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Preliminary In-Flight Ice Accretion Measurements for Validation of Simulation Methods

by
Kevin Harold Glenney, B.Eng

A thesis submitted to the Faculty
of Graduate Studies and Research
in partial fulfilment of the
requirements for the degree of
Master of Engineering

Department of
Mechanical and Aerospace Engineering
Ottawa-Carleton Institute for Mechanical and Aerospace Engineering
Carleton University
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April 1999

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The Faculty of Graduate Studies and Research
acceptance of the thesis**

**Preliminary In-Flight Ice Accretion Measurements for
Validation of Simulation Methods**

Submitted by

**Kevin Harold Glenney, B. Eng
in partial fulfilment of the requirements
for the degree of Master of Engineering**

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April 1999**

Abstract

This thesis outlines an experiment whose objective was to obtain in-flight data suitable for the validation of ice accretion simulation methods. Flights in conjunction with the Canadian Freezing Drizzle Experiment III (CFDEIII) were conducted during the period of December 1997 through February 1998. Data were obtained for ice accretions on an antenna dome mounted on the upper aft fuselage of a Convair 580 aircraft. The aim of the project was to document the build-up of ice with respect to time and the atmospheric and flight conditions during the accretion period. Unfortunately, subsequent data processing revealed that the raw ice accretion data were not sufficiently accurate for the intended purpose due to unforeseen imaging problems.

For the purpose of generating 3 dimensional representations of ice accretion, stereo images of the CAL SatCom dome were collected from two miniature digital video cameras. 3-D representations were generated at time steps of approximately two minutes. Due to imaging problems, ice surface models were only generated for one icing case. These representations were then used to generate 2-D cross sections of ice at equal spanwise intervals across the dome. The relative positions of the 2-D cross sections could not be established with sufficient accuracy to be useful. Recommendations are made on how to overcome the difficulties in possible future experiments.

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List of Figures

Figure 1.1 NRC Convair 580.....	2
Figure 1.2 Yearly accidents related to icing.....	4
Figure 1.3 Eurocopter Super Puma.....	5
Figure 2.1 Photogrammetry Basics	15
Figure 3.1 Side and top view of Convair 580 antenna locations.....	18
Table 3.1 Convair 580 parameters.....	19
Figure 3.2 Forward Scattering Spectrometer Probe	20
Figure 3.3 Miniature Elmo video camera.....	21
Figure 3.4 30mW diode laser	22
Figure 3.5 Camera and Radome configuration.....	24
Figure 3.6 Schematic and dimensions of camera set-up	24
Figure 3.7 Wing Pylon on NRC Convair 580	25
Figure 3.8 CAL SatCom Antenna Dome.....	26
Figure 3.9 Computer/video console on Convair 580.....	28
Figure 3.10 3D-Builder environment	31
Figure 3.11 Rhinoceros Operating Environment.....	32
Figure 3.12 Calibration Plate.....	33
Figure 3.13 Stereo Pair of Calibration Plate.....	33
Figure 3.14 Difference in pixel dimensions	35
Figure 4.1.1 Shadow Zone.....	38
Figure 4.1.2 Propeller Slip Stream - Suggested explanation of skewed ice accretions and presence of moisture and slush blotches.....	39
Figure 4.1.3 Flat Plate Analysis of Boundary Layer Thickness.....	41
Figure 4.2.1 Clean dome with tape grid for 3D Builder analysis.....	42
Figure 4.2.2 Result of clean dome analysis with 3D-Builder and Rhino	43

Figure 4.3.1 Iced dome of case C-715	44
Figure 4.4.1 Iced dome of case C-719	45
Figure 4.5.1 Iced dome of case C-721	46
Figure 4.6.1 Icing Accumulation Cylinder of case C-722a.....	47
Figure 4.6.2 Iced dome of case C-722a.....	47
Figure 4.7.1 Icing Accumulation Cylinder of case C-722b.....	48
Figure 4.7.2 Iced dome of case C-722b.....	48
Figure 4.8.1 Icing Accumulation Cylinder of case C-723a.....	49
Figure 4.8.2 Iced dome of case C-723a.....	49
Figure 4.9.1 Icing Accumulation Cylinder of case C-723b.....	50
Figure 4.9.2 Iced dome of case C-723b.....	50
Figure 4.10.1 Icing Accumulation Cylinder of case C-725.....	51
Figure 4.10.2 Iced dome of case C-725.....	51
Figure 4.10.3 C-725-1 Ice model at 14:07:35	52
Figure 4.10.4 C-725-2 C-725-3 Ice model at 14:04:22	52
Figure 4.10.5 C-725-3 Ice model at 14:01:34	52
Figure 4.10.6 C-725-4 Ice model at 13:58:21	53
Figure 4.10.7 C-725-5 Ice model at 13:56:03	53
Figure 4.10.8 C-725 2D cross sections from analysis with 3D-Builder and Rhino	54
Figure 4.11.1 Icing Accumulation Cylinder of case C-726.....	55
Figure 4.11.2 Iced dome of case C-726.....	55

List of Appendices

Appendix A	Flight Data.....	68
Appendix B	IDL Routines.....	73
Appendix C	Laser Safety Report.....	85
Appendix D	Calibration Plate.....	91
Appendix E	Sample Calculations.....	93
Appendix F	Atmospheric and Aircraft Flight Data / Graphs.....	97
Appendix G	Convair 580 Instrumentation List for CFDE III.....	151

Nomenclature

AES	Atmospheric Environment Services
CFDE III	Canadian Freezing Drizzle Experiment III
FSSP	Forward Scattering Spectrometer Probe
FRL	Flight Research Laboratory
GMT	Greenwich Mean Time
IAS	Indicated Air Speed
IAT	Indicated Air Temperature
LWC	Liquid Water Content (g/cm³)
MeVD	Mean Volume Diameter (μm)
MVD	Median Volume Diameter (μm)
NASA	National Aeronautics and Space Administration
NLWC	Nevzorev Liquid Water Content (g/cm³)
NRC	National Research Council
NTWC	Nevzorev Total Water Content (g/cm³)
OAT	Outside Air Temperature
SLD	Super-cooled Large Droplets
TAS	True Air Speed
ZL	Freezing Drizzle
ZR	Freezing Rain
α	Angle of Attack
β	Side Slip Angle

Table of Contents

ABSTRACT	I
ACKNOWLEDGEMENTS	II
LIST OF FIGURES.....	III
LIST OF APPENDICES	V
NOMENCLATURE	VI
CHAPTER 1 INTRODUCTION.....	1
1.1 CFDEIII BACKGROUND: OPPORTUNITY FOR PROJECT	1
1.2 OBJECTIVE AND SCOPE	2
1.3 IMPORTANCE OF RESEARCH FOR ICING	4
CHAPTER 2 BACKGROUND INFORMATION	8
2.1 THE ICE ACCRETION PROCESS	8
<i>Basic Principles of Ice Accretion</i>	8
<i>Performance and Safety issues</i>	10
2.2 PREVIOUS IN-FLIGHT ICING STUDIES	11
<i>Current techniques</i>	11
<i>NASA Twin Otter experiments</i>	13
2.3 PHOTOGRAMMETRY AND IMAGING	14
<i>Photogrammetry Techniques</i>	15
CHAPTER 3 DESCRIPTION OF EXPERIMENTS.....	18
3.1 TIME LINE.....	18
3.2 AIRCRAFT CONFIGURATION	18
3.3 AVAILABLE INSTRUMENTATION.....	19
3.4 BASIC CONFIGURATION OF THE EXPERIMENT	22
<i>Camera and dome location</i>	22
<i>Description of camera set-up and reasons for this approach</i>	23
<i>Other options explored</i>	25
3.5 DATA RECORDING EQUIPMENT AND TECHNIQUES	26
<i>Data Analysis</i>	28
3.6 SELECTION OF ICE ACCRETION CASES.....	29
3.7 PHOTOGRAMMETRIC ANALYSIS METHODS	30
<i>Software selection and description</i>	30
<i>Lens calibration</i>	32
<i>Accuracy estimates and Imaging Problems</i>	34
CHAPTER 4 RESULTS AND DISCUSSION.....	38
4.1 INITIAL CALCULATIONS AND STUDIES	38
4.2 IMAGES OF THE CLEAN DOME	42
4.3 CASE 1 - FLIGHT C-715.....	44
4.4 CASE 2 - FLIGHT C-719.....	45
4.5 CASE 3 - FLIGHT C-721.....	46
4.6 CASE 4 - FLIGHT C-722 CASE A.....	47
4.7 CASE 5 FLIGHT C-722 CASE B	48
4.8 CASE 6 - FLIGHT C-723 CASE A.....	49

4.9 CASE 7 - FLIGHT C-723 CASE B	50
4.10 CASE 8 - FLIGHT C-725.....	51
4.11 CASE 9 - FLIGHT C-726.....	55
4.11 DISCUSSION OF RESULTS.....	56
CHAPTER 5 RECOMENDATIONS FOR FUTURE PROJECTS.....	58
5.1 SUGGESTIONS FOR THE IMPROVEMENT OF RESULTS	58
5.2 PROPOSED METHOD FOR FUTURE EXPERIMENTS	61
5.3 POSSIBLE FUTURE WORK.....	62
CHAPTER 6 CONCLUSIONS	63
REFERENCES	64
APPENDICES.....	67

Chapter 1 INTRODUCTION

1.1 CFDEIII Background: opportunity for project

The Canadian Freezing Drizzle Experiment (CFDE) has been conducted three times since 1994 and has grown to include workers from NRC, AES, NASA, Concordia University, and Carleton University. CFDE's original mission was to investigate the formation mechanisms of freezing drizzle (ZL) and Super cooled Large Droplets (SLD) to gain a better understanding of freezing precipitation characteristics, which could lead to improvements in the safety of aircraft operations. In CFDE III, measurement methods and forecasting were improved and the goals of the experiments were expanded to include characterising in-flight ice accretion. The aircraft used for the experiment was the NRC Convair 580, a twin turbo-prop aircraft modified for research use (Figure 1.1). Equipped with a comprehensive array of atmospheric data probes and flight monitoring equipment, the aircraft was flown into known icing conditions with the intent of measuring and characterising cloud physics, ice accretion, and the effect of ice on aircraft performance. With all of the atmospheric and flight conditions monitored, it was recognised that there existed the potential to collect a comprehensive data set of icing cases for the validation of ice accretion simulation methods.

Figure 1.1 NRC Convair 580

1.2 Objective and Scope

The main objective of the present thesis project was to characterise the build-up of ice on an aircraft structure with respect to time by cataloguing several in-flight icing cases.

Stereo digital video images and atmospheric and flight data were expected to provide the necessary data to select, extract, and document 3D representations and 2D profiles of the ice accretions and the conditions under which they occurred. This thesis documents the methods used and the photogrammetry results of the experiment. It also includes suggestions on improving the method for use in future icing experiments using photogrammetric analysis. There were nine icing cases of interest collected during the period of January 17 through February 12, 1998. Only one case was analysed via photogrammetry due to unforeseen imaging problems.

The first phase of the project work was to determine the most appropriate means of measuring ice accretion in the available time. This was found to be photogrammetry, using two video cameras to obtain digital stereo images. The camera installation was designed by working with NRC's design office and shop personnel. Research on the availability and capability of computer programs for processing 3D image data revealed that it should be possible to achieve at least a modest degree of accuracy.

The second phase of the project was the collection of icing data. During this phase there were 29 flights averaging approximately 3 hours each. Video recordings were made during each flight and upon review of the flight tapes and flight notes it was possible to select a few promising cases.

The third phase of the project involved setting up and learning software to analyse the selected cases. The main computer programs involved include: 3D-Builder, Rhinoceros, IDL, and Excel. 3D-Builder is a photogrammetry program for generating 3D models from 2D images. Rhinoceros is a relatively new CAD program that was used to analyse the 3D data files generated by 3D-Builder and to extract the ice profiles. IDL (Interactive Data Language) provided the tools necessary to analyse the flight and atmospheric data. A few small programs (see Appendix B) were written for IDL to aid in this analysis. EXCEL was used to reduce AES data files to the time slots of each icing case and to convert the files to a form compatible with IDL. These data files are available in text format from Dr. Richard Kind of Carleton University.

1.3 Importance of Research for Icing

Due to icing related accidents such as those of the American Eagle ATR 72 at Roselawn, Indiana in October 1994¹, the Brasilia EMB-120 near Detroit, Michigan in January 1997², and the West Air EMB-120 incident at Sacramento, California in March of 1998³, there are renewed concerns about safety and performance related to icing. These concerns are heightened by the increased frequency of aircraft flying in adverse weather conditions. Every year there is an average of 30 aircraft accidents related to in-flight icing (Figure 1.2). Of those accidents the great majority involve general aviation aircraft and nearly half involve fatalities.

Figure 1.2 Yearly accidents related to icing

AGARD report AR-344, Ice Accretion Simulation, Report of the Fluid Dynamics Panel Working Group 20, Dec. 1997

¹ This accident killed all 68 people onboard

² Icing is attributed as one of the causes of this crash, all 29 people on board were killed

³ The aircraft encountered a sudden roll due to ice build-up but was able to recover by extending its flaps. No one was hurt. The ATR at Roselawn attempted to extend its flaps but an airspeed limitation in the flight computer prevented their deployment

The build-up of ice on aircraft structures has been a concern since the early days of flight. Most of the information available today is from work completed during the 1940's and 1950's and many of the certification requirements are still based on research from this period [13]. Advances in aircraft performance have expanded the envelope of conditions in which aircraft operate. However, the threat of in-flight icing is just as critical now as it was then due to increased traffic and increased pressure for aircraft to fly at all times regardless of weather conditions. More recent icing studies have focused on the certification of helicopters for flight in icing conditions. Power requirements for electric rotor anti-icing and ice accretion formation characteristics are the main foci of interest. The Eurocopter Super Puma (Figure 1.3) is currently the only helicopter in the world certified for flight into known icing conditions.

Figure 1.3   Eurocopter Super Puma

Advances in measuring techniques and weather forecasting have improved the ability to predict where and how icing occurs but it is becoming more apparent that icing conditions are often substantially different from those assumed in the certification requirements. Thus, in-flight icing remains a serious safety issue that can be addressed by developing improved aircraft design tools for ice detection and protection systems.

Tools currently available include in-flight testing, simulated in-flight testing, and icing wind tunnel testing. Computational methods are another tool and good in-flight icing data is essential for their validation. In-flight icing problems can also be addressed by developing improved operating practices which are based on a better understanding of icing phenomena. Again, the study of in-flight icing is essential in acquiring this knowledge.

The degradation of aircraft performance due to ice is directly linked to flight safety. A large degradation in performance results in insufficient lift and increased drag. If necessary, aircraft are de-iced on the ground so that they are 'clean' upon take-off. Aircraft certified for flight in icing conditions must be fitted with some form of ice protection system. Pneumatic leading edge boots and ducted hot air are the main forms of de/anti-icing available. One problem with these systems is that they don't adequately address run-back ice. Run-back ice tends to occur when liquid water content (LWC) is particularly high and when heating of leading edges is insufficient to vaporise all of the impinging water. Ice typically forms on all forward-facing surfaces but in some cases can grow back along the surface of the wing. This is called run-back ice. If it grows beyond the reach of the anti-icing system on the leading edge of the wing an accretion is created that cannot be removed. This was determined to be the cause of the ATR-72 accident of 1994 [14]. Understanding the mechanisms of ice accretion is critical to anti-icing system design since these systems add weight, require external power, and are only effective when conditions are not too severe.

