AIRBORNE MEASUREMENTS FOR CLOUD MICROPHYSICS

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I. GENERAL

The Research Aviation Facility (RAF) provides airborne instrumentation for acquiring data in support of various facets of cloud microphysical research. These instruments measure the amount of cloud water, particle concentration, shapes, and sizes. Instrument configurations vary according to aircraft and scientific objective and scientists who use data from these instruments should be aware of the measurement limitations imposed in general by the capabilities of the instruments and by particular mounting configurations when applicable.

A. Cloud Particle Measurements

The accurate measurement of cloud particles is complicated by the large range of sizes, shapes, and concentrations found in the natural cloud types and conditions. In a cloudy environment, particle diameters may be as small as \(10^{-6}\) cm, as in the case of cloud condensation nuclei, or larger than 1 cm, which is not unusual for graupel and aggregates of ice crystals. The concentrations of these particles range from \(> 1000\) cm\(^{-3}\) for the smaller sizes to \(< 0.1\) \(\ell^{-1}\) at the largest sizes. The particles may be spherical water droplets or complex dendritic ice crystals. The ability to analyze all of these types of particles both quantitatively and qualitatively requires more than a single instrument. The RAF presently has instrumentation capable of measuring particles over the range of 0.12 \(\mu\)m to \(> 6,400\) \(\mu\)m in diameter by using combinations of particle probes that are manufactured by Particle Measuring Systems, Inc.\(^1\) (PMS). Aerosol particles ranging in size from 0.12 \(\mu\)m to 3.1 \(\mu\)m are sized and counted with the active scattering aerosol spectrometer probe (ASASP). Water droplets from 0.5 \(\mu\)m to 45 \(\mu\)m in diameter are measured with the forward scattering spectrometer probe (FSSP). Water and/or ice particles ranging in diameter from 10 to 4,500 \(\mu\)m are sized and counted using one-dimensional (1D) optical array probes.

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\(^1\) Particle Measuring Systems, Inc., 1855 57th Street, Boulder, Colorado 80301
Fig. 1. A schematic representation illustrating locations of PMS and hot-wire liquid water content probes on the NCAR aircraft.
OAPs. These OAP probes thus overlap the FSSP in the cloud droplet range and extend to all but the largest sizes of hydrometeors usually encountered. If further differentiation between ice and water is desired, mixed-phase particles may be detected using the two-dimensional (2D) optical array probes for particles with diameters ranging from 25 to > 6,400 μm. A summary of these probes, listing their size ranges and resolutions, is given in Table I. Figure 1 illustrates the locations on each aircraft where the instruments are usually mounted.

B. Cloud Liquid Water Content Measurements

The amount of liquid water for a given volume of air may be determined through mass integration of the particle distributions measured by the PMS probes. Another method of directly measuring the liquid water content is with two different types of hot-wire probes (manufactured by Cloud Technology\(^2\) and PMS, Inc.). These instruments relate the change in resistance of a heated sensing wire to the amount of cooling caused by the vaporization of cloud droplets impinging on the sensors.

The liquid water content in super-cooled clouds can also be estimated from the Rosemount icing rate detector, described in the next section. Although liquid water estimates from this sensor are not as accurate as those from the hot wire probes, much lower liquid water contents can be detected. The ice probe is especially useful in mixed phase clouds where measurements from other methods of detection are affected by ice particles.

C. Cloud Icing Measurements

The icing rate in supercooled clouds can estimated through the use of the previously described instruments and their measurement of droplet size and liquid water content. As a direct measurement of icing rate, the RAF uses a Model 871 icing detector manufactured by the Rosemount Engineering Co.\(^3\) This probe produces a voltage proportional to the ice accumulated on a cylinder which is exposed to supercooled water droplets in the airstream.

D. Particle Spatial Distribution Measurements

Small-scale structure of cloud particle distributions are measured using the particle spacing monitor (PSM) developed at RAF. By measuring the arrival times between individual particles detected by either the FSSP or 1D OAPs, the spacing between particles are measured directly. The 2D OAPs also provide the interarrival times of particles which they image.

\(^2\) Cloud Technology, 606 Wellsbury Ct., Palo Alto, California 94306
\(^3\) Rosemount Engineering Co., P.O. Box 35129, Minneapolis, Minnesota 55435
II. THE ACTIVE SCATTERING AEROSOL
and FORWARD SCATTERING SPECTROMETER PROBES

A. Operating Principles

The ASASP and FSSP relate the amount of forward-scattered light by a spherical
particle to its size according to electro- magnetic wave scattering theory. The ASASP uses
a aerodynamically focused airstream to define a fixed sample volume (Fig. 2). The FSSP
uses two photodetectors to define the sample volume in which the particles will be detected.
One photodetector is optically masked so that only the light outside the defined depth-
of-field (DOF) is detected. The signal from this detector is used to discriminate particles
outside the DOF (Fig. 3). The source of illumination is a He-Ne laser operating at a
wavelength of 6328 angstroms. All the optics and electronics are integrally packaged with
the exception of the data system required to store the accumulated size and concentration
information.

