

**COCKPIT WEATHER INFORMATION
SYSTEM REQUIREMENTS FOR
FLIGHT OPERATIONS IN ICING CONDITIONS**

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ABSTRACT

In order to support the development of remote sensing technologies, the requirements of cockpit information systems for flight operations in icing conditions were investigated. Pilot information needs were investigated in a web-based survey. Results identified important information elements, frequently used information paths for obtaining icing-related information, and data on significant icing encounters and key icing-related information and decision criteria. In addition, the influence of potential ice detection system features on pilot decision-making was investigated in a web-based experiment. Results showed that the use of graphical displays improved pilot decision-making over existing text-based icing information. The use of vertical view was found to support better decision-making. Range enhancement was not found to have strong positive influence; however the minimum range tested was 25 nautical miles, which may be in excess of current technical capabilities. The depiction of multiple icing severity levels was not found to be as important as accurate information on the location of icing conditions. This may have significant impact for remote sensing and forecasting efforts currently under way, as the technical challenges for accurate detection of icing presence may be significantly inferior to those of accurate detection of multiple icing severity levels.

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LIST OF ACRONYMS

AGATE	Advanced GA Transport Experiments
AGL	Above Ground Level
AIM	Aeronautical Information Manual
ASL	Above Sea Level
ASOS	Automated Surface Observing System
ASRS	Aviation Safety Reporting System
ATC	Air Traffic Control
ATIS	Automatic Terminal Information Service
AWOS	Automated Weather Observing System
dBZ	Decibels of Reflectivity
DOT	Department of Transport
DUAT	Direct User Access Terminal
EFAS	En Route Flight Advisory Service
FA	Area Forecast
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
FD	Winds and Temperature Aloft Forecast
FSS	Flight Service Station
GA	General Aviation
HIWAS	Hazardous In-flight Weather Advisory Service
html	Hyper Text Makeup Language
IAS	Indicated Airspeed
IFR	Instrument Flight Rules
IMC	Instrument Meteorological Conditions
KBAL	Baltimore VOR
KBWI or BWI	Baltimore airport identifier
KIAD or IAD	Dulles airport identifier
KPHL or PHL	Philadelphia airport identifier
LIDAR	Light Detection and Ranging
MEA	Minimum En-route Altitude
METAR	Aviation Routine Weather Report
MHz	Megahertz
MSL	Mean Sea Level
MVD	Median Volume Diameter
MVFR	Marginal VFR
N/A	Not Available
NASA	National Aeronautics and Space Administration
NDB	Non-Directional Beacon
nm	Nautical Miles
NOAA	National Oceanic and Atmospheric Administration
NOTAM	Notice to Airmen
NTSB	National Transportation Safety Board
OAT	Outside Air Temperature
PLI	“Party-Line” Information

PIREP	Pilot Report
RADAR	Radio Detection and Ranging
SIGMET	Significant Meteorological Advisory Alert
SLW	Supercooled Liquid Water
TAF	International Aerodrome Forecast
TWEB	Transcribed Weather Broadcasts
VFR	Visual Flight Rules
VMC	Visual Meteorological Conditions
VOR	Very high frequency Omni-directional Radio range
ZR	Freezing Rain

1 INTRODUCTION

1.1 CONTEXT

Aircraft icing remains a significant aviation weather hazard for both civil and military aircraft operations. The need for improved forecasts and sensed information on location and severity has been emphasized following recent in-flight icing accidents, including the loss of control of a Comair Embraer EMB-120RT in Monroe, MI in January of 1997 (NTSB, 1998), and the uncontrolled collision with terrain of an American Eagle ATR-72 in Roselawn, IN in October, 1994 (NTSB, 1996).

General aviation (GA) accidents related to in-flight icing are also of concern. Accident statistics over a ten-year period (between 1982 and mid-1993) have shown that airframe icing is one of the top ten factors in fatal weather-related general aviation accidents. Overall, adverse weather conditions were involved in 27% of the 22,053 GA airplane accidents of all types. Structural icing was involved in 637 accidents of which, 172 were fatal (AOPA Air Safety Foundation, 1996). The NTSB puts the overwhelming responsibility for weather accidents (94% of the cases) on pilots. Several known-ice-approved aircraft have had difficulty with ice accumulation behind the de-ice boots (Landsberg, 1985). Tail icing has brought down several regional airliners, and could very well be a problem on general aviation aircraft as well (Horne, 1994).

In addition, flight restrictions due to icing limitations impact both civil and military aircraft operations.

1.2 ICING INFORMATION NEEDS IN THE COCKPIT

Aircraft may be approved to fly into known-icing following an icing certification process which involves flight testing in conditions described in the Federal Aviation Regulations (Part 25, Appendix C). Icing-approved aircraft are nevertheless not tested for, and consequently not certified for flight into severe icing conditions, freezing rain and supercooled large drops. Hence there remain possible meteorological scenarios that are unsafe to their operations. Many GA aircraft are not certified for operations into known or forecast icing conditions and must avoid any level of icing conditions. Operational issues in icing conditions need therefore to be examined under two distinct categories, according to the icing certification level of aircraft.

It has been realized that icing information is important for the safety and efficiency of flight operations. Efforts have recently been initiated for improving information on icing conditions, including the ability to forecast and to remotely sense icing conditions. The task is a challenging one since the severity of aircraft icing is sensitive to a number of atmospheric parameters that

make forecasting and the identification of hazardous icing conditions difficult. The ultimate objective of detecting and forecasting icing conditions is to provide enhanced information to support optimal decision making in flight operations.

To help develop icing information products that meet the needs of the operational community, understanding pilot information requirements and operational strategies is desirable. In addition, the identification and evaluation of features of information presentation that meet pilot needs in flight operations will help define optimal information interfaces.

The preliminary steps of a human-centered approach described by Hansman *et al.* (1997) was applied for the evaluation of functional requirements of in-flight icing information systems in the cockpit. This approach involves evaluating key elements and their respective dynamics for the evaluation of flight-critical system: pilots, information systems and aircraft systems as they relate in this case to icing conditions. It includes identifying and completing part-task evaluations of information display features as they influence pilot decisions (Hansman *et al.*, 1997)

1.3 DOCUMENT OVERVIEW

The report of this research project is presented in seven chapters. Background information on icing meteorology, certification and terminology is provided in Chapter 2. An overview of current icing information aimed at supporting operations in icing conditions is given in Chapter 3. Together, those two chapters attempt to provide the reader with proper ground before continuing with an evaluation of use and usefulness of icing information for pilots. Chapter 4 reports on the first step of this effort, which involved a survey of pilot information needs and strategies for operations in icing conditions. Building on the results of this work, and more specifically on the identification of important display issues of enhanced icing information systems, the following two chapters lead into the report of a web-based experiment that addressed icing information system concepts. Chapter 5 presents the design and Chapter 6 presents the results of this experiment. Chapter 7 synthesizes the results of this study.

2 BACKGROUND ON AIRCRAFT ICING

Ice accretion on an airplane structure may significantly alter flight safety. Its impact affects various aircraft systems in the absence or lack of sufficient ice protection. Possible effects of ice accretion are listed below.

- π Ice build up on the airframe structure can modify the airflow pattern around airfoils of wings and propeller blades, leading to a potential loss of lift and an increase in drag. Figure 2-1 illustrates ice build up on an airfoil leading edge.



Figure 2-1: Mixed Ice Accretion on Airfoil Leading Edge

(Photography taken during Electro-Expulsive Separation System demonstration

Source: <http://www.nctn.hq.nasa.gov/innovation/Innovation63/deicer.htm>)

- π Loss of engine power or even engine failure may occur as a result of ice blocking the engine air intake or ice ingestion causing structural damage.
- π Loss of propeller efficiency may occur due to ice build up. On small helicopters, the increase in airfoil drag may be sufficient to force the rotorcraft to land.
- π Weight increase and change in the position of the aircraft centre of gravity may occur due to significant ice accretion.
- π Unbalancing of the various control surfaces and the propeller, due to ice accretion and possible self-shedding may cause vibrations and / or lack of control effectiveness.
- π Blockage of the pitot tube or static vent may produce errors in pressure instruments.
- π Degradation in radio communications and radio navigation equipment may occur as a consequence of ice build up on antennae.
- π If ice accretes on the windshield, it may degrade visibility.

The effects of ice accretion are multiple and may be cumulative in affecting the safety of operations. Background information on icing meteorology is provided in this chapter to help understand the key parameters associated with icing. An overview of the current operating rules and issues associated with how they may affect pilot information needs is subsequently mentioned. The currently used icing terminology is also presented. This will set a common ground before proceeding along with the subsequent discussions.

2.1 ICING METEOROLOGY

Ice accretion on aircraft structures may occur when ambient meteorological conditions are within specific ranges of thermodynamic states. Three types of ice accretion are typically distinguished: 1) Rime ice forms when the supercooled droplets in the cloud freeze on impact with the aircraft surface. Trapped air gives the ice its white and opaque appearance. 2) Glaze ice forms when the droplets do not freeze on impact. Instead, they either coalesce with other droplets to form much larger liquid surface drops or else they merge with a liquid film on the surface. In either case, when the water freezes, no air is trapped and the ice is essentially transparent. Glaze ice is harder and denser than rime ice. 3) Mixed ice is a combination of both rime and glaze ice. Either type of ice may form simultaneously on different regions of the same surface or on different size components.

The most important meteorological factors affecting icing severity are the temperature, the droplet size distribution and the supercooled Liquid Water Content (LWC). An understanding of how these variables may influence the potential for airframe icing may be beyond the needs of the operational community of pilots. It is nevertheless relevant to acknowledging trade-off issues involved in the conception of measurements and detection systems, and in the dissemination of icing conditions.

Freezing rain is precipitating supercooled water droplets which freezes upon impact with the ground or any exposed surface. The temperature of the impacted surface must initially be below freezing. Droplet sizes are large, approximately 1,000 microns in diameter, and liquid water contents average 0.15 g.m^{-3} . Normally, freezing rain occurs in the altitude range 0 to 5,000 feet above sea level (ASL) and is associated with a melting layer or inversion. In general, pilots are cautioned to avoid flying in freezing rain conditions because rapid ice accretion on all surfaces results in rapid reduction of aircraft performance and loss of windshield visibility (US DOT, 1991).

Areas of greatest icing concern in the United States are the Great Lakes, coastal areas, and mountainous regions, although cold fronts with freezing rain and / or other icing condition can occur in most areas.

Dynamic factors such as airspeed, airfoil shape and the efficiency of anti- and de-icing equipment influence the ice accretion process. These variables are highly specific to aircraft types and would require a much more in-depth presentation. As it does not fall within the scope of background information for this work, it will not be discussed in this document.

An overview of how variables such as temperature, droplet size and liquid water content may influence ice accretion is provided in this subsection on icing meteorology.

2.1.1 TEMPERATURE

The regions of icing potential usually correspond to regions where the ambient air temperature ranges between 0°C and -20°C. No icing is expected above the freezing level (this excludes the possibility of icing on descending aircraft whose surfaces may be below 0°C while the air temperature is above 0°C). Also, significant SLW is rarely found at temperatures below -20°C, except for the case of convective clouds.

The clear-to-rime icing distinction is strongly affected by the outside air temperature. At colder temperatures, droplets are more likely to freeze on impact rather than run along the airframe surface. There is some degree of warming on the leading edge of the airframe due to aerodynamic heating. The degree of heating is proportional to the square of the airspeed: temperature is raised by approximately 1°C at 100 knots, and by nearly 10°C at 500 knots. The nonlinear dependence of icing severity on temperature, which is affected by the airspeed, makes it difficult to use outside air temperature alone to assess icing severity potential (Hansman, 1989). Total air temperature is commonly used instead.

2.1.2 DROPLET SIZE

The impinging mass flux distribution which determines aircraft ice accretion rate is shown to be related to the atmospheric droplet size distribution through the droplet collection efficiency of the body (Hansman, 1994), as shown in Equation 2.1.

$$\mathbf{f}(D_{eq}) = UH \frac{4}{3} \rho \mathbf{r}_l \left[\frac{D_{eq}}{2} \right]^3 \mathbf{h}(D_{eq}) f(D_{eq}) \quad (2.1)$$

U refers to the freestream velocity, H to the thickness of the structure, ρ to the density of the droplets, and $\mathbf{h}(D_{eq})$ to the collection efficiency of the structure. From Equation 2.1, it is clear that the impinging mass distribution function is significantly different from the droplet size distribution function due to the size dependence of the collection efficiency and the D_{eq}^3 volume term. The rate of ice accumulation can be obtained by integrating $\mathbf{f}(D_{eq})$ over all droplet sizes.

Factors such as the ambient vapor pressure, the type of condensation nuclei, the agitation mechanisms, the phases of water present, etc. will influence the overall distribution of droplet size in a given airmass. For a given airfoil and airspeed, impaction efficiency increases with droplet size. Smaller droplets tend to follow airflow streamlines around objects, while larger droplets with higher inertia tend to cross those streamlines and impact on the airframe.

Droplet size is difficult to measure and predict. Previous work has provided means to estimate droplet size according to cloud type, altitude and temperature in various geographical locations.

Such estimates have limitations. A single value will not adequately characterize the large end or tail of the distribution, and may hence fail in predicting the nature of the accreted ice. The median volume diameter (MVD) is currently used to characterize the droplet size distribution. However, MVD may not adequately characterize those cases in which large supercooled droplets, which have diameters comprised between 50 and hundreds of micrometers, are present, as suggested by Politovich (1989).

2.1.3 LIQUID WATER CONTENT

The mass of supercooled liquid water (SLW) available to accrete upon the airframe will influence the ice accretion extent and shape. Hansman (1989) has shown that, given the same temperature and droplet size, an increase in SLW content can cause a transition from rime to mixed icing. Also, the higher the rate of SLW impaction on the leading edge of a wing, the more likely it will run back along the wing before adequate latent heat can be released and the SLW freezes. SLW content below 0.01 g.m^{-3} is thought to represent no icing hazard.

2.2 CERTIFICATION FOR FLIGHT INTO KNOWN ICING

Aircraft certification for operations in icing conditions is granted after demonstration of safe operations under satisfaction of both continuous maximum and intermittent maximum criteria of icing conditions of the Federal Aviation Regulations (FAR) Part 25 Appendix C. The design criteria is described in terms of cloud liquid water content, cloud mean effective drop diameter, ambient temperature, pressure altitude, horizontal cloud extent and cloud type. Safety and efficiency issues that pertain to aircraft that are not approved and those that are approved for flight into known icing are described below.

2.2.1 AIRCRAFT NOT APPROVED FOR FLIGHT INTO KNOWN ICING

Aircraft that are not equipped with adequate ice protection systems are not certified for operating in conditions referred to as known or forecast icing conditions in the FAR. Operators of such aircraft are, in as much as they can, constrained to avoiding icing conditions; reality has nevertheless shown the occurrence of incidents and accidents resulting from ice impact.

Aircraft in this category are usually small aircraft, for which the relative cost, weight and limited available excess engine power to drive accessories prevent operators from equipping them with ice protection systems. Also, they may have reduced system redundancies and thus reduced reliability. A majority of GA aircraft has flight performances that limit re-routing maneuvers. For example, typical service ceiling, between 10,000 and 15,000 feet, may not allow overflight of hazardous icing conditions. Their limited range may prevent them from reaching zones and alternate airports where significantly different weather and icing conditions may exist. Speed limitations may influence the time spent in hazardous icing conditions and the overall potential for cumulative accretion.

2.2.2 AIRCRAFT APPROVED FOR FLIGHT INTO KNOWN ICING

Aircraft approved for flight into known icing can cross a variety of sizes and powerplants (e.g., piston engines, turboprop engines and propellers, or jet engines with high or low bypass ratio), each affecting ice protection in distinct ways, including the excess power that can be used to drive accessories such as these systems. Ice protection systems that support operations in icing conditions fall mainly under two categories: anti-icing and de-icing systems. Anti-icing system (e.g., electro-thermal systems, hot air systems, etc.) prevent ice accretion on critical aerodynamic surfaces such as wings, tailplane as well as on the windshields. De-icing systems (e.g., pneumatic boots, electro-impulse systems, etc.) provide the capability to shed layers of ice once accumulated. In addition to corresponding to distinct management operations, those two types of ice protection system are also typically installed on aircraft with distinct flight performance (e.g., service ceiling, cruising speed, etc.). Information needs for such operations are accordingly influenced.

For all aircraft, including aircraft that are equipped with ice-protectin systems, there exists hazardous icing conditions, that are characterized by properties properties beyond those specified in the criteria of FAR Appendix C. According to the Aeronautical Information Manual (AIM), such conditions are referred to as severe icing conditions. They support a “rate of accumulation [...] such that de-icing/anti-icing equipment fails to reduce or control the hazard. Immediate flight diversion is necessary”.

2.3 ICING TERMINOLOGY

Current terminology for referring to the level of severity of icing conditions is defined in the Aeronautical Information Manual (AIM). Those definitions are provided below (US DOT, 1998).

- π **Trace:** Ice becomes perceptible. Rate of accumulation is slightly greater than the rate of sublimation. It is not hazardous even though de-icing / anti-icing equipment is not utilised unless encountered for an extended period of time (over an hour)
- π **Light:** The rate of accumulation may create a problem if flight is prolonged in this environment (over an hour). Occasional use of de-icing / anti-icing equipment removes/prevents accumulation. It does not present a problem if the de-icing / anti-icing equipment is used.
- π **Moderate:** The rate of accumulation is such that even short encounters become potentially hazardous and use of de-icing / anti-icing equipment or flight diversion is necessary.
- π **Severe:** The rate of accumulation is such that de-icing or anti-icing equipment fails to reduce or control the hazard. Immediate flight diversion is necessary.

Identification of the severity of icing conditions is difficult even when pilot reports of icing are available. The trace-light-moderate-severe severity index is subject to pilots' concept of their airplanes' ability to deal with icing and has often little to do with meteorology. Auld (1998) summarizes problems associated with the current icing severity classification. Research is underway and advisory groups are working to help define new terminology to characterize conditions that include supercooled large drops (SLD) and conditions with high LWC. Proper characterization of those conditions, in a timely manner and with high spatial resolution, as well as adequate dissemination to users, are highly desirable.

Another issue relating to the icing terminology relates to the expression used in the FAR, Part 25, Appendix C. Flight restrictions for all operations refer to specific levels of severity of "known or forecast" icing conditions. There is no explicitly formulated definition of what the "known" and "forecast" attributes refer to. For example, the period of validity and spatial extent inferred from pilot reports are not specified.

3 OVERVIEW OF CURRENTLY AVAILABLE ICING INFORMATION

Information available in the cockpit is likely to influence pilots' decisions. Since icing conditions have the potential to affect the safety and efficiency of flight operations, information on meteorological conditions that are conducive to airframe icing is important. Icing information may be categorized in the following groups: 1) in-situ, on the aircraft; 2) reported from other aircraft that may have experienced icing; from 3) forecasts; and possibly from 4) remote sensing. Forecasting and remote sensing of the icing threat is desirable. The meteorological parameters required for the remote detection of icing conditions are not currently routinely measured. Also, information on icing conditions that is currently available to pilots is limited. Before attempting to identify requirements for remote sensing, a task which is described in the subsequent chapters, a discussion of currently available information that relates to icing conditions was made. This discussion addresses the information currently available to pilots in terms of content and dissemination path, and mentions approaches to the icing issues.

3.1 CURRENTLY AVAILABLE INFORMATION

This section provides an overview of the information typically available to pilots in the pre-flight phase and during the flight. It is aimed at describing the various types of information to set a background to the following chapters.

3.1.1 COMPOSITION AND CONTENT

DIRECT OBSERVATIONS, INSTRUMENTS AND SENSORS

Information available by direct visual observation includes ice accretion on leading edges and other aircraft components with sharp edges, as well as observable weather phenomena such as cloud, precipitation and visibility that may indicate the humidity level and the phase of water droplets.

Measurements of temperature (outside air temperature or total air temperature, according to the equipment), measurements from ice detection systems when available, and airborne Doppler radar returns may as well provide information that is used by pilots to assess the potential for icing conditions in their neighborhood.

REPORTS

Numerous types of reports are compiled by the various weather service organizations and disseminated to pilots via the support of the Flight Service Station (FSS). A brief overview is presented below.

AVIATION ROUTINE WEATHER REPORTS (METAR)

This hourly report contains general weather information centered around an airport. It includes information that may be useful for assessing the potential for icing conditions, such as visibility, runway visual range, present weather phenomena (such as precipitation, obscuration or other), sky conditions (including sky cover and cloud height), temperature and dewpoint, altimeter setting, recent weather, etc.

PILOT REPORTS

Pilot Reports (PIREPs) are weather reports formulated by pilots on observed in-flight weather conditions and transmitted via Air Traffic Control (ATC) or FSS facilities. Icing conditions are reported in an icing PIREP according to the trace-light-moderate-severe terminology described in section 2.3. An icing PIREP is required to contain the following elements (US DOT, 1998):

- 1) Aircraft identification
- 2) Location
- 3) Time
- 4) Intensity or type
- 5) Altitude or flight level
- 6) Aircraft type
- 7) Indicated airspeed (IAS)
- 8) Outside air temperature (OAT)

An example of an icing PIREP in original and decoded form is provided below.

UA/OV 12 SW LWM/TM 1330/FL 120/TP BE55/SK 026 BKN 034/044
BKN-OVC/TA -11/IC MDT RIME 060-080/RM R TURBC INCR
WWD MH 270 TAS 185

This PIREP was submitted 12 nautical miles southwest of LWM at time 1330Z; altitude, 12,000 feet MSL; aircraft type, Beech Baron; sky cover is first cloud layer, base 2,600 feet MSL broken, with tops at 3,400 feet MSL; and second cloud layer, base 4,400 feet MSL broken, occasionally overcast, with no reported tops; temperature, minus 11°C; icing, moderate rime between 6,000 and 8,000 feet MSL; remarks are: turbulence increasing westward, magnetic heading 270, true airspeed 185 knots.

Pilot reports may be the best source--sometimes the only source--of weather information between weather stations. Since they are voluntary and depend on the recent traffic however, they may not be available at the time and place where the information is needed.

CHARTS

Weather depiction charts may either be available via personal computer or their information may be translated by a briefer. They provide information on general weather conditions such as areas where the conditions dictate that the operating rules in effect are either Instrument Flight Rules (IFR), Marginal Visual Flight Rules (MVFR) or Visual Flight Rules (VFR). Such rules are typically determined by cloud base and visibility, position of fronts, visibility and precipitation. Surface analysis charts provide an overview of surface temperatures, dewpoint temperatures, total sky cover, visibility and precipitation. Radar summary charts show areas of heavy precipitation and predict their direction of movement. They do not detect icing conditions per se.

FORECASTS

AREA FORECAST (FA) AND TRANSCRIBED WEATHER BROADCAST (TWEB) ROUTE FORECAST

An Area Forecast (FA) gives a prediction of the weather expected throughout a given area for a twelve-hour time interval. FAs are issued four times a day. The message begins with a prognosis and subsequently focuses on various regions, providing expected clouds and weather, icing and turbulence information. A categorical outlook is also found at the end of the FA. It summarizes, for the period of validity, the expected weather under three categories: IFR, MVFR or VFR. TWEB Route Forecasts provide information similar to an area forecast but in a route format.

INTERNATIONAL AERODROME FORECAST (TAF)

The Aerodrome Forecast (TAF) describes the most probable weather conditions expected for an aerodrome, within five nautical miles of the center of the runway complex. TAFs are scheduled four times daily for twelve or twenty-four hour periods. Their weather section includes mention of the intensity of precipitation.

WINDS AND TEMPERATURE ALOFT FORECASTS (FD)

The Winds and Temperature Aloft Forecast (FD) includes upper temperatures in degrees Celsius, which are often used to determine freezing levels, which, in turn are used by pilots to determine icing areas. Temperature data is provided at 6,000 feet and above in 3,000 foot increments. Also, FDs are prepared twice daily.

LOW-LEVEL SIGNIFICANT WEATHER PROGNOSTIC CHARTS

Issued four times daily, these charts depict forecast conditions over the next 24 hours from the issuance time. They provide information on forecast IFR, MVFR and VFR weather, forecast freezing levels, position and movement of pressure systems and precipitation and/or thunderstorms.

WEATHER ADVISORIES

AIRMET

An AIRMET is an in-flight weather advisory issued only to amend the area forecast concerning weather phenomena which are of operational interest to all aircraft and potentially hazardous to aircraft having limited capability because of lack of equipment, instrumentation, or pilot qualification. AIRMETs cover moderate icing and freezing precipitation over a six-hour period and are issued four times a day (US DOT, 1998).

ICING AIRMET

An Icing AIRMET is a forecast of non-thunderstorm-related icing of light or greater intensity, often using VOR points to outline the area of icing (Thom, 1994). It includes freezing level information. An example of Icing AIRMET is provided below.

```
BOSZ WA 202045
AIRMET ZULU UPDT 3 FOR ICE AND FRZLVL VALID UNTIL 210300
AIRMET ICE...NH MA RI CT NY PA NJ MD DC DE AND CSTL WTRS
FROM ENE TO 150NE ACK TO 200SE ACK TO 150SE SIE TO DCA
  TO HAR TO HNK TO ENE
LGT-OCNL MOD RIME ICGIC BLW 160. CONDS MOVG NEWD AND
CONTG BYD 03Z THRU 09Z.
FRZLVL...AT OR NEAR SFC THRUT FA AREA.
```

This AIRMET was prepared on the 20th at 3:45pm, eastern time (EST--2045Z) in Boston and reads as follows. It is an AIRMET Zulu (third update) for ice and freezing level valid until the 20th at 10:00pm EST (0300Z). AIRMET – ice, for New Hampshire, Massachusetts, Rhode Island, Connecticut, New York, Pennsylvania, New Jersey, Maryland, District of Columbia, Delaware, and coastal waters. It forecasts from east-northeast to 150 miles northeast of Nantucket MA [ACK], to 200 miles southeast of Nantucket MA [ACK], to 150 miles southeast of Sea Isle [SIE VOR], to Washington DC [DCA], to Harrisburg [HAR VOR], to Hancock [HNK VOR], to east-northeast, conditions of light and occasional moderate rime icing in clouds below 16,000 feet. The conditions are expected to move northeastward and continue beyond 10pm EST (03Z), thru 4am EST (09Z). The freezing level at Oregon is near the surface throughout the Area Forecast (FA) area.

SIGMET

A SIGMET is a weather advisory that concerns weather of greater severity than that covered by and AIRMET and significant to the safety of all aircraft. An SIGMET covers extreme icing.

ICING SIGMET

An Icing SIGMET is a forecast similar to an Icing AIRMET but which concerns severe non-thunderstorm-related icing.

CENTER WEATHER ADVISORIES (CWA)

Advice of the sudden development in the weather situation will often first be issued in the form of a Center Weather Advisory, for conditions beginning within 2 hours. This may be used to supplement an area forecast or prior to the issue of the appropriate AIRMET or SIGMET (Thom, 1994).

VFR NOT RECOMMENDED (VNR)

This statement will be mentioned in a standard briefing when VFR flight operations are considered inadvisable (Thom, 1994).

SEVERE WEATHER OUTLOOK CHARTS (AC)

This chart is issued each morning and provides a preliminary 24-hour outlook for watch areas, etc. (Thom, 1994).

3.1.2 INFORMATION PATHS

Information dissemination to pilots in the pre-flight phase and during the flight is mentioned below.

STANDARD PRE-FLIGHT BRIEFING

Information disseminated as part of the standard weather briefing prior to a flight includes at least the following items: 1) A weather synopsis, which is a brief summary statement explaining the causes of the weather, and including the locations and movements of highs, lows and fronts; 2) A summary of adverse conditions, that is information about any conditions that could be hazardous, such as thunderstorms, low ceilings, poor visibility, icing and including AIRMETs and SIGMETs; 3) Current weather to be found along the route; 4) An en-route forecast; 5) Destination terminal forecast; 6) Winds aloft and temperature forecast, and 7) Notices to Airmen (NOTAMs).

EN-ROUTE WEATHER INFORMATION

The En-route Flight Advisory Service (EFAS) on 122.0 MHz is used en-route. Continuous in-flight weather advisories are broadcast on HIWAS (Hazardous In-flight Weather Advisory Service). Transcribed WEather Broadcasts (TWEB) also provide continuous broadcasts of recorded weather and NOTAM information on certain Non-Directional Beacons (NDBs) and Very high frequency Omni-directional Radio range (VOR). The Automatic Terminal Information Service (ATIS) is a continuous broadcast of recorded information at certain airports containing weather information, runway in use and other pertinent information. Other automated

systems include the Automated Weather Observing System (AWOS) and the Automated Surface Observing System (ASOS), which report temperature, dewpoint, visibility, and cloud/ceiling data. ASOS also provides precipitation information and freezing rain occurrence.

3.2 APPROACHES TO ICING ISSUES

Flight safety and efficiency improvements with regard to icing can be accomplished using the following approaches:

- π By extending aircraft tolerance to icing: this can be achieved by improving the ice protection systems and, with pilots in the loop, by improving the information that supports ice protection system management.
- π By supporting appropriate escape and avoidance maneuvers around icing conditions that are beyond the tolerance level of aircraft: this can be accomplished by improving the remote detection of such icing conditions, and by improving icing forecasts.

Efforts along those two approaches are desirable for improving the navigability of aircraft in the air transportation system. Areas investigated along the first approach include the development of tools to help diagnose the status and effect of ice accretion on aircraft dynamics (Bragg *et al.*, 2000). Areas investigated along the second approach include the development of diagnosis and forecast models providing spatial information on icing potential (Politovich *et al.*, 1996) and the development of icing remote sensing systems, undertaken by NASA, the FAA, the Department of Defense, the National Center for Atmospheric Research and NOAA (Ryerson *et al.*, 2000). Additional efforts of interest include the development of data link, the automatic generation of PIREPs, the development of graphical cockpit information systems (e.g., Avydine, Allied Signal) under NASA's Advanced General Aviation Transport Experiments (AGATE) program.

4 SURVEY OF PILOT INFORMATION NEEDS AND STRATEGIES FOR OPERATING IN ICING CONDITIONS

In order to set functional requirements of cockpit information systems to help pilots operate in icing conditions, an attempt at understanding pilot information needs and icing-related decision-making issues was made. A survey of the pilot community was conducted and yielded insights on icing-related pilot information needs within the current system of aviation weather dissemination. Also, an analysis of pilot decision criteria allowed to characterize features of desirable icing-related information.

This chapter presents an overview of the survey results on pilot information needs and strategies for operating in icing conditions. It is divided up into two major parts. The first part reports on the method employed, including an overview of the survey design, distribution and analysis. The second part describes the results obtained for each of the seven sections of the survey.

4.1 METHOD

The survey was organized to explore three aspects of the influence of information on pilot icing-related decision-making:

- π Pilot use of currently available information, including the frequency of use and perceived importance of various elements of information typically obtained prior to and during a flight.
- π Pilot decision-making approach to dealing with potential and actual icing situations.
- π Pilot identification of desired attributes of new icing information systems

4.1.1 WEB-BASED SURVEY DESIGN

In order to take advantage of the wide distribution potential of the World Wide Web and use the convenience of electronic collection of scripts, the survey was prepared on Hyper Text Markup Language (html). Sample webpages are included in Appendix A. The survey was divided in seven sections, each of which are described below.

SECTION 1 - SUBJECT BACKGROUND INFORMATION

Pilots from all operational categories were reached in the notification process of this survey. In order to provide a basis for analyzing the data according to factors that may influence the need for icing information, pilots were asked to indicate their primary and secondary categories of operation, from the following list: General Aviation (GA), Corporate, Commuter Airline, Major Air Carrier, Civil Helicopter, Military Helicopter, Military High-Performance and Military Transport. Additional information was collected from the test subjects, including certificates and ratings held, flight experience, geographic region of operation and other factors pertaining to pilot flight operations.

SECTION 2 - IMPORTANCE OF CURRENTLY AVAILABLE INFORMATION

Pilots were asked to rate the importance of currently available information elements for making icing-related decisions. Elements were listed in three categories: 1) Direct Visual Observations, Instruments and Sensors, included information elements directly observable, such as clouds and visibility, and information obtained by the pilot from onboard instruments such as temperature probes and weather radar, etc.; 2) Reported Observations and Measurements, included information collected at other locations and reported to the pilot, such as airport surface observations (METARs), pilot reports (PIREPs), “party-line” information (PLI), etc. 3) Forecasts, included relevant weather forecasts such as area forecasts (FA), terminal forecasts (TAF), etc. The elements listed under each category are given in Table 4-1. Although AIRMETs and SIGMETs were listed under the Reported Observations and Measurements category, they may contain both diagnostic and forecast information.

Direct Visual Observations, Instruments and Sensors	Reported Observations and Measurements	Forecasts
Visual Observation of Clouds	Surface Observations (METARs)	Area Forecast (FA)
Visual Observation of Precipitation	Satellite Images	Terminal Forecast (TAF)
Visibility	Radar Images	Winds Aloft Forecast (FD)
Ice Accretion on Aircraft Components	Icing AIRMETs	Freezing Levels
Outside Air Temperature Measurement	Other AIRMETs (e.g., Convective AIRMETs)	Specific Icing Forecasts (Specify)
Total Air Temperature Measurement	Icing SIGMETs	
Airborne Weather Radar	Other SIGMETs (e.g., Convective SIGMETs)	
Ice Detection System	PIREPs (Pilot Reports)	
Other (Specify)	ATIS (Automated Terminal Information System)	
	"Party-Line" Information (Overheard Communications Addressed to Other Aircraft)	
	Other (Specify)	

Table 4-1: Weather Information Elements Listed Under Three Categories

An example of the importance rating scale used in shown in Table 4-2. Pilots were asked to rate importance of each information element according to a 1 to 5 scale with anchors of Trivial for 1 and Critical for 5; a non-applicable (N/A) option was also provided.

