



# NASA/FAA/NCAR Supercooled Large Droplet Icing Flight Research: Summary of Winter 96-97 Flight Operations

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Summary of Winter 96-97 Flight Operations**

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**ABSTRACT**

During the winter of 1996-97, a flight research program was conducted at the NASA-Lewis Research Center to study the characteristics of Supercooled Large Droplets (SLD) within the Great Lakes region. This flight program was a joint effort between the National Aeronautics and Space Administration (NASA), the National Center for Atmospheric Research (NCAR), and the Federal Aviation Administration (FAA).

Based on weather forecasts and real-time in-flight guidance provided by NCAR, the NASA-Lewis Icing Research Aircraft was flown to locations where conditions were believed to be conducive to the formation of Supercooled Large Droplets aloft. Onboard instrumentation was then used to record meteorological, ice accretion, and aero-performance characteristics encountered during the flight. A total of 29 icing research flights were conducted, during which "conventional" small droplet icing, SLD, and mixed phase conditions were encountered aloft.

This paper will describe how flight operations were conducted, provide an operational summary of the flights, present selected experimental results from one typical research flight, and conclude with practical "lessons learned" from this first year of operation.

**NOMENCLATURE**

AIRMET	AIRman's METeorological Information
FAA	Federal Aviation Administration
FAR-25	Federal Aviation Regulation Part 25, Appendix C, Icing Envelope
FSSP	Forward Scattering Spectrometry Probe
LWC	Liquid Water Content ( $\text{g/m}^3$ )
MVD	Median Volumetric Diameter ( $\mu\text{m}$ )
NCAR	National Center for Atmospheric Research
OAP	Optical Array Probe
PIREP	Pilot Report
SATCOM	Satellite Communication
SIGMET	SIGNificant METeorological Information
SLD	Supercooled Large Droplet
$T_s$	Static Temperature ( $^{\circ}\text{C}$ )
$T_t$	Total Temperature ( $^{\circ}\text{C}$ )
UTC	Universal Time Code

**INTRODUCTION**

Today, international attention has been focused on the solution of a severe icing condition that has been implicated in a number of commuter aircraft icing incidents, the most publicized being the ATR-72 crash

in 1994. This condition poses a hazard to aircraft because it is believed to contain Supercooled Large Droplets (SLD), which are droplets having diameters greater than 50 $\mu$ m (including freezing drizzle and freezing rain). These droplet sizes exceed the "conventional" small droplet size range in the current FAR-25 aircraft icing certification envelope of 10 to 40 $\mu$ m. To adequately develop a technological response to this icing hazard requires an understanding of its meteorological parameters such as droplet size, liquid water content, temperature, etc.

Unfortunately, the SLD meteorological database is very limited, especially in the Great Lakes Region. A series of FAA In-flight Icing Conferences on SLD (1995-1996) have specifically identified a need to obtain SLD meteorological data in the Great Lakes Region.<sup>1</sup> This need is further emphasized by the relatively frequent occurrence of SLD in the Great Lakes region, the increasing number of commuter aircraft flights there, and thus the increased likelihood of an aircraft encountering SLD.<sup>2,3</sup>

### **SLD FLIGHT RESEARCH PROGRAM**

To meet this need for acquiring an SLD icing database, a cooperative SLD flight research program between NASA, NCAR, and the FAA was developed. Each organization fulfilled a unique role within this cooperative program. NASA provided the Twin Otter icing research aircraft with flight operations support, and shared program sponsorship with the FAA. The FAA provided program oversight, advocacy, and co-sponsored the program with NASA. Also, the FAA agreed to serve as the depository for the flight research data. NCAR provided its meteorological expertise in aviation weather forecast and SLD weather tools, and utilized this expertise to provide pre-flight SLD icing forecasts and in-flight guidance to NASA.

Data from the SLD icing database was intended to achieve four primary technical objectives:

- Characterization of the SLD environment aloft (droplet size distribution, LWC, vertical & horizontal extent)
- Development of improved SLD diagnostic / weather forecast tools
- Extension of icing simulation capabilities (icing tunnels, icing prediction codes)
- Providing educational information about SLD to pilots and the flying community

To better understand how SLD "Flight Data" will be

used to accomplish the 4 primary technical objectives, a data flow diagram was developed. This data flow diagram is illustrated in Figure 1. The term Flight Data includes meteorological data (droplet size, LWC, altitude, temperature, etc), ice shape data (stereo photography, video), and aircraft performance data (lift, drag, etc). Program objectives are depicted by the boxes labeled "SLD Weather Tools Development", "SLD Characterization", and "SLD Icing Simulation". The "lines" which interconnect these boxes illustrate flow of data between these boxes.

Other organizations such as Atmospheric Environment Services (AES), Robotic Vision Systems Incorporated (RVSI), and B. F. Goodrich (BFG) also made significant contributions to this SLD icing flight research program. Atmospheric Environment Services aided NASA by leasing meteorological probes, assisting in developing data acquisition software and functional check/calibration procedures for the Twin Otter instrumentation, and collaborating with NASA on the analysis of selected SLD icing encounters. RVSI contributed use of its ice detection system that monitored ice buildup along the upper surface of the Twin Otter right wing. B.F. Goodrich provided a customized de-icer boot for the video pod support strut which was mounted to the upper fuselage of the Twin Otter.

### **ICING RESEARCH AIRCRAFT**

NASA's Icing Research Aircraft, a modified DeHavilland DHC-6 Twin Otter was used to acquire SLD icing research data. As shown in Figure 2, it is a high-wing, twin-engine, commuter class aircraft that has been outfitted with instrumentation to measure icing-related meteorological conditions, document wing ice accretions, and measure resultant aircraft performance degradation. With a maximum gross weight of 11,000 pounds, it cruises at 125 knots and has an operating range of approximately 300 nautical miles. Additional physical characteristics of the aircraft are listed in Table I.

Ice protection on a typical Twin Otter consists of pneumatic de-icer boots on the wing and horizontal stabilizer, windshield heat, pitot-static heat, and deflector doors on the engine intakes. Supplemental ice protection equipment on NASA's Icing Research Aircraft include pneumatic de-icer boots on the vertical stabilizer, wing struts and main gear struts, electro-thermal de-icers on the propeller blades, and electro-

thermal anti-icers on the engine inlets.

#### Data Acquisition

The icing research data system flown on the Twin Otter incorporated the following categories of instrumentation: 1) cloud physics instruments, 2) air data instruments, 3) global positioning system, and 4) signal conditioning and data acquisition system. Each of these instrumentation groupings will be described below. Specifications for selected instruments are listed in Table II.

Cloud physics instruments measured cloud particle sizes, and the cloud water content. Three Particle Measuring System (PMS) particle-sizing probes were mounted under the Twin Otter wing. A Forward Scattering Spectrometry Probe (FSSP-100) measured particles in the size range from 2 to 47 microns in one-dimensional orientation (Figure 3). An Optical Array Probe (OAP1D-260X) measured particles in the size range from 7 to 625 microns in a one-dimensional orientation (Figure 3). The third particle sizing probe was an Optical Array Probe (OAP 2D-C Grey) which measured particles in the size range from 7.5 to 968 microns in a two-dimensional orientation (Figure 4).

Cloud water content was measured by a CSIRO-King Liquid Water Content (LWC) probe, and by a Nevzorov Total Water Content (TWC) / Liquid Water Content (LWC) probe. The CSIRO-King probe was mounted on the fuselage upstream of the windshield. The Nevzorov probe was mounted on the left side of the fuselage upstream of the pilot's door. The Nevzorov probe was designed to measure both the amounts of liquid water in the cloud and the total water in two-phase clouds (ice and liquid particles present). A Rosemount Ice Detector was also included in this suite of instruments and was mounted on the fuselage upstream of the windshield (Figure 5).

Air data instruments measured outside air temperature, dew point temperature, pressure altitude, aircraft airspeed, angle-of-attack and angle-of-sideslip. Outside air temperature was measured by a Rosemount 102AU1AF Outside Air Temperature (OAT) probe, for which the data can be resolved into total air temperature ( $T_t$ ) and static air temperature ( $T_s$ ). Dew point temperature was measured using a General Eastern Dew Point Hygrometer. Pressure altitude and

aircraft airspeed were determined by a Rosemount Altitude/Airspeed transducer in conjunction with a Rosemount 858 probe head extended from the aircraft on a 9 foot noseboom. Aircraft angle of attack and sideslip were sensed through the Rosemount 858 probe head and three specific differential pressure transducers.

Aircraft position was determined using a Trimball TNL-3100 Global Positioning System. This system provided latitude and longitude positioning to correlate radar, satellite, and other meteorological data to the in-situ meteorological measurements recorded by the aircraft.

The signal conditioning and data acquisition system consisted of a Precision Filters System 6000 filter/pre-amplifier unit and a Science Engineering & Associates (S.E.A.) Lite 18 data acquisition system. A total of 40 analog channels of data were digitized at an acquisition rate of 10 samples/second with 16-bit resolution. The S.E.A. Lite 18 is a "ruggedized" 486 microcomputer which controlled the data acquisition, data storage and data display.

#### Ice Accretion Documentation

Ice accretion documentation was accomplished by employing a wing stereo photography system, an over wing video system, and a tail video system. The wing stereo photography system consisted of two 70 mm format Hasselblad cameras with 250 mm lenses mounted in the nose of the aircraft behind optical glass viewports (Figure 6). This system was used to obtain stereo pair photo images of the wing's leading edge. These stereo pair photos were then processed using photogrammetric analysis techniques to produce (two-dimensional slices) of the leading edge ice shape.<sup>4</sup>

For documenting ice accretions on the wing upper surface, an over-wing video system was developed. This system was composed of a Cohu video camera, a Fujinon 10.5-147 mm zoom lens and a side-looking mirror, all of which was contained in a weatherproof pod that was extended above the fuselage centerline to provide a 7 degree look-down angle at a specified wing span position on the right wing (Figure 6). The video data was displayed to researchers on a 5.9 inch LCD monitor and recorded in SVHS format.