B. Calibration Procedures

The ASASP and FSSP are calibrated periodically before and after each field project
to check for sizing accuracy. Monodispersed glass beads are used to determine the necessary
sizing information with appropriate corrections made for the index of refraction differences
between glass and water. The laser beam diameter and DOF are also checked periodically
in order to maintain an accurate record of the sample volume of the FSSP. The flow rate
through the ASASP, which is a constant-volume device, is also routinely checked.

C. ASASP and FSSP Limitations

Cloud particle concentrations measured by these probes are under-estimated when
particles are either coincident in the beam or pass through the sensing area of the probe
during the electronic processing period of a previous particle. The combination of these
effects typically exceeds 10% when the natural particle concentrations are greater than 300
cm⁻³. The majority of these losses, however, may be recovered as described by Baum-

The sizing accuracy is affected by several factors. Although the lasers used in the
probes are operated in a higher-order mode to produce a semi-uniform beam intensity,
there are still significant non-uniformities which affect the amount of light that a particle
scatters. This problem is compounded by the response time of the electronics that causes
particles to be undersized at airspeeds greater than about 50 m s⁻¹. Corrections are
applied to the data that account for this problem (Baumgardner, 1987). Mis-sizing will
also occur as a result of particles coincident in the beam which will be detected as a single
particle but sized somewhat larger. This type of sizing error will usually be negligible and,
at present, no attempt is made to correct the data for this event. However, special software
is available through the RAF that can be used when special processing is desired by the
user.

Another limitation implied in the principles of operation is that these probes cannot
discriminate between water and ice particles. Ice particles pass through the sample
volume of these probes in random orientations and the measured sizes will depend upon
Fig. 2. A schematic diagram of the ASASP's optical detection system.
Fig. 3. A schematic diagram of the FSSP's optical detection system.
this orientation and the shape of the crystals. Ice particles outside the nominal sample area of these probes will sometimes be sized and counted if they fall partially within the sample volume. Therefore, the sample volume for ice particles will be indeterminate. For these reasons, the FSSP or ASASP should not be used for ice crystal measurements, and measurements from these probes should be used carefully whenever they are used in known mixed-phase situations. In these conditions, the spectra usually show a characteristic flat shape in the larger size channels.

III. THE ONE-DIMENSIONAL OPTICAL ARRAY PROBE

A. Operating Principles

The 1D illuminates a linear array of photodiodes with a He-Ne laser. As a particle passes through this focused beam, a shadow image is cast on the diodes (Fig. 4) and a count of the total number of occulted diodes represents the particle size. The diodes at each end of the array act as a mechanism for rejecting those particles which do not pass entirely within the bounds of the linear array and would be undersized otherwise. The 1D probe types are differentiated by their magnification factors according to the size range desired. The 200X sizes particles with diameters from 40 \( \mu \text{m} \) to 280 \( \mu \text{m} \) in 20 \( \mu \text{m} \) increments; the 200Y sizes particles from 300 \( \mu \text{m} \) to 4,500 \( \mu \text{m} \) in 300 \( \mu \text{m} \) increments; and the 260X sizes particles from 40 \( \mu \text{m} \) to 620 \( \mu \text{m} \) in 10 \( \mu \text{m} \) increments.

B. Calibration Procedures

The 1D probes are calibrated periodically before and after each field project. The imaging probes are quite stable in their sizing of particles and changes occur only because of changes in optical path or exceptionally dirty optical components. The sizing calibration is done with monodispersed particles such as glass or polystyrene beads. These particles are projected across the DOF until a statistically suitable number of counts have been accumulated. Routine maintenance is a part of RAF procedures for insuring the integrity of the measurements. Such maintenance includes checking laser alignment and cleaning dirty optical elements.

C. 1D Probe Limitations

The electronic response time of these instruments imposes some limitations on the minimum detectable size. A photodiode is registered as shadowed when its output is detected to change by 50%. However, even when a particle shadows 50% of a diode, the detected change may be less than this if the particle passes too rapidly across the array. This condition depends upon the size of the particle as well as the width of the array. The 200X and 260X have lower size limits of 40 \( \mu \text{m} \) at a speed of 100 m \( \text{s}^{-1} \) because of this effect.

Although the 1D probes will detect any particles which cause the diode array to be occulted, these probes cannot differentiate shapes, types, or particle orientation. If liquid water content information is desired, some fairly loose assumptions must be made with
Fig. 4. A graphical representation of the optical probe's imaging principles.
regards to the phase, habit, and density of the particles. These assumptions can lead to non-trivial errors.