	N/A	Importance				
		Trivial 1	2	3	4	Critical 5
METAR	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
PIREPs	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
PLI	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
etc.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Table 4-2: Example of Survey Format (Information Importance)

SECTION 3 - USE OF CURRENT ICING INFORMATION PATHS:

Pilots were asked to “indicate how [they] typically obtain icing information from the paths mentioned”. The specific paths through which pilots receive icing information, listed in Table 4-3, were rated on a scale defined with five anchors, as indicated in Table 4-4.

Pre-Flight Phase

- Direct Observations
- AM Radio
- FSS, Weather Office or Dispatch in Person
- FSS, Weather Office or Dispatch by Phone
- Dispatch Paperwork
- DUATS
- Web

Commercial Weather Provider (Specify)

In-Flight

- Direct Observations
- Airborne Sensors
- ACARS
- Flight Watch (122.0)
- ATC
- FSS, Weather Office or Dispatch on Radio
- Party-Line Information (Overheard Communications Addressed to Other Aircraft)
- Other (Specify)

Table 4-3: Information Path Elements Listed Under Flight Phases

Since the technology available is highly dependent on the phase of flight, the various paths were evaluated under two phases of flight, namely pre-flight and in-flight phases.

	Never	Rarely	Sometimes	Often	Always
Direct Observations	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
PLI	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
ATC	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
FSS or Dispatch on Radio	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
etc.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Table 4-4: Example of Survey Format (Frequency of Use of Current Information Paths – In-Flight)

SECTION 4 - ADDITIONAL INFORMATION DESIRED:

Pilots were asked through a free-response question, to identify additional information they would envision to be useful to help support icing-related decisions.

SECTION 5 - INFORMATION ON SIGNIFICANT AIRCRAFT ICING ENCOUNTERS:

This section elicited subjects' exposure to icing conditions in their primary category of operations. The free-response question solicited anecdotal descriptions of significant aircraft icing encounters and was stated as: "Please describe your most significant icing encounter in as much detail as possible".

SECTION 6 - KEY ICING-RELATED DECISIONS:

Pilots were asked to describe "key icing-related decisions of a typical flight in potential icing conditions". Also, ratings on relative importance of ground versus in-flight icing were collected, according to a five-anchor comparative scale.

SECTION 7 - EVALUATION OF REMOTE ICE DETECTION SYSTEM REQUIREMENTS:

In the final section, pilots were asked to perform a subjective evaluation of usefulness of potential remote icing detection systems, and queried on sensor minimum useful range and maximum affordable cost.

4.1.2 SURVEY DISTRIBUTION

The survey was posted on the worldwide web during a two-month period. A broad range of the pilot community was solicited by electronic mail, electronic newsletter (e.g. AvFlash), web posting (e.g. AvWeb, Bluecoat Digest, aol.com), and other coverage (Business & Commercial Aviation Magazine, 1998). Most of the documented responses were collected within 24 hours following the issue of the AvFlash electronic newsletter. Also, since responses were obtained from subjects who voluntarily self-reported to the survey webpage, results are expected to carry a bias towards pilots who are more computer literate and more interested in icing than the overall pilot population.

4.1.3 DATA ANALYSIS

Questions of both multiple-response and free-response types were used throughout the survey. Methodologies for analyzing data compiled in both cases are described below.

MULTIPLE-RESPONSE QUESTIONS

Multiple-response questions in Section 2 provided data on ratings of importance of currently available information. Ratings of 4 and above were tabulated and are referred to as “important” in the following. Multiple-response questions in section 3 provided data on ratings of frequency of use of current information paths. Ratings of *often* and *always* were tabulated and are referred to as “frequently used” in the discussion.

FREE-RESPONSE QUESTIONS

Free-response questions were used in sections 4, 5 and 6. Responses in each section were evaluated by an analyst and grouped according to common responses. Recurring groups were identified and counts were compiled. A second analyst reviewed results for corroboration. The methodology is referred below as the recurring-object taxonomy. Narratives on significant aircraft icing encounters collected in section 5 were classified according to impact of aircraft structural icing on operations and escape actions. Results from the General Aviation community were compared with 36 reports collected from the NASA-administered Aviation Safety Reporting System (ASRS) database over an eight-year period (ASRS, 1998). Both analyses were performed using the recurring-object taxonomy. Descriptions of key icing-related decisions collected in section 6 were classified according to two distinct themes: decision type (e.g., go/no-go, avoidance, escape, etc.) and information elements that served as decision criteria (e.g., temperature, visible moisture, etc.).

4.2 SURVEY RESULTS

4.2.1 SECTION 1 - RESPONSE AND SCOPE OF ANALYSIS

Data was received from 589 pilots with representation from the operational categories shown in Table 4-5. Most of the respondents (95%) were instrument-rated pilots and GA pilots (73%) dominated responses. Due to low response rate from the helicopter pilot community, responses from this subgroup was disregarded in the following analysis. The analysis hence focuses on results from fixed-wing aircraft pilots only.

Operational Category	Primary	Secondary
General Aviation	426	78
Corporate	62	28
Major Air Carrier	39	3
Military Transport	17	4
Commuter Airline	14	5
Military Helicopter	11	2
Military High-Performance	8	5
Civil Helicopter	3	5

Table 4-5: Respondents' Primary and Secondary Operational Category

Respondents' operations were primarily based in the United States and in Canada (96%). They averaged 3,412 hours of total flight time, 686 hours of instrument time (ranging between an average of 366 hours of instrument time for GA pilots to an average of 3,033 hours of instrument time for major air carrier pilots). Their average age was 44 years old. Only 3% of the respondents were female. A total of 28% of respondents operated aircraft certified for icing.

4.2.2 SECTION 2 - IMPORTANCE OF CURRENTLY AVAILABLE INFORMATION:

1) DIRECT VISUAL OBSERVATIONS, INSTRUMENTS AND SENSORS:

Figure 4-1 depicts the percentage of pilots who rated the listed information items as important. Ice accretion was rated important by more than 90% of pilots in all operational categories. Other information elements indicated as important by more than 50% of pilots in each operational categories include temperature (outside air or total) and precipitation.

Clouds were indicated as important by a majority of Corporate and Major Air Carrier respondents. In most cases, pilots from these groups operate jet aircraft at cruising altitudes above typical cloud deck altitude and procedurally use visible moisture and total air temperature

(TAT) below a predetermined value (typically +10°C) as information criteria for activation of the ice protection system.

A large percentage of military transport pilots indicated radar as important (53%), ice detection systems as important (41%) and a small percentage indicated visibility as important (12%). GA pilots indicated low importance of radar and ice protection systems that they are not typically equipped with.

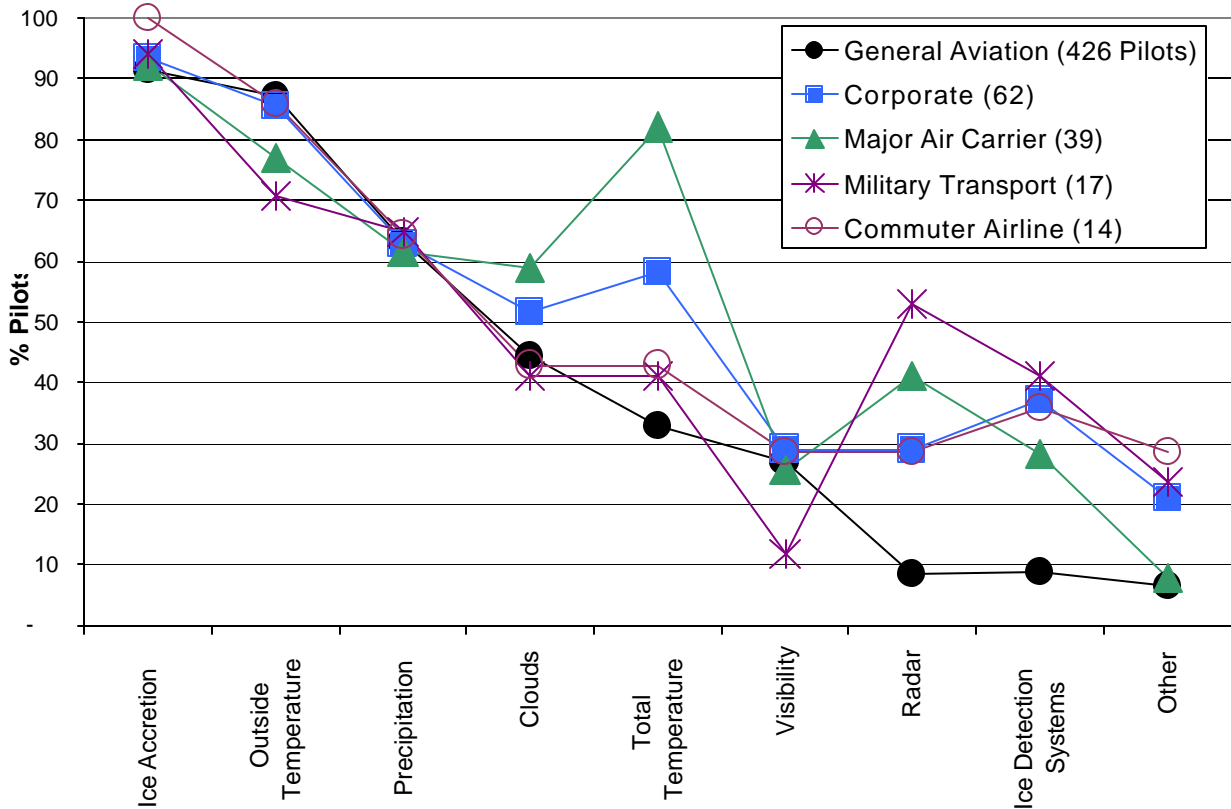


Figure 4-1: Importance of Direct Visual Observations, Instruments and Sensors

II) REPORTED OBSERVATIONS AND MEASUREMENTS:

The importance ratings of the reported observations and measurements information elements are presented in Figure 4.2. A large percentage of pilots rated PIREPs as important: over 60% in all operational categories, and up to 100% for Military Transport pilots.

Military Transport pilots unanimously rated Icing SIGMETs and Icing AIRMETs as equally important, followed by METAR (77%), Other SIGMETs (77%) and PLI (71%).

For 92% of Commuter Airline pilots, PLI was rated as important, followed by PIREPs (86%) and METAR (66%) and Icing SIGMETs (65%). Commuter Airline pilots also indicated in greater percentage compared to other pilots, ATIS information as important (50%).

Compared to pilots of other operational categories, a smaller percentage of Major Air Carrier pilots indicated as important the information elements listed. Information elements listed as important include PIREPs (63%), Icing SIGMETs (59%), PLI (57%) and METAR (56%).

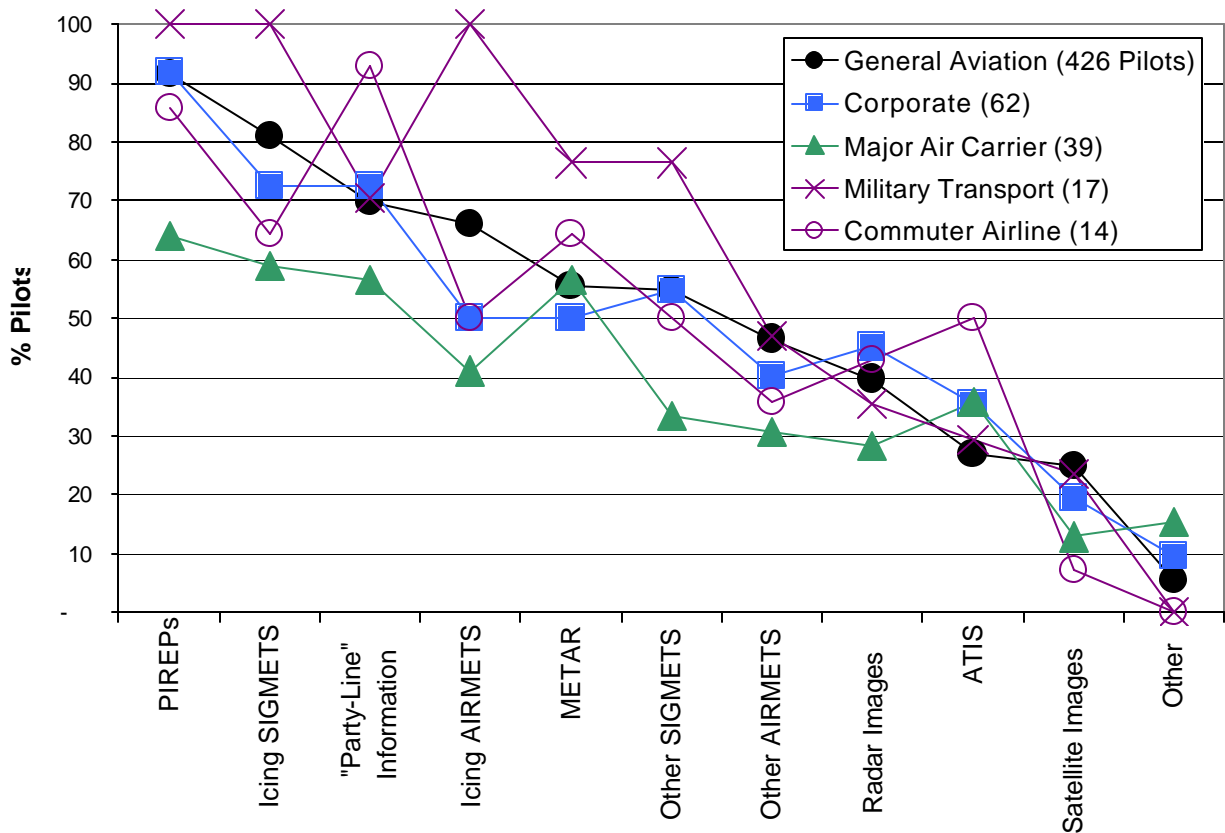


Figure 4-2: Importance of Reported Observations and Measurements

A large percentage of Corporate pilots (92%) indicated PIREPs to be important, followed by PLI (73%), Icing SIGMETs (72%) and Other SIGMETs (55%). A larger percentage of Corporate pilots (46%) than pilots of other operational categories indicated Radar Images as important.

GA pilots indicated, in large percentage, PIREPs to be important (92%), followed by Icing SIGMETs (81%), PLI (70%), Icing AIRMETs (67%), METAR (56%) and Other SIGMETs (55%). A larger percentage of GA pilots (25%) and Military Transport pilots (24%) than pilots of other operational categories indicated Satellite Images as important.

III) FORECASTS:

The percentages of pilots rating forecast items as important is presented in Figure 4-3. Except for Major Air Carrier pilots (39%), a majority of pilots (over 70% in all other operational categories) indicated Freezing Levels as important. Because of the nature of this information element, this may indicate the perceived importance of information along the vertical dimension.

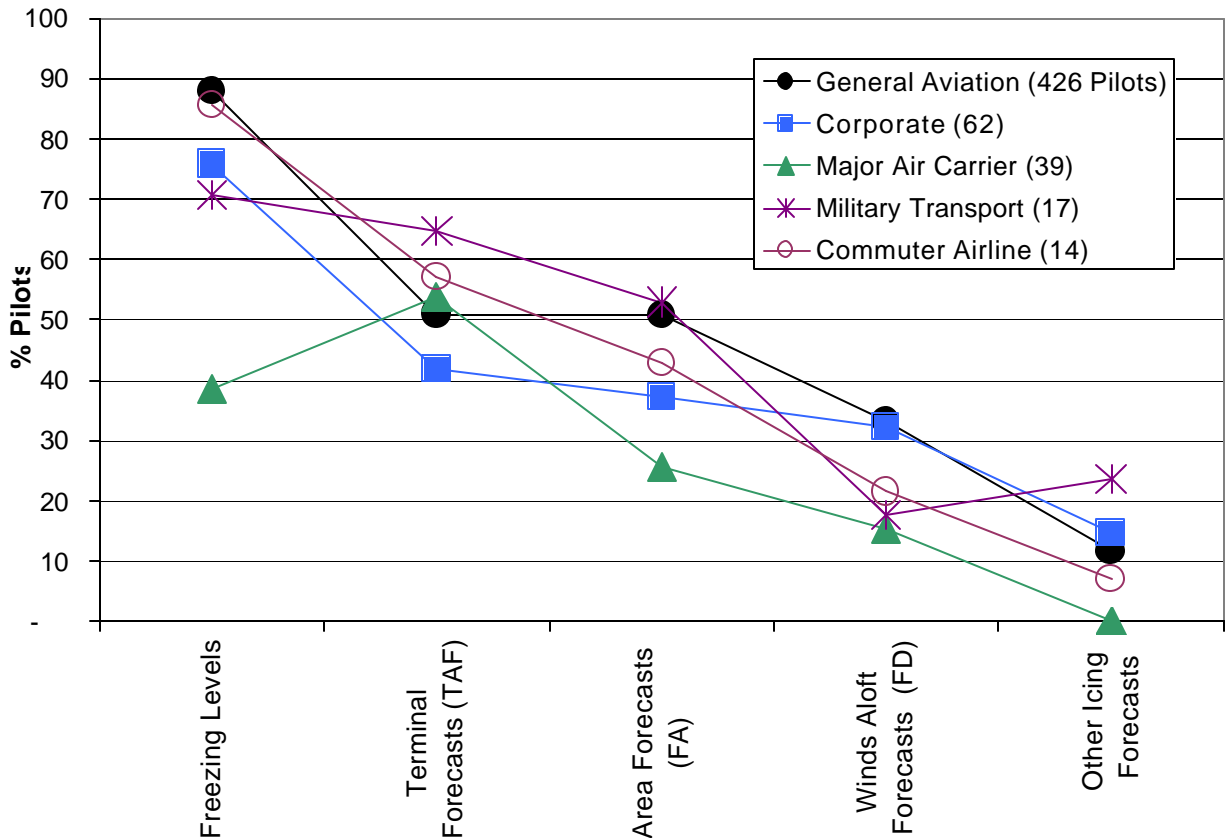


Figure 4-3: Importance of Forecasts

Except for Corporate pilots, a majority of pilots indicated TAF as important forecast information elements. Overall, FDs and Other Icing Forecasts were rated less often than other elements as important by pilots in all operational categories. Other Icing Forecasts were indicated as important by a larger percentage of Military Transport pilots (23%) compared to pilots of other operational categories.

4.2.3 SECTION 3 - USE OF CURRENT ICING INFORMATION PATHS

PRE-FLIGHT PHASE

The percentage of pilots who reported frequent use of specific paths for acquiring icing information is depicted in Figure 4-4 for the pre-flight phase. The information paths are ranked according to decreasing indicated information path use across all operational categories. Information frequently received by phone from the Flight Service Station (FSS), Weather Office and Dispatch, was indicated by a majority of Commuter (79%), GA (78%) and Corporate (61%) pilots. Information frequently received in person from the same services was indicated by a majority of Military Transport pilots (65%). The most frequently used icing information path for Major Air Carrier Pilots was indicated to be the Dispatch Paperwork (64%).

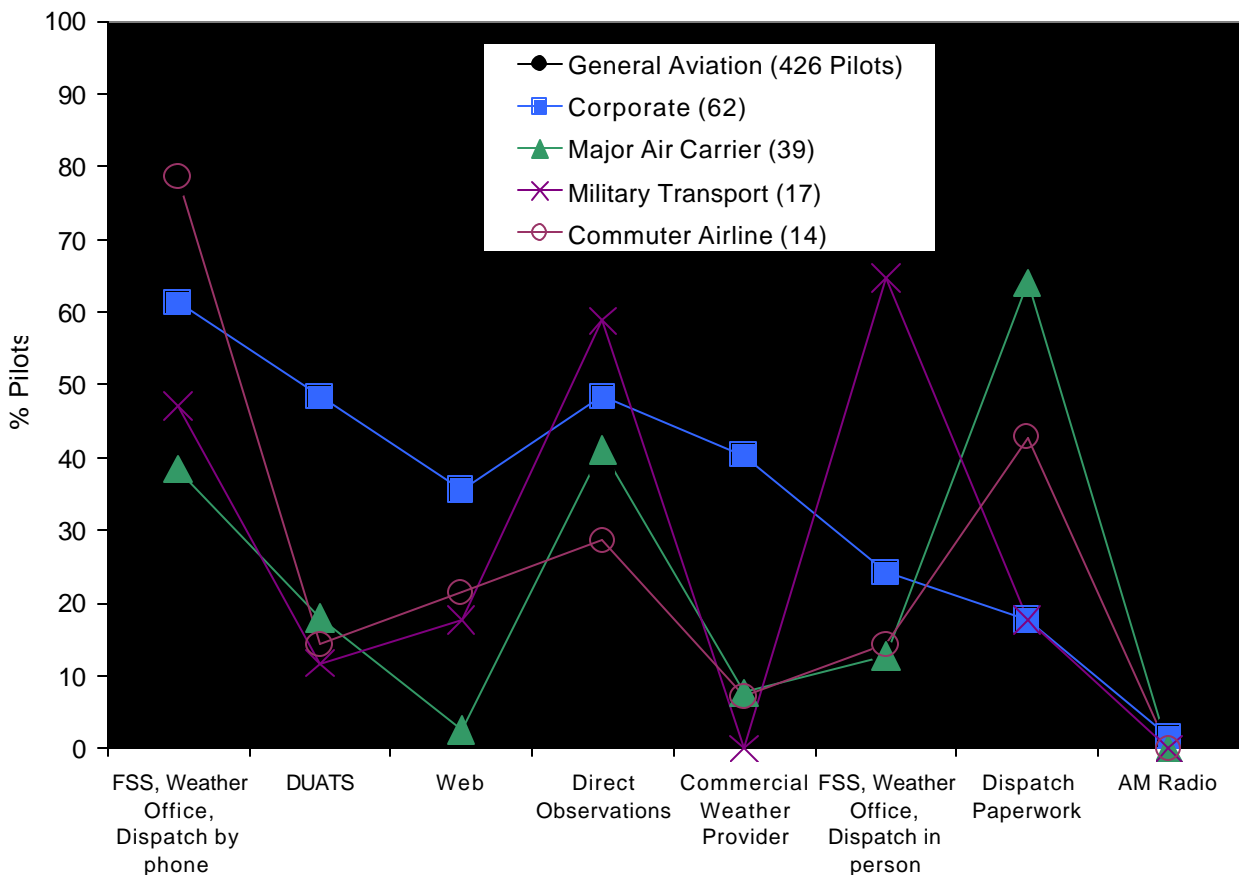


Figure 4-4: Reported “Frequent” Use of Pre-Flight Icing Information Path

A majority of GA pilots also indicated frequent use of the Direct User Access Terminal (DUAT - 62%) and the Web (50%). Those information paths was indicated less frequently by Corporate pilots (49% and 35% for DUATS and Web, respectively) and much less frequently used by pilots of other operational categories (less than 25%).

Other information elements which were considered important by the different groups were the following: A large percentage of Corporate pilots also indicated frequent use of Direct Observations (48%) and frequent use of Commercial Weather Provider information elements (40%). Major Air Carrier pilots indicated the frequent use Direct Observations (40%), followed by FSS, Weather Office and Dispatch by phone (38%). A majority of Military Transport pilots indicated the frequent use of Direct Observations (58%), followed by FSS, Weather Office and Dispatch by phone (47%). Commuter Airline pilots indicated the frequent use of Dispatch Paperwork (43%). AM Radio was not indicated to be frequently used (less than 5% across all operational categories).

IN-FLIGHT

The percentage of pilots who reported frequent use of in-flight icing information paths in-flight is depicted in Figure 4-5. Information paths are ranked by use across all operational categories.

Information accessed via Direct Observations was indicated to be frequently used by over 75% of pilots in all operational categories. “Party-Line” Information (PLI) was also indicated to be frequently used by a majority of Commuter Airline (72%), GA (57%) and Corporate (55%) pilots.

Other frequently used information paths indicated by GA pilots included Air Traffic Control (ATC – 48%), En-route Flight Advisory Service (EFAS - 47%), and FSS or Dispatch on radio (45%). It was found that pilots of other operational categories indicated a smaller percentage (between 7 and 20%) use of EFAS, in comparison to GA pilots. It was also found that GA pilots indicated in much smaller percentage (8%) frequent use of Airborne Sensors, in comparison to pilots of other operational categories (over 30%). A majority of Military Transport pilots indicated more frequent use of FSS or Dispatch on radio (53%) than pilots of other operational categories.

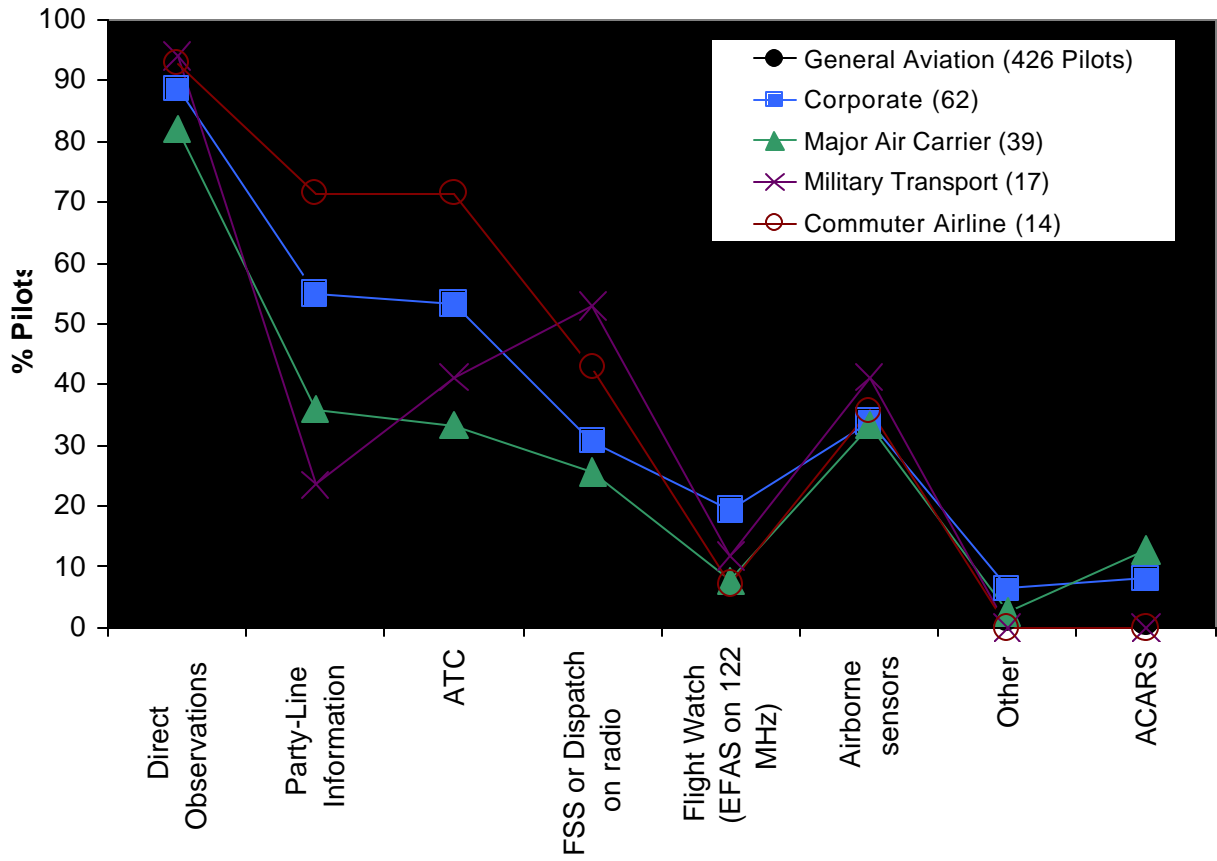


Figure 4-5: In-Flight Icing Information Path Use (Frequency)

4.2.4 SECTION 4 - ADDITIONAL INFORMATION DESIRED:

Figure 4-6 presents results on pilot reports of additional information that would help support icing-related decisions. It was found that more PIREPs would be desired by most pilots (except for Major Air Carrier pilots); better forecasts and graphical information would also be highly desirable.

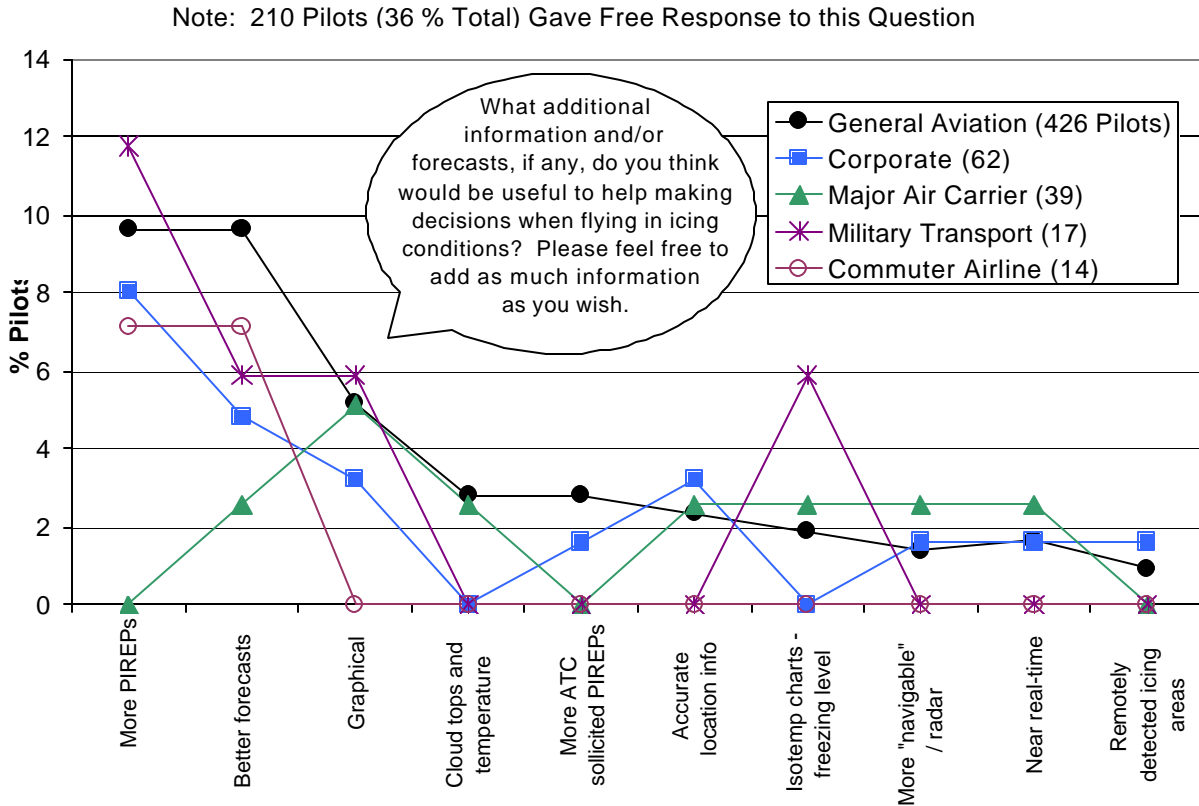


Figure 4-6: Additional Information Desired

Additional information desired by pilots included the following elements: Iso-temperature Charts with Freezing Level information was indicated by Military Transport, Major Air Carrier and GA pilots; elements such as Accurate Information on Icing-Zone Location, radar-like information, Near-Real time information, were indicated by Corporate, Major Air Carrier and GA pilots; Cloud Tops and Temperature were indicated by GA and Major Air Carrier pilots; More ATC solicited PIREPs and Remotely Detected Icing Areas were indicated by GA and Corporate pilots.

4.2.5 SECTION 5 - INFORMATION ON SIGNIFICANT AIRCRAFT ICING ENCOUNTERS:

Figure 4-7 depicts the ten recurring areas of ice impact according to survey results and NASA ASRS reports. The most frequently mentioned icing impacts, recurring in 6% of the cases in the survey results and in 17% of the cases in the ASRS results referred to Difficulty Holding Altitude. The second most frequently reported icing problems were related to Instrumentation (such as pitot, static or venturi) problems. Other recurrent aircraft performance problems included Difficulty to Climb (5% of survey results), Controllability problems (3% and 5% in survey and ASRS results, respectively), Flaps and/or Gear deployment problems (2% of survey results), Engine Failure (2% of survey results) and Propeller Imbalance (1% of survey results).

Other recurrent ice accretion effects not directly impacting aircraft performance but seriously affecting flight operations include: Reduced visibility in approach with ice-covered windshield (5% of survey results), Induction system problems (3% of survey results and 8% of ASRS results), and Antenna icing problems causing Failure of navigation and / or communication systems (1% of survey results and 5% of ASRS results).