The original goal of CFDE was the study of formation mechanisms of super cooled large droplets (SLD) (not covered here). This is an important area of interest since it may lead to improved prediction that would allow pilots to avoid flying into these areas.

Avoidance of icing conditions is often the only option for small, unprotected aircraft.

Avoidance is also sometimes the only option for large commercial aircraft when icing conditions are severe.

Consequently, there is a need to improve ice prevention and validate ice prediction techniques to help solve the safety and performance issues related to aircraft icing. By combining the results from all of the ways of examining ice accretion a clearer picture of the phenomena can be obtained and better ways can be devised for the prevention and prediction of ice accretion on aircraft.

Chapter 2 BACKGROUND INFORMATION

2.1 The Ice Accretion Process

Ice can accrete on aircraft flying through clouds when temperatures at ground level are well above or below 0°C. Therefore, the danger to aircraft is not limited to the winter months. Icing occurs most frequently in areas such as the Great Lakes region, and coastal regions where the weather systems absorb and expel large amounts of moisture from/to the bodies they are passing over. Icing also tends to occur at lower altitudes (ie. <20000ft) where the majority of clouds form. Small turbo-prop aircraft are at higher risk of encountering in-flight icing because they spend more of their time at the lower altitudes. However, all aircraft are subject to icing in the most critical phases of flight, take-off and landing, and thus require icing protection systems.

Basic Principles of Ice Accretion

Ice accretion occurs because of the presence of moisture in the air coupled with low ambient static temperatures. There are two forms of in-flight ice accretion, rime ice and glaze ice. Rime ice occurs when tiny droplets of water are super-cooled and impact the surface of the aircraft. The droplets instantly freeze and a uniform white granular coating results. Rime ice accretions are typically somewhat aerodynamic in shape but degrade performance significantly due to their rough surface. Glaze ice occurs at warmer temperatures when larger super-cooled droplets impinging on the surface of the aircraft do not instantly freeze in their entirety. The unfrozen water runs back before freezing causing non uniform ice build-up and sometimes horn-like shapes on leading edges.

Glaze ice is much more dense than rime ice since the impinging water has time to flow before it freezes. Rime and glaze ice represent the two extremes of ice formation and the resulting ice accretions are usually somewhere in between.

In conventional icing, droplet sizes range from 10 to 40 μm . This is the small droplet size range specified in the FAR-25 Appendix C icing certification envelope [16][22] and is consistent with the cases encountered in this project. Super-cooled Large Droplet (SLD) icing occurs where droplets are as small as 50 μm but is more common when droplets are in the range of 150 to 400 μm . SLD is usually present in freezing rain or drizzle and has been the focus of several studies and discussions over the last few years. NASA recently performed a similar experiment using photogrammetry in the Great Lakes area to study SLD. This will be discussed in the next section.

Run-back icing is an extreme form of glaze ice. It can result if the anti-icing system does not clear the ice or water sufficiently to prevent liquid water from freezing as it flows back over the wing. If run-back ice is allowed to form and subsequent flight involves icing conditions the run-back ice will continue to grow and can pose a serious hazard to the aircraft.

Another form of ice build up that is not due to in-flight icing but can pose a risk to flight is ice that occurs due to cold soaking. A wing full of fuel that has been cooled either by flight at high altitude or by low ambient temperature will condense the moisture in the surrounding air if it suddenly encounters a more moist atmosphere. One case of cold

soaked icing yielded a sheet of ice 17mm thick [1]. This could pose a serious threat to the aircraft if it was to take off in such a condition.

Performance and Safety issues

Surface roughness and change in shape are the main factors in aircraft performance degradation with respect to ice. Poor performance with respect to lift and drag results in increased stall speeds which reduces the margin of safety. Even small amounts of ice can degrade performance to dangerous levels. It affects lateral and longitudinal handling and stability. Ice build-up on engine intakes is another concern. In severe cases it can lead to engine flame out. Also, ice shedding can damage the aircraft if it is sucked into an engine or if it strikes another part of the aircraft. One of the most dangerous conditions is ice contaminated tailplane stall (ICTS). In this case, ice forms on the horizontal tail and increases the stall speed of the tail. If the horizontal tail stall speed increases to a value that is close to or above the stall speed of the wing, recovery from an inadvertent wing stall is very difficult if not impossible.

Related to performance is the ability to monitor airspeed. Ice can accrete on and block Pitot probes that measure pressure differences to give airspeed. If the airspeed cannot be properly monitored pilots have no way of maintaining correct airspeed and the aircraft is at risk of stalling.

2.2   *Previous In-Flight Icing Studies*

Current techniques

In-flight testing, simulated in-flight testing, wind tunnel testing, and computer simulation, are the four ways that icing can be examined.

In-flight testing gives the most realistic representation of the icing phenomena but does not lend itself to easy observation or constant conditions. Measurement of the flight and environmental conditions is difficult due to the number and accuracy of probes required for a complete data set. Also, in order to find the appropriate conditions excellent planning and forecasting are required. Cost is a large factor in determining the success of an in-flight icing experiment because it determines the extent of instrumentation, the number of flight hours, and the number of man-hours available for analysis. With all of this, complete results from in-flight icing are difficult to obtain. They are however essential for validation of the other forms of testing and simulation.

Simulated in-flight testing has the advantage of relatively constant conditions and the ability to vary altitude and temperature. In this scenario a tanker aircraft flies in front of the accreting aircraft and creates a localised cloud of water. Problems associated with this type of in-flight testing stem from turbulence generated by the lead aircraft and/or spray nozzles, prevention of the spray from freezing, atomising the water, poor simulation of droplet size and distribution, and cost. Another method of simulating ice accretion when conditions are dry is to attach artificial ice shapes to the wing leading edges. Here, conditions are much more controlled and it is easier and safer to measure

performance parameters. One cannot however determine how ice forms from this method. For helicopters, it is possible to simulate in-flight icing near the ground in front of an icing spray rig. In this case, only low flight velocities are possible and temperature and altitude cannot be varied. Other problems with simulated in-flight testing are related to instrumentation and observation as with regular in-flight testing.

Icing wind tunnel testing provides the easiest way to observe icing. Greater control over conditions is available and it is easier to access the experiment for observation and alteration. The problems with icing wind tunnel testing include restricted size, and limited control of altitude, humidity, wall interference, and turbulence. In addition, the turbulence and humidity conditions may introduce a uniform frost layer that would not normally be present. This makes the extent of icing appear greater than it should. When combined with other experiments to explain the differences in results, icing wind tunnel testing gives a reasonable picture of icing phenomena.

Computer simulation is an increasingly important method that is, in part, a result of the other three ice observation methods. With the aid and modification of computational fluid dynamics (CFD) programs, it is possible to simulate the ice accretion process. As with the other methods one of the drawbacks is cost. In this case, the costs are associated with computing time, software, hardware, and man-hours. Another drawback with simulation is that the results are only as good as the models they are based on. For this reason, it is necessary to perfect the model used by the CFD code. Testing and comparison of results with real cases is the only way to do this.

Most ice prediction techniques are based on trajectory codes for predicting trajectories of the supercooled droplets as they approach the aircraft. These codes have been fairly successful for determining collection efficiency for 2 and 3 dimensional problems as well as in predicting the formation of rime ice [1 (pg 1-9)]. Although there has been a significant amount of progress in the area of glaze ice prediction, glaze ice is not as easily predicted by these codes and more work is required in this area to produce better results.

By combining the results from, and continuing to advance all of these methods the understanding of ice accretion will improve. Implementation of this knowledge will help improve safety and performance.

NASA Twin Otter experiments

The NASA Lewis Research Centre in Cleveland, Ohio has been performing in-flight ice accretion experiments for several years. The most recent report available is from the winter of 1996-97[26]. This experiment was concerned with acquiring in-flight data of SLD icing. The research aircraft was a DeHavilland DHC-6 Twin Otter with cloud physics, air data, and global positioning instrumentation similar to that of the Convair 580 used for this thesis experiment. Ice accretion was documented by the use of a stereo photography system, an over wing video system, and a tail video system. The stereo photography system used two 70 mm Hasselbald cameras with 250 mm lenses. The stereo cameras were mounted at a converging angle of 36 degrees in the nose of the aircraft and pointed at the wing to collect stereo images of ice accretion. The stereo images were then processed using photogrammetric analysis techniques to get two

dimensional ice sections. These sections were constructed from points spread laterally over approximately 4 inch sections of the wing. After four seasons of testing the method became refined enough to provide reasonable results. The results were compared to the results of the NASA developed LEWICE ice accretion analysis program. There was only fair agreement between the predicted and measured ice shapes but the cross sectional areas were close. NASA had image accuracy and instrumentation problems similar to those encountered in the present project. These problems were largely overcome during a four year period predating the 1988 report [25].

2.3   *Photogrammetry and Imaging*

Photogrammetry is the method by which a three dimensional representation of an object is obtained from a series of 2 dimensional images. Its original purpose was for topographic mapping and surveying. The techniques for photogrammetry were invented before photography and have been expanded to include radar, infra red, and microwave imaging. This places photogrammetry in the field of remote sensing. It has been used to accurately map most of the world via satellite and aerial techniques. It has been employed in medicine, construction, art, and forensic science for accident investigation and scene recreation. Photogrammetry is defined as the art and science of generating 3 dimensional models of real world objects from 2 dimensional images of the object.

The main requirements for photogrammetry include:

- 2 or more **accurate, high resolution, overlapping** images of the object that are processed in **exactly** the same format.

- 2 or more **accurately** placed control points visible in at least 2 of the images. The more control points that are present the better the calculation.
- accurate documentation of the camera properties and experiment set-up including camera location, camera resolution, lens focal length and distortion parameters.

Photogrammetry Techniques

Photogrammetry is based on triangle geometry and the properties of light. The main goal is to obtain height data (Z) from the X and Y data of points in a series of photos. Figure 2.1 shows the simplest case of vertical stereo photogrammetry.

Figure 2.1 Photogrammetry Basics

The basic equations are as follows and the variables are detailed in Figure 2.1 above.

$$Z_a = H - Bf/P_a$$

Z_a is the calculated height of the point, H is the height at which the photo was taken, B is the distance between the cameras, f is the focal length of the camera lens, and P_a is the difference between the point co-ordinates in the photos, $x_a - x_b$. The X and Y co-ordinates are calculated as follows:

$$X_a = B(x_a/P_a)$$

$$Y_a = B(y_a/P_a)$$

where the a and b subscripts denote the image that the calculations are done for. The calculations of X , Y , and Z can be repeated for each image and an average can be found that improves the accuracy of the measurements. The more images that are taken from different viewpoints the better the results - providing the other requirements are met.

The major problems with photogrammetry as stated in the “Manual of Photogrammetry” [12] that apply for this project include the following:

- each exposure should be at exactly the ideal position and altitude, determined in advance.
- the optical axis of the lenses should be exactly vertical at the instant of exposure (for vertical photography), or the angle of deviation from the vertical should be known exactly.
- the cameras should be oriented in azimuth at the instant of exposure, precisely as planned in advance.
- the camera lenses should be free of distortion and otherwise optically perfect.

- the cameras should have stable and known metrical characteristics, and should be in perfect adjustment.
- atmospheric conditions during the photo should be perfect
- the exact location and orientation of the cameras should be known in advance.
- there should be no movement of the cameras while the images are being taken
- the optical properties and distortion characteristics should be known exactly
- the photo print should be made on a perfectly flat surface

Camera calibration solves a few of these problems and minimises distortion due to optical distortion from the lenses. The software used for this thesis project had the capability of calibrating and locating the position of the cameras. This option could not be used however, since the cameras were modified when they were removed from the aircraft, essentially voiding any calibration attempt. Also, because only one reference point was visible in both images and the co-ordinate axes were not well defined in the images it was not possible to have the software calculate camera locations.

Traditional photogrammetry uses vertical photography in which the images are taken pointing in the same direction. For the purpose of this project, it was necessary to use convergent photography to get the most overlap of the images. This allowed mapping the entire leading face of the dome with just 2 cameras. The project was limited to a space of approximately 1.3 metres along the upper aft section of the fuselage and due to space and installation limitations only 2 cameras were permitted.

Chapter 3 Description of Experiments

3.1 Time line

The project began in May of 1997 with commencement of in-flight experiments required by mid December 1997. Installation of the cameras and SatCom dome was completed at the end of December and minor adjustments were necessary to position the cameras.

Adjustments were made between test flights. The first usable icing case was recorded on January 17, 1998 and the last was recorded on February 12, 1998. Analysis of the data commenced in May of 1998 and the final report was prepared in April of 1999.

3.2 Aircraft Configuration

The basic aircraft configuration can be seen in Figure 3.1. The configuration of the antennae on top of the aircraft were of particular interest for the proposed CFD analysis.

Propeller location was another area of interest since the flow around the dome was affected by the propeller slipstream (discussed in chapter 4).

Figure 3.1 Side and top view of Convair 580 antenna locations

Table 3.1 shows the main aircraft parameters of interest for this project. These parameters would be useful for the CFD analysis as well.

Table 3.1 Convair 580 parameters

Airfoil section	
Root	NACA 63, 4-120
26.85% semispan	NACA 63, 4-419
Tip	NACA 63 ₂ – 415
Aerodynamic washout	1°
Wing area	920 ft ²
Span	105ft 4in
Root chord	13ft 6in
Tip chord	4ft 6in
Taper ratio	3:1
Wing incidence (relative to fuselage CL)	4°
Dihedral (wing station 0ft to 8.0ft)	4° 50'
Dihedral (wing station 8.0ft to tip)	6° 30'
Mean Aerodynamic Chord (MAC)	9ft 6.3in
Fuselage diameter	9ft 5in
Overall length	79ft 2in
Overall height	28ft 2in
Design gross weight	47000 lb

3.3 Available Instrumentation

The aircraft was heavily instrumented for cloud microphysics measurements. Appendix G shows the list of instruments installed for the project. Dynamic and static temperatures were measured by three different temperature probes. A Rosemount icing detector and an icing accumulation cylinder (IAC) were located on a pylon under the port wing. The Rosemount icing detector measures changes in frequency of an aluminum rod as it accretes ice. It can be electrothermally de-iced. The IAC was recorded by a video camera in the port wing tip pod. Examples of the ice that accreted on this device can be seen in the Results sections of Chapter 4. Liquid water content (LWC) was measured with two different instruments including a King LWC probe, and Nevzorev LWC and

TWC (total water content) probe. These probes are hot wire devices that correlate the energy required to evaporate impinging water with LWC and TWC. The Nevzorev measurements were used as the primary source for LWC and TWC since there was no TWC measurement with the King probe. This information was used to examine the consistency of the conditions and the phase composition of the cloud. Forward Scattering Spectrometer Probes (FSSP) were used to measure droplet concentrations in various size ranges. These probes base their measurements on light that is scattered from incoming water droplets. The scattered light is collected on a photo diode and interpreted in the form of droplet size. The FSSP information was used to plot the droplet size spectra which helped determine if the icing conditions involved small or large droplets. The information from these probes was also used to calculate and plot the median volume diameter (MVD) for each case. This was compared to the mean volume diameter (MeVD) deduced from the FSSP data to ensure consistency and to check for errors or instrumentation problems. Figure 3.1 shows a typical FSSP probe as it would be mounted in a pod similar to the ones used on the Convair 580.