The 1D probes are unable to resolve particles coincident in the beam; however, this type of error can usually be neglected since concentrations of particles of the size measured by these instruments are normally quite small.

Obtaining a statistically representative sample of the cloud particle population can also be a problem because of the relatively small sample volume of these instruments and the small concentrations of larger particles in a cloud. The sample volume of these probes is size dependent. Appendix A discusses how to calculate these sample volumes.

IV. THE TWO-DIMENSIONAL OPTICAL ARRAY PROBE

A. Operating Principles

The 2D OAP’s optical detection system is almost identical to that of the 1D probe. Whereas the 1D probes only give information about the maximum dimension along the array width, the 2Ds also give information about the area and shape of the particle and don’t reject particles that shadow end elements. As a particle passes through the 2D’s DOF and occults the diodes in the array, the shadowed state of each diode is stored each time the probe moves the distance of one array width. These image slices are restored during analysis later to form a reconstructed two-dimensional image of each particle. This method of measurement allows the shape of the particle to be discerned as well its size. Some information concerning the composition of the particle may be deduced from the shape and from other information such as the temperature, liquid water content, or altitude at which the aircraft made its measurements. The 2Ds are classified as either a 2D-C (cloud particle probe), which detects particles with diameters from 50 μm to > 800 μm in 25 μm intervals, or as a 2D-P (precipitation probe), which detects particles with diameters from 200 μm to > 6,400 μm in 200 μm intervals.

The 2D probes also send to the data system a “Shadow-Or” count which is generated every time a particle passes through the laser. The image data is stored by the data system asynchronously and requires separate processing from the synchronous data from other sensors. However, the Shadow-Or count is accumulated at the same rate as the rest of the synchronous data and can be used to calculate estimates of particle concentrations.

B. Calibration Procedures

The 2D probes are calibrated and aligned with the same procedures and regularity as the 1D probes.
C. 2D Probe Limitations

One limitation arises from the large quantity of information produced by the 2Ds which is necessary for the two-dimensional description of a particle. If the 2D probe is operated at its maximum sampling rate, a typical 7-inch reel of magnetic tape will be filled in about five minutes, or about the same time as it would take to make a single cloud pass. The maximum rate at which the 2D probe can store image slices is $4 \times 10^6$ slices per second. This rate will not impose airspeed limitations on the lower-resolution probes. However, for the 25 $\mu$m-resolution 2D-C probe, this will mean that images will become distorted at airspeeds greater than 100 m s$^{-1}$. When the airspeed exceeds 100 m s$^{-1}$, the slice rate is maintained at the maximum rate. This causes shortened images along the direction of flight.

The high sampling rate of the 2D probe will sometimes impose another limitation on particle measurements. The image slices are stored temporarily in buffers in the probe. After one buffer is filled with 1,024 image slices, it is transferred to the data system while a second buffer is being filled. Although the image data may be collected at a rate up to $4 \times 10^6$ slices per second, it can only be transferred to the data system at about $3 \times 10^4$ slices per second. This poses a problem only during episodes of high ice concentration. During these periods, the second buffer can become filled before the first buffer has finished emptying to the data system. This condition is called an “overload”, and simply means that the probe is unable to take data during these periods.

The orientation of ice crystals can be affected by air distortions caused by the aircraft. Measurements at the the mounting locations of the PMS probes on the King Air (Fig. 1) are particularly susceptible to these effects because of sheared flow in front of the probe. Crystals such as plates and dendrites have been observed to rotate into preferred orientations that will cause them to be viewed on edge if the orientation of the probes is not adjusted to account for these rotations. The 1D and 2D probes are flown in an orientation to minimize these effects; however, the image data should be viewed with discretion.

D. Data Reduction

During the flight, the 2D images may be displayed on a CRT but no hard copy is currently available. After the project the 2D data are processed by programs that eliminate spurious particles, plot the images on microfilm, and print derived values of concentration and size distributions. Appendix C provides a more complete description of the criteria used for detecting and eliminating spurious particles. RAF Bulletin 9 describes the standard output products of RAF data processing.

Interpretation of the 2D images is highly subjective. For this reason, the RAF does not process the image data with any automatic pattern recognition software and leaves that option to the user.
V. THE PARTICLE SPACING MONITOR

A. Operating Principles

The particle spacing monitor (PSM) provides a measurement of the small-scale structure of cloud particle distributions by measuring the spacing between individual particles. This instrument monitors the total particle count from an FSSP or 1D probe and measures the time between successive counts. This time is encoded into one of 64 size channels and sent to the data system in the same manner as particle size data from other 1D probes. The time-to-channel relationship can be set to any desired value depending upon the expected distribution of the cloud particles. Figures 5a and 5b are schematic representations of the PSM and an example of the type of distribution produced by this instrument, respectively.

