Wind Tunnel Tests of the Airborne PVM-100A Response to Large Droplets

M. WENDISCH
Institute for Tropospheric Research, Leipzig, Germany

T. J. GARRETT
Department of Atmospheric Sciences, University of Washington, Seattle, Washington, and Meteorology Department, University of Utah, Salt Lake City, Utah

J. W. STRAPP
Meteorological Service of Canada, Downsview, Ontario, Canada

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ABSTRACT

The Gerber Scientific, Inc. Particle Volume Monitor (PVM) is widely used to measure the liquid water content (LWC) and droplet effective radius \( r_{\text{eff}} \) of water clouds. The LWC response of the airborne version of this instrument, the PVM-100A, was evaluated in two independent wet wind tunnel experiments under well-controlled conditions. Earlier studies predict that the PVM-100 (the ground-based version of the PVM) theoretical response to monodisperse droplets diminishes for droplet diameters larger than about 40 \( \mu \text{m} \). However, results from the wind tunnel experiments presented in this paper show that the response of the PVM-100A to monodisperse droplets begins to decrease when the droplet diameter is between 20- and 30- \( \mu \text{m} \) diameter. For polydisperse droplet populations (such as those found in natural clouds) the efficiency of the airborne PVM-100A for sensing LWC begins to decrease when the median volume diameter (MVD) of the droplet size distribution is above 20 \( \mu \text{m} \), falling to 50% efficiency for an MVD of 50 \( \mu \text{m} \). Therefore, measurements of LWC obtained from the PVM-100A in natural clouds with broad droplet size distributions (and large values of MVD) should be treated with caution.

1. Introduction

The PVM (Particle Volume Monitor, manufactured by Gerber Scientific, Inc., Reston, Virginia) is a compact and durable optical instrument used to measure liquid water content (LWC) and to derive \( r_{\text{eff}} \) (droplet effective radius) in water clouds. In contrast to single particle counters [such as the Particle Measurement Systems (PMS) FSSP-100, Forward Scattering Spectrometer Probe, see, e.g., Cerni (1983)], which detect laser light scattered by single droplets, the PVM measures laser light (wavelength \( \sim 780 \text{ nm} \)) scattered by an ensemble of droplets passing through the sample volume of the probe. A portion of laser light scattered in the forward direction is collected by a system of lenses and directed through two spatial filters. The first filter converts scattered light to a signal proportional to the particle volume density (or LWC) of droplets within the probe’s sample volume; the second filter produces a signal proportional to the particle surface area density (PSA). From the ratio of these two quantities \( r_{\text{eff}} \) is derived. The signals measured behind the two filters are exactly proportional to LWC and PSA for only a limited range of droplet sizes, as determined by the precise design of the spatial filters. For a detailed description of PVM operating principles the reader is referred to Wertheimer and Wilcock (1976), Blyth et al. (1984), Gerber (1984, 1991), and Gerber et al. (1994).

The two most commonly used versions of the PVM are the ground-based PVM-100 and the airborne PVM-100A. The spatial filter characteristics of these probes are designed to weight scattered light such that the photodetector signal is directly proportional to LWC or PSA for a wide range of particle sizes. The spatial filter characteristics of the PVM-100 and PVM-100A are obtained using the same numerical inversion technique (Gerber 1991; Gerber et al. 1994). However, the inversion should yield different spatial filter characteristics since the instrument optics and geometry of the PVM-100 and PVM-100A differ. The theoretical response function for the ground-based PVM-100 is 100% for monodisperse droplets with diameters between 4 and about 40 \( \mu \text{m} \),
An evaluation of the accuracy of measurements of LWC from the PVM-100A was conducted in two separate wind tunnels: the National Aeronautics and Space Agency (NASA) Icing Research Tunnel (Cleveland, Ohio) and the NASA Tunnel of Canada Altitude Icing Wind Tunnel (Ottawa, Canada). The NASA tunnel uses an icing blade, and the NRC Tunnel a rotating icing cylinder as reference techniques for calibrating values of LWC within the tunnels. These techniques determine tunnel LWC based on the amount of ice accreted on a blade or rod during a specific time interval. Stallabrass (1978) performed an error analysis on the factors affecting the rotating icing cylinder measurement, and implied that
an absolute accuracy of a few percent should be achievable, and that icing blade measurements were of similar accuracy. Additional errors arise from variations in the repeatability of conditions within the respective tunnels. STR have reported on the comparisons of icing blade and icing cylinder LWC measurements in the NASA tunnel. The authors estimate an overall scaling uncertainty in reference LWC for a population of test points of the order of 5%, with a random scatter dispersion of approximately 3.5% for individual 2-min-averaged test points due to tunnel repeatability.