Figure 3.2 Forward Scattering Spectrometer Probe

The installation consisted of the CAL SatCOM antenna fairing (the dome), two cameras with cables and control boxes, one 30 mW laser with 5 degree diffractive grid generator, two camera mounts, two camera fairings, a pre-existing video switcher, and the necessary connectors and hardware to ensure maintenance of fuselage pressurisation. The cameras were set up to obtain stereo images of the dome and the laser was used to create a grid for enhanced ice definition and ease of photogrammetric analysis. Initial flights indicated that it would be necessary to paint the fairing black to obtain better contrast between the ice and the dome and to improve laser visibility. These flights showed that the laser was not powerful enough for the projected grid to be viewed with the light conditions in the clouds and the resolution and sensitivity of the cameras. Night flights early in the project showed that the laser was working but was too diffuse to be of any use. The laser was selected for its near infrared light since the cameras were most sensitive to infrared wavelengths. A laser safety report was prepared for the operational use of the laser (see Appendix C). Figures 3.3 and 3.4 show the camera and laser units used.

Figure 3.3 Miniature Elmo video camera

Figure 3.4 30mW diode laser

3.4 Basic configuration of the experiment

Camera and dome location

Ideally, for the purpose of this experiment, the antenna should have been located in an area where the flow was undisturbed. Options for the location of the dome were on the top of the fuselage either near the cockpit or the vertical tail. The possibility of ice shedding from the dome and striking the vertical tail was of particular concern for the forward dome location. Calculations were done to determine if there was a significant difference in the speed of a chunk of ice accelerating towards the vertical tail from the front of the aircraft or from the back of the aircraft. The difference was found to be about 2 meters per second meaning that most of the acceleration is completed in a very short period of time. The other concern was that ice shedding from the front could get further above the fuselage and strike the tail at a more direct angle causing more damage.

The decision was finally made to place the dome at the back of the fuselage near the vertical tail to minimize the dangers associated with ice shedding and striking the tail-plane at a high velocity (see Figures 3.1 and 3.6). An interesting aspect of this dome location was that a previous report [3] concluded, via inviscid potential flow and droplet trajectory analysis, that this was an area of ‘shadowing’ in which no droplets should be

present and no ice should accrete. Reports such as this one deterred the Boeing Company from installing an icing probe on the aircraft as part of the CFDEIII experiments.

Description of camera set-up and reasons for this approach

Physical constraints such as not being able to modify the dome in any way except to paint it eliminated all but the photogrammetry option for acquisition of ice accretion data. The basic configuration of the experiment can be seen in Figures 3.5 and 3.6. There are two cameras mounted in front of the dome at a converging angle of approximately 15 degrees. This angle was conducive to photogrammetric analysis and convenient for installation. The aim of arranging the cameras in this way was to get the most possible overlap of image and to get the most possible common points in each view. Originally, for redundancy in the images and as an additional quality check, three cameras were considered. However, due to lack of time and money a side camera was not included. Initial concerns about avoiding disruption of the approaching flow were obviated by the fact that there were numerous antennae located upstream and on top of the fuselage at or near the aircraft's plane of symmetry. Additional concerns about the conditions of the flow approaching the dome were the effect of the propeller slipstream washing over the fuselage and the fact that the propellers tended to shed water and slush into the area. There were, however, no other options available for the placement of the dome and this was how the experiment proceeded. In retrospect, a third or even a fourth camera would have been useful in refining the quality of the 3D images. This would, however, have increased the amount of time required to complete each analysis.

Figure 3.5 Camera and Radome configuration

Figure 3.6 Schematic and dimensions of camera set-up

Control points were necessary to give the photogrammetry software a reference point by which to base calculations on. Originally, rivets on the dome were to be used for this purpose. A problem realized midway through the project was the lack of constraint on the selected control points due to the fact that ice was able to build on them.

Other options explored

Several other measurement approaches were considered before the photogrammetry method was selected. The NRC Convair 580 was fitted with under-wing pylons which were not anti-iced. Observation of ice accretion on one of the pylons (Figure 3.7) was the option originally considered for the experiment.

Figure 3.7 Wing Pylon on NRC Convair 580

The initial idea was to use an internal scanning ultra sonic or microwave sensor in the leading edge of the pylon that would map the thickness of the ice. This idea may have been feasible but it was not explored to its full potential because of the move to the dome location. An external laser scanning system was also considered. The laser was to be used with a single video camera to collect profiles of the ice accretion via photogrammetry techniques. A difficulty with this method was that the laser and camera installation had to be scanned in order to generate more than one cross section across the dome. Multiple lasers could have been used instead of scanning. Both of these

approaches would increase the installation complexity and create a larger disturbance in the flow due to increased size. The laser method was not selected, which was fortunate because early flights revealed that the laser beam would have been too diffused to be of any use. The final method that was explored before the project was moved to the SatCom dome was an ice marking method. This idea would have involved the use of heated spikes that would expel coloured fluid to mark the ice by spreading dye aft with the on-coming flow. None of these ideas could have been implemented with exception of the laser system because of the decision to move the experiment to the CAL SatCom dome (Figure 3.8). As already mentioned, no physical modifications could be made to the dome except to paint it. The final option was the stereo video photogrammetry method. This was the only option considered feasible in the allotted time schedule.

Figure 3.8 CAL SatCom Antenna Dome

3.5   *Data recording equipment and techniques*

The aircraft was fitted with three personal computers configured to handle incoming data from the various cameras, probes and antennae. These computers were linked to a video cassette recorder (VCR) and video switching unit to capture images from up to 6 video inputs. Four video inputs were available. Two video inputs were dedicated to the

cameras of the present experiment, one was dedicated to the icing accumulation cylinder on the wing pylon, and the fourth video input displayed time, airspeed, altitude, and temperature. Each of these video inputs were constantly cycled and recorded throughout the flights. Images of the dome were also digitally captured on the computer, during flight, when it was apparent from the video output that significant ice was accreting on the dome. There were only 52 in-flight digital captures for all of the flights since video was to be the major source for images of the dome. Figure 3.9 shows the main console used for monitoring and capturing digital images of the dome. Aircraft position (latitude and longitude) was determined via the global positioning system(GPS) and was available at the computer consoles. The computers captured images and data from the cameras, probes and antennae. Video data was recorded on tape, and captured periodically in digital form by computer.

Data of interest to NRC was recorded in files that were readable by an IDL routine called Uff_read (see Appendix B). The data could be interpreted by reading a text file that listed the titles of each column of the data. Each file contained time in seconds from Greenwich Mean Time (GMT), date, aircraft attitude and performance parameters, atmospheric conditions, and aircraft location in terms of latitude and longitude. The information that was extracted from these files includes aircraft angle of attack (α) and side slip angle (β).

AES data was recorded and stored in the format of text files and was imported to an Excel spreadsheet for locating the icing cases. These files included time and date,

location, altitude, atmospheric conditions, King probe data, Nevzorev probe data, and FSSP96 and 124 data. The information that was used from these files includes altitude, true airspeed, pressure, static temperature, Nevzorev total water content (NTWC), Nevzorev liquid water content (NLWC), and FSSP data. The King probe LWC data was examined and compared to the Nevzorev probe measurements.

Figure 3.9 Computer/video console on Convair 580

Data Analysis

MVD was determined from the two FSSP's. FSSP96 recorded droplet concentrations in the range from $2\mu\text{m}$ to $47\mu\text{m}$ in increments of $3\mu\text{m}$ and FSSP124 recorded droplet concentrations in the range from $5\mu\text{m}$ to $95\mu\text{m}$ in increments of $6\mu\text{m}$. This information was combined, sorted, and interpolated to $1\mu\text{m}$ via the MVDPLOT and SPAKIM routines in IDL (Appendix B). MVD was then calculated for each second of the selected cases by determining the median value from the FSSP concentration data and storing it in

an array. The Median Volume Diameter is defined as the particle diameter that divides the total mass of the sample in half. The MVD array was then plotted against time to see how the MVD conditions varied over the accretion period (see Appendix F). Droplet size spectra were plotted in IDL by the SPECTRA routine from the FSSP data using similar logic without the MVD calculation. The altitude, pressure, temperature, α , β , NLWC, and NTWC data was read into IDL and plotted via plot commands (Appendix F).

3.6 Selection of Ice Accretion cases

Icing encounters occurred during a number of flights and ice images and other data were recorded using the aforementioned techniques. Only certain cases were selected for detailed analysis. Cases were selected based on image quality, duration, consistency of conditions, and atmospheric data. Image quality and definition determined if photo analysis was possible. Shorter cases were selected since conditions were not as variable and ice accretion rates were typically higher than in the longer cases. Atmospheric data analysis including phase (ie. combination of liquid versus solid) and LWC determined which cases were most appropriate for CFD analysis and which cases would receive in-depth analysis including 3D imaging with respect to time, MVD calculation, and droplet size spectra analysis.

In addition to video images of the dome, the video recording of the main atmospheric and flight conditions was helpful in locating the main data for icing cases and determining which cases were created under the most constant conditions.

3.7   *Photogrammetric Analysis Methods*

Software selection and description

Originally, consideration was given to developing a photogrammetry data reduction program to deduce the ice thickness. It was soon found that this would be a very large undertaking for the desired results. A search for currently available software revealed that there were a few reasonably priced systems available on the market. These systems included 3D-Builder, PhotoModeler, and an NRC program written by Dr. Sabrey El-Hakim. In speaking with the various customer relations and technical support people for each of the programs it became evident that the program with the most support, the best apparent accuracy, and the quickest learning curve for the associated cost was 3D-Builder. Additional support related to 3D-Builder was offered by Gerry Robertson (3D Construction Co.), who was at the leading edge of photogrammetry and affiliated with El-Hakim of NRC. There was also a desire from the Flight Research Lab (FRL) to set up a completely independent photogrammetry system and it was felt that 3D-Builder was the most economical way to proceed. Photomodeller was not employed because there was a lack of reference and lower accuracy, and the NRC program was not selected due to a lack of support from the FRL. The NRC program may have been the better route since it included an expert technical support person, target recognition, and calibration techniques appropriate to the set-up of the project. Figure 3.10 shows an example of the operating environment of 3D-Builder.

Figure 3.10 3D-Builder environment

To complete the 3D image analysis it was necessary to use a CAD package. The CAD package was used to construct 2D cross sections of the ice on the dome from the 3D models generated by 3D-Builder. Several packages were tried before the final one was found. A free demo version of a modelling program called Rhinoceros was found on the internet at www.rhinoceros.com. This program accepted 3D-Builder export file types and increased modelling capabilities by 2 orders of magnitude over previously tried programs including DynaCADD, CadKey, and I-DEAS. Figure 3.11 shows an example of the Rhinoceros operating environment with a model of the clean dome.

Figure 3.11 Rhinoceros Operating Environment

Another program that was employed for the data analysis was IDL (Interactive Data Language). IDL is a scientific computing environment that combines mathematics, data visualization, graphics, and a graphical user interface toolkit to analyze and visualize data. Its operating environment is similar to the C++ programming language and it utilises a fourth generation language for application programming. Its main use for this project was to analyse and plot the atmospheric data and to calculate and extract MVD and droplet size spectra information from the FSSP data. Several IDL routines which are included in Appendix B were written to process this information.

Lens calibration

Lens calibration was investigated and attempted but due to project time constraints and the order in which events occurred proper calibration of the lenses could not be achieved. The first attempt at calibrating the cameras was the manufacture of a calibration plate

(Figure 3.12). The plate consisted of 18 bolts carefully located in 3D space via CNC machine and Vernier caliper. See Appendix D for bolt head co-ordinates. Images of this plate (Figure 3.13) were used by EL-Hakim to determine the distortion parameters of the cameras and the actual camera locations. The results of this analysis were in error since the calculated camera locations were significantly different than the measured locations. Access to El-Hakim's calibration analysis was limited and thus, could not be properly checked. Also, this work was completed before the 3D-Builder software was chosen and the calibration was not compatible with 3D-Builder.

Figure 3.12 Calibration Plate

Figure 3.13 Stereo Pair of Calibration Plate

A final attempt at calibrating the lenses was made using the calibration charts provided by 3D-Builder. However, when the cameras were removed from the aircraft the lenses were rotated. Lens distortion occurs radially and tangentially so any movement of the lens relative to the CCD array changes the locations of distortion in the camera and eliminates any confidence in the calibration.

Accuracy estimates and Imaging Problems

Accuracy is dependent on several factors. First, camera quality plays a major role. Quality refers mainly to lens quality and camera resolution. Any distortion in the lens will contribute to errors since projections are not perfect. The lens calibration in 3D-Builder could have taken care of this problem had the lenses been properly calibrated. Camera resolution is partly responsible for the accuracy with which points can be calculated. The camera resolution was 768 by 494 pixels on a CCD array size of 6.54 mm by 4.89 mm. This resolution is far from that of a photograph but is reasonable for the size and cost of the camera. 3D-Builder allowed sub-pixel point placement so errors due to pixel size were somewhat dependent on the ability of the user to decide where the points should be located. Second, accuracy is affected by the accuracy of the location of control points. Measuring the location of the control points and cameras accurately was a problem since this had to be done with crude instruments after the cameras and dome were installed on the aircraft. Control point measurement was done to an accuracy of approximately $\pm 5\text{mm}$ which would introduce a shift in the position of the surfaces. This shift would be consistent from surface to surface but would introduce a small amount of error in the size and shape of the final 3D models. A third source of error was the process

by which images were collected. The ice images were first recorded on video tape and then captured in the computer from video. One problem with this was that any instability in the video image was recorded in the digital capture and introduced error into the analysis. This would not be a serious problem if the distortion was consistent from image to image. Unfortunately, this was not the case and every video capture was slightly different due to electrical interference and jitter from the video switcher. This introduced more error. The clean dome was digitally captured directly from the cameras to the computer. This was the best method for acquiring the images since the distortion was minimized by eliminating the video capture step. There was still, however, jitter from the video switcher and electrical systems on the aircraft. Another problem was that the video captures were recorded using 640 by 480 pixel arrays whereas the direct captures were recorded in 632 by 434 pixel arrays (Figure 3.14 shows an example of the difference).