B. PSM Limitations

The PSM is only limited by the probe to which it is attached. For example, when attached to the FSSP, the minimum spacing between particles that the PSM can measure is slightly greater than the combined transit time of a particle through the laser and the subsequent electronic delay time. This is usually on the order of 7-8 μs, or a spacing of 0.7-0.8 mm if the aircraft is flying at 100 m s\(^{-1}\).

VI. THE CLOUD TECHNOLOGY AND PMS/CSIRO PROBES

A. Operating Principles

The operating principle of these two instruments (commonly referred to as the JW and KING probes, respectively) are based upon measuring the amount of cooling of a heated sensor by the evaporation of water droplets as they impact the sensor. These devices, that are shown schematically in Figs. 6a and 6b, differ in their methods of measuring the amount of cooling. The JW senses changes in the resistance of the heated element as it cools, and through calibration, relates it to the liquid water content. Cooling is also caused by convective heat losses, so the probe measures these losses with a heated wire oriented so as to be out of the droplet stream but still in a component of the airstream. This “compensation” signal is subtracted electronically from the sensing wire signal so that the resultant measurement is only of the liquid water component of cooling. The KING probe operates as a constant-temperature probe and measures the amount of power necessary to maintain the heated element at the same temperature while it is cooled by convection and evaporation. The liquid water content can be directly related to the power consumption using the energy equation that relates the total energy supplied to the sensing element to the energy lost through convection and evaporation. Convective heat losses are determined through calibration in dry air over a range of air speeds and temperatures.
Fig. 5a. Block diagram illustrating the PMS's operating principles.
Fig. 5b. An example of the measured time interval distribution of cloud droplets.
Fig. 6a. Cross sectional diagram of the Johnson-Williams probe.
Fig. 6b. Graphical illustration of the PMS/CSIRO hot-wire probe.
B. Calibration Procedures

The JW probe requires wind tunnel calibrations to establish the gain coefficients for each individual sensing head. The compensation wire offset is adjusted during speed runs at different altitudes prior to the beginning of a field program.

The KING probe requires no calibration for determining the power loss-to-liquid water content, as this is determined from the energy balance equation (Appendix B). The convective heat losses must be determined, however, since they are affected by the environmental conditions, e.g., air density, viscosity, thermal conductivity, etc., and the wire dimensions and temperature. The dry air heat loss term is explained also in Appendix B.

C. Liquid Water Content Probe Limitations

The JW probe is sensitive to liquid water content values down to approximately $0.05 \ \text{g m}^{-3}$, below which the inherent noise of the instrument masks any signal. The dry air compensation wire does not adequately remove all the effects of convective heat losses. This limitation is seen when the out of cloud measurements vary as much as $\pm 0.1 \ \text{g m}^{-3}$. These drifts are removed during data processing when possible (Appendix B).

As a device for measuring relative changes in the liquid water content, the JW has proved fairly reliable under a wide range of conditions. However, its accuracy as an absolute measure of liquid water content is questionable without measuring its response in a calibrated wind tunnel. Such calibrations have proved to be the best method of determining JW probe reliability and calibration. Extensive testing has shown that the response of this probe differs with each sensing element. Without a careful calibration, the accuracy of these probes is no better than approximately $\pm 20\%$.

Under particularly severe conditions where the liquid water content is greater than $1.0 \ \text{g m}^{-3}$ and the temperature is below $-15 \ ^\circ\text{C}$, the heaters in the JW sensing head are not sufficient to melt ice quickly enough that has accumulated on the probe shield. Subsequently, ice builds on the compensation wire and erroneous data are obtained.

When droplet diameters exceed about $30 \ \mu\text{m}$, droplets begin to break up on the sensing elements of both the JW and KING probes and are removed by the airflow before they have totally evaporated. Under these circumstances, both probes will underestimate the liquid water content.

Both the JW and KING probes respond to ice particles as well as water droplets. However, these probes are not calibrated with respect to ice and caution should be used when interpreting data from these probes in mixed phased environments.

The KING probe is considered by the RAF to be the primary instrument for measuring liquid water content because of its reliability and easy calibration. The JW is flown as a redundant measurement should there be a failure of the KING probe.