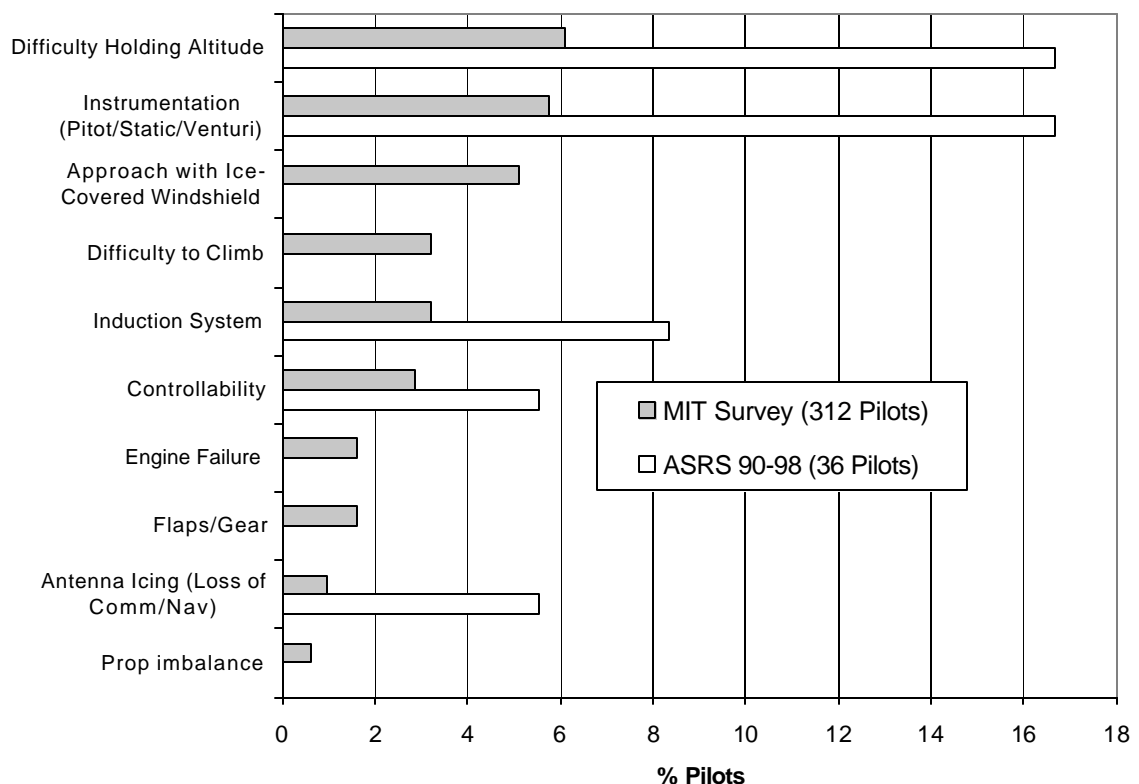


Figure 4-7: Reported Icing Impact (GA only)

Figure 4-8 depicts the nine recurring themes of reported pilot escape actions according to the survey results. The most frequently mentioned escape actions included Descending to Warm conditions--conditions where warmer air temperature does not support ice accretion--or VMC (18% of survey results and 16% of ASRS results) and Diverting to Land (13% of survey results and 36% of ASRS results). It was found that escape actions involving vertical maneuvers (i.e., including either a climb or a descent) accounted for 44% of all ASRS narratives and 12% of all survey responses. It was also found that 3% of pilots in the survey results and 14% of pilots in the ASRS results declared either an emergency or requested priority with ATC.

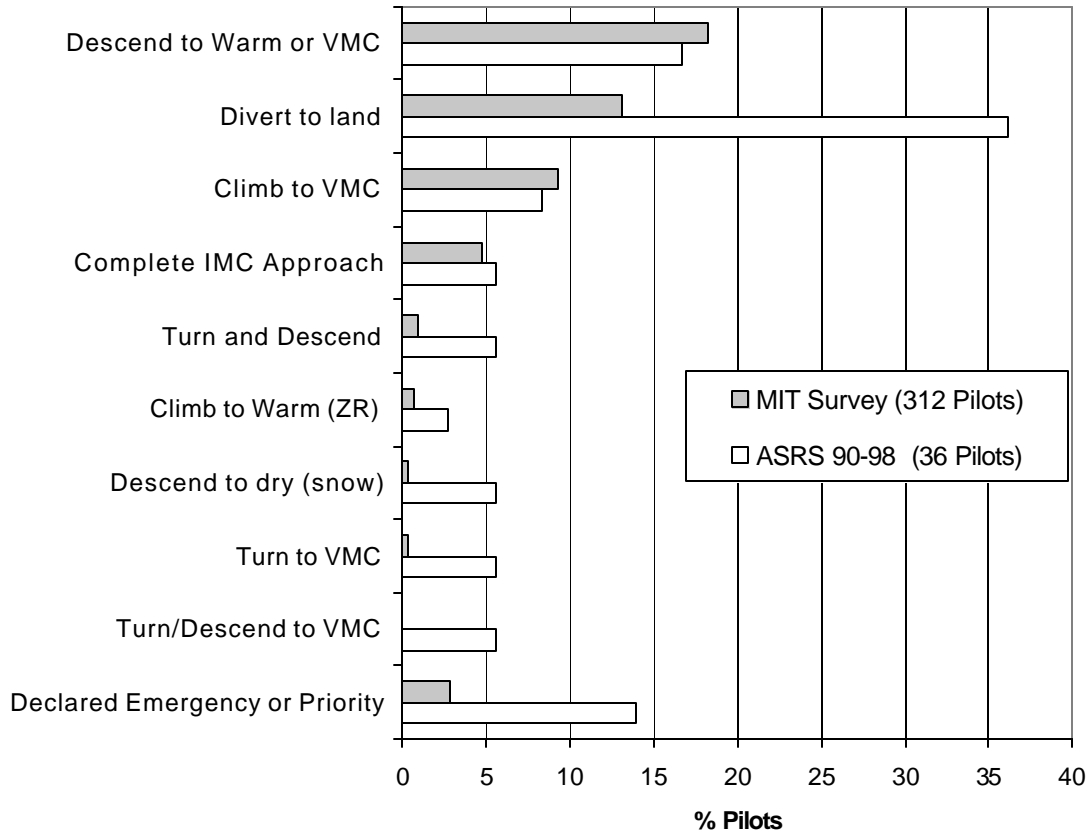


Figure 4-8: Reported Escape Actions (GA only)

4.2.6 SECTION 6 - KEY ICING-RELATED DECISIONS:

Data on key icing-related decisions is presented in Figure 4-9 for all operational categories. It should be noted that the data is dominated by responses from GA pilots (73%) and pilots flying aircraft not equipped for flight in known icing (72%). Recurring icing-related decisions were the Go/No-Go decision (42%), the Escape decision (23%), the Avoidance versus Penetration decision (8%) and decisions regarding the Management of the Ice Protection Systems (6%). Pilots also mentioned key icing-related decision such as Proceed/Not-Proceed (3%), the action of Monitoring the situation (3%) and strategic Route Optimization decisions (2%). In a few cases, pilots also mentioned the identification of whether or not they were in a situation worth Declaring as an Emergency (1%). The dominant criteria used by pilots for making strategic go/no-go decisions was indicated to be the escape route accessibility. In turn, it was found that the evaluation of an optimal escape route involved deciding between actions such as climbing, descending, reversing course or landing at an alternate destination. Avoidance criteria were mentioned to include avoiding visible moisture at temperatures below freezing.

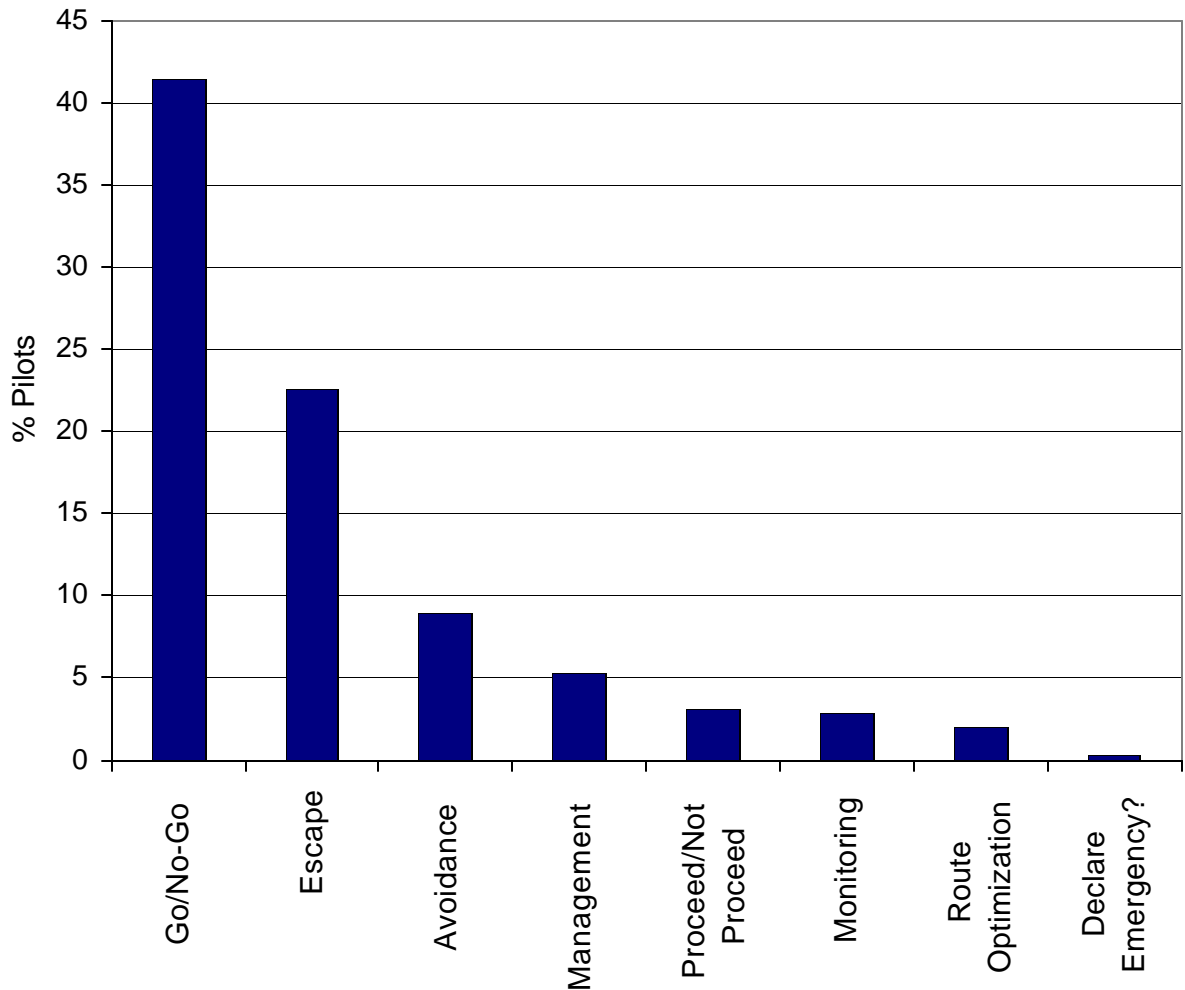


Figure 4-9: Key Icing-Related Decisions

In addressing key icing-related decisions, pilots also mentioned key information criteria used in the decision-making process; these were also analyzed with the recurring-object taxonomy, and results are shown in Figure 4-10.

The most frequently recurring decision information criteria included visible moisture, clouds or precipitation in the terminology of pilots (33%), Temperature (30%) and Icing (29%). Other criteria mentioned included Synoptic weather conditions (3%) and the Confirmation of icing conditions via either in-situ observation or PIREPs (1%).

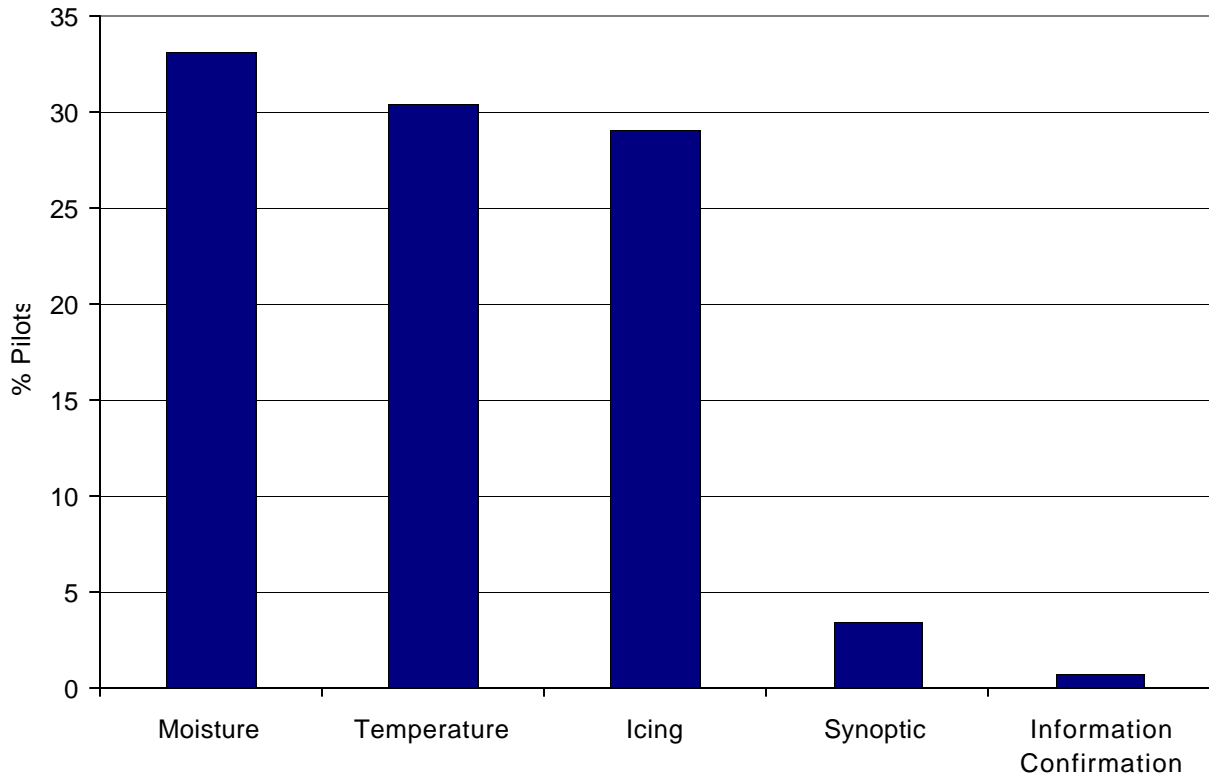


Figure 4-10: Key Icing-Related Decision Information

Figures 4-11 through 4-13 depict a more detailed analysis of information used to support decisions within the moisture, temperature and icing categories. As depicted in Figure 4-11, Moisture information criteria included primarily Cloud Tops and Bases or Layer Thickness (mentioned by 35% of pilots) and boundaries of Instrument Meteorological Conditions to Visual Meteorological Conditions (IMC/VMC) areas (32%). Other criteria included Freezing Rain (13%), Ceiling Above Ground Level (AGL – 8%), Moisture Amount in Clouds or radar reflectivity (decibels of reflectivity, dBZ, on radar – 6%), Cloud Type (5%) or variations of temperature over time (Trends – 2%).

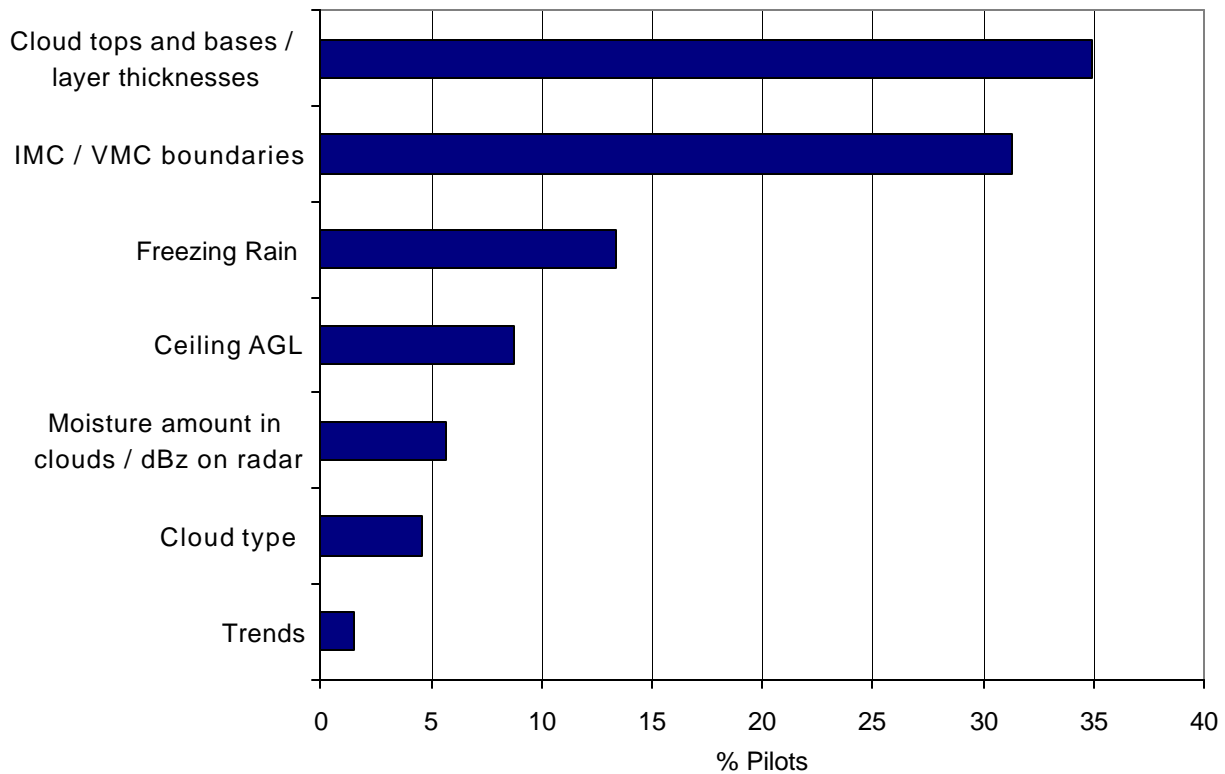


Figure 4-11: Moisture Information

As depicted in Figure 4-12, key Temperature information criteria included single or multiple Freezing Levels (mentioned by 33% of pilots), the distribution of the Temperature Field (26%), Local Outside Air Temperature (OAT) measurements, the identification of the Warm layers (12%), and in smaller percentage, Dewpoint (2%) and Temperature trends (1%).

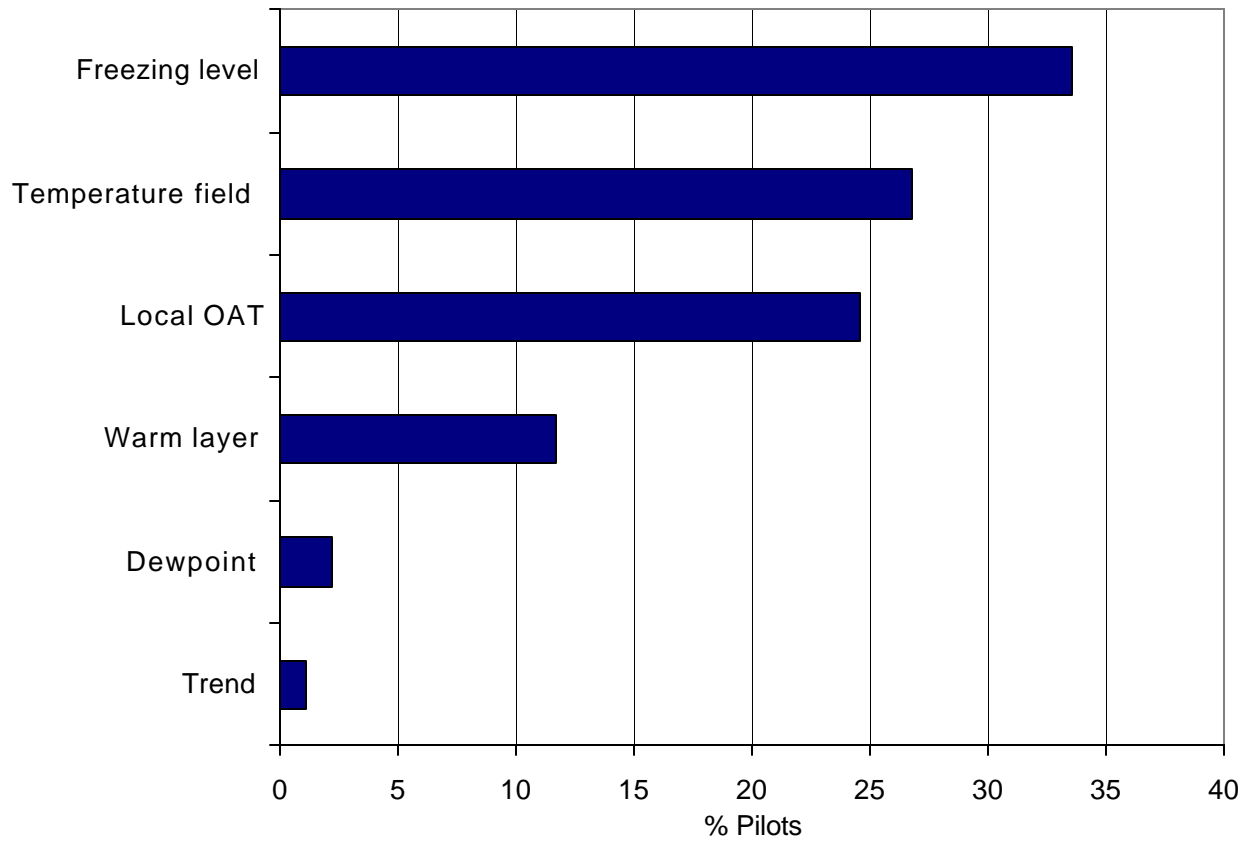


Figure 4-12: Temperature Information

Key decision information criteria directly related to icing are depicted on Figure 4-12. As depicted in Figure 4-13, key Icing information criteria included Corroborated Icing Zone information, via either in-situ observations or PIREPs (mentioned by 52% of pilots), Icing-Free Zones (15%), the spatial extent of the icing conditions (12% and 8% for vertical and horizontal extent, respectively), icing Type (7%), icing Intensity (5%) and icing Probability (2%).

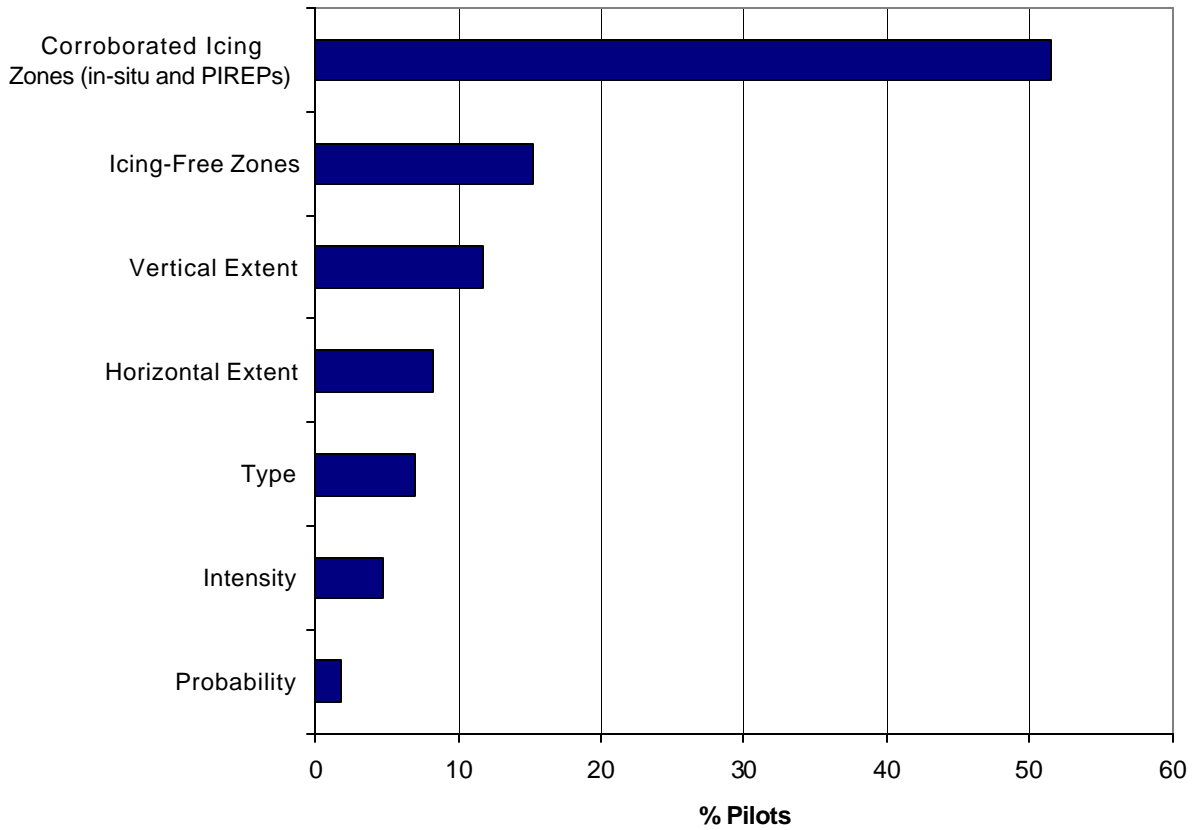


Figure 4-13: Icing Information

4.2.7 SECTION 7 - EVALUATION OF REMOTE ICE DETECTION SYSTEM REQUIREMENTS:

Table 4-6 shows results for the questions relating to the performance of remote ice detection systems. A majority of GA pilots (70%) indicated they would desire a range of at least 20 nautical miles. Indications from pilots across other operational categories showed that, to reach a majority of pilots by operational category, a range of at least 40 nautical miles would be desired by Military Transport, Corporate and Commuter Airline pilots, and a range of at least 80 nautical miles would be desired by Major Air Carrier pilots.

Considerable differences in indicated acceptable costs for remote ice detection systems were found for pilots of the different operational categories. The cost which at least a majority of GA and Military Transport pilots would be willing to pay was found to be \$1,000; the cost that at least a majority of Corporate pilots would be willing to pay was found to be \$5,000. Less than 50% of Major Air Carrier and Corporate pilots indicated that they would pay for remote ice detection systems.

In-flight icing was indicated to be a more important issue than in-flight icing by GA, while it was found to be as important by pilots of other operational categories. Results were also obtained on the perceived utility of remote ice detection systems according to the remote sensing platform. It was found that both airborne and ground-based remote ice detection systems would be very useful to GA and Corporate pilots; datalink was found very useful by GA, Corporate and Commuter pilots.

Pilots rated airborne and ground-based remote sensing systems and datalink technologies as very useful. A majority of pilots in all operational categories indicated a minimum useful range of 40 nm, except for major air carrier. It was found that over 40% of pilots in all categories would pay up to \$5,000 for in-flight icing avionics except for major air carriers. A lower number of pilots would pay up to \$10,000, especially within general aviation (13%).

4. Survey of Pilot Information Needs and Strategies for Operating in Icing Conditions

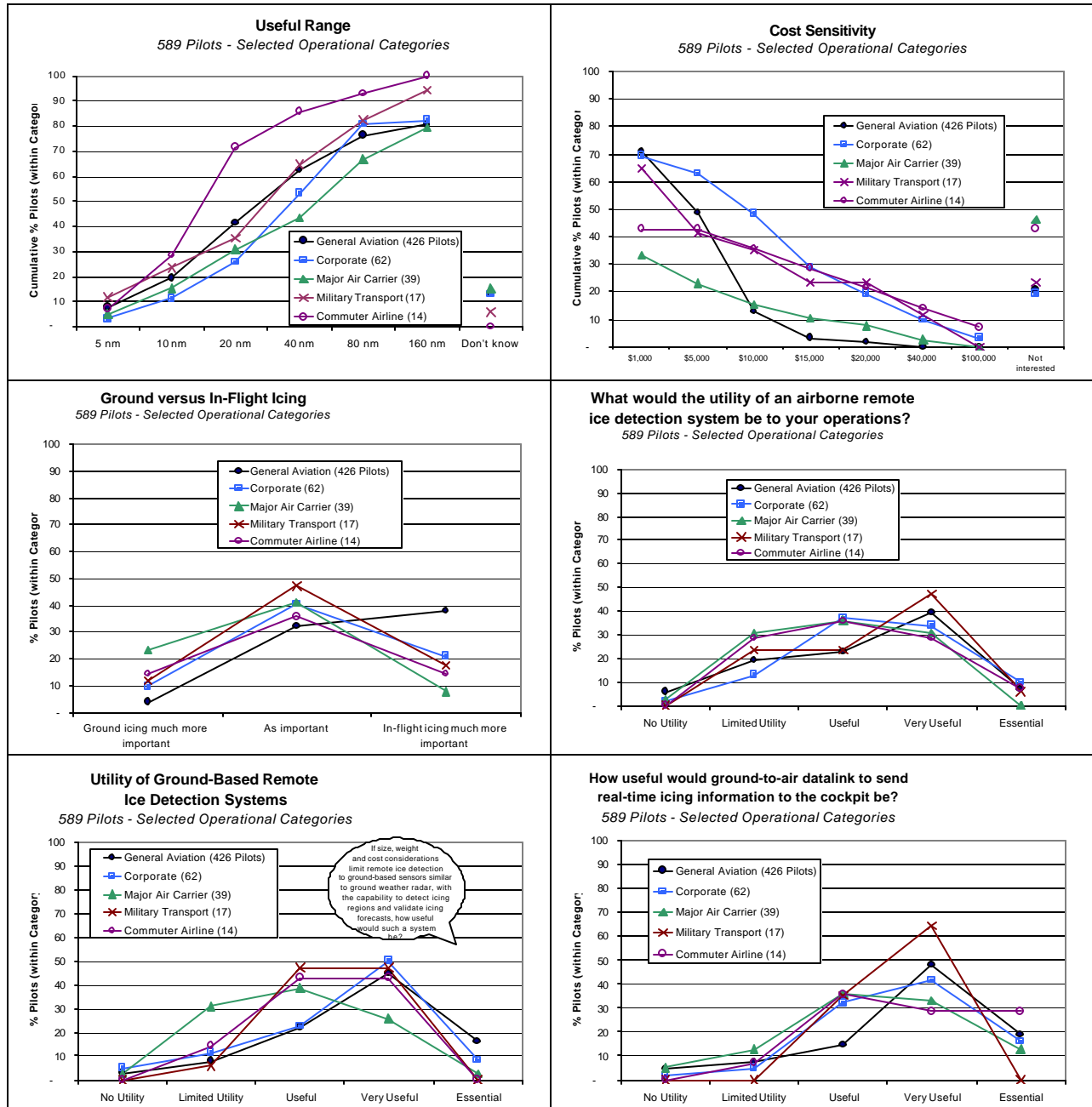


Table 4-6: Remote Ice Detection Systems Performance Evaluation

4.3 CONCLUSIONS

Pilot information needs and strategies were investigated in a survey performed on the World Wide Web. Although a majority of respondents were general aviation pilots, significant responses were received from pilots in other operational categories, and responses were analyzed according to the primary operational categories indicated.

Pilots identified several key icing-related decisions. In order of decreasing recurrence, the following decisions were mentioned: 1) the pre-departure go/no-go decision; 2) the identification of an escape path along the intended route of flight; 3) the decision of whether to penetrate or to avoid the icing conditions; 4) for known-icing approved aircraft operations, decisions relating to the management of ice protection systems. A key information criterion, in most decisions mentioned above by general aviation pilots, was the ability to identify viable escape paths.

Results also indicated that a key information element required to support important icing decisions, is the spatial distribution of the icing threat field. Decision criteria relating to accurate spatial location of icing conditions were mentioned more often than criteria relating to icing severity. The analysis also suggested that pilots perceive information on locations where atmospheric conditions are *not* conducive to icing to be beneficial in supporting escape decisions.

Common strategies for escaping icing conditions included vertical maneuvers. This is related to the icing threat field spatial distribution and the typical differences in distances to horizontal and vertical boundaries. Except for weather conditions associated with vertical convection, much stronger temperature and liquid water content (LWC) gradients along the vertical dimension than along the horizontal dimension often characterize the icing threat field. Hence information on icing conditions along the vertical dimension would be desirable.

High reliance is observed on information originating from direct observations and PIREPs. Information gathered from such “air truth” data points is often spatially and temporarily discontinuous, and even sometimes scarce. Means to extend the fielded information is highly desirable.

5 DESIGN OF WEB-BASED EXPERIMENT ON ICING REMOTE SENSING DISPLAYS

In order to investigate the influence of display features of icing remote sensing systems on pilot routing decisions, a web-based experiment was conducted. The study was ultimately aimed at providing functional requirements for the development of remote sensing and forecasting systems (Ryerson, 1998; US DOT, 1998; Quadrant, 1998; Politovich, 1989) consistent with an integrated human-centered system approach (Hansman *et al.*, 1997).

Icing information issues identified in the survey analysis presented in Chapter 4 were investigated in test scenarios that focused on tactical en-route decisions in icing weather situations. Features of cockpit icing information systems were manipulated as independent variables in this experiment and pilot routing decisions and comfort levels were analyzed. Also, since flight operations for aircraft equipped with ice protection systems are fundamentally different than those of aircraft not equipped with ice protection systems, the experiment distinguished the two types of operations.

5.1 ICING REMOTE SENSING DISPLAY ISSUES

The objective of this experiment was to investigate the influence of selected display features of potential icing remote detection systems on pilot decision-making. The experiment attempted to provide a basis for understanding how remotely sensed icing information, presented in graphical form, could support pilot decision-making when operating in icing conditions. A more detailed investigation of the influence of graphical information was performed by looking at the impact of three carefully selected variables based on the results of the survey reported on in the previous chapter.

