Performance of the Precipitation Occurrence Sensor System as a Precipitation Gauge

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ABSTRACT

The Precipitation Occurrence Sensor System (POSS) is a small X-band Doppler radar originally developed by the Meteorological Service of Canada for reporting the occurrence, type, and intensity of precipitation from Automated Weather Observing Stations. This study evaluates POSS as a gauge for measuring amounts of both liquid and solid precipitation. Different precipitation rate estimation algorithms are described. The effect of different solid precipitation types on the Doppler velocity spectrum is discussed. Lacking any accepted reference for high temporal resolution rates, the POSS precipitation rate measurements are integrated over time periods ranging from 6 h to one day and validated against international and Canadian reference gauges. Data from a wide range of sites across Canada and for periods of several years are used. The statistical performance of POSS is described in terms of the distribution of ratios of POSS to reference gauge amounts (catch ratios). In liquid precipitation the median of the catch ratio distribution is 82% and the interquartile range was between 12% and 19% about the median. In solid precipitation the median is 90% and the interquartile range is between 17% and 24% about the median. The underestimation in both liquid and solid precipitation is shown to be a function of precipitation rate and phase. The effects of radome wetting, raindrop splashing, wind, and the radar “brightband” effect on the estimation of precipitation rates are discussed.

1. Introduction

High temporal resolution measurements of precipitation are required for a variety of nowcasting applications where rate, phase, or visibility is a concern. These include prediction of hazardous road conditions when visibility is reduced by precipitation or surfaces are made slippery (Sass 1997). In airport operations, precipitation can reduce visibility affecting safety during take-off and landing (Rasmussen et al. 1999). Freezing or solid precipitation rate is also an important factor in the determination of the time period during which anti-icing fluids applied to aircraft surfaces are effective (Rasmussen et al. 2001).

Weighing type gauges that are used operationally in national meteorological networks have limitations with respect to high temporal resolution rate measurement. They typically do not have the sensitivity (inadequate signal-to-noise ratio) to report rates averaged over short time intervals. For example, the Geonor weighing gauge used in the Canadian automated network has a sensitivity of about 0.6 mm (K. Devine 2007, personal communication). Also, weighing gauges rely on catching precipitation falling through the orifice of a container and the wind affects the amount of the precipitation collected (e.g., Nešpor and Sevruk 1999). This effect is more pronounced in snow than rain. For example, underestimation by 50% of snowfall water equivalent amounts at wind speeds of 4 m s\(^{-1}\) is common (Goodison et al. 1998; Yang et al. 1994) if no wind shielding is used. An additional problem occurs when freezing or solid precipitation sticks to the gauge orifice affecting the accuracy of the timing and rate estimation of the event. The use of auxiliary heaters applied to the gauge can result in underestimation due to evaporation.

A variety of indirect sensing techniques have the potential to give “instantaneous” rate measurements but all have their strengths and weaknesses. They do not measure the precipitation directly, so there is the ques-
tion of the degree of correlation between the sensed parameter and the precipitation rate. For example, a “microphone type” disdrometer (Joss and Waldvogel 1967) measures the momentum transferred to a sensing surface by impacting hydrometeors. A relatively new sensor, known as the “Hotplate” (Rasmussen et al. 2005), measures the latent heat of fusion and vaporization to estimate the liquid water equivalent amount of precipitation falling on a small heated circular plate.

Another technique used by sensors such as the Vaisala FD12P (http://www.vaisala.com/businessareas/instruments/products/presentweather) is based on the measurement of optical scattering by precipitation particles falling through a sampling volume. The scattering amplitude is proportional to the geometric cross section of the hydrometeor. However, in the case of snowflakes, this is not a good indicator of the water content of the flake (Rasmussen et al. 1999).

Radars have an advantage over optical sensors in that the measured signal is proportional to the sum of the squares of the mass of each scatterer (Marshall and Gunn 1952) provided that the scatterer’s size parameter is in the Rayleigh scattering range. This condition is met at X-band radar wavelengths for both liquid and solid spherical particles of diameter less than 3 mm (Matrosov 1992). Another advantage of radars is that the airflow in the sampling volume is less disturbed by the instrument compared to some optical devices (Nešpor et al. 2000).

The Precipitation Occurrence Sensor System (POSS) is a small X-band Doppler radar originally developed by the Meteorological Service of Canada for reporting the occurrence, type, and intensity of precipitation from Canadian Automated Weather Observing Stations (AWOS). The principles of operation have been described by Sheppard (1990, hereafter S90), Sheppard and Joe (1994) describe its use as a disdrometer and demonstrate its ability to estimate precipitation type (Sheppard and Joe 2000). Sheppard (2007) analyses the sampling errors specific to POSS measurements.

Our long-term objective is to validate POSS precipitation rate measurements. Validation of any precipitation measurement requires a reference instrument with a specified uncertainty. There is no internationally recognized field standard for precipitation rate. However, there are recognized standards for accumulated precipitation amount collected over longer periods of time, typically in the order of hours (Sevruk and Hamon 1984; Goodison et al. 1998). These are manual gauges used by a trained observer, following strict established procedures. Validation of precipitation accumulation using these references is a necessary but not sufficient condition to the validation of precipitation rate measurements since high-frequency fluctuations can average out.

In this paper, 1-min rate estimates derived from POSS Doppler velocity spectral measurements in liquid and solid precipitation are integrated for several hours and compared to amounts from manual references. It is only possible for this study to demonstrate the necessary condition of the validation process since there are no accepted references at shorter time scales. However, validation of accumulated amounts measured over periods that include both low and high rates should provide a level of qualitative confidence in the POSS when used for shorter time scales.

2. POSS description

POSS is a bistatic, continuous wave, horizontally polarized, X-band Doppler radar (Fig. 1). The transmitter and receiver antenna are smooth-walled pyramidal horns angled from the vertical by 20° so that the antenna axes intersect at about 34 cm above the radome windows. Details of the radar characteristics are given in Table 1 of Sheppard (2007).