D. Data Reduction

Processing of the data from these probes includes corrections for airspeed on the JW and dry air heat losses on the KING probe.
<table>
<thead>
<tr>
<th>INSTRUMENT</th>
<th>MEASUREMENT RANGE</th>
<th>BIN WIDTH $\mu$m</th>
<th>VELOCITY RANGE m s$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>FSSP$^1$, $^3$</td>
<td>0.5 $\mu$m – 7.5 $\mu$m diameter$^2$</td>
<td>(0.5 $\mu$m)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.0 $\mu$m – 15.0 $\mu$m diameter</td>
<td>(1.0 $\mu$m)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.0 $\mu$m – 32.0 $\mu$m diameter</td>
<td>(2.0 $\mu$m)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.0 $\mu$m – 47.0 $\mu$m diameter</td>
<td>(3.0 $\mu$m)</td>
<td></td>
</tr>
<tr>
<td>ASASP</td>
<td>0.12 $\mu$m – 3.12 $\mu$m diameter</td>
<td>(0.25 – 0.375 $\mu$m progressively weighted)</td>
<td></td>
</tr>
<tr>
<td>200X</td>
<td>40 $\mu$m – 280 $\mu$m diameter</td>
<td>(20 $\mu$m)</td>
<td></td>
</tr>
<tr>
<td>260X</td>
<td>40 $\mu$m – 620 $\mu$m diameter</td>
<td>(10 $\mu$m)</td>
<td></td>
</tr>
<tr>
<td>200Y</td>
<td>300 $\mu$m – 4500 $\mu$m diameter</td>
<td>(300 $\mu$m)</td>
<td></td>
</tr>
<tr>
<td>2D-C</td>
<td>25 $\mu$m – &gt; 800 $\mu$m diameter</td>
<td>(25 $\mu$m)</td>
<td></td>
</tr>
<tr>
<td>2D-P</td>
<td>200 $\mu$m – &gt; 6400 $\mu$m diameter</td>
<td>(200 $\mu$m)</td>
<td></td>
</tr>
<tr>
<td>PSM</td>
<td>Variable</td>
<td>Variable</td>
<td></td>
</tr>
<tr>
<td>JW</td>
<td>0.1 – 6.0 g m$^{-3}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PMS/CSIRO</td>
<td>0.0 – 3.0 g m$^{-3}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ice Detector</td>
<td>0.0 – 0.5 ± 0.13 mm of ice</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^1$ Size ranges programmatically changeable during flight.
$^2$ Nominal values; calibrated values may vary after airspeed corrections.
$^3$ Size corrections are applied to data for airspeeds $>$100 m s$^{-1}$. 
VII. THE ROSEMOUNT ICING DETECTOR

A. Operating Principles

The model 871 detector, shown schematically in Fig. 7, measures the amount of ice mass accumulation on a metal cylinder. The property of certain metals known as magnetostriction is employed to drive the sensing probe cylinder at its natural frequency of 40 kHz. As the ice accretes on the cylinder, the frequency of the vibration decreases. A phase-locked loop detects the change in frequency and a voltage proportional to this change is recorded by the data system. When a preset voltage threshold is reached, the probe tip is heated for a fixed, short period of time to remove the ice, whereupon the cycle is repeated. This probe is primarily an icing detector; however, with additional information about the temperature and air speed, an ice water content can be estimated from its measurements.

B. Calibrations

The frequency change versus mass relationship is known through both theoretical and empirical studies. Wind tunnel tests have been conducted in which the operation of this probe was studied during typical airspeeds and icing conditions to establish the gain coefficients of the instrument. Flight data is also used to determine the calibration coefficients that are used to calculate the ice water content from these probes. The liquid water content is derived from the equations described in Appendix B.

C. Icing Detector Limitations

The ice probe is a very sensitive device and responds to very small ice water contents. Data loss occurs, however, during the deicing period and for about a five second period after this as the probe reaches equilibrium with the ambient temperature.

Ice water contents derived from the icing rate measurements have an uncertainty on the order of 20% as a result of uncertainties in droplet collection efficiency and sampling volume.

VIII. FURTHER INFORMATION

Investigators interested in discussing additional aspects of cloud physical measurement should contact the Facility Manager at 303/497-1032. Additional information on the instrumentation discussed above may be found in the references listed at the end of this bulletin.
![Diagram of Rosemount ice detector with dimensions and labels.](image)

Fig. 7. A schematic drawing of the Rosemount ice detector (reproduced from the Rosemount, Inc. ice detector operations manual).
APPENDIX A

Calculation of Particle Spectrum Parameters

The particle distributions measured by the ASASP, FSSP, 1D, and 2D are usually characterized by the total concentration, the mean diameter, the standard deviation, and the liquid water content. An explanation and derivation of these parameters follow.