Icing remote sensing display features of interest were identified to include range, vertical depiction and icing severity level discrimination. Spatial range or display area coverage is of interest because sensors being considered for icing remote sensing have different range and scanning capabilities (Ryerson, 1998). Pilot operational strategies in icing conditions include primarily vertical escape and avoidance maneuvers; for this reason, the use of a vertical view was investigated.

The third display feature of interest, the level of discrimination of icing severity, is based on the hypothesis that accurate remote detection of atmospheric conditions that *are not* conducive to icing conditions would be technically easier than the detection of conditions that *are* conducive to icing conditions. Therefore, a simple single-level display of ice presence was tested.

Pilot risk perception in hazardous situations may be affected by the information available to support a decision. Comfort level with icing-related decisions is thought to provide an indication of pilot risk perception. The level of comfort may nevertheless not correlate with the quality of a routing decision. The experiment was designed to evaluate pilot comfort levels in making re-routing decisions and the possible relationship between decision comfort level and decision quality.

5.2 SUMMARY OF EXPERIMENTAL OBJECTIVES

The experiment attempted to address the following questions:

- o How would remotely sensed icing information support pilot decision-making when operating in icing conditions?
- o How would fundamental display features of icing remote sensing systems influence pilot decision-making in operations in icing conditions? More specifically, what is the influence of depiction of horizontal icing information, spatial coverage, the provision of a profile display, and the number of levels of severity of icing information on pilot decisions?
- o How would pilot confidence in their decisions vary according to the icing information presented? How does it relate to the quality of pilot decisions?
- o Does icing-related graphical information influence pilot decisions differently depending on the level of ice-protection?

Flight-scenario dependent icing remote sensing display issues were also investigated, as described below.

- o What is the influence of the visibility of an escape routes on the level of risk tolerated by pilots? How is pilot comfort level affected?
- o When icing avoidance is feasible with both vertical and horizontal deviation, is there a specific preference for either equipped or non-equipped flight operations?

5.3 BACKGROUND ON SITUATION AWARENESS MEASUREMENTS

In order to evaluate the performance of a human-machine system, performance-based measurements of situation awareness have been developed (Endsley, 1995; Pritchett *et al.*, 1995). The use of testable responses for evaluating situation awareness consists of presenting subjects with realistic situations during simulation runs which, if they have sufficient situation awareness, require decisive and identifiable actions (Pritchett *et al.*, 1995).

The design of flight scenarios using testable responses must have specific traits. Situations must be designed such that, should the user have sufficient situation awareness, a clear and unambiguous response is mandated. In addition, the situations should be chosen to cover the domain of important situations in which the system is expected to perform. Finally, the situations must represent believable and recognizable occurrences to which the subject can be expected to react as they would in the real, non-simulated environment (Pritchett *et al.*, 1995).

5.4 METHOD

A part-task experiment probing fundamental icing remote sensing display features was conducted, using a testable response method (Pritchett *et al.*, 1995). This method uses situations as input and actions or decisions as output, as illustrated in Figure 5-1. Flight scenarios and user interfaces were varied in the experiment.

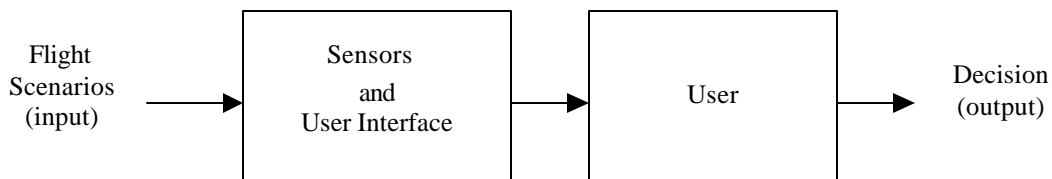


Figure 5-1: Use of Testable Response to Flight Scenarios

** Adapted from Pritchett et al. (1995)*

This subsection provides an overview of the experimental method employed. First, the set of independent variables used in the experiment is presented. The five prototype icing remote sensing displays used in the experiment are subsequently described. A description of the dependent experimental variables is provided, followed by a description of the design of the four experimental flight scenario.

5.4.1 INDEPENDENT VARIABLES

The experiment used two independent variables including the features of the icing display and the level of ice-protection equipment on the aircraft. In order to study the effect of display features on pilot re-routing decisions, selected display features were varied in the five prototype displays shown in Figure 5-2. Display A provided textual information only, based on surface observations and PIREPs, when available, and hence served as a baseline display. The most enhanced icing display, Display E, had a maximum range of 50 nm with both horizontal and vertical depictions of icing conditions. Icing conditions were displayed in three levels: Severe, Icing and Trace described in Table 5-1. Each of the other displays had less enhanced features than Display E in one area. Display B had a range limitation of 25 nm (or half the range of Display E) to allow for investigation of the effect of sensor range. Display C had only one level of icing (i.e., icing presence). This allowed for investigation of the impact of providing icing

severity diagnostic information. Display D did not have a vertical depiction, to allow for evaluation of the effect of a vertical display.

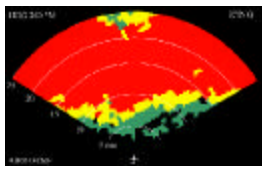
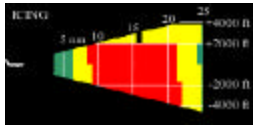
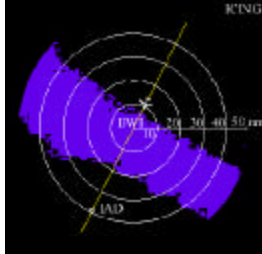
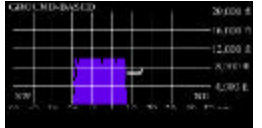
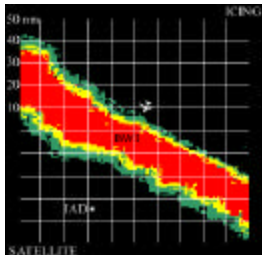
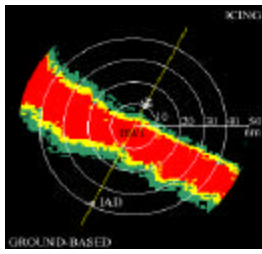
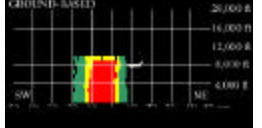
Display	Name in Web-Based Experiment	Graphical Representation	Sensor Range [nm]	Vertical View	Type of Icing Info.
Display A	Textual Information	8	8	8	8
Display B (3D, min range, 3 levels)	Airborne Icing Severity System		25 Min. Range		Icing Severity 3 Levels
Display C (3D, max range, 1 levels)	Ground-based Icing Presence System		50 Max. Range		Icing Presence 1 Level
Display D (2D, max range, 3 levels)	Satellite-based Icing Severity System		50 Max. Range	8	Icing Severity 3 Levels
Display E (3D, max range, 3 levels)	Ground-based Icing Severity System		50 Max. Range		Icing Severity 3 Levels

Figure 5-2: Display Feature Matrix

* Actual displays are in color. Display B, D and E depict three levels of icing severity as green, yellow and red; Display C depicts one level of icing as blue.

In order for the subject pilots to be able to discriminate between the different displays, each display was related to a hypothetical remote sensing system or platform, which could support the display features. The most enhanced display, Display E, was identified as a Ground-Based Icing Severity System. As shown in Figure 5-2, the other displays, A, B, C and D were referred to as Textual Information, Airborne Icing Severity System, Ground-Based Icing Presence System, and Satellite-Based Icing Severity System, respectively. It should be noted that these designations were simply used to ease the identification of the display and do not imply the existence of such sensor systems. Sample pages of the experiment are presented in Appendix B.

PROTOTYPE ICING DISPLAY DETAILS

A detailed description of the icing information presented on Displays B, D and E was provided to subjects in the pre-scenario briefing section of the experiment. The color-coded severity levels were defined according to the definitions provided in the Airmen Information Manual (US DOT, 1999). A set of physical criteria based on Liquid Water Content (LWC), drop size and temperature (T) ranges was also provided. Green was defined as defined to induce trace icing, based on LWC less than 0.1 g/m^3 and temperatures below $2 \text{ }^\circ\text{C}$. Red was defined to include severe icing, based on LWC greater than 1.2 g/m^3 and temperatures below $2 \text{ }^\circ\text{C}$, or large drops and temperatures below $2 \text{ }^\circ\text{C}$. Yellow was defined to include icing based on criteria between the trace and severe ice definitions. Black corresponded to no measured signal and hence no detected icing conditions.

Severity Level	Color	Criteria	Definition
No Icing	Black	No signal return	-
Trace	Green	LWC < 0.1 g/m^3 And T < $2 \text{ }^\circ\text{C}$	Ice becomes perceptible. Rate of accumulation is not hazardous even when no ice-protection system is utilized, unless encountered for over 1 hour.
Icing	Yellow	$0.11 < \text{LWC} < 1.2 \text{ g/m}^3$ and T < $2 \text{ }^\circ\text{C}$	Light & moderate ice accretion. The rate of accretion is potentially hazardous without ice-protection systems, and over extended period of time even with the utilization of ice-protection system.
Severe Icing	Red	LWC > 1.2 g/m^3 Or Large Drops And T < $2 \text{ }^\circ\text{C}$	The rate of accretion is such that ice-protection equipment fails to reduce or control the hazard. Immediate diversion is necessary.

Table 5-1: Legend of Icing Severity Systems

DISPLAY A (TEXT ONLY)

Display A provided textual information only. Information based on reported airport surface observations, conditions observable in-flight and PIREPs, when available. It served as baseline information that would correspond to information currently available in the cockpit nowadays. It should be noted that the same textual information was also provided with all the graphical displays.

DISPLAY B (3D, MIN RANGE, 3 LEVELS) - AIRBORNE ICING SEVERITY SYSTEM

Display B (3D, min range, 3 levels) featured an aircraft-centered perspective and reduced horizontal and vertical ranges in comparison to the ground-based system. An example of depiction of icing conditions by Display B is shown in Figure 5-3. The forward range was restricted to 25 nautical miles (nm), the angular range set to 120° (similar to airborne weather radar). With a vertical angular range of 6°, the vertical coverage at maximum forward range was 8,000 feet.

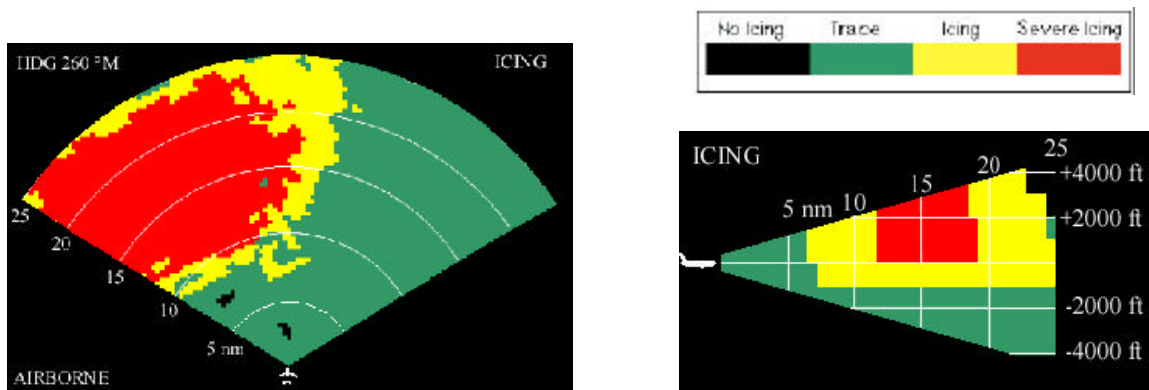


Figure 5-3: Plan and Profile Views of Display B (3D, min range, 3 levels)

DISPLAY C (3D, MAX RANGE, 1 LEVEL) - GROUND-BASED ICING PRESENCE SYSTEM

Display C only depicted ice presence and used a different color coding. A detailed description of the legend for Display C was provided to the test subjects in the pre-scenario briefing and is shown in Table 5-2.

Icing Level	Color	Criteria	Definition
No Icing	Black	T > 2°C Or Outside Clouds	Based on signal returns, black zones within the system range correspond to locations where atmospheric conditions are not conducive to aircraft structural icing.
Icing	Blue	No return	Blue areas are by default areas where weather conditions may be conducive to aircraft icing; no severity index depiction is enabled.

Table 5-2: Legend of Display C (3D, max range, 1 level)

Display C measurements were based on the detection of conditions not conducive to aircraft icing such as temperature and cloud detection (although the details were not provided). Black corresponded to these areas, and blue, by inference, corresponded to areas where icing was possible.

An example of depiction of icing conditions by Display C (3D, max range, 1 level) is shown in Figure 5-4. The plan-view display was centered at Baltimore airport (BWI), provided a 50-nm range corresponding to a 100-nm-area coverage in a North-up coordinate frame and depicted ten-nm-range rings centered at Baltimore airport. The vertical-view display was also centered at BWI and provided a 20,000-foot vertical coverage. Own aircraft position and destination, Washington Dulles airport (IAD), were also depicted on both displays.

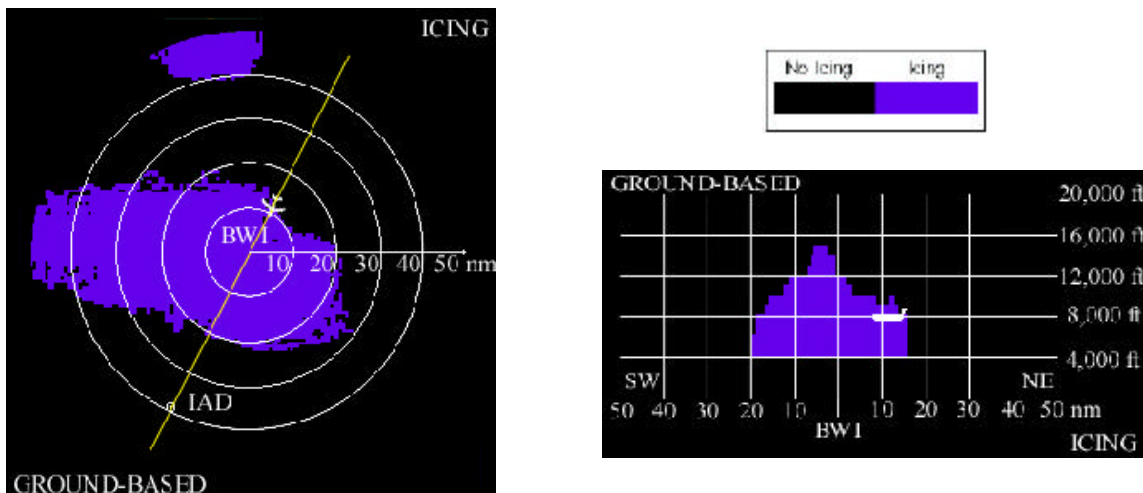


Figure 5-4: Plan and Profile Views of Display C (3D, max range, 1 level)

DISPLAY D (2D, MAX RANGE, 3 LEVELS) - SATELLITE-BASED ICING SEVERITY SYSTEM

Display D (2D, max range, 3 levels) mainly differed from the most enhanced display, Display E, by the lack of a vertical depiction. An example of depiction of icing conditions by Display D is shown in Figure 5-5.

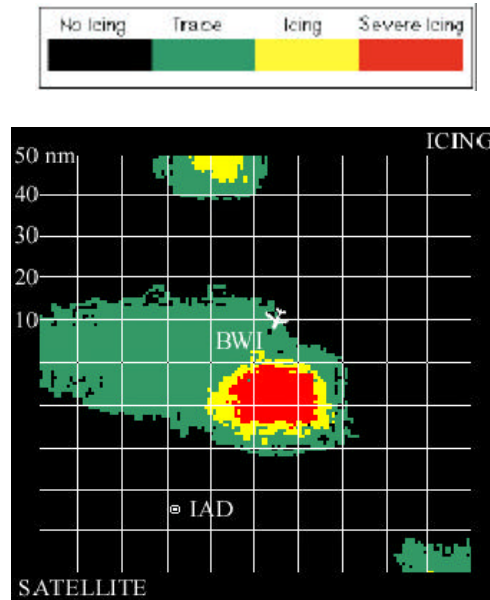


Figure 5-5: Display D (2D, max range, 3 levels)

DISPLAY E (3D, MAX RANGE, 3 LEVELS) - GROUND-BASED ICING SEVERITY SYSTEM

Display E (3D, max range, 3 levels) was the most enhanced system and had a range of 50 nm. An example of depiction of icing conditions by Display E is shown in Figure 5-6.

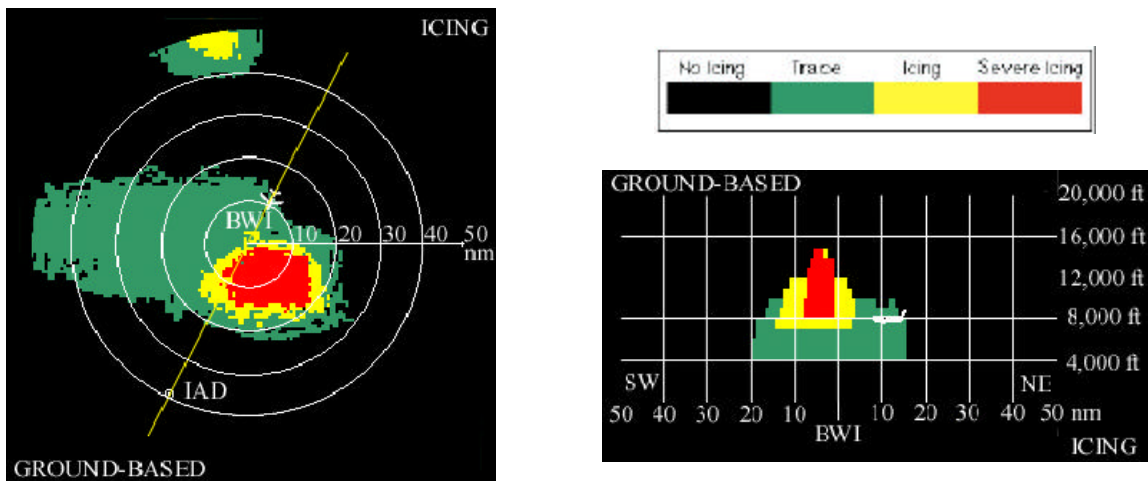


Figure 5-6: Plan and Profile Views of Display E (3D, min range, 3 levels)

ICE-PROTECTION EQUIPMENT LEVEL

With regard to icing, flight operations have different operating rules according to whether or not the aircraft is certified for flight operations in known-icing conditions, as defined by the Federal Aviation Regulations, Part 25, Appendix C. It should be noted that aircraft are not certified for flight in severe icing conditions, which are outside of the Part 25, Appendix C envelope. These include large droplets and high-LWC conditions.

Aircraft that are not certified are not approved for operations in known-icing conditions and need to avoid or escape from all levels of icing conditions. Because the icing restriction is based on the demonstration of aircraft operations under such restrictions with specified ice-protection equipment, operations under such restrictions are referred to, throughout this document, as non-equipped operations. In turn, known-icing approved operations are termed ice-protection equipped operations, or in short, equipped operations.

Based on their reported experience, each pilot in the experiment was assigned to an equipped or non-equipped group. For the experiment, the equipped pilots were given a light twin-engine aircraft which was equipped for and certified for flight into known-icing conditions; the non-equipped group was given a similar aircraft without ice protection equipment.

5.4.2 DEPENDENT VARIABLES

In order to probe the influence of the various displays, data was collected for each event on pilot tactical re-routing decisions and comfort levels; a free-response question also probed pilots' rationale behind their re-routing decisions. In completing the experiment, pilots were also asked to indicate their relative preference for each display.

For each flight event, the first question was stated as: "What is your decision?" Pilots indicated their routing or re-routing decision in a multiple-response field. Figure 5-7 (left) shows an example of a pilot's decision to perform a 30°-lateral deviation and a climb to 10,000 feet. The right portion of Figure 5-7 shows the complete set of decision options provided in the multiple-response field. As shown, pilots could choose from a discrete set of cruising altitudes for flights under instrument flight rules when headed in a westerly direction, and ranging between the stated Minimum En-route Altitude (MEA) of 3,000 feet and the indicated aircraft maximum ceiling of 15,000 feet.

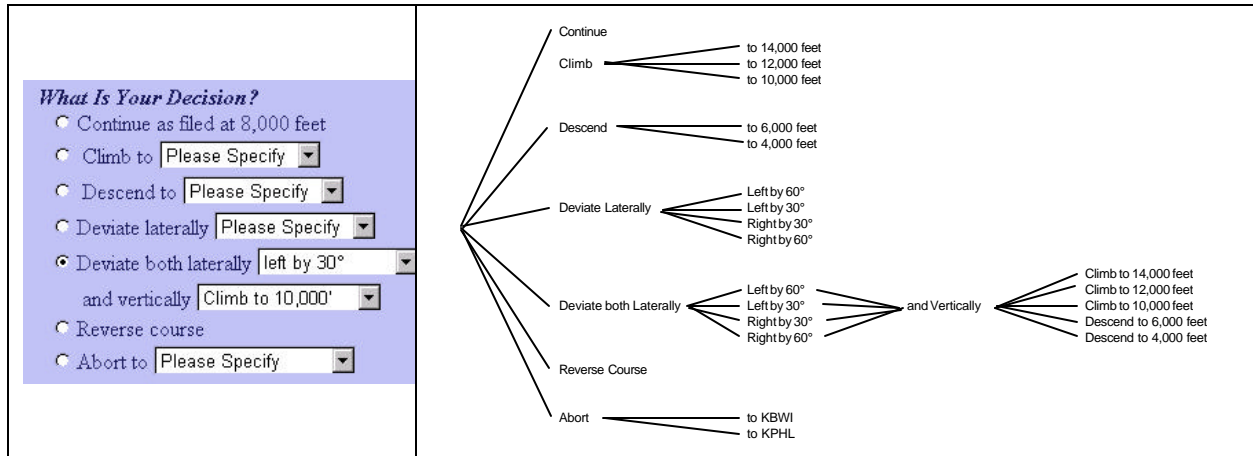


Figure 5-7: Example of Routing Decision Space (left) and Complete Routing Decision Tree (right)

(Source: WEB-BASED EXPERIMENT ON PROTOTYPE IN-FLIGHT ICING AVOIDANCE SYSTEMS, http://eyeager.mit.edu/icing_avionics)

Each routing decision was rated according to a decision quality rating scheme. In each flight scenario, a set of good, acceptable and poor decisions has been identified based on optimal strategic routing for pilots with full situation awareness. This experimental approach, based on the testable response method (Pritchett *et al.*, 1995) provided means to rate pilots' response based on optimal situation awareness criteria, and hence determine the influence of information presentation on pilot decisions.

5.4.3 FLIGHT SCENARIO DESIGN

Using each of the five display systems, pilots were exposed to a set of four icing-intensive scenarios: 1) Warm Front Avoidance; 2) Embedded Convective Weather Avoidance; 3) VMC-on-Top Avoidance; 4) Stable Layer Escape. As indicated by their names, three of the four flight scenarios consisted of penetration-versus-avoidance situations, while one of the scenarios involved a situation of immersion in icing conditions where an escape maneuver is necessary. Each test subject hence went through a set of 20 events. A description of the operational constraints involved in each flight scenario is provided in the following paragraphs.

Prior to starting the experiment, pilots were given a pre-flight briefing which stated that all flight scenarios would start at the same geographical location illustrated in Figure 5-8, that is, 50 nm from destination, Washington Dulles airport (KIAD) and as they would be heading towards Baltimore (KBWI), which was located 10 nm ahead along the planned route. The distance from neighboring radio-navigational aids and airports, including Philadelphia (KPHL) was also provided. As mentioned above, the aircraft maximum ceiling was given to be 15,000 feet and the MEA to be 3,000 feet. Figure 5-8 depicts the aircraft location in each experimental flight scenario.



Figure 5-8: Graphical Support in Experimental Pre-Scenario Briefing

SCENARIO 1: WARM FRONT AVOIDANCE

The icing threat field in this flight scenario was distributed so as to call for vertical avoidance maneuvering, preclude a specific flight abortion option (i.e., aborting to KBWI), and display strong gradients of icing severity levels close to the boundaries of the zone of icing conditions.

In this flight scenario, pilots were presented with a situation involving a warm front intersecting with the planned route. Observable conditions outside the window were Instrument Meteorological Conditions (IMC) and the Outside Air Temperature (OAT) probe indicated +1°C. Freezing rain was reported at KBWI. Surface observations were also provided at three neighboring airports: KPHL reported an overcast conditions at 15,000 feet, a temperature of -4°C and a dewpoint of -10°C; KBWI reported overcast conditions at 200 feet, freezing rain, a temperature of -3°C and a dewpoint of -4°C; KIAD reported scattered conditions at 2,000 feet, a temperature of -2°C and a dewpoint of -3°C. No PIREP was reported, so there was no indication of the altitude at which the freezing precipitation could be overflow.

Figure 5-9 shows the presentation of weather conditions as seen by the most enhanced display, Display E (3D, min range, 3 levels). Figure 5-10 shows the other three display presentations in scenario 1.

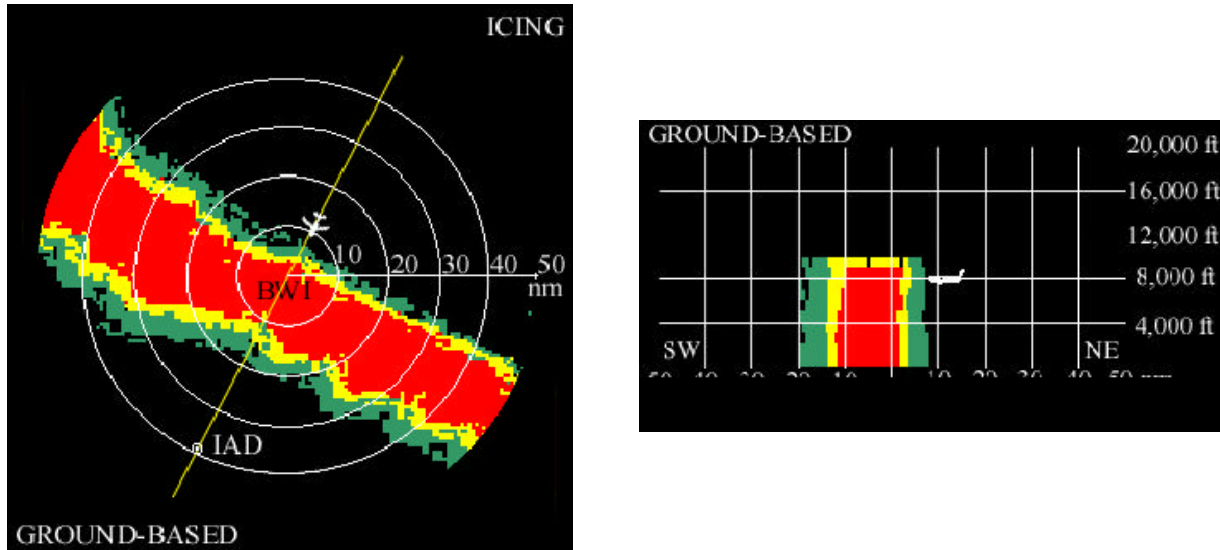


Figure 5-9: Display E (3D, Max Range, 3 Levels) View of Warm Front Avoidance Scenario (Scenario 1)

With optimal situation awareness of the conditions, the expected re-routing decision was for the pilots to top the freezing precipitation and continue towards destination.

Display B (3D, min Range, 3 levels)	Display C (3D, max Range, 1 level)	Display D (2D, max Range, 3 levels)

Figure 5-10: Other Displays' Perspective of Warm Front Avoidance Scenario (Scenario 1)

SCENARIO 2: EMBEDDED CONVECTIVE WEATHER AVOIDANCE

The icing threat field in this flight scenario was distributed so as to call for either vertical or lateral avoidance maneuvering. A much smaller gradient of icing severity was provided and

cruising through conditions that are conducive to trace icing at varying distances from the icing-free zones both laterally and vertically was made possible. The inferior boundary of the icing threat field lied at an altitude above the MEA, while its superior boundary lied in localized areas at an altitude above the aircraft ceiling.

This flight scenario was set in IMC where convective cells were embedded in stratus clouds. The aircraft had entered an area where conditions may have been conducive to trace icing. Observable conditions were IMC. The aircraft had recently experienced light-to-moderate chop at cruising altitude and embedded cumulus conditions were expected. The outside air temperature indicated +2°C and there was no observation of ice accretion. A light twin-engine aircraft cruising at 8,000 feet 25 nm West of the own aircraft location had recently reported a PIREP of moderate icing and an outside air temperature of 0°C. The surface observations at neighboring airports reported the following conditions: overcast at 3,000 feet at KPHL, temperature of 7 °C, dewpoint of 4 °C; BWI reported overcast conditions at 3,000 feet, a surface temperature of 8 °C and a dewpoint of 6 °C; KIAD reported overcast conditions at 4,000 feet, a surface temperature of 8 °C and a dewpoint of 6 °C.

Figure 5-11 shows the presentation of weather conditions as seen by the most enhanced display, Display E (3D, min range, 3 levels). Figure 5-12 shows the other three display presentations in scenario 2.

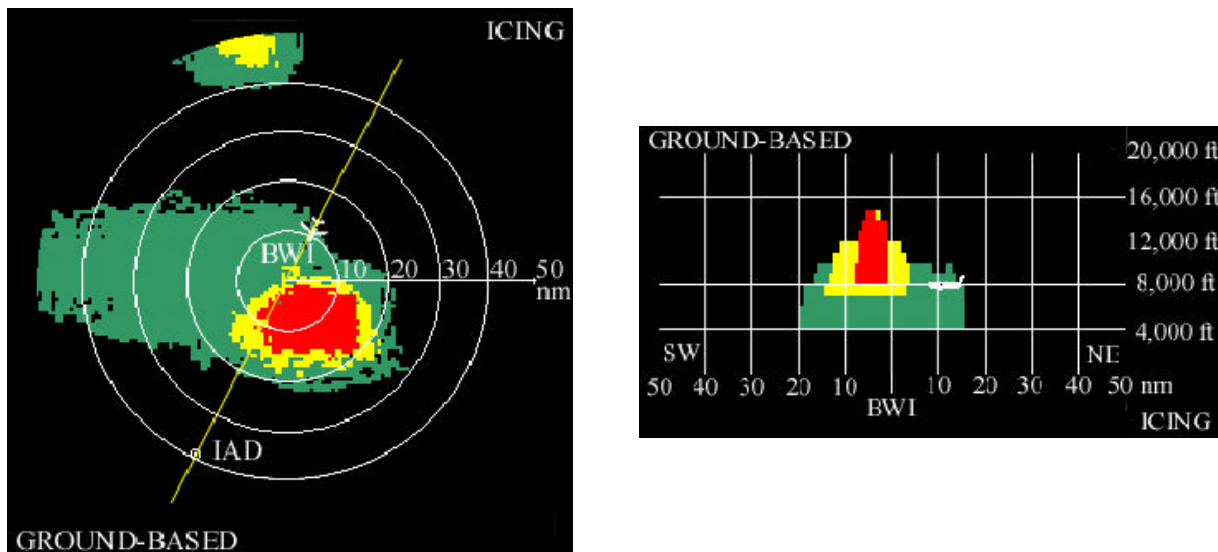


Figure 5-11: Display E (3D, Max Range, 3 Levels) View of Embedded Convective Weather Avoidance Scenario (Scenario 2)

Distinct behaviors were expected for pilots operating with non-equipped aircraft and equipped aircraft. With optimal situation awareness, it was expected that pilots would opt for a descent to 4,000 feet. Lateral deviation to the right of the planned course was also considered good for equipped operations. Particular attention was given in the design of the scenario to provide a basis for testing the influence of icing presentation on the preference between vertical and lateral re-routing in the latter type of flight operations.

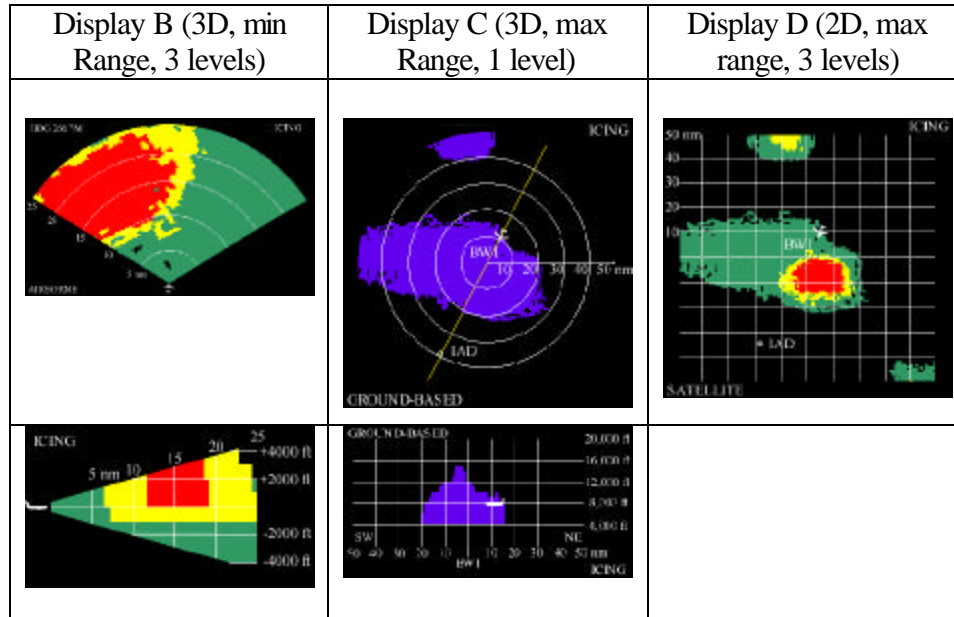


Figure 5-12: Other Displays' Perspective of Embedded Convective Weather Avoidance Scenario (Scenario 2)

SCENARIO 3: VMC-ON-TOP AVOIDANCE

The icing threat field in this flight scenario was distributed so as to call for vertical avoidance maneuvering. Increasing level of icing severity was found along the route within a cloud deck with sufficient horizontal extent (over 100 nm) that it didn't terminate before reaching the proximity of the destination airport. Both options of flying above and underneath the cloud deck seem appropriate for short range tactical avoidance, but the right course of action involves maneuvering so as to fly under it only. Penetration through various levels of icing severity is possible according to the indicated re-routing maneuvers.

