Testing and Performance of Two-Dimensional Optical Array Spectrometers with Greyscale

PAUL JOE* AND ROLAND LIST

University of Toronto, Toronto, Ont., M5S 1A7, Canada

(Manuscript received 19 December 1985, in final form 31 July 1986)

ABSTRACT

Two laboratory optical array spectrometers with greyscale were evaluated for their sizing, depth of field and timing performance; these three factors are necessary to calculate concentrations and liquid water contents. The probes were of 10 and 150 μm resolution with 40, 60, 80% and 25, 50, 75% threshold detection, respectively. Sizing was a function of the particle location in the sample area and may be in error by up to four channels; the effect is most pronounced for smaller particles. The greyscale feature is a quantitative measure of the sharpness of focus of the particle image. It permits the determination of the particle location in the sample area which, in turn, permits the rejection of extraneous or the misaligned particles. It also allows for a more accurate and user-definable sample volume. The timing check revealed substantial errors which were corrected via software. Comparison with several methods of estimating liquid water content showed consistent results. The sizing and depth of field results are applicable to the more popular nongreyscale probes since these effects depend on the optics and not on the greyscale feature. The greyscale probes provide definite advantages which would be useful in airborne applications.

1. Introduction

The knowledge of particle size distributions is fundamental in the study of precipitation growth and evolution. Several instruments have been developed to measure these distributions from airborne platforms. In particular, two-dimensional optical array spectrometers (OAP) have been popular for measurements of particles greater than 25 μm in size (Knollenberg, 1976). An advanced laboratory version of these imaging probes is the two-dimensional optical array spectrometer with greyscale; hereafter, known as the 2DGS probe. This paper describes the operation of two 2DGS probes (Fig. 1) of different resolution (10 and 150 μm) and threshold detection levels (40, 60, 80% and 25, 50, 75%). The advantages of the 2DGS probes over OAP probes are particle size as a function of sample location due to the greyscale or multiple threshold detection level feature; superior image quality due to rejection hardware; particle concentration computation due to single particle processing; and the particle data processing system (PDPS-11C) which controls the probe and displays real-time information or plays back recorded data.

This paper will examine the 2DGS in three critical areas: the sizing, the sample volume and the timing of particle arrivals. These factors determine the ability of the system to measure size distributions and concentrations.

2. The 2DGS hardware system

a. Overview

The 2DGS consists of two units: a probe and the PDPS-11C which includes the data acquisition system (DAS). A schematic of the system is presented in Fig. 2. The PDPS-11C consists of data acquisition hardware (DAH) and a Digital Equipment Corporation LSI-11 central processing unit (CPU). The DAH handles the data transfer from the probe to the CPU and then to the magnetic tape. Peripherals include a color CRT for display of histograms and particle images, a printer-plottter for hardcopy, dual-drive mini-cassette tape drives, a full keyboard, a time of day clock with a selectable intervalometer and an automatic slide rate generator for probe control. In addition, a nine-track magnetic tape drive is optional. Up to four one-dimensional probes and eight analog voltages may be connected to the PDPS-11C.

b. The probes

The probes consist of a 6 mW He-Ne laser operating at 6328 nm, lenses, a 64 element linear array of photodiodes, amplification, detection and storage electronics. The development and use of the linear array has been discussed by Knollenberg (1970). The laser beam is deflected, shaped and enlarged into an elliptical

* Present affiliation: Atmospheric Environment Service, Downsview, Ont., M3H 5T4, Canada.

† By Particle Measuring Systems (PMS) Inc. of Boulder, Colo.

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shape, using mirrors and cylindrical lenses, before entering the sampling region. It is then received by a second set of lenses before impinging on the photodiode array. This latter optical system determines the probe resolution and the location of the object plane. The photodiodes are circular with a diameter of 180 μm and positioned with a center-to-center spacing of 200 μm. The output from all 64 photodiodes is recorded simultaneously at a preselected rate (5 kHz to 5 MHz).

For a particle that is larger than the probe resolution, the probe only "sees" a slice of the particle, at a given instant. Thus, an image of the particle is generated in the probe memory registers using successive slices of coded particle data.