The bistatic radar equation is given by

\[
\text{FIG. 1. Photograph of the POSS.}
\]
Here, \( V_{\text{av}} \) and \( F_r \) are the average transmitted and received powers, respectively.

\[
F_r = \frac{P_tL_wG_1(\theta_s, \phi_s)G_2(\pi - \theta_s, \pi - \phi_s)\sigma(\theta_s, \phi_s, \theta_s, \phi_s)}{64\pi^3R_i^2R_s^2},
\]

(1)

where \( F_r \) and \( F_t \) are the transmitted and received powers, respectively, \( L_w \) is the combined radome transmission factor, that is, \( (1 - L_w) \) is the total attenuation of both radomes, \( G_1(\theta_s, \phi_s) \) is the transmitter antenna gain in the direction of the scatterer at the incident zenith and azimuth angles \((\theta_s, \phi_s)\), respectively, \( G_2(\pi - \theta_s, \pi - \phi_s) \) is the receiver antenna gain in the direction of the scatterer at the scattered zenith and azimuth angles \((\theta_s, \phi_s)\), respectively, \( \sigma(\theta_s, \phi_s, \theta_s, \phi_s) \) is the angular scattering cross section of a single particle, \( R_i \) and \( R_s \) are the distances from the scatterer to the transmitter and receiver antennas, respectively. Note that \( \sigma(\theta_s, \phi_s, \theta_s, \phi_s) \) will be written simply as \( \sigma \) in this paper.

The fundamental relationship between the measured Doppler power density spectrum \( S(f) \) (power Hz\(^{-1}\)) and the number concentration per diameter interval \( N(D_m) \) (m\(^{-3}\) mm\(^{-1}\)) of the hydrometeors of liquid-equivalent-volume-spherical-diameter \( D_m \), density \( \rho \), and shape \( h \), is subject to the wind velocity \( w \) and is given by

\[
S(f) = \int_{D_{\text{min}}}^{D_{\text{max}}} N(D_m)\int_{D_{\text{min}}}^{D_{\text{max}}} V(D_m, \rho, h, w)S(f, D_m, \rho, h, w) dD_m.
\]

(2)

Here \( V(D_m, \rho, h, w) \) is the sampling volume (m\(^3\)) and \( S(f, D_m, \rho, h, w) \) is the volume-averaged Doppler power density at frequency \( f \), from a single scatterer. The products \( V(D_m, \rho, h, w)S(f, D_m, \rho, h, w) \) are referred to here as “weighting functions”; \( D_{\text{min}} \) is the minimum detectable diameter determined by the radar characteristics. For liquid, \( D_{\text{min}} = 0.34 \) mm; \( D_{\text{max}} \) is the maximum diameter present in the hydrometeor distribution.

The analog Doppler signal measured by POSS is digitized and transformed by fast Fourier transform to 64 discrete Doppler velocity spectral components with a resolution of 0.22 m s\(^{-1}\). The signal processing details are given in S90 and in Table 1 of Sheppard (2007). The moments of the discrete Doppler velocity spectrum are calculated in real time. The 0th moment \( (P_o) \) is defined as the sum of the power over all Doppler velocity spectral components.

The POSS is a continuous-wave radar. The sampling volume is defined by the distance at which a scatterer can be detected by the receiver. This distance is a function of \( \sigma \) of the particles. The sampling volume perimeter is also dependent on wind speed since the measurement is done over a finite time (typically, 64 ms). The sampling volume is in both the near and far field of the antennas. The location of the scatterers in the sampling volume is not known. Therefore, the calibration of the POSS is based on volume-averaged Doppler spectra. The calibration is a function of the hydrometeor’s mass, density, phase, and shape (see section 3).

The sampling volume is orders of magnitude larger than other disdrometers, for example, the Joss–Waldvogel disdrometer (Joss and Waldvogel 1967) or the two-dimensional video disdrometer (Kruger and Krajewski 2002). Therefore the usual natural “Poisson variability” is not a factor. POSS has unique sampling errors compared to other disdrometers because both the spectral power and frequency generated by a scatterer are dependent on its location in the sampling volume (Sheppard 2007). However, because POSS rates are integrated for several hours for comparison to observed amounts, sampling issues are not relevant.

3. POSS calibration

The POSS calibration procedure combines laboratory measurements and a physical model to simulate the Doppler signal generated by a hydrometeor traversing the sampling volume in order to determine the weighting functions (2), for specific wind conditions, and hydrometeor mass, density, phase, and shape. These values are required to mathematically invert the measured \( S(f) \) to estimate \( N(D_m) \) (S90). The “forward” model (2) can also be used to calculate \( S(f) \) for hypothetical \( N(D_m) \) associated with various precipitation types and rates. From these, regression equations for precipitation rate can be determined (see section 4).

There are three general components required for the simulation of the Doppler signal: the radar system constants [all factors in (1) excluding \( \sigma \)], the velocity vector of the hydrometeor, and \( \sigma \) at each bistatic scattering angle in (1). The last two factors are both functions of the hydrometeor’s mass, density, phase, and shape.

The radar system constants in the near field of the antenna are measured in a laboratory using distilled water drops of known size released from a hypodermic needle so that they fall through the POSS sampling volume at specific locations (section 4 of S90 and section 3 of Sheppard 2007). For calibration purposes, it is not necessary that the drops fall at terminal velocity. The vertical position of the accelerating drop at any time after release is found using an algorithm given by Wall (1975). At each bistatic scattering angle in (1), the
The term $\sigma$ of the drop used in the calibration is calculated using the T-matrix method (Mishchenko 2000). The measured power and the calculated $\sigma$ determine the radar system constant at each location from (1). In the far field, a theoretical model is used to compute the combined antenna gain for smooth-walled pyramidal horns (Sletten 1988).

The second component of the simulation is the hydrometeor’s velocity vector, which is the resultant of its terminal velocity and the wind velocity vector. The magnitude of the terminal velocity $|v_t|$ in still air, neglecting buoyancy, is given by

$$|v_t| = \sqrt{\frac{2mg}{AC_D\rho_w}},$$

(3)

where $m$ is the mass of the particle, $g$ is the acceleration due to gravity, $A$ is the cross-sectional area of the surface normal to the flow, $C_D$ is the drag coefficient, and $\rho_w$ is the density of the atmosphere. In liquid precipitation, (3) is well represented by a ninth-order polynomial of $D_m$ (Beard 1977).

In solid precipitation, because of the variety of shapes and densities, $m$, $A$, and $C_D$ in (3) are not unique functions of $D_m$. The terminal velocity is calculated following the approach of Mitchell (1996) as extended by Khvorostyanov and Curry (2002, 2005). Central to this approach is the use of empirical power-law expressions:

$$m = aD_{\text{max}}^\beta$$

(4a)

and

$$A = \gamma D_{\text{max}}^\delta,$$

(4b)

where $D_{\text{max}}$ is the maximum dimension of the solid particle and the parameters $\alpha$, $\beta$, $\gamma$, and $\delta$ depend on the hydrometeor type (Table 1 of Mitchell 1996; Mitchell and Heymsfield 2005).

