Cloud Sampling Instruments for Icing Flight Tests: (3) Cloud Droplet 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 popular droplet sizers. 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
- DOT/FAA/AR-TN06/32, Cloud Sampling Instruments for Icing Flight Tests: (4) Large Drop Sizers

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LIST OF ACRONYMS

ACO	Aircraft certification office
CFR	Code of Federal Regulations
FAA	Federal Aviation Administration
FSSP	Forward Scattering Spectrometer Probe
IRT	Icing Research Wind Tunnel
MVD	Median-volume diameter
OAP	Optical array probe
PMS	Particle Measuring Systems, Inc.
TAS	True airspeed

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 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 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 using the various instruments and analyzing the data therefrom. It was also based on information in the scientific and technical literature [2-6] 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.

FORWARD SCATTERING SPECTROMETER PROBE

The following is a description of the Forward Scattering Spectrometer Probe (FSSP):

- Classification: Optical, single-particle size spectrometer.

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

- Purpose of Instrument: To detect, count, and classify individual cloud droplets by size.

- Specifications:

  - Drop-size range: 1- to 45-µm or 1- to 95-µm diameter

  - Sampling rate: Down to 0.1 second

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

  - Probe weight: 45 pounds (22 kg)

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

  - Cost of new probe: $30,000

- Intended Use: Airborne cloud physics research.

BACKGROUND.

The FSSP (shown in figure 1) 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 labor-intensive droplet counting and sizing procedures. The PMS line of cloud physics instrumentation was sold in 2000 to a new firm, Particle Metrics, Inc.

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

PRINCIPLE OF OPERATION.

The FSSP is based on the principle that water droplets in the 1- to 100-μm-diameter range will scatter visible light with an intensity that is proportional to square of the droplet diameter. The probe uses a low-power laser beam to illuminate droplets passing though a tiny (0.08 mm^3) sensitive volume of space in front of the probe. This volume is small enough that, for ordinary cloud droplet concentrations (up to a few hundred per cubic centimeter), only one droplet will be in the sensitive volume during the microsecond or so needed to detect and size it. The individual droplets are sized by the intensity of light that each droplet scatters in a near-forward cone of directions out of the laser beam. The flashes of light are detected by a ring-shaped photodetector that outputs a voltage pulse whose magnitude is proportional to the intensity of the light flash. The voltage pulses are electronically compared to a scale of 15 sequential voltage intervals corresponding to 15 different droplet diameter intervals determined by the classical Mie-scattering theory of optics. Thus, droplets within the size range of the instrument are registered as a count in one of these fifteen size intervals. The intervals are typically 3-μm wide, ranging from 3 to 45 μm for most cases. This range easily covers most cloud droplet populations, where the mode diameter is usually less than 10 μm and few, if any, are recorded in sizes above about 30 μm.

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

The following lists the advantages and disadvantages of the FSSP:

- Advantages
  - Provides a good, continuous record of droplet sizes and numbers in clouds
  - Provides digital readout and storage of data
  - Tracks actual fluctuations in cloud density (droplet count and liquid water content (LWC))
  - Resolves droplet size distributions into 15 size categories (bins)
  - LWC and median-volume diameter (MVD) can be easily computed from the drop-size distributions

- Disadvantages
  - Subject to several types of systematic error (see the next section, Known Sources of Error)
  - Requires a trained, experienced operator and data analyst
  - Subject to icing in moderate or greater icing conditions
  - May not be suitable at jet speeds
  - Probe and cabling may not be easy to install on production aircraft
  - Cannot generally distinguish between water droplets and ice particles in clouds
  - Probe may not be suitable in icing wind tunnels where high droplet counts and large LWCs are present
  - Relatively expensive to purchase or rent

KNOWN SOURCES OF ERROR.

PROBE SATURATION. When clouds are too dense or airspeeds are too fast, the rate that droplets pass through the sensitive volume of the laser beam can be too fast for the electronics to respond to each droplet. This results in an undercounting of the droplets that becomes more serious the denser the cloud and/or the faster the aircraft. In FSSP's produced after about 1980, the activity rate is recorded so the data analyst can use it in a prescribed way to estimate a correction for the undercount. The ideal operating conditions for the FSSP are for droplet densities less than about 500 cm^{-3} and airspeeds less than about 150 kt.

Large concentrations of droplets may be found in icing wind tunnels, too. Due to the nature of the spray nozzles, large numbers of small droplets may be inadvertently generated in order to produce larger-desired LWCs or drop-size distributions into the larger drop-size range. In this case, the overabundance of small droplets compared to normal cloud concentrations can overwhelm the probe such that the droplet count is underestimated in all sizes. This can result in an apparent disagreement between LWC as computed from the FSSP drop-size distribution and the LWC determined by previous tunnel calibrations or as measured by other independent probes in the tunnel.

ICING AND FOGGING EFFECTS. Although the FSSP is equipped with internal heaters to help keep the probe free of ice, sometimes ice will still accumulate around the optically sensitive areas (figure 2a and 2b) and interfere with the free airflow or the optical path. In this case, the probe will usually exhibit what appears to be a slowly declining droplet concentration as the ice accumulates. Because the probe is often mounted in a location that is not visible from the cabin, ice can accumulate on the probe without the crew knowing it. As a result, the inexperienced observer or analyst can easily mistake this false decline for real. The only way to cure this problem is for the aircraft to fly into above-freezing air until the ice has melted. Fogging of (condensation on) the lenses will have the same effect and can happen when the aircraft descends from cold air into warmer, humid air.

CALIBRATION ERRORS. The calibration of the FSSP is usually not a problem, but on occasion, the calibration may change a little due to electronic or optical problems. The airspeed and cloud density effects explained above may also cause a temporary shift in the calibration while the conditions persist. In these cases, there can be significant errors in any computations (such as LWC) that are based on the droplet size distribution. Because LWC depends on the cube of the droplet diameter,

$$LWC = N(4/3)\pi r^3$$

the LWC will also be in error by the cube of any sizing errors. For example, if the calibration is shifted by just one bin width (2 μm on the 2- to 30-μm range), an LWC of 0.22 g/m^3 for a typical size distribution will be erroneously computed as 0.12 g/m^3 or 0.33 g/m^3, depending on whether the droplets were sized incorrectly as 2 μm smaller or 2 μm larger.

The FSSP is usually calibrated by dropping into the sensitive volume a stream of tiny, specially manufactured glass beads all of approximately the same size (of the order of 20 μm). These simulate water droplets, which are difficult to produce and control in these required sizes. A simpler method for routinely checking the calibration of the FSSP in the field is also available [6].

PRACTICAL RECOMMENDATIONS.

Because of the various sources of error, including possible calibration shifts mentioned earlier, the computed LWC should always be checked against an independent, direct measurement of LWC, such as with a hot-wire probe. For quality assurance purposes, this cross check is always used by cloud physics researchers as a way to detect malfunctions in either the FSSP or the independent LWC sensor. Normally, the two LWCs will differ somewhat anyway, but if the difference exceeds either 50% or a few tenths of a g/m^3, then there is probably something wrong with one of the measurements.

Because it takes an experienced eye to detect the subtle effects of droplet overload, ice accretion on the probe, fogged lenses, and other possible sources of error or failure, it is highly advisable to hire an experienced contractor to install and operate the FSSP system and to analyze the data. Otherwise, expensive drop size data from entire flights could be erroneous and unusable due to unforeseen or unrecognized problems. Corrections of the data for airspeed and other effects also require an analyst who is experienced in the accepted data processing procedures.

DATA PROCESSING AND ANALYSES.

DROPLET CONCENTRATIONS. The first step in processing the data is to convert raw droplet counts (table 1) for each sampling interval (typically 1 second) to actual droplet concentrations (table 2). This requires knowledge of the sample volume (cm^3/sec) during the cloud penetrations. The sample volume is the product of the laser beam effective width (d) and depth of field (DOF), and the true airspeed (TAS), or

$$V = (VAR)(DOF)(D)(TAS) \tag{1}$$

where *VAR* is a correction factor known as the velocity acceptance ratio. The *DOF* and the effective beam width are given by the manufacturer for each individual probe. Typically, $DOF \cong 2.4$ mm and $D \cong 0.2$ mm. The *VAR* typically has a value of about 0.6 but will vary between about 0.3 and 0.9, depending on whether a large or small number of droplets is detected by the probe each second. It is available as an output signal from the probe. Additional correction factors are sometimes needed on an ad hoc basis, depending on the condition of the probe and the operational experience with using it. From equation 1, a typical value of the sample volume is $V \cong 26$ cm^3/sec for an airspeed of 177 kt (91 m/s).

The next step is to convert the raw counts to actual droplet concentrations. As an example, table 3 shows the conversion of the data for 17:44:37 in table 1 using a sample volume of 26 cm^3/sec.