Figure 3.14 Difference in pixel dimensions

These images cover the same real area but are recorded by a different pixel array size. The difference was accommodated by converting the video-captured images to the direct capture pixel dimensions of 632 by 434 pixels. The effect was to stretch and compress the image length and height respectively. Again, the images get distorted and there is no

way of confirming that the conversion is correct. The next source of error in the method is the lack of reference points. If the centre reference point had been clear of ice it may have been possible to reduce bias error. A few attempts were made to remedy this problem by cutting and pasting the corner and reference points of the clean dome images into the iced dome images to fix the reference points. This was unsuccessful since the pasted reference point ended up on the wrong side of the iced reference point which led to two conclusions. If the cut and paste was true, the clean reference point would be closer to the camera than the iced reference point. Knowing this not to be true, there had to be distortion between the images due to the video to digital to pixel size conversions and electrical interference from the video switcher and aircraft electrical systems. A final attempt at reducing the bias error was made using the direct digital captures of the iced dome. This eliminated the pixel size conversion distortion but not the video switcher and electrical interference distortion and no improvement in accuracy was gained. From the results, it was evident that the bias error was not consistent from surface to surface since, as will be seen later, the profiles overlap and were out of order relative to the time increments. It was also apparent that the profiles away from the centre of the dome were offset more than the profiles at the centre. This suggests any of the following; a non-uniform distortion in the conversion from video to digital and/or a non uniform distortion within the images and/or that the ice was building around the edges of the dome faster than it was at the centre. The accuracy of the models relative to one another was between 1:50 and 1:100 according to the accuracy approximation in the 3D Builder manual for uncalibrated, medium resolution cameras. This means that the error between the surfaces is up to $\pm 2.5\text{cm}$ in the direction of the air flow (Z direction) which was sufficient to

account for the physically impossible overlaps. The X, Y error was much smaller since the X and Y axes are oriented perpendicular to the direction of the cameras.

It was initially assumed that video data would be adequate for the 3D analysis, however, the combination of no camera calibration, lack of reference points, and electrical distortion of the images demonstrated that higher standards were required for this to work. Finally, there was some question about the selection of the points in the images during the process of calculating the 3D models. It cannot be known from the images whether the points were in fact on the surface of the ice. They could be trapped air that was below the ice surface. This was another possible source of error in the surfaces generated by 3D-Builder.

3D models were generated at two minute time intervals and there was a requirement to have separate solid models of each ice surface so they could be analysed in the CAD package. The individual models look reasonable but, as shown later, when the cross sections are extracted from the models and put together there was significant overlapping of the surface contours. This overlapping was so severe that entire ice surfaces end up behind the surface of the dome and out of order relative to the time increments.

Unfortunately, due the problems outlined above this difficulty was not solvable for the current experiment.

Chapter 4 RESULTS AND DISCUSSION

4.1 Initial calculations and studies

A previous study [3] indicated that there should be a 'shadow zone' on the upper surface of the fuselage where no water droplets enter and coalesce on the aircraft's surface.

Figure 4.1.1 shows this effect.

Figure 4.1.1 Shadow Zone

The results of the present experiment seem to disagree with the shadow zone theory. It was postulated that airflow from the propellers (prop wash) was washing over the fuselage and carrying water droplets with it. Assuming a 2 degree entrainment angle as the flow moves aft from the propellers it was estimated that the fuselage will begin to interfere at a distance of about 3 metres from the plane of the propellers (Figure 4.1.2). This suggests that the swirling flow in the propeller slipstream (Figure 4.1.2) must begin to flow laterally over the fuselage causing the ice accretions to be skewed to the right. The presence of the wing would inhibit the prop wash from circling and cause more lateral air flow over the fuselage. In addition, water and slush may be getting thrown or batted by the propellers into the region of the dome. The propeller has an electrical anti-icing system that switches every 15 seconds between 8 areas on the propellers [18]. This

means that the propellers would have been shedding ice or slush in icing conditions. It was noted that blotches of slush periodically appeared on the dome.

Figure 4.1.2 Propeller Slip Stream - Suggested explanation of skewed ice accretions and presence of moisture and slush blotches

Note: figures not to scale

Other sources of moisture blotches on the dome could be shedding from the various antennae and probes upstream of the installation. Turbulence and mixing with the free stream flow would cause water droplets to become entrained in the boundary layer and

impinge on the dome. All of this could explain the difference between the theoretical explanation of reference [3] and the behaviour observed in the present experiment.

An initial study assuming 100% impingement was completed to estimate how much ice could accrete in a set period of time if all of the water directly upstream of the dome impinged on it. Two cases were examined initially. The first case was for a LWC of 1g/m^3 over a 2 mile flight distance. In this case, 193 grams of ice would accrete. At an airspeed of 150 Knots this would take about 50 seconds to accrete. The second case was for a LWC of 0.25 g/m^3 over a 20 mile flight distance. In this case, 485 grams of ice would accrete. At an airspeed of 150 Knots this would take about 8 minutes to accrete. These LWC's were selected from the graph of LWC vs. horizontal extent in Appendix E.

From the images obtained in the experiment, ice was accreting on approximately 70 percent of the frontal area of the dome. For Case 2, if a 40 percent impingement rate is assumed on 70 percent of the dome area it would be possible to collect about 135 g of ice on an area approximately 12cm by 24cm. Using this, the ice on the dome would be about 5 mm thick for a LWC of 0.25 g/m^3 over 20 Nm. This analysis was completed for each case at the average LWC and speed over the case time to give an idea of the possible ice accretion and to compare with the ice accumulation cylinder accretion. Sample calculations are shown in Appendix E. Ice thickness for each case is presented in sections 4.3 through 4.11.

Another area of interest is the fact that the boundary layer at the dome would be deeper than the dome. This was examined using a flat plate boundary layer analysis (Figure 4.1.3).

Figure 4.1.3 Flat Plate Analysis of Boundary Layer Thickness

For a turbulent boundary layer the thickness can be estimated from :

$$\frac{\delta}{x} = \frac{0.16}{\text{Re}_x^{1/7}} \quad 4.1.1$$

which is valid for Reynolds numbers above 10^6 ,

δ is the boundary layer thickness, x is the distance along the plate, and Re is the Reynolds number which was found to be approximately 10^7 . Appendix E details this calculation. Equation 4.1.1 gives a boundary layer thickness, δ , for a flat plate to be about 16.6 cm deep at the dome location. Due to the fact that the various antennae upstream of the dome are introducing disturbances it is likely that the boundary layer would be even thicker and more turbulent causing unknown amounts of water entrainment. Considering that the dome is only 15 cm high it is probably completely immersed in the boundary layer. Detailed analysis of this region would be very difficult due to the complex configuration of antennae in the upstream flow and due to the effects that the propellers introduce to the flow.

4.2 *Images of the Clean Dome*

Figure 4.2.1 Clean dome with tape grid for 3D Builder analysis

The images of the clean dome (example Figure 4.2.1) were captured directly to the computer on the aircraft so the errors due to the video capture were not present. Also, the images were captured with the aircraft electrics off and the other cameras eliminated from the sequence for the video switcher. This eliminated most of the distortion due to electrical interference. Note the cleanness of the image edges relative to later images that were captured from the video tapes. Lack of camera calibration and accuracy in the measured co-ordinates of the reference points and cameras still exist. The results of the 3D analysis were fairly good and were in good agreement with the actual dome shape and size. Figure 4.2.2 shows a view of the 3D model of the clean dome.

Figure 4.2.2 Result of clean dome analysis with 3D-Builder and Rhino

4.3 Case 1 - Flight C-715

Figure 4.3.1 Iced dome of case C-715

This flight was conducted before the reference points were added and after use of the laser had been discontinued. The skewed ice formation, presumably due to propeller slipstream is quite pronounced. No digital images were captured in flight. The ice was well defined around the edges of the dome in these images. From the video it appears that the white portions of ice were not bonded to the surface of the dome. Total time approx. 12 min

Averages:

Altitude	8000ft
Airspeed	100m/s
Static Temperature	-12 °C
LWC	0.4g/m ³
TWC	0.5g/m ³
MVD	20µm

-Calculated ice thickness assuming 40% impingement on 70% of the area: 11.5mm

4.4 Case 2 - Flight C-719

Figure 4.4.1 Iced dome of case C-719

This flight was also conducted before the reference points were added. Ice formation was poorly defined but looked thick around the outer edges of the dome. No pictures were digitally captured in flight. At 21:41 GMT during this flight, the ELT antenna had accreted enough ice to fall into the field of view of the cameras. At this point it had about 1cm of ice built around it. At 21:45 GMT, the ELT antenna was gone.

Total time approx. 11 min

Averages:

Altitude	4250ft
Airspeed	100m/s
Static Temperature	-3.5°C
LWC	0.25g/m ³
TWC	0.27g/m ³
MVD	23µm

-Calculated ice thickness assuming 40% impingement on 70% of the area: 6.6mm

4.5 Case 3 - Flight C-721

Figure 4.5.1 Iced dome of case C-721

No reference points were available on this flight as well. Good definition in images. No digital images were captured during the case. Skewed ice formation was pronounced.

Total time approx. 15 min

Averages:

Altitude	5000ft
Airspeed	97m/s
Static Temperature	-6.5°C
LWC	0.15g/m ³
TWC	0.17g/m ³
MVD	19µm

-Calculated ice thickness assuming 40% impingement on 70% of the area: 5.2mm

4.6 Case 4 - Flight C-722 case A

Figure 4.6.1 Icing Accumulation Cylinder of case C-722a

Figure 4.6.2 Iced dome of case C-722a

No reference points. Reasonable definition in images. Digital image captures at 20:36, and 21:08 GMT. Skewed ice formation. Total time approx. 22 min

Averages:

Altitude	10000ft
Airspeed	100m/s
Static Temperature	-15 °C
LWC	0.15g/m ³
TWC	0.15g/m ³
MVD	35µm

- Calculated ice thickness assuming 40% impingement on 70% of the area: 8.0mm
- Ice thickness on IAC approximately: 25mm

4.7 Case 5 Flight C-722 case B

Figure 4.7.1 Icing Accumulation Cylinder of case C-722b

Figure 4.7.2 Iced dome of case C-722b

No reference points. Good definition in images. Digital image capture at 21:44. Skewed ice formation. Total time approx. 22 min

Averages:

Altitude	7000ft
Airspeed	100m/s
Static Temperature	-9°C
LWC	0.15g/m ³
TWC	0.15g/m ³
MVD	35µm

- Calculated ice thickness assuming 40% impingement on 70% of the area: 8mm
- Ice thickness on IAC approximately: 20mm

4.8 Case 6 - Flight C-723 case A

Figure 4.8.1 Icing Accumulation Cylinder of case C-723a

Figure 4.8.2 Iced dome of case C-723a

No reference points. Good definition in images. Digital image captures at 21:05, 21:15, and 21:20 GMT. Skewed ice formation. Total time approx. 10 min

Averages:

Altitude	2500ft
Airspeed	80m/s
Static Temperature	-6 °C
LWC	0.25g/m ³
TWC	0.3g/m ³
MVD	15μm
α	1.5°
β	0.5°

- Calculated ice thickness assuming 40% impingement on 70% of the area: 4.8mm
- Ice thickness on IAC approximately: 25mm

4.9 Case 7 - Flight C-723 case B

Figure 4.9.1 Icing Accumulation Cylinder of case C-723b

Figure 4.9.2 Iced dome of case C-723b

No reference points. Good definition in images. Digital image captures at 21:37, 21:40, and 22:06 GMT. Skewed ice formation not as pronounced. Total time approx. 10 min.

Averages:

Altitude	2500ft
Airspeed	80m/s
Static Temperature	-6°C
LWC	0.3g/m ³
TWC	0.35g/m ³
MVD	13μm
α	1.5°
β	0.5°

- Calculated ice thickness assuming 40% impingement on 70% of the area: 5.8mm
- Ice thickness on IAC approximately: 10mm

4.10 Case 8 - Flight C-725

Figure 4.10.1 Icing Accumulation Cylinder of case C-725

Figure 4.10.2 Iced dome of case C-725

Reference points present. Good image definition. Digital image capture at 14:01 GMT.

Skewed ice formation. Total time approx. 12 min

Averages:

Altitude	9500ft
Airspeed	105m/s
Static Temperature	-8 °C
LWC	0.35g/m ³
TWC	0.35g/m ³
MVD	20µm
AOA	2.5°
SSA	0.25°

-Calculated ice thickness assuming 40% impingement on 70% of the area: 10.6mm

-Ice thickness on IAC approximately: 20mm

Figure 4.10.3 C-725-1 Ice model at 14:07:35

Figure 4.10.4 C-725-2 C-725-3 Ice model at 14:04:22

Figure 4.10.5 C-725-3 Ice model at 14:01:34

Figure 4.10.6 C-725-4 Ice model at 13:58:21

Figure 4.10.7 C-725-5 Ice model at 13:56:03

These models (Figures 4.10.3 to 4.10.7) are ordered in sequence from the end of the icing case to the start of the icing case. It is evident from these images that the ice models are not accurately located since parts of the ice surfaces are behind the dome and there appears to be more ice on earlier models than on later models. This effect can also be seen in the 2D cross sections of Figure 4.10.8 below.

Figure 4.10.8 C-725 2D cross sections from analysis with 3D-Builder and Rhino

The above sections were taken at 25 mm intervals across the dome. The cross sections for the profiles in 3 are taken from the centreline of the dome.

Colour index:		Time of image capture
red	C725-1	14:07:35
purple	C725-2	14:04:22
blue	C-725-3	14:01:34
green	C-725-4	13:58:21
yellow	C-725-5	13:56:03
black	clean dome	

Images for the analysis of this case were captured from the video recordings taken during the flight.

4.11 Case 9 - Flight C-726

Figure 4.11.1 Icing Accumulation Cylinder of case C-726

Figure 4.11.2 Iced dome of case C-726

Reference points present. Good image definition. Digital image capture at 21:57 GMT.

Total time approx. 26 min

Averages:

Altitude	4300ft
Airspeed	101m/s
Static Temperature	-6.5
LWC	0.18g/m ³
TWC	0.2g/m ³
MVD	15μm
α	1.25°
β	0.75°

-Calculated ice thickness assuming 40% impingement on 70% of the area: 11.3mm

-Ice thickness on IAC approximately: 25mm

4.11 Discussion of Results

It is apparent from the flight images that there was some inconsistency between the direct digital captures of the clean dome and the video captures of the icing cases. This inconsistency is most evident in the bottom right corner of the images and is present for all of the icing cases. Comparison of Note 1 on Figure 4.3.1 and Note 2 on Figure 4.2.1 shows one difference between the direct digital captures and the video digital captures.

Post flight inspection revealed that the most ice was built up on the front most section of the dome (see Note 3 on Figure 4.3.1). This was also evident from the fact that this was the last area to melt when the aircraft exited the clouds to de-ice. In most images this area was not well defined by ice discontinuities.

The ice accretion on the IAC appears to be about three times as much as that on the dome in most of the cases. It would be interesting to see what the results would be if the upstream fuselage was clear of antennae and the effect of the propellers was eliminated.

Cases C-725 and C-726 were the only cases that could be analysed with 3D Builder since the other cases did not contain the required reference points. Cases C-723a and C-723b each had 3 direct image captures during the accretion period that were between 3 and 6 minutes apart. If these cases had contained the reference points necessary for the 3D analysis they could have been examined. Case C-725 was selected as the initial case for analysis and was used to try to solve the aforementioned imaging problems.

Unfortunately, these problems could not be solved with the available analysis tools.

For case C-725 the results show that there is a significant error in the image data. The overlapping surfaces are not physically possible especially the ones that are mostly behind the dome.

Airspeed, static temperature, LWC, TWC, MVD, α , and β were recorded for every second of the flights. α and β were only obtained for flights C-725 and C-726. Appendix F contains the data relevant to each case in graphical format.