The flight scenario was set in Visual Meteorological Conditions (VMC). Weather along the planned route of flight was such that the aircraft was about to over-fly a progressively raising cloud deck located approximately 1,000 feet below. This layer of clouds had conditions conducive to aircraft icing. The aircraft was projected to penetrate the icing conditions unless re-routing was initiated. The OAT indicated 0°C and no ice accretion had been observable. A PIREP had been given 10 nm further along the planned route. A light twin-engine aircraft descending through 6,000 feet had reported moderate icing and an outside air temperature of -1°C. The surface observations at neighboring airports reported the following conditions: KPHL reported overcast conditions at 4,000 feet, temperature of 9°C, dewpoint of 6°C; BWI reported overcast conditions at 3,000 feet, surface temperature of 10°C, dewpoint of 6°C. IAD reported overcast conditions at 4,000 feet, surface temperature of 10°C, dewpoint of 6°C.

Figure 5-13 shows the presentation of weather conditions as seen by the most enhanced display, Display E (3D, min range, 3 levels). Figure 5-14 shows the other three display presentations in scenario 3.

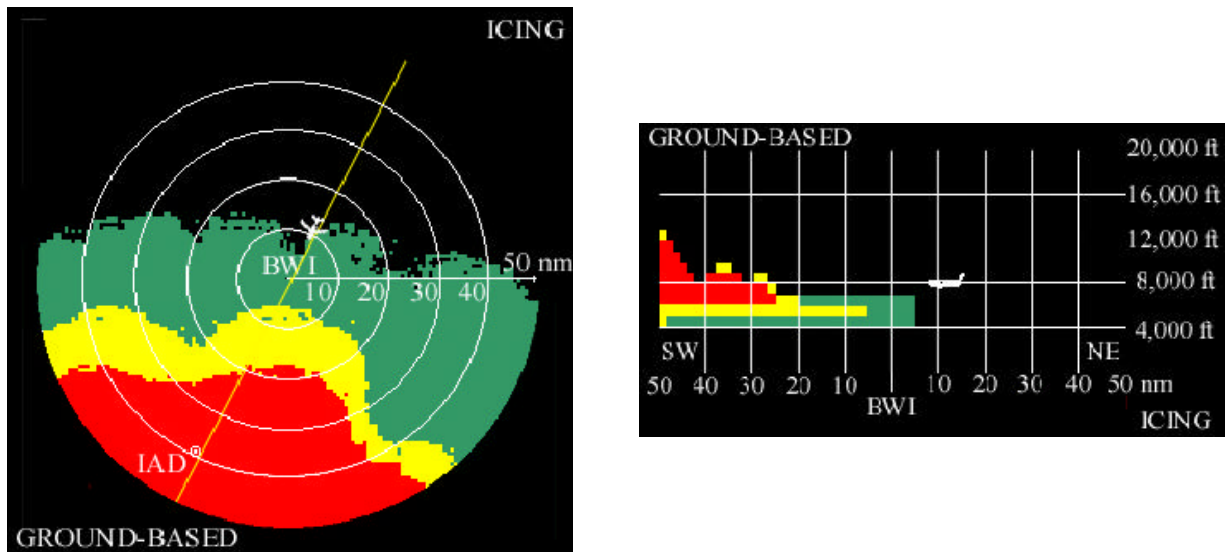


Figure 5-13: Display E (3D, Max Range, 3 Levels) View of VMC-on-Top Avoidance Scenario (Scenario 3)

Display B (3D, min Range, 3 levels)	Display C (3D, max Range, 1 level)	Display D (2D, max range, 3 levels)

Figure 5-14: Other Displays' Perspective of VMC-on-Top Avoidance Scenario (Scenario 3)

With optimal situation awareness, it was expected that pilots would descend to 4,000 feet and proceed to destination.

SCENARIO 4: STABLE LAYER ESCAPE

The icing threat field in this flight scenario was distributed so as to call for vertical escape maneuvering. A small gradient of icing severity was provided within an extended field of icing conditions (of the order of over 100 nm), and the only viable escape maneuver was designed to require a climb above the cruising altitude.

The flight scenario took place in IMC, where conditions were conducive to airframe icing; it was hence referred to as an escape scenario. The own aircraft had just started to accumulate light-to-moderate ice accretion. No PIREP had been reported. The surface observations at neighboring airports reported the following conditions: KPHL reported overcast conditions at 3,000 feet, a temperature of 0°C and a dewpoint of -3°C; KBWI reported overcast conditions at 2,000 feet, a temperature of 1°C and a dewpoint of -3°C; KIAD reported scattered conditions at 2,000 feet, a temperature of 1°C and a dewpoint of -2°C.

Figure 5-15 shows the presentation of weather conditions as seen by the most enhanced display, Display E (3D, min range, 3 levels). Figure 5-16 shows the other three display presentations in scenario 4.

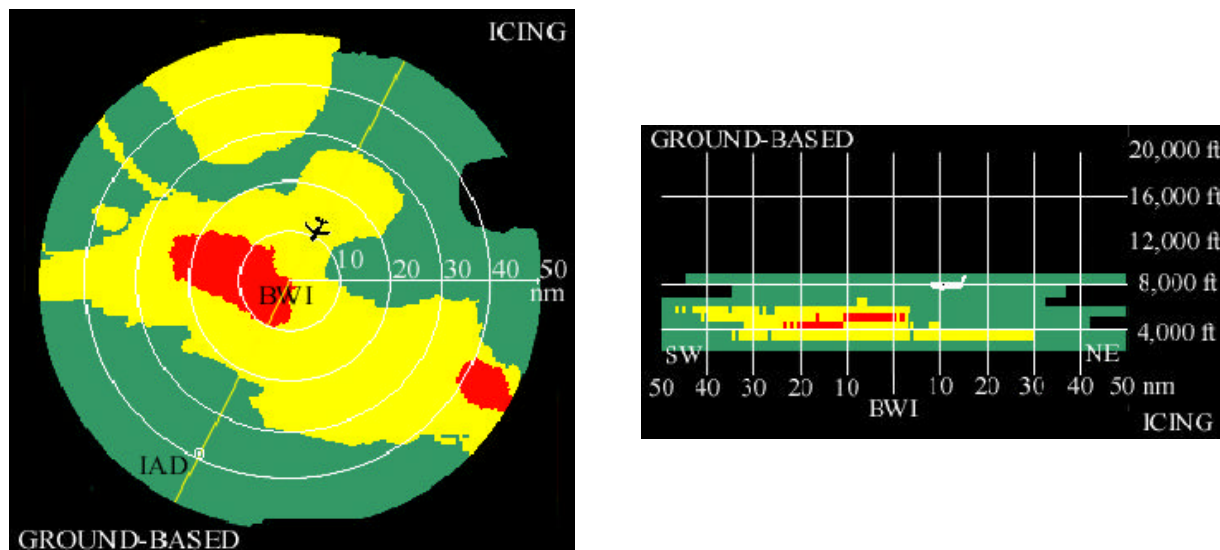


Figure 5-15: Display E (3D, Max Range, 3 Levels) View of Stable-Layer Escape Scenario (Scenario 4)

With optimal situation awareness, it was expected that pilots would escape the icing conditions by climbing above 9,000 feet and proceed towards destination.

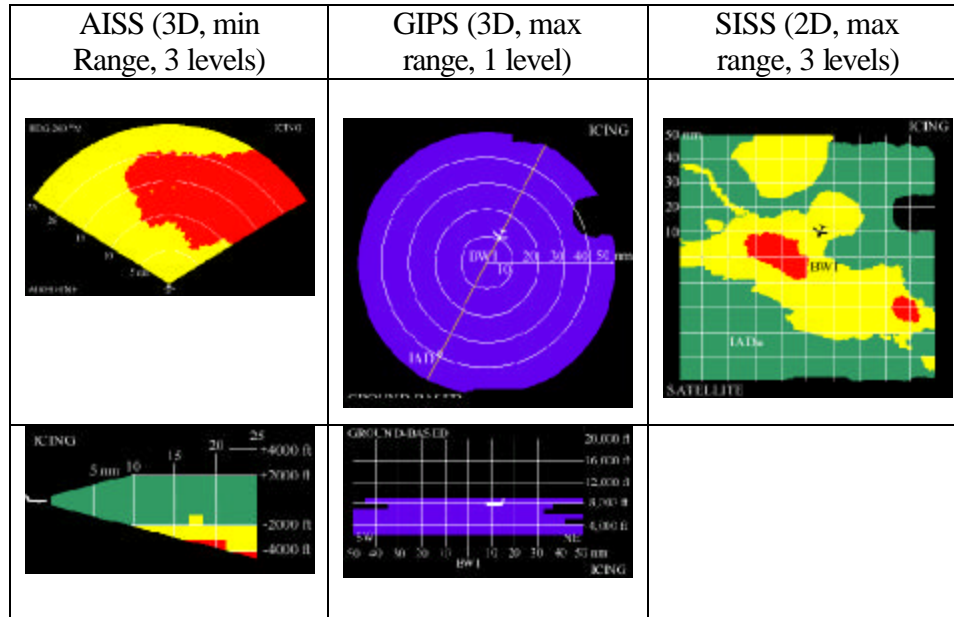


Figure 5-16: Other Displays' Perspective of Stable-Layer Escape Scenario (Scenario 4)

5.5 EXPERIMENTAL PROTOCOL

The experiment was posted on the worldwide web during the month of July 1999. Similar to the web-based survey on pilot information needs and strategies for operations in icing conditions reported on in Chapter 4, a broad range of the pilot community was solicited by electronic mail, electronic newsletter (e.g., AvFlash) and web posting (e.g., AvWeb, Bluecoat Digest, aol.com, IAOPA website).

Counterbalancing was performed by rotating the order of display and flight scenario presentations between subjects, based on five types of subjects. Table 5-3 shows the counterbalancing matrix. The first letter of each cell correspond to the information type (t, a, b, c and d correspond to displays A through E; the second letter corresponded to the flight scenario page, with p, a, b, c and d corresponding to pre-flight briefing, scenarios 1, 2, 3 and 4 respectively). For example, a subject of type 1 would run through the pre-flight briefing with Display A (text only), scenario 1 through 4 with Display A, the pre-flight briefing with Display B (3D, min range, 3 levels), scenario 2, 4, 1 and 3, respectively, with Display B, etc. The attribution of subject type 1 through 5 was performed continuously based on the order test subjects accessed the experiment first webpage.

It is speculated that the considerable duration of the experiment (approximately 45 minutes to complete) caused a fraction of the test subjects who had started the experiment not to complete it.

Since responses were obtained from subjects who voluntarily self-reported to the survey webpage, results are expected to carry a bias towards pilots who are more computer literate and more interested in icing issues than the overall pilot population.

Subject 1	tp	ta	tb	tc	td	ap	ab	ad	aa	ac	bp	bd	bc	bb	ba	cp	cc	ca	cd	cb	dp	da	dc	db	dd
Subject 2	ap	aa	ab	ac	ad	cp	cb	cd	ca	cc	dp	dd	dc	db	da	bp	bc	ba	bd	bb	tp	ta	tc	tb	td
Subject 3	bp	ba	bb	bc	bd	dp	db	dd	da	dc	ap	ad	ac	ab	aa	tp	tc	ta	td	tb	cp	ca	cc	cb	cd
Subject 4	cp	ca	cb	cc	cd	bp	bb	bd	ba	bc	tp	td	tc	tb	ta	dp	dc	da	dd	db	ap	aa	ac	ab	ad
Subject 5	dp	da	db	dc	dd	tp	tb	td	ta	tc	cp	cd	cc	cb	ca	ap	ac	aa	ad	ab	bp	ba	bc	bb	bd

Table 5-3: Experiment Counterbalancing Matrix

5.6 ANALYSIS OF DECISIONS

For each scenario and level of ice-protection equipment, a three-level decision rating scheme, classifying good, acceptable and poor decisions, was prepared by two expert analysts. The decision space was first evaluated according to whether the subsequent aircraft routing or re-routing maneuver would lead to penetration of trace, icing or severe levels of icing conditions. The quality of the decision was evaluated independently of the display used. Based on the icing severity level projected to be penetrated according to indicated re-routing maneuvers, the decisions as were rated as good, acceptable or poor decisions, according to safety and efficiency considerations.

For pilots of the equipped group, the evaluation was performed as follows. If the aircraft was projected to penetrate into severe icing conditions, the decision was rated as poor. If the aircraft was projected to penetrate into trace icing with a non-optimal routing, or it was projected to abort the flight or reverse course safely, the decision was rated as acceptable. If the decision corresponded to an optimal icing avoidance or escape maneuver, it was rated as good. For projected trajectories at the boundary of conditions of distinct severity levels, the more conservative rating was applied.

For the non-equipped group, the evaluation was performed based on more conservative criteria. In avoidance cases, if the aircraft was projected to enter any level of icing conditions, the decision was rated as poor. If the decision lead to optimal avoidance or escape, it was rated as good. If the decision involved an escape maneuver with somewhat more than minimal exposure to trace icing but no exposure to higher levels, it was rated as acceptable. For projected trajectories at the boundary of conditions of different severity levels, the more conservative rating was applied, except if it was at a minimal altitude and in an area where no icing conditions were depicted at airports where it is possible to abort.

6 RESULTS OF WEB-BASED EXPERIMENT ON ICING REMOTE SENSING DISPLAYS

The results of the experiment on icing remote sensing displays are presented in eight sections. The first section summarizes subjects' background information. The two subsequent sections, 6.2 and 6.3, provide a description of the decision quality in each flight scenario for equipped and non-equipped operations, respectively. Section 6.4 provides a summary of the quality of the routing and re-routing decisions. Section 6.5 reports on the results relating to pilots' indications of comfort levels and a correlation analysis with decision quality. Section 6.6 reports on an analysis of pilot display preference ratings of the five types of displays. The last section concludes on the results of the web-based experiment.

6.1 RESPONSE AND BACKGROUND INFORMATION

A total of 230 pilot valid scripts were used in the web-based experiment analysis. Statistical information of test subjects is presented in Table 6-1. As shown, pilots typically operating in known-icing approved operations, referred to as equipped operations throughout the presentation of the analysis, had considerably more flight experience and qualifications.

Operational Category	Total Time (hours)	Instrument Time (hours)	Age	Sex % male	Commercial %	ATP %	Instructor %	Instrument %	Average X-C Range (nm)
Certified	9494	2062	48	98%	38	72	48	91	698
Non-Certified	1407	302	40	97%	15	10	16	84	337

Table 6-1: Subject Experience

Figures 6-1 and 6-2 present the distribution of subject's icing experience and understanding of issues associated with airframe icing, respectively. As can be seen, equipped pilots had significantly more experience and familiarity with issues relating to in-flight icing than non-equipped pilots.

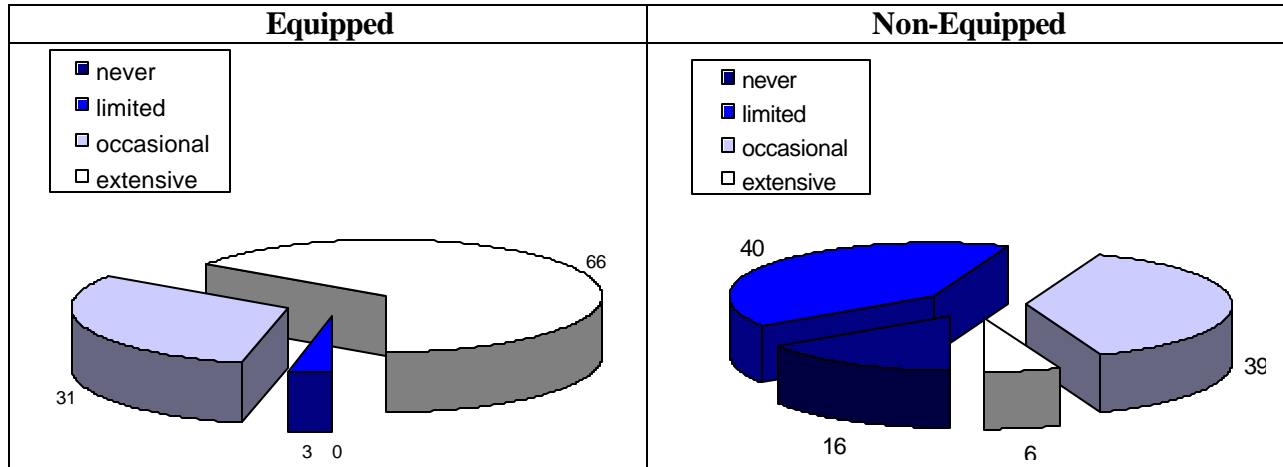


Figure 6-1: Subject's Reported Experience in Icing Conditions

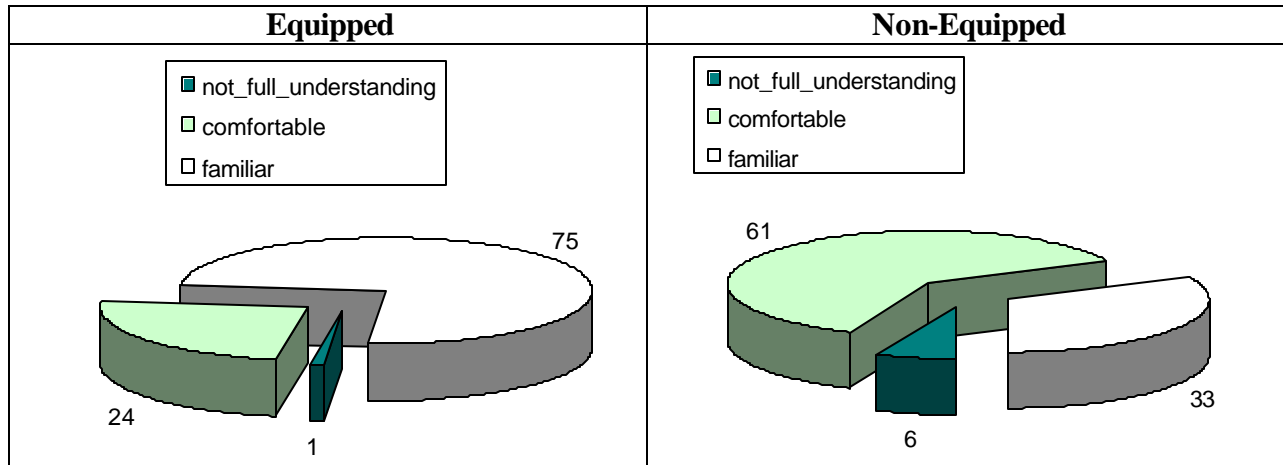


Figure 6-2: Subject's Reported Understanding of Aircraft Icing

6.2 ROUTING DECISIONS FOR EQUIPPED OPERATIONS

Pilot decision quality was evaluated based on the routing decisions they indicated in each flight scenario. Results averaged over all flight scenarios for equipped pilots are presented in Figure 6-3. As can be seen, a larger percentage (53%) of pilots indicated poor routing decisions based on textual information only, compared to when making decisions with graphical information (with Displays B through E). Also, on average, decisions indicated with Display E (3D, max range, 3 levels) were much better than with the other types of graphical displays: only 9% of pilots indicated poor decisions and 64% of pilots indicated good decisions.

Considerable variability in the distribution was found across flight scenarios. A more detailed analysis for each scenario should help understand differences in decision quality as they relate to the flight-scenario specific re-routing maneuvers.

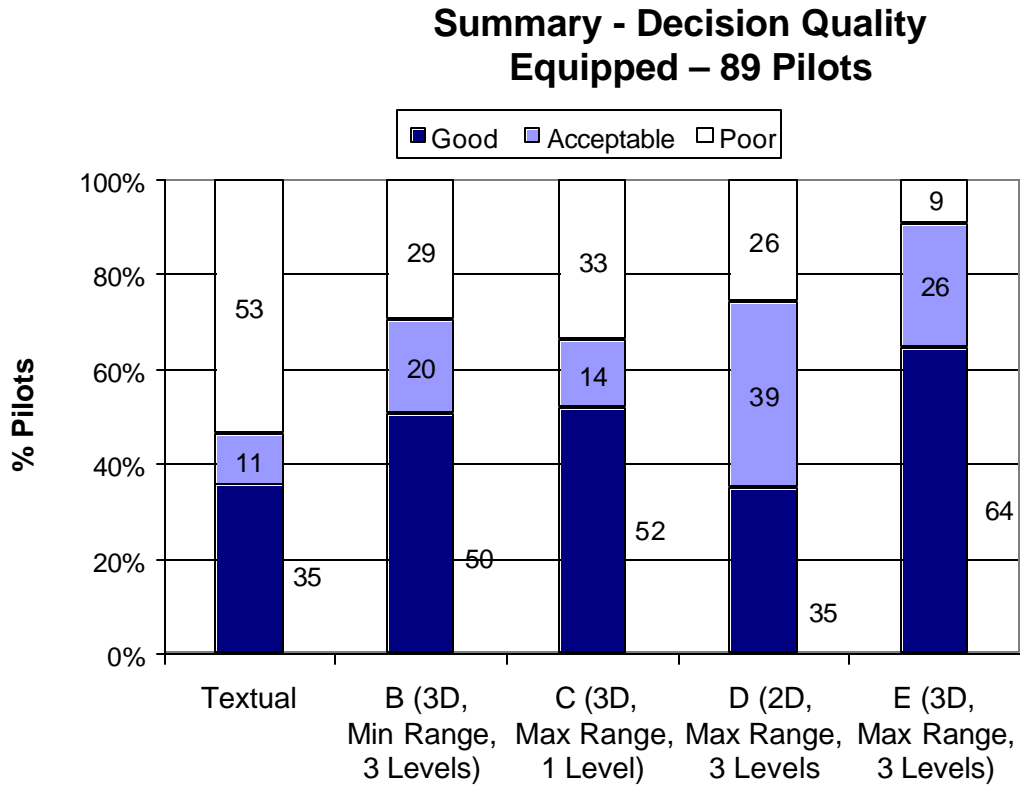


Figure 6-3: Summary of Decision Quality throughout Flight Scenarios for Equipped Pilots

6.2.1 SCENARIO 1: WARM FRONT AVOIDANCE SCENARIO

Figure 6-4 depicts the level of graphical information support provided in scenario 1 (as already presented in Figures 5-9 and 5-10).

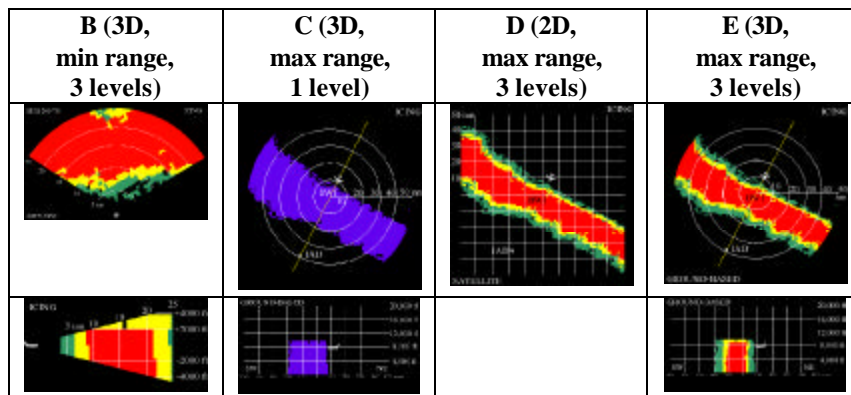


Figure 6-4: Displays in Scenario 1

The percentage of pilots who made good, acceptable and poor decisions in Scenario 1 is presented in Figure 6-5. As can be seen, pilots made fewer poor decisions based on information from Displays E and B than with information from the other displays.

Decision Quality - Warm Front Avoidance (Scenario 1) Operations with Ice Protection Equipment - 89 Subjects

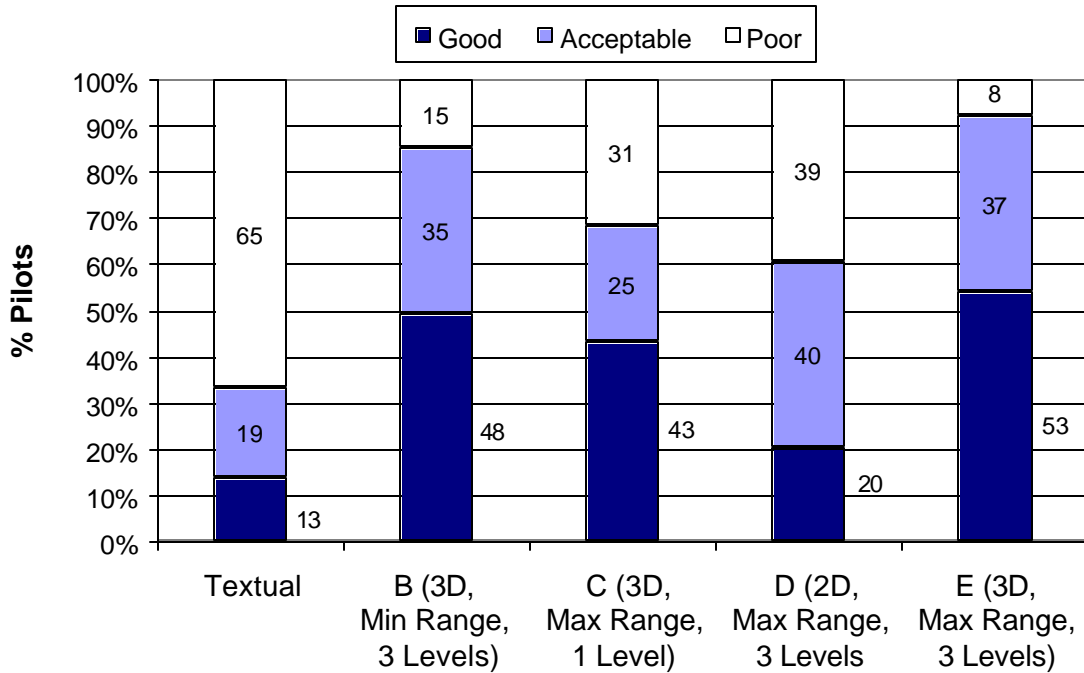


Figure 6-5: Decision Quality Distribution in Scenario 1

This distribution of decision quality can be understood by considering the results presented in Figure 6-6, which provides the detailed distribution of re-routing decisions with each type of display used. The good decision was evaluated to be to initiate a climb to top the freezing rain, as indicated in the top part of Figure 6-6. Routing decisions that led to penetrating into severe icing was rated as poor; routing decisions that lead into yellow over a short distance, or that involved making a conservative flight abortion, or non-optimal course deviation outside severe icing conditions were rated as acceptable.

Decision Rating Scheme (Scenario 1, Equipped Operations)	<table border="1"> <thead> <tr> <th colspan="2"></th> <th>Good</th> <th>Acceptable</th> <th>Poor</th> <th colspan="2"></th> </tr> </thead> <tbody> <tr> <td colspan="7" style="text-align: center;">Decision Rating (Equipped)</td> </tr> <tr> <td>L 60°</td> <td>L 30°</td> <td>14000</td> <td></td> <td></td> <td>R 30°</td> <td>R 60°</td> </tr> <tr> <td>L 60°</td> <td>L 30°</td> <td>12000</td> <td></td> <td></td> <td>R 30°</td> <td>R 60°</td> </tr> <tr> <td>L 60°</td> <td>L 30°</td> <td>10000</td> <td></td> <td></td> <td>R 30°</td> <td>R 60°</td> </tr> <tr> <td>L 60°</td> <td>L 30°</td> <td>8000</td> <td></td> <td></td> <td>R 30°</td> <td>R 60°</td> </tr> <tr> <td>L 60°</td> <td>L 30°</td> <td>6000</td> <td></td> <td></td> <td>R 30°</td> <td>R 60°</td> </tr> <tr> <td>L 60°</td> <td>L 30°</td> <td>4000</td> <td></td> <td></td> <td>R 30°</td> <td>R 60°</td> </tr> <tr> <td colspan="7" style="text-align: center;">Abort to KBWL Reverse Course Abort to KPHL</td> </tr> </tbody> </table>			Good	Acceptable	Poor			Decision Rating (Equipped)							L 60°	L 30°	14000			R 30°	R 60°	L 60°	L 30°	12000			R 30°	R 60°	L 60°	L 30°	10000			R 30°	R 60°	L 60°	L 30°	8000			R 30°	R 60°	L 60°	L 30°	6000			R 30°	R 60°	L 60°	L 30°	4000			R 30°	R 60°	Abort to KBWL Reverse Course Abort to KPHL						
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0.0	0.0	22.5	0.0	0.0																																																												
0.0	0.0	4.5	0.0	0.0																																																												
0.0	0.0	2.2	0.0	0.0																																																												
0.0	0.0	1.1	0.0	0.0																																																												
0.0 6.7 5.6																																																																

Figure 6-6: *Distribution of Pilots' Re-Routing Decisions (Scenario 1, Equipped Operations)*

Figure 6-6 presents a mapping methodology used to analyse the routing results. The top table shows the decision rating scheme that was used to evaluate each cell of the decision space (which was presented in Figure 5-7) in Scenario 1 for Equipped operations. It should be noted that the cells corresponding to routing that included both lateral and vertical deviations are labeled with the lateral deviation angle only; the corresponding flight altitude is

found by looking at the central column value in the same row. It should be noted that the cell labeled 8,000 feet corresponds to pilots' indicated routing decisions of continuing as filed since the cruising altitude in all flight scenarios was 8,000 feet. For example, the top left cell of this table corresponds to an indicated routing that involved a climb to 14,000 feet and a deviation of 60° to the left of the initial course. According to the legend included in the same table (in its top portion), such a routing decision was rated as acceptable.

In the five lower tables, the value in each cell corresponds to the percentage of pilots who indicated they would re-route towards a specific solution of the decision space (e.g., to 14,000 feet and 60° left). A table is presented for each of the five displays. For example, using Display E, the number of pilots who indicated they would continue at 8,000 feet was equal to 4.5%, and the number of pilots who indicated they would climb to 14,000 feet and deviate right by 30° was equal to 1.1%.

--

When provided with textual information only, a majority of pilots (64%) indicated they would continue as filed. A small number indicated they would climb to either 12,000 or 14,000 feet (13%), which was rated as a good decision. The large number of non-course-alteration explains mostly the large amount of poor decisions (65%) with textual information only.

When provided with information from the Display B (3D, min range, 3 levels), a large number of pilots (48%) indicated that they would climb to either 12,000 or 14,000 feet. A large number of pilots also indicated they would climb, reverse course, or abort to KPHL, which were rated as acceptable decisions. This explains the small number of poor decisions (15%).

When provided with information from the Display C (3D, max range, 1 level), a large number of pilots (43%) also indicated they would climb to either 12,000 feet or 14,000 feet. More pilots indicated than with the Display B (3D, min range, 3 levels) indicated that they would continue toward destination, cruising at an altitude where they would tolerate to penetrate into the zone where icing conditions were depicted to be present (e.g., 18% would continue at 8,000 feet, 10% would descend to 6,000 feet). This explains the larger amount of poor decisions (31%) observed with this display.

When provided with information from the Display D (2D, max range, 3 levels), almost one third of the pilots (31%) mentioned they would continue as planned at 8,000 feet. This explains the large percentage of poor decisions (39%). Without graphical support to make vertical re-routing maneuvers, the largest percentage of pilots mentioned they would reverse course or abort to KPHL (33%). This explains the large number of acceptable decisions (40%).

When provided with information from Display E (3D, max range, 3 levels), most of the pilots (53%) indicated that they would climb to either 12,000 feet or 14,000 feet. Also, few pilots (7%) indicated that they would proceed towards destination at altitudes that would lead them through the zone depicted as severe icing (depicted in red). This result correlates with the number of poor decisions.

6.2.2 SCENARIO 2: EMBEDDED CONVECTIVE WEATHER AVOIDANCE

Figure 6-6 depicts the level of graphical information support provided in Scenario 2 (as already presented in Figures 5-11 and 5-12). The percentage of pilots who made good, acceptable and poor decisions in Scenario 2 is presented in Figure 6-7. An unusually high percentage (91%) of good routing decisions was observed with information from Display B (3D, min range, 3 levels).