A particle passing through the sample area will cast a shadow on the array. If the particle passes through the beam near the object plane, it will be sharply imaged and its shadow will be dark with a sharp edge; whereas, one farther away from the object plane will produce a greyer and fuzzier edged shadow. In order to determine the degree of shadowing that has occurred, the output from each photodiode is amplified and compared to its own quiescent or reference voltage. Four levels of shadowing can be sensed using threshold detection and digital electronics. For the 150 μm probe, the detection levels are 0–25, 25–50, 50–75 and 75–100%. The corresponding break points for the 10 μm probe are 40, 60 and 80%. A photodiode is deemed to be shadowed at the null minimum (MIN), middle (MID) or maximum (MAX) levels, respectively. Nongreyscale OAPs only have the 50% detection threshold level.

c. Hardware rejection

There is rejection hardware in the probe. The probe will register a particle only if there is at least one diode shadowed at the MAX level. This is known as depth-of-field rejection since the shadow of a particle falling far from the object plane will be diffuse and not trigger any diodes at the MAX level. A particle will be rejected...
if there are not enough successive slices of data. This is minimum length rejection and is used to eliminate small particles from consideration so as to improve the probability of capturing large particles. The third criterion is end element rejection, which eliminates particles traversing over either end element of the linear array, allowing only images of entire particles to be accepted. These three rejection criteria were user-controlled through the PDPS-11C software.

3. Size and depth of field considerations

a. The sample volume

The sample volume must be defined in order to calculate concentration. It is the product of three dimensions: the effective width of the photodiode array (EAW), the depth of field (DOF) of the optical system and the length of the sample volume. The latter dimension is a product of the relative velocity of the particle and the probe active time (PAT), and is discussed in section 4.

The EAW is a function of the probe resolution, the number of photodiodes in the linear array, and also on the algorithm used to handle partial images of particles. It is a trivial problem to classify a particle if its entire shadow is within the boundaries of the array. A small particle (with respect to the array width) has a broad width through which it can pass and meet this condition. However, for a large particle there is a very narrow width through which the particle can pass and be sized. Techniques have been developed to reconstruct partial images in order to increase the EAW for large particles. The paper of Heymsfield and Parrish (1978) discusses some of the software techniques used to extend the EAW; this paper concentrates on the hardware performance of the system. The technique used in this paper is the “center-in” technique which requires that the center of the particle be within but not on the boundaries of the photodiode array.

The DOF used by the PMS software is given by

\[ \text{DOF} = d_0 \times D^2 \]  

where DOF is in meters, \( D \) is the particle diameter in meters and \( d_0 = 2.5 \times 10^6 \text{ m}^{-1} \) (Knollenberg, 1970). The mechanical depth of field for the 10 and 150 \( \mu \text{m} \) probe is 24.1 and 26.0 cm, respectively (see Fig. 1). In theory, the particle will not trigger any diodes at the MAX level and hence will not be recorded by the probe if it lies outside this DOF. This paper presents an experimental evaluation of this formulation.

b. Size and depth of field calibration technique

Glass beads\(^2\) or small ball bearings were dropped through a funnel into the laser beam to calibrate the size and depth of field behavior of the probes. A selection of the glass beads was sorted for sphericity and sized under a Projectina microscope. Five sizes of glass beads were used to calibrate the 10 \( \mu \text{m} \) probe: 42 ± 5, 125 ± 15, 240 ± 15, 400 ± 15 and 590 ± 40 \( \mu \text{m} \). Six sizes of ball bearings were used to calibrate the 150 \( \mu \text{m} \) probe: 0.159, 0.238, 0.318, 0.476 and 0.635 cm (±0.003). A small sample of about 5 to 20 particles were collated into a mixture. This mixture was sprinkled through a funnel just above the beam at various distances from the object plane (DOP) of the optical lens system until a sufficient number of images were recorded for each particle size. The funnel was clamped to a vernier scale with a precision of <0.1 mm and the diameter of the funnel throat was just larger than the largest particle in the mixture; i.e., \( \sim 1 \text{ mm} \) and \( \sim 1 \text{ cm} \), respectively. Therefore, the error in the location of the injection point was about half these values; 0.5 and 5 mm, respectively.