The pod also accommodated a modified RVSI ID-1H Wide Area Ice Detection system that provided visual depiction of nearly the entire right wing upper surface and where ice was accumulating on it (Figure 7).

Ice accretion on the lower surface of the horizontal tail was documented using a Cohu video camera and a Computar 8.5-51 mm zoom lens mounted to the lower surface of the fuselage on a pan-and-tilt platform. This assembly was housed within a NASA designed and fabricated fairing (Figure 6). Identical to the over-wing video system, the tail video data was annotated, displayed to researchers, and recorded in SVHS format.

#### Aircraft Performance Measurement

Aircraft performance degradation was determined using the previously described air data instrumentation, an inertial sensor package, and engine/prop data. Inertial sensors consisted of three orthogonally mounted linear accelerometers, three orthogonally mounted angular rate gyros, and a vertical gyro to provide pitch and roll angle data. These sensors were mounted near the aircraft center of gravity. Thrust calculations were made by measuring propeller RPM and engine torque values to determine propeller advance ratio and engine power coefficient. Thrust coefficient was then determined using Hartzell propeller data tables. These sensors enabled real-time calculation of overall aircraft lift and drag performance.

### SLD FLIGHT OPERATIONS

#### Pre-Season Preparations

Prior to the start of flight operations, NCAR scientists studied the climatology of Cleveland. Meteorological records acquired between 1961 and 1990 were examined to determine when SLD was most likely to occur in the region. Figure 8 is a bar chart showing the number of hours of freezing precipitation reported in Cleveland over a 30 year period. It can be seen that the highest probability of encountering SLD in Cleveland occurs in the months of December, January, February, and March.

Since the NCAR forecasters were primarily stationed in Boulder Colorado, while NASA researchers and aircraft were based in Cleveland, it was necessary to develop an easy way for project personnel to view

weather data during pre-flight briefings. To this end, NCAR developed an internet web page where real-time images of NCAR icing products, radar, satellite, surface observations and pilot reports were available, as well as textual surface observations, terminal forecasts, AIRMETs, SIGMETs and PIREPs. The web page allowed NASA personnel to access images and data that NCAR forecasters presented in preparation for daily operations, while pilots could access the latest data necessary for official flight planning.

#### Daily Pre-Flight Checks

SLD flight operations typically consisted of a sequence of daily activities beginning with a pre-flight checkout of the aircraft and instrumentation at 6:00 AM Eastern Time (11:00 UTC). Functional instrumentation checks were performed to insure that instrumentation was operating properly. In the case of the droplet sizing probes, glass beads were used to checkout the FSSP, while a reticle wheel was used to checkout the OAP-1D 260X and OAP 2D-C grey. If the functional checks revealed a problem, corrective action was taken prior to the flight. Figure 9 shows the quality control procedure applied to the droplet sizing probes, as well as the other instrumentation.

#### Daily Weather Briefing

Daily weather briefings were given at 7 a.m. Eastern Time (12:00 UTC). Forecasters prepared and presented their briefings using a combination of observed and forecast meteorological conditions. Key data sets for forecasters included:

- Infrared satellite imagery (to determine cloud location, cloud top temperature, cloud top altitude and likelihood of liquid water vs. ice crystals)
- Sounding data (to determine altitudes for icing and cloud structure)
- Radar (to identify areas of precipitation, banding, edges and relate them to different icing scenarios)
- Surface observations (find SLD indicators at the ground, precipitation types & intensities, cloud bases and cloud coverage)
- Surface and upper air charts (determine locations of fronts, lifting zones, moisture, ideal temperature ranges)
- PIREPs (determine where icing is being reported now, including altitudes, what type of icing and who it was reported by)
- Forecast model output (forecast locations, motion, changes in structure of icing clouds, provide long-range outlooks)

The forecaster would integrate information from these

data sources to identify SLD and other icing areas. Next they would develop a suggested flight location, along with a strategy for sampling the clouds and an escape route. A detailed, one page write-up of this information would be faxed to NASA researchers before the briefing. At 7 a.m., the weather scenario and proposed flight plan would be discussed. If consensus was reached, the flight crew would typically prepare for 8-9 a.m. takeoff. Sometimes icing was not expected to develop until later in the day and update briefings were given. Outlooks for the next day or two were typically given as part of the morning briefing or during the post flight debriefing.

#### Daily Research Flights

Typically, the data acquisition would be started just prior to takeoff so that information on the cloud base, cloud top, and vertical temperature profile could be obtained during the climb after takeoff. After the climb was completed, the aircraft would be flown at an altitude prescribed in the weather briefing. While in flight, the Twin Otter crew was in contact with the NCAR meteorologists via a SATCOM communication link providing real-time feedback about cloud conditions to the NCAR team, and receiving in-flight guidance from them.

As the aircraft neared the area of forecast SLD, an attempt was made to perform a sounding of the cloud. In some cases this was accomplished by executing a missed approach if an airfield was nearby. In other cases, it involved an ascent / descent to establish cloud top & cloud base, as well as altitudes of the freezing level, liquid water, and SLD. Sometimes air traffic control restrictions limited the ability to completely execute this sounding.

After the sounding was accomplished, the aircraft was flown at a prescribed altitude into the SLD conditions. Monitoring of the 2D-grey probe images displayed by the data system indicated when SLD conditions were encountered. Once encountered, the cloud was typically sampled via a series of horizontal transects approximating a stair-step profile. The combination of the sounding, and the stepped horizontal transects provided vertical and horizontal profiles of the SLD and the environment that surrounded it. Such information is critical to the understanding of the cause of the SLD and its variability in three-dimensional space.

During some of the research flights the de-icer boots were not activated while sampling the SLD icing conditions. For these flights, ice was allowed to

accrete on the airframe as horizontal transects were being flown. At some point, a decision was made to exit the icing condition to document the SLD ice accretion with the stereo photography system, and measure its effect on aircraft performance. This was done by climbing above the cloud deck into clear air and then taking stereo photographs of the right wing. Next the performance effect of the airframe icing was determined with an acceleration/deceleration maneuver to measure the decrease in maximum airspeed, and increase in stall speed with the aircraft "iced up".

#### Daily Post-Flight Briefing

After the conclusion of each flight, a de-briefing session was conducted with the NASA pilots, operations staff, researchers, and the NCAR meteorological team. The purpose of this session was to review how the flight was conducted, to identify areas for improvement, and to identify aircraft or instrumentation problems requiring resolution. If time permitted videotapes from the over-wing and tail video systems were reviewed. An attempt was also made to quickly scan meteorological data acquired during the flight, to identify any instrumentation problems that may have occurred.

### SUMMARY OF RESEARCH FLIGHTS

A total of 29 research flights were conducted during two time periods: January 13, 1997 through February 5, 1997, and March 6, 1997 through April 3, 1997. Originally it had been planned to conduct flight operations continuously from January through April. An engine problem on the Twin Otter interrupted operations for 1 month, during which time the engine was repaired.

Of the 29 research flights, four were conducted in clear air for the purpose of establishing the ice-free "baseline" performance of the NASA Twin Otter. The remaining 25 flights were conducted in icing conditions ranging from conventional cloud size drops to freezing drizzle and freezing rain. A summary of these research flights is contained in Table III.

NASA Lewis Research Center was used as a base for SLD flight operations, which were generally conducted within Ohio and the states that surround it. A typical day of flight operations was usually characterized by two SLD icing research flights. The first flight originated at NASA, followed by a re-fueling stop at another airport (such as Akron-Canton OH, Erie PA, etc) and the second flight returned to NASA. There were some exceptions to this typical daily schedule, such as the eight days having only a single research

flight, and one instance where 3 research flights were conducted within the same day.

Reflecting on the 1996-97 icing research flights as a group, it is possible to make some general observations:

- Mixed-phase conditions (simultaneous presence of liquid water & ice) were encountered quite frequently.
- When small supercooled droplet icing conditions were encountered, relatively high LWC (up to  $0.6 \text{ g/m}^3$ ) was observed with the highest values typically found just below the cloud top.
- When SLD icing conditions were encountered, relatively low LWC ( $< 0.2 \text{ g/m}^3$ ) was observed.
- Some icing encounters contained significant concentrations of both small and large supercooled water droplets. For these "in-cloud" encounters two peaks in the droplet spectra have been observed, one for the smaller drops and one for the larger drops. SLD was also sampled below cloud and in between cloud decks where only large drops were observed.
- During the first portion of the flight season (January & early February), SLD conditions appeared to be more prevalent than later in the season (March) when small droplets with high LWC were encountered more frequently. This agrees with the climatological data for Cleveland shown in Figure 8.
- During small droplet encounters having relatively high LWC ( $0.5 \text{ g/m}^3$ ), the visibility within the cloud was significantly reduced, when compared with SLD encounters (LWC typically  $< 0.2 \text{ g/m}^3$ ). This observation is expected based on scattering theory.

Of the 25 icing research flights, three of the flights were believed to contain a prolonged exposure to SLD icing conditions: (1) Flight 97-07A on January 15, 1997, (2) Flight 97-11B on January 24, 1997, and (3) Flight 97-14B on February 4, 1997. These flights were given priority and selected for detailed analysis before the other 22 flights. The analysis was focused toward determining a representative droplet size distribution and LWC for the encounter, as well as evaluating the meteorological conditions associated with the formation of the SLD encounter.