Total Concentration

Particle concentration is defined as the number of particles per unit volume. In the case of the ASASP and FSSP, the dimensions are the number of particles per cubic centimeter. Concentrations measured by the imaging probes are usually expressed in number per liter. The method of calculating the total concentration is

\[ C_T = \sum_{i=1}^{m} \frac{n_i}{SV} \]

where

- \( C_T \) = total concentration
- \( n_i \) = number of particles accumulated in channel i (for all probes but the FSSP)
- \( \sum n_i \) = total droplets passing through the DOF for the FSSP
- \( m \) = total number of size channels
- \( SV \) = sample volume

The sample volume is defined as

\[ SV = (TAS)(SA)(T) \]

where

- \( TAS \) = true airspeed
- \( SA \) = sample area
- \( T \) = sampling period

The sample area is determined for the FSSP, by

\[ SA = (DOF)(BD) \]

and for the imaging probes, by

\[ SA = (DOF)(ESW) \]
where

\[ DOF = \text{depth of field} \]
\[ BD = \text{effective beam diameter} \]
\[ ESW = \text{effective sample width}. \]

The ASASP is a constant-volume device and is set to 1.0 cm\(^3\) s\(^{-1}\). The \( DOF \) and \( ESW \) of the imaging probes are functions of the particle size and are calculated as (Knollenberg, 1970):

\[ DOF = \frac{6R^2}{\lambda} \]

where

\[ R = \text{radius of the particle (mm)} \]
\[ \lambda = \text{the laser wavelength} = 0.6328 \times 10^{-3} \text{ mm} \]

which gives a \( DOF \) of

\[ DOF = 9482R^2. \]

The \( DOF \) of the instruments is limited by the distance between probe arm tips. The maximum depth of field for the 200X, 260X, and 2D-C is 61 mm, which corresponds to a particle radius of 80 \( \mu \)m. The 200Y and 2D-P have a maximum depth of field of 261 mm for particles 165 \( \mu \)m or larger in radius.

The effective sample width for the 1D probes is defined as

\[ ESW = \frac{D(N - X - 1)}{M} \]

where

\[ D = \text{diode diameter} = 0.2 \text{ mm} \]
\[ M = \text{probe magnification factor} \]
\[ N = \text{number of diodes in the array} \]
\[ X = \text{number of diodes shadowed by a particle} \]

This method of determining the effective sample width is used to account for the fact that as particles get larger, the probability increases that they will occult an end diode
and be rejected. Table A.1 tabulates M, N, and sample area formulas for each of the 1D imaging probes.

<table>
<thead>
<tr>
<th>PROBE TYPE</th>
<th>Magnification M</th>
<th>DIODES in ARRAY N</th>
<th>SAMPLE AREA EQUATION (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200X</td>
<td>10</td>
<td>16</td>
<td>189.6 · (15 − X) · R² (R ≤ 80 μm)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.22 · (15 − X)           (R &gt; 80 μm)</td>
</tr>
<tr>
<td>260X</td>
<td>20</td>
<td>64</td>
<td>94.8 · (63 − X) · R² (R &lt; 95 μm)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>.86 · (63 − X)            (R ≥ 95 μm)</td>
</tr>
<tr>
<td>200Y</td>
<td>.667</td>
<td>24</td>
<td>284.30 · (23 − X) · R² (R &lt; 175 μm)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>87.3 · (23 − X)           (R ≥ 175 μm)</td>
</tr>
</tbody>
</table>

The ESW of the 2D probes is determined in a different fashion than that for the 1D probes since particles which shadow the end diodes are not rejected and can be included in the sample statistics if the sample volume is adjusted accordingly. A particle weighting technique is used which increases the ESW with increasing particle size. Figures A.1 and A.2 show the sampling areas for the five probes as a function of particle diameter.

Mean Diameter and Standard Deviation

The mean diameter is the arithmetic average of all particle diameters and is calculated by

$$D = \frac{1}{N_T} \sum_{i=1}^{m} \frac{(n_i d_i)}{N_T}$$

The standard deviation is a measure of the deviations from the mean, calculated by

$$S = \sqrt{ \frac{\sum_{i=1}^{m} n_i d_i^2}{N_T} - \overline{D}^2}$$
Fig. A.1. The relationship between sample area and particle diameter for the three types of cloud droplet probes.
Fig. A.2. The relationship between sample area and particle diameter for the two types of precipitation probes.
where
\[ \bar{D} = \text{mean diameter (\(\mu m\))} \]
\[ S = \text{standard deviation (\(\mu m\))} \]
\[ n_i = \text{number of particles in channel } i \]
\[ d_i = \text{size which channel } i \text{ represents (\(\mu m\))} \]
\[ m = \text{number of channels} \]
\[ N_T = \text{total number of particles} \]

**Liquid/Ice Water Content**

The liquid or ice water content is calculated from the measured size spectra using a summation of the individual particle masses per unit sample volume, i.e.,

\[ \frac{LWC}{IWC} = \frac{\pi \rho_w}{6} \sum_{i=1}^{m} N_i d_{ie}^3 \]

where
\[ \rho_w = \text{density of water} \]
\[ N_i = \text{concentration of particles in size channel } i \]
\[ d_{ie} = \text{equivalent melted diameter (the size an ice particle would be if it were melted) in size channel } i. \]

The equivalent melted diameter is strongly dependent upon the particle habit which is measured. The method for choosing this value must be specified by the user.
APPENDIX B

