and the size distribution of Rensch and Long. For this calculation, the number of particles intercepting the sample beam was estimated from the beam cross section and path length parameters.

Figure 5 compares the experimental results with attenuation calculated using Eq. (7), due to Ulbrich and Atlas (1985). The computed results follow the experimental curve to within ±17% for parameter values \( N_0 = 6.8 \times 10^4 \text{ m}^{-3} \text{ cm}^{-1} \) and \( \mu = 1.5 \).

Our results are in agreement with those of Rensch and Long (1970), Sokolov (1970), Chu and Hogg (1968), and Atlas (1953) for the extinction of visible wavelengths propagating in rain. The calibration curve of Fig. 3 is within ±30% of the calculations based on the theoretical models. Results calculated from equations taken from Ulbrich and Atlas (1985) appear to be in best agreement with the experimental findings:

\[
v(r) = 9.58 \left\{ 1 - \exp \left( \frac{r}{0.885} \right)^{1.147} \right\}
\]

where \( v(r) \) is the raindrop fall velocity (m s⁻¹), and \( r \) is the raindrop radius (mm). The other equations used and cited above are

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\[ N(r) = N_0 \exp\left(-\gamma \frac{D}{2}\right), \quad (13) \]
\[ N_0 = 8.26 \times 10^4 + 1.38 \times 10R^3 - 2.62R^2, \]
\[ \gamma = 7.29R^{-0.20} \]

where \( \mu = 0 \) and \( \gamma \) and \( N_0 \) are also parameters of Eq. (3);

\[ n(r) = \frac{2}{\sqrt{\pi}} \left( \frac{0.4}{\sigma(r)} \right) \exp\left\{ \frac{(r - r_0(R))^2}{\sigma(r)^2} \right\} \quad (14) \]

where \( r_0 = 0.45 \log(R) + 0.05 \) and \( \sigma = 0.05 \log(R) + 0.05 \).

where \( R \) is the mean particle radius (cm), \( \sigma \) the particle radius standard deviation, \( n(r) \) the normalized standard
particle distribution, and \( R \) the rainfall rate (mm h\(^{-1}\)), the particle fall velocity is calculated by

\[
v(r) = 9.6[1 - \exp(-11r)]
\]

(15)

where \( v(r) \) is the particle fall velocity (m s\(^{-1}\)), and \( r \) is the particle radius (cm).

5. Conclusions

From the statistical parameters of Table 1, it would appear that the single-detector infrared remote-sensing instrument performed adequately for rainfall rates up to 90 mm h\(^{-1}\). The performance of the one-detector optical system is comparable to that of the two-detector system previously tested. The differences between the two systems may be attributed to a smaller sample-beam power collected with the optical switching arrangement and to increased turbulence noise associated with a smaller sensing beam diameter (Wang et al., 1983) of the single-detector system. The asymptotic behavior of the calibration curve for heavy rainfall can be attributed to increased forward scattering of the sensing-beam radiation back into the sample path (Chu and Hogg, 1968; Kazovsky, 1984; Mironov and Tuzova, 1980; Fante, 1985). Since the receiver and transmitter fields of view are identical, backscatter will also have a small influence on the results (Ryan et al., 1978).

Of the theoretical models investigated, the calculations using the velocity profile of Eq. (7) (cf. Atlas and Ulbrich, 1977) and the gamma size distribution of Deirmendjian (1975) allow the most accurate fit of the experimental results to calculated results based on the theory of Ulbrich and Atlas (1985).

While a two-detector system provides adequate accuracy for short-term measurements, a single-detector system, in spite of its greater complexity, yields a greater degree of long-term stability, making this type of system preferable for long-term precipitation monitoring. Portability and battery operation of the instrument allow the system to be used for mobile or remote location precipitation measurement.

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REFERENCES