This is an actual size distribution as recorded by an FSSP set on the 3- to 45-µm range. The mode (peak) droplet count is at 9-µm diameter in this case, and no droplets larger than 36-µm diameter were detected. The total droplet concentration is 146 per cubic centimeter for this particular 1-second sample. A value of 100 to 400 is typical of most continental clouds. The droplet size distribution is shown in figure 3.

Comment on Drop-Size Distributions. The distributions, shown in tables 1 and 2 and in figure 3, are typical for most natural clouds. That is, most cloud droplets are found in sizes below 20-µm diameter, and the last few size channels of the FSSP are usually empty (on the 3- to 45-µm range scale). Thus, except in the case of drizzle or other large (precipitation-sized) drops, the FSSP alone is sufficient for documenting the full range of cloud droplets in icing flight tests.

Other probes, like the PMS optical array probes (OAP) used for measuring larger drops, are not necessary for icing flights unless freezing drizzle or freezing rain is involved. These latter two situations are commonly called supercooled large droplet (SLD) conditions. In any case, it is usually difficult enough to find a place on the airframe to mount an FSSP, let alone another probe (OAP) of the same size.

CLOUD WATER CONCENTRATION. This quantity, usually known as the LWC to distinguish it from any measure of ice particle mass concentration, can be easily computed from the drop-size distribution. The mass of an individual cloud droplet is simply the volume of a sphere multiplied by the density of water. That is

$$m = \rho(4/3)\pi r^3$$

where $\rho = 1\ g/cm^3$ and r is the radius of the droplet. If the radius is given in centimeters, then the droplet mass is in units of grams. If there are n droplets of the same size per cubic centimeter, then the LWC represented by those droplets is just $(n)x(m)$ and is given in units of grams/cm^3. Because these values are so small, the unit of volume to be considered is increased to a cubic meter so that the usual units for this quantity are grams per cubic meter. Values for stratiform clouds are a few tenths of a gram per cubic meter, whereas the total LWC can momentarily range as high as a few grams per cubic meter in strong convective clouds.

Using the example size distribution in table 3, table 4 shows the LWCs that are found for each size bin.

In this example, the total LWC adds up to 0.20 g/m^3. The LWC distribution is shown in figure 4, which is a mass-weighted distribution, so it looks different from figure 3.

Comment on LWC Distributions. Figure 4 illustrates a comparison between a typical LWC distribution and one of the five hypothetical LWC distributions invented by Langmuir and Blodgett [7] in 1946. These Langmuir distributions, as they are called, are used primarily in rotating multicylinder measurements when it is desired to relate an approximate drop-size (or LWC) distribution to the observed ice accretion amounts on the cylinders. The five arbitrary symmetric distributions, named A, B, C, D, and E in order of increasing width, were invented as a substitute in the absence of any measured drop-size distribution.

Sometimes, one of these Langmuir distributions will be selected by icing practitioners for some design problem at hand. The Langmuir-D distribution seems to be a favorite, possibly because it is used in a lone example in a standard reference book (see page 2-16 of reference 8). But a recent study [9] found that the Langmuir-B distribution appears to match actual cloud droplet distributions the best. In figure 4, the Langmuir-B distribution is shown in comparison to the example distribution.

DROPLET MEDIAN-VOLUME DIAMETER. In icing applications, the median-volume diameter (MVD) has traditionally been used to represent the size distribution of the cloud droplets. The MVD is the droplet size that divides the LWC in half. That is, half the LWC is contained in droplets smaller than the MVD and half is contained in droplets larger than the MVD. The MVD cannot be measured directly, but must be computed from the droplet size distribution. One simply adds incremental LWCs, conventionally starting at the lower end of the size distribution, until half the total LWC is accounted for. In table 2, one can visually determine that the MVD is about 18 μm. A more exact interpolation would show that the actual MVD is probably closer to 17 μm, but for icing applications, an error of one or two microns is of no consequence.

All computations can be routinely performed using a computer program or by embedding formulas in the cells of a computerized spreadsheet representing tables 1 and 2.

RECOMMENDED DATA DISPLAYS. A clear, understandable, unambiguous display of relevant cloud variables is essential for documenting, analyzing, and evaluating the icing encounters.

Time Histories. An important way to visualize cloud density and uniformity during icing exposures is to graph droplet concentration, MVD, and LWC as a function of time. This is easy to do if these variables have been computed and loaded into a computerized spreadsheet. The built-in charting capabilities of the spreadsheet software can then be used to quickly produce the required graphs. Some examples are shown in figures 5-7.

Comparison With Design Conditions in 14 CFR Parts 25 and 29, Appendix C. Suggestions for comparing FSSP-derived LWC and MVD with the LWC versus MVD curves in figures 1 and 4 of 14 CFR Parts 25 and 29, Appendix C can be found in reference 10.

DROPLET IMPACTORS

The following is a description of the Soot, Powder, Gelatin, or Oil-Coated Droplet Impactor

- Classification: Mechanical, cloud droplet replicator
- Manufacturer: No commercial supplier known. Typically hand crafted by a machinist using diagrams from original designers in university or other laboratories
-
- Purpose: To collect a sample of droplets for counting and sizing
- Specifications:
    - Drop-size range: Typically about 5-μm diameter and larger
    - Sampling rate: Occasional
    - Physical size: Various—from a cylindrical probe about 1 inch in diameter to a "gun" apparatus about 20 inches long
    - Probe weight: Typically a few pounds
- Accessories needed: Laboratory microscope & photo attachment, slide-coating supplies
- Intended Use: Airborne cloud physics research

BACKGROUND.

Impactors (shown in figure 8) using coated glass slides are one of the earliest devices for sampling and preserving a measurable image of droplets in clouds. Various models were developed in the 1950s and earlier by cloud physics researchers. Because this is old technology, there are few, if any, new references. A good overview is given in reference 11. The models range from simple frames holding a single slide to more sophisticated, multislide cloud "guns" [12-17]. Detailed procedures are given in [18]. Except for occasional use at remote sites, some special applications, or for occasional spot checking of droplet sprays, these labor-intensive devices have been replaced, especially for airborne use, by more efficient electro-optical droplet size spectrometers since the appearance of the latter in the 1970s.

PRINCIPLE OF OPERATION.

A glass slide (typically about 1/4 inch wide by an inch or more long) is prepared by coating it with a thin (70- to 100-µm) coating of carbon black (soot), MgO powder, or viscous oil. The slide is then mounted against a rod of similar diameter or loaded into a tube-like holder with an open cutout or aperture part way along the tube. To expose the slide, the tube is extended into the droplet-laden airstream at right angles to the flow. This is sometimes done by manually pushing the holder part way out of a tube mounted in a window plug or hatch for a short, timed interval. For more repeatable timing of the exposure, a spring-loaded or compressed gas propellant is released to propel the slide past the aperture where the droplets can momentarily impinge on the slide. The droplets leave size-proportional pits in the soot or powder, or are captured as water bubbles in the oil. These pits or bubbles remain and can be counted and sized under a microscope at a later, convenient time and place. An example of cloud droplets captured on an oiled slide is shown in figure 9.

The following lists the advantages and disadvantages of the impactor:

- Advantages
  - Impactors are relatively simple and inexpensive.
  - Convenient for occasional checks of droplet size distributions and relative indications of droplet concentrations.
  - Small, lightweight, and portable. Does not require electrical power or any recording device.
- Disadvantages
  - Method is subject to several sources of error (see the next section, Known Sources of Error).
  - Is only a spot (occasional) sampler—not convenient for frequent sampling or mapping highly variable droplet populations.
  - Is of questionable value for natural icing flights due to its spot-sampling limitation.
  - Counting and sizing the droplet images is laborious and tedious.

KNOWN SOURCES OF ERROR.

DISCRIMINATION AGAINST SMALLER DROPLETS.

Collection Efficiency Effects. The collection efficiency of the slides is not the same for all droplet sizes. The efficiency depends on the airspeed, the size of the droplets, the width of the glass slide, and the mounting rod or tube exposed to the airstream. The efficiency decreases with decreasing droplet size such that droplets smaller than about 10-μm diameter may be significantly undercounted as a result of being deflected around the slide and the tube housing.

Visual Recognition Difficulties. Impact pits smaller than about 5-μm diameter are difficult to see in the coatings. The pits lack contrast and begin to blend with the microscopic graininess of the coating. Five microns is also about the limit of resolution for ordinary optical microscopes generally used for these measurements. So even if the pits were not absent due to low collection efficiencies, they are difficult to see for diameters smaller than about 5 μm.

In addition, even if smaller, marginally recognizable pits are present, analysts tend to ignore them in favor of the easily recognizable larger pits, especially if the marginal pits exist in great numbers as may be typical of a natural cloud droplet population. Analysts may consider it to be a waste of time to size and count the more difficult, small images, especially if there are a number of slides to be analyzed.