Chapter 5 RECOMENDATIONS FOR FUTURE PROJECTS

5.1 Suggestions for the improvement of results

Project time constraints and ambiguous information about the location of the experiment at the beginning of the project resulted in difficulties, at the time, in determining exactly how to proceed. In future icing experiments utilising this method it is strongly recommended that the specific photogrammetry software be studied before the experiment is carried out. The photogrammetry software for this project was acquired after the cameras and dome were installed on the aircraft and after most of the flights had been conducted. A clear understanding of the software requirements would have made it possible to add the necessary control points. It would not have made it clear that electrical distortion was a problem until the 3D analysis was complete. However, pre-flight testing of the system as installed on the aircraft would probably have identified this problem. Such pre-flight testing is recommended.

Understanding the operation of the photogrammetry software is essential for proper camera calibration as well. All of the photogrammetry programs explored included a calibration procedure which could easily have been employed if the program had been available before the experiment had been conducted. Camera calibration should be carefully planned at the start of the project to ensure that it can be properly carried out. Camera parameters should also be carefully documented.

One problem with the project was the lack of ability to accurately measure the location of the control points and cameras. Higher quality measuring devices would improve this situation. The calibration plate images were a solution for this since the calibration points were located accurately via CNC machine. If the various inconsistent distortions in image processing had not been present the calibration points could have been used with the iced dome images to give accurate reference points and camera locations. It is also important for control points to be kept clean of ice in order for them to maintain the same co-ordinates in each captured image. Accurate control points would allow the photogrammetry software to more accurately locate the surfaces and points relative to one another.

Areas for accuracy improvement with respect to the camera set-up include the use of more than two cameras, optimal camera placement and image overlap, proper camera calibration, and the use of higher resolution cameras. The use of more than two cameras means that the images could focus on a smaller area of the dome allowing a more direct view of the dome so that outlying points in the images would be subject to less pronounced errors. Multiple cameras would also allow more distance calculations to be made for the same point and thus better accuracy. Cameras should be pointed at angles which cover the approximate range of curvature of the surface being recorded. This would minimize errors in the ice thickness. Proper calibration of the camera lenses is necessary to compensate for irregularities in the lens shape. This must be done with the camera configuration that is used for the experiment.

Distortions due to electrical interference is a problem that was not realized until the end of the project. This interference may be partially eliminated by using a stabilized power source. Elimination of electrical interference from aircraft systems and the video switcher could also be accomplished by using high quality still cameras instead of video cameras. Extreme care would have to be taken in developing the images to avoid other distortions. The use of still cameras would also greatly improve image resolution. One problem with still cameras is that high quality cameras and lenses tend to be much larger than is practical for projects like this where space is limited. If video cameras are used, precautions should be taken to minimize the effect of external electrical devices. One improvement would be to capture all of the images directly from the cameras to the computer. It would be useful to automate this procedure since manual image capturing requires a dedicated crew member. In order to get a complete time history of each icing case it would be necessary to constantly collect digital images at a set frequency throughout the flight. Memory requirements for image capturing would be a major factor in the implementation of this option. The use of compressed image formats should be used to minimize the required memory storage. Another improvement would be to eliminate the video switcher and have a completely independent system from the other experiments.

Finally, in order to get a better idea of what the flow is doing during flight it might be useful to implement a simple weather vane in the view of the cameras. Still cameras would not be of much use for this idea but a secondary video system could be used for qualitative analysis to see approximate icing rates and flow characteristics.

5.2 Proposed method for future experiments

The following list details in sequential order, the proposed procedure for obtaining accurate 3D models that can be used to compare with CFD analysis.

1. Select photogrammetry software and understand its requirements and operation. Also, select compatible auxiliary software (ie. CAD packages and image visualization software) for model analysis and manipulation.
2. Determine what equipment (ie. cameras, lenses, computers) will be used to collect the images based on resolution, size, accuracy, and cost.
3. Determine what and how atmospheric and aircraft performance parameters will be recorded so that the data can be used for CFD analysis.
4. Determine how the images will be processed and the associated image processing errors.
5. Calibrate cameras in accordance with selected photogrammetry software (ie. use of calibration charts or calibration plate, and use of camera/lens configuration for the experiment).
6. Determine location of experiment (the earlier this is done the better).
7. Design camera configuration, mounts, fairings, and electrical installation based on location and photogrammetry requirements.
8. Construct camera mounts, fairings, and electrical installation.
9. Install the equipment and test the overall system by recording and processing images of simulated ice accretions.

10. Conduct icing flights and collect images.
11. Analyse image data to construct 3D models and extract 2D ice accretion profiles.

5.3 Possible Future work

One of the original plans of the project was to provide Concordia University with the flight data to see if the photogrammetry results could be matched by CFD results. The idea was to provide all flight data except for the video images and photogrammetry results until the CFD analysis was complete. This would have provided an unbiased result for comparison. Since the photogrammetry results were not as successful as hoped this comparison will have to be made from future experiments of this nature.

If a reasonable size database is to be constructed more icing experiments are necessary. The experiments should be carried out on areas of the aircraft where the flow is undisturbed. If more icing tests are done, this thesis can serve as a guide for setting up the experiment and reducing errors in the results.

Chapter 6 CONCLUSIONS

Although the results are not as accurate and complete as hoped, some important lessons were learned:

- The photogrammetry method of this experiment and the routines developed for analyzing FSSP data can be applied to future in-flight ice accretion experiments.
- The major solutions for the errors are the use of several well defined reference points and co-ordinate axes, and consistent image capturing and processing methods.
- Proper calibration of the cameras is very important. With proper calibration and consistent image processing it would be theoretically possible to get accuracy up to 1:3000 with 3D Builder.
- The use of digital video cameras is convenient but good quality, high resolution cameras are essential for accurate photogrammetric analysis. Direct digital capture of the digital camera output appears to be essential.
- In future experiments the body or surface on which ice accretion is to be recorded should be located where the approaching flow is as little disturbed as possible
- The ice thickness on the icing accumulation cylinder appears to be about three times as much as that for the calculations of possible ice thickness on the dome. This implies any of the following: the assumed impingement rate is too small, or the different configuration causes a lower impingement rate, or the ice formations are of different densities, or there is some truth to the tendency for a shadow zone on top of the fuselage.

Considering the combination of errors in the method and the lack of experience with photogrammetry the results were surprisingly close to being successful. In order to get reasonable results the 3D analysis has to be improved as outlined above. For this project an accuracy of 1:1000 or $\pm 1\text{mm}$ would be acceptable.

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Appendices

Appendix A

Flight Data

Appendix A

best cases	located on:		ranked	AES data times		NRC data times (GMT)
C715	tape 1	12 min	3	20:00:00	20:12:00	7553 to 8273 (64447)
C721	tape 2 & 3	15 min	4			
C722	tape 1	34 min	5			
C723	tape 1	11 min	1	21:09:00	21:22:20	6433 to 7233 (69707)
C723	tape 2	10 min	2	21:33:30	21:44:00	7903 to 8533 (69707)
C725	tape 1	35 min	7	13:52:18	15:25:00	171 to 2133 (49767)
C726	tape 2	26 min	6	21:25:00	21:41:01	4254 to 5215 (72846)

NOTE: Times are the difference between the start of the flight (number in brackets) and the start of the icing case. Data records start at t=0

Flight C715

Time	Altitude (feet ASL)	OAT (deg C)	IAT (deg C)	IAS (knots)	GS (knots)	Comments
20:00:50	7774	-11.1	-5.7	201	186	climbing
20:03:02	9291	-7.4	-2	205	201	turning on top of clouds
20:04:00	9039	-7.4	-1.9	206	188	descending through clouds
20:05:00	8647	-13.2	-7.5	207	198	
20:06:00	8558	-12.8	-7.7	197	180	
20:06:58	8532	-12.8	-8	192	176	building very nicely
20:07:58	8551	-12.7	-7.8	194	177	
20:08:56	8558	-12.8	-7.8	196	183	
20:09:55	8549	-12.8	-7.9	194	181	
20:10:54	8543	-12.7	-8	191	174	ice broke off
20:11:53	7632	-11.2	-3.3	245	232	

Extra Comments

no control points
no digitally captured images
ice defined very well
white portions of ice don't seem to be attached/bonded to the dome
total time approx. 12 min.

Flight C719

Time	Altitude (feet ASL)	OAT (deg C)	IAT (deg C)	IAS (knots)	GS (knots)	Comments
20:33:02	4302	-3.3	1.6	195	191	ice on icing rod, no noticeable ice on dome
20:35:00	4297	-3.1	1.7	192	188	water streaming on front window
20:39:00	4294	-2.9	1.8	191	187	some ice around outer edge of dome
20:42:09	5666	-4	0.3	181	174	ice building around outer edge of dome
20:43:38	7178	-6.4	-1.5	192	190	

Extra Comments

no control points
no digitally captured images
ice defined poorly
significant ice around outer edge of dome

Flight C721 tape 1

Time	Altitude (feet ASL)	OAT (deg C)	IAT (deg C)	IAS (knots)	GS (knots)	Comments
14:19:45	4530	-7.8	-3.4	185	183	
14:24:33	5092	-8.7	-4.2	186	178	building
14:27:32	5080	-9.1	-4.6	185	182	
14:31:11	5817	-8.1	-3.5	189	184	out of cloud
14:32:20	6070	-5.3	0	203	209	ice melting
14:34:21	5568	-4.8	0.5	203	207	going back in cloud
14:35:58	4424	-7.1	-2.2	194	198	building again
14:38:44	4197	-6.1	-1.3	192	196	
14:40:45	5801	-6.6	-2.3	183	188	out of cloud
14:43:04	4856	-7.1	-2.2	193	202	incloud
14:49:15	5473	-7.3	-2.5	191	198	ice breaks off
						ice melting
15:38:00	7997	-2.3	3.8			can see ice separating from dome water streaming out from under ice.

Extra comments

no control points

Appendix A

Flight C721 tape 2

Time	Altitude (feet ASL)	OAT (deg C)	IAT (deg C)	IAS (knots)	GS (knots)	Comments
17:08:32	5505	-7.8	-1.9	212	203	ice building
17:10:23	4434	-6.5	-1.1	202	189	raydome not clear
17:13:49	3421	-4.6	-0.2	184	172	
17:14:18	3814	-5.8	-1.1	190	178	ice separating
17:16:18	5056	-9.4	-4.8	187	174	breaking through cloud top
17:19:30	5071	-9.9	-5.1	190	180	building
17:21:07	5076	-10	-5.3	191	178	building
17:22:15	5601	-6.7	-2.1	188	175	out of cloud
17:22:56	5107	-6.4	-1.9	186	188	fairly good picture, ice starting to melt
17:25:39	4451	-8.6	-3.8	191	197	ice building again
17:29:48	4494	-7.8	-3.4	183	183	ice going slowly
17:38:40	4603	-6.8	-2.2	188	191	
17:42:47	4954	-6.4	-2.1	182	181	building?
17:43:56	5057	-6.7	-2	190	190	fairly well defined
17:45:44	5072	-6.7	-2	191	188	building
17:50:19	4878	-5.3	-0.5	193	188	"
17:53:20	6159	-8	-3.4	188	176	"
17:54:05	6768	-5.4	-0.7	190	176	out of cloud, melting
17:54:52	6357	-8.8	-4	192	181	back in cloud, building
18:02:30	6612	-4.7	-2	185	171	out of cloud, melting
Extra comments						
no control points						
good definition						
digital pictures?						

very
nice

Flight C722

Time	Altitude (feet ASL)	OAT (deg C)	IAT (deg C)	IAS (knots)	GS (knots)	Comments
20:18:53	9110	-11.4	-7.5	152	179	
20:21:15	10254	-12.9	-8.9	220	149	
20:36:41	8778	-10.9	-6.4	120	166	little change, more ice on probe
20:38:00	8763	-11	-6.5	123	168	building
20:40:00	9210	-12.3		156		"
20:40:54	9208	-12.4	-8.3	156	159	large ice particles
20:42:45	9250	-12.2	-7.9	158	163	moderate drizzle
20:46:01	10489	-14.5	-10.3	213	162	not much water
20:47:00	11464	-15.7		267		smaller drops have higher LWC
20:48:34	12000	-16.7		293		
20:49:00	12191	-16.7		293		buliding, clear sky
20:52:00	12160	-17.3		289		clear sky
21:02:00	8585	-10.8		80	168	building
21:04:00	7023	-7.7		-2	161	"
21:06:00	4756	-3.9		-2	150	cracking
21:11:00	4203	-3.7		-2	163	more craking
21:15:00	7120	-7.5		-2	157	clear
21:19:00	10862	-14.9		279	162	clear
21:20:08	11205	-15.1	-10.8	291	163	clear, good picture
21:21:00	10945	-15.2		281	230	clear
Extra comments						
no control points						

best
"

Appendix A

Flight C723

Time	Altitude (feet ASL)	OAT (deg C)	IAT (deg C)	IAS (knots)	GS (knots)	Comments
20:56:36	2927	-7.7	-3.8	183	170	
20:58:53	2901	-6.6	-4.1	161	138	
21:01:11	2317	-5.7	-2.9	165	147	
21:04:23	2796	-6.7	-3.1	178	166	
21:06:40	3043	-0.2	3.8	199	181	melting
21:08:58	2866	-6.5	-2.1	201	185	nearly gone
21:10:45	2778	-5.5	-2	183	165	building
21:12:39	2743	-6.2	-3.4	167	1533	"
21:14:26	2512	-6	-3	168	160	building fast!
21:15:49	1900	-4.6	-2.4	143	136	
21:16:44	1718	-4.3	-2.1	143	136	lots of ice on probe
21:17:41	1710	-4.3	-2.3	141	131	
21:18:33	1728	-4.5	-2.2	148	139	
21:19:28	2613	-6.4	-2.3	191	182	climbing to gear ice
21:20:27	2984	-4.5	0.1	207	194	
21:21:22	3329	-2	1.6	188	179	melting
21:22:18	3977	1.9	6	190	192	splattery
21:33:43	2816	-6.3	-3.2	172	161	fairly clam
21:35:32	2791	-6.4	-3.8	161	138	
21:36:57	2496	-5.8	-3.1	164	148	building fast
21:38:13	1908	-4.7	-2.6	142	132	climbing spiral
21:39:41	1726	-4.2	-2	147	137	
21:41:04	2295	-5.7	-2.6	166	156	
21:41:59	3227	-1.1	3.1	194	177	splattery
21:42:29	3837	1.6	5.8	193	172	melting
21:43:51	6017	0.6	4.7	191	183	"
21:44:43	6095	0.6	6.6	223	222	"
21:46:05	6090	0.7	6.6	225	220	"
Extra comments						
no control points						

Flight C725

Time	Altitude (feet ASL)	OAT (deg C)	IAT (deg C)	IAS (knots)	GS (knots)	Comments
13:52:18	9626	-7.2	-2.9	214	225	clear
13:54:11	9662	-7.9	-3	215	223	
13:56:29	9602	-7.8	-3	210	217	dotted - blotchy
13:58:22	9608	-7.4	-2.9	208	216	
14:00:37	9609	-7.5	-2.9	206	212	building
14:02:57	9609	-6.5	-2.1	205	211	
14:04:49	10421	-7.6	-2.9	203	213	
14:06:40	11540	-9.5	-3.7	231	237	
14:08:32	12501	-11.1	-6.3	215	214	O.K. definition
14:10:48	14029	-14.4	-9.6	213	213	
14:12:40	15079	-16.1	-11.3	217	217	
14:14:31	15608	-17.2	-12.4	216	218	constant
14:16:58	15143	-16.3	-11.5	213	218	
14:18:41	13477	-13	-8.4	208	213	
14:20:59	11576	-9.4	-4.9	204	214	
14:23:17	9890	-6.2	-1.6	207	206	melting
14:27:28	6670	-1.9	2.5	202	198	"
Extra comments						
control points present but not adequately defined						