Both tunnels provide liquid sprays with repeatable values of MVD. These values of MVD can be determined from accurate measurements of the size distribution of droplets within the tunnel. In the NASA tunnel, MVD calibrations for different spray settings were previously established using PMS FSSP-100 and one-dimensional optical array probes (OAPs) (Knollenberg 1981). For this study, however, values of MVD were determined using composite droplet size distributions obtained combining data from a phase Doppler particle analyzer (PDPA; Bachalo 1980) and OAP (OAP-2DC and OAP-2DP) measurements (see STR). Large discrepancies were observed between the values of MVD obtained from the NASA calibration and the corresponding values measured by the combined PDPA and OAPs for identical spray settings. For several reasons, discussed in detail by STR, the original MVD calibration performed by NASA has not been used, but instead values of MVD derived from the composite droplet size distributions obtained using PDPA and OAP measurements have been adopted. The accuracy of MVD estimates for this set of composite spectra is estimated roughly at ±10% for test points below 29.5-μm MVD, degrading to ±30% for the test points between 30.8- and 128.6-μm MVD, and improving to ±10% for the 216- and 236-μm test points. Discrepancies with the NASA standard MVDs exceed these values, especially in the intermediate MVD range, and the reader is referred to STR for further discussion.

In the NRC tunnel, values of MVD for different spray settings have been derived from droplet size distributions measured by a Malvern 2600c Droplet and Particle Size Analyser (Swithinbank et al. 1977). The Malvern device is inherently calibrated from basic diffraction principles without resorting to a reference standard (Dodge and Rhodes 1987). Spray droplets pass through a laser beam and diffract light onto a lens, which is focused on a sensor. The intensity and location of the light on the sensor is a function of droplet concentration and size. The Malvern 2600c was calibrated with a reference reticle prior to and following the wind tunnel studies at the NRC tunnel. Hirleman and Dodge (1985) show the average error in values of \( r_{\text{MVD}} \) obtained from the Malvern, based on 20 measurements of a reference reticle, is 2.7%. An intercomparison in the NRC wind tunnel of PDPA and the Malvern 2600c measurements of the MVD of droplet sprays (M. Oleskiw 2001, personal communication) showed the two probes to be well correlated between 12- and 60-μm MVD. The Malvern’s MVD estimates were about 5 μm smaller than those from the PDPA at the low end of this range, but were in agreement at the upper end.

The NASA PVM-100A tests were conducted during three days of experiments in September/October 1998. Altogether, about 150 runs with different spray conditions in warm (0°C) and cold (−6°C) environments at two air speeds (67 and 100 m s\(^{-1}\)) were carried out with the National Center for Atmospheric Research (NCAR) PVM-100A (serial no. 013). The tunnel LWC varied between 0.23 and 1.41 g m\(^{-3}\). The NRC PVM-100A data were collected in April 1999 with the University of Washington (UW) PVM-100A (serial no. 003). The NRC wind tunnel provides the opportunity to test the PVM-100A over a wider range of LWC values than in the NASA tunnel. Icing cylinder measurements of LWC varied between 0.08 and 2.1 g m\(^{-3}\) during the NRC tests.

Values of LWC from the PVM-100A and wind tunnel reference technique discussed in this paper represent means, averaged over the time interval of the spray settings. The PVM-100A is an optical ensemble-particle probe, and as expected, no air speed dependence was observed in either the NASA or NRC dataset. Furthermore, no temperature dependence was detected in the experiments.

