Cloud Sampling Instruments for Icing Flight Tests: (4) Large Drop Sizers

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16. Abstract

This series of technical notes, "Cloud Sampling Instruments for Icing Test Flights," provides information and guidance for devices that are most commonly used for measuring cloud water and droplet sizes during aircraft certification test flights in natural icing conditions. Advice is given on the suitability, procedure, and precautions for using various instruments and on data analysis techniques. This technical note is devoted to the so-called optical array probe—a commercially available device for counting and sizing individual drops in the diameter range of 100 to 300 µm or more. The other technical notes in the series are:

- DOT/FAA/AR-TN06/29, Cloud Sampling Instruments for Icing Flight Tests: (1) Icing Rate Indicators
- DOT/FAA/AR-TN06/30, Cloud Sampling Instruments for Icing Flight Tests: (2) Cloud Water Concentration Indicators
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LIST OF ACRONYMS

2D	Two-dimensional
ACO	Aircraft Certification Office
CFR	Code of Federal Regulations
FAA	Federal Aviation Administration
FSSP	Forward scattering spectrometer probe
LWC	Liquid water content
MVD	Median-volume diameter
OAP	Optical array probe
PMS	Particle Measuring Systems, Inc.
SLD	Supercooled large droplets

INTRODUCTION

Federal aviation regulations, such as Title 14 Code of Federal Regulations (CFR) 25.1419 "Ice Protection" require that, for aircraft being certificated for flight in icing conditions, flight tests be conducted in measured natural or simulated icing conditions. Different aircraft manufacturers have employed different types of instrumentation to measure the relevant icing cloud variables, primarily water content, droplet sizes, and temperature. The available instrumentation ranges from simple to complex, from old to new, and from relatively inexpensive to expensive. Most of the instrumentation comes from the cloud physics research community and requires a certain amount of knowledge and experience to ensure that the probes are properly installed, calibrated, and operated. In addition, all probe types can have subtle systematic errors that may be difficult to recognize by the inexperienced operator or data analyst.

The Federal Aviation Administration (FAA) aircraft certification offices (ACO) have had little guidance on this type of instrumentation and, as a result of these complexities, have had to rely on the aircraft manufacturers to supply presumably adequate instrumentation and technicians or to hire experienced contractors to install and operate suitable instrumentation and analyze the icing cloud data.

To help standardize policy and procedures among ACOs for icing certification projects, there was a need for official guidance on instrumentation for measuring the properties of icing conditions during natural icing test flights. This need was solidified as part of Task A.13.4 of the revised "FAA Aircraft Icing Plan" [1] of 2000, which calls for the FAA to develop certification guidance for measuring natural icing conditions.

The result was the following series of stand-alone technical notes—one for each type of instrument.

- DOT/FAA/AR-TN06/29, Cloud Sampling Instruments for Icing Flight Tests: (1) Icing Rate Indicators
- DOT/FAA/AR-TN06/30, Cloud Sampling Instruments for Icing Flight Tests: (2) Cloud Water Concentration Indicators
- DOT/FAA/AR-TN06/31, Cloud Sampling Instruments for Icing Flight Tests: (3) Cloud Droplet Sizers
- DOT/FAA/AR-TN06/32, Cloud Sampling Instruments for Icing Flight Tests: (4) Large Drop Sizers

The technical notes are intended to be a ready reference for ACOs, designated engineering representatives, aircraft manufacturers, and any other interested parties. They include advice on the suitability, procedure, and precautions for the most commonly used instruments for in-flight measurement of icing cloud variables. They also include advice on data quality assurance, data processing, and presentation of results.

The information and guidance was based on the author's own extensive experience with using the various instruments and analyzing the data therefrom. It was also based on information in the scientific and technical literature [2-5] and on the lessons learned during a comprehensive instrument comparison exercise conducted in 1998 in the Icing Research Wind Tunnel at the National Aeronautics and Space Administration Glenn Research Center near Cleveland, Ohio.

THE OPTICAL ARRAY PROBE

The following is a description of the Optical Array Probe (OAP):

- Classification: Optical, single-particle size spectrometer.

- Manufacturer: Particle Metrics, Inc.
  5505 Airport Boulevard
  Boulder, Colorado 80301
  Telephone: 1-303-247-0411

- Purpose: To detect, count, and classify individual drizzle or raindrops or ice particles by size.