A typical image (Fig. 3) shows a figure composed of three elliptical or circular rings corresponding to the three levels of detection. The shape of the figure is controlled by the operator through the slice-rate thumbwheels. The shading is not continuous but is made up of discrete pixels which represent the photodiode signals. A line of dots, in the direction of the \( X \)-axis, is an instantaneous recording of the 64 diodes. A line of dots along the \( Y \)-axis represents consecutive recordings

\(^2\) Manufactured by Precision Glass Beads.
of the same photodiode. In this study, the maximum dimension in the $X$ direction at the middle threshold level (WMID) is used as the width parameter.

The closer the particle is to the object plane, the smaller the areal extent of the outer two rings. The ratio of the total number of diodes shadowed at the maximum threshold level divided by all the diodes shadowed is defined as the $RMAX$ ratio. Similarly, $RMID$ is defined in a similar fashion using the number of diodes shadowed at the middle and maximum levels. Elongation or shearing of the particle image would not have any effect on these ratios, provided that each ring is sheared or stretched by the same factor.

c. Size calibration

Figures 4 and 5 show the size calibration results for the 10 and 150 $\mu$m probes, respectively. The 150 $\mu$m probe was also operated with a mirror extension (96.5 cm) to the probe in order to laterally translate the sample region of the probe (Fig. 5b).

The results for the 10 $\mu$m probe (Fig. 4) reveal several interesting points. For a given particle size, the results show a local minimum at the object plane. Then, as DOP increases, the relationship becomes relatively flat, and then wavelike in form. If WMID is assumed to be proportional to the particle size, which is the standard approach, then the particle sizing will depend on the location of the particle in the sample area.

The average of the WMID values in the flat regions of Figs. 4 and 5, where the standard deviation of the measurements were consistent, were plotted as a function of the particle size in Fig. 6 and 7. The results show a linear relationship between WMID and particle diameter, as expected.

One other feature of the two curves for particle sizes 42 and 125 $\mu$m in Fig. 4 is the extent of the measurements. Where there are no data points, there were no particle images recorded even though particles were dropped through the sample beam. There appears to be little correlation with the theoretical depth of field (line A on Fig. 4) as given by (1).

The wavelike behavior, due to optical degradation of the particle image, causes dispersion in the sizing. As the size increases the effect is less evident, as seen by comparing Fig. 4 and 5. The problem is to eliminate those particles which are badly imaged and missed. For each particle size, the limiting value of DOP can be identified (albeit arbitrarily) where particles are missed (line B on Fig. 4). Table 1 lists the maximum or threshold values of DOP beyond which WMID is considered unreliable as a linear parameter for the particle diameter. A least-squares curve fit to the data is given by

$$DOP_{max} = d_1 D + d_2 D^2$$

(2)

where $d_1 = 6.34 \times 10^4$, $d_2 = 17.767 \times 10^4$ m$^{-1}$. DOP$_{max}$ is in meters and $D$ is in meters. The RMAX values corresponding to the threshold DOP values are also
Fig. 5. Size calibration for the 150 μm probe. In contrast with the previous figure, this probe is devoid of the sizing problems, even with an extended path length to the sample area (b). Typical standard deviation errors are indicated and are larger for the extended sample area. The data for the 6.35 mm particle is reconstructed from partial images and hence the larger error bars.

presented in Table 1. These values are fitted with a least-squares curve of the form:

\[ \text{RMAX}_{\text{thr}} = r_1 + r_2D + r_3D^2 \]  \hspace{1cm} (3)

where \( r_1 = 6.53 \times 10^{-2}, r_2 = 0.145 \times 10^3 \text{ m}^{-1}, r_3 = 1.31 \times 10^6 \text{ m}^{-2} \) and \( D \) is in meters.

The RMAX ratio feature provides an additional variable which can be used to locate the particle and therefore also to define a smaller sample area than the optical sample area. This has several advantages: first, particles that are missized can be eliminated since they appear at the edges of the sample volume; secondly, for laboratory conditions in which the liquid water contents vary in small distances, the sample volume may be restricted to the region of interest; and thirdly, superior images and hence more accurately sized par-

Fig. 6. The WMID as a function of particle size for the 10 μm probe. The measurements near the object plane (delineated by line B in Fig. 4) were averaged and compared to the particle size. The inverse slope of this graph yields the probe resolution.