3. Measurements

a. Linearity of the response of the PVM-100A to LWC

The first goal of the experiments conducted in the NASA and NRC wind tunnels was to determine if the PVM-100A responds linearly over a wide range of values of LWC. Stepwise changes in LWC for various fixed values of MVD (so-called MVD sweeps) were conducted in the NASA and NRC wind tunnels. It was not practical to keep the MVDs exactly constant during an MVD sweep; therefore, the MVDs vary within a limited range. Figure 1 shows a comparison of PVM-100A and reference technique measurements of LWC in the NASA and NRC wind tunnels for three MVD sweeps, together with a least squares regression of the data. In the NASA tunnel a lower-range (MVD between 12.9 and 17.6 μm) and a higher-range (MVD between 29.5 and 32.5 μm; average 31 μm) MVD sweep was performed. In the NRC tunnel a 22-μm MVD sweep was carried out (±1 μm variability). The data in Fig. 1 show that LWC measurements from the PVM-100A and reference technique are well correlated in both tunnels. In the NASA tunnel, for the lower-range MVD sweep, the NRC PVM-100A is in excellent agreement with the icing blade standard. However, for the higher-range MVD sweep, measurements of LWC from the PVM-100A are significantly lower than from the reference...
Fig. 1. LWC measurements (MVD sweeps) obtained from the PVM-100A (LWC_{PVM}) as a function of tunnel calibration values (LWC_{TUNNEL}) for the lower-range (average value 15 μm) and higher-range MVD sweeps (average value 31 μm) in the NASA wind tunnel and the 22-μm MVD sweep (±1 μm variability) in the NRC wind tunnel. MVDs were determined using composite droplet size distributions from combined PDPA and OAP (NASA tunnel) and Malvern (NRC tunnel) measurements. The solid lines represent respective linear regression fits (constrained through the origin). Coefficients of determination values $r^2$ and slopes are given in Table 1. The two dashed lines with the slopes of 0.95 and 1.05 indicate the overall scaling accuracy of 5% estimated for the LWCPVMTUNNEL reference method.

Table 1 summarizes regression data for all MVD sweeps conducted in the NASA wind tunnel. Uncertainties in the measured values of MVD (determined from the standard deviation in MVD for different runs of the respective MVD sweep) and values of the coefficient of determination are given only for MVD sweeps with more than five runs. Although the data are limited, the results suggest LWC_{PVM} responds linearly to LWC_{TUNNEL} for values of MVD up to 30 μm. The slope of the regression decreases monotonically with the tunnel MVD. This suggests the response of the PVM-100A to LWC decreases for increasing MVD.

b. Measured PVM-100A efficiency function

To investigate the diminishing response of the PVM-100A to increasing MVD, all data collected in the wind tunnel experiments are used, including data from the MVD sweeps, to determine the “efficiency” of the PVM-100A, $E_{PVM}$, for a given setting of LWC_{TUNNEL} and MVD:

$$E_{PVM} = \frac{\text{LWC}_{PVM}(\text{LWC}_{TUNNEL}, \text{MVD})}{\text{LWC}_{TUNNEL}},$$

where LWC_{PVM} and LWC_{TUNNEL} represent LWC in the wind tunnel from the PVM-100A and reference method, respectively.

In Fig. 2, measured values of $E_{PVM}$ are plotted versus MVD. Previous measurements of PVM-100A efficiency from the ECN wind tunnel (Gerber et al. 1994) are included for comparison. The measured efficiency of the PVM-100A decreases logarithmically in both the NASA and NRC datasets. A least squares logarithmic regression to the data yields an efficiency function $E_{PVM}(\text{MVD})$, which expresses the sensitivity of PVM-100A response to droplet MVD. The regression shows the measured efficiency for the PVM-100A decreases to ≈50% for MVDs of 50 μm. The efficiency function for the UW PVM-100A in the NRC tunnel is lower than the efficiency function for the NCAR PVM-100A in the NASA tunnel when values of MVD are less than 30 μm. For larger values of MVD, the efficiency functions of the two probes converge. It is unclear whether the differences are due to differences between the PVM-100A probes themselves or differences between the techniques used to measure MVD in the NASA and NRC wind tunnels. Data obtained in the ECN wind tunnel appear reasonably close to the values measured in the more detailed assessment of the PVM-100A that was performed in the NASA and NRC wind tunnels.