Appendix A

Flight C726

	Time	Altitude (feet ASL)	OAT (deg C)	IAT (deg C)	IAS (knots)	GS (knots)	Comments
26 min	21:23:44	4253	-6.6	-2.2	210	194	
	21:25:36	4220	-6.3	-1.6	211	204	building
	21:27:55	4214	-5.9	-1.3	210	203	
	21:29:45	4240	-4.8	-0.1	213	202	
	21:31:36	4250	-5.2	-0.6	212	201	slow
	21:33:56	4263	-6	-1.6	210	202	
	21:35:46	4244	-6.5	-1.9	212	201	
	21:37:36	4260	-6	-1.3	213	200	
	21:39:56	4178	-5.6	-1.1	210	199	faster
	21:41:46	4393	-5.8	-1.1	203	188	
	21:43:36	4560	-5.5	-0.9	214	195	
	21:45:56	6400	-8.2	-3.6	205	196	
	21:47:46	7368	-9.1	-3.6	222	226	constant
	21:49:36	6926	-8.5	-3.4	218	214	clear
	21:51:56	6343	-7.7	-2.8	216	219	
	21:53:46	6363	-7.5	-2.7	214	219	probe full of ice - 5 cm
	21:55:11	6393	-7.4	-2.6	216	224	ice breaking off
	21:57:55	4765	-5	-0.7	200	208	
	21:59:47	3379	-2.8	1.1	196	205	
	22:01:38	3369	-2	0.9	195	165	
	22:04:22	2430	-0.9	2	169	125	melting
Extra comments							
control points present but not adequately defined							

Appendix B

IDL Routines

Appendix B mvdplot.pro

C:\RSI\TDL51\lib\cfdel\mvdplot.pro

Page 1

```

pro mvdplot, fileid, med, ar, x5, x4, y4, x2, y2, x, y

;takes FSSP 96 and 124 concentration data and interpolates to one micron
;then calculates MVD for every second of the flight

5  ;med = array of MVD for every second of flight
   ;ar = data file of test case
   ;x4, y4 = data from both FSSP's sorted into ascending order
   ;x2, y2 = interpolated data
10  ;x, y = unsorted data from both FSSP's

   ;print, 'enter file to load in quotations'
   ;read, fileid
   ;openr, unitno, fileid, /get_lun

15  fordk, 61, rw, ar, fileid

   x=fltarr(30)                ;define array to store x coordinates of data
   y=fltarr(30)                ;define array to store y coordinates of data
   r=findgen(15)+1.0           ;define incrementing array for manipulation of x
20  x(0:14)=(x(0:14)+3.0)*r+0.5 ;x axis divisions for F96 data
   x(15:29)=(x(15:29)+6.0)*r+2.0 ;x axis divisions for F124 data
   x2=findgen(880)/10.+4.0     ;array to store the interpolated data
   x3=sort(x)                  ;sort data so that spakim interpolates properly
25  x4=x(sort(x))               ;array to define time axis
   x5=findgen(rw)
   med=fltarr(rw)

   for k=0, rw-1 do begin      ;repeat for every second of the case

30  y(0:14)=ar(26:40,k)/3.0     ;F96 probe data / 3 micron bandwidth (normalized)
   y(15:29)=ar(45:59,k)/6.0    ;F124 probe data / 6 micron bandwidth (normalized)

   y4=y(x3)                    ;sort data so that spakim interpolates properly

35  ytot=total(y)               ;eliminate any rows that contain only zeros
   if ytot le 0 then begin      ;since spakim cannot handle them
     med(k)=0.                  ;set MVD to 0
     goto, nill
40  endif

   spakim, x4, y4, x2, y2       ;call to interpolation procedure SPAKIM

   y3=fltarr(880)+y2*x2^3       ;calculate mass in each particle size & store in y3
45  totmass=total(y3)           ;find the total mass of the sample

   half=0                       ;initialize variable

   for n=0., 879. do begin      ;search for the median volume diameter
50  half=half+y3(n)
   if (half gt totmass/2) then begin ;to find MedianVD, calculate total mass and
     medvd=n/10.+4.             ;divide it in half. MVD=value at half
     goto, found
   endif
55  endfor
   found: med(k)=medvd           ;store medvd in array med
   nill:
   endfor

60  return

end

```

C:\RST\IDL51\lib\cfdel\spectra.pro

Page 1

```

pro spectra, fileid, data, rw

;takes FSSP 96 and 124 concentration data and interpolates to one micron
;then plots the data on a 3-D scale for every second of the flight
5 ;xaxis=size, yaxis=concentration, zaxis=time

;med = array of MVD for every second of flight
;ar = data file of test case
;x4,y4 = data from both FSSP's sorted into ascending order
10 ;x2,y2 = interpolated data
;x,y = unsorted data from both FSSP's

;print, 'enter file to load in quotations'
;read, fileid
15 ;openr, unitno, fileid, /get_lun

fordk, 61, rw, ar, fileid

20 x=fltarr(30) ;define array to store x coordinates of data
y=fltarr(30) ;define array to store y coordinates of data
r=findgen(15)+1.0 ;define incrementing array for manipulation of x
x(0:14)=(x(0:14)+3.0)*r+0.5 ;x axis divisions for F96 data
x(15:29)=(x(15:29)+6.0)*r+2.0 ;x axis divisions for F124 data
x2=findgen(88)+4.0 ;array to store the interpolated data
25 x3=sort(x) ;sort data so that spakim interpolates properly
x4=x(sort(x))

data=fltarr(88, rw)

30 for k=0, rw-1 do begin ;repeat for every second of the case
y(0:14)=ar(26:40, k)/3.0 ;F96 probe data / 3 micron bandwidth (normalized)
y(15:29)=ar(45:59, k)/6.0 ;F124 probe data / 6 micron bandwidth (normalized)
35 y4=y(x3) ;sort data so that spakim interpolates properly

ytot=total(y) ;eliminate any rows that contain only zeros
if ytot eq 0 then begin ;since spakim cannot handle them
40 data(*, k)=0 ;set array elements to 0
goto, nill
endif

spakim, x4, y4, x2, y2 ;call to interpolation procedure SPAKIM
45 for f=0.87 do begin
data(*, k)=y2*4/3*3.14159*((x2(f)/2/10000)^3)*1000000 ;g/cm^3*10^6 create array of data
endfor
nill:
endfor
50 return

end

55

```

C:\RS1\IDL51\lib\cfde3\spakim.pro

Page 1

```

pro spakim,x,y,xout,yout,incol,outcol,help=help
; the ultimate in Akima splines for array type data
; can handle several columns at a time as well as the simple
; vector inputs. This procedure locates the bracketing nodes for the spline
5 ; using the HUNT procedure. It stores the bracketing positions for
; subsequent calls if multicolumn splines are requested thus speeding
; up the process considerably
; On Input:
;   X: vector or column of independent variables to be used as nodes for
10 ;   the spline process
;   Y: vector, column or array of dependent values to be fitted to akima
;   splines. If an array is specified then INCOL must be given as well
; XOUT: interpolation locations at which ordinate values are to be
;   determined using the splines
15 ;
; Extra Inputs: (y=array case)
; INCOL: (not optional for this case) a vector of column positions in Y containing the dependent n
; values to be fit separately by spline routine
; OUTCOL: (optional) allows user to specify the order in which the
20 ;   interpolated columns are to be written into YOUT
;
; On output:
;   YOUT: interpolation result. Form will depend of the structure of the
;   inputs
25 ;
; Written by Malcolm Davidson
;   NRC Summer Student
;   10/07/1990
;
; This version for WAVE 3.03 D.M. 18-feb-1991
30 ;
; Test structure of input parameters
if keyword_set (help) then begin
  print, 'usage:spakim,x,y,xout,yout,incol,outcol,help,=help'
  return
35 endif

dimx=size(x)
dimy=size(y)
dimxo=size(xout)
inputs=n_params(dum)
if inputs ge 5 then begin
  outstr=size(incol)
  ncol=outstr(1)
  if inputs eq 6 then begin
    if max(outcol) gt ncol-1 then begin
      print, 'Dimensions of output array exceeded by OUTCOL vector'
      goto, endlbl
    endif
  endif
50   if inputs eq 5 then outcol=indgen(ncol)
endif
fl=0
if (dimx(0) eq 2) and (dimx(1) eq 1) then fl=1
if (dimx(0) eq 1) and (dimx(1) ge 5) then fl=1
55 if fl eq 0 then begin
  print, 'Wrong input structure for independent variable x'
  goto, endlbl
endif
60 fl=0
;test for IDL following 5 lines of conditional logic disabled
;if (dimxo(0) eq 2) and (dimxo(1) eq 1) then fl=1
;if (dimxo(0) eq 1) and (dimxo(1) ge 5) then fl=1
;if fl eq 0 then begin
65 ; print, 'Wrong input structure for independent variable xout'
; goto, endlbl
;endif
fl=0
if (dimy(0) eq 2) and (dimy(1) eq 1) then fl=1
if (dimy(0) eq 1) and (dimy(1) gt 5) then fl=1
70 if (dimy(0) eq 2) and (dimy(1) gt 1) then fl=2
if fl eq 0 then begin
  print, 'Wrong input structure for dependent variables y'
  goto, endlbl
75 endif
if fl eq 2 and ((inputs le 4) or (inputs ge 6)) then begin

```

```

        print, 'Not enough parameters on procedure call'
        goto, endbl1
    endif
80    ;
    ; perform calls to spakim routine
    ; if simple (1D) inputs
    common xdiff,xx,position,pasnb
    if fl eq 1 then begin
85        pasnb=0
        spak,x,y,xout,yout
    ;
    ; otherwise set up multiple calls to spakim
    endif else begin
90    print, 'Starting the Akima spline for multiple rows/columns'
    ; common block to store x intervals and positions for subsequent calls
    ; common xdiff,xx,position,pasnb
    yout=fltarr(ncol,max(dimxo(1:2)))
    fl=1
95    for i=0, ncol-1 do begin
        pasnb=i
        ; select column position for INCOL list
        colnb=incol(i)
        spak,x,y(colnb,*),xout,ytemp
100    ; select output column from OUTCOL list
        colex,ytemp,yout,outcol(i)
    endfor
    endelse
endbl1:
105    return
end
;
;
;
110    pro spak,x,y,xout,yout
    ; procedure to do an AKIMA spline. Especially suited for for the SPAKIM
    ; routine since it stores the intermediate results in a common block
    ; which speeds up the process if many calls with the same X and XOUT
    ; abscissa are made. Works as a stand alone procedure as well with the
115    ; usual simple inputs
    ; On Input:
    ;   X: vector or column of independent variables to be used as nodes for
    ;       the spline process
    ;   Y: vector, column of dependent values to be fitted to akima
120    ;   splines.
    ; XOUT: interpolation locations at which ordinate values are to be
    ;       determined using the splines
    ; On output:
    ; YOUT: vector of interpolated ordinate values using the spline procedure
125    ; Common block:
    ; in order to use the common block feature (optional) the calling level must
    ; declare a common block called XDIFF. This is done through the statement
    ;   COMMON XDIFF,(variable for x intervals),(variable for XOUT
    ;   positions), PASNB (variable that tells the procedure wether to
130    ;   reevaluate the intermediate steps)
    ; in order to save time on subsequent calls, the variable PASSNB should
    ; be incremented to a value greated than zero. Set PASNB eq 0 if you
    ; want the intermediate steps reevaluated
    ;
135    ; code by MD summer 1990
    ; updated for WAVE ver 3.03 by DM 18-Feb-1991
    ;
    common xdiff,xr,ps,pasnb
    ccount=01
140    if n_elements(pasnb) eq 0 then pasnb=0
    dims=size(x)
    if dims(0) eq 2 then n=max(dims(1:2)) else n=dims(1)
    dims=size(xout)
    if dims(0) eq 2 then n2=max(dims(1:2)) else n2=dims(1)
145    t=fltarr(n)
    wrkvec=fltarr(n)
    yout=xout
    if pasnb eq 0 then begin
        xr=fltarr(n2)
150    ps=lonarr(n2)
    endif
    ; calculate derivatives using forward differences

```

```

      xd=shift(x,-1)
      xd=xd-x
155   xd(n-1)=xd(n-2)
      yd=shift(y,-1)
      yd=yd-y
      m=yd/xd
      m(n-1)=2*m(n-2)-m(n-3)
160   ; calculate local derivatives t(2) to t(n-3)
      mind=indgen(n-4)+2
      dims=size(mind)
      flagvec=lonarr(dims(1))
      m43=abs(m(mind+1)-m(mind))
165   m21=abs(m(mind-1)-m(mind-2))
      ind1=where((m43 eq 0) and (m21 eq 0),ccount)
      if ccount gt 0 then begin
        t(ind1)=0.5*(m(ind1+2)+m(ind1+1))
        flagvec(ind1)=-99999
170   endif
      ind2=mind(where(flagvec ne -99999,ccount))
      if ccount gt 0 then $
        t(ind2)=(m43(ind2-2)*m(ind2-1)+m21(ind2-2)*m(ind2))/(m43(ind2-2)+m21(ind2-2))
      ; special end-point cases
175   if (m(0) ne m(1)) then t(0)=0.5*(3*m(0)-m(1)) else t(0)=m(0)
      m21=abs(m(2)-m(1))
      m10=abs(m(1)-m(0))
      if (m(1) eq m(0)) and (m(0) eq m(2)) then t(1)=m(1) else begin
        t(1)=(m(0)*m21+m(1)*m10)/(m21+m10)
180   endelse
      if (m(n-2) ne m(n-3)) then t(n-1)=0.5*(3*m(n-2)-m(n-3)) else t(n-1)=m(n-2)
      m32=abs(m(n-2)-m(n-3))
      m21=abs(m(n-3)-m(n-4))
      if (m(n-2) eq m(n-3)) and (m(n-3) eq m(n-4)) then t(n-2)=m(n-2) else begin
185   t(n-2)=(m(n-3)*m32+m(n-2)*m21)/(m32+m21)
      endelse
      ; calculate coefficients of interpolating polynomial
      p0=y
      p1=t
190   t2=shift(t,-1)
      if m(n-1) eq m(n-2) then t(n-1)=0.5*(3*m(n-1)-m(n-2)) else t2(n-1)=m(n-1)
      p2=(3.0*m-2.0*t-t2)/xd
      p3=(t+t2-2*m)/(xd*xd)
      if pasnb eq 0 then begin ;if first pass locate intervals and locations
195   pos=0
      ; determine position
      for i=0l,n2-1 do begin
        hat,x,n,xout(i),pos
        xr(i)=xout(i)-x(pos)
200   ps(i)=pos
        yout(i)=poly(xr(i),[p0(pos),p1(pos),p2(pos),p3(pos)])
      endfor
      endif else begin
        for i=0l,n2-1 do begin ;otherwise just perform polynomial splines using
205   ; stored values
        pos=ps(i)
        yout(i)=poly(xr(i),[p0(pos),p1(pos),p2(pos),p3(pos)])
      endfor
      endelse
210   return
      end
      ;
      ;
      ;
215   pro hnt,xx,n,x,jlo
      ; see stand alone HUNT routine for documentation
      ;this version for wave 3.03 DM 18-feb-1991
      if (jlo lt 0) or (jlo gt n-1) then begin
        jlo=0l
220   jhi=n
        goto, lb13
      endif
      inc=1l
      if x ge xx(jlo) then begin
225   lb11: jhi=jlo+inc
        if jhi gt n-1 then jhi=n else begin
          if x ge xx(jhi) then begin
            jlo=jhi