The result of the bias against small droplets is that the MVD computed from the apparent drop-size distribution will be biased toward larger values. This will show up as a discrepancy when compared to MVDs computed from electro-optical drop-size spectrometers such as the FSSP.

Operation Bias. Knowing that dense clouds are preferred for natural icing flight tests, the operator of the impactor may be inclined to selectively expose the slides only during the denser cloud parcels and ignore thinner clouds even though the latter may be predominant. The aircraft may temporarily accrete more ice in the denser cloud parcels, but the thinner clouds will contribute to the overall ice accretion too. Unless the cloud conditions are practically uniform during the exposure, selectively measuring the drop-size distribution only in the denser portions of the clouds will misrepresent the overall icing encounter.

PIT-TO-DROPLET DIAMETER RATIOS. The pits made in the coating are always somewhat larger than the original droplet diameter. This is due to some flattening and spreading of the droplet upon impact. The ratio depends on the coating, the airspeed, and the drop size, but it has been reported (page 4 of reference 11) that for MGO coatings, the droplet-to-pit diameter ratio is 0.86 for droplets larger than 20 μm. For smaller droplets, the ratio steadily decreases. Thus, unless the calibration of the pits in terms of actual droplet size is known, the apparent drop sizes will be too large by an uncertain amount.

SAMPLE VOLUME UNCERTAINTIES. Depending on the method of exposing the slide, timing the exposure, and estimating the local airspeed, the volume of air sampled during the exposure can be more or less uncertain. Although this will not affect the relative drop-size distribution, the amount of uncertainty will proportionally degrade the accuracy of the LWC computed from the apparent drop-size distribution. For automatic exposures in a gun-type device, the sample volume and LWC uncertainty may be as much as ±20%. For manually exposed and timed samples, the uncertainty will be much worse. Moreover, the intermittent nature of the samples means that it will be impossible to know the overall average LWC to which the aircraft is exposed during a complete icing encounter anyway. Coupled with the aforementioned biases and possible uncertainties in drop size, it is clear that the impactor method cannot be relied upon to yield accurate LWCs.

SAMPLING LOCATION CONCERNS. Because impactors are manually operated devices, they must be operated from inside the aircraft cabin and through a window plug or hatch somewhere along the fuselage. These along-the-fuselage locations can result in the sample being obtained from an airstream in which certain droplet sizes have been depleted or increased due to inertial sorting by the deflection of the airstream around the nose of the aircraft. This concern is discussed in references 13-15.

Another problem on single-engined, propeller-driven airplanes is the difficulty in obtaining exposures outside the propeller wash, unless the instrument is mounted under a wing outboard of the propeller and operated remotely.

PRACTICAL RECOMMENDATIONS.

Because of its limitations and disadvantages, the droplet impactor method is of questionable value for natural icing flight tests. Research in the Flight Safety Research Branch at the FAA William J. Hughes Technical Center has shown that 75% of the time the MVD is within ±5 μm of 15 μm anyway (see figure 27 of reference 10). That is, MVDs are not as variable as may have been believed, and the larger the MVD above 15 μm, the rarer it is and the shorter it lasts. This means that it may be possible to assume an MVD of 15 μm for the purposes of natural icing flight tests, unless there is some specific reason to have an exact value. In any case, the impactor method will overestimate the value of the MVD by an unknown amount and will not represent the entire icing encounter anyway, due to the intermittent nature of the samples.

If an impactor seems necessary and no equipment or experience is available in your company or agency, it may be possible to hire an experienced user from one of the few universities that has a cloud physics group in an atmospheric sciences department. The possibilities are the University of Wyoming (Laramie), University of Washington (Seattle), Missouri School of Mines (Rolla), Desert Research Institute (Reno), State University of New York (Albany), and the National Center for Atmospheric Research (Boulder, CO). Impactors may still be used by researchers at these institutions for spot measurements at remote sites.

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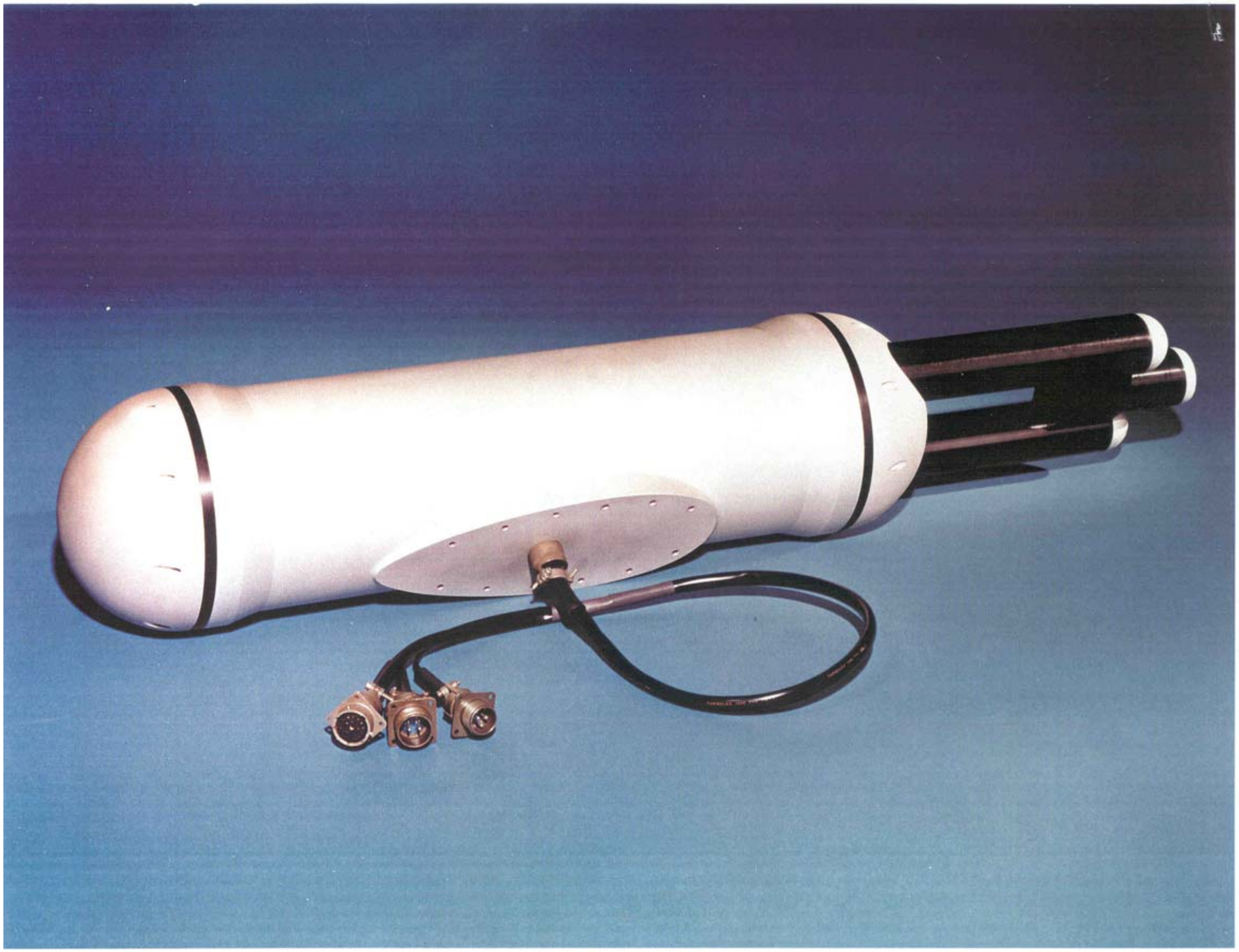

FIGURE 1. THE FORWARD SCATTERING SPECTROMETER PROBE
(Courtesy of Particle Measuring Systems (PMS), Inc.)