The mass in (4a) is converted to $D_m$ assuming the density of liquid water is 1 g cm$^{-3}$. Examples of the terminal velocity as a function of $D_m$ are given in Fig. 2. Six different types of solid precipitation are presented: aggregates of thin plates (S3); stellar crystals with broad arms (P1d); densely rimed dendrites; lump graupel (R4b); crystals with sector-like branches (P1b); hexagonal plates (P1a). The designators in parentheses, where available, follow the classification scheme of Magono and Lee (1966). The symbols in Fig. 2 are plotted over the range of $D_m$ corresponding to the range of $D_{\text{max}}$ given in Table 1 of Mitchell (1996). Hydrometeors of equal mass fall with a range of terminal velocities. For example, for a $D_m = 1$ mm, $|v_t|$ ranges from 0.9 to 2 m s$^{-1}$ for the six types evaluated here.

The third component of the simulation model is the calculation of $\sigma$ for the specified hydrometeor characteristics. Again this is done using the T-matrix software of Mishchenko (2000). This software requires specification of the equal-volume spherical diameter $D_s$, the complex refractive index $(m_s)$, and specification of the hydrometeor shape. For liquid water, $m_s$ has real part $\text{Re}(m_s) = 7.96$ and imaginary part $\text{Im}(m_s) = -2.13$ (Ray 1972). The shape of falling raindrops distorts from spheres due to aerodynamic effects. An oblate shape at terminal velocity is assumed (Brandes et al. 2002):

$$r = 0.9951 + 0.025 10D_s - 0.03644D_s^2 + 0.00503D_s^3$$

$$- 0.000249 2D_s^4,$$

(5)

where $r$ is the ratio of the axis of rotational symmetry to horizontal axis, and $D_s$ is in millimeters.

For solid phase, $m_s$ depends on the bulk density of the hydrometeor ($\rho$). Following the approach of Fujiki et al. (1994) by applying the Maxwell-Garnett (1904) mixing rules for an air–ice mixture, and using the complex refractive index of Gunn and East (1954) for ice at $0^\circ$C, regression equations of $m_s$ on $\rho$ over the range of 0.01 to 0.92 g cm$^{-3}$ were determined for the real part.
Re(m_i) = 1 + 0.6791\rho_s + 0.0913\rho_s^2 + 0.0418\rho_s^3 \\
+ 0.0554\rho_s^4 

(6a)

and the imaginary part Im(m_i):

Im(m_i) = -0.0012\rho_s - 0.0015\rho_s^2. 

(6b)

Marshall and Gunn (1952) showed that the backscattering cross section of a spherical solid hydrometeor is proportional to the square of its ice mass, independent of its density \( \rho_i \), provided that its size, \( D_s \), is in the Rayleigh scattering region, that is, both \( \pi D_s/\lambda \ll 1 \) and \( |m_i| \pi D_s/\lambda \ll 1 \), where \( \lambda \) is the radar wavelength.

To determine the validity of the Rayleigh approximation for any hydrometeor with diameter \( D_m \) it is necessary to specify \( \rho_i \) to calculate \( D_s \) using

\[ D_s = (\rho_w/\rho_i)^{1/3}D_m, \]

(7a)

where \( \rho_w = 1.0 \text{ g cm}^{-3} \) is the density of liquid water. Alternatively, \( D_s \) can be expressed in terms of \( D_s \), the diameter of an ice sphere of the same mass, by

\[ D_s = (\rho_i/\rho_s)^{1/3}D_m. \]

(7b)

where \( \rho_i = 0.92 \text{ g cm}^{-3} \) is the density of ice. Magono and Nakamura (1965) estimated from measurements including both wet and dry aggregates the relationship

\[ \rho_s = 2D_s^{-2}, \]

(8a)
equivalently, by substitution of (7a),

\[ \rho_s = 8D_m^{-6}, \]

(8b)

where \( D_s \) and \( D_m \) are in mm and \( \rho_s \) is in g cm\(^{-3}\). When the wet aggregate data are excluded from Fig. 3 of Magono and Nakamura (1965) we estimate the relationships for dry aggregates:

\[ \rho_s = 0.162D_s^{-1}. \]

(9a)

\[ \rho_s = 0.065D_m^{-1.5}. \]

(9b)

Fabry and Szymcer (1999) found the same exponents by a similar process.

For single crystals, \( \rho_s \) are given in Table 2 of Rasmussen et al. (1999). Unlike for aggregates, for each crystal habit a constant density is assumed over the corresponding range of sizes given in his Table 2.

The validity of the Rayleigh criteria is evaluated for the scattering angle (approximately 130°) at the location in the measurement volume where the product of the antenna gains and the inverse distance squared factors in (1) is a maximum. The ratio of \( \sigma \) for hydrometeors of specified \( D_s, \rho_i \), and shape, to \( \sigma \) for a spherical hydrometeor of the same ice mass, is given in Fig. 3 as a function of \( D_l \) and \( D_m \). The numbers near the symbols are the \( D_l \) values calculated using (7b).

Aggregates and lump graupel are approximated here as spheres. For sizes in the Rayleigh scattering range, the \( \sigma \) ratio is 1 regardless of \( \rho_i \), confirming Marshall and Gunn (1952). For the range of \( D_l \) shown here, the ratio decreases from 1 as \( D_l \) increases and enters the Mie scattering range. The value of \( D_l \) at which this starts to occur depends on \( \rho_i \) according to (7b). Aggregates with densities varying according to (8b) or (9b) start to exceed the Rayleigh criteria at about \( D_l = 1.5 \text{ mm} \) (\( D_s = 1.5 \text{ mm} \)) and \( D_l = 1 \text{ mm} \) (\( D_s = 2.5 \text{ mm} \)), respectively. For lump graupel of fixed density 0.3 g cm\(^{-3}\), the ratio decreases by about 10% at \( D_l = 3 \text{ mm} \) (\( D_S = 4.3 \text{ mm} \)).

The effect of changing the shape of the solid particle from that of a sphere is also shown in Fig. 3. The T-matrix software is capable of calculations for a limited variety of hydrometeor shapes (Mishchenko and Travis 1998). The \( \sigma \) ratio for a disc with aspect ratio (axis of rotation to diameter) \( AR = 0.1 \) and \( \rho_i = 0.9 \text{ g cm}^{-3} \) (representing a hex plate) is greater than 2 and also increases slightly over the range of \( D_l \) presented here. All other crystal types given in Fig. 2 were represented.
by oblate spheroids with AR = 0.1. For example, the σ ratio for a rimed dendrite with ρ = 0.58 g cm\(^{-3}\) is about 1.6, and increases slightly with size.