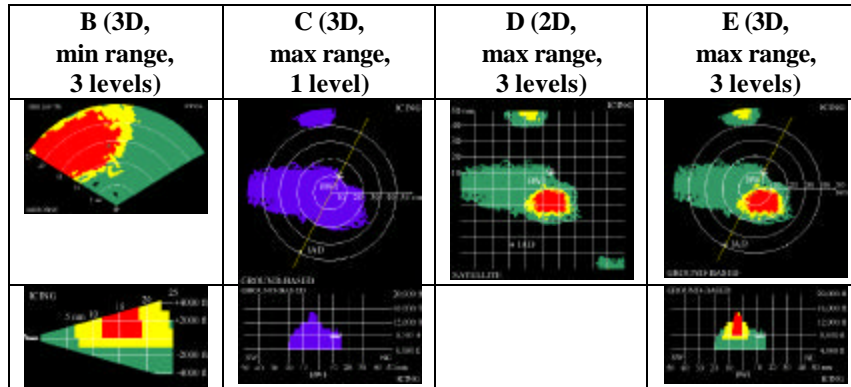


Figure 6-6: Displays in Scenario 2

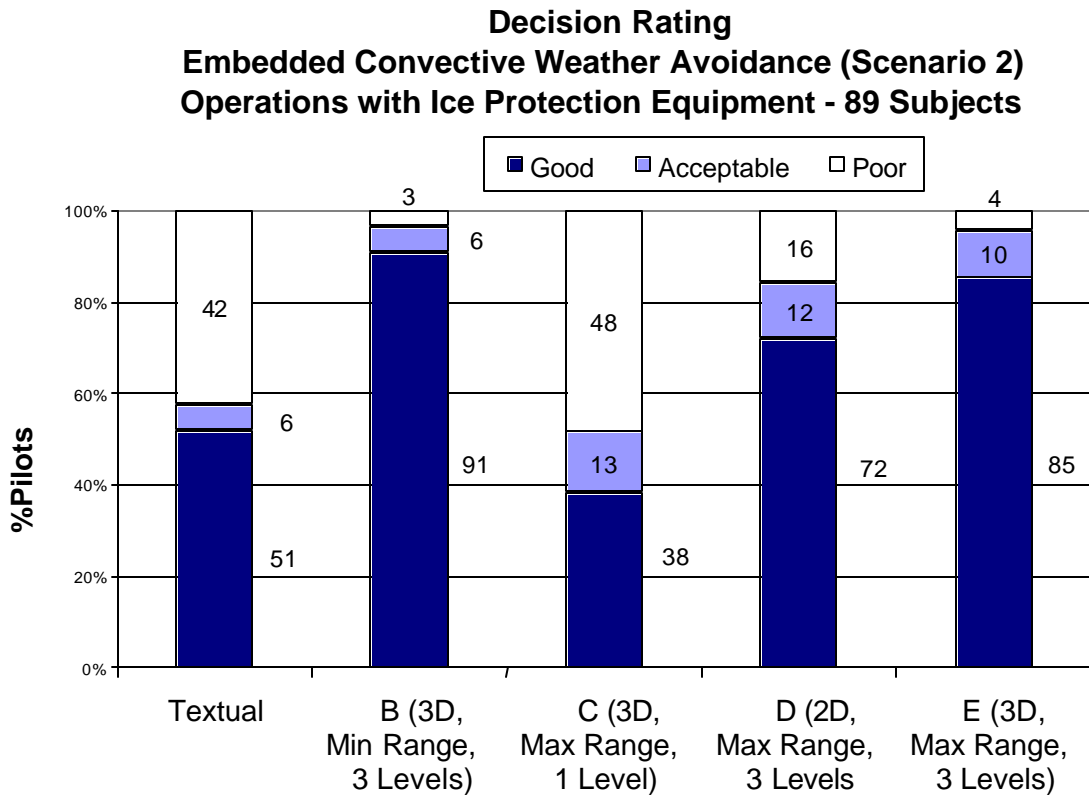


Figure 6-7: Decision Quality Distribution in Scenario 2

As can be seen, support from Display E (3D, max range, 3 levels) also provided a basis for a high percentage of good decisions (85%) and very low percentage of poor decisions (4%). In comparison with average results throughout flight scenarios that were presented in Figure 6-3, better decisions are found overall, except with the use of Display C (3D, max range, 1 level). Explanations are provided below, based on the detailed analysis of the routing distributions presented in Figure 6-8.

For known-icing approved operations, routing decisions leading to penetration into icing conditions beyond the capabilities of ice-protection equipped aircraft, as depicted by yellow and red levels of icing severity on the 3 displays incorporating such information (namely the Displays B, C and D), were classified by expert analyst as poor decisions. Decisions involving a combination of a deviation to the right (by 30° or 60°) and a descent (to either 6,000 feet or 4,000 feet) were classified as good decisions.

When provided with textual information only, a majority of pilots (51%) indicated they would descend to either 6,000 feet or 4,000 feet, cruising altitudes that are closer to the reported ceiling altitudes at KBWI and KIAD. A smaller percentage (42% combined) indicated they would continue either continue as filed or initiate a climb; such decisions were rated as poor decisions. This explains the distribution of good (51%) and poor (42%) decisions.

When provided with information from Display B (3D, min range, 3 levels), a large percentage of pilots (91%) indicated that they would re-route with a combination of descent and deviation to the right. The limited range of Display B (3D, min range, 3 levels) seemed sufficient to support well-informed decisions in this flight scenario.

When provided with information from Display C (3D, max range, 1 level), a large percentage (48%) of pilots indicated that they would re-route by either climbing or deviating left, or a combination of both. As can be seen on Figure 6-8 by looking at Display E (3D, max range, 3 levels), such re-routing maneuvers lead to penetration into more severe icing conditions, and were hence associated with poor decisions. It is speculated that those pilots have opted for shorter distances in the depicted icing conditions. The lack of information on icing severity did not allow them to identify zones where severe icing conditions were present.

When provided with information from Display D (2D, max range, 3 levels), a majority of pilots (51%) indicated they would deviate right at the same altitude. Another large number indicated they would make a combination of descent and right turn (10%) or simply a descent (11%). This overall contributed to a large percentage of good decisions (72%).

When provided with information from the Display E (3D, max range, 3 levels), 27% of the pilots indicated a deviation to the right, 27% indicated a descent, and 31% indicated a combination of both maneuvers. This more even distribution indicates no strong preference for vertical versus horizontal deviation. In comparison with the decision of pilots based on information from the Display D (2D, max range, 3 levels), this suggests that provision of the vertical display contributed to deviation along the dimension of the display.

Decision Rating Scheme (Scenario 2, Equipped Operations)	Decision Rating (Equipped)				
	Good		Acceptable	Poor	
	L 60°	L 30°	14000.0	R 30°	R 60°
	L 60°	L 30°	12000.0	R 30°	R 60°
	L 60°	L 30°	10000.0	R 30°	R 60°
	L 60°	L 30°	8000.0	R 30°	R 60°
	L 60°	L 30°	6000.0	R 30°	R 60°
	L 60°	L 30°	4000.0	R 30°	R 60°
	Abort to KBWI				
	Reverse Course				
	Abort to KPHL				
Text	ta Decision Space				
	0.0	0.0	1.1	0.0	0.0
	0.0	0.0	2.2	0.0	0.0
	0.0	0.0	2.2	0.0	0.0
	0.0	0.0	36.0	0.0	0.0
	0.0	1.1	9.0	0.0	0.0
	0.0	1.1	41.6	0.0	0.0
			3.4		
		0.0			
		0.0			
Display B (3D, min range, 3 levels)	aa Decision Space				
	0.0	0.0	0.0	0.0	0.0
	0.0	0.0	0.0	0.0	0.0
	0.0	0.0	0.0	0.0	0.0
	0.0	0.0	3.4	15.7	2.2
	0.0	1.1	19.1	20.2	1.1
	0.0	2.2	18.0	14.6	0.0
			0.0		
		1.1			
		1.1			
Display C (3D, max range, 1 level)	bb Decision Space				
	1.1	1.1	10.1	0.0	0.0
	1.1	0.0	4.5	0.0	0.0
	0.0	0.0	1.1	0.0	0.0
	5.6	1.1	22.5	0.0	0.0
	1.1	0.0	4.5	0.0	0.0
	4.5	1.1	33.7	0.0	0.0
			1.1		
		2.2			
		3.4			
Display D (2D, max range, 3 levels)	cb Decision Space				
	0.0	0.0	0.0	3.4	0.0
	0.0	0.0	0.0	0.0	0.0
	0.0	0.0	0.0	4.5	0.0
	7.9	2.2	5.6	42.7	7.9
	0.0	1.1	2.2	9.0	1.1
	0.0	0.0	9.0	0.0	0.0
			0.0		
		2.2			
		1.1			
Display E (3D, max range, 3 levels)	da Decision Space				
	0.0	0.0	0.0	1.1	1.1
	1.1	0.0	0.0	2.2	1.1
	0.0	0.0	0.0	0.0	0.0
	0.0	0.0	3.4	21.3	5.6
	0.0	1.1	13.5	10.1	0.0
	1.1	0.0	13.5	14.6	6.7
			0.0		
		1.1			
		1.1			

Figure 6-8: Distribution of Pilots' Re-Routing Decisions (Scenario 2, Equipped Operations)

6.2.3 SCENARIO 3: VMC-ON-TOP AVOIDANCE

Figure 6-9 depicts the level of graphical information support provided in Scenario 1 (as already presented in Figures 5-13 and 5-14). The distribution of pilots who made good, acceptable and poor decisions in Scenario 3 is presented in Figure 6-10. A surprisingly large percentage of poor decisions was observed with information from Display B (3D, min range, 3 levels). In comparison with the summary of results presented in Figure 6-3, a larger number of poor decisions were made with all types of displays. Much stronger differences are found for decisions made with the Display B (3D, min range, 3 levels) and textual information; this difference is of 67% and 31%, respectively. Explanations for the distribution observed is provided below.

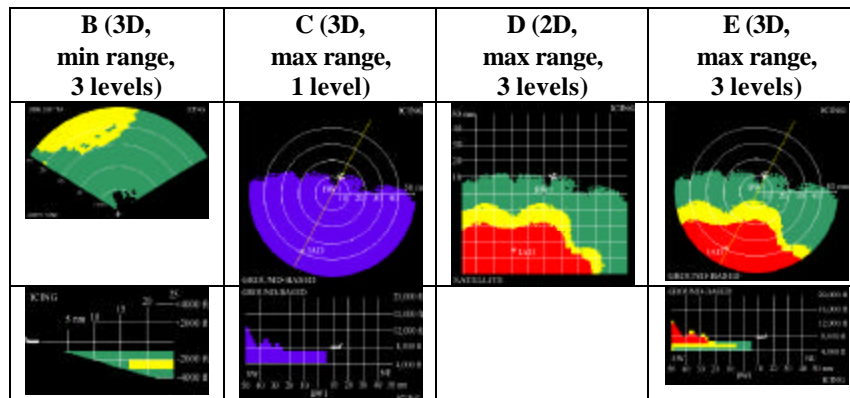


Figure 6-9: Displays in Scenario 3

A detailed distribution of re-routing decisions is found in Figure 6-11. A descent to 4,000 feet was rated as good, as it would allow to reach destination via the most efficient route that would avoid penetration in zones of light to moderate icing conditions. Other less efficient route that would also avoid penetration in zones of light to moderate icing conditions were rated as acceptable.

When provided with textual information only, most pilots (79%) indicated they would continue as filed. The second most popular routing decision involved a descent (in 15% of the cases). This explains the very low percentage of good decisions (12%) and large percentage of poor decisions (84%). Although a PIREP that indicates icing conditions ahead along the route at a lower altitude has been transmitted, no information is readily available about the spatial location of the possible icing threat. No indication is provided to pilots that would suggest that an immediate descent would be a wise thing to initiate.

When provided with information from Display B (3D, min range, 3 levels), a large percentage of pilots (82%) indicated that they would also continue as filed. Another small number (10%) mentioned that they would deviate to the right of the planned course. Based on the information presented with reduced range, it seems that the decision was based on avoiding overflying light to moderate icing conditions (marked by the yellow zone on the display).

**Decision Rating - VMC-On-Top Avoidance (Scenario 3)
Operations with Ice Protection Equipment - 89 Subjects**

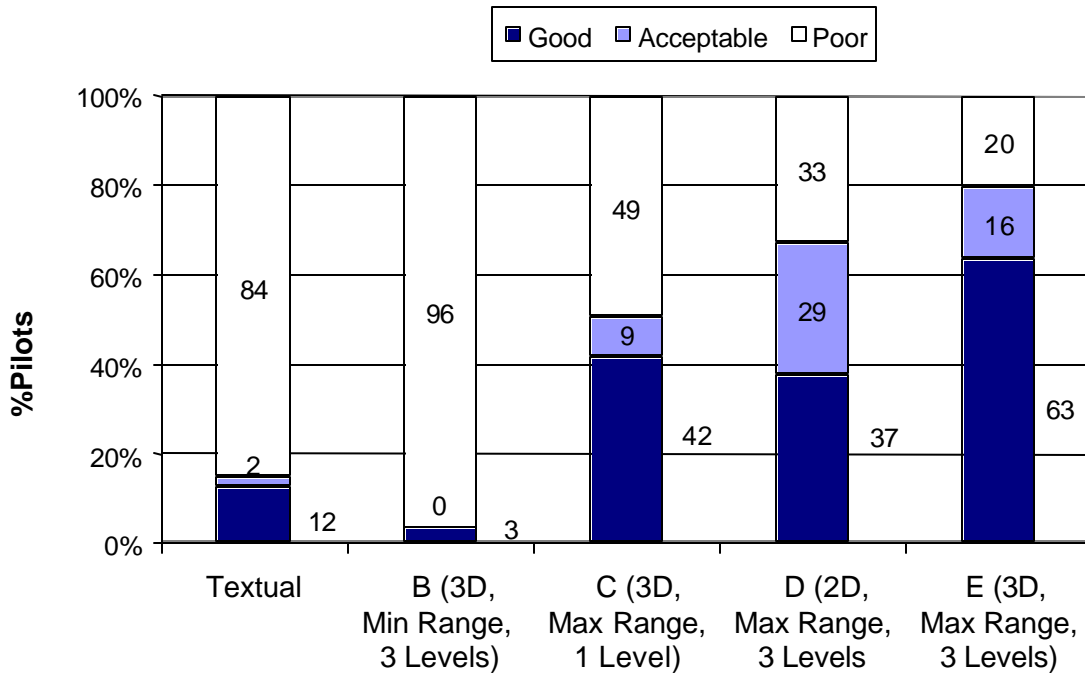


Figure 6-10: Decision Quality Distribution in Scenario 3

When provided with information from Display C (3D, max range, 1 level), a large percentage of pilots (42%) indicated that they would descend to 4,000 feet. Another 35% of the pilots mentioned that they would continue as filed at 8,000 feet. Some 14% mentioned they would initiate a climb. The overall percentage of poor decisions added up to 49% based on the mentioned distribution. The lack of severity information did not support decisions that would help avoid severe icing conditions.

When provided with information from Display D (2D, max range, 3 levels), 37% of the pilots indicated they would descend to 4,000 feet. Other popular decisions involved continuing as filed (for 26% of the pilots) and aborting to land at KBWI (25%). Although Display D (2D, max range, 3 levels) does not provide a vertical cross-section of the icing conditions, and since destination is within the range of the display, and based on the reported temperatures and ceiling it is speculated that it was possible for pilots to identify that an cruising altitude of 4,000 feet was a safe one. The lack of vertical information is speculated to have led the most conservative pilots to abort the flight.

When provided with information from Display E (3D, max range, 3 levels), most of the pilots (63%) indicated that they would re-route to 4,000 feet. This explains the large percentage of good decisions (which is also 63% since it was the only decision rated as good).

Decision Rating Scheme (Scenario 3, Equipped Operations)	Decision Rating (Equipped)				
	Good	Acceptable	Poor		
	L 60°	L 30°	14,000	R 30°	R 60°
	L 60°	L 30°	12,000	R 30°	R 60°
	L 60°	L 30°	10,000	R 30°	R 60°
	L 60°	L 30°	8,000	R 30°	R 60°
	L 60°	L 30°	6,000	R 30°	R 60°
	L 60°	L 30°	4,000	R 30°	R 60°
	Abort to KBWI Reverse Course Abort to KPHL				
Text	ta Decision Space				
	0.0	0.0	0.0	0.0	0.0
	0.0	0.0	0.0	0.0	0.0
	0.0	0.0	3.4	0.0	0.0
	0.0	0.0	78.7	0.0	0.0
	0.0	0.0	2.2	0.0	0.0
	0.0	1.1	12.4	0.0	0.0
			1.1		
			0.0		
			0.0		
Display B (3D, min range, 3 levels)	aa Decision Space				
	0.0	0.0	0.0	0.0	0.0
	0.0	0.0	0.0	1.1	0.0
	0.0	0.0	0.0	0.0	0.0
	0.0	2.2	82.0	10.1	0.0
	0.0	0.0	0.0	0.0	0.0
	0.0	0.0	3.4	0.0	0.0
			0.0		
			0.0		
			0.0		
Display C (3D, max range, 1 level)	bb Decision Space				
	0.0	0.0	4.5	0.0	0.0
	0.0	0.0	3.4	0.0	0.0
	0.0	0.0	5.6	0.0	0.0
	0.0	0.0	34.8	0.0	0.0
	0.0	0.0	1.1	0.0	0.0
	1.1		41.5	0.0	0.0
			7.9		
			0.0		
			0.0		
Display D (2D, max range, 3 levels)	cb Decision Space				
	0.0	0.0	0.0	0.0	0.0
	0.0	0.0	1.1	1.1	0.0
	0.0	0.0	1.1	0.0	0.0
	0.0	0.0	25.8	0.0	0.0
	0.0	0.0	3.4	0.0	0.0
	0.0	0.0	37.1	0.0	1.1
			24.7		
			0.0		
			3.4		
Display E (3D, max range, 3 levels)	da Decision Space				
	0.0	0.0	2.2	0.0	0.0
	0.0	0.0	1.1	0.0	0.0
	0.0	0.0	1.1	0.0	0.0
	0.0	0.0	12.4	1.1	0.0
	0.0	0.0	2.2	0.0	0.0
	0.0	0.0	62.9	0.0	0.0
			14.6		
			0.0		
			1.1		

*Figure 6-11: Distribution of Pilot Re-Routing Decisions
(Scenario 3, Equipped Operations)*

6.2.4 SCENARIO 4: STABLE LAYER ESCAPE

Figure 6-12 depicts the level of graphical information support provided in scenario 1 (as already presented in Figures 5-15 and 5-16). The percentage of pilots who made good, acceptable and poor decisions in scenario 4 is presented in Figure 6-13. Overall, the distribution of decisions in Scenario 4 for equipped operations is characterized by a small number of poor decisions with all types of information support provided. In comparison to the averaged decision quality throughout flight scenarios presented in Figure 6-3, a larger number of good decisions with three of the five types of information support provided were observed. A smaller percentage (by 11%) of good decisions was made based on information from Display E (3D, max range, 3 levels), and a significantly smaller number of good decisions was made based on the information provided by the Display D (2D, max range, 3 levels).

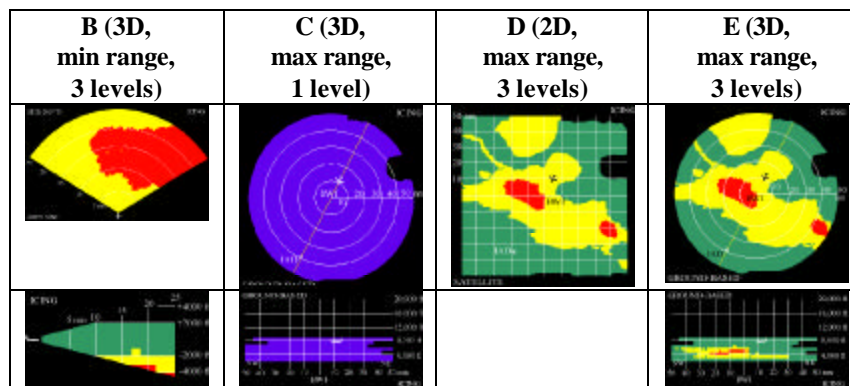


Figure 6-12: Displays in Scenario 4

A detailed distribution of decision quality according to the type of information system used is found in Figure 6-14. Due to the distribution of the icing conditions, and considering safety and efficiency of flight operations, the good flight routing decision was identified to involve overflying the light to moderate icing conditions (by staying at or above 8,000 feet), initiate a descent when reaching an area beyond the light to moderate icing conditions, but keep the same planned ground track. Poor decisions involved flight routes that would lead to penetration into light or more severe icing conditions (corresponding to yellow and red zones).

When provided with textual information only, a majority of pilots indicated they would either continue as filed or climb without lateral deviation (for a total of 64%). Another group of pilots (19%) indicated they would descend; others indicated they would either reverse course or abort the flight (16%). This distribution explains the distribution of good (64%), acceptable (16%) and poor (19%) decisions.

When provided with information from Display B (3D, min range, 3 levels), a large number of pilots indicated that they would either continue as filed or climb (57% overall), which corresponds to the percentage of good decisions. Basing their decision on information presented by both the plan view and profile view display, another group indicated that they would include a lateral deviation to the left (32%). Although this seemed appropriate based on the reduced range

information presented, it did not correspond to the most desirable set of routing decisions to be made; this mostly explains the percentage of acceptable decisions (38%).

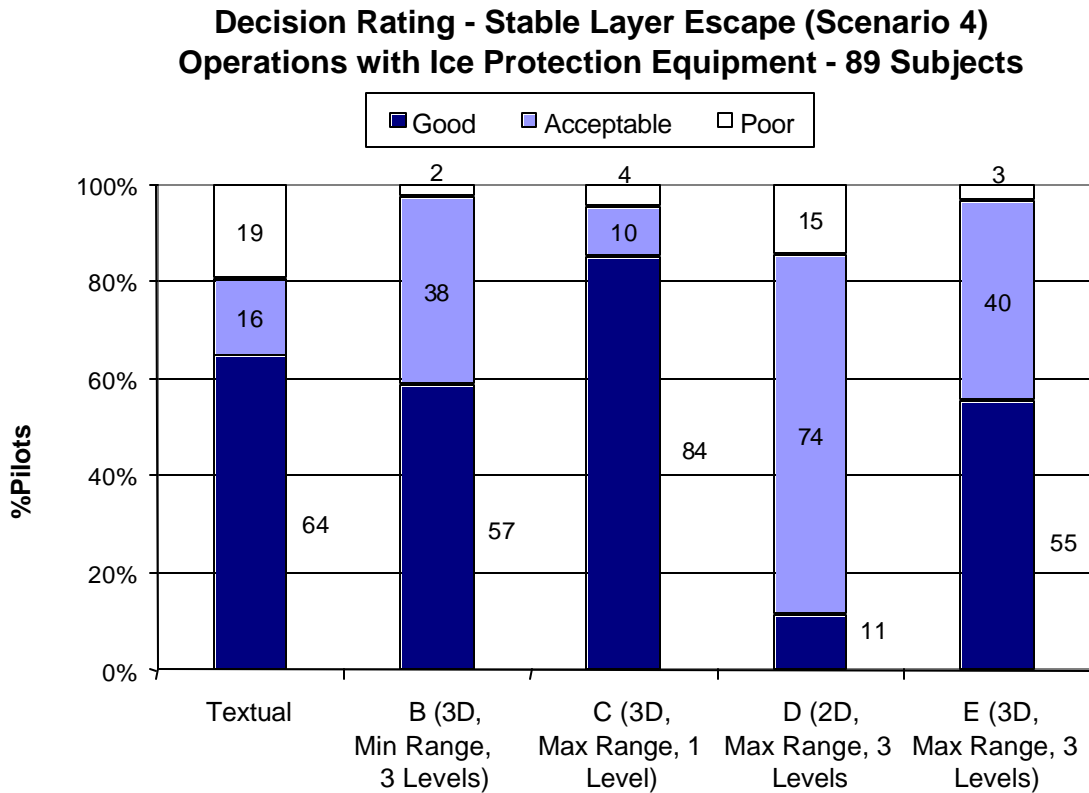


Figure 6-13: Decision Quality Distribution in Scenario 4

When provided with information from Display C (3D, max range, 1 level), a vast majority of pilots indicated that they would either initiate a climb to overfly the depicted icing conditions (74%) or continue as filed (10%) and in doing so, tolerate to proceed within the depicted icing conditions at an altitude in proximity of an escape route. This corresponds to the large percentage of good decisions (84%).

When provided with information from Display D (2D, max range, 3 levels), a vast majority of pilots indicated that their re-routing maneuver would involve a lateral deviation to the left. Although it was an appropriate maneuver to perform, it did not correspond to the most efficient route and was as such rated as acceptable. This explains the large percentage of acceptable decisions with the use of the Display D (2D, max range, 3 levels).

When provided with information from Display E (3D, max range, 3 levels), a majority of pilots indicated that they would either continue as filed or climb (55%), which corresponded to good decisions. A significant percentage of pilots also indicated a deviation to the left (37%), at various altitudes. This relates to the large percentage of acceptable decisions (40%).

Decision Rating Scheme (Scenario 4, Equipped Operations)	Decision Rating (Equipped)				
	Good		Acceptable	Poor	
	L 60°	L 30°	14,000	R 30°	R 60°
	L 60°	L 30°	12,000	R 30°	R 60°
	L 60°	L 30°	10,000	R 30°	R 60°
	L 60°	L 30°	8,000	R 30°	R 60°
	L 60°	L 30°	6,000	R 30°	R 60°
	L 60°	L 30°	4,000	R 30°	R 60°
	Abort to KBWI Reverse Course Abort to KPHL				
Text	ta				
	Decision Space				
	0.0	0.0	10.1	0.0	0.0
	0.0	0.0	14.6	0.0	0.0
	0.0	0.0	9.0	0.0	0.0
	0.0	0.0	30.3	0.0	0.0
	0.0	0.0	6.7	0.0	0.0
	0.0	0.0	12.4	0.0	0.0
		7.9			
		4.5			
		3.4			
Display B (3D, Min range, 3 levels)	aa				
	Decision Space				
	0.0	0.0	3.4	0.0	0.0
	1.1	6.7	10.1	0.0	0.0
	1.1	5.6	5.6	0.0	0.0
	5.6	12.4	38.2	0.0	0.0
	0.0	0.0	0.0	0.0	0.0
	0.0	2.2	0.0	0.0	0.0
		1.1			
		4.5			
		0.0			
Display C (3D, max range, 1 level)	bb				
	Decision Space				
	0.0	0.0	1.1	0.0	0.0
	0.0	0.0	36.0	0.0	0.0
	0.0	0.0	37.1	0.0	0.0
	0.0	0.0	10.1	0.0	0.0
	0.0	0.0	1.1	0.0	0.0
	0.0	0.0	2.2	1.1	0.0
		4.5			
		2.2			
		3.4			
Display D (2D, max range, 3 levels)	cb				
	Decision Space				
	3.4	2.2	2.2	0.0	2.2
	1.1	5.6	0.0	0.0	1.1
	0.0	5.6	2.2	0.0	0.0
	10.1	34.8	6.7	0.0	2.2
	0.0	1.1	0.0	0.0	0.0
	2.2	9.0	2.2	0.0	0.0
		0.0			
		4.5			
		1.1			
Display E (3D, max range, 3 levels)	da				
	Decision Space				
	0.0	2.2	0.0	0.0	0.0
	1.1	5.6	12.4	0.0	0.0
	2.2	7.9	18.0	0.0	0.0
	2.2	14.6	24.7	0.0	0.0
	0.0	0.0	0.0	0.0	0.0
	0.0	1.1	1.1	1.1	0.0
		0.0			
		1.1			
		3.4			

Figure 6-14: Distribution of Pilot Re-Routing Decisions (Scenario 4, Equipped Operations)

6.3 ROUTING DECISIONS FOR NON-EQUIPPED OPERATIONS

As previously mentioned, decision rating schemes for non-equipped operations were distinct than the decision rating schemes for equipped operations. Any level of icing conditions is considered intolerable for the former type of operation. The routing decisions for the former type of operations were rated according to a more conservative rating scheme: any avoidance and escape maneuvers from zones where icing conditions are expected was rated as good.

As shown in Figure 6-15, and similarly to the decision quality results for equipped pilots, it was found that better decisions were made with support from graphical information (with Displays B through E) than with textual information only. The largest number of poor decisions was made with text only (56% of pilots). Also, the smallest number of poor decisions was made with the most enhanced information using Display E (22%). Considerable variability in the distribution was found across flight scenarios. A more detailed analysis for each scenario should help understand differences in decision quality as they relate to the flight-scenario specific re-routing maneuvers.

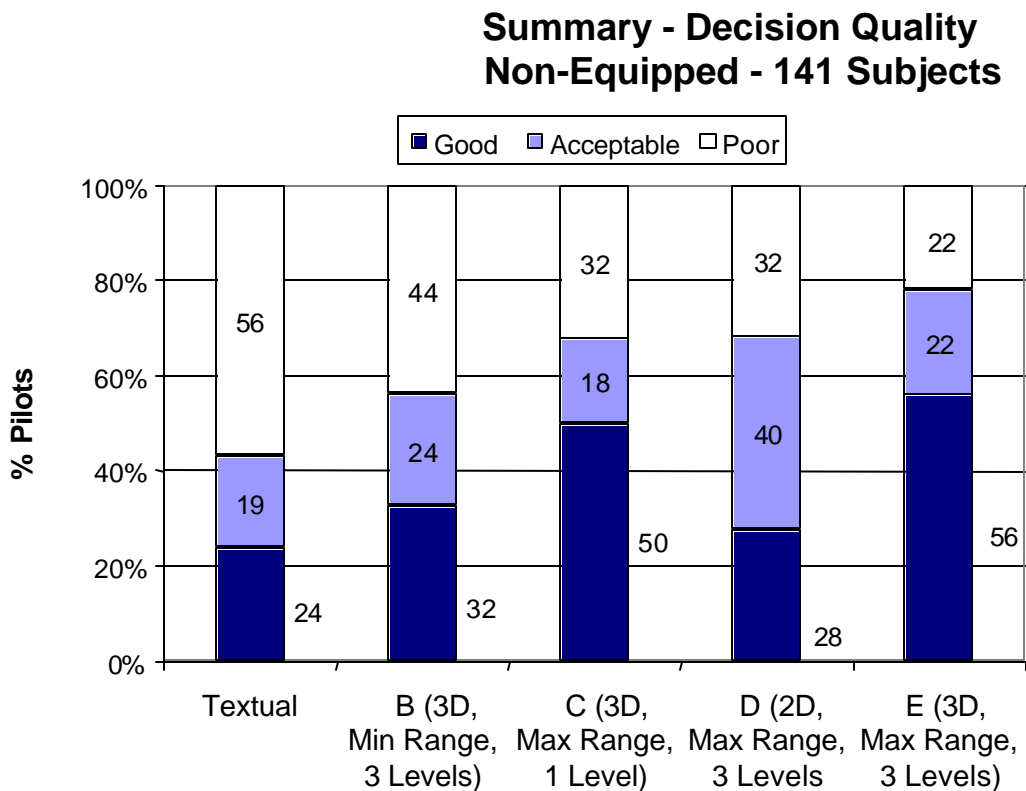


Figure 6-15: Summary of Decision Quality throughout Flight Scenarios for Non-Equipped Operations

6.3.1 SCENARIO 1: WARM FRONT AVOIDANCE SCENARIO

Figure 6-16 depicts the level of graphical information support provided in Scenario 1 (as already presented Figures 5-9 and 5-10). The percentage of pilots who made good, acceptable and poor decisions in Scenario 1 is presented in Figure 6-17. The distribution of decisions in Scenario 1 for non-equipped operations is not significantly different than the summary of decision quality throughout flight scenarios, except for the much smaller percentage (10% instead of 44%) of poor decisions when provided with information from Display B (3D, min range, 3 levels).

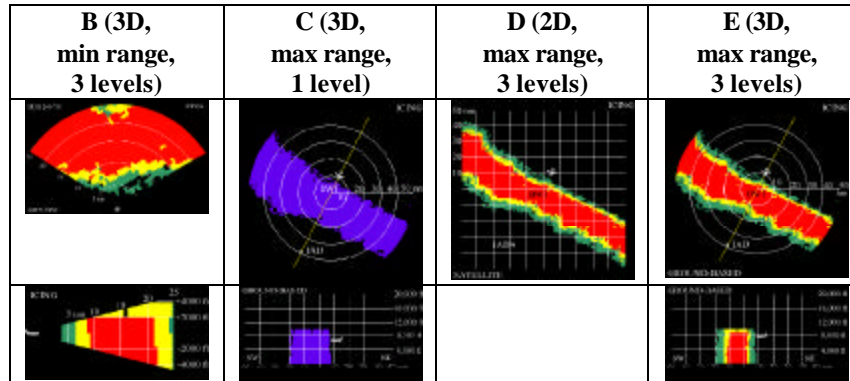


Figure 6-16: Displays in Scenario 1

A detailed distribution of decision quality according to the type of information system used is found in Figure 6-18. Due to the spatial distribution of the icing conditions, and considering safety and efficiency of flight operations, the good flight routing decision was identified to involve overflying any level of icing conditions, by climbing to at least 12,000 feet. Acceptable decisions involved avoiding the icing by any other means, that is by either reversing course, aborting to KPHL, or climbing and making a turn.

When provided with textual information only, a majority of pilots (51%) indicated they would continue as filed. This mostly explains the large percentage of poor decisions (57%). A very small amount of pilots indicated that they would climb to either 12,000 feet or 14,000 feet. Their decision is likely based on weather knowledge, cues from the reported surface conditions at KBWI and destination (KIAD) and related to an evaluation of where temperatures with increasing are likely to be cold to sustain freezing precipitation. A significant number of pilots mentioned that they would avoid the location where icing conditions are possibly present, by either aborting to KPHL or reversing course (31%).