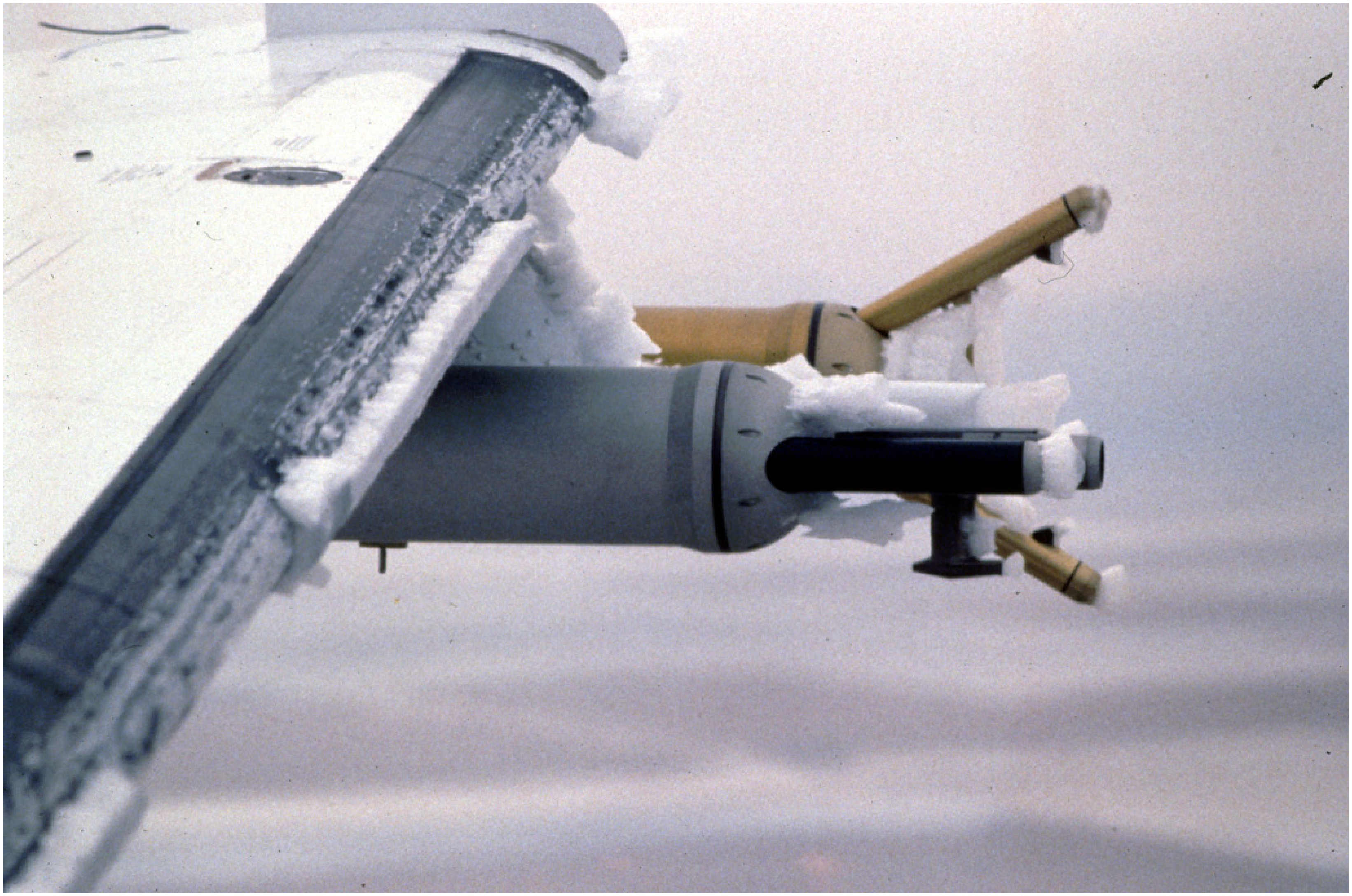

FIGURE 2a. EXAMPLE OF ICED-UP FSSP (INBOARD) AND OAP (200-Y) DURING AN ICING FLIGHT

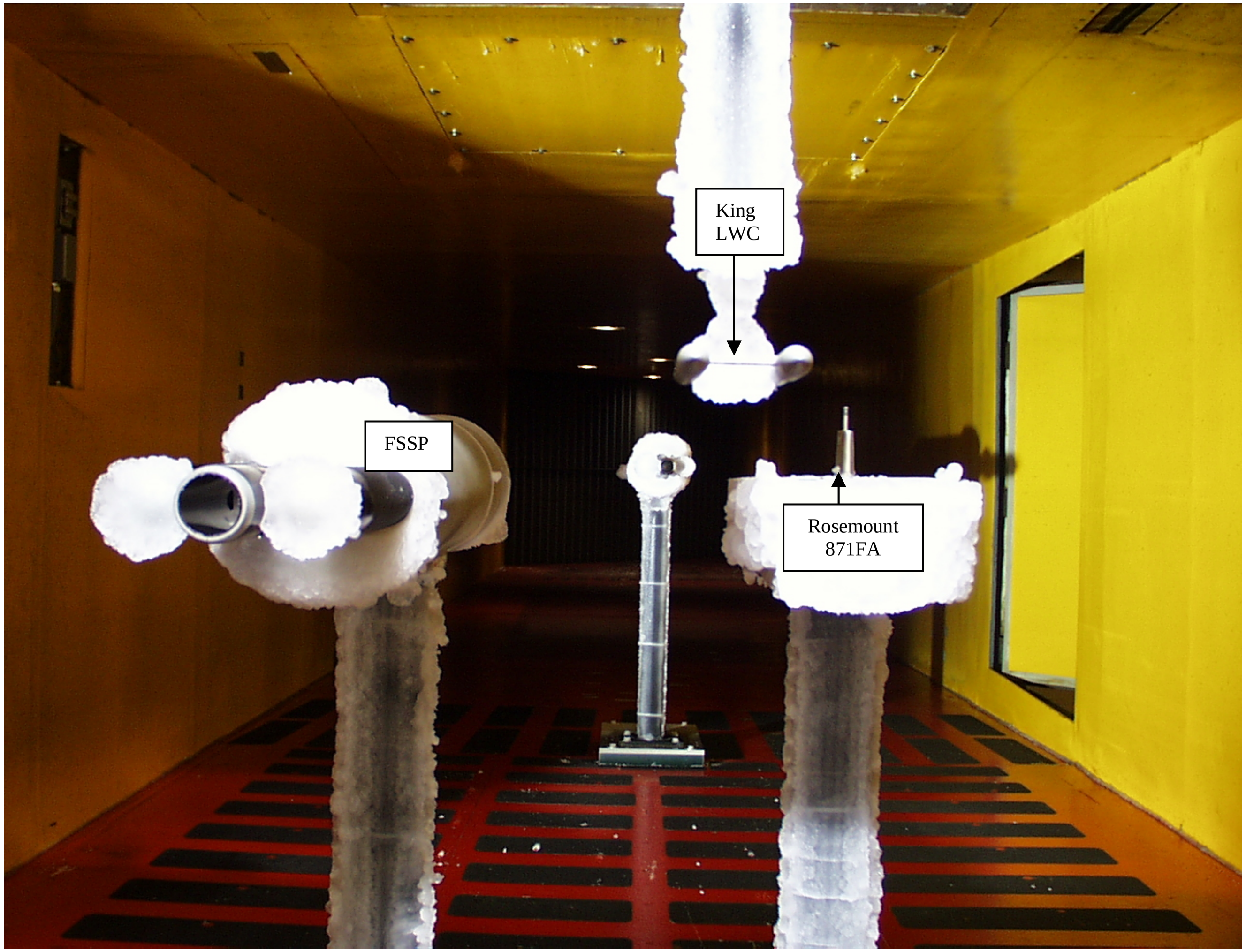

FIGURE 2b. PHOTOGRAPH OF THE ROSEMOUNT 871FA, THE KING LWC PROBE, AND THE FSSP DROPLET SIZE SPECTROMETER IN THE IRT DURING TESTS ON OCTOBER 6, 2000
(The Rosemount 871FA is clearly ice-free, except for the stand upon which it is mounted. The other probes suffer from inadequate anti-icing, leading to eventual ice accumulation which can distort the airflow in the sensing area of the probes, especially for the FSSP.)