Fig. 7. As in Fig. 6 except for the 150 μm probe. There is only slight difference with the 95.6 cm extension (not shown).
TABLE 1. Maximum distance from object plane for “accurate”
particle sizing for the 10 μm probe.

<table>
<thead>
<tr>
<th>Diameter (μm)</th>
<th>DOP_{\text{max}} (cm)</th>
<th>R_{\text{max}}</th>
</tr>
</thead>
<tbody>
<tr>
<td>42</td>
<td>0.16</td>
<td>0.063</td>
</tr>
<tr>
<td>125</td>
<td>0.87</td>
<td>0.128</td>
</tr>
<tr>
<td>240</td>
<td>2.78</td>
<td>0.158</td>
</tr>
<tr>
<td>400</td>
<td>6.32</td>
<td>0.336</td>
</tr>
<tr>
<td>590*</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Mechanical limit applies here; tests were not done.

cicles are analyzed since the higher threshold detection
level provides a stringent requirement on acceptable
particle images.

d. Depth of field calibration

The greyscale or multiple threshold detection feature
of these probes provides the capability to compute the
location of a particle in the sample area. Figures 8 and
9 present plots of RMAX as a function of DOP for the
10 and 150 μm probes. The plots show that for the 10
μm probe, RMAX decreases monotonically with DOP.
However, for the 150 μm probe, no significant relation-
ship appears. The data for the RMID ratio, another
possible parameter, was scattered and no obvious rela-
tion exists (Fig. 10). The data in Fig. 8 can be fitted
with a curve of the form

\[
DOP = b_0 \left( \frac{1}{RMAX^{1/b_1}} - 1 \right)
\]  

(4)

where

\[
b_1 = \frac{a_0}{(D \times 10^6 + 1)^{a_1}}
\]  

(5)

Fig. 8. The RMAX ratio as a function of the DOP for the 10 μm
probe. This ratio is a quantitative measure of the sharpness of focus
of the particle and therefore of its location with respect to the object
plane. Note the significantly larger error bar for the 590 μm particle
which, in the most part, has been reconstructed from partial images.

Fig. 9. As in Fig. 8 for the 150 μm probe. The particle images for
this probe are well defined and are reflected in these greater RMAX
ratios. Compared to the data for the 10 μm probe, no distinct or
obvious relationship appears that can be exploited to locate the particle
in the sample area.

where \(b_0 = 2.54 \times 10^{-2}\) m, \(a_0 = 9480.6\) and \(a_1 = 1.522\);
DOP is in meters and \(D\) is in meters. Thus, given the
particle diameter, the quantity \(b_1\) may be calculated
from (5) and with RMAX, the DOP may be calculated
from (4). The particle diameter is calculated by mul-
tiplying WMID by the probe resolution (RES);

\[
D = \text{WMID} \times \text{RES}
\]  

(6)

where WMID is number of diodes and RES is units of
meters per diode; \(D\) is in meters.
FIG. 10. Another possible parameter to examine for a sample area relationship is the RMD ratio which is defined in a similar fashion to the RMAX ratio. No obvious relationship exists.

e. Size rejection algorithm

For the 10 \( \mu m \) probe, the sizing algorithm was as follows: the particle size was assumed to be given by (6); then, RMAX\(_{in} \), for that particle size was calculated using (3); this value was compared to the RMAX value of the particle; if smaller, then the particle was acceptable; if larger, then the particle was rejected. Particles which fall just beyond the maximum acceptable DOP will be missed into a smaller category and will suffer a more stringent RMAX criteria and, therefore, will be rejected. Particles falling farther out will be missed into a larger category but will have smaller RMAX values and hence will also be rejected. The sizing algorithm for the 150 \( \mu m \) probe, both extended and unextended, is given by (6).

4. Timing considerations

a. Data collection and timing

This section briefly describes how a particle image is recorded by the PDPS-11C system. With the reception of the operator-initiated start command, the probe begins to interrogate the photodiodes and starts a time clock. Probe rejection hardware is placed in a ready state, when a particle shadows the photodiodes. If a good particle has been received, the data shifts through the memory buffer and stops on the count of 504 image slices. If an invalid particle has been received then the rejection hardware is reset and collection continues. Then, the PDPS-11C halts the time count, the probe goes into a wait state and signals to the PDPS-11C that it has data to transfer. Image data that are received subsequent to the valid particle, but before the probe goes “dead”, is recorded in the probe buffer but are not utilized. Thus, an error arises; more particles are received than are counted or conversely, the system overtimes particle arrivals which results in an underestimation of concentration. When the probe goes into the wait or “dead” state, particles passing through the sample area will not be recorded.