The Doppler signal produced by any hydrometeor of specified characteristics can be computed using the three components (radar constants, velocity vector, and σ) described above, for any path through the sampling volume. The weighting functions are calculated by averaging the simulated Doppler velocity spectra associated with a large number of trajectories spanning the sampling volume for a specified hydrometeor type and wind vector.

4. Precipitation estimation algorithms

The precipitation rate \( R \) (mm h\(^{-1}\)) is defined as the mass flux and given by

\[
R = 3.6 \times 10^{-3} \frac{\pi}{6} \int_{D_{\text{min}}}^{D_{\text{max}}} v(D_m) N(D_m) D_m^3 dD_m,
\]

(10)

where \( v(D_m) \) is the downward vertical component of the velocity (m s\(^{-1}\)) of the hydrometeor, \( N(D_m) \) is the number concentration per diameter interval (m\(^{-3}\) mm\(^{-1}\)), and \( D_{\text{min}} \) and \( D_{\text{max}} \) are the minimum and maximum diameters in the hydrometeor size distribution (HSD).

The factor \( 3.6 \times 10^{-3} \) converts the mass flux from units of mg m\(^{-2}\) s\(^{-1}\) to the more conventional mm h\(^{-1}\) assuming the density of liquid water is 1 g cm\(^{-3}\).

Another formulation of (10) that is used to estimate precipitation rate is

\[
R = 3.6 \bar{v}_w W,
\]

(11)

where \( W \) (g m\(^{-2}\)) is the hydrometeor water content of the air defined by

\[
W = 10^{-3} \frac{\pi}{6} \int_{D_{\text{min}}}^{D_{\text{max}}} N(D_m) D_m^3 dD_m,
\]

(12)

again assuming the density of liquid water is 1 g cm\(^{-3}\).

Here \( \bar{v}_w \) is the “mass-weighted mean downward component of vertical velocity” defined by

\[
\bar{v}_w = \frac{\int_{D_{\text{min}}}^{D_{\text{max}}} v(D_m) N(D_m) D_m^3 dD_m}{\int_{D_{\text{min}}}^{D_{\text{max}}} N(D_m) D_m^3 dD_m}.
\]

(13)

Equations (10)–(13) are general and do not assume a particular functional shape of the HSD, nor phase of the hydrometeors.

This paper presents results of POSS estimates of precipitation amounts derived by integration of 1-min-average rates determined using three different methods. The first is referred to as the mass flux (MF) method. \( N(D_m) \) is estimated by inverting (2) using predetermined weighting functions. The rate is calculated directly from (10). In practice lack of knowledge of the hydrometeor type, and the effects of the wind, make this method problematic in solid precipitation.

The second method is analogous to the so-called \( Z–R \) method used by large weather surveillance radars where a regression between the radar reflectivity factor \( Z \) and \( R \) is performed. Pulsed radars that have a fixed sampling volume for all particle sizes in the distribution can estimate \( Z \) directly from the measurement of the total received power regardless of the form of the HSD. However, the \( Z–R \) regression coefficients will depend on the form of the HSD.

The sampling volume of the POSS is different for each hydrometeor size. Therefore the 0th moment of the Doppler spectrum \( (P_0) \), generated by a distribution of drop sizes, is received from a distribution of sampling volumes; \( P_0 \) is not linearly related to \( Z \), but a second-order regression of log\( R \) on log\( P_0 \) can be used to estimate precipitation rate. This method is referred to as the “RP” method.

As for \( Z–R \), the RP regression coefficients will depend on the form of the HSD. For liquid, the Marshall–Palmer (MP) model (Marshall and Palmer 1948) is used

\[
N(D_m) = N_0 e^{-\lambda D_m},
\]

(14)

where \( N_0 = 8000 \) m\(^{-3}\) mm\(^{-1}\), \( \lambda = 4.1 \) \( R_{\text{MP}} \)\(^{0.21}\) mm\(^{-1}\), and \( R_{\text{MP}} \) is referred to here as the “MP model rate” in mm h\(^{-1}\). Different HSDs are generated by varying \( \lambda (R_{\text{MP}}) \) in (14). For each HSD, a pair of \( \log R \) and \( \log P_0 \) values is calculated from (10) and (2), respectively, assuming \( D_{\text{min}} = 5.34 \) mm, the maximum POSS measurement channel.

A second-order polynomial regression of \( \log R \) on \( \log P_0 \) (Fig. 4) is used for the liquid precipitation data analysis of section 7a.

The effect on the regression of truncating the HSD in (10) and (2) at values of \( D_{\text{min}} \) corresponding to POSS measurement channel diameters <5.34 mm was evaluated. Different HSDs were generated with uniform probability by assigning values of \( D_{\text{min}} \) equal to each of the 34 POSS channel diameters. A second-order polynomial regression of data generated in this way has a standard error of estimate of \( \log R \) of 0.18, which corresponds to a factor of 1.5 for \( R \). This regression was not used in the analysis.

For solid precipitation, the assumed size distribution is the Sekhon–Srivastava (1970) model for snow, which has the same exponential form as (14), but with \( N_0 = 2500 \) \( R_{\text{SS}} \)\(^{-0.94}\) m\(^{-3}\) mm\(^{-1}\), and \( \lambda = 2.29 \) \( R_{\text{SS}} \)\(^{-0.45}\) mm\(^{-1}\).
Here $R_m$ is the model water equivalent rate in mm h$^{-1}$. Note that the diameter given in the Sekhon–Srivastava (1970) model is $D_m$. As for the liquid case, different HSDs are generated by varying $\lambda(R_m)$, but for solid precipitation the effect of variations of $D_{\text{max}}$ was included in the calibration used in the analysis of section 7b. Each of the seven solid hydrometeor types is used to generate data pairs of log $R$, log $P_0$ shown in Fig. 4. For aggregates, the $D_i$ versus $P_i$ relationships for both the wet and dry (8b) and the dry only (9b) are used to calculate $P_0$. A single composite second-order polynomial regression of log $R$ on log $P_0$ was determined for solid precipitation. The standard error of estimate of log $R$ is 0.15, which corresponds to a factor of 1.4 for $R$.