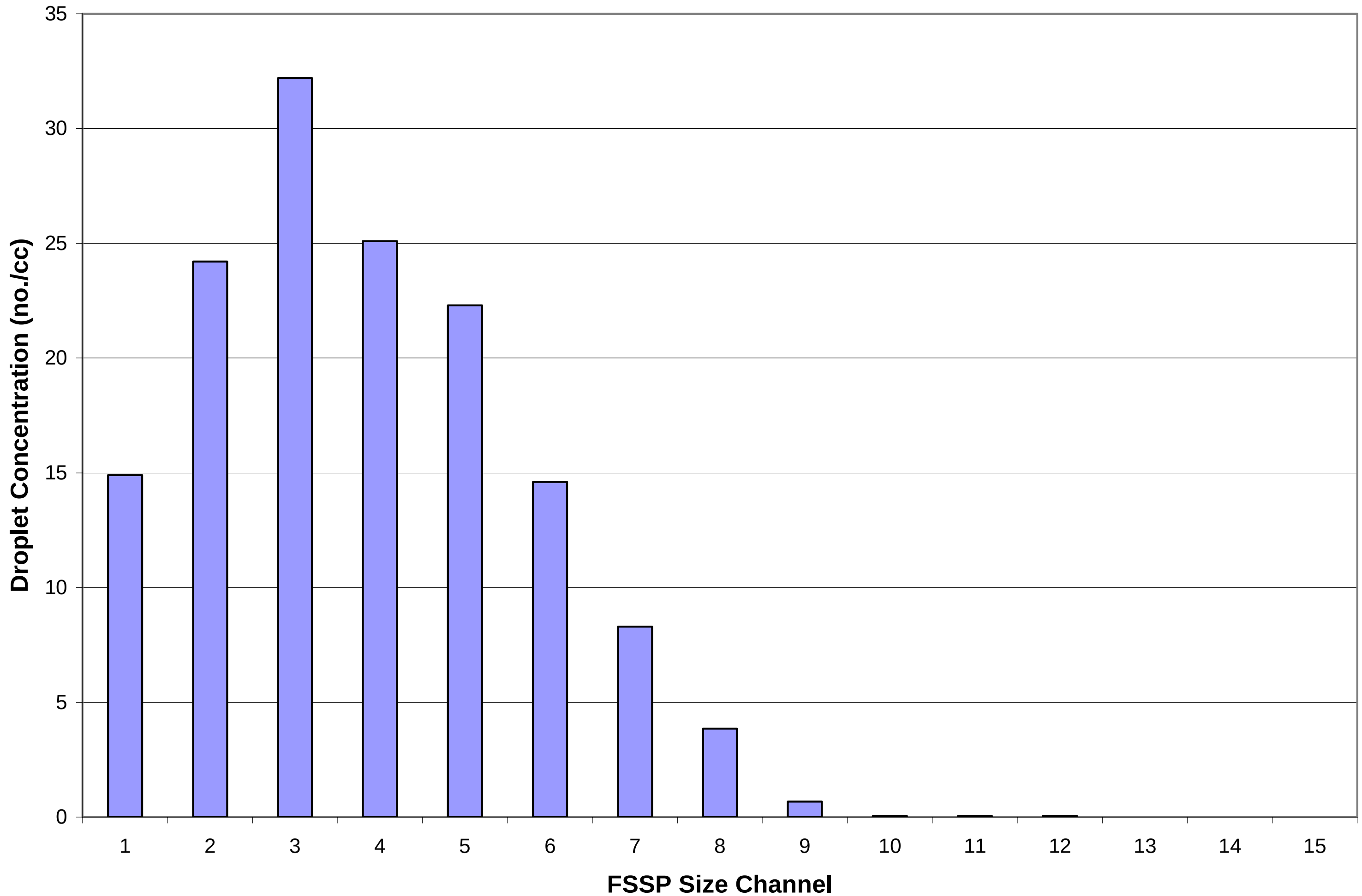

FIGURE 3. SAMPLE DROP-SIZE DISTRIBUTION FROM THE FSSP

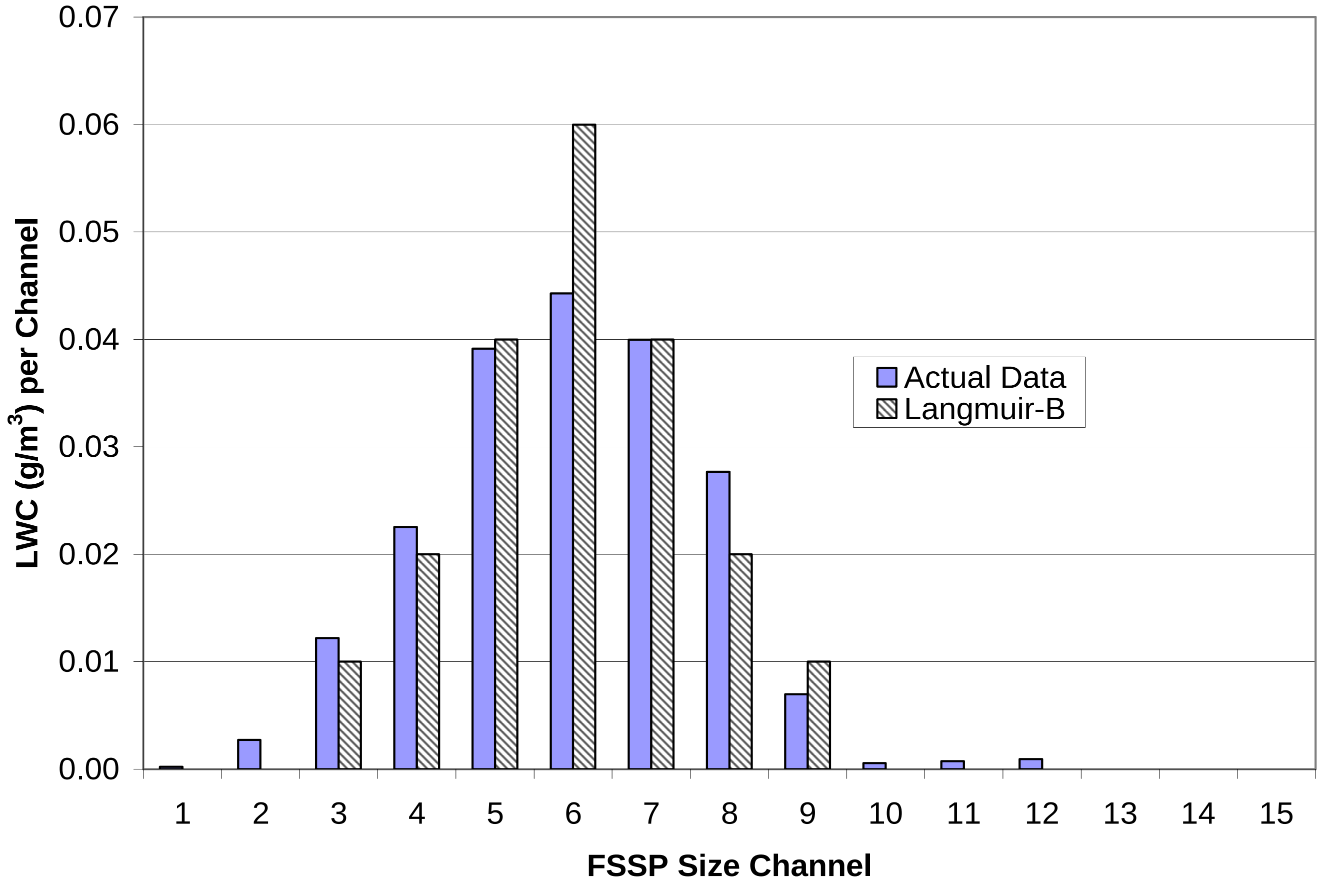

FIGURE 4. SAMPLE LWC DISTRIBUTION COMPUTED FROM DATA IN FIGURE 3

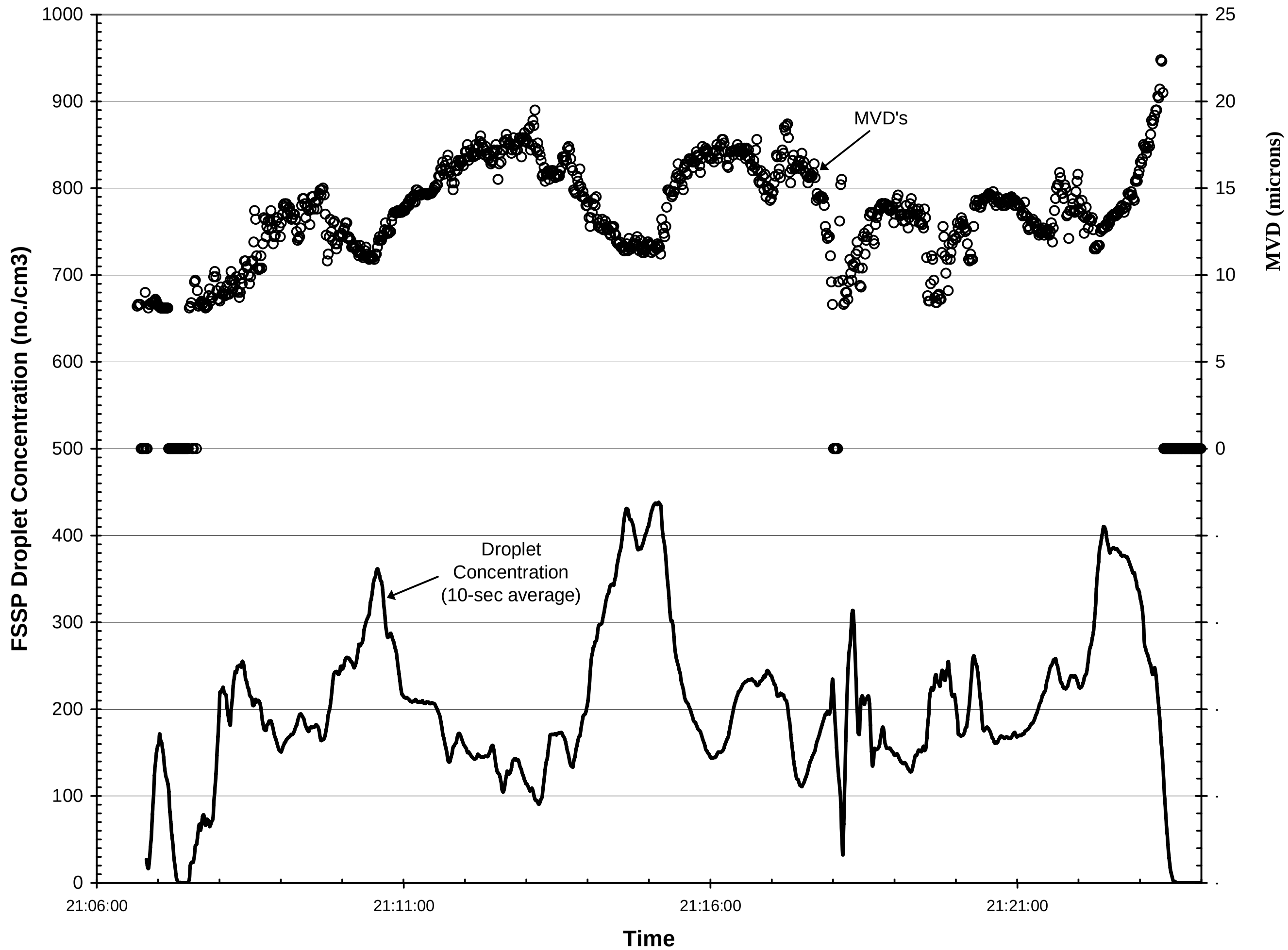

FIGURE 5. EXAMPLE OF RECOMMENDED TYPE OF DISPLAY FOR TIME HISTORIES OF DROPLET CONCENTRATION AND MVD AS DERIVED FROM THE FSSP
(The concentration is best represented, as shown, by a 10-sec time average and smooth curve drawn through the 1-sec data points.)