At the time of this writing, the analysis of the above mentioned 3 SLD flights is nearing completion and the remaining 22 research flights are in the initial phases of analysis. For the 3 priority flight cases,

Atmospheric Environment Services (AES) analyzed the micro-scale parameters (e.g.- droplet size distribution, LWC, etc), while the National Center for Atmospheric Research (NCAR) analyzed the associated synoptic and mesoscale weather. Some results extracted from one of these cases will be presented in the next section.

### ANATOMY OF AN SLD ENCOUNTER

During the second research flight (97-14B) on February 4, 1997, SLD icing conditions were encountered while the Twin Otter was flying over Lake Erie. There were some periods where primarily supercooled liquid water was present, and some periods where mixed-phase (liquid water & ice) conditions were present. This was typical of most of the research flights conducted during the winter of 1996-97.

Selected flight data from Flight 97-14B will be presented and discussed. The intent of this section is to provide the reader with a general idea of the weather conditions, LWC, and droplet spectra associated with an SLD encounter. A more comprehensive treatment of the winter 96-97 SLD flight data is planned for future reports, once the flight data have been fully analyzed.

The synoptic scale weather conditions associated with this flight will be discussed first. Then "Quick-look" flight data will be used to illustrate how the flight evolved in time. Finally a representative SLD droplet spectra and LWC will be presented for a selected time period during the flight.

#### Weather Conditions

The synoptic weather scenario on February 4th was rather complicated. At 700 millibars (see Figure 10), a low was centered over southwest Iowa. Dry air was moving toward the project area from the southwest, and had reached central Missouri by 12 UTC. Saturated conditions were evident across all of Ohio, Indiana and southern Michigan, ahead of a trough axis extending southeastward from the low. Temperatures across the project area (at 700 millibars or approximate altitude of 3000 m) were between 0 and -7 degrees Celsius.

At the surface, a well organized, low-pressure center moved from southeast Iowa toward Chicago between 12 and 18 UTC. At 18 UTC, the 1006 millibar low was centered over Chicago and featured a warm front which extended across southwestern Ohio to the Tennessee/North Carolina border and a surface trough



which extended across southern Michigan and Lake Erie (Figure 11).

Ahead of the warm front, freezing rain and some freezing drizzle was reported across central Michigan, southern Ontario, western New York, and central Pennsylvania, while rain was occurring in western Pennsylvania. Stations across most of Ohio, including Cleveland, had been reporting rain in previous hours, but this rain had moved to the East, leaving the Cleveland area beneath non-precipitating, overcast clouds.

The aforementioned surface trough tilted northward with height, with warm advection and overrunning conditions evident at all levels above the trough (indicative of a warm frontal structure). In places where warm cloud tops were in place, the lifting from the warm frontal structure and overrunning conditions produced supercooled liquid water and SLD aloft. The warm cloud tops developed as dry air moved into the Cleveland area above 15000 feet after 18 UTC, removing a deep, cold cloud shield that was in place aloft (Figure 12). During the second flight on this day, the Twin Otter flew into these clouds, and encountered both small and large supercooled liquid water drops and relatively few ice crystals.

#### Summary "Quick Look Flight Data"

"Quick look" summary plots of the second flight on 2/04/97 are shown in Figure 13. These time history plots were generated to provide a first-order analysis of the flight data. Figures 13-A, B, and C show time histories of altitude, temperature, and ice detector output. There were two time periods during this flight where SLD was encountered: (1) 18:24 through 18:44 UTC, and (2) 19:06 through 19:16 UTC. Selected data from the first time period will be presented and discussed.

The Twin Otter took off out of Cleveland at 17:54 UTC and began ascending to an altitude of 13000 ft (4000 m). The pre-flight briefing indicated that icing conditions could be expected above 6500 feet (2000 m).

The freezing level was reached at ( $T_i = 0^\circ \text{C}$ ) at 8500 ft (2700 m), and the ice detector began icing up at 9000 ft thus indicating the presence of supercooled liquid water droplets.

Flight notes indicated that a buildup of clear ice was visible on the wing and tail boots at 18:24 UTC. Review of over-wing and tail video showed this ice extending in the chordwise direction to the edge of the

boot, providing visual confirmation that a large droplet encounter was occurring. At this time the Twin Otter was flying over Lake Erie at an altitude of 13000 ft (4000 m), and the static temperature was  $-10^\circ \text{C}$ . The LWC was fluctuating between 0.1 to  $0.2 \text{ g/m}^3$ , the FSSP was indicating an MVD of 10 to  $20 \mu\text{m}$ , and visual images of large droplets were observed from the OAP 2D-C grey probe. Sampling of this condition continued until 18:44 when the aircraft conducted a maneuver to evaluate the "iced" aircraft performance degradation.

#### Droplet Spectra and LWC

Figure 14 displays a 9 minute segment of cloud microphysical data collected during a nearly constant altitude traverse from 18:24 - 18:52 UTC at approximately 13000 ft (4000 m). The segment displayed is typical of the entire traverse. The Twin Otter aircraft passed in and out of areas of elevated liquid water content of up to  $\sim 0.5 \text{ g/m}^3$ . During these periods, the estimated FSSP drop concentration were relatively low at  $< 100 \text{ cm}^{-3}$ , levels which are conducive to the formation of large droplets. Drizzle drops up to several hundreds of microns were commonly observed throughout the entire period. Although occasional large ice particles were observed, the 2D imagery is dominated for the most part by water droplets. Sample drizzle images recorded by the OAP 2D-C grey at 18:34:30 are contained in Figure 15. The figure contains both in-focus and out of focus images, the latter of which are eliminated for the most part by 2D image analysis software. Relatively sharply focused circular images in excess of  $300 \mu\text{m}$  are clearly visible.

The upper plot in Figure 14 displays 60 second average Nevzorov total water contents and the median volume diameter estimated by combining Nevzorov TWC, FSSP, and OAP 2D-C grey data. The data are preliminary and have not undergone rigorous quality control or final corrections, and are presented for illustrative purposes only. Note that high MVDs are observed both in areas of relatively high LWC (e.g. 18:34 - 18:35), and areas of low LWC (e.g. 18:42 - 18:43). Conventional small-droplets dominate the droplet mass in the central region of the figure, where MVDs as low as  $18 \mu\text{m}$  are observed. One possible explanation for such observations is that drizzle may be forming at a higher altitude, and falling into this area characterized by conventional small-droplet intermittent clouds.

The upper plots in Figure 16 display the average drop

spectrum for the period of 18:34-18:35 UTC. The data have been assembled using information from the FSSP-100 (2-47 $\mu$ m), the OAP 2D-C grey (7.5-968 $\mu$ m), and the Nevzorov TWC probe. Large ice particles have been eliminated from these spectra by a first stage automated process, followed by a manual interactive inspection of processed images. This time period is characterized by a moderately high LWC and MVD (0.23 g/m<sup>3</sup>, ~75  $\mu$ m), and relatively low small drop concentrations (~20 cm<sup>-3</sup>). The LWC distribution is bimodal, with a peak at ~25  $\mu$ m and a secondary drizzle peak at ~300  $\mu$ m.

The lower plots in Figure 16 display the average drop spectrum characteristics for the entire period of 18:34 - 18:43. It can be seen that the drizzle component is weaker over this long average, with a LWC of 0.11 g/m<sup>3</sup>, and a MVD of 27  $\mu$ m. Interestingly, the small droplet components of the two distributions are quite similar, with average total concentrations of ~20 cm<sup>-3</sup> in both cases.

The liquid water content of droplets larger than 50  $\mu$ m is also shown in Figure 14 (50  $\mu$ m is a commonly used threshold size for drizzle). Note that this parameter is a much better indicator of hazardous conditions than the median volume diameter by itself. For example, note that although the median volume diameter rises to ~165  $\mu$ m at 18:42-18:43, the LWC > 50  $\mu$ m is only 0.002 g/m<sup>3</sup>. During the period of 18:36-18:37, even though the MVD is only 27  $\mu$ m, the LWC > 50  $\mu$ m reaches 0.1 g/m<sup>3</sup> (see top plot of Figure 14).

These observations of supercooled drizzle were made in relatively high altitude cloud 13000 ft (~4000 m), and at relatively cold temperature (-8 to -10 C). Although the aircraft did not climb to higher altitudes to directly determine if a melting layer existed above the SLD layer, there was no indication from sounding or model data that such a layer existed. It is therefore most likely that the supercooled drizzle observed in this case developed from a condensation-coalescence process, as has been observed and described previously by others (Politovitch 1989, Cober et al. 1996).<sup>5,6</sup>

### SUMMARY

This paper described the conduct of the NASA/FAA/NCAR Supercooled Large Droplet Icing Flight research program during the winter of 1996-97 and presented selected results. Twenty-nine research flights were conducted during which a variety of icing conditions were encountered - mixed phase,

conventional small droplet, and large droplet (>50 $\mu$ m). Three of the research flights were identified as having prolonged SLD encounters and were designated as "priority" analysis cases. The analysis of these "priority" cases is near completion, and the remaining flight cases are in the initial phases of analysis. Results from these analyses will be documented in future technical reports.