- Specifications:

  - Drop-size range: Customizable from 10-150 μm or 20-300 μm and larger

  - Sampling rate: Down to 0.1 sec

  - Physical size: Cylindrical pod about 7 inches (18 cm) wide by 30 inches (76 cm) long, (see figure 1)

  - Probe weight: 45 pounds (22 kg)

  - Accessories needed: Electronic control system; computer or digital data recorder

  - Cost of new probe: $36,000

- Intended Use: Airborne cloud physics research

BACKGROUND.

The OAP and related cloud droplet-size spectrometers were introduced by Particle Measuring Systems (PMS), Inc., in the early 1970s as a new generation of automatic, electro-optical, droplet sizing and counting systems for airborne cloud physics research. These new probes provided fast response, high-resolution, and continuous in situ sampling with automatic size categorization and real-time digital readout and display of size distributions. Digital storage of the data provided a continuous, second-by-second record of the changing droplet populations during cloud penetrations. All of these features were great improvements over the previously available impactor methods with their intermittent sampling and labor-intensive droplet counting and sizing procedures. The PMS line of cloud physics instrumentation has been sold recently to a new firm, Particle Metrics, Inc.

In addition to airborne cloud physics measurements, the OAP has been used to document droplet-size distributions in water sprays in icing wind tunnels and behind airborne spray tankers.

PRINCIPLE OF OPERATION.

These probes use a miniature row of 24, 32, or 64 closely-spaced, 180-μm diameter photodiodes to detect the passing shadows of droplets moving through a narrow laser beam projected between two tubes extending forward of the canister-shaped probe body (see figure 1). In flight, these light-sensitive diodes must detect particle (droplet) shadows passing across the line of diodes at aircraft speeds. The minimum detectable drop size is usually about 10 or 20 μm. The maximum detectable drop size is determined by the optical magnification and the length of the diode array. Typically the nominal size ranges are 20 to 300 μm for the 1D-C or cloud probe, and 300- to 4500-μm diameter for the 1D-P or precipitation probe. The 1D indicates that these probes register only one dimension—the length of the shadow along the diode array. For spherical water drops, this is their diameter. There is no direct way to distinguish between water droplets and ice crystals.

The probes basically count the number of shadows in each of 15, 30, or 60 discrete size intervals determined by the number of the photodiodes. These probes do not measure the liquid water content (LWC) or median-volume diameter (MVD) directly, but rather the drop-size distributions from which the LWC and MVD may be computed.

A variation on this design is the two-dimensional (2D) probe. Models of this type scan the shadows as they pass across the row of diodes, thus revealing and recording the 2D shape of the shadow. This allows the researcher to distinguish between round water droplets and angular ice crystals or snowflakes, as well as to study the individual shapes of the solid particles.

For more details on the principle of operation, consult the owner's manual and the discussions in references 2 through 5.

USE IN ICING RESEARCH FLIGHTS. Because these probes are sensitive mainly to drizzle (50-500 μm) or larger precipitation drops, they are seldom needed for icing tests in ordinary clouds, where droplets smaller than 50-μm diameter prevail. Most of the time, one finds few, if any, counts registered on the OAPs during natural icing flights in supercooled water clouds.

The OAPs become necessary when flights in supercooled large droplets (SLD) are of interest. SLD generally refers to any droplets larger than 50 μm, including freezing drizzle and freezing rain. Some icing wind tunnels have experimented with producing SLD sprays and, in the mid-1990s, the U.S. Air Force icing spray tanker produced an SLD spray to test several aircraft models for wing and tailplane icing in these conditions. In this case, both a Forward Scattering Spectrometer Probe (FSSP) (see the third technical note in this series) [6] and an OAP are necessary to cover the full range of drop sizes that were present.

By recording angular particle shapes, the 2D OAPs can be helpful in identifying or verifying glaciated portions of any cloud pass. This is usually unnecessary unless one is trying to distinguish between ice particles and SLD during natural icing flights. Otherwise, an icing rate meter and other visual cues can usually enable one to tell the difference between glaciated and supercooled cloud segments. Recognizing glaciated conditions is not a concern for wind tunnel or airborne tanker sprays because no ice crystals or snowflakes are produced there.