A third estimation method, using (11), was developed to directly incorporate the Doppler velocity information. This method will be referred to as the “RPV” method. It is similar in principle to one proposed by Ulbrich (1992) for liquid precipitation. It approximates the mass flux but is less sensitive to wind effects. From computer model simulations, it can be shown that $P_0$ is relatively unaffected by the wind and is correlated to $W$ in (12). The parameter $\bar{v}_m$ in (13) is not directly measured by the POSS. The POSS measures both the first moment of the Doppler velocity spectrum (the power weighted mean velocity) and the velocity at the mode of the Doppler spectrum. The first moment is affected by horizontal winds because of the bistatic geometry of POSS. The magnitude of the mode velocity can be used to estimate $\bar{v}_m$ in (13) because it is relatively insensitive to horizontal winds, and vertical winds are small near the surface. Using the same HSDs as in the RP method, a regression of $W$ on $P_0$ is first established. Then a second regression is performed between $R$ and the product of the mode velocity and $W(P_0)$ estimated from the first regression.

### 5. Validation references

Internationally recognized references, with specified measurement uncertainty, are all manual gauges and can only measure the water equivalent accumulated amount of precipitation over periods of several hours, and do not and cannot accurately measure average rate over time scales in the order of minutes required for high temporal resolution applications. International reference gauges were available at the Centre for Atmospheric Research Experiments (CARE) test site at Egbert, Ontario, Canada. Canadian national standards were used at six other sites. They were also compared to the international standards at Egbert as part of the validation procedure.

#### a. Liquid precipitation

The “pit gauge” (Fig. 5) was the reference gauge used in the second World Meteorological Organization (WMO) intercomparison of national precipitation gauges (Sevruk and Hamon 1984). The pit gauge used in this validation consisted of a Canadian “Type B” national standard liquid precipitation gauge (orifice area =100 cm$^2$) installed in a 1.5-m square pit about 0.5 m deep with a gravel base. The pit was covered with a metal grid to inhibit splashing. The gauge was mounted so that its orifice was at the height of the upper surface of the grid in order to minimize the effects of wind. Sevruk (1981) estimates that the uncertainty of the pit gauge is about 2%, if no correction is applied for losses due to “wetting” of the gauge. The pit gauge observations at the Egbert test site were made twice daily.

At the other sites, the reference amounts are daily manual observations using the Type B gauge mounted on the surface with the orifice at about 0.4 m. The Type B mounted on the surface underestimates the pit gauge by <2% and has an uncertainty of about 6% for amounts <5 mm and 3% for amounts ≥5 mm (K. DeVine 2007, personal communication).

#### b. Solid precipitation

The Double Fence Intercomparison Reference (DFIR) (Fig. 6) was developed as part of the WMO
Solid Precipitation Measurement Intercomparison (Goodison et al. 1998) as a secondary standard for the measurement of solid precipitation. The primary standard, against which it was calibrated, is a Tretyakov gauge in a bush at Valdai in the Russian Federation. The DFIR is a manual Tretyakov gauge with an “Alter” type shield mounted at the center of two concentric octagonal fences, the outer one of which is about 12 m in diameter. Golubev (1986) determined that the DFIR measured between 92% and 96% of the primary reference “bush gauge” at Valdai. Observations were made twice daily using the DFIR at Egbert.

At other sites, manual measurements using the standard Canadian snow gauge with a Nipher wind shield (Fig. 7) are used for the reference amounts. Its performance with respect to underestimation bias due to wind effects was found to be the best of all the participating gauges in the WMO intercomparison (Goodison et al. 1998). The uncertainty in the Nipher shielded snow gauge measurements, after correction for wind bias, is estimated from Goodison et al. (1998) to be about 7%. This is consistent with the performance of the Nipher shielded snow gauge compared to the DFIR at Egbert (summarized in Table 2).

6. Data analysis

Data were collected from seven sites across Canada. The research sites at Egbert, Pearson International Airport (YYZ) at Toronto, and Downsview are all in southern Ontario. The other sites were ones used during a 1-yr evaluation of the Canadian AWOS conducted in 1995–96 (Aviation AWOS Performance Evaluation Group 1997). They were selected to represent the diverse Canadian climate including maritime, continental, and mountainous environments.

Qualified meteorological observers were used to define the precipitation type. Their reports were examined for each accumulation period to determine if the event was liquid, solid, or mixed. A separate analysis is performed for liquid and solid precipitation events. Periods when the observer reported mixed precipitation are excluded from the current analysis.

The MF, RP, and RPV methods are used to estimate the average water equivalent precipitation rate each minute. At the Egbert site, in liquid precipitation, two separate MF analyses were performed for comparison purposes. The first used weighting functions assuming calm conditions and the second used weighting functions appropriate to the 1-min-average wind speed measured at the sensor height. At the other sites, weighting functions specific to the wind speed were used. At all sites except Egbert, the anemometer measurement was at 10 m. The wind speed at the POSS height of 3 m was estimated, using a logarithmic wind profile law given in Yang et al. (1998), to be about 79% of the 10-m value.

The 1-min-average POSS estimates were accumulated over the time period between measurements by the observer. Reference measurements of less than 1-mm accumulation are excluded because of the uncertainty in manual observations of small quantities of precipitation due to evaporation and wetting losses. However, it is important to note that the POSS can estimate rates as low as 0.001 mm h\(^{-1}\) in liquid precipitation and 0.002 mm h\(^{-1}\) water equivalent in solid precipitation. For example, a frequency distribution of 1-min-average water equivalent rates in solid precipitation is given in Fig. 8 for the winter of 1997/98 at the Egbert test site. Low intensity rates are the most common and are important to many applications such as nowcasting for aircraft anti-icing requirements (Rasmussen et al. 2001).
The dispersion of the logarithm of amounts, measured by POSS or other gauges, as a function of the logarithm of reference amounts (e.g., Fig. 9a) is approximately uniform over the entire reference range indicating that the measurement errors are fractional rather than absolute. For this reason the performance of precipitation gauges is frequently described by the “catch ratio” of the sensor estimate to the reference observation amount. Outliers can strongly influence statistics such as the mean and standard deviation, and therefore, quartile statistics are used to describe the distribution (Wilks 1995). The median catch ratio ($Q_2$) is an indicator of the bias. The interquartile range (IQR) is the difference of the third ($Q_3$) and first ($Q_1$) quartiles and is a measure of the dispersion of the distribution. These statistics for some of the estimation methods for liquid and solid precipitation are given in Tables 1 and 2, respectively. Note that if all values in the distribution are systematically underestimated then the IQR will also be underestimated by the same percentage.