With the first year of flight operations completed, it is now possible to reflect on the practical lessons learned relative to conducting SLD icing flight research:

- NCAR forecasting and in-flight guidance was a key element in locating SLD icing conditions aloft. These forecasts were based on the past experience of the NCAR meteorological team and the use of SLD weather tools. Since SLD was limited in terms of the physical location and extent of time it existed, it was extremely difficult to forecast. In some instances it was forecast, but the aircraft did not have the range or speed to get to the SLD location before it is believed to have ended. In other instances where SLD was forecast but not observed, the strongest indicator of SLD aloft (freezing precipitation at the surface) was not present.
- Another key element in locating SLD conditions aloft was the SATCOM. The ability to provide real-time feedback about meteorological conditions to NCAR scientists, and then to receive immediate in-flight guidance was considered essential to successfully locating and sampling SLD icing conditions.
- The flight patterns agreed upon "on-paper" in pre-flight briefings were simple to conceive of, but sometimes proved difficult to execute in practice due to air traffic control restrictions. Practical difficulties were encountered obtaining clearances to operate at a desired altitude if the airspace was busy. Also, in some cases the minimum allowable altitude was above cloud base, therefore preventing us from completing a "sounding".
- The presence of the NCAR scientists at NASA for 1 month and their presence on SLD icing research flights provided firsthand experience about the limitations inherent conducting flight research operations. These limitations were considered in subsequent pre-flight briefing and in-flight guidance to NASA. This situational awareness

was particularly valuable when the Twin Otter was in the process of acquiring in-situ data, and a change to the flight pattern was required due to operational limitations (e.g. - air traffic control, limited fuel). Familiarity with these operational constraints enabled them to suggest the best alternative change to the flight pattern in real-time, resulting in an optimum compromise between research objectives and what could practically be accomplished.

- There was sometimes a conflict between objectives to sample the clouds versus obtaining aircraft performance degradation data. Depending on the location of forecast SLD and the fuel expended to get there, there was a limited amount of time to perform in-situ research. Thus, when the aircraft encountered SLD conditions there was not always enough time to perform vertical soundings, horizontal transects of the cloud, and then conduct the iced aircraft performance degradation maneuvers. Therefore, performance degradation data were not gathered on all icing research flights. Though it is desired to acquire both types of data on each research flight, it is acknowledged that this may not always be possible.
- A considerable investment of financial resources and time is required to obtain quality SLD flight data. Besides the financial investment to purchase instrumentation (which can be quite substantial), a significant amount of time is required to perform calibrations, routine functional checks, and maintenance if necessary. In addition, a significant time investment is required to ensure that the data acquisition software and hardware are acquiring data as required. Another important aspect of the data acquisition process involves the time investment to perform a post-flight inspection of newly acquired data immediately after the flight. Finally the sheer volume of data acquired requires a time investment to organize and manage the data.

#### **ACKNOWLEDGEMENTS**

The conduct of a flight research program is based on the collective efforts of many individuals, and would not have been possible without their contributions.

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2. Bernstein, B. C. and Brown, B. G., *A Climatology of Supercooled Large Drop Conditions Based Upon Surface Observations and Pilot Reports of Icing*, 7<sup>th</sup> Conference on Aviation, Range and Aerospace Meteorology, Long Beach, CA, February 2-7, 1997. American Meteorology Society, Boston, pp. 82-87.

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5. Politovich, M. K., *Aircraft Icing Caused by Large Supercooled Droplets.* J. Appl. Meteor., 28, pp 856-86, 1989.
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**Table I: Physical Characteristics of Twin Otter Research Aircraft**

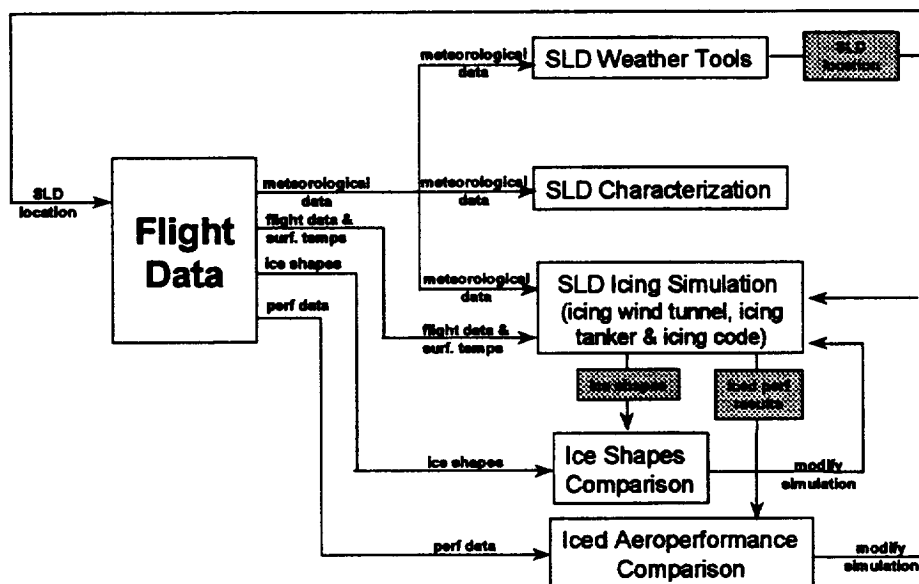
CHARACTERISTIC	VALUE
Mass, kg	4510 (Low) 4970 (High)
WING:	
Area, m <sup>2</sup>	39.02
Aspect ratio	10.06
Span, m	19.81
Mean geometric chord, m	1.98
Airfoil section (17% thickness)	"DeHavilland High Lift"
HORIZONTAL TAIL:	
Area, m <sup>2</sup>	9.10
Aspect ratio	4.35
Span, m	6.30
Mean geometric chord, m	1.45
Airfoil section (inverted)	NACA 63A213
POWER PLANT:	Pratt & Whitney PT6A-20A turbine engines
PROPELLER:	Hartzell 3 bladed

**Table II: Twin Otter Instrumentation Specifications**

PARAMETER / SENSOR	RANGE	RESOLUTION
FSSP-100	2.0 – 47 $\mu\text{m}$	3 $\mu\text{m}$ bins
OAP-1D-260X	7 – 625 $\mu\text{m}$	10 $\mu\text{m}$ bins
OAP 2D-C Grey	7.5 – 968 $\mu\text{m}$	15 $\mu\text{m}$ bins
LWC, Csiro-King	0 – 1.00 gm/m <sup>3</sup>	—
LWC, Attex Nevzorov	.003 – 3.00 gm/m <sup>3</sup>	.003 gm/m <sup>3</sup>
TWC, Attex Nevzorov	.003 – 3.00 gm/m <sup>3</sup>	.003 gm/m <sup>3</sup>
$\alpha$ , Rosemount 858	+15°, -10°	0.003°
$\beta$ , Rosemount 858	±15°	0.003°
V, Rosemount 542K	0 to 190 knot	0.076 knot
Alt, Rosemount 542K	0 to 15K ft	8.2 ft
OAT, Rosemount 102AU1P	-20° to 30° F	0.041°F
A <sub>x</sub> & A <sub>y</sub> Sundstrand QA-700	± 1g	.0002g
A <sub>z</sub> , Sundstrand QA-700	+3g, -1g	.0009g

**Table III. Summary Of SLD Icing Research Flights**

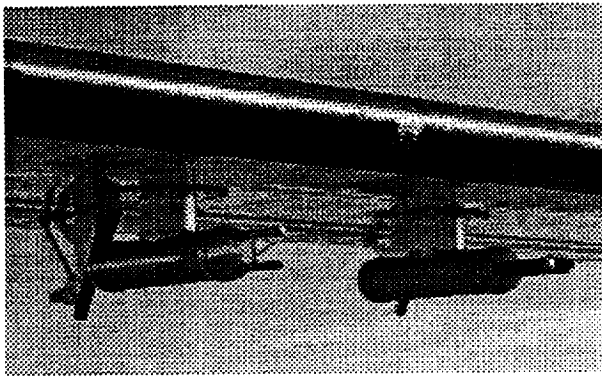
Date	Flight No.	Take-Off Time (UTC)	Landing Time (UTC)	Flight Time	Test Location	Flight Objective
01/13/97	97-05	14:40	17:00	2.3	Mansfield, OH	Baseline Performance
01/15/97	97-07A	13:10	15:23	2.2	Indianapolis, IN	Icing Research
01/15/97	97-07B	16:52	18:42	1.8	Indianapolis, IN – Cleveland, OH	Icing Research
01/21/97	97-08	16:00	17:30	1.5	Mansfield, OH	Baseline Performance
01/22/97	97-09A	17:26	19:29	2.1	Selfridge AFB-London, Ont.	Icing Research
01/22/97	97-09B	20:37	22:51	2.2	Selfridge AFB-Cleveland, OH	Icing Research
01/23/97	97-10A	14:32	16:16	1.7	Erie-Bradford, PA	Icing Research
01/23/97	97-10B	17:09	18:40	1.5	Bradford, PA-Cleveland, OH	Icing Research
01/24/97	97-11A	17:10	19:18	2.1	Akron-Canton, OH	Icing Research
01/24/97	97-11B	20:16	21:54	1.6	Mansfield, OH	Icing Research
01/27/97	97-12	13:30	15:52	2.4	Mansfield-Toledo?	Icing Research
01/31/97	97-13A	15:58	18:15	2.3	Parkersburg, WV	Icing Research
01/31/97	97-13B	19:28	21:03	1.6	Parkersburg, WV-Cleveland, OH	Icing Research
02/04/97	97-14A	13:12	14:41	1.5	Erie, PA	Icing Research
02/04/97	97-14B	17:54	20:04	2.2	Cleveland, OH (over lake)	Icing Research
02/05/97	97-15	13:40	16:07	2.5	Akron-Canton, OH	Icing Research
03/06/97	97-21A	14:59	16:34	1.6	Erie, PA	Icing Research
03/06/97	97-21B	17:19	18:06	0.8	Erie, PA-Cleveland, OH	Icing Research
03/07/97	97-22	13:23	15:16	1.9	Cleveland, OH	Baseline Performance
03/11/97	97-23A	13:15	14:58	1.7	Cleveland, OH-Erie, PA	Icing Research
03/11/97	97-23B	15:55	17:14	1.3	Erie, PA-Cleveland, OH	Icing Research
03/11/97	97-23C	18:21	20:06	1.8	Akron-Canton, OH	Icing Research
03/13/97	97-24A	18:48	20:36	1.8	Cleveland, OH-Flint, MI	Icing Research
03/13/97	97-24B	21:29	22:52	1.4	Flint, MI-Cleveland, OH	Icing Research
03/14/97	97-25A	17:44	19:46	2.0	Cleveland, OH-Ft. Wayne, IN	Icing Research
03/14/97	97-25B	20:58	22:50	1.9	Ft. Wayne, IN-Cleveland, OH	Icing Research
03/20/97	97-27	12:49	14:42	1.9	Pelee Island	Icing Research
03/25/97	97-28	13:55	15:29	1.6	Sandusky, OH	Icing Research
04/03/97	97-29	18:37	20:35	2.0	Cleveland, OH	Baseline Performance