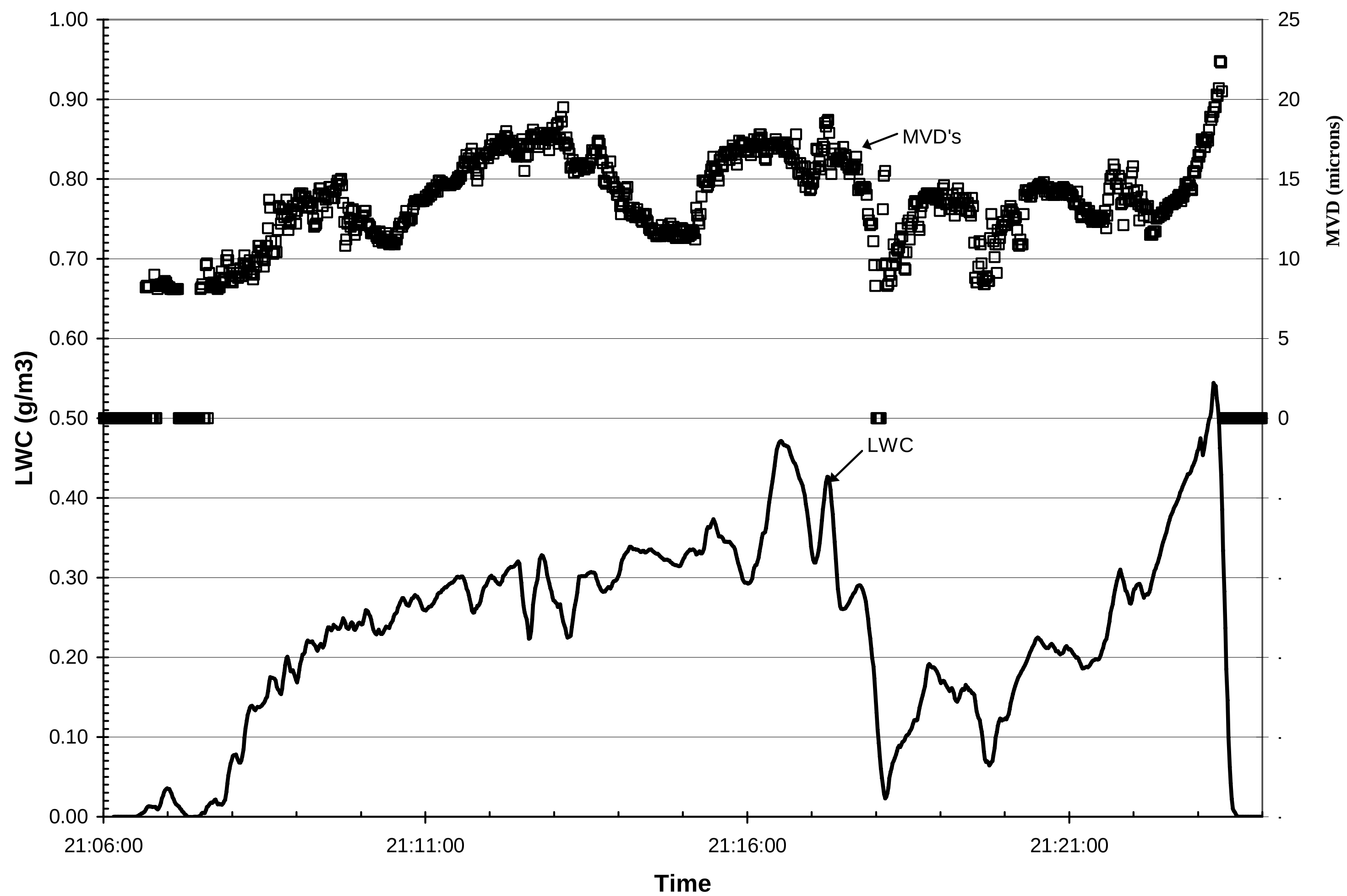

FIGURE 6. EXAMPLE OF RECOMMENDED TYPE OF DISPLAY FOR TIME HISTORIES OF LWC AND MVD AS DERIVED FROM THE FSSP
(The LWC is best represented, as shown, by a 5- or10-sec time average and smooth curve drawn through the 1-sec data points.)

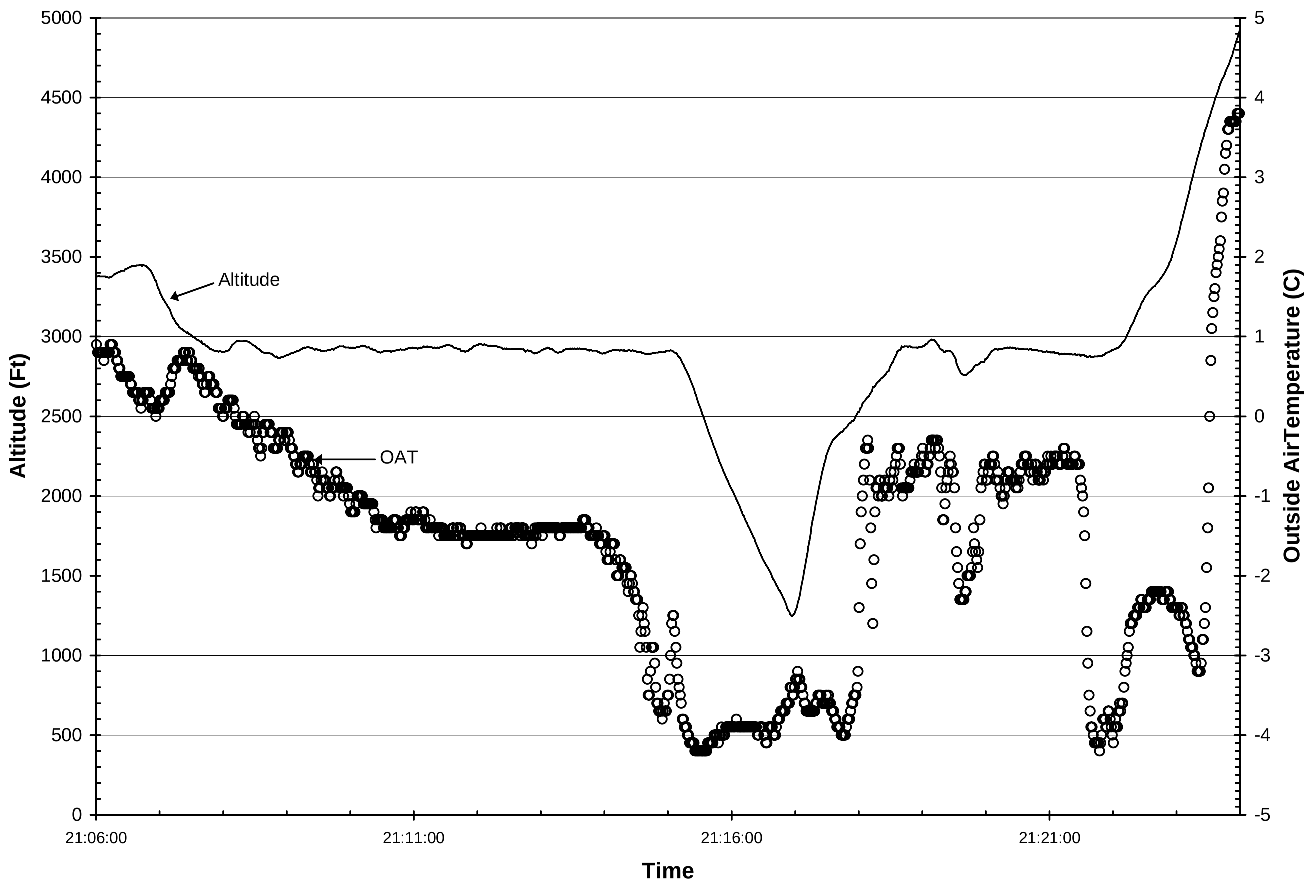

FIGURE 7. EXAMPLE OF RECOMMENDED TYPE OF DISPLAY FOR TIME HISTORIES OF ALTITUDE AND AIR TEMPERATURE DURING ICING ENCOUNTERS