4. Calculated PVM-100A efficiency function and comparison with measurements

The measured efficiency function, $E_{PVM}(\text{MVD})$, can be recalculated from the measured droplet size distribution, $d(\text{LWC})/dD$, and a droplet size response function, $R_{PVM}(D)$, where $R_{PVM}(D)$ represents the fraction of LWC sensed by the PVM-100A at droplet diameter $D$. If the droplet size distribution and response function are accurately known, then the theoretical PVM efficiency function is given by
Fig. 2. Measured efficiency of the PVM-100A [Eq. (1)] in the
NASA and NRC experiments (for the NASA data, see also Table 1).
The dashed (NASA) and dashed-dotted (NRC) lines are logarithmic
fits to the data, representing the measured efficiency function
\( E_{\text{PVM}}(\text{MVD}) \), where NASA: 
\[ E_{\text{PVM}}(\text{MVD}) = -0.438 \ln(\text{MVD}) + 2.21 \quad (r^2 = 0.976); \]
and NRC: 
\[ E_{\text{PVM}}(\text{MVD}) = -0.362 \ln(\text{MVD}) + 1.88 \quad (r^2 = 0.983). \]
Black crosses are from Table 1 in Gerber et al. (1994).

Fig. 3. PVM-100A response functions \( R_{\text{PVM}}(D) \) with 
\( D \) the droplet diameter [see Eq. (2)]. The open triangles represent the published
data and are adopted from Fig. 4 of Gerber (1991). The other three
types of open symbols are obtained by shifting the original Gerber
(1991) response data along the droplet diameter axis by \(-10\), \(-20\),
and \(-30\) \(\mu m\). The solid lines represent fourth-order polynomial fits
to the data [see Eq. (3) and Table 2].

\[
E_{\text{PVM}}(\text{MVD}) = \frac{\int d(LWC) dD'(D') R_{\text{PVM}}(D') dD'}{\int d(LWC) dD'(D') dD'}. \quad (2)
\]

Four different types of response functions \( R_{\text{PVM}}(D) \) are
used in the calculations to estimate the efficiency of
PVM-100A detection of LWC within different droplet
sizes (Fig. 3). The baseline response function is \( R_{\text{PVM}}(D) \)
for the ground-based PVM-100 (Gerber 1991), which
has a 50% response for 2- and 70-\(\mu m\) droplet diameters
and a uniform, perfect response between 4- and 35-\(\mu m\)
droplet diameter. Between 35 and 100 \(\mu m\), this curve
is parameterized using a fourth-order polynomial fit:

\[
R_{\text{PVM}}(D) = \sum_{i=0}^{4} a_i D^i. \quad (3)
\]

Between 100- and 300-\(\mu m\) droplet diameter, a linear fit
is assumed yielding a value for \( R_{\text{PVM}}(D) \) of zero at 300-
\(\mu m\) droplet diameter. For droplet diameters greater than
300 \(\mu m\), \( R_{\text{PVM}}(D) \) equals zero. Above 100 \(\mu m\), the exact
shape of \( R_{\text{PVM}}(D) \) has negligible influence on the
following calculations.

In addition, three hypothetical PVM-100A response functions are used, which are derived by shifting the
Gerber (1991) response function along the diameter axis
by diameters of \(-10\), \(-20\), and \(-30\) \(\mu m\). This approach
allows to simulate a diminishing response of the PVM-
100A to large droplets while maintaining the shape of
the tail for the original \( R_{\text{PVM}}(D) \) given by Gerber (1991).

Fourth-order polynomial fitting parameters for the dif-
ferent response functions (Fig. 3) are given in Table 2.

Droplet LWC size distributions, obtained in the wind
walls and used in Eq. (2), are presented in Figs. 4a
and 4b. The sprays produced in the tunnels show size
distributions broader than is typical for atmospheric
clouds. However, in principle, the PVM-100A operation
does not make any assumption about the shape of the
droplet size distribution. Therefore, wind tunnel results
presented here should be applicable to natural clouds.

From Eq. (2), the efficiency function, \( E_{\text{PVM}}(\text{MVD}) \),
of the PVM-100A is calculated for each estimate of the
response function, \( R_{\text{PVM}}(D) \), and the range of values of
MVD measured in the NASA and NRC wind tunnels.
The results are shown in Figs. 5a and 5b. The measured
efficiency function of the PVM-100A (section 3) is
cluded for comparison. A fourth-order polynomial fit to
the calculated \( E_{\text{PVM}}(\text{MVD}) \) shown in Figs. 5a and 5b is
given in Tables 3a (NASA data) and 3b (NRC data).
The fit is of form

\[
E_{\text{PVM}}(\text{MVD}) = \sum_{i=0}^{4} b_i (\text{MVD})^i. \quad (4)
\]

This fit may be used to correct measurements of LWC
obtained from the PVM-100A in natural clouds.