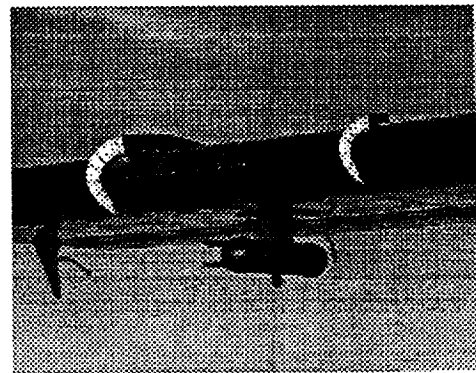
**Figure 1 – SLD Flight Research Data Flow Diagram.**



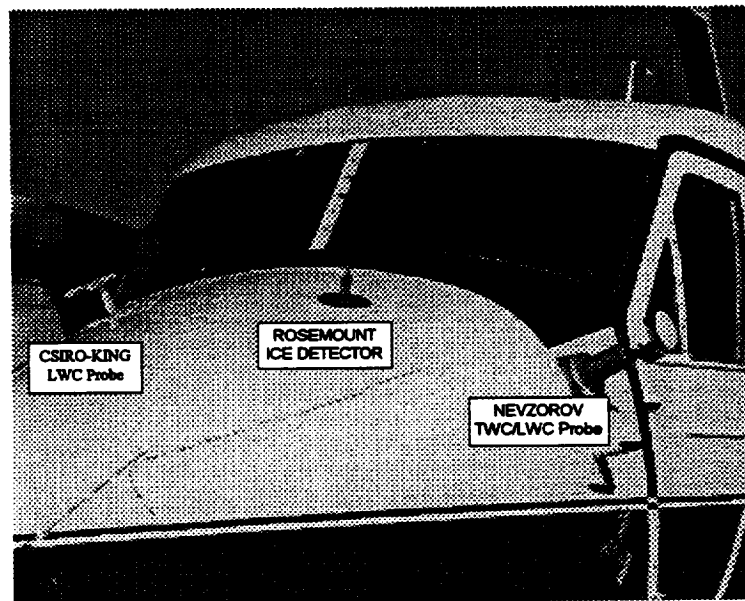
**Figure 2 - NASA Icing Research Aircraft.**



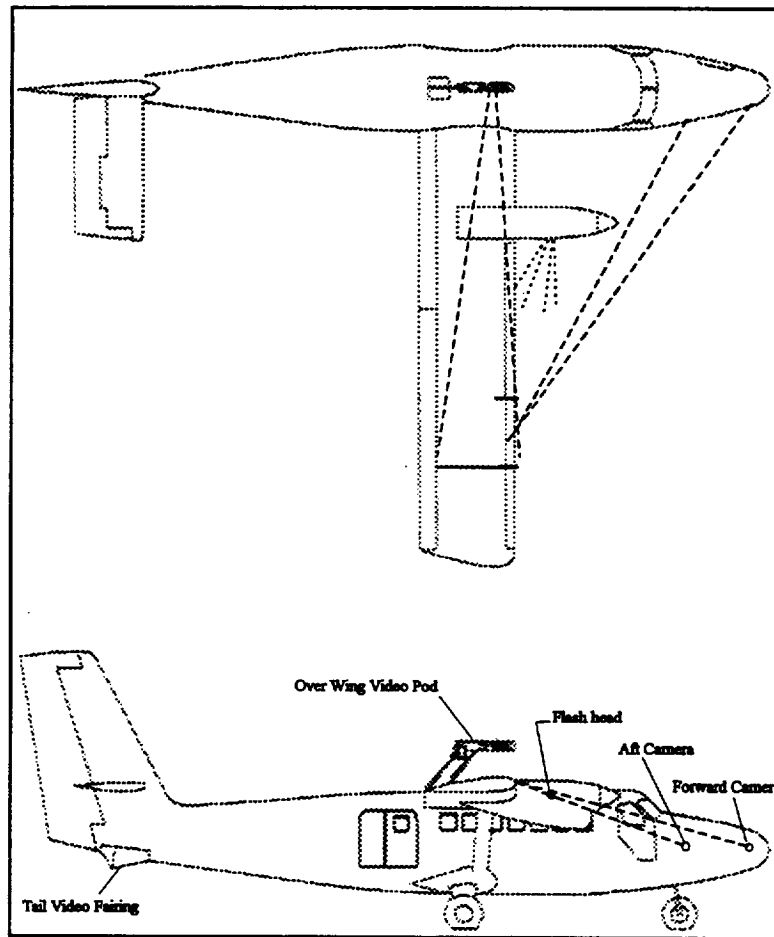
**Figure 3 - OAP-260X & FSSP-100 Probes.**



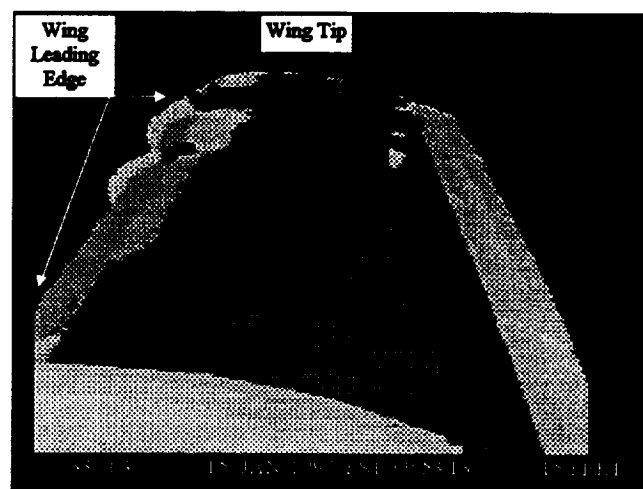
**Figure 4 - OAP-2D-Grey Probe.**



**Figure 5 - LWC/TWC Probes and Ice Detector.**



**Figure 6 - Ice Documentation Systems Layout.**



**Figure 7 - RVSI ID-1H Image of Right Wing with Ice.**



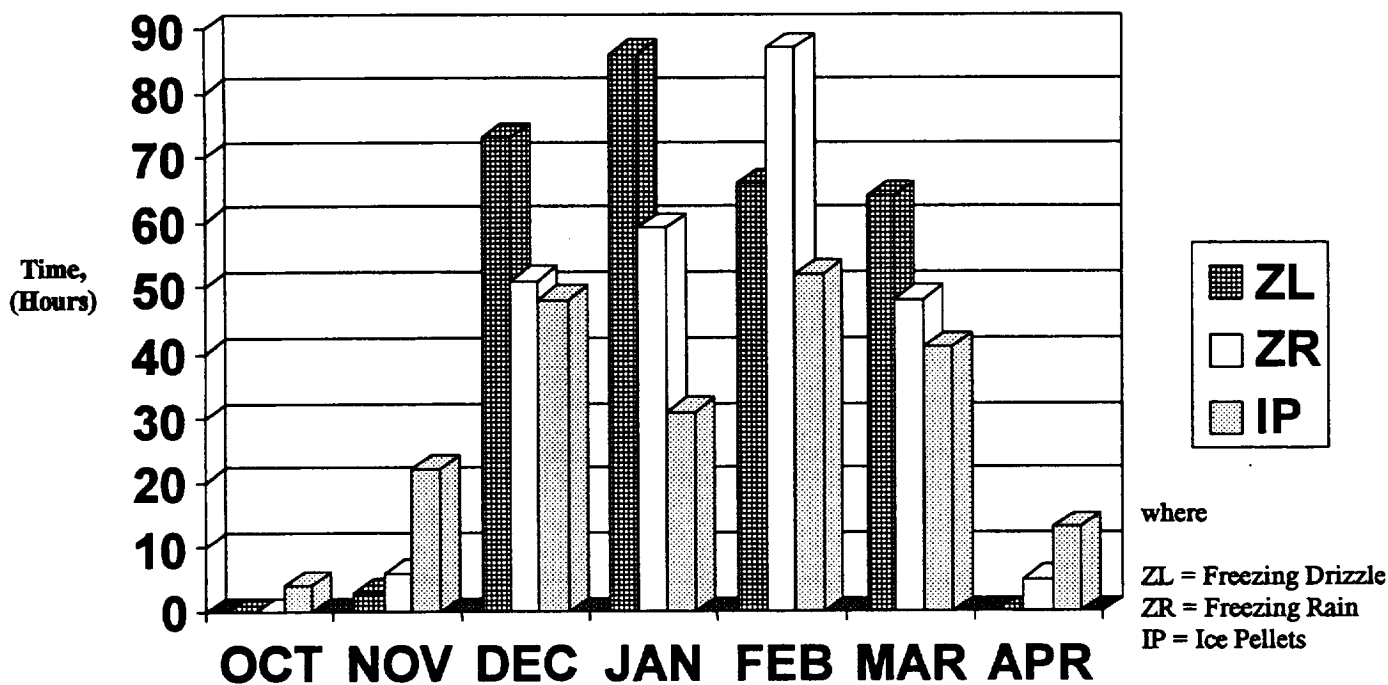


Figure 8 – Climatology: When does SLD occur at Cleveland, Ohio.  
 (hours of freezing precipitation over last 30 years)