```

C:\RSI\IDL51\lib\cfde3\spakim.pro

Page 4

```
        inc=inc+inc
230      goto, lbl1
        endif
      endelse
    endif else begin
      jhi=jlo
235      lbl2: jlo=jhi-inc
        if jlo lt 0 then jlo=0 else begin
          if x lt xx(jlo) then begin
            jhi=jlo
            inc=inc+inc
240          goto, lbl2
          endif
        endelse
      endelse
      lbl3: if (jhi-jlo) le 1 then goto, endibl
245      jm=(jhi+jlo)/2
        if x ge xx(jm) then jlo=jm else jhi=jm
        goto, lbl3
      endibl:
      return
250    end
```

```

pro printer, a ; a=chart title

; procedure to print directly to the printer

5  set_plot, 'printer' ;set plotting device to the printer

; !p.multi=[0,1,2] ;set plot to put two plots on a page
; !p.multi=0 ;set plot to put one plot on a page
; !x.margin=[25,0] ;single plot xmargin for 3D plots
10 ; !x.margin=[20,3] ;single plot xmarginfor x-y plots
; !y.margin=[25,10] ;single plot ymargin
; !x.margin=[20,3] ;double plot xmargin
; !y.margin=[10,10] ;double plot ymargin

15

;alpha pod corrected (angle of attack) plots
;from AES data CD's, see strplhz file on CD for heading details

20 ;UFF_READ,'c:\kevin\cfde3data\nrc data files\c715.s01',PARAMS715,DAT715
;plot, dat715(84,7553:8273),xtitle='time (seconds)',ytitle='pod alpha',,title='Angle of Attack fo

;UFF_READ,'c:\kevin\cfde3data\nrc data files\c719.s01',PARAMS719,DAT719
25 ;plot, dat719(84,*),xtitle='time (seconds)',ytitle='pod alpha',,title='Angle of Attack for C-719'

;UFF_READ,'c:\kevin\cfde3data\nrc data files\c721.s01',PARAMS721,DAT721
;plot, dat721(84,*),xtitle='time (seconds)',ytitle='pod alpha',,title='Angle of Attack for C-721'

30 ;UFF_READ,'c:\kevin\cfde3data\nrc data files\c722.s01',PARAMS722,DAT722
;plot, dat722(84,*),xtitle='time (seconds)',ytitle='pod alpha',,title='Angle of Attack for C-722'

;UFF_READ,'c:\kevin\cfde3data\nrc data files\c723.s01',PARAMS723a,DAT723a
35 ;plot, dat723a(84,6433:7233),xtitle='time (seconds)',ytitle='pod alpha',title='Angle of Attack fo

;UFF_READ,'c:\kevin\cfde3data\nrc data files\c723.s01',PARAMS723b,DAT723b
;plot, dat723b(84,7903:8533),xtitle='time (seconds)',ytitle='pod alpha',title='Angle of Attack fo

40 ;UFF_READ,'c:\kevin\cfde3data\nrc data files\c725.s01',PARAMS725,DAT725
;plot, dat725(84,171:2133),xtitle='time (seconds)',ytitle='pod alpha',title='Angle of Attack for C

;UFF_READ,'c:\kevin\cfde3data\nrc data files\c726.s01',PARAMS726,DAT726
;plot, dat726(84,4254:5215),xtitle='time (seconds)',ytitle='pod alpha',title='Angle of Attack for

45

;beta pod corrected (side slip angle) plots
;from AES data CD's, see strplhz file on CD for heading details

50 ;UFF_READ,'c:\kevin\cfde3data\nrc data files\c715.s01',PARAMS715,DAT715
;plot, dat715(86,7553:8273),xtitle='time (seconds)',ytitle='pod beta',title='Side Slip Angle for C

;UFF_READ,'c:\kevin\cfde3data\nrc data files\c719.s01',PARAMS719,DAT719
55 ;plot, dat719(86,*),xtitle='time (seconds)',ytitle='pod beta',title='Side Slip Angle for C-719'

;UFF_READ,'c:\kevin\cfde3data\nrc data files\c721.s01',PARAMS721,DAT721
;plot, dat721(86,*),xtitle='time (seconds)',ytitle='pod beta',title='Side Slip Angle for C-721'

60 ;UFF_READ,'c:\kevin\cfde3data\nrc data files\c722.s01',PARAMS722,DAT722
;plot, dat722(86,*),xtitle='time (seconds)',ytitle='pod beta',title='Side Slip Angle for C-722'

;UFF_READ,'c:\kevin\cfde3data\nrc data files\c723.s01',PARAMS723a,DAT723a
65 ;plot, dat723a(86,6433:7233),xtitle='time (seconds)',ytitle='pod beta',title='Side Slip Angle for

;UFF_READ,'c:\kevin\cfde3data\nrc data files\c723.s01',PARAMS723b,DAT723b
;plot, dat723b(86,7903:8533),xtitle='time (seconds)',ytitle='pod beta',title='Side Slip Angle for

70 ;UFF_READ,'c:\kevin\cfde3data\nrc data files\c725.s01',PARAMS725,DAT725
;plot, dat725(86,171:2133),xtitle='time (seconds)',ytitle='pod beta',title='Side Slip Angle for C-

;UFF_READ,'c:\kevin\cfde3data\nrc data files\c726.s01',PARAMS726,DAT726
;plot, dat726(86,4254:5215),xtitle='time (seconds)',ytitle='pod beta',title='Side Slip Angle for C

75

```

Appendix B printer.pro

C:\RSI\IDL51\lib\cfde3\printer.pro

Page 2

```

;direct plots from the data provided by AES

;fordk, 61,rw,ar,'c:\kevin\cfde3data\980117a.txt'
80 ;fordk, 61,rw,ar,'c:\kevin\cfde3data\980122a.txt'
;fordk, 61,rw,ar,'c:\kevin\cfde3data\980124a.txt'
;fordk, 61,rw,ar,'c:\kevin\cfde3data\980202a.txt'
;fordk, 61,rw,ar,'c:\kevin\cfde3data\980209a.txt'
;fordk, 61,rw,ar,'c:\kevin\cfde3data\980209b.txt'
85 ;fordk, 61,rw,ar,'c:\kevin\cfde3data\980212aa.txt'
;fordk, 61,rw,ar,'c:\kevin\cfde3data\980212ba.txt'
;x5=findgen(rw)
;plot,x5,ar(1,*),xtitle='time (seconds)',ytitle='altitude (Kft)',title=a ;altitude
;plot,x5,ar(8,*),xtitle='time (seconds)',ytitle='true air speed (m/s)',title=a ;TAS (m/s
90 ;plot,x5,ar(9,*),xtitle='time (seconds)',ytitle='pressure (mb)',title=a ;pressure
;plot,x5,ar(11,*),xtitle='time (seconds)',ytitle='static temperature (deg C)',title=a ;temperat
;plot,x5,ar(15,*),xtitle='time (seconds)',ytitle='Nevzorev LWC (g/cm^3)',title=a ;LWC (g/c
;plot,x5,ar(16,*),xtitle='time (seconds)',ytitle='Nevzorev TWC (g/cm^3)',title=a ;TWC (g/c
;plot,x5,ar(16,*)-ar(15,*),xtitle='time (seconds)',ytitle='Ice content (NTWC-NLWC)';title=a ;TWC

95

;MVD plots

;mvdplot, 'c:\kevin\cfde3data\980117a.txt', med,ar,x5,x4,y4,x2,y2,x,y
100 ;plot,x5,med,xtitle='time (seconds)',ytitle='size (um)',title='MVD for case C-715'

;mvdplot, 'c:\kevin\cfde3data\980122a.txt', med,ar,x5,x4,y4,x2,y2,x,y
;plot,x5,med,xtitle='time (seconds)',ytitle='size (um)',title='MVD for case C-719'

105 ;mvdplot, 'c:\kevin\cfde3data\980124a.txt', med,ar,x5,x4,y4,x2,y2,x,y
;plot,x5,med,xtitle='time (seconds)',ytitle='size (um)',title='MVD for case C-721'

;mvdplot, 'c:\kevin\cfde3data\980202a.txt', med,ar,x5,x4,y4,x2,y2,x,y
110 ;plot,x5,med,xtitle='time (seconds)',ytitle='size (um)',title='MVD for case C-722'

;mvdplot, 'c:\kevin\cfde3data\980209a.txt', med,ar,x5,x4,y4,x2,y2,x,y
;plot,x5,med,xtitle='time (seconds)',ytitle='size (um)',title='MVD for case C-723a'

;mvdplot, 'c:\kevin\cfde3data\980209b.txt', med,ar,x5,x4,y4,x2,y2,x,y
115 ;plot,x5,med,xtitle='time (seconds)',ytitle='size (um)',title='MVD for case C-723b'

;mvdplot, 'c:\kevin\cfde3data\980212aa.txt', med,ar,x5,x4,y4,x2,y2,x,y
;plot,x5,med,xtitle='time (seconds)',ytitle='size (um)',title='MVD for case C-725'

120 ;mvdplot, 'c:\kevin\cfde3data\980202ba1.txt', med,ar,x5,x4,y4,x2,y2,x,y
;plot,x5,med,xtitle='time (seconds)',ytitle='size (um)',title='MVD for case C-726'

125

;comparison of FSSP Mean VD with calculated Median VD

;mvd96, 'c:\kevin\cfde3data\980117a.txt', med,ar,x5
;plot,x5,med,xtitle='time (seconds)',ytitle='size (um)',title=a
130 ;oplot,ar(41,*)

;mvd24, 'c:\kevin\cfde3data\980117a.txt', med,ar,x5
;plot,x5,med,xtitle='time (seconds)',ytitle='size (um)',title=a
;oplot,ar(60,*)
135

;3D plots of droplet size spectra

140 ;spectra, 'c:\kevin\cfde3data\980117a.txt', data,rw
;surface, data(0:26,*),findgen(27)+4,findgen(rw),ax=70,az=25,/upper_only,min_value=0.5
;xtitle='Droplet Size Spectra (um)',ytitle='time (seconds)'

145 ;spectra, 'c:\kevin\cfde3data\980122a.txt', data,rw
;surface, data(0:26,*),findgen(27)+4,findgen(rw),ax=70,az=25,/upper_only,min_value=0.5
;xtitle='Droplet Size Spectra (um)',ytitle='time (seconds)'

150 ;spectra, 'c:\kevin\cfde3data\980124a.txt', data,rw
;surface, data(0:26,*),findgen(27)+4,findgen(rw),ax=70,az=25,/upper_only,min_value=0.5
;xtitle='Droplet Size Spectra (um)',ytitle='time (seconds)'

```


C:\RSI\IDL51\lib\cfde3\printer.pro

Page 3

```

;spectra, 'c:\kevin\cfde3data\980202a.txt', data,rw
;surface, data(0:26,*),findgen(27)+4,findgen(rw),ax=70,az=25,/upper_only,min_value=0,$
155 ;xtitle='Droplet Size Spectra (um)',ytitle='time (seconds)'

;spectra, 'c:\kevin\cfde3data\980209a.txt', data,rw
;surface, data(0:21,*),findgen(22)+4,findgen(rw),ax=70,az=25,/upper_only,min_value=0,$
;xtitle='Droplet Size Spectra (um)',ytitle='time (seconds)'
160

;spectra, 'c:\kevin\cfde3data\980209b.txt', data,rw
;surface, data(0:21,*),findgen(22)+4,findgen(rw),ax=70,az=25,/upper_only,min_value=0,$
;xtitle='Droplet Size Spectra (um)',ytitle='time (seconds)'

165 ;spectra, 'c:\kevin\cfde3data\980212aa.txt', data,rw
;surface, data(0:26,0:899),findgen(27)+4,findgen(900),ax=70,az=25,/upper_only,min_value=0,$
;xtitle='Droplet Size Spectra (um)',ytitle='time (seconds)'

;spectra, 'c:\kevin\cfde3data\980212ba.txt', data,rw
170 ;surface, data(0:21,*),findgen(22)+4,findgen(rw),ax=70,az=25,/upper_only,min_value=0,$
;xtitle='Droplet Size Spectra (um)',ytitle='time (seconds)'

device, /close_document
175 set_plot, 'win'
loadct, 39
;p.multi=0
!x.margin=[10,3]
!y.margin=[4,2]
180 return
end

```

```

PRO UFF_READ, FNAME, PARAMS, DAT, HELP=HELP
;
; read in data from a file and returns parameters and data.
;
; in the common data file format as specified by Stewart and Ma
tthew Bastian
;
; John Hayes 06-March-94
;
;
;
IF KEYWORD_SET (HELP) THEN BEGIN
PRINT, 'USAGE: UFF_RD_, FNAME, PARAMS, DAT, HELP=HELP'
PRINT, 'PARAMS - STRING OF PARAMETERS'
PRINT, 'DAT - ARRAY OF DATA'
RETURN
ENDIF
VersionId = string (replicate (32b, 8))
Title = string (replicate (32b, 32))
Date = string (replicate (32b, 32))
SubTitle = string (replicate (32b, 32))
ParamWidth = 01
ParamNum = 01
SampleRate = 01
NumPts = 01
EventMask = 01

;
; open the entered file for reading
;
on_ioerror, BadData

openr, 1, FNAME, /stream

;
; read in the fixed size portion of the header
;
readu, 1, VersionId
readu, 1, Title
readu, 1, Date
readu, 1, SubTitle
readu, 1, ParamWidth
readu, 1, ParamNum
readu, 1, SampleRate
readu, 1, NumPts

```

```

readu, 1, EventMask

PRINT, 'Loading the data set ...'

;
; start loading in the variable portion of the header
;
; note that the following three lines of code are by no means fo
ol proof
; and could potentially cause the program to bomb if ParamNum is
greater
; than 2*ParamNumFirstTime. Not likely but not inconceivable eit
her!
;
Params = string (replicate (string (replicate (32b, ParamWidth))
,ParamNum))

readu, 1, Params
ParamNames = Params

;
; this code allocate twice the size of the data array as necessa
ry.
; This allows for the potential of loading in multiple data sets
.
;

Dat = fltarr (ParamNum, NumPts, /nozero) ; give array room to g
row

readu, 1, Dat
print, 'Done'

close, 1
return

BadData:
    print, "I/O error occured while reading the data set"

    stop
end

```

Appendix C
Laser Safety Report

Appendix C

Laser Safety Report for CAL Radome Icing Project

By Kevin Glenney
December 11/ 1997

1.0 Introduction

The CAL Radome Icing Project will involve the installation and testing of two Elmo MN401X video cameras and one 30 mW diode laser projected through a diffractive grid generator onto the CALradome orientation. The purpose of the project is to measure and document the shapes of ice that build up over time under varying atmospheric conditions. The purpose of this report is to verify that the potential hazards are addressed and that there are no hazards that will pose a risk to personnel or bystanders.