After receiving the valid particle signal from the probe and when it is ready to receive data, the PDPS-11C transfers the data from the probe via direct memory access (DMA), through the DAH, to one of two 504 slice image buffers in the DAS operating in a flip-flop mode to avoid data jams. Particle length, width and area information, also generated in probe hardware, is sent to a separate 256 particle data buffer. In real-time processing, the former buffer is used for image display and the latter for histogram generation and display. When the buffers are full, they are sent to the magnetic tape.

The third dimension of the sample volume was calculated as the product of the relative air velocity of a particle and PAT. If particle arrivals were constant and uniform, then it would appear that the system would underestimate the actual particle interarrival time since some time is missing due to processing of the particle image by the PDPS-11C. However, when particle arrivals are random, then their distribution and, therefore, the average particle interarrival time, will be correctly estimated. Every time the probe starts up, it is assumed that a particle arrives randomly and therefore independent of the previous particle. In contrast, particle arrivals are dependent for the uniform case. This describes the classic waiting time paradox in statistics (Feller, 1968, 1971).

b. Timing calibration

Besides the transit time through the probe buffer, there are also time losses due to PDPS-11C and probe interactions. Therefore, it was necessary to measure the timing of the entire system. The 150 \( \mu m \) probe was used for this test.

A 2.26 mm (No. 43) diameter drill bit was used to make a cone shaped impression in a 0.064 cm thick sheet of 15 \( \times \) 15 cm plexiglas. The opaque impression was located at a distance of 38 mm from the center of the sheet. The opaqueness was sufficient to “trigger” the photodiodes of the 2DGS. In fact, a spectrum of particles could be simulated by drilling impressions of different sizes into the plexiglas. A rod, inserted through a 0.95 cm hole in the center of the plexiglas sheet of film, was attached with a ring clamp arrangement. The rod was connected, via a gear and chain mount unit, to a small variable speed DC motor controlled by a motor speed control unit. The Plexiglas slide was rotated at various frequencies, and the PAT was recorded.

An alternative arrangement was made to test the smaller resolution probe. A white 5 mm spherical dot on a black background was photographed on 35 mm
high contrast copy film (Kodak). A hole was punched through the center of an individual film frame (24 × 36 mm) which could then be clamped to the rotating rod.

c. Timing corrections

Figure 11 shows the results for the corrected probe active time \( T_{\text{pat}} \) as a function of the true period \( T \) of rotation. The data were generated with circular particle images so that the transfer times \( T_{\text{transfer}} \) of the data from the probe to DAH for the images were constant. The data points were averaged over 5 s of real time.

Three features are evident: the scatter of points for a fixed period \( T \), the linear relationship between the \( T \) and \( T_{\text{pat}} \), and the scatter of points at about 0.09 seconds.

First, the scatter of points for a fixed period was due to the averaging procedure. The system started up randomly; thus, the first interarrival time varied from 0 to \( T \) and subsequent times were less than \( T \) due to system dead time. There was more scatter at large \( T \) due to fewer measurements as a result of the constant 5 s averaging. The rotation rate was accurate to 0.1 Hz.

Secondly, the linear relationship may be explained by consideration of the active and dead times of the system. The data were unloaded from the probe through the DAH to the CPU, at a maximum rate of 1 word per 16 μs. An end of particle (EOP) signal was sent back to the probe when the DAH senses an all-light slice (no particle in view). Therefore, the true particle period is given by

\[
T = T_{\text{pat}} + T_{\text{buffer}} + T_{\text{transfer}} + T_{\text{eop}}
\]

where \( T_{\text{buffer}} \) is the probe transfer time and \( T_{\text{eop}} \) is the transfer of the EOP with

\[
T_{\text{buffer}} = (N_{\text{a}} - N_{\text{d}})T_{\text{a}}
\]