The following lists the advantages and disadvantages of the OAP:

- Advantages

    - Provides a good, continuous record of drizzle or raindrop sizes and numbers
    - Provides digital readout and storage of data
    - Tracks actual fluctuations in drop-size distributions and associated LWC
    - Resolves drop-size distributions into 15 or more size categories (bins)
    - LWC and MVD can be easily computed from the drop-size distributions

- Disadvantages

    - Probe is subject to several types of systematic error (see the next section Known Sources of Error)

    - Requires a trained, experienced operator and data analyst

    - Probe is subject to icing in moderate or greater icing conditions

    - Probe may not be suitable at jet speeds

    - Probe and cabling may not be easy to install on production aircraft

    - 1D probes cannot distinguish between water droplets and ice particles in clouds

    - Relatively expensive to purchase or rent

KNOWN SOURCES OF ERROR.

MISTAKING ICE PARTICLES FOR WATER DROPS. The 1D OAP cannot distinguish between particle shapes, and it blindly indicates apparent size based solely on the width of the particle shadow. Therefore, users of the data must be kept aware of when the flight was in glaciated or mixed-phase ice OAP data. There is no way to recognize which counts are ice particles, except to use a 2D OAP instead.

UNDERCOUNTING OF SMALLER DROPS. The OAPs have a well-known problem: they seriously undercount droplets in the lower end of their drop size range. They may also undercount droplets whose size is near the upper end of the range for that probe. The reasons for the undercounting are somewhat complicated to explain to those unfamiliar with the design of the probes. The undercounting is due to the limitations of: (1) the response time of the electronics for the smaller droplets at aircraft speeds, (2) the optical means for keeping droplets in focus, and (3) the discrete picket fence nature of the diode array for sizing the shadows of the droplets.

The net result is that there is a marked roll off or undercounting of droplets in the lower end of the drop-size range, and an uncertainty in the actual drop sizes by at least one diode width. A typical example of the behavior is shown in figure 2(a) [5]. This can cause uncertainty in both the LWC and MVD computed from the recorded number of droplets in each size interval. This uncertainty can be serious when the droplets in the 20- to 100-µm-diameter interval are important, as they are in SLD icing conditions. Several ways of dealing with the problem have been proposed.

<u>THE ATTEMPTED SOLUTIONS</u>. The basic idea is to get the recorded size distribution (figure 2(a)) to look like figure 2(b). The simplest solution is just to ignore the first three size intervals and rely on the data from the probe covering the next smaller size range. The PMS FSSP probe usually covers the 3- to 45-µm-size range and can fill in for the first few size intervals of the 1D-C or 2D-C probes. Likewise, the upper size range of these latter two probes overlap the first few size intervals of the 1D-P or 2D-P probes. This simple correction scheme sometimes gives believable-looking drop-size distributions and sometimes not.

Another solution was recommended by the original manufacturer, PMS, Inc., in the owner's manuals. Their solution was to boost the recorded droplet counts in the first few size intervals by different fixed amounts to give closer-to-reality values. This appears to give reasonable-looking continuity between the portions of the drop-size distributions contributed by each of the available probes (FSSP and 1D-C, for example).

In the search for a better understanding of the problem and a better correction scheme, some experienced users of the OAPs recently undertook thorough tests and analyses of the probes' electronics and optical functions [5]. The result was a scheme for correcting the sampling volume for airspeed effects. As is seen in figure 2(b), this also appears to give reasonable-looking continuity between the portions of the drop-size distributions contributed by each of the available probes.

<u>So What's the Problem</u>? This apparently solved problem may reappear when computed LWCs and MVDs are compared using the different probe-correction schemes. This is explained as follows.

The volume of a droplet of radius r is given by the simple formula for a sphere,

$$v = (4/3)\pi r^3$$

and the water content (or mass) in each size interval is given by

$$nv$$

where n is the number of droplets in the size interval. This means that the total computed LWC depends not only on knowing the correct number of droplets in each size interval, but also knowing what size (radius) the droplets actually are. Any errors in the drop size are cubed in the LWC formula, so small differences in drop-size assignment can have a large effect on the computed LWC.

This is where any discrepancies between the various probe-correction schemes really show up. It appears to be possible to have more than a factor of two differences in the computed LWC depending on which correction scheme is used. The differences in computed MVD may be nearly as large.

The simple procedures for computing LWC and MVD are straightforward and are essentially the same for all users. It is the methods of correcting for probe counting and sizing deficiencies that are different.

<u>What Can be Done About it</u>? This uncertainty in probe response for SLD conditions has plagued the users of these probes all along. The problem was brought to the attention of the aviation community by the droplet measurement team during the ATR tanker tests where the possible legal and technical ramifications of such uncertainties could not be ignored.