7. Results and discussion

a. Liquid

1) Effect of Wind

Figures 9a and 9b compare accumulated amounts of liquid precipitation estimated using the MF and RP methods to those measured by the pit gauge (>1 mm) at the Egbert test site from September 1997 to April 2004. The RPV method produced results very similar to the RP method. The data are classified according to the maximum of the 1-min-average wind speed at sensor height, during the accumulation period. At low wind speeds (<6 m s$^{-1}$), the MF data (Fig. 9a) show less dispersion than the RP distribution, with the exception of some outliers discussed below. At higher wind speeds (>6 m s$^{-1}$), the MF method (Fig. 9b) overestimates more frequently than the RP method.

Horizontal winds will increase the second moment of $S(f)$ (the Doppler velocity spectrum) in (2) due to the bistatic antenna geometry. If $S(f)$ is inverted using weighting functions for calm conditions, the resultant $N(D_m)$ will have an excess number of the smallest and largest diameter raindrops, which causes an overestimation of the MF rate (Sheppard and Joe 1994). The vertical winds near the surface are small and do not affect the results. The RP method is more robust than the MF method at large wind speeds because it is independent of the second moment of the Doppler spectrum. It depends only on the 0th moment of the Doppler spectrum, which is less affected by horizontal wind.

The analysis was repeated using weighting functions in (2) that were specific to the wind conditions. This method is designated MF*. Figure 10 shows the same
data as in Fig. 9b (wind speed $\geq 6$ m s$^{-1}$) with and without wind correction. The wind-adjusted weighting functions reduced the magnitude of the overestimation, but only marginally.

The degree to which wind affects the accumulated amount will depend on the climatology of the site. As with conventional gauges, it may be possible to reduce the wind effect by using appropriate shielding, but care must be taken to avoid any motion of the shield that might be detected by the POSS.

### 2) EFFECT OF SPLASHING

The MF method sometimes overestimates, regardless of wind speed, as seen in Fig. 9a. Raindrops impacting the radomes may splash into the sampling volume and produce a low Doppler velocity artifact. The inversion algorithm then converts this artifact to an excessively large number of small diameter drops. This is filtered by signal processing. In high intensity events, this filter is not completely effective. Analysis of the outliers in Figs. 9a and 9b revealed that even a brief period of high intensity rate can cause large overestimation. As for the case of horizontal winds, the RP method is less affected by splashing than the MF method. However, it cannot distinguish power generated by the incoming raindrops (signal) from that generated by the splash (noise), so there will still be some overestimation.

### 3) OTHER SOURCES OF ERROR

Figures 9 and 10 show that on average the POSS underestimates the pit gauge. Both methods also show some underestimation outliers that were identified as extended periods of very light drizzle that were accumulated by the pit gauge but not detected by POSS. Figure 11 excludes these outliers and those caused by splashing in order to evaluate the relationship between the underestimation and precipitation rate. Figure 11 is a plot of the MF* catch ratio as a function of the average precipitation rate for the accumulation periods belonging to the low wind speed data subset. The average...
is defined as the pit gauge amount divided by the total number of minutes that the POSS detected precipitation. The calculation of the average pit gauge rate is independent of the POSS rate estimation. In general, the data show a power-law relationship, with negative exponent, between the catch ratio and average pit gauge rate.

One possible cause of the underestimation is absorption by water on the radomes. This loss is well known for weather surveillance radars and can also be verified from laboratory measurements with the POSS. It depends on the surface properties of the Lexan material. The calibration simulation assumed that there were no radome losses, that is, \( L_w = 1 \) in (1).

A power-law regression of catch ratio on the average pit gauge rate is shown in Fig. 11 for the Egbert data. It was found that the exponent of the power-law regression was similar from site to site but the coefficient varied.

Once the source of the underestimation as a function of precipitation rate is understood, a correction can be applied to the 1-min-average rates, but in this paper the statistics are presented without corrections.

4) QUARTILE STATISTICS

The liquid precipitation catch ratios from the Egbert test site for the period from September 1997 to April 2004 using the MF* (wind corrected), RP, and RPV methods compared to the pit gauge reference are shown in Fig. 12. For comparison, statistics are also given for the manual Type B, and an unheated automated Geonor weighing gauge with Alter shield, for the period from January 1998 to April 2004. The Geonor is used in the automated Canadian surface network. Figure 12 is a “box plot” where the lower and upper ends of the box are drawn at Q1 and Q3, respectively, and the bar through the box at Q2. The lower and upper ends of the vertical line are drawn at the minimum value \( (Q1 - 1.5 \text{ IQR}) \) and the maximum value \( (Q3 + 1.5 \text{ IQR}) \), respectively. Data outside this range are considered outliers and are represented by crosses.

As expected, the Type B manual gauge performed the best with no underestimation bias (as represented by the median catch ratio) and the IQR was only 4%. The Geonor underestimated the pit gauge by about 9% with an IQR of about 15%. The POSS underestimated by about 18% with an IQR of 31%.

Table 1 gives the quartiles of the frequency distribution of catch ratios including the outliers for all test sites where the number of data is significant. All median ratios are less than one. The range of median catch ratios amongst the sites exceeds the manufacturer’s calibration tolerance of \( \pm 7\% \). The variability of the radome losses discussed in section 7a(3) is a possible explanation.

The distributions are positively skewed, that is, \( (Q3 - Q2) > (Q2 - Q1) \). The distribution using the wind-corrected MF* method has the lowest dispersion as measured by the IQR statistic \( (Q3 - Q1) \) at all sites except at YXT where the RP method was slightly better. The regression methods, when compared to the MF method, reduce the number of overestimation outliers caused by the wind, or by splashing on the radomes (see
Figs. 9a and 9b). The MF method reduces the under-
estimation catch ratio range $Q_2 / H_{11002} Q_1$ compared to the
regression methods. Regression methods are subject to the same source of
error that can occur when using the $Z - R$ estimation
method used by weather surveillance radars. If the ac-
tual $N(D_m)$ provided by nature does not match the hy-
pothetical model used to establish the regression coef-
ficients, then errors result. For these datasets this oc-
curs most frequently in drizzle or light rain resulting in
underestimation as seen in Figs. 9a and 9b. The inclu-
sion of the mode velocity in the RPV regression slightly
increased the IQR for liquid precipitation.

At the YYZ site only, the reference measurements

TABLE 1. Statistics for the distribution of catch ratios of the Type B manual gauge, the Geonor weighing gauge, and the POSS to the reference gauge at several sites in liquid precipitation. Different POSS estimation methods are compared. $Q_1$, $Q_2$, and $Q_3$ are the first quartile, median, and third quartile of the catch ratio distribution, respectively. $IQR = Q_3 - Q_1$. MF* = mass flux estimation method with weighting functions corrected for wind speed.