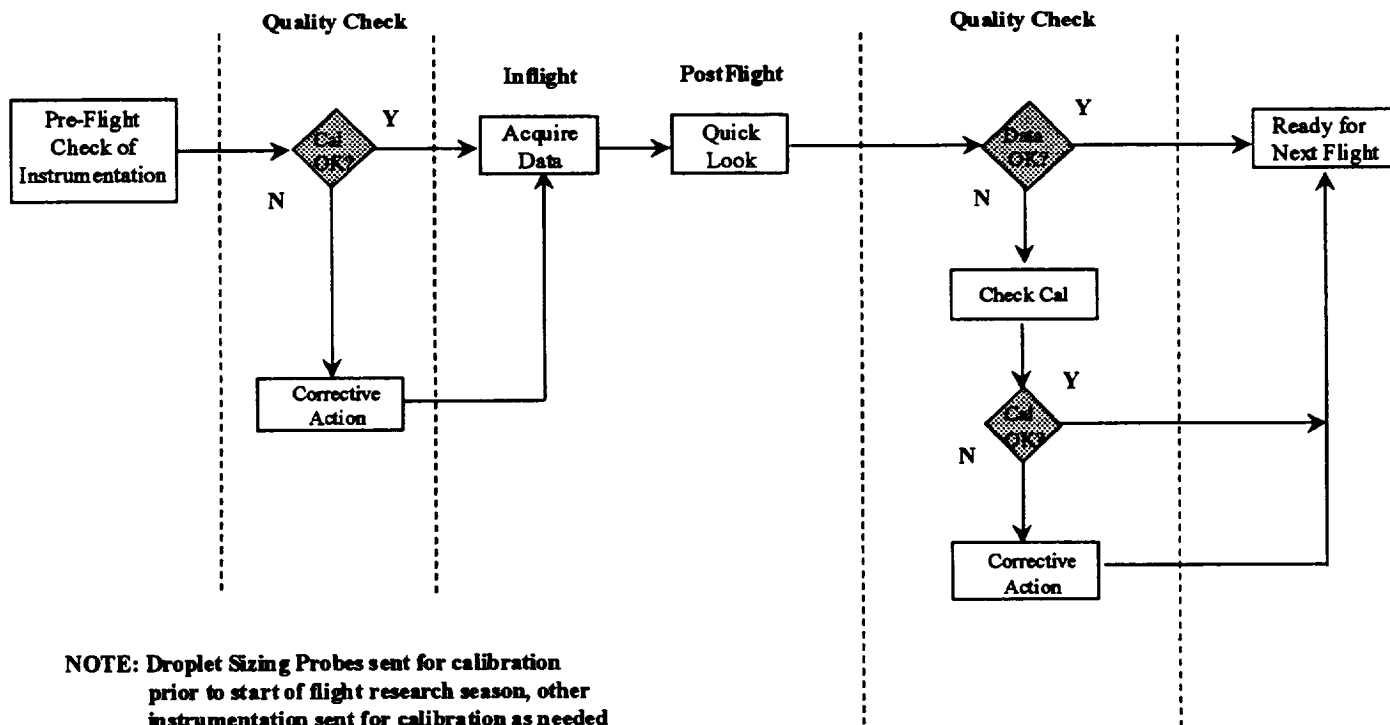
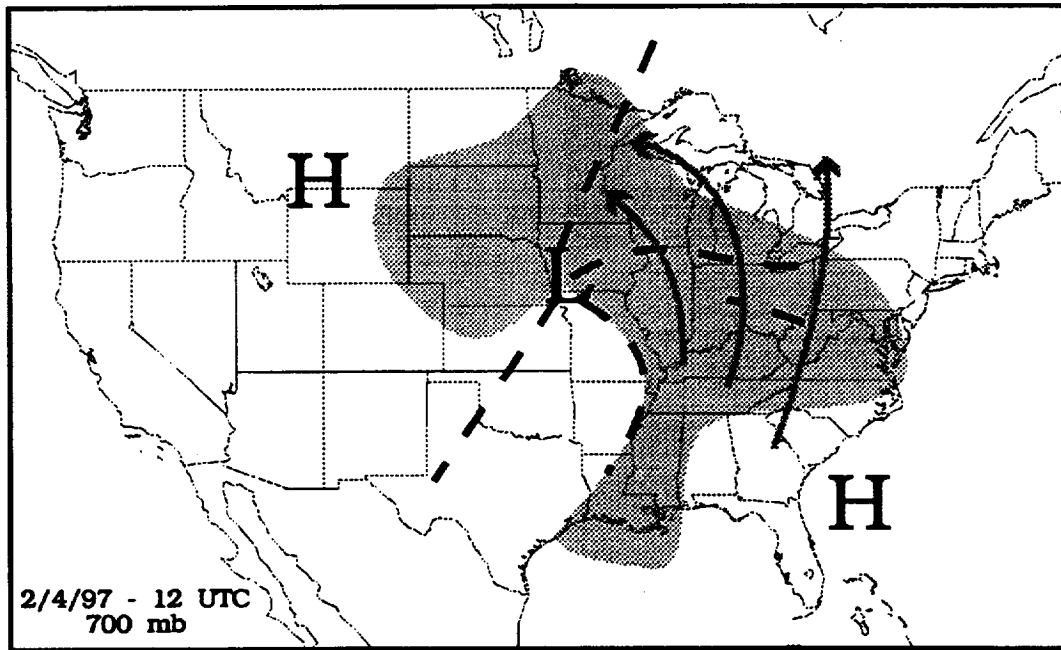
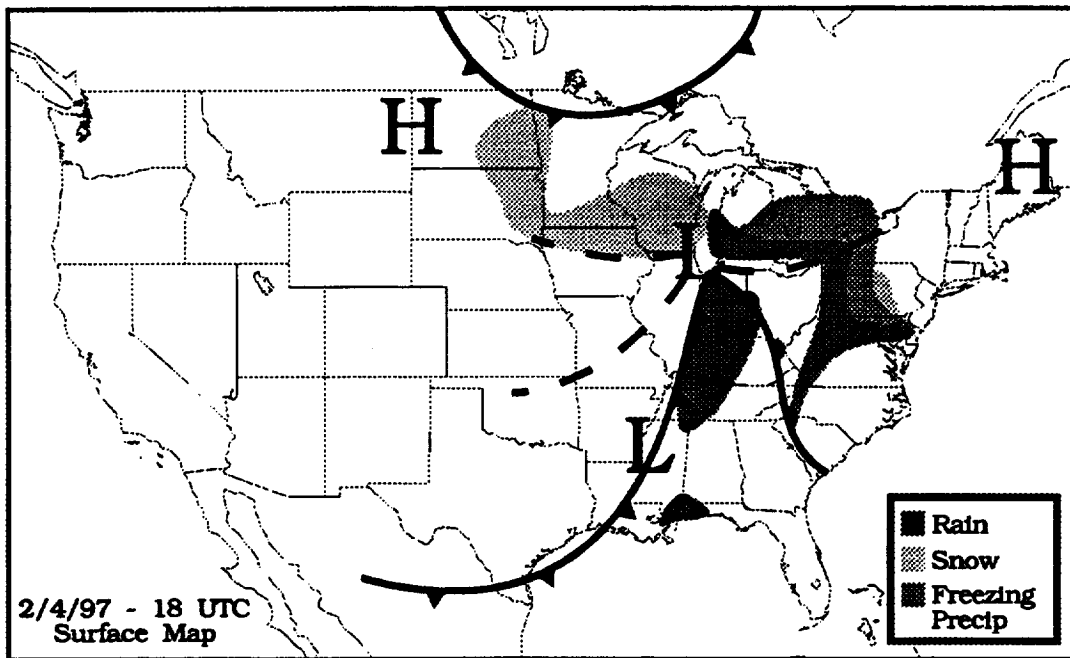