Liquid Water Content Calculations

PMS/CSIRO Liquid Water Content

The electrical power required to maintain the sensor of this probe at a constant temperature must compensate for heat losses from the sensor to the passing air stream and to that absorbed by impinging droplets. This is expressed through an energy balance equation as

\[ P = P_d + P_w \]  \hspace{1cm} (B.1)

where the losses to the air, \( P_d \), are described by

\[ P_d = \pi k(T_s - T_a)N \]  \hspace{1cm} (B.2)

and the losses to the droplets, \( P_w \), are similarly expressed as

\[ P_w = l \cdot d \cdot w \cdot v \cdot [L_v + c(T_b - T_a)] \]  \hspace{1cm} (B.3)

where

- \( Nu \) = the Nusselt number
- \( k \) = thermal conductivity of dry air
- \( l \) = length of sensor
- \( d \) = diameter of sensor
- \( T_s \) = temperature of sensor
- \( T_a \) = temperature of air
- \( T_b \) = boiling point of water
- \( L_v \) = latent heat of vaporization
- \( c \) = specific heat of water
- \( v \) = airspeed
- \( w \) = liquid water content

The liquid water content can be immediately obtained by measuring the power \( P \), if the value for the Nusselt number is known. The Nusselt number can be determined as a function of the Reynolds number, \( Re \), that take the form of a power law

\[ Nu = A \cdot Re^\varepsilon \]  \hspace{1cm} (B.4)
where A and x are determined empirically from flight data taken at several altitudes and airspeeds.

**JW Baseline Drift Removal**

The compensation wire in the JW partially removes the effects of convective heat losses from the JW measurements. However, the compensation is affected by changes in temperature and pressure and often times the zero baseline of the instrument will drift by .2-.3 g/m³ when out of cloud. This zero offset can be removed when the FSSP is present by using this probe to detect the presence of cloud. When the FSSP indicates the absence of cloud, a running average is maintained of the JW measured LWC. During the cloud penetration, this average offset value is subtracted from the measurements.

**Rosemount Ice Detector LWC Calculations**

The voltage output of the Rosemount ice detector is directly proportional to the mass of ice that accretes on the sensor. When the aircraft is in cloud, the voltage increases steadily as ice builds on the sensor up to the point that a preset threshold is reached and the sensor heat is activated to remove the ice. An estimate of the LWC can be made from the voltage rate of change if several assumptions are made. The mass accumulated on the sensor is determined by

\[ m = E_c \cdot d \cdot l \cdot v \cdot w \cdot t \]  

(B.5)

where

\[ E_c = \text{the droplet collection efficiency of the sensor} \]

\[ d = \text{the diameter of the sensor} \]

\[ l = \text{the length of the sensor} \]

\[ v = \text{the aircraft velocity} \]

\[ w = \text{the LWC} \]

\[ t = \text{the accumulation time} \]

Thus the mass accumulation rate is

\[ \frac{dm}{dt} = k \cdot w \]  

(B.6)

where

\[ k = E_c \cdot d \cdot l \cdot v \]  

(B.7)

The voltage-to-mass calibration factor is determined either in laboratory calibrations or with inflight comparisons with other LWC measurements. If the voltage-to-mass calibration is described by

\[ V = G \cdot m \]  

(B.8)
then

\[
\frac{dV}{dt} = G \frac{dm}{dt}
\]  \hspace{1cm} (B.9)

and solving for the LWC, \( w \),

\[
w = \frac{l \, dV}{Gk \, t}
\]  \hspace{1cm} (B.10)

This expression for the LWC can be evaluated if the collection efficiency is known and if the diameter and length of the sensor can be assumed to be constant. These assumptions involve some uncertainty since the collection efficiency is a function of the diameter of the sensor, the size of the water droplets the speed of the aircraft, and the temperature and viscosity of the air. The estimated uncertainty in collection efficiency is on the order of 20%.

An additional uncertainty in the evaluation of (B.10) arises because of the assumption of constant diameter and length of the sensor. Wind tunnel and laboratory tests have shown that ice does not accumulate evenly on the ice probe sensor because of aerodynamic effects around the probe. Thus the value of \( l \) is variable depending upon the environmental conditions. The ice mass that builds on the sensor changes the effective cross section of the probe so that the value of \( l \) changes as a function of time, airspeed and liquid water content. There is a 30% uncertainty in estimating the sample volume because of these factors.

Finally, the gain, \( G \), is a function of where the ice accretes to the sensor and can change as much as 30% during the accumulation period depending upon the accretion pattern.