<table>
<thead>
<tr>
<th>Site</th>
<th>Period</th>
<th>Reference frequency of obs</th>
<th>Method</th>
<th>No. of obs</th>
<th>$Q_1$</th>
<th>$Q_2$</th>
<th>$Q_3$</th>
<th>IQR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Egbert, ON</td>
<td>Jan 1998–Apr 2004</td>
<td>Pit twice daily</td>
<td>Type B</td>
<td>295</td>
<td>0.96</td>
<td>1.00</td>
<td>1.00</td>
<td>0.04</td>
</tr>
<tr>
<td>Egbert, ON</td>
<td>Jan 1998–Apr 2004</td>
<td>Pit twice daily</td>
<td>Geonor with Alter shield</td>
<td>295</td>
<td>0.82</td>
<td>0.91</td>
<td>0.97</td>
<td>0.15</td>
</tr>
<tr>
<td>Egbert, ON</td>
<td>Sep 1997–Apr 2004</td>
<td>Pit twice daily</td>
<td>MF</td>
<td>278</td>
<td>0.72</td>
<td>0.86</td>
<td>1.07</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>MF*</td>
<td>278</td>
<td>0.70</td>
<td>0.82</td>
<td>1.01</td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>RP</td>
<td>278</td>
<td>0.66</td>
<td>0.81</td>
<td>1.02</td>
<td>0.36</td>
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<td></td>
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<td>RPV</td>
<td>278</td>
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<td>0.78</td>
<td>1.02</td>
<td>0.41</td>
</tr>
<tr>
<td>YYZ Toronto, ON</td>
<td>Nov 1995–Aug 2003</td>
<td>Type B 6 h</td>
<td>MF*</td>
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<td>1.00</td>
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<td></td>
<td>RP</td>
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<td>0.82</td>
<td>1.07</td>
<td>0.43</td>
</tr>
<tr>
<td>YYZ Toronto, ON</td>
<td>Nov 1995–Aug 2003</td>
<td>Type B 24 h</td>
<td>MF*</td>
<td>444</td>
<td>0.69</td>
<td>0.80</td>
<td>1.02</td>
<td>0.33</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td>RP</td>
<td>444</td>
<td>0.69</td>
<td>0.87</td>
<td>1.05</td>
<td>0.36</td>
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<td></td>
<td></td>
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<td>1.05</td>
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<tr>
<td>DOW Downsvie, ON</td>
<td>Nov 1997–Feb 2004</td>
<td>Type B 24 h</td>
<td>MF*</td>
<td>353</td>
<td>0.85</td>
<td>0.95</td>
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<td>RP</td>
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<tr>
<td>YQV Yorkton, SK</td>
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<td>Type B 24 h</td>
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<td>YXT Terrace, BC</td>
<td>Oct 1995–Aug 1996</td>
<td>Type B 24 h</td>
<td>MF*</td>
<td>75</td>
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<td>0.86</td>
<td>1.01</td>
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<td></td>
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<td>RP</td>
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<td>0.74</td>
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<td>1.04</td>
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</tr>
<tr>
<td>YQM Moncton, NB</td>
<td>Sep 1995–Aug 1996</td>
<td>Type B 24 h</td>
<td>MF*</td>
<td>61</td>
<td>0.52</td>
<td>0.63</td>
<td>0.77</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>RP</td>
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<td>0.44</td>
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<td>0.77</td>
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<td>0.39</td>
<td>0.62</td>
<td>0.74</td>
<td>0.35</td>
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</table>

TABLE 2. Statistics for the distribution of catch ratios of the Nipher shielded manual gauge, the Geonor weighing gauge, and the POSS to the reference gauge at several sites in solid precipitation. Different POSS estimation methods are compared.

<table>
<thead>
<tr>
<th>Site</th>
<th>Period</th>
<th>Reference frequency of obs</th>
<th>Method</th>
<th>No. of obs</th>
<th>$Q_1$</th>
<th>$Q_2$</th>
<th>$Q_3$</th>
<th>IQR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Egbert</td>
<td>Jan 1998–Apr 2004</td>
<td>DFIR twice daily</td>
<td>Manual gauge with Nipher shield</td>
<td>135</td>
<td>0.81</td>
<td>0.91</td>
<td>1.00</td>
<td>0.19</td>
</tr>
<tr>
<td>Egbert</td>
<td>Jan 1998–Apr 2004</td>
<td>DFIR twice daily</td>
<td>Geonor with Alter shield</td>
<td>135</td>
<td>0.43</td>
<td>0.66</td>
<td>0.86</td>
<td>0.43</td>
</tr>
<tr>
<td>Egbert</td>
<td>Nov 1997–Apr 2004</td>
<td>DFIR twice daily</td>
<td>RP</td>
<td>108</td>
<td>0.61</td>
<td>0.79</td>
<td>1.06</td>
<td>0.45</td>
</tr>
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<td></td>
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<td></td>
<td>RPV</td>
<td>108</td>
<td>0.73</td>
<td>0.90</td>
<td>1.14</td>
<td>0.41</td>
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<td>YYZ</td>
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<td>Nipher 6 h</td>
<td>RP</td>
<td>184</td>
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<td></td>
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<td>YYZ</td>
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<td>Nipher 24 h</td>
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<td>107</td>
<td>0.58</td>
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<td>0.95</td>
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<td></td>
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<td>RPV</td>
<td>107</td>
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<td>0.92</td>
<td>1.30</td>
<td>0.62</td>
</tr>
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<td>Nipher 24 h</td>
<td>RP</td>
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<td>1.16</td>
<td>0.54</td>
</tr>
<tr>
<td>YQV</td>
<td>Nov 1995–Oct 2003</td>
<td>Nipher 24 h</td>
<td>RP</td>
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<td>0.55</td>
<td>0.75</td>
<td>1.05</td>
<td>0.50</td>
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<td>YYC</td>
<td>Sep 1995–Aug 1996</td>
<td>Nipher 24 h</td>
<td>RP</td>
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<td>0.40</td>
<td>0.65</td>
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<tr>
<td></td>
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<td>0.63</td>
<td>0.93</td>
<td>0.56</td>
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</table>
were made every 6 h. The quartile statistics for the MF* method were similar for the 6- and 24-h periods but the regression methods underestimate the 6-h more than the 24-h amounts.

b. Solid

Figure 13 compares the DFIR observations from the Egbert site to POSS estimates using the RP and RPV methods for the period from September 1997 to April 2004. The distributions are similar except that the RPV method is in better agreement with the DFIR for higher accumulated amounts.