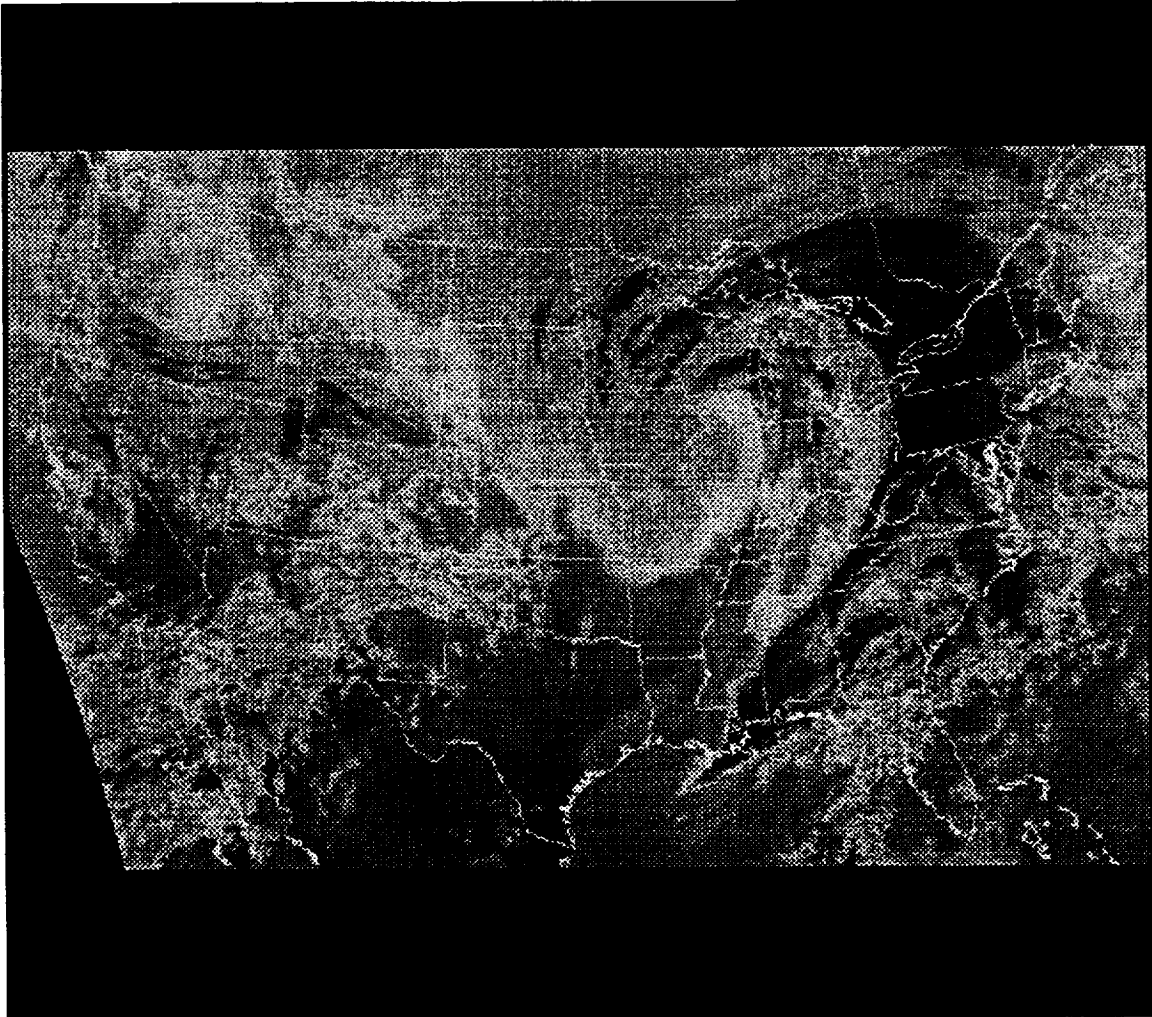
Figure 9 – SLD Instrumentation Quality Control Process.



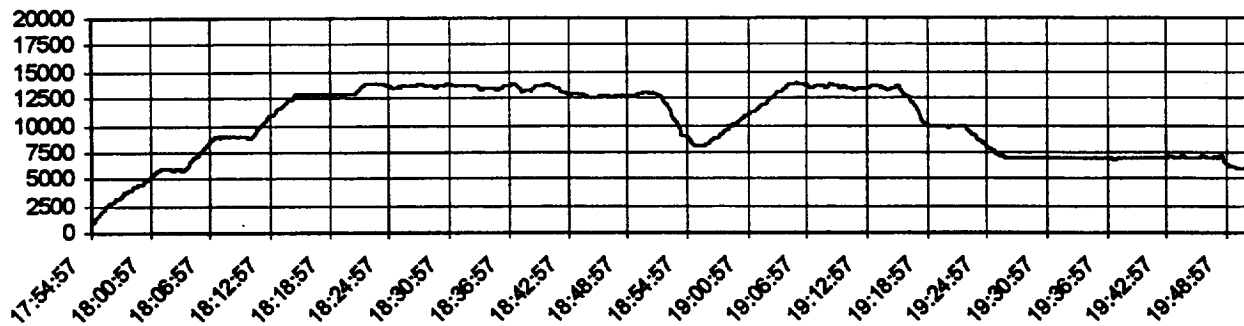
**Figure 10 – Locations of Low Centers (L), High Centers (H), Troughs (dashed lines), Saturated Conditions (DPD < 5 C, shaded), and Warm Advection (Arrows) at 700 mb at 12 UTC on 4 February 1997. Arrows show the direction of the winds, which are causing the warm advection. DPD = Dew Point Depression.**



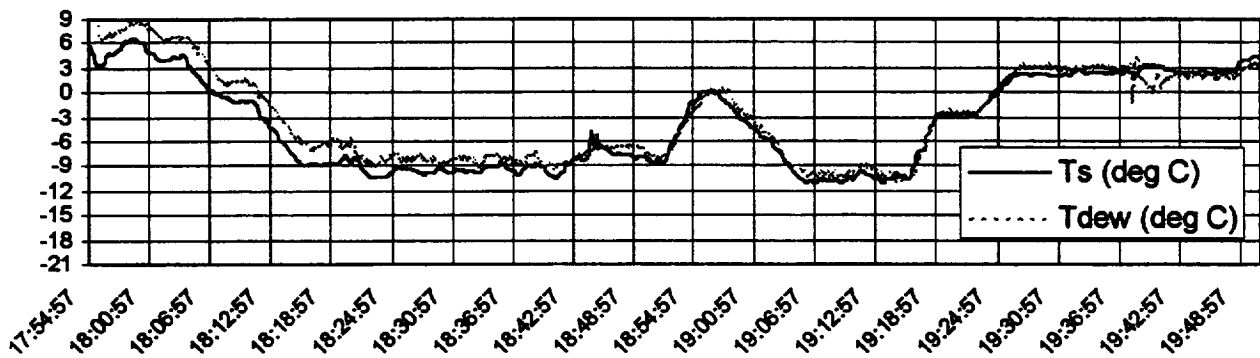
**Figure 11 – Locations of Low Pressure Centers (L), High Pressure Centers (H), Cold Fronts (barbed solid lines), Warm Fronts (solid lines with half circles), Troughs (dashed lines), Areas of Rain (dark shading), Areas of Freezing Precipitation (medium shading), and areas of snow (light shading) at the surface at 18 UTC on 4 February 1997. Freezing precipitation includes freezing rain, ice pellets and freezing drizzle.**



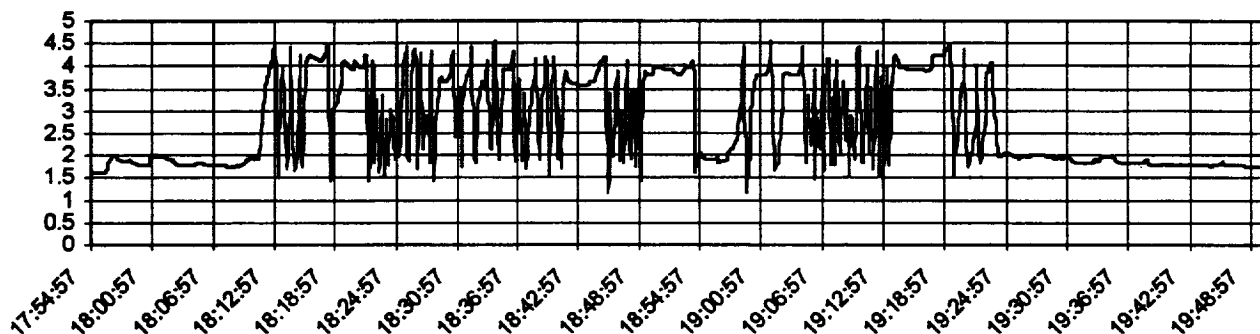
**Figure 12 – Infrared Satellite Image for 1809 UTC on 4 February 1997. Darker shaded areas indicate colder cloud tops, while lighter shaded area indicate warmer cloud tops. The darkest shaded areas (e.g. over Pennsylvania) have CTT (Cloud Top Temperatures) less than  $-40^{\circ}\text{C}$ , while the lightest shaded areas (e.g. just west of Cleveland) have CTT greater than  $-10^{\circ}\text{C}$ . CTT over Lake Erie at the time of flight was  $-13^{\circ}\text{C}$ .**