But the main reason why this problem has not yet been solved with certainty is the lack of an independent, trustworthy LWC meter for large droplets. Such a device would provide a long-needed, absolute calibration and response check for the PMS 1D and 2D probes. That is, only when the computed LWC matches a trusted, directly measured LWC can it be assumed that the probe is correctly calibrated for drop-size intervals and properly adjusted for undercounting and possible undersizing at aircraft speeds.

The hot-wire LWC meters routinely in use on cloud physics research aircraft are satisfactory for ordinary cloud droplets that are mostly confined to diameters smaller than 50 μm. Depending on their design, hot-wire probes become increasingly inaccurate as droplets increase in size above the 40- or 50-μm diameter.

So far, no sponsor of cloud physics research has been interested in funding the development of a LWC sensor for these large and infrequent droplets that seemed of little practical concern to most cloud physics problems.

This problem is not peculiar to the tanker spray measuring team but to all users of these probes. An individual probe usually gives a consistent indication of the relative size distribution of the droplets. But the accuracy of the droplet counts and sizes decreases toward the upper, and especially toward the lower end of the applicable drop-size range. This inaccuracy can be substantially mitigated by various correction schemes. But the absolute accuracy of any subsequent LWC and MVD computations is unknown without an independent, absolute LWC measurement as an inflight calibration point or at least as a laboratory standard for calibrating large droplet probes in a wet wind tunnel.

Fortunately, these problems are of no concern for most natural icing flights, where ordinary supercooled clouds are involved and cloud droplets are all smaller than 50 μm. In this case, a single FSSP and a hot-wire LWC meter is sufficient. In some cases, just an icing rate meter may be adequate for documenting the icing conditions (see separate write-up on the Rosemount Model 871FA Ice Detector in the first technical note in this series [7]).

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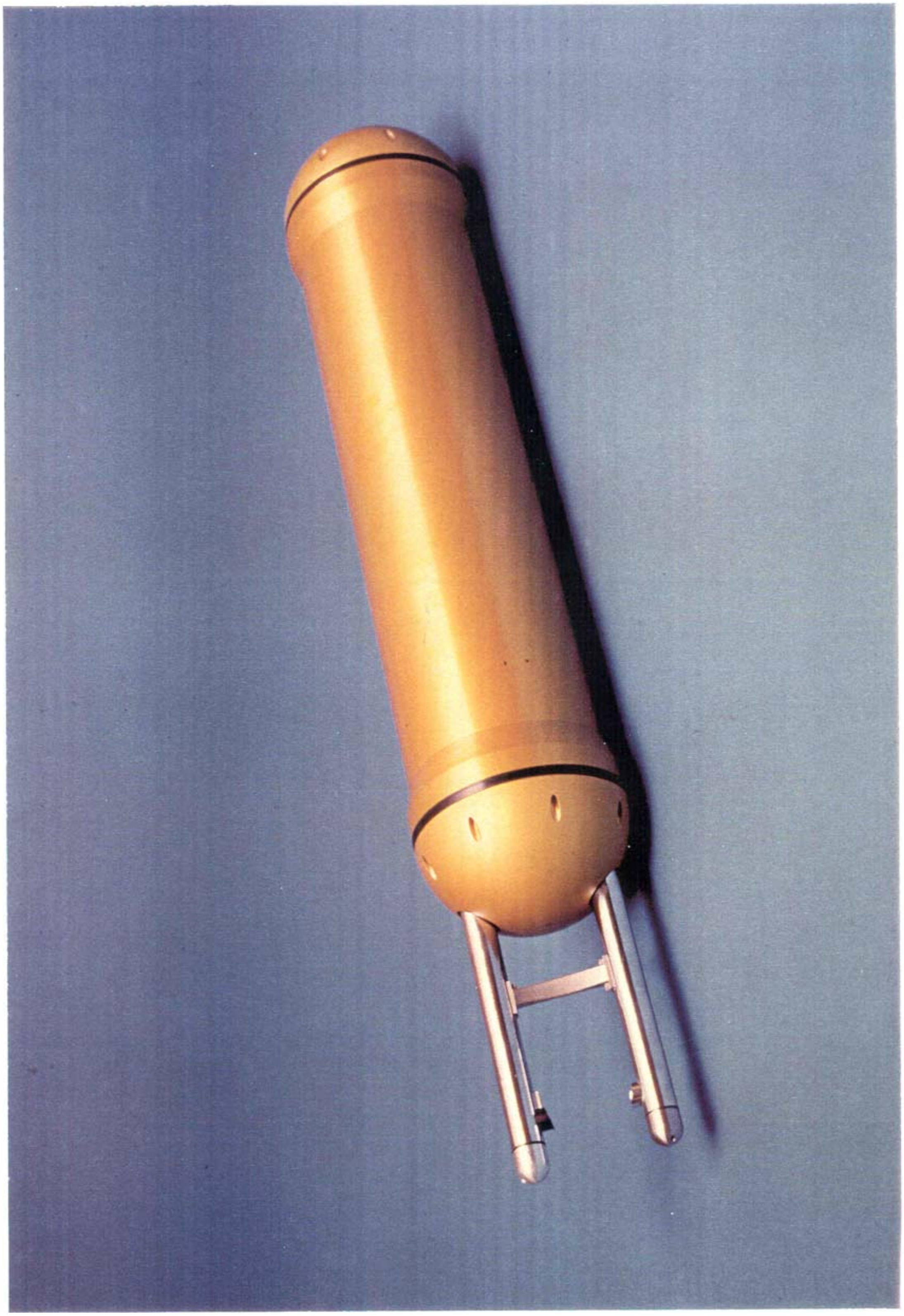