1) EFFECT OF WIND

As mentioned above, manual and automated weighing gauges have larger uncertainty in the measurement of solid, compared to liquid precipitation, primarily due to wind effects. For example, Fig. 14 shows a regression curve of catch ratio on wind speed for the Nipher shielded manual gauge as determined during the WMO Solid Precipitation Measurement Intercomparison (Goodison et al. 1998).

For POSS, wind affects the MF estimation method more significantly in snow than rain and these results are not presented here. A horizontal wind as low as 1 m s$^{-1}$ will cause a solid particle falling at a terminal velocity of 1 m s$^{-1}$ to traverse the sampling volume at
an angle of 45° from vertical. Because raindrops fall at much greater terminal velocities, their trajectories remain closer to vertical. Therefore both horizontal and vertical winds will have a greater effect on the weighting functions in snow than rain. Even if the weighting functions appropriate to the 1-min-average wind speed were applied in (2), the effects of turbulence are likely to be more problematic than for rain.

The regression methods show no correlation with wind speed as seen in the example of the RP method in Fig. 14, because the 0th moment and the mode velocity of the Doppler spectra are relatively unaffected by horizontal winds.

2) EFFECT OF TEMPERATURE

POSS estimates are affected by the well known “brightband” effect seen by weather surveillance radars. Melting snowflakes can have complex ice, water, and air morphologies (Fabry and Szyrmer 1999). The $\sigma$ can be significantly larger than those used in the calibration simulations for “dry snow” of section 3. Figure 15 shows this effect for 6-h accumulation periods at YYZ when the maximum air temperatures were near 0°C.

3) OTHER SOURCES OF ERROR

Similar to Fig. 11 for liquid precipitation, Fig. 16 gives the catch ratio in solid precipitation versus the average water equivalent precipitation rate from the DFIR during each accumulation period for the Egbert data. The power-law regression fit for solid precipitation has a more negative exponent than for liquid. The cause of this is unknown and requires further study. It may indicate inadequacies in the HSD models used for either the liquid or solid precipitation, or both. Another possibility is differences in the radome wetting process for liquid and solid precipitation. The radomes are heated at ambient temperatures below freezing and some forms of solid precipitation will melt and remain as liquid on the radome while other types may bounce off the radomes before melting. As for liquid, the exponent of the power law is similar for most sites but the coefficient varies.

4) QUARTILE STATISTICS

Figure 17 compares the quartile statistics and outliers for the RP and RPV methods at the Egbert test site for the period from September 1997 to April 2004 to those for the manual gauge with Nipher shield and an unheated automated Geonor weighing gauge with Alter shield for the period from January 1998 to April 2004. As expected the Nipher gauge performed the best. The median catch ratio underestimated the DFIR by...
about 9% and the IQR = 19%. The POSS RPV method had significantly less underestimation than the Geonor.

Table 2 also gives the POSS quartiles statistics at other sites if the number of observations was significant. The median of the distribution of catch ratios using the RPV distribution was closer to 1 than for the RP method at five of the six sites. As for liquid, the range of median values at the different sites exceeded that expected from calibration tolerances alone.

The catch ratio distributions were positively skewed, with RPV method more skewed than the RP method. The RP interquartile ranges were consistent with the standard error of estimate given for the RP regression determined in Fig. 4.

8. Conclusions

We have quantified the performance of POSS as a precipitation gauge by comparing amounts determined by integration of 1-min-average POSS rates with accumulations over periods of 6 h and greater measured by observers using both international and Canadian national manual reference gauges at several sites over several years. This is a necessary condition for the validation of high temporal resolution rates.

For all estimation methods, in both liquid and solid precipitation, the POSS underestimates the reference gauge as indicated by the median of the catch ratio frequency distribution. In liquid precipitation at five of six sites, the wind-corrected mass flux (MF) estimation method has a smaller dispersion (IQR) of catch ratios compared to the regression estimation methods. Using the pit gauge as a reference, the median of catch ratios is 82%. The IQR is −12% to +19% about the median value. Overestimation caused by horizontal wind becomes significant at speeds greater than 6 m s⁻¹. Splashing of raindrops on the radomes during very high intensity events can result in large overestimation of rate. Estimation methods using regression of precipitation rate on the 0th moment (RP method) or on both the 0th moment and the mode velocity of the Doppler spectrum (RPV) reduce some cases of overestimation by the MF method caused by splashing or wind, but have a larger uncertainty than the MF method at lower wind speeds.

The POSS’s performance in solid precipitation was comparable or superior to the Geonor weighing gauge used in automated Canadian networks. The median of the catch ratios using RPV method is 90% and the IQR is −17% to +24% about this value when the DFIR is the reference. This dispersion is consistent with that determined from an RP regression analysis and is due to both the variability caused by hydrometeor type and distribution.

At the sites using the Nipher shielded gauge as the

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Fig. 15. Ratio of POSS RP estimate to 6-h Nipher gauge observations at YYZ in solid precipitation as a function of the maximum temperature during the accumulation period showing “bright band” effect.

Fig. 16. Ratio of RP POSS estimates in solid precipitation to the DFIR observation at Egbert as a function of the average DFIR precipitation rate during accumulation period. The dashed line is the regression line shown in Fig. 11 for the corresponding relationship in liquid precipitation.
reference, the RP method gave substantially lower dispersion of catch ratios than the RPV method, but the median also showed greater underestimation. There are larger uncertainties using the MF method in solid than in liquid precipitation due to the lack of knowledge of the hydrometeor density and shape, and the greater effect of wind.

For both liquid and solid precipitation the underestimation is a function of the average precipitation rate measured by the reference gauge over the accumulation period. This may be due to absorption losses caused by radome wetting. In general, the underestimation in solid precipitation is greater than in liquid. Additional research is required to better understand this effect so that a correction factor can be applied to the 1-min-average precipitation rate estimates.

In spite of the underestimation, for high temporal resolution nowcasting applications, the sensitivity of POSS to extremely low precipitation rates in both liquid and solid precipitation is a significant advantage over conventional weighing gauges. The question of how well the POSS measures 1-min-average precipitation rates awaits a suitable reference. Preliminary comparisons of different technologies that output high temporal resolution precipitation rates (e.g., the Hotplate) have been made but not reported here. The good correlation between the different technologies indicates that these instruments are able to measure precipitation rates at minute time scales.

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REFERENCES