**A). Altitude (ft) vs Time (UTC)**



**B). Temperature (°C) vs Time (UTC)**



**C). Ice Detector Output (volts) vs Time (UTC)**

**Figure 13 – Quick Look Summary Data from Flight 97 – 14B on 4 February 1997.**

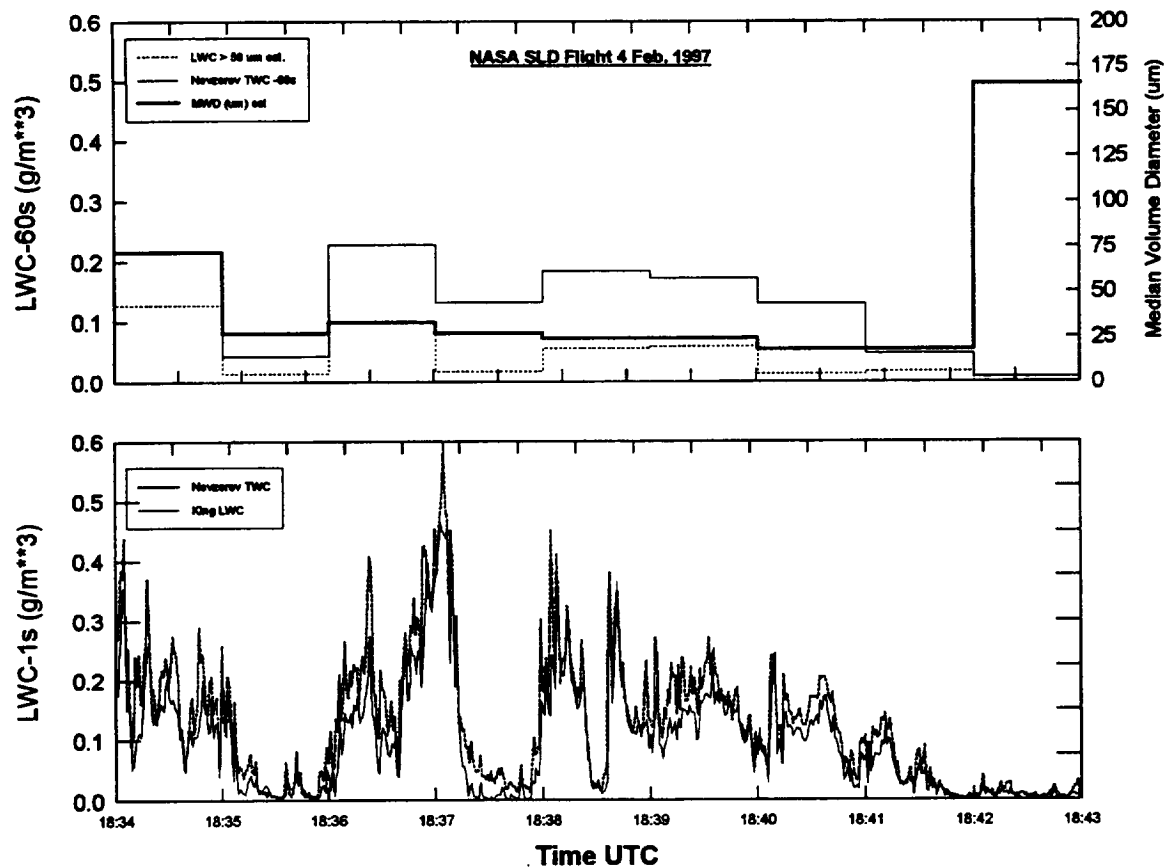


Figure 14 - NASA Twin Otter cloud microphysical data for 4 Feb. 1997, 18:34-18:43 UTC. The aircraft flight altitude was ~4000 m, and the temperature was -8 to -10 C. The upper plot displays one minute average parameters ( LWC, LWC > 50  $\mu\text{m}$ , MVD), and the lower plot displays the more detailed structure with 1 second Nevzorov TWC and PMS King hot wire water contents.

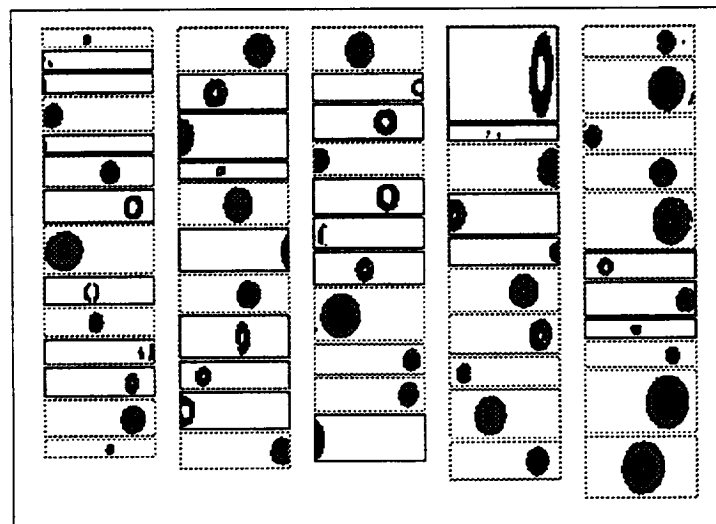
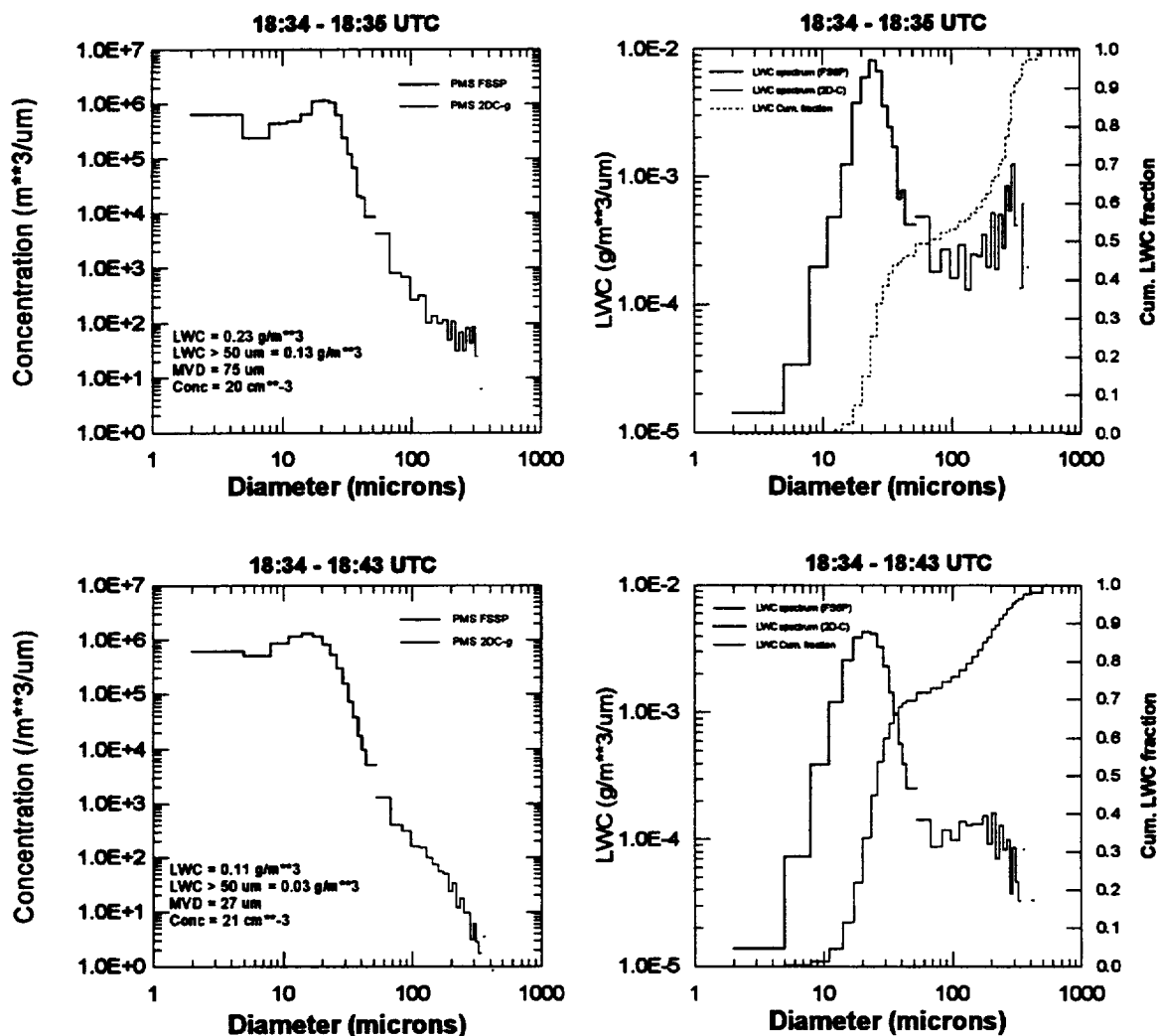


Figure 15 - PMS 2DC grey imagery collected 4 Feb. 1997, 18:35:30, in drizzle at ~4000 m, -9 C. Each image is shown here surrounded by a box, whose width is 960  $\mu\text{m}$ . Three levels of laser shadow are shown (75% black, 50% grey, 25% outer black).



**Figure 16 - Average particle spectra for the period of 18:34-18:43 UTC, 4 Feb. 1997. The upper plots show data from the first one minute of the period, with a relatively high MVD of  $\sim 75 \mu\text{m}$ . The lower plots show average data for the entire period. In each panel, the left figure displays the average concentrations from the PMS FSSP and 2D-C grey probes. The right figure shows the liquid water spectrum. And the cumulative liquid water fraction.**



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13. ABSTRACT (Maximum 200 words)  During the winter of 1996-97, a flight research program was conducted at the NASA-Lewis Research Center to study the characteristics of Supercooled Large Droplets (SLD) within the Great Lakes region. This flight program was a joint effort between the National Aeronautics and Space Administration (NASA), the National Center for Atmospheric Research (NCAR), and the Federal Aviation Administration (FAA). Based on weather forecasts and real-time in-flight guidance provided by NCAR, the NASA-Lewis Icing Research Aircraft was flown to locations where conditions were believed to be conducive to the formation of Supercooled Large Droplets aloft. Onboard instrumentation was then used to record meteorological, ice accretion, and aero-performance characteristics encountered during the flight. A total of 29 icing research flights were conducted, during which "conventional" small droplet icing, SLD, and mixed phase conditions were encountered aloft. This paper will describe how flight operations were conducted, provide an operational summary of the flights, present selected experimental results from one typical research flight, and conclude with practical "lessons learned" from this first year of operation.				
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