FIGURE 1. THE MODEL 200X SERIES OF OAP FROM PMS

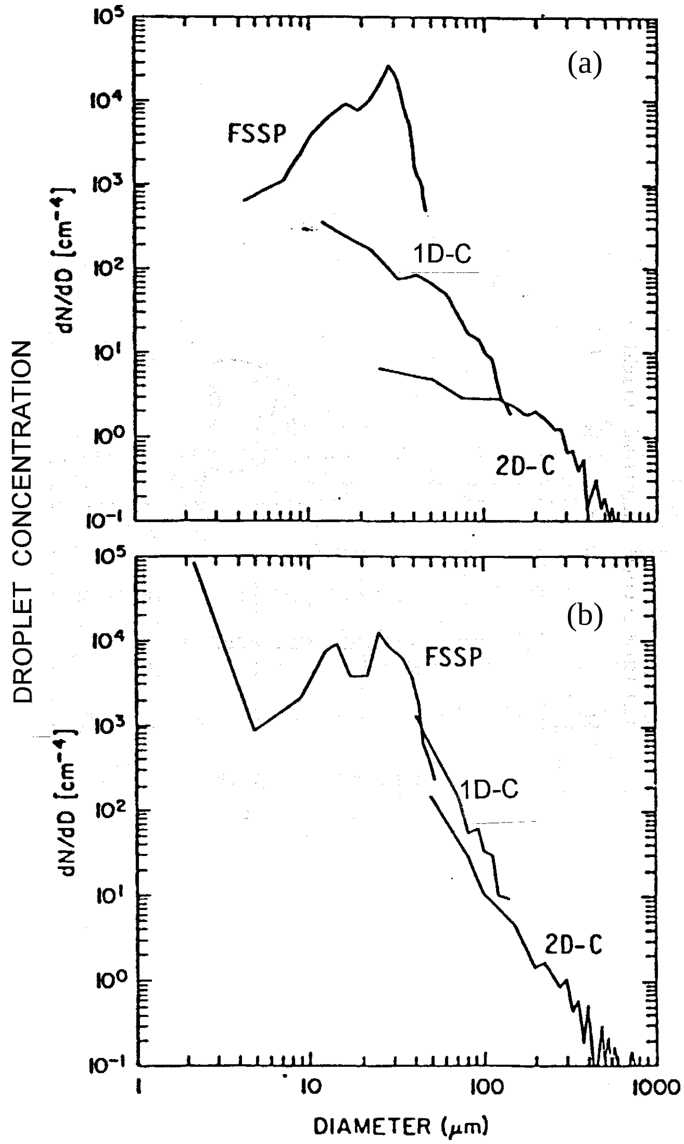

FIGURE 2. EXAMPLE [5] OF A COMPOSITE DROP-SIZE DISTRIBUTION IN CLOUD AND DRIZZLE FROM THREE COMPLEMENTARY PMS DROP-SIZE SPECTROMETERS: (a) AS RECORDED AND (b) AFTER ADJUSTMENT FOR AIRSPEED EFFECTS