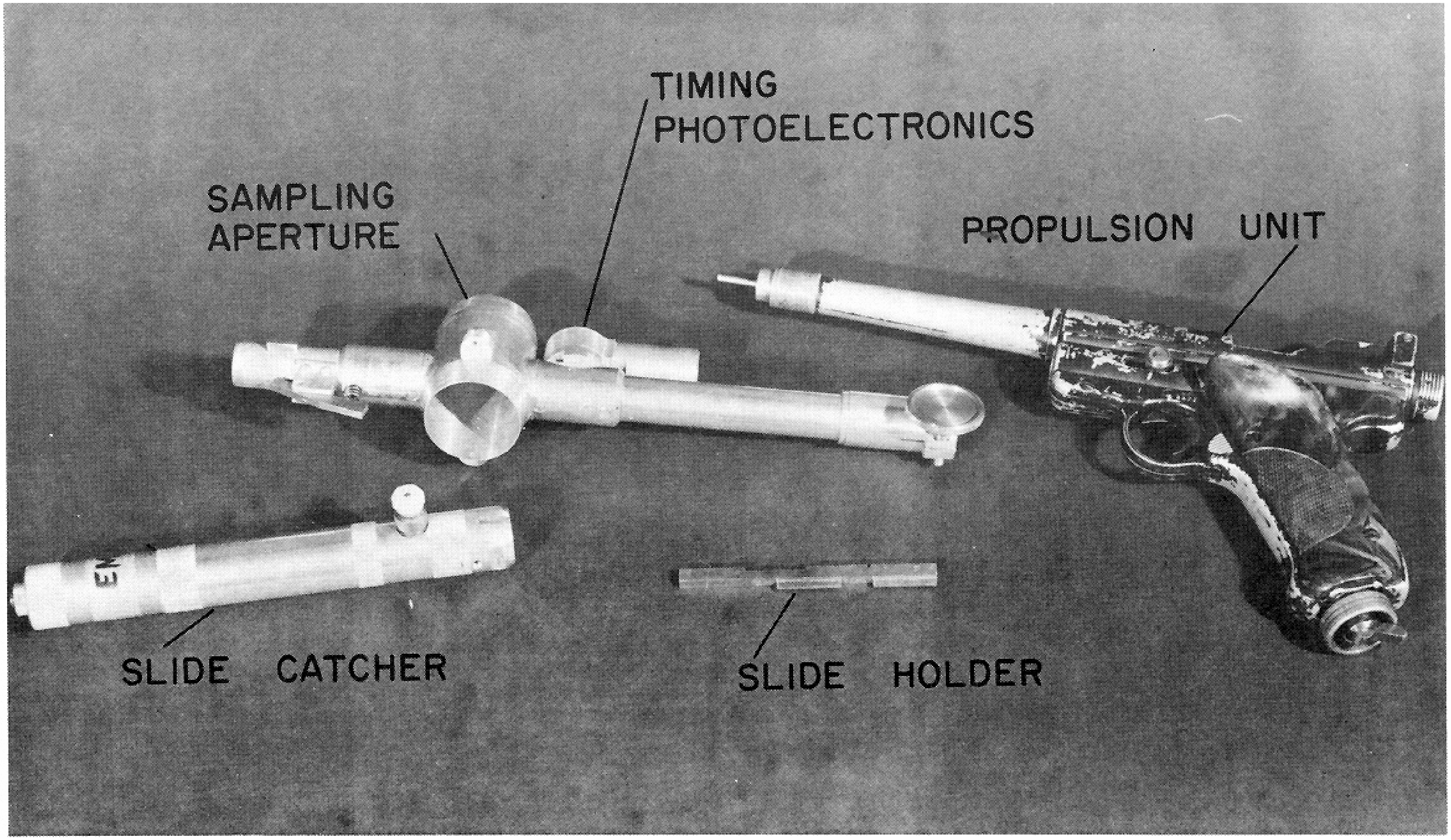

FIGURE 8. "CLOUD GUN" ASSEMBLY USED AT THE NATIONAL CENTER FOR ATMOSPHERIC RESEARCH (NCAR) IN BOULDER, COLORADO
(Photo courtesy of Dr. Marcia Politovich, NCAR)

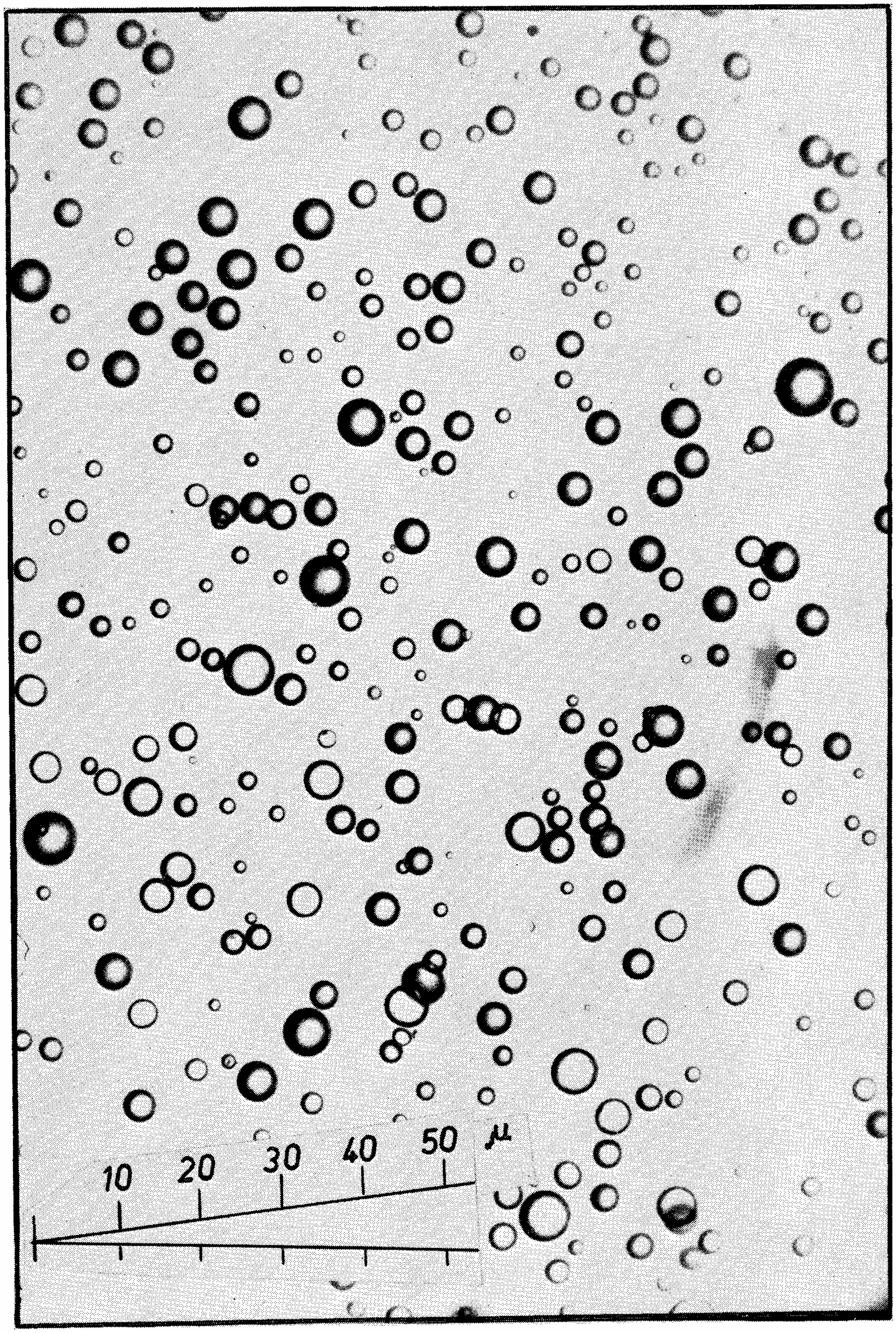

FIGURE 9. PHOTOGRAPH OF CLOUD DROPLETS CAPTURED ON AN OILED SLIDE [16]