where \( N_{\text{a}} \) is the number of slices of the particle image which equals 15 for a 2.26 mm size image at 150 μm resolution. Here \( T_{\text{a}} \) is the clock rate at which the photodiodes are sampled, and data are shifted through the probe buffer. The clock rate is set equal to \( d/(VN_{\text{a}}) \) where the particle velocity \( V \) is given by \( 2\piUr \), \( d \) is the particle size, \( \Omega \) is the rotation rate of the plate, and \( r \) is the distance of the particle impression from the plate center. Therefore

\[
T_{\text{buffer}} = 0.3T
\]

\[
T_{\text{transfer}} = (N_{\text{a}} + 2.5) \times 8 \text{ words per slice} \times 16 \mu\text{s per word} = 2.24 \mu\text{s}
\]

and

\[
T_{\text{eop}} = 8 \mu\text{s}
\]

The \( T_{\text{transfer}} \) represents the shortest possible time for the transfer of data from the probe to the DAS. It does not consider interactions with the DAH. The factor 2.5 arises from DAH handling of the data. Thus,

\[
T_{\text{pat}} = t_{1}T + t_{0}
\]

where \( t_{1} = 0.70 \) and \( t_{0} = 2.24 \times 10^{-3} \) s. The dashed line in Fig. 11 has been drawn to lie just above all the measured data points, to reflect the line that would be produced if the random startup was removed. It has a slope of 0.72 which compares very well with the calculated value of 0.70.

Therefore, the system correctly times particle arrivals in accordance with a type 1 counter and provides a “correct” measure of the distribution of interarrival times. If particles are to be rejected then their times must be rejected as well (Feller, 1968, 1971).

Thirdly, at \( T = 0.09 \) s, the PAT data were much more scattered and approached zero. This was a synchronization of the particle arrival and the probe startup, i.e., as the system was reset to receive a particle, the particle came into the field of view, therefore yielding a PAT value of approximately zero.

Then

\[
T_{\text{transfer}} = 0.70T.
\]

Since \( T = 0.09 \), \( T_{\text{transfer}} = 63 \) ms. This is an order of magnitude larger than the estimated DMA time of 2.24 ms and reflects computational, reset and overhead times in the PDPS-11C. This value could also be estimated from the intercept of the points in the Fig. 11 \([t_{0} \text{ in } (9)]\); however, the precision of the data was not sufficient to determine it accurately.

It should be noted that the relative magnitude of the correction increases with number concentration. As concentration increases, more particles will be in the

---

**Fig. 11.** Plot of the corrected interarrival time between particles as measured by the 2DGS as a function of the true interarrival time. The slope of solid line is 0.70 which has been calculated based on known delay times in the 2DGS system, and the dashed line is the envelope to the largest values in each group.
probe memory buffer than counted; therefore, the particle concentrations become increasingly underestimated.

5. Liquid water comparisons

a. LWC measurement techniques

Optical array spectrometers represent the state-of-the-art technique of measuring number and mass distributions and liquid water contents (LWC). More traditional laboratory techniques such as the collection of droplets or drops on oil-coated glass slides and cylinder icing are either laborious to analyze, limited by collection efficiency effects, or both. These latter approaches can only be regarded as approximations. The LWC provided by the 2DGS was compared to estimates made by three different methods.

An icing wind tunnel with a spray produced by an atomizing nozzle\(^3\) was available. Slowly rotating cylinders (0.5 Hz), 1.9 cm in diameter, were iced under dry growth conditions (\(<-20^\circ\text{C}\)), where shedding and bouncing losses were not significant (Joe et al., 1980). This was adequate for low LWCs. The LWC was related to the ice deposit by

\[
\text{LWC} = \frac{\Delta D}{\Delta t} \frac{\pi f_i}{2VE} \quad (11)
\]

where \(\Delta D/\Delta t\) is the average growth rate of the ice deposit, \(f_i\) the ice density, \(V\) the relative velocity of the cylinder to the airflow, and \(E\) the collection efficiency.

At slightly larger LWCs, an aluminum slab (1.9 \(\times\) 4.8 cm) chilled in liquid nitrogen (\(-196^\circ\text{C}\)) was inserted into the sample area and quickly removed. Thus, water droplets hitting the slab would quickly freeze. The LWC is related to the accreted water mass by

\[
\text{LWC} = \frac{\Delta M}{\Delta t} \frac{1}{AVE} \quad (12)
\]

where \(\Delta M/\Delta t\) is the mass accretion rate, \(A\) the cross-sectional area of the slab and \(V\) and \(E\) as previously defined.