Assuming measurements of the droplet size distri-
bution in the wind tunnels are perfectly accurate, and
the correct response function is used, the calculated ef-
ciency function \( E_{\text{PVM}}(\text{MVD}) \) should be identical with
the measured efficiency function. However, both Figs. 5a and 5b suggest the Gerber (1991) response function results in significant overestimation of the measurement efficiency of the PVM-100A for MVD > 17 μm in the NASA wind tunnel, and for MVD > 12 μm in the NRC wind tunnel. The difference between the calculated and measured PVM-100A efficiency functions is smaller for the hypothetical response functions where it is assumed that the theoretical response of the PVM-100A is less than that proposed for the ground-based PVM-100 (Gerber 1991).

For the NCAR PVM-100A tested in the NASA wind tunnel, the agreement between the calculated and measured efficiency functions $E_{PVM}(MVD)$ is best if the “Gerber-20 μm” response function is used (Fig. 5a). This suggests that, whereas the drop off in the original PVM-100 response function of Gerber (1991) begins at droplet diameters of about 40 μm, the response function of the airborne PVM-100A starts to drop off between 20- and 30-μm droplet diameter. Uncertainties remain regarding the accuracy of the MVD measurements in the NASA wind tunnel. Note, however, that use of the FSSP-100 (also measured during these tests at the NASA wind tunnel), rather than the PDPA, to derive MVD from the composite size distributions yields similar conclusions regarding the values of $R_{PVM}$.

For the UW PVM-100A tested in the NRC wind tunnel, a good fit between the calculated and measured $E_{PVM}(MVD)$ is obtained for the “Gerber-30 μm” response function (Fig. 5b). Therefore, the estimated response function $R_{PVM}(D)$ for the UW PVM-100A begins to drop off for droplet diameters greater than about 20 μm, and falls off more sharply for larger droplet sizes.

5. Conclusions

The efficiency function of the PVM-100A with respect to droplet MVD has been measured and calculated during two independent experiments conducted in the NASA and NRC wind tunnels. The theoretical response of the ground-based PVM-100 to monodisperse droplets has been suggested by Gerber (1991) to fall off beginning at droplet diameters of about 40-μm diameter and larger. The measurements of the efficiency function obtained in the NASA and NRC wind tunnels suggest the drop off in the response of the airborne PVM-100A to monodisperse droplets begins between 20- and 30-μm diameter. For a polydisperse droplet population, this implies the efficiency of the PVM-100A begins to decrease when the MVD of the droplet size distribution is above 20 μm. When the MVD is as large as 50 μm, the PVM-100A efficiency decreases to 50%.

Natural water clouds occasionally have broad droplet size distributions with a significant fraction of their LWC contained in droplets with diameters >20 μm. It is likely the PVM-100A underestimates LWC in these clouds.

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| Table 3. (a) Fit parameter [corresponding to Eq. (4)] for the PVM-100A efficiency function $E_{PVM}(MVD)$ shown as solid lines in Fig. 5a (NASA tests). The coefficient of determination $r^2$ is also given. (b) As in (a), except for Fig. 5b (NRC tests). |

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FIG. 4. (a) Logarithmic LWC size distributions for different spray settings during the NASA wind tunnel tests. The curves represent different values of MVD (between 13 and 51 μm). The distributions are a composite of PDPA and OAP measurements. (b) Logarithmic LWC size distribution for different spray settings during the NRC wind tunnel tests. The curves represent different values of MVD (between 10 and 53 μm). The distributions are derived from the Malvern-type of instrument.

Fig. 5. (a) Calculated efficiency functions of the NCAR PVM-100A in the NASA wind tunnel. The measured efficiency function of the NCAR PVM-100A is shown by the dashed line (identical to the dashed line in Fig. 2). (b) Calculated efficiency functions of the UW PVM-100A in the NRC wind tunnel. The measured efficiency function of the UW PVM-100A is shown by the dashed–dotted line (identical to the dashed–dotted line in Fig. 2).

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