TABLE 1. SAMPLE OF RAW FSSP DATA: SECOND-BY-SECOND DROPLET COUNTS IN EACH SIZE CHANNEL

TIME (hhmmss)	Ch. 1 (no./sec)	Ch. 2 (no./sec)	Ch. 3 (no./sec)	Ch. 4 (no./sec)	Ch. 5 (no./sec)	Ch. 6 (no./sec)	Ch. 7 (no./sec)	Ch. 8 (no./sec)	Ch. 9 (no./sec)	Ch. 10 (no./sec)	Ch. 11 (no./sec)	Ch. 12 (no./sec)	Ch. 13 (no./sec)	Ch. 14 (no./sec)	Ch. 15 (no./sec)
174434	600	1247	872	188	134	97	53	28	5	1	0	1	0	0	0
174435	924	1961	1260	251	150	107	68	50	21	1	0	0	0	0	0
174436	543	898	1165	567	378	306	144	78	19	2	0	0	0	0	0
174437	394	642	852	664	590	387	219	102	18	1	1	1	0	0	0
174438	372	279	491	800	916	497	234	76	7	0	0	0	0	0	0
174439	320	212	397	799	1014	511	159	48	7	0	0	0	0	0	0
174440	327	188	435	861	1014	578	190	40	8	2	0	0	0	0	0
174441	355	178	419	774	997	574	195	49	7	1	2	0	0	0	0
174442	341	163	388	785	982	545	179	41	11	0	1	0	0	0	0
174443	344	202	415	881	1118	529	145	32	6	1	0	0	0	0	0
174444	381	218	501	1016	1121	513	218	54	2	0	0	0	0	1	0
174445	362	226	514	1120	1288	488	195	54	4	2	1	0	0	0	0
174446	417	236	502	1164	1321	613	188	44	4	2	0	0	0	0	0
174447	429	212	477	1069	1243	571	270	67	4	1	0	0	0	0	0
174448	445	248	426	910	950	715	475	64	6	0	0	0	0	0	0
174449	233	102	153	269	574	892	524	73	10	2	0	0	0	0	0
174450	121	66	68	249	487	702	405	43	3	2	0	0	0	0	0
174451	75	46	63	122	314	686	348	12	3	1	0	1	0	0	0
174452	87	37	37	131	295	658	405	32	1	0	0	0	0	1	0
174453	99	40	46	137	390	650	397	62	4	0	1	0	0	0	0
174454	106	40	70	199	509	547	329	31	6	0	0	0	0	0	0
174455	77	109	232	317	273	346	211	14	2	1	0	0	0	0	0
174456	60	47	101	139	283	488	237	14	3	0	0	0	0	0	0
174457	55	37	53	128	315	510	182	38	3	2	0	0	0	0	0
174458	108	40	104	302	622	450	198	55	3	0	0	0	0	0	0
174459	164	104	196	399	517	463	343	40	1	1	2	0	0	0	0
174500	216	173	150	234	343	364	236	39	4	0	0	0	0	0	0
174501	193	158	233	259	230	299	245	22	1	0	0	0	0	0	0
174502	53	60	91	151	210	303	153	3	1	0	0	0	0	0	0
174503	43	73	281	336	306	174	29	3	0	0	0	0	0	0	0
174504	49	69	241	402	237	83	1	1	0	0	0	0	0	0	0
174505	36	105	488	433	153	33	2	0	0	0	0	0	0	0	0
174506	426	974	298	21	1	0	0	0	0	0	0	2	0	0	0

TABLE 2. SAMPLE OF PROCESSED FSSP DATA: COMPUTED DROPLET CONCENTRATIONS FOR EACH SIZE CHANNEL

	Total	Channel-by-Channel Droplet Concentration (no./cc)														
TIME	Conc.	Ch. 1	Ch. 2	Ch. 3	Ch. 4	Ch. 5	Ch. 6	Ch. 7	Ch. 8	Ch. 9	Ch. 10	Ch. 11	Ch. 12	Ch. 13	Ch. 14	Ch. 15
(hhmmss)	N/cc	3 um	6 um	9 um	12 um	15 um	18 um	21 um	24 um	27 um	30 um	33 um	36 um	39 um	42 um	45 um
174434	124	23	48	33	7	5	4	2	1	0.2	0.04	0	0.04	0	0	0
174435	179	35	73	47	9	6	4	3	2	0.8	0.04	0	0	0	0	0
174436	161	21	35	46	22	15	12	6	3	0.8	0.08	0	0	0	0	0
174437	146	15	24	32	25	22	15	8	4	0.7	0.04	0.04	0.04	0	0	0
174438	143	14	11	19	31	36	19	9	3	0.3	0	0	0	0	0	0
174439	135	13	8	16	31	40	20	6	2	0.3	0	0	0	0	0	0
174440	140	13	7	17	33	39	22	7	2	0.3	0.08	0	0	0	0	0
174441	137	14	7	16	30	39	22	8	2	0.3	0.04	0.08	0	0	0	0
174442	137	14	7	16	31	39	22	7	2	0.4	0	0.04	0	0	0	0
174443	145	14	8	16	35	44	21	6	1	0.2	0.04	0	0	0	0	0
174444	161	15	9	20	41	45	21	9	2	0.1	0	0	0	0	0.04	0
174445	165	14	9	20	44	50	19	8	2	0.2	0.08	0.04	0	0	0	0
174446	175	16	9	20	45	51	24	7	2	0.2	0.08	0	0	0	0	0
174447	172	17	8	19	42	49	23	11	3	0.2	0.04	0	0	0	0	0
174448	165	17	10	17	36	37	28	19	3	0.2	0	0	0	0	0	0
174449	114	9	4	6	11	23	36	21	3	0.4	0.08	0	0	0	0	0
174450	83	5	3	3	10	19	27	16	2	0.1	0.08	0	0	0	0	0
174451	64	3	2	2	5	12	26	13	0	0.1	0.04	0	0.04	0	0	0
174452	65	3	1	1	5	11	26	16	1	0.0	0	0	0	0	0.04	0
174453	69	4	2	2	5	15	25	15	2	0.2	0	0.04	0	0	0	0
174454	69	4	2	3	7	19	20	12	1	0.2	0	0	0	0	0	0
174455	52	3	4	8	11	9	11	7	0	0.1	0.03	0	0	0	0	0
174456	48	2	2	4	5	10	17	8	0	0.1	0	0	0	0	0	0
174457	51	2	1	2	5	12	20	7	1	0.1	0.08	0	0	0	0	0
174458	69	4	2	4	11	23	17	7	2	0.1	0	0	0	0	0	0
174459	84	6	4	7	15	20	18	13	2	0.0	0.04	0.08	0	0	0	0
174500	60	7	6	5	8	12	12	8	1	0.1	0	0	0	0	0	0
174501	54	6	5	8	9	8	10	8	1	0.0	0	0	0	0	0	0
174502	35	2	2	3	5	7	10	5	0	0.0	0	0	0	0	0	0
174503	39	1	2	9	11	10	5	1	0	0	0	0	0	0	0	0
174504	38	2	2	8	14	8	3	0	0	0	0	0	0	0	0	0
174505	40	1	3	16	14	5	1	0	0	0	0	0	0	0	0	0
174506	58	14	33	10	1	0	0	0	0	0	0	0	0.068	0	0	0

TABLE 3. EXAMPLE SIZE DISTRIBUTION

Bin	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Bin Center Diameter (μm)	3	6	9	12	15	18	21	24	27	30	33	36	39	42	45
Raw Count (no./sec)	394	642	852	664	590	387	219	102	18	1	1	1	0	0	0
Concentration (no./cm^3)	15	24	32	25	22	15	8	4	0.7	0	0	0	0	0	0

TABLE 4. THE LWCS FOR THE EXAMPLE SIZE DISTRIBUTION

Bin	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Bin Center Diameter (μm)	3	6	9	12	15	18	21	24	27	30	33	36	39	42	45
Concentration (no./cm^3)	15	24	32	25	22	15	8	4	0.7	0	0	0	0	0	0
LWC (g/m^3)	0.0002	0.003	0.012	0.022	0.04	0.05	0.04	0.03	0.007	0	0	0	0	0	0