When provided with information from Display B (3D, min range, 3 levels), a larger percentage of pilots indicated that they would climb to 12,000 feet or 14,000 feet (27%). This increase in percentage is related to the fact that the information presented may have confirmed what some pilots were able to infer and risks they were willing to accept. A much larger percentage of pilots mentioned that they would abort to KPHL or reverse course (60%). This mostly explains the distribution of pilots who made good (27%) and acceptable (62%) decisions.

When provided with information from Display C (3D, max range, 1 level), a majority of pilots indicated that they would either climb to 12,000 feet or 14,000 feet (52%), which corresponds to the proportion of good decisions. Another group of pilots (21%) indicated that they would tolerate being at the upper boundary of the zone where icing conditions are depicted. Since the icing conditions at that boundary were light-to-moderate icing conditions, this routing decision was rated as a poor decision. A small percentage of pilots indicated that they would continue, descend or abort the flight to KBWI, which corresponded to penetration into the freezing rain zone (11%). This added up to 33% of poor decisions for this case.

**Decision Quality - Warm Front Avoidance (Scenario 1)
Operations without Ice Protection Equipment - 141 Subjects**

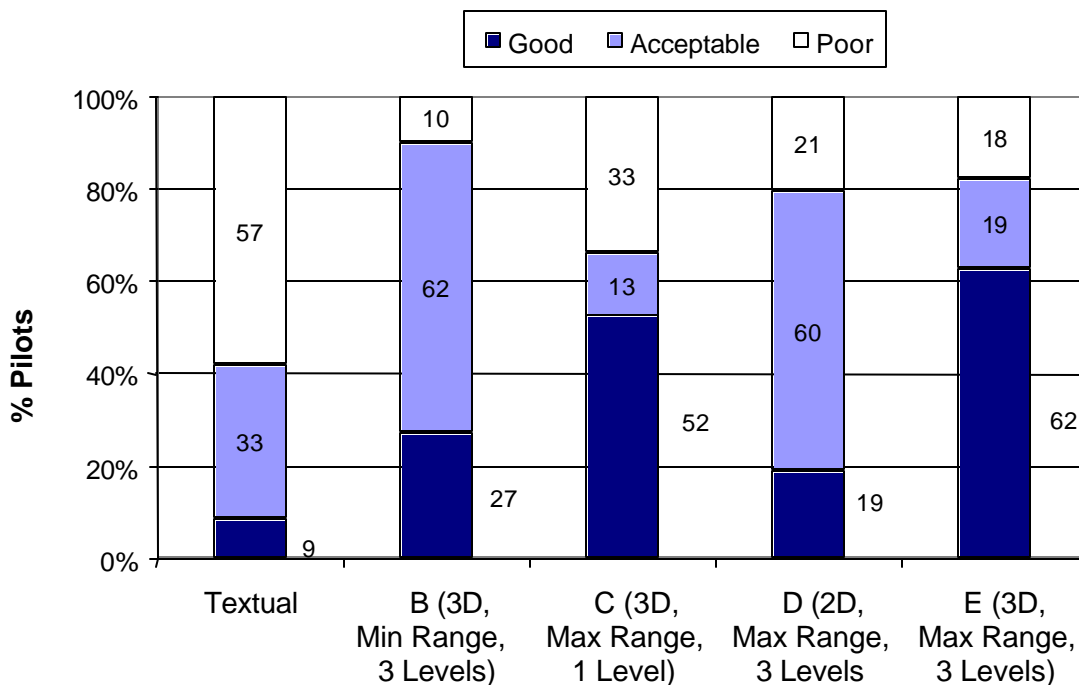


Figure 6-17: Decision Quality Distribution in Scenario 1

When provided with information from Display D (2D, max range, 3 levels), a majority of pilots indicated that they would reverse course or abort to KPHL (60% overall), which corresponded to acceptable decisions. This observation corresponds once more to the dominance of re-routing decisions made according to the plane along which information is provided. Another percentage of pilots (19%) mentioned that they would either climb to 12,000 feet or 14,000 feet. It is speculated that those pilots did not need the support of vertical graphical information to be able to infer the zones where freezing rain may not be present based on the provided information.

When provided with information from the Display E (3D, max range, 3 levels), a majority of pilots indicated that they would climb to a safe altitude above the icing conditions (62%). Another group of pilots (16%) indicated that they would tolerate being at the upper boundary of the icing zones, despite the fact that it was clear that such conditions were depicted to correspond

to light-to-moderate icing conditions. This group of pilots accounts for most of the subjects who made poor decisions.

Decision Rating Scheme (Scenario 1, Non-Equipped Operations)	Decision Rating (Non-Equipped)				
	Good		Acceptable	Poor	
	L 60°	L 30°	14,000	R 30°	R 60°
	L 60°	L 30°	12,000	R 30°	R 60°
	L 60°	L 30°	10,000	R 30°	R 60°
	L 60°	L 30°	8,000	R 30°	R 60°
	L 60°	L 30°	6,000	R 30°	R 60°
	L 60°	L 30°	4,000	R 30°	R 60°
	Abort to KBWI Reverse Course Abort to KPHL				
Text	Warm Front Avoidance		ta	Textual	
			Decision Space		
	0.0	1.4	4.3	0.0	0.0
	0.0	0.0	4.3	0.0	0.0
	0.0	0.0	4.3	0.0	0.0
	0.0	0.0	51.1	0.0	0.7
	0.0	0.0	0.0	0.0	0.0
	0.0	0.0	0.7	0.0	0.0
			0.0		
			5.7		
		25.5			
Display B (3D, Min range, 3 levels)	Warm Front Avoidance		aa	Airborne Icing Severity	
			Decision Space		
	0.0	0.0	12.8	0.7	0.0
	0.0	0.0	14.2	0.0	1.4
	0.0	0.0	3.5	0.0	0.0
	0.7	0.0	0.7	0.0	0.0
	0.0	0.0	0.7	0.0	0.0
	0.0	0.0	1.4	0.0	0.0
			2.8		
			24.1		
		36.2			
Display C (3D, max range, 1 level)	Warm Front Avoidance		ba	Ground-Based Icing Presence	
			Decision Space		
	0.0	0.0	3.5	0.0	0.0
	0.0	0.0	48.2	0.7	0.0
	1.4	0.0	20.6	0.0	0.0
	0.0	0.0	7.1	0.0	0.0
	0.0	0.0	2.1	0.0	0.0
	0.0	0.0	0.7	0.0	0.0
			1.4		
			3.5		
		9.2			
Display D (2D, max range, 3 levels)	Warm Front Avoidance		ca	Satellite-Based Icing Severity	
			Decision Space		
	0.0	0.0	9.2	0.0	0.0
	0.0	0.0	9.9	0.0	0.0
	0.0	0.0	2.1	0.0	0.0
	0.7	0.0	14.2	0.0	0.0
	0.0	0.0	0.7	0.0	0.0
	0.0	0.0	2.1	0.0	0.0
			0.7		
			18.4		
		41.8			
Display E (3D, max range, 3 levels)	Warm Front Avoidance		da	Ground-Based Icing Severity	
			Decision Space		
	0.0	0.0	9.2	0.0	0.0
	1.1	0.0	53.2	0.0	1.1
	0.0	0.0	15.6	0.0	0.0
	0.0	0.0	0.7	0.0	0.0
	0.0	0.0	0.0	0.0	0.0
	0.0	0.0	0.7	0.0	0.0
			0.7		
			7.1		
		9.9			

Figure 6-18: Distribution of Pilot Re-Routing Decisions
(Scenario 1, Non-Equipped Operations)

6.3.2 SCENARIO 2: EMBEDDED CONVECTIVE WEATHER AVOIDANCE

Figure 6-19 depicts the level of graphical information support provided in Scenario 2 (as already presented in Figure 5-11 and Figure 5-12). The percentage of pilots who made good, acceptable and poor decisions in Scenario 2 is presented in Figure 6-20. The distribution of decisions in Scenario 2 for non-equipped operations is characterized by little variation in decision quality with all five types of information support.

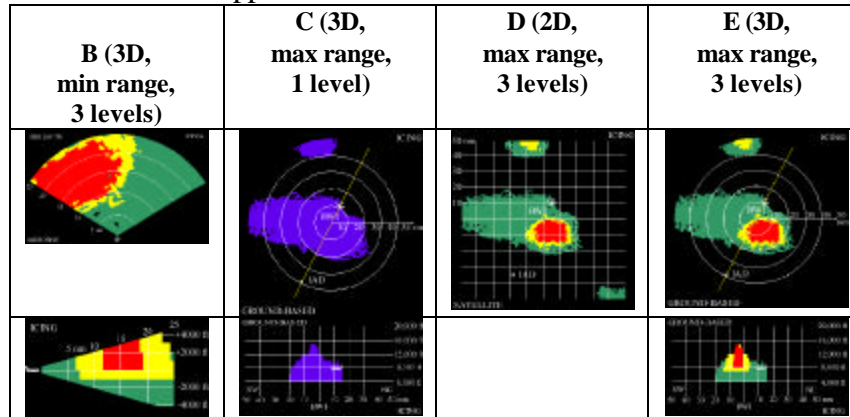


Figure 6-19: Displays in Scenario 2

A detailed distribution of decision quality according to the type of information system used is found in Figure 6-21. Due to the spatial distribution of icing conditions, and based on flight safety criteria, the good flight routing decision was identified to involve descending to the lower boundaries of the icing conditions and above the MEA. Acceptable decisions involved avoiding the icing conditions by doing a right climb, reversing course or aborting. Other routing decisions were rated as poor decisions.

When provided with textual information only, a group of pilots (33%) indicated that they would continue as filed, another group indicated that their re-routing maneuver would involve a descent (48%), with a majority of them indicating a descent to 4,000 feet (38%). Other decisions involved a number of various routing actions. Overall, a majority of pilots indicated decisions that were rated as poor (56%).

When provided with information from Display B (3D, min range, 3 levels), a much smaller percentage of pilots indicated that they would continue as filed (1%). Instead, most of the pilots indicated that they would re-route with a maneuver involving a descent (76%). Within this group, 38% indicated a descent to 4,000 feet, which corresponds to the percentage of good decisions. Most pilots' decisions (52%) did nevertheless fall within the poor rating classification according to the conservative decision-rating scheme established.

When provided with information from Display C (3D, max range, 1 level), 43% of pilots mentioned that they would descend to 4,000 feet. Other pilots' indicated a variety a re-routing decisions covering most of the decision space. A large percentage of the pilots (45%) indicated decisions that were rated as poor.

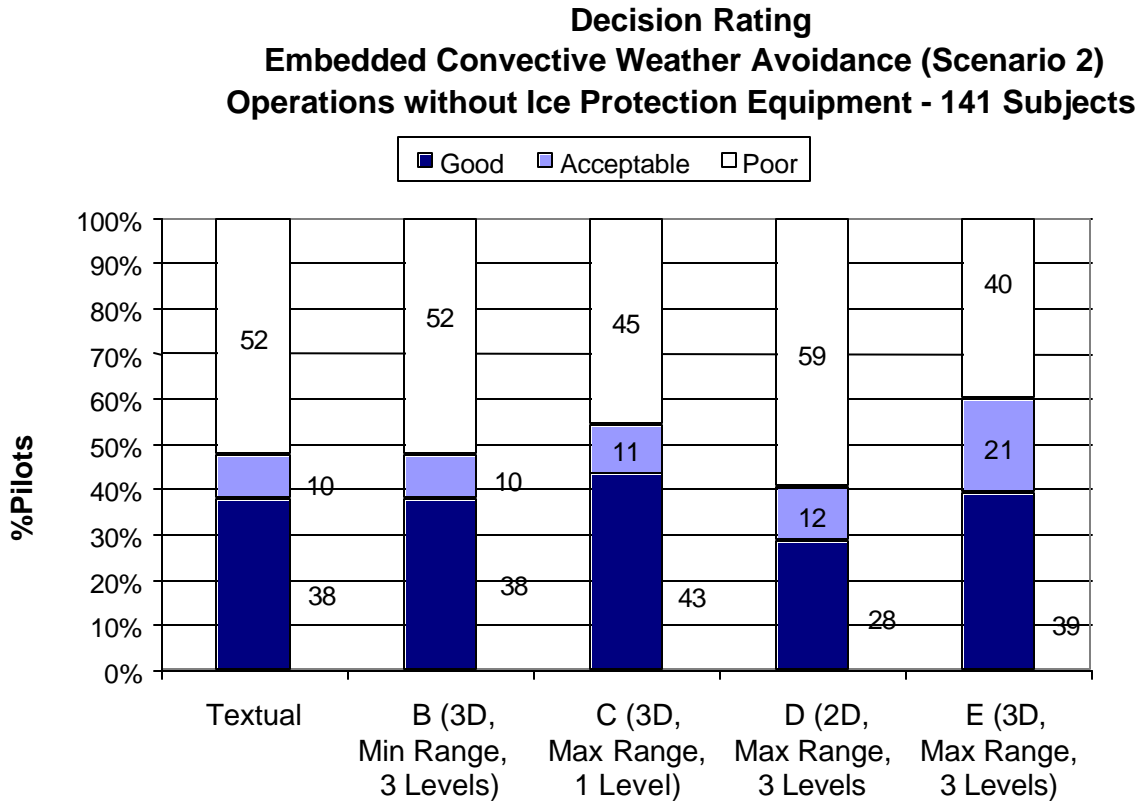


Figure 6-20: Decision Quality Distribution in Scenario 2

When provided with information from Display D (2D, max range, 3 levels), most of the pilots (75%) indicated they would re-route with maneuvers involving lateral deviation to the right, and only 21% of those would involve a descent to 4,000 feet. Overall, the percentage of good decisions only accounted for 28%. This corresponds again to the observation made above about the fact that the correspondence between the dominant plane of deviation and the plane of graphical information.

When provided with information from Display E (3D, max range, 3 levels), pilots indicated re-routing maneuvers that involve lateral deviation to the right in 56% of the cases, and re-routing maneuvers that involve a descent in 60% of the cases.

6. Results of Web-Based Experiment on Icing Remote Sensing Displays

Decision Rating Scheme (Scenario 2, Non-Equipped Operations)	Decision Rating (Non-Equipped)				
	Good		Acceptable	Poor	
	L 60°	L 30°	14,000	R 30°	R 60°
	L 60°	L 30°	12,000	R 30°	R 60°
	L 60°	L 30°	10,000	R 30°	R 60°
	L 60°	L 30°	8,000	R 30°	R 60°
	L 60°	L 30°	6,000	R 30°	R 60°
	L 60°	L 30°	4,000	R 30°	R 60°
	Abort to KBWI Reverse Course Abort to KPHL				
Text	ta Decision Space				
	0.0	0.0	2.1	0.0	0.0
	0.0	0.0	2.1	0.0	0.0
	0.0	0.7	2.8	0.7	0.0
	0.0	0.7	32.6	0.7	0.0
	0.0	0.0	9.9	0.0	0.0
	0.0	2.1	34.8	0.7	0.0
	5.7 1.4 2.1				
Display B (3D, Min range, 3 levels)	aa Decision Space				
	0.0	0.0	0.7	1.4	0.0
	0.0	0.0	0.0	0.0	0.0
	0.0	0.0	0.0	0.0	0.0
	0.0	0.7	0.7	9.9	1.4
	0.0	0.7	14.2	23.4	0.0
	0.0	0.0	14.2	20.6	2.8
	7.1 0.7 0.7				
Display C (3D, max range, 1 level)	bb Decision Space				
	2.8	2.1	10.6	0.0	0.7
	4.3	0.0	2.1	0.0	0.0
	0.7	0.0	0.7	0.0	0.0
	6.4	0.0	9.9	0.0	0.7
	0.0	0.0	5.0	0.0	0.0
	8.5	0.7	33.3	0.0	0.7
	2.8 2.8 4.3				
Display D (2D, max range, 3 levels)	cb Decision Space				
	0.7	0.0	1.4	0.0	0.7
	0.0	0.0	0.0	5.7	0.0
	0.0	0.7	0.0	3.5	0.0
	5.0	2.8	2.1	27.7	8.5
	0.0	0.0	2.1	7.1	0.7
	2.1	1.4	4.3	17.0	3.5
	0.7 0.7 0.7				
Display E (3D, max range, 3 levels)	da Decision Space				
	0.0	0.0	0.0	0.7	0.7
	0.0	1.4	0.0	7.1	2.1
	0.0	0.0	0.0	2.8	0.0
	0.0	2.1	2.1	10.6	2.1
	0.7	1.4	9.9	9.2	0.0
	2.1	0.7	15.6	19.9	0.7
	1.4 2.1 3.5				

*Figure 6-21: Distribution of Pilot Re-Routing Decisions
(Scenario 2, Non-Equipped Operations)*

6.3.3 SCENARIO 3: VMC-ON-TOP AVOIDANCE

Figure 6-22 depicts the level of graphical information support provided in Scenario 3 (as already presented in Figures 5-13 and 5-14).

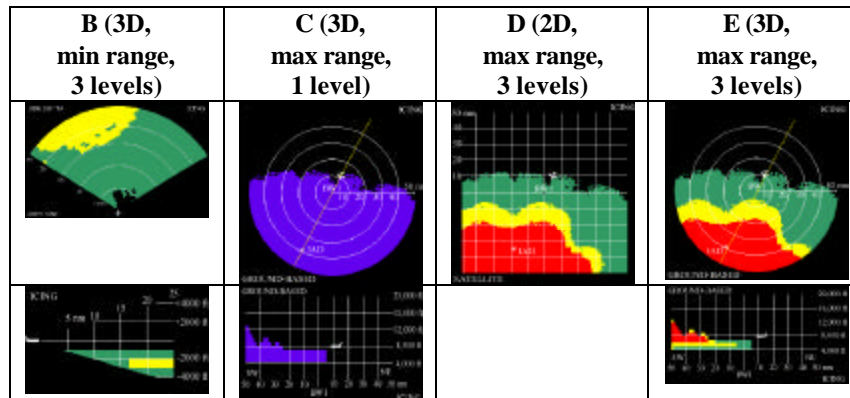


Figure 6-22: Displays in Scenario 3

The percentage of pilots who made good, acceptable and poor decisions in Scenario 3 is presented in Figure 6-23. The distribution of decisions in Scenario 3 for non-equipped operations is characterized by better decisions when provided with graphical information with maximum range.

A detailed distribution of decision quality according to the type of information system used is found in Figure 6-24. Due to the spatial distribution of icing conditions, and based on flight safety criteria, the good flight routing decision was identified to involve descending to the lower boundaries of the icing conditions and above the MEA. Acceptable decisions involved avoiding the icing conditions by descending along other routes, reversing course or aborting the flight. Other re-routing decisions were rated as poor decisions.

When provided with textual information only, the majority of pilots (65%) indicated that they would continue as filed. Only 23% of them mentioned that they would initiate a descent to 4,000 feet. This accounted for the majority of poor decisions.

When provided with information from Display B (3D, min range, 3 levels), a larger percentage of pilots (70%) mentioned that they would continue as filed. The limited range of the display suggested that a descent would lead into worse conditions than continuing at the current altitude. This would explain the larger percentage of poor decisions.

When provided with information from Display C (3D, max range, 1 level), 40% of pilots indicated that they would descend to 4,000 feet and proceed towards destination. A much smaller percentage (22%) would continue as filed.

**Decision Rating - VMC-On-Top Avoidance (Scenario 3)
Operations without Ice Protection Equipment - 141 Subjects**

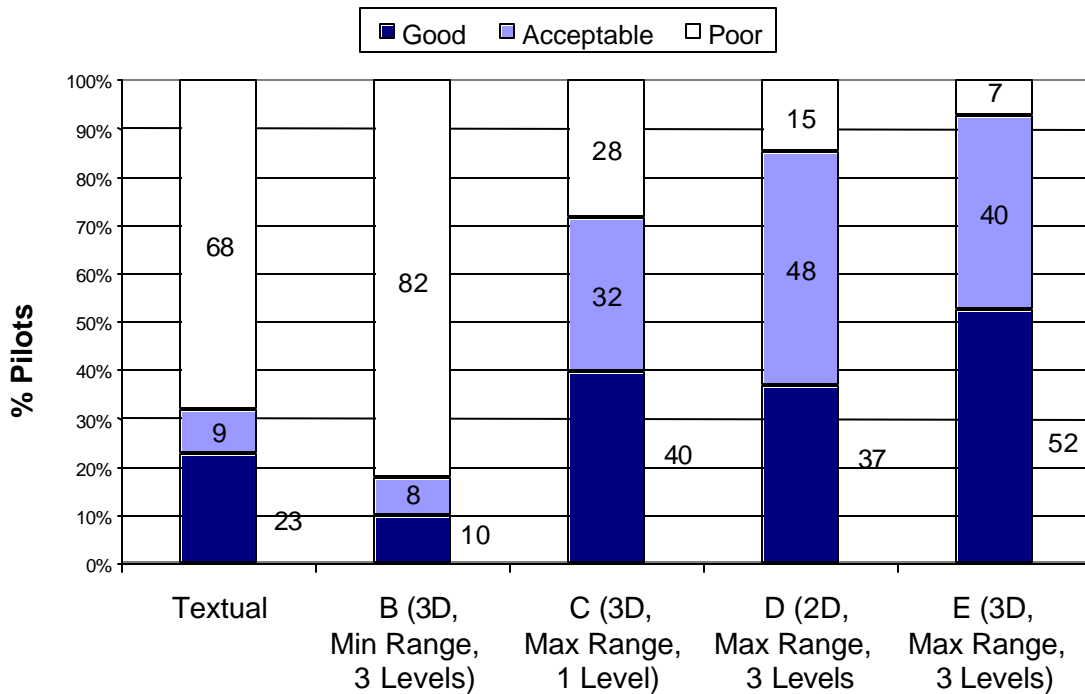


Figure 6-23: Decision Quality Distribution in Scenario 3

When provided with information from Display D (2D, max range, 3 levels), a similar percentage of pilots (40%) indicated that they would descend to 4,000 feet and a larger percentage of pilots (44%) indicated that they would abort.

When provided with information from Display E (3D, max range, 3 levels), most of the pilots (52%) indicated that they would descend to 4,000 feet. Another group of pilots (35%) indicated that they would abort to KBWI. This mostly explains the distribution of good (52%) and acceptable (40%) distribution.

Decision Rating Scheme (Scenario 3, Non-Equipped Operations)	Decision Rating (Non-Equipped)				
	Good	Acceptable	Poor		
Text	L 60°	L 30°	14,000	R 30°	R 60°
	L 60°	L 30°	12,000	R 30°	R 60°
	L 60°	L 30°	10,000	R 30°	R 60°
	L 60°	L 30°	8,000	R 30°	R 60°
	L 60°	L 30°	6,000	R 30°	R 60°
	L 60°	L 30°	4,000	R 30°	R 60°
	Abort to KBWI				
	Reverse Course				
	Abort to KPHL				
Display B (3D, Min range, 3 levels)	Decision Space				
	0.0	0.0	0.0	0.0	0.0
	0.0	0.0	0.7	0.0	0.0
	0.0	0.0	1.4	0.0	0.0
	0.0	0.0	64.5	0.0	0.0
	0.0	0.0	1.4	0.0	0.0
	0.0	0.7	22.7	0.0	0.0
	4.3				
	0.7				
	3.5				
Display C (3D, max range, 1 level)	Decision Space				
	0.0	0.0	0.0	0.0	0.0
	0.0	0.0	0.0	0.0	0.0
	0.0	0.0	4.3	0.0	0.0
	0.0	0.0	70.2	7.8	0.0
	0.0	0.0	0.0	0.0	0.0
	0.0	0.0	9.9	3.5	0.0
	3.5				
	0.0				
	0.7				
Display D (2D, max range, 3 levels)	Decision Space				
	0.0	0.0	3.5	0.0	0.0
	0.0	0.0	0.7	0.0	0.0
	0.0	0.0	2.1	0.0	0.0
	0.0	0.0	22.0	0.0	0.0
	0.0	0.0	0.0	0.0	0.0
	0.0	0.0	39.7	0.0	0.0
	15.6				
	5.0				
	11.3				
Display E (3D, max range, 3 levels)	Decision Space				
	0.0	0.0	0.7	0.0	0.0
	0.0	0.0	0.0	0.0	0.0
	0.0	0.0	0.7	0.0	0.0
	0.7	0.0	4.3	0.0	0.0
	0.0	0.0	0.0	0.7	0.0
	0.0	0.0	52.5	0.0	0.0
	34.8				
	1.4				
	4.3				

Figure 6-24: Distribution of Pilot Re-Routing Decisions (Scenario 3, Non-Known-Icing Approved Operations)

6.3.4 SCENARIO 4: STABLE LAYER ESCAPE

Figure 6-25 depicts the level of graphical information support provided in Scenario 4 (as already presented in Figures 5-15 and 5-16).

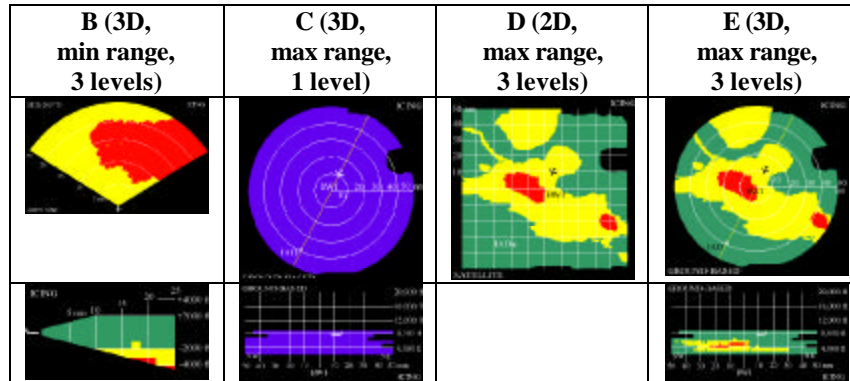


Figure 6-25: Displays in Scenario 4

The percentage of pilots who made good, acceptable and poor decisions in Scenario 4 is presented in Figure 6-26. The distribution of decisions in Scenario 4 for non-known-icing approved operations is characterized by better routing decisions based on information support from Display C (3D, max range, 1 level) and Display E (3D, max range, 3 levels) than with other systems.

A detailed distribution of decision quality according to the type of information system used is found in Figure 6-27. Due to the spatial distribution of icing conditions, and based on flight safety criteria, the good flight routing decision was identified to involve climbing above the icing conditions at an altitude higher than 8,000 feet. Acceptable decisions involved reversing course and aborting to KPHL in order to avoid the depicted icing conditions. Other routing decisions were rated as poor decisions.

When provided with textual information only, pilots re-routing decisions included principally climbing (26%), aborting to KBWI (28%), reversing course (20%), descending (14%). It seems that no specific maneuver was significantly preferred based on the lack of spatial information on the icing conditions.

**Decision Rating - Stable Layer Escape (Scenario 4)
Operations without Ice Protection Equipment - 141 Subjects**

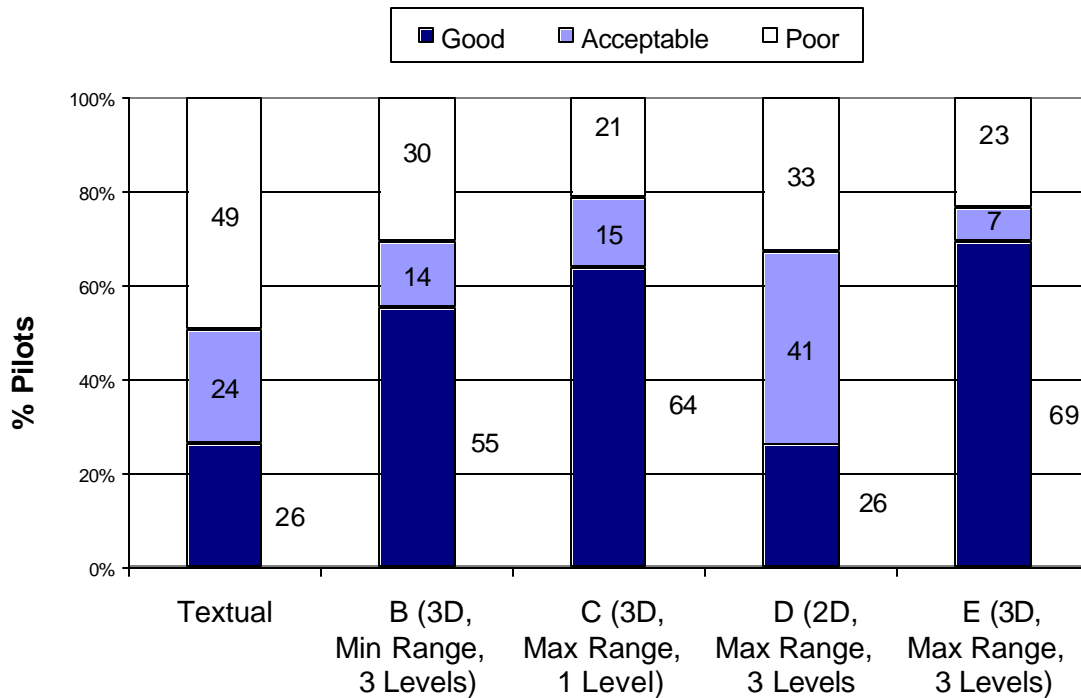


Figure 6-26: Decision Quality Distribution in Scenario 4

When provided with information from Display B (3D, min range, 3 levels), a majority of pilots (55%) indicated that they would make a maneuver involving a climb, which explains the percentage of good decisions. A smaller group of pilots indicated that they would continue as filed (16%), abort (13%) or reverse course (10%).

When provided with information from Display C (3D, max range, 1 level), a majority of pilots indicated that they would climb (64%), which explains the percentage of good decisions.

When provided with information from Display D (2D, max range, 3 levels), pilots indicated mainly that they would either deviate left (in 43% of the cases), abort to KPHL (24%) or reverse course (17%). Once more, the re-routing decisions associated with support from the plan view display only are dominated by lateral rerouting.

When provided with information from Display E (3D, max range, 3 levels), a majority of pilots (59%) indicated they would chose re-routing maneuvers that involve climbing, with much less lateral deviation (only 18% of the cases), course reversal (1%) and course abortion (7% overall).

Decision Rating Scheme (Scenario 4, Non-Equipped Operations)	Decision Rating (Non-Equipped)				
	Good		Acceptable	Poor	
Text	L 60°	L 30°	14,000	R 30°	R 60°
	L 60°	L 30°	12,000	R 30°	R 60°
	L 60°	L 30°	10,000	R 30°	R 60°
	L 60°	L 30°	8,000	R 30°	R 60°
	L 60°	L 30°	6,000	R 30°	R 60°
	L 60°	L 30°	4,000	R 30°	R 60°
	Abort to KBWI				
	Reverse Course				
	Abort to KPHL				
	ta Decision Space				
0.0	0.0	5.7	0.0	0.0	
0.0	0.0	9.9	0.0	0.0	
0.0	0.0	10.6	0.0	0.0	
0.0	0.0	6.4	0.0	0.0	
0.0	0.0	4.3	0.0	0.0	
0.0	0.0	9.9	0.0	0.0	
28.4					
19.9					
4.3					
Display B (3D, Min range, 3 levels)	aa Decision Space				
	0.7	0.7	2.1	0.0	0.0
	0.7	8.5	19.1	0.0	0.0
	0.7	3.5	18.4	0.7	0.0
	0.0	5.7	15.6	0.0	0.7
	0.0	0.0	0.0	0.0	0.0
	0.0	0.0	0.0	0.0	0.0
	8.5				
	9.9				
	4.3				
Display C (3D, max range, 1 level)	bb Decision Space				
	0.0	0.0	2.8	0.0	0.0
	0.0	0.0	29.8	0.0	0.0
	0.0	0.7	30.5	0.0	0.0
	0.7	0.0	2.8	0.0	0.0
	0.0	0.0	1.4	0.0	0.0
	0.0	0.0	0.0	0.0	0.0
	16.3				
	6.4				
	8.5				
Display D (2D, max range, 3 levels)	cb Decision Space				
	0.0	4.3	1.4	0.0	0.0
	3.5	7.1	0.0	0.0	0.0
	2.1	7.1	0.7	0.0	0.0
	2.8	12.1	0.7	0.0	0.7
	0.0	0.0	0.7	0.0	0.7
	0.0	3.5	0.7	0.7	0.7
	9.2				
	17.0				
	24.1				
Display E (3D, max range, 3 levels)	ca Decision Space				
	0.0	1.4	1.4	0.0	0.0
	0.0	3.5	15.6	0.0	0.0
	0.0	4.3	41.8	0.0	0.7
	0.7	6.4	13.5	0.0	0.7
	0.0	0.0	0.0	0.0	0.0
	0.0	0.0	0.7	0.0	0.0
	1.4				
	1.4				
	5.7				

Figure 6-27: Distribution of Pilot Re-Routing Decisions (Scenario 4, Non-Equipped Operations)

6.4 SUMMARY OF RESULTS ON DECISION QUALITY

The detailed analysis presented above provided insights into the influence of icing information presentation on re-routing decisions. Throughout flight scenarios, it has been observed that various display features provided variable degrees of situation awareness and lead pilots to re-route in specific ways.

When provided with textual icing information, pilots indicated more willingness to continue as filed in hazardous icing conditions compared to with graphical displays. This was particularly true in Scenarios 1 and 3. When the pilots elected to maneuver with textual information only, they were more likely to reverse course or abort than to elect either lateral or vertical deviations.