The third method was to measure the mass flux of water through the sample area and estimate the LWC in the region of interest by examining the profiles of LWC by the rotating cylinder method. The LWC was related to the flow rate by

\[
\text{LWC} = \frac{F}{AV} \quad (13)
\]

where \(F\) is the flow rate and \(A\) and \(V\) are as previously defined.

b. LWC comparison

The LWC as calculated by the 2DGS is compared with the best estimates of the LWC produced by the other techniques (Fig. 12). The results are comparable within the range of errors (\(\pm 50\%\)). The LWC was plotted against the nominal flow rate (\(\eta f_r\)) as given by the flow control rotometer. The line drawn on Fig. 12 is the LWC as estimated by assuming that the water is uniformly injected into a circular area of 8.3 cm, at a velocity of 22 m s\(^{-1}\) at the measuring section. The actual flow rate through the nozzle was measured by collecting the ejected water in a bag and weighing its contents. In the range of flow rates (>\(1.0\) cm\(^3\) s\(^{-1}\)), the actual to nominal flow rate fraction was 0.9 \(\pm\) 0.1. Below 1.0 cm\(^3\) s\(^{-1}\), this fraction had a dependency described by

\(^3\)Spraying Systems Inc., air cap 67147ss and fluid cap 2850ss.
\[
\frac{mfr}{nfr} = n_1 \times nfr + n_2
\]  

(14)

where \(mfr\) is the measured flow rate, \(n_1 = 0.7\) s (cm\(^{-3}\)) and \(n_2 = 0.2\). The values presented were not corrected for this latter behavior; the effect is that this technique will overestimate the LWC for nominal flow rates less than 1.0 cm\(^3\) s\(^{-1}\).

The cylinder technique requires an estimate of the collection efficiency and the ice density. The mean volume diameter of the droplet was greater than 60 \(\mu\)m (see Fig. 13), as indicated by the size distributions given by the 2DGS. With droplets of this size, the collision efficiency will be very close to unity. This approach can only be used for low LWCs where shedding was not observed (Joe et al., 1980). Therefore, the net collection efficiency could be assumed to be 1. The ice density was measured by mixing isopropyl alcohol (sp. gr. 0.785) and water in various proportions to create baths of different densities. The bath in which the ice was neutrally buoyant would yield the ice density. The density of the ice so measured was 0.880 \(\pm\) 0.005 g m\(^{-3}\). This slab technique employs a direct measurement of the ice deposit and does not require the ice density. The comparisons are encouraging and are consistent with the best available estimates, yielding confidence that the 2DGS can measure LWC with a reasonable degree of certainty.

6. Nongreyscale size correction algorithm

a. Geometric dispersion

Sizing errors occur, solely due to the geometry of the linear photodiode array. A shift in position by half a diode of a particle shadow can affect its size classification. This positional dependence is conceptually expressed as a capture probability. For each size category, it is defined as the fraction of particles of any size, randomly distributed through the sample area, that will be classified in that particular bin. This may be calculated assuming that the decrease in the light incident on the photodiodes is assumed to be linearly related to the shadow area.

The capture probabilities for a particular size bin are triangular in shape (Fig. 14), adjacent channels overlap and the modal value of the probability function is larger than their nominal values. Particles that actually have their diameters within the nominal bin widths will be sized in that bin with a 75% probability. The other 25% will be equally counted in adjacent bins, except for the lowest channel where the lowest 12.5% are lost. In other words, spectral broadening occurs as a result of the geometry of the photodiodes.

The net particle dispersion, both optical and geometric, shown in Fig. 4 is summarized in Table 2. The entries in the table give the probability of observing a particle of a particular nominal size regardless of its location in the sample area. This describes the overall dispersive effect of the 2DGS in its ability to classify particles for their size.

b. Correction algorithm

The data presented in Fig. 4 have been transformed by the two different instrument effects (previously described). This paper rejects incorrectly sized particles using the algorithm presented in section 3e. However, this approach is not possible with nongreyscale OAP probes, since the greyscale feature was used to eliminate particles.