2.0 Laser Safety Officers (LSO)

According to the Flight Research Lab Standard Engineering Practices Manual (FRLSEPM) section 5 there will be one LSO and one deputy LSO. The LSO will be Kevin Glenney and the deputy LSO will be Dave Marcotte.

3.0 Definition of terms and variables

r_{NHZ}	safe distance to view a laser reflection (Non Hazard Zone).
r_{NOHD}	safe distance to view direct laser light Non Ocular Hazard Distance)
MPE_1	Maximum Permissible Exposure for the unaided eye
MPE_2	Maximum Permissible Exposure for the aided eye (night viewing through a 50 mm optic lens
ϕ	Laser divergence (radians)
Φ	Laser power (Watts)
θ	Viewing angle of a reflection
ρ	Spectral reflectance

4.0 Hazards

The 30 mW laser diode is a class IIIb laser. It will be projected through a diffractive grid generator to produce a 16" x 16", 9 x 9 grid on the CALradome.

Appendix C

4.1 Potential Hazards

1. Direct viewing of 30 mW laser
2. Direct viewing of diffused laser
3. Viewing of reflection inside r_{NHZ}
4. Viewing by bystander of direct diffused laser

Note: hazards 1-3 are only possible during installation. Providing conscious effort is made to avoid, 1-3 are not a problem.

4.2 Summary of MPE and safe viewing distances

For a 400 - 700 nm laser table 5 of ANSI Z136.1 gives:

$$\text{MPE}_1 = 2.5 \times 10^{-3} \text{ W/cm}^2 \text{ for 0.25 seconds}$$

In case of viewing by bystanders, reduce MPE_1 by 51 (ratio of a 50 mm optic lens area to 7 mm eye lens area):

$$\text{MPE}_2 = 4.09 \times 10^{-5} \text{ W/cm}^2 \text{ for 0.25 seconds}$$

Safe viewing distance for 30 mW laser alone:

$$\begin{aligned} r_{\text{NOHD}} &= 97.59 \text{ m for } \text{MPE}_1 \\ r_{\text{NOHD}} &= 763.03 \text{ m for } \text{MPE}_2 \end{aligned}$$

Safe viewing distance for diffused laser grid lines:

$$\begin{aligned} r_{\text{NOHD}} &= 0.95 \text{ m for } \text{MPE}_1 \\ r_{\text{NOHD}} &= 7.46 \text{ m for } \text{MPE}_2 \end{aligned}$$

Safe viewing distance for diffused laser grid point:

$$\begin{aligned} r_{\text{NOHD}} &= 30.86 \text{ m for } \text{MPE}_1 \\ r_{\text{NOHD}} &= 241.29 \text{ m for } \text{MPE}_2 \end{aligned}$$

Safe viewing distance for diffused laser grid point:

$$\begin{aligned} r_{\text{NHZ}} &= 0.0185 \text{ m for } \text{MPE}_1 \\ r_{\text{NHZ}} &= 0.1450 \text{ m for } \text{MPE}_2 \end{aligned}$$

*Note that the calculations do not include allowances for laser or grid generator efficiencies so the viewing ranges are conservative.

Appendix C

4.3 Installation/testing requirements to avoid direct viewing of laser

- 1 Power to laser only if laser light is confined to reflect from low spectral reflectance barrier such as: sheet, plywood, wall.
- 2 Personnel are not allowed between laser and barrier.

4.4 Laser Alignment Procedures

- 1 Laser will not be powered during installation on the aircraft
- 2 Alignment will be provided by the bracket that holds the camera and the laser
- 3 If the laser needs to be powered on the ground once installed a barrier (as outlines in section 4.3 will be provided

4.5 Discussion of free laser energy

The only laser energy that will not be contained or confined on the radome is that of the lines which do not fall on the radome. The safe distance for viewing through 50 mm optics at night is 7.5 m which is impossible for this situation - especially in flight.

It is being proposed that the laser be controlled by a separate weight on wheels switch so that it can not be operated on the ground. This would prevent ground crew/personnel from inadvertently being exposed to the laser.

Should the laser become dislodged and point away from the radome the safe distance would be about 242 m when viewed through 50 mm optics. This is also impossible when the aircraft is in flight.

1. Laser will not be on at this altitude
2. Laser is pointing horizontally aft on the aircraft
3. Laser is located on top of the aircraft
4. Separation from other aircraft will be greater than 242 m
5. Laser is contained under a fairing that will only allow the light to be directed at the radome.

5.0 Conclusions

From the calculations it is evident that once installed there is minimal hazard for bystanders. Also, providing good laser handling practices are followed (e. No direct viewing of the laser) the installation hazards will be minimal. Installation does not require the laser to be powered and testing will be done according to section 4.3. From the calculations it is safe to say that there is no risk to bystanders or other aircraft while the aircraft is in flight since the safe distance is 7.5 m for an unaided eye. The aided eye case is improbable for the reasons listed in section 4.5

The diffusing optic is mounted inside the same mount that is used to hold a line projecting optic. It is highly unlikely that this piece would become separated from the laser. If it did become separated the laser light would be contained on the radome and there would be no risk to bystanders or other aircraft.

Appendix C

Calculations for MPE, r_{NHZ} and r_{NOHD}

Safe viewing distances

1 Direct viewing of 30 mW laser

$$r_{NOHD} = \frac{1}{\phi} \sqrt{\frac{1.27\Phi}{MPE}}$$

$$\Phi = 30 \text{ mW}$$

$$MPE_1 = 2.5 \text{ mW/cm}^2$$

$$MPE_2 = 0.0409 \text{ mW/cm}^2$$

$$\phi = 0.0004 \text{ rad (from Melles Griot)}$$

$$= 97.6 \text{ m (MPE}_1)$$

$$= 763.0 \text{ m (MPE}_2)$$

2 Direct viewing of diffused laser lines

Using the same equation as above and pro rating ϕ to account for area not covered by the laser in the grid --> ratio of line area to grid area:

$$\phi = 15^\circ = 0.2618 \text{ rad} \quad \text{ratio} = 40/256$$

$$\phi' = \phi \times \text{ratio} = 0.0409 \text{ rad}$$

$$r_{NOHD} = 0.95 \text{ m (MPE}_1)$$

$$= 7.46 \text{ m (MPE}_2)$$

3 Direct viewing of grid point

$$r_{NOHD} = 30.86 \text{ m (MPE}_1)$$

$$= 241.29 \text{ m (MPE}_2)$$

$$\phi = 0.0004 \text{ rad}$$

$$\Phi = 10\% \text{ of power} = 0.003 \text{ mW}$$

*Grid point will be projected on to the radome at all times. Therefore, it will not be an ocular hazard

4 Spectral reflection of 30 mW laser

$$r_{NHZ} = \sqrt{\frac{\rho\Phi\cos\theta_v}{\pi MPE}}$$

$\rho = 0.9$ --> spectral reflectance of a diffuse object (anodized instrument in this case --> high reflectance)

$$\Phi = 0.03 \text{ W}$$

$$\theta_v = 0 \text{ rad}$$

$$= 0.02 \text{ m (MPE}_1)$$

$$= 0.15 \text{ m (MPE}_2)$$

This analysis does not take into account losses in the diffractive optic. Therefore, the calculations err on the high side. Thor Optical estimated the losses to be between 65 and 85% for the diffractive optic.

Appendix C

Calculations for MPE, r_{NHZ} and r_{NOHD}

Approximate laser divergence WRT Power and eye safety:

area of grid and dot from a viewing distance of 40" is as follows

$$\text{Lines} = 16" \times \frac{1}{8}" \times 20 = 40''^2 \rightarrow \text{assume 90\% of power to lines}$$

$$\text{Dot} = \frac{1}{8}" \times \frac{1}{8}" \times 1 = \frac{1}{64}''^2 \rightarrow \text{assume 10\% of power to dot}$$

Using a 30 mW laser with an efficiency (η) of 80%, Power (P) = 24 mW

Power density in lines at 40"

$$P_L = 24 \times 0.9 = 21.6 \text{ mW}$$

$$A_L = 40''^2$$

$$\rho = \frac{21.6}{40} = 0.54 \text{ mW}/_{\text{in}}^2 = 0.08370 \text{ mW}/_{\text{cm}}^2$$

Power density in dot at 40"

$$P_L = 24 \times 0.1 = 2.4 \text{ mW}$$

$$A_L = \frac{1}{64}''^2$$

$$\rho = \frac{2.4}{(1/64)} = 153.6 \text{ mW}/_{\text{in}}^2 = 23.8 \text{ mW}/_{\text{cm}}^2$$

Calculation of MPE

From ANSI Z136.1-1993

MPE for a 670 nm laser (type InGaA1P),

$$\text{MPE}_1 = 2.5 \text{ mW}/_{\text{cm}}^2 \text{ for 0.25 seconds (aversion time)}$$

From table 5 of ANSI Z136.1-1993,

$$\text{MPE} = (1.8t^{3/4} \times 10^{-3})/t = 2.55 \text{ mW}/_{\text{cm}}^2 \text{ where } t=0.25 \text{ sec}$$

In case of viewing by bystanders, ANSI Z136.1-1993 suggests reducing the MPE by 51, the ratio of a 50 mm optic lense area to a 7 mm eye lense area.

therefore,

$$\text{MPE}_2 = \frac{2.5}{51} = .0409 \text{ mW}/_{\text{cm}}^2$$

Appendix D
Calibration Plate

APPENDIX D Calibration Plate Details

Calibration Plate

point	Millimeters			Inches		
	x	y	z	x	y	z
1	0	0	5.57	0	0	0.2195
2	50.8	101.6	30.45	2	4	1.199
3	50.8	50.8	49.92	2	2	1.9655
4	50.8	-50.8	47.36	2	-2	1.8645
5	50.8	-101.6	25.58	2	-4	1.007
6	101.6	0	37.03	4	0	1.458
7	152.4	50.8	24.09	6	2	0.9485
8	152.4	-50.8	43.55	6	-2	1.7145
9	203.2	101.6	48.88	8	4	1.9245
10	203.2	0	36.47	8	0	1.436
11	254	50.8	45.29	10	2	1.783
12	254	-50.8	26.78	10	-2	1.0545
13	304.8	0	30.47	12	0	1.1995
14	355.6	101.6	46.25	14	4	1.821
15	355.6	50.8	37.62	14	2	1.481
16	355.6	-50.8	50.2	14	-2	1.9765
17	355.6	-101.6	37.12	14	-4	1.4615
18	406.4	0	45.73	16	0	1.8005

Appendix E

Sample Calculations

Appendix E

Sample calculation of possible ice accretion weight:

Area=0.0525 m² (area of dome exposed perpendicular to air flow)

Case 2, LWC=0.25 g/m³, Distance=20 Nm (37040 m)

$$\text{Weight of Ice} = 0.25 \times 37040 \times 0.0525$$

$$\text{Weight of Ice} = 485 \text{ g}$$

Sample calculation of possible ice accretion thickness for test cases:

mass of ice = Area × % of area × % impingement × LWC × Speed × time

ice thickness = mass of ice / (density × Area × % of area)

ice thickness = % impingement × LWC × speed × time / density

$$=(0.4 \times 0.35 \text{ g/m}^3 \times 101\text{m/s} \times (12 \text{ min} \times 60 \text{ s/min}) / 1000000 \text{ g/m}^3) \times 1000\text{mm/m}$$

$$=10.2\text{mm}$$

Boundary layer thickness calculation:

For a laminar boundary layer the thickness can be estimated from the following equation

which is valid for Reynolds numbers up to 10⁶:

$$\frac{\delta}{x} = \frac{5.0}{\text{Re}_x^{1/2}}$$

For a turbulent boundary layer the thickness can be estimated from :

$$\frac{\delta}{x} = \frac{0.16}{\text{Re}_x^{1/7}}$$

this is valid for Reynolds numbers above 10⁶:

Appendix E

δ is the boundary layer thickness, x is the distance along the plate, and Re is the Reynolds number given by :

$$Re_x = \frac{\rho V x}{\mu}$$

where ρ is the fluid density, V is the aircraft speed, x is the scaling distance, and μ is the fluid viscosity. In this case, the values used for the variables in Re were as follows:

$$V=200 \text{ KTS (103 m/s)}$$

$$\rho=1.203 \text{ kg/m}^3$$

$$\mu=1.8 \times 10^{-5} \text{ N}\cdot\text{s/m}^2$$

$$x=14.4 \text{ m}$$

with these values:

$$Re=99127200$$

which is above $Re=10^6$ so the turbulent case applies. Calculating δ from Equation 4.2 the boundary layer for a flat plate would be about 16.6 cm deep.

HORIZONTAL EXTENT OF ICING CLOUDS

- * WATER INTERCEPTED $\propto$ LWC $\cdot$ x DISTANCE
- * TIME IN CLOUD = EXTENT / SPEED

Appendix F

Atmospheric and Aircraft Flight Data / Graphs

Appendix F

Flight C-715

C-715

Appendix F

Flight C-719

C-719

Appendix F

Flight C-721

C-721

Appendix F

Flight C-722

C-722

Appendix F

Flight C-723a

C-723

Appendix F

Flight C-723b

C-7236

Appendix F

Flight C-725

C-725

Appendix F

Flight C-726

C-726

Appendix F

**Comparison of calculated Median Volume Diameter and FSSP recorded Mean
Volume Diameter**

FSSP 96

FSSP 124

Appendix G

Convair 580 Instrumentation List for CFDE III

Appendix G

Convair 580 Instrumentation List for CFDE III

Instrument	Variable
Rosemount Temperature Probe	Temperature
Reverse Flow Temperature	Temperature
Cambridge Dewpoint Hygrometer	Dewpoint
University of Warsaw Temperature	High frequency temp variations
Rosemount 858 Probe	3D wind gusts
King Probe (short and long types)	Liquid water content
Nevzorev Probe	Liquid and total water content
PMS PCASP	Aerosol (0.13-3 μ m)
PMS FSSP 100x	Droplets (2-30 or 3-47 μ m)
PMS FSSP 100x	Droplets (5-95 μ m)
PMS 2DC Mono	Particles (25-800 μ m)
PMS 2DC Grey	Particles (25-1600 μ m)
PMS 2DP Mono	Particles (200-6400 μ m)
SPEC Cloud Particle Imager	Particles >2.5 μ m
Desert Research Institute Replicator	Particles
Desert Research Institute Cloudscope	Particles
Rosemount Icing Detector	Icing rate
Vibrometer Icing Detector	Icing rate
Airbus Certification Rod	Icing rate
Stereo Video System for SatCom antenna dome	Ice thickness
LIDAR (532 and 1064 nm)	
Bendix radar altimeter	Altitude
TRT radar altimeter	Altitude
Digiquartz static pressure on fuselage	Altitude (pressure)
Pitot under wing, static pressure on fuselage	Airspeed (true, indicated)
GPS, LTN-91 Inertial Navigation System	Position
LTN-91 Inertial Navigation System	Attitude, accelerations, heading, ground speed
3-axis speeds with respect to ground	GPS
Rosemount temperature probe (deiced)	Temperature