The total uncertainty in estimating the LWC from (B.10) is approximately 50% if the theoretical derivation of \( w \) is used along with the estimates of collection efficiency, sample volume, and voltage-to-mass calibration. However, the value of the product \( Gk \) can be determined empirically without having to assume specific values for the components that go into the derivation of these variables. If \( Gk \) is determined by comparisons with the LWC from the hot-wire probes, the resulting accuracy in the derived LWC is decreased to approximately 20%.
APPENDIX C
Spurious Image Rejection Techniques
In the Processing of Data from the 2D Probe

The 2D probes capture the image of particles in the shape of shadows that pass across the linear array of diodes. Some of these images are not truly representative of real particles, but are the result of splashing or breakup of ice or water on the probe arm tips. In especially heavy concentrations of raindrops, liquid water content, or graupel, the rate at which these spurious images are generated can be high and will seriously bias the derived concentrations and size distributions. The remainder of this appendix describes each type of spurious image, its cause, and the pattern recognition technique used to identify and reject it.

Short Arrival Time Rejection

When a particle strikes the armtip of the probe the result is a cloud of secondary particles that stream through the probes sample volume (Fig. C.1). The distance between these particles will be quite small and the measured particle interarrival times will also be very short. On the average, cloud particles are distributed homogeneously and the spacing between them is random and determined by the average concentration, c. Although some of the distances between particles can be short, on average, the spacing is

$$l_a = (1/C)^{1/3}$$  \hspace{1cm} (C.1)

Thus, when particles in the size range of the 2D probes are even in modest concentrations of 1 - 10 \( \ell \) \(^{-1}\), the average spacing is on the order of 5 to 10 cm.

The 2D probes measure the distance between particles along with the particle image. The majority of spurious particles generated by collisions with the probe tips will be rejected if a threshold is specified that is much smaller than the average expected spacing between particles. This threshold will eliminate some legitimate particles, of course, since there is a finite probability that the spacing between some particles is very short. The fraction of particles erroneously eliminated can be calculated if the particles are assumed to be distributed randomly in space with an exponential probability distribution function

$$P(l < l_t) = 1 - e^{-l_t/l_a}$$  \hspace{1cm} (C.2)

where

$$l = \text{the distance between particles}$$

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\[ l_t = \text{the threshold distance} \]

**Hollow and Gapped Particle Rejection**

Another characteristic of particles created spuriously by armtip collisions is that they will be so close together that the probe cannot recognize the end of one particle and the start of another and the result is an image that looks like a number of distinct particles in the same image frame (Fig. C.2). This condition is detected in the analysis in two different ways. Sometimes several blank image slices will occur within the image (Fig. C.2). When this condition is detected, the particle is rejected. The other method is to measure the ratio of the area of the shadow image to the area of the rectangle that would enclose the image and reject the image if this ratio is less than a preset threshold. This fraction (shown graphically in Fig. C.3) is determined by

\[ f = \frac{A}{XY} \quad \text{(C.3)} \]

where \( A \) is the image area expressed in number of diodes shadowed and \( X \) and \( Y \) are the lengths of the sides of the rectangle that circumscribe the image. These lengths are also expressed in terms of the number of diodes.

The threshold is usually set to 0.4, a value that has been determined empirically after visually examining a large number of spurious 2D images and calculating the average fraction, \( f \), from C.3.

**Water Streamer Rejection**

Under conditions of heavy liquid water content, pools of water will build on the splashguards of the probe and eventually be discharged across the opening in the armtip and will appear as an elongated image (Fig. C.4). These images are rejected by comparing the length of the particle along the direction of flight to its width along the diode array. If the length is greater than six times the width, the particle is assumed to be a “streaker” and is rejected. This criteria will also sometimes reject larger particles or particles only partially in the sample volume. To minimize rejecting too many of these type of particle, extra constraints are imposed on the rejection criterium. When the width of the particle is greater than three-quarters of the array width, or if any of the diode array end elements are shadowed, then the rejection criterium is not imposed.

**Blank Image Rejection**

The 2D probe will often register the occurrence of a particle but the resulting image frame will be blank. The “zero area” images are usually the result of particles whose size is of the same order as the resolution of the probe. When a particle enters the beam the
Fig. C.1. Example of spurious particles generated by the breakup of a larger particle on the probe tip.
Fig. C.2. This figure shows an example of a gapped image.
Fig. C.3. This is a schematic representation of the algorithm used for rejecting hollow particles.
Fig. C.4. A typical "streaker" image is shown in this figure.
2D probe is placed in a ready state and waits until the occurrence of the next cycle of the timing clock (which is called the true air speed clock since the frequency is proportional to the aircraft velocity). If the particle is small, it will have passed completely across the array by the time the next clock cycle occurs. In these cases, the shadow state of the diodes is not captured in time yet the event is still recorded by the probe by the appropriate time word in the data buffer.

Most of these zero-area events are caused by legitimate particles and could be used to calculate the total concentration; however, it is left to the discretion of the investigator whether or not to reject these events and exclude them from the analysis of the data.
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