An alternate approach would be to invert the measured observations using the transformations described by Table 2. That is;

\[
y_{true} = Ky_{meas}
\]  

(15)

where \(y_{true}\) is the true particle distribution, \(K\) is the transformation matrix and \(y_{meas}\) is the measured particle distribution. The elements of the transformation matrix are given by the product of two factors;

\[
K = G \cdot O
\]  

(16)

where \(G\) describes the geometric effect and \(O\) is the optical effect dispersion matrix. The matrix \(K\) statistically describes the manner in which the 2DGS observes a particle of a given size.

The entire transformation matrix can be created with more measurements and interpolation between values. Thus, the algorithm to calculate the true distribution from the measured distribution is to invert the trans-
formation matrix $K$ and apply it to the measured data to retrieve the "true" spectrum. This is not a trivial problem and has not been attempted here. This problem has been discussed in many publications (to list a few, Crump and Seinfeld, 1982; Twomey, 1975, Backus and Gilbert, 1970). The algorithm, as formulated, should only be applied to the raw counts in each channel; if applied to concentrations or distributions then sample volume considerations must be taken into account.

7. Conclusions

This paper presented the evaluation of a 10 and 150 μm resolution two-dimensional optical array spectrometer with greyscale. Three areas have been identified that must be calibrated in order to correctly measure size distributions and concentrations: the sizing of particles as a function of sample area location, the sample area definition and the timing of particle interarrivals.

The tests have shown that the sizing behavior of imaging spectrometers, including nongrey scale probes, are a function of particle location in the sample volume and that particles may be missized by up to four channels, particularly for particles smaller than 200 μm. These errors apply also to nongrey scale probes where no correction procedure are known.

The depth-of-field of the probe also proved to be larger than the values quoted by the manufacturer leading to overestimates of concentrations. This error would apply to nongrey scale probes as well.

The greyscale feature provides an additional variable (the RMAX ratio) which can be used to locate the particle, and to define a smaller sample area than the optical sample area. The advantages are the following: particles that are missized can be eliminated since they appear at the edges of the sample volume; for laboratory conditions in which the liquid water contents vary in small distances, the sample volume may be restricted to the region of interest; and superior images and hence more accurately sized particles are analyzed due to stringent acceptance criteria. This would be useful in airborne applications where slow moving probe-tip shed particles pose problems (Heymsfield and Baumgardner, 1985), since they may be easily identified in hardware or software and hence rejected.

The greyscale probe proved to operate as a type 1 counter. Therefore, concentrations may be computed from the interarrival time between particles, the particle velocities and the sample area for each particle size. Experiments using a simulated particle identified an overtiming of particle interarrival times. After correction, it proved to be statistically consistent with a type 1 counter.

The direct application of these results to other probes including nongrey scale probes should be done with caution. The sizing, depth of field and sample volume behaviors are functions of the optical system. It would not be surprising to qualitatively but not quantitatively find the same effects. It should be noted that nonspherical particles have not been investigated, and these results may not apply to ice particles because of their irregular shape.

The evaluation of a 10 and 150 μm resolution two-dimensional greyscale optical array spectrometer have demonstrated their capability of measuring droplet size distributions, concentrations and liquid water contents, and suggests that they provide superior estimates to nongrey scale probes.

Acknowledgments. This research was conducted under a grant from the National Research Council of Canada and the Atmospheric Environment Service. The first author also acknowledges AES for a postgraduate scholarship as well as loan of the precipitation greyscale probe. Thanks go to Cliff Montgomery of

<table>
<thead>
<tr>
<th>Table 2. Size classification probability table.</th>
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<tr>
<td>Bead size</td>
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<tr>
<td></td>
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<tr>
<td>125</td>
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<td>240</td>
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<td>400</td>
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Fig. 14. A plot of the capture probabilities for the first three channels of a hypothetical 200 μm resolution probe. The quasi-triangular shape of the curves is due to the circular geometry of the photodiodes (assumed to be 180 μm in diameter). This figure shows that the nominal channel boundaries are defined for convenience only; the actual channel widths overlap. The parameter $N$ identifies the threshold detection level and the parameter $RP$ identifies the radius of the photodiodes. The center to center distance between diodes is assumed to be 200 μm.
Particle Measuring Systems for invaluable assistance and discussions.

REFERENCES