When provided with information from the limited-range Display B (3D, min range, 3 levels), pilots were observed to optimize tactical rather than strategic routing. The appropriateness of such decisions was observed to depend on the spatial extent of the icing threat field. For example, equipped pilots using Display B(3D, min range, 3 levels) performed well in the embedded convective weather scenario, Scenario 2, with 91% good decisions. Conversely, in the VMC-on-Top scenario, Scenario 3, pilots performed poorly (96% of equipped pilots and 82% of non-equipped pilots) with Display B.

When provided with information from the single-severity-level depiction Display C (3D, max range, 1 level), pilots tended to select re-routing decisions involving minimal exposure to the icing conditions. This was observed in scenarios 2 and 3.

When provided with information from the 2D Display D (2D, max range, 3 levels), a consistent preference for horizontal maneuvers over vertical maneuvers was observed in comparison with the most enhanced display, Display E (3D, max range, 3 levels).

Pilots using the most enhanced display, Display E (3D, max range, 3 levels), were observed to have the smallest number of poor decisions. This percentage reached only 9% for equipped pilots and 22% for non-equipped pilots.

The only significant overall difference between pilots of equipped and non-equipped operations appeared to be that the latter group was more likely to abort or reverse course.

6.5 DECISION COMFORT LEVELS

Pilots were queried on their comfort level after making each decision. The distribution of pilots' comfort level is presented below, followed by an analysis of correlation between comfort level and decision quality.

6.5.1 RESULTS

The results for equipped and non-equipped pilots averaged over all four scenarios are shown in Figure 6-28. The summary results show that less non-equipped pilots indicated that they were either comfortable or very comfortable in making their routing or re-routing decisions. Results also show that pilots indicated higher comfort levels when support information from the most enhanced display, Display E (3D, max range, 3 levels) was available, and lower comfort levels when only textual information was available.

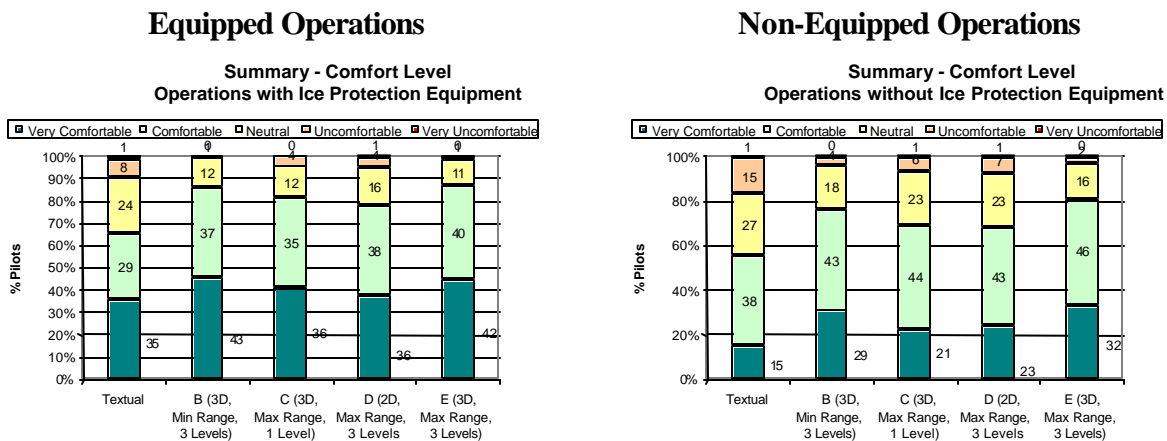


Figure 6-28: Summary of Pilot Comfort Levels throughout Flight Scenarios

Detailed results of pilot comfort levels for all 20 events (i.e., for the four flight scenarios and based on information from the five icing displays) are included in Appendix D. Results show that pilots indicated higher comfort levels with support information from Display E (3D, max range, 3 levels), and lower comfort levels with textual information only.

6.5.2 CORRELATION ANALYSIS BETWEEN DECISION QUALITY AND COMFORT LEVEL

To test the strength of the association between the distributions of decision quality and comfort level, a simple correlation analysis (Hogg, 1992) was performed using the sample correlation coefficient $r_{x,y}$ obtained from Equation 6.1.

$$r_{x,y} = \frac{\text{cov}(x, y)}{s_x \cdot s_y} \tag{6.1}$$

The covariance and sample standard deviations were obtained from Equations 6.2, 6.3 and 6.4.

$$\text{cov}(x, y) = \frac{1}{n} \sum (x_j - m_x)(y_j - m_y) \tag{6.2}$$

$$s_x^2 = \frac{1}{n} \sum (X_j - m_x)^2 \tag{6.3}$$

$$s_y^2 = \frac{1}{n} \sum (X_j - m_y)^2 \tag{6.4}$$

Table 6-2 shows the correlation coefficients for the sets of twenty events for both equipped and non-equipped operations. As can be seen, with a value of 0.33, the highest correlation coefficient between pilot decision quality and comfort level was found in Scenario 1 with the use of Display D (2D, max range, 3 levels). A majority of coefficients were lower than 0.1.

		Text	Display B	Display C	Display D	Display E
Equipped	Scenario 1	0.04	-0.11	0.16	0.33	0.19
	Scenario 2	0.06	0.11	0.08	-0.07	-0.01
	Scenario 3	-0.10	-0.04	-0.04	0.08	-0.04
	Scenario 4	0.05	0.03	0.25	0.12	0.19
Non-Equipped	Scenario 1	0.26	-0.11	0.13	0.14	0.04
	Scenario 2	0.03	-0.06	0.03	0.04	0.09
	Scenario 3	0.03	-0.01	-0.01	-0.01	-0.06
	Scenario 4	0.02	0.04	-0.07	0.15	0.14

Table 6-2: Correlation Coefficients Between Distributions of Pilots' Decision Quality and Comfort Levels

Because this result was unexpected, further care was given in characterizing the relationship between indicated comfort level and decision quality. The lack of correlation can be seen in Figure 6-29. Results for equipped pilots are shown on the left and results for non-equipped pilots are shown on the right. Overall, pilots of non-equipped operations were less comfortable in making their routing decisions; this result correlates with pilot flight and icing experience.

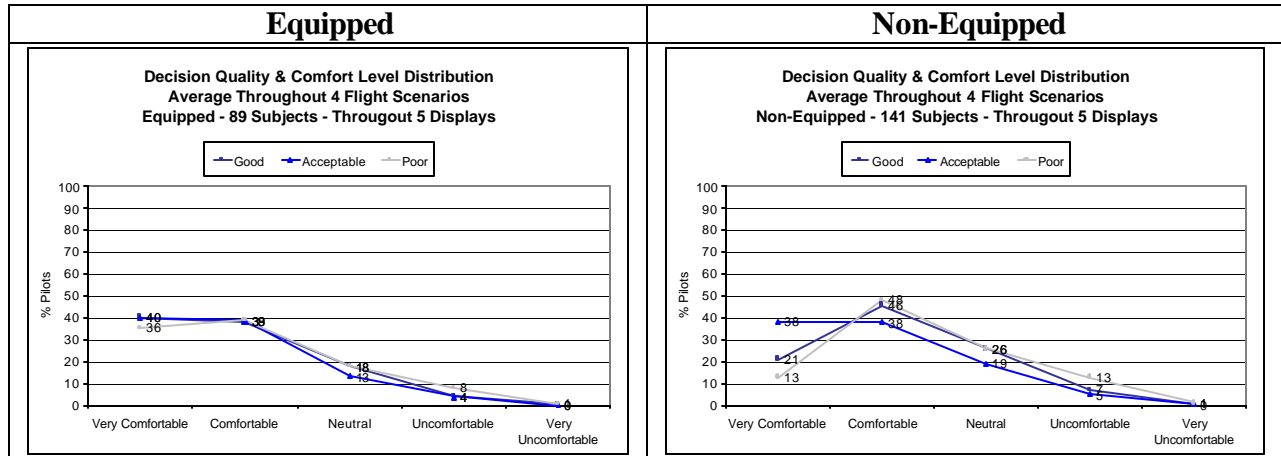


Figure 6-29: Distribution of Pilot Comfort Level for Three Levels of Decision Quality

6.6 SUBJECTIVE DISPLAY COMPARISON

Results of pilot subjective ratings of relative display preferences are presented in Tables 6-3 and 6-4. Each cell corresponds to the ratio of the number of pilots who indicated preference for the displays along the rows over the displays along the columns.

In both tables, displays are ranked according to their indicated preference. Each cell indicates the dominance ratio for the column display over the row display. For example, Display C (3D, max range, 1 level) was preferred 38 times over Display A (text only).

	A Text only	D (2D, max range, 3 levels)	C (3D, max range, 1 level)	E (3D, max range, 3 levels)	B (3D, min range, 3 levels)
A	1	40	38	40	26
D	-	1	1	8	9
C	-	-	1	10	6
E	-	-	-	1	2
B	-	-	-	-	1

Table 6-3: Display Preference Ratings (Equipped)

For pilots of both types of operations, results show pilot preference for graphical displays over text, and preference for 3D displays (i.e., displays incorporating both horizontal and profile views) over 2D displays. Also, for both types of flight operations, preferences are indicated within the 3D-display group for three levels of icing information over range enhancement.

	A	D (2D, max range, 3 levels)	C (3D, max range, 1 level)	B (3D, min range, 3 levels)	E (3D, max range, 3 levels)
A	1	129	128	Infinity	Infinity
D	-	1	2	9	13
C	-	-	1	5	20
B	-	-	-	1	1
E	-	-	-	-	1

Table 6-4: Display Preference Ratings (Non-Equipped)

The only significant difference between equipped and non-equipped pilots was that twice as many equipped pilots indicated preference for Display B (3D, min range, 3 levels) over Display E (3D, max range, 3 levels), while the preference is reversed for pilots of non-equipped operations (for which 22% more pilots indicated preference for Display E over B).

6.7 SUMMARY OF INFLUENCE OF DISPLAY FEATURES

In the following, the influence of the display features will be discussed in terms of the combined objective and subjective results mentioned above.

6.7.1 INFLUENCE OF GRAPHICAL INFORMATION

The objective decision performance, the decision comfort level and the subjective comparisons all indicated that graphical icing information is desirable.

Decisions made without the support of graphical information were, in all cases, inferior to decisions made with the graphical information. As shown in Figures 6-3 and 6-15, for both equipped and non-equipped operations, respectively, the largest percentage (over 50%) made poor decisions when using textual information only (53% of pilots in equipped operations, and 56% of pilots in non-equipped operations). Also, the lowest percentage of pilots made good decisions based on textual information only: 35% and 24%, for equipped and non-equipped operations, respectively.

When provided with textual information only, fewer pilots rated their decisions as very comfortable and comfortable. Also, Display A (text only) was by far the least preferred display of all.

6.7.2 INFLUENCE OF VERTICAL DISPLAY

For both equipped and non-equipped groups, a consistently smaller percentage of good decisions and larger percentage of poor decisions was observed with Display D (2D, max range, 3 levels) than with Display E (3D, max range, 3 levels). A vertical view was found to be valuable in

identifying vertical maneuvers, which often corresponded to the most appropriate escape and avoidance maneuvers in the flight scenarios encountered.

The lack of vertical depiction in Display D (2D, max range, 3 levels) corresponded with more lateral deviations than vertical deviations in cases where both vertical and lateral maneuvers were available.

A consistently larger percentage of poor decisions was observed when the vertical display was not available (e.g., with Displays D and A). The importance of the vertical display was also apparent in the subjective ratings. Lower decision comfort levels were reported with Display D than with Display E (3D, max range, 3 levels). Display D (2D, max range, 3 levels) was the least preferred graphical display.

6.7.3 INFLUENCE OF RANGE

The only significant effect of range on decision quality was observed in scenario 3 where the larger range of the most enhanced display, Display E (3D, max range, 3 levels), provided visibility of possible severe icing exposure which was not apparent in the shorter range display. Also, pilot decision comfort level was not significantly different with the shorter range display, Display B (3D, min range, 3 levels), than with other displays, except from Display A (text only).

Range and display perspective are thought to be confounded in the experiment, specifically for equipped pilots. Equipped pilots actually indicated preference for the shorter range Display B (3D, min range, 3 levels) over other displays. Display B (3D, min range, 3 levels) was preferred by a factor of two over Display E (3D, max range, 3 levels), and by much greater factors over other displays. Although the experiment did not directly investigate the percentage of pilots which used airborne weather radar, based on their flight qualifications (i.e., with 72% of equipped pilots indicating that they are qualified as airline transport pilots), it is likely that most of equipped pilots operate with airborne weather radar, which have features similar to Display B(3D, min range, 3 levels). The indicated preference of equipped pilots for Display B (3D, min range, 3 levels) – referred to as Airborne Icing Severity System in the experiment – is thought to relate to a preference to aircraft-centered perspective.

6.7.4 INFLUENCE OF ICING SEVERITY LEVELS

The single-severity-level display, Display C (3D, max range, 1 level) was found to support decision quality which was similar to with the most enhanced display, Display E (3D, max range, 3 levels). This indicates that information on severity level may not be as important as good spatial information on the icing conditions. Indicated decision comfort levels with Displays C (3D, max range, 1 level) and E (3D, max range, 3 levels) were similar. However, Display C (3D, max range, 1 level) was the least preferred of the 3D displays.

6.8 CONCLUSIONS

The main conclusions of this experiment on the influence of icing information on pilot strategies are summarized below.

- π Graphical horizontal depiction of remotely detected icing information was found to be very valuable in supporting good routing decisions and was found to be desired by the subjects.
- π Vertical depiction combined with horizontal depiction of icing conditions was found, overall, to support better decision-making, as it supported the most appropriate selection of vertical and horizontal escape and avoidance maneuvers.
- π Range was not found to have a strong effect in the experiment. However, the shortest range tested was 25 nautical miles.
- π The single-severity-level display, Display C, was not the most preferred 3D display. However, similar decision quality and comfort levels were nevertheless observed with Display C. This indicates that good spatial information may be more important than information that allows detecting multiple severity levels of icing conditions. This has significant implications for the remote ice sensing and forecasting efforts because it may be technically easier to detect regions where ice is unlikely than where ice potential exists.

7 CONCLUSIONS

In order to identify system requirements of cockpit weather information for flight operations in icing conditions, a web-based survey and a web-based experiment addressed to pilots were conducted. This work provided a basis for understanding pilot information needs and strategies for operating in icing conditions, and for evaluating the influence of icing information on pilot routing decision-making. Results can be summarized as indicated below.

- π The desirability of remote detection of icing conditions was confirmed with both survey and experiment and the value of horizontal depiction of icing conditions in supporting pilot routing decision was confirmed by the web-based experiment. However market studies in the web-based survey indicated cost sensitivity for equipping with airborne remote ice detection equipment.
- π The importance of PIREPs, which serve as “air truth” data in the current information system was identified in the survey.
- π The importance of vertical maneuvers to escape from and avoid icing conditions was identified in the web-based survey. Also, a desire for information on freezing levels, and cloud tops and bases, which vary along the vertical dimension, was found to be desired. In the scenarios of the web-based experiment, which were based on realistic weather situations, the routing behavior of pilots was found to vary according to the graphical information presented. More specifically, a reticence of pilots to maneuver along the vertical dimension when they were not provided with vertical information was observed. It is concluded that, to support appropriate escape and avoidance maneuvers, information along the vertical plane would be highly desirable.
- π Range enhancement, based on the web-based experiment results, was not found to have a strong positive influence on pilot decision-making. The minimum range tested, however, was 25 nautical miles, which may be in excess of current technical capabilities.
- π Based on the results of the experiment, little correlation was found between pilot decision quality and comfort levels in making such decisions. Care should be taken in interpreting this result due to the limited scope of the web-based experiment. However, the results are intriguing in that they indicated that pilot confidence may not be a good indicator of judgment in some cases.
- π The importance of accurate location of icing-free zones was identified. Based on the survey results, a desire for information on the boundaries of the icing threat field was indicated. In absence of such information, freezing levels and cloud tops and bases, to support avoidance and escape maneuvers were thought useful. Based on the experiment results, it was found to be more important to provide pilots with information on the spatial location of icing than identifying differences in icing severity. This result, combined with the fact that it may

technically be easier to remotely detect icing-free zones—where the temperature is above the freezing level or where LWC is significantly small—may have significant implications for remote sensing and forecasting efforts.

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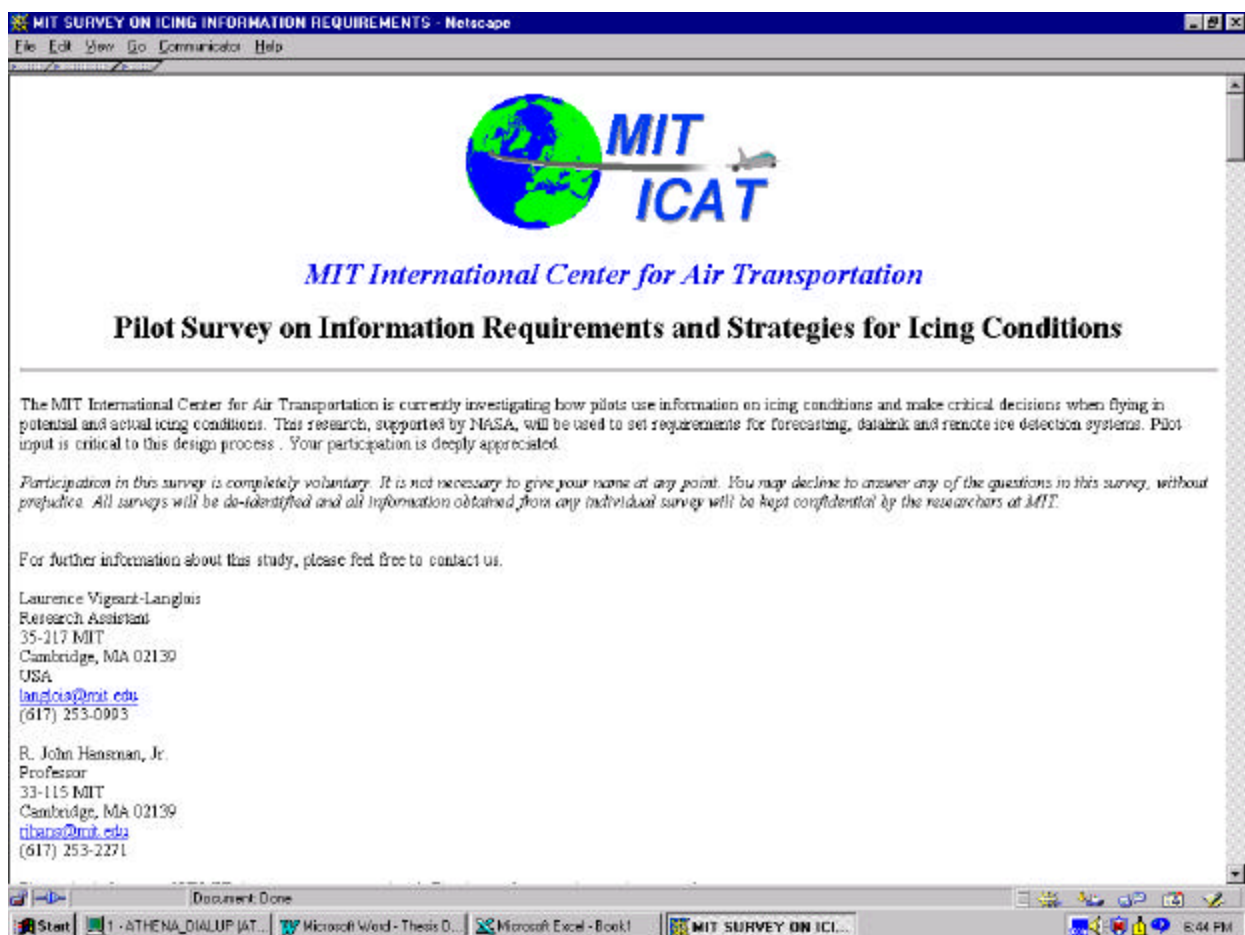
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APPENDIX A – SAMPLE PAGES OF WEB-BASED SURVEY ON PILOT INFORMATION NEEDS AND STRATEGIES FOR OPERATING IN ICING CONDITIONS



BACKGROUND INFORMATION

Certificates and ratings

Please check the boxes that correspond to your highest certificates and ratings.

Certificates

- Student
- Recreational
- Private
- Commercial
- Airline Transport
- Instructor

Ratings

- Airplane
- Rotorcraft
- Glider
- Lighter-than-air

Airplane Class Ratings

- Single-engine Land
- Multiengine Land
- Single-engine Sea
- Multiengine Sea

Rotorcraft Class Ratings

- Helicopter
- Gyroplanes

Lighter-than-air Class Ratings

- Airship
- Free Balloon

Instruments Ratings

- Instrument-Airplane
- Instrument-Helicopter

Instructor Ratings

- Airplane Single-engine
- Airplane Multiengine
- Rotorcraft Helicopter
- Instrument-Airplane
- Instrument-Helicopter
- Glider
- Other (specify)

Flight Experience

Total flight time (hours):

Total instrument time (including simulator, hood and actual instrument time (hours):

Actual instrument time (hours):

Cross-country time (hours):

Other Information

Sex: Male Female

Age:

Do you own or have you owned an aircraft? Yes No

Operational Category

Because different user groups may fly aircraft equipped with significantly different levels of ice protection systems, the need for icing information will vary accordingly, e.g., major air carrier equipped with full ice protection system versus light general aviation aircraft equipped with limited ice protection equipment.

Please indicate below the primary type of flying you do in potential icing conditions by checking the appropriate box:

- General Aviation
- Corporate
- Commuter Airline
- Major Air Carrier
- Civil - Helicopter
- Military - Helicopter
- Military - Transport
- Military - High Performance

Do you also fly in another operational category? Yes No

If yes, please specify by checking the appropriate box:

- General Aviation
- Corporate
- Commuter Airline
- Major Air Carrier
- Civil - Helicopter
- Military - Helicopter
- Military - Transport
- Military - High Performance

Base airport of operations

What is your base airport of operations?

ICING INFORMATION EVALUATION

Information

A list of various types of information is provided below. Please rate the importance of this information for making **icing-related decisions**. If this information is not available to you, please check the **N/A** column.

Direct Visual Observations, Instruments and Sensors	N/A	Importance				
		Trivial 1	2	3	4	Critical 5
Visual observation of Clouds	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Visual observation of Precipitation	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Visibility	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ice accretion on aircraft components	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Outside Air Temperature Measurement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Total Air Temperature Measurement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Airborne weather radar	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ice detection system	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Other (specify) <input type="text"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Reported Observations and Measurements

	Importance					
	N/A	Trivial 1	2	3	4	Critical 5
Surface observations (METAR)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Satellite images	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Radar images	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Long AIRMETS	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Other AIRMETS (e.g., convective AIRMETS)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Long SIGMETS	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Other SIGMETS (e.g., convective SIGMETS)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
PIREPS (Pilot reports)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
ATIS (Automated Terminal Information System)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Party-line information (overhead communications addressed to other aircraft)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Other (specify)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Forecasts

	Importance					
	N/A	Trivial 1	2	3	4	Critical 5
Area forecasts (FA)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Terminal forecasts (TAF)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Winds aloft forecasts (FD)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Freezing levels	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Specific icing forecasts (specify)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Where do you get icing information?

Please indicate how you typically obtain icing information from the paths mentioned below, both when you are on the ground (in the pre-flight phase) and in the air.

On the Ground (In the Pre-Flight Phase)	How Often Do You Obtain Icing Information from Each Path?				
	Never	Rarely	Sometimes	Often	Always
Direct observations	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
AD Radio	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
FSS, Weather office or Dispatch in person	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
FSS, Weather office or Dispatch by phone	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Dispatch paperwork	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
DUATS	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Web	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Commercial weather provider (specify)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

During the Flight	How Often Do You Obtain Icing Information from Each Path?				
	Never	Rarely	Sometimes	Often	Always
Direct observations	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Airborne sensors	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
ACARS	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Flight watch (122.0)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
ATC	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
FSS, Weather Office or Dispatch on Radio	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Party-Line information (overhead communications addressed to other aircraft)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Other (specify)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

EXPERIENCE AND STRATEGY

The following questions focus on your exposure to flying in icing conditions in the operational category you mentioned above.

Aircraft type

Please give the aircraft type with which you have had the most significant exposure to icing conditions. In this section, please reply to the following questions based on your experience flying this aircraft.

Is this aircraft certified to fly in icing conditions? Yes No

Ice protection capability

Is this aircraft equipped with de-icing or anti-icing systems mentioned below?

	De-icing systems	Anti-icing systems
Wing	<input type="checkbox"/>	<input type="checkbox"/>
Empennage	<input type="checkbox"/>	<input type="checkbox"/>
Windshield	<input type="checkbox"/>	<input type="checkbox"/>
Engine	<input type="checkbox"/>	<input type="checkbox"/>

Additional Information and Forecasts You Would Like to Have

What additional information and/or forecasts, if any, do you think would be useful to help making decisions when flying in icing conditions? Please feel free to add as much information as you wish.

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Ice protection capability

Is this aircraft equipped with de-icing or anti-icing systems mentioned below?

	De-icing systems	Anti-icing systems
Wing	<input type="checkbox"/>	<input type="checkbox"/>
Empennage	<input type="checkbox"/>	<input type="checkbox"/>
Windshield	<input type="checkbox"/>	<input type="checkbox"/>
Engine	<input type="checkbox"/>	<input type="checkbox"/>

Please indicate if this aircraft is also equipped with the systems mentioned below:

Pitot heat
 Ice detector
 Total air temperature probe
 Carburetor heat
 Other systems (specify)

Significant aircraft icing encounter

Please describe your most significant icing encounter in as much detail as possible. If none, check the box: Please feel free to add as much information as you wish.

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Key icing-related decisions

What are, in your opinion, key icing-related decisions of a typical flight in potential icing conditions? Please feel free to add as much information as you wish.

Ground versus in-flight icing

Please rate below the relative importance of ground icing versus in-flight icing for this type of operation.

Ground icing			In-flight icing	
Much more important	More important	As important	More important	Much more important
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

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EVALUATION OF NEW REMOTE ICE DETECTION SYSTEMS

NASA is exploring the development of remote ice detection systems which might allow the detection of icing conditions similar to airborne weather radar. Please provide your opinion on its utility and required performance by answering the questions below.

1. What would the utility of an airborne remote ice detection system be to your operations?

No utility	Limited utility	Useful	Very useful	Essential
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

2. If size, weight and cost considerations limit remote ice detection to ground-based sensors similar to ground weather radar, with the capability to detect icing regions and validate icing forecasts, how useful would such a system be?

No utility	Limited utility	Useful	Very useful	Essential
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

3. How useful would ground-to-air datalink to send real-time icing information to the cockpit be?

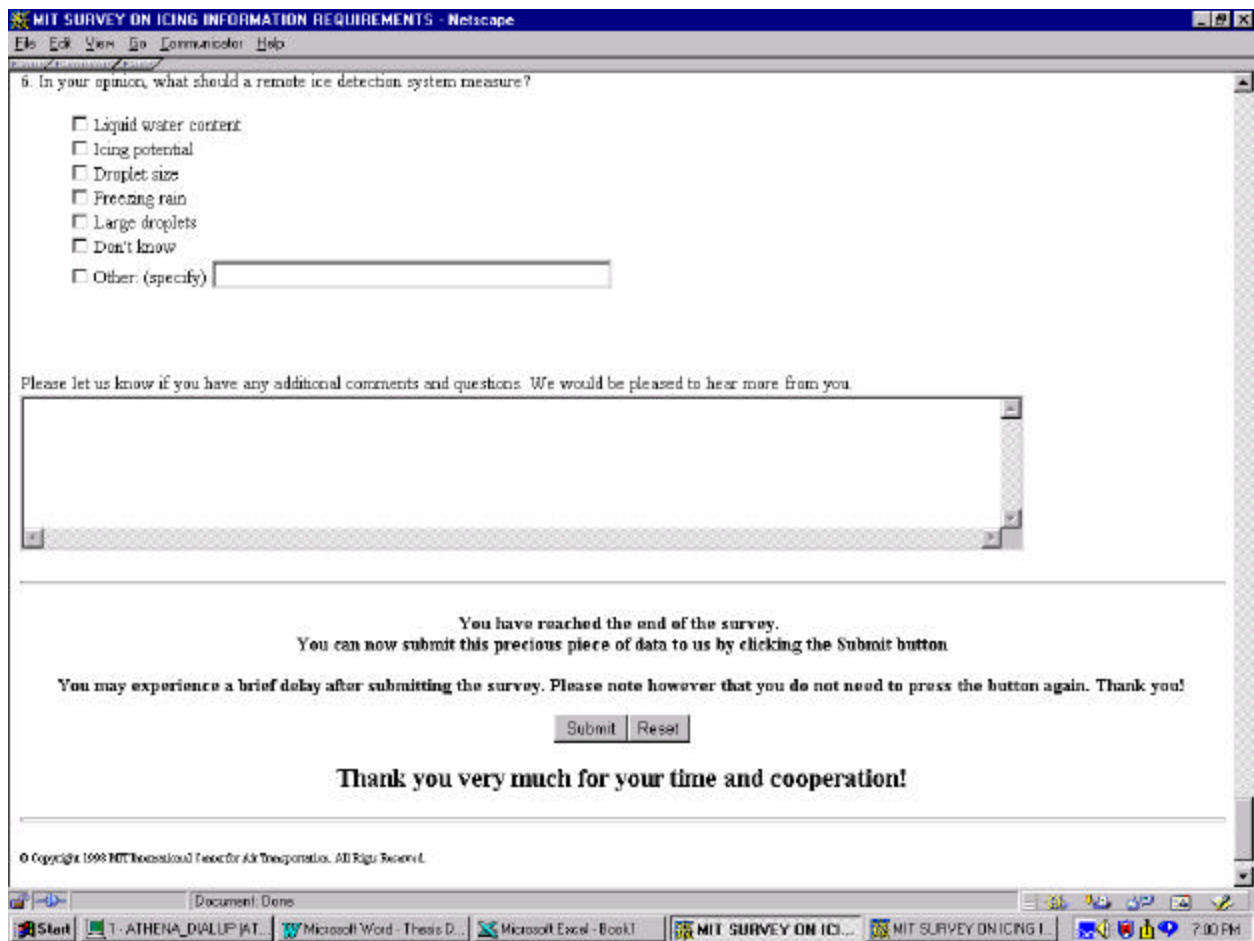
No utility	Limited utility	Useful	Very useful	Essential
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

4. To help you avoid icing conditions, what minimum useful range should a remote ice detection system have?

1 nm
 5 nm
 10 nm
 20 nm
 40 nm
 80 nm
 160 nm
 Don't know

5. What is the highest cost you would be willing to pay for a remote ice detection system?

\$1,000
 \$5,000
 \$10,000
 \$15,000
 \$20,000
 \$40,000
 \$100,000
 Not interested



APPENDIX B – SAMPLE PAGES OF WEB-BASED EXPERIMENT ON ICING REMOTE SENSING DISPLAYS



Experiment Introductory Page

MIT EXPERIMENT ON PROTOTYPE IN-FLIGHT ICING AVOIDANCE SYSTEMS - Netscape

File Edit View Go Communicator Help

Back Forward Reload Home Search Netscape Print Security Stop

Bookmarks Location http://cywages.mit.edu/icing_avionics/bs.asp

What's Related

BACKGROUND INFORMATION

Please check all boxes that apply.

Certificate

Student Commercial

Recreational ATP

Private Instructor

Rating

Airplane Glider

Rotorcraft Lighter-than-air

Airplane Class Rating

Single-Engine Land Single-Engine Sea

Multi-Engine Land Multi-Engine Sea

Rotorcraft Class Rating

Helicopter Gyroplane

Lighter-than-air Class Rating

Airship Free Balloon

Instrument Rating

Instrument-Airplane Instrument-Helicopter

Instructor Rating

Airplane Single-Engine Helicopter

Airplane Multi-Engine Instrument-Helicopter

Instrument-Airplane Glider

Other (specify)

Document Done

Start Microsoft Word - Thesis D... Microsoft Excel - Book1 1-ATHENA_DIALOG [AT... MIT EXPERIMENT O... MIT EXPERIMENT ON P... 12:17 AM

MIT EXPERIMENT ON PROTOTYPE IN-FLIGHT ICING AVOIDANCE SYSTEMS - Netscape

File Edit View Go Communicator Help

Flight Experience

Total flight time: hours

Instrument time: hours

What range do you typically cover on a cross-country flight? nm

Base airport of operations (ICAO indicator):

Icing Experience

Please rate your level of experience with in-flight aircraft icing:

I have had extensive experience with aircraft in-flight icing

I have had occasional experience with aircraft in-flight icing

I have had limited experience with aircraft in-flight icing (1 to 3 air sorties)

I have never experienced aircraft in-flight icing

Please indicate on which type of aircraft you acquired most of your cross-country experience:

On an aircraft CERTIFIED for flight into known icing (according to FAR Part 25, Appendix C criteria)

On an aircraft NOT CERTIFIED for flight into known icing

Understanding of icing

Please rate your level of understanding of hazards associated with aircraft icing:

I am familiar with the contemporary literature and have extensive technical understanding

I am comfortable with the information required to operate under IFR

I know that I do not fully understand the hazards associated with aircraft icing

Statistical Information

Sex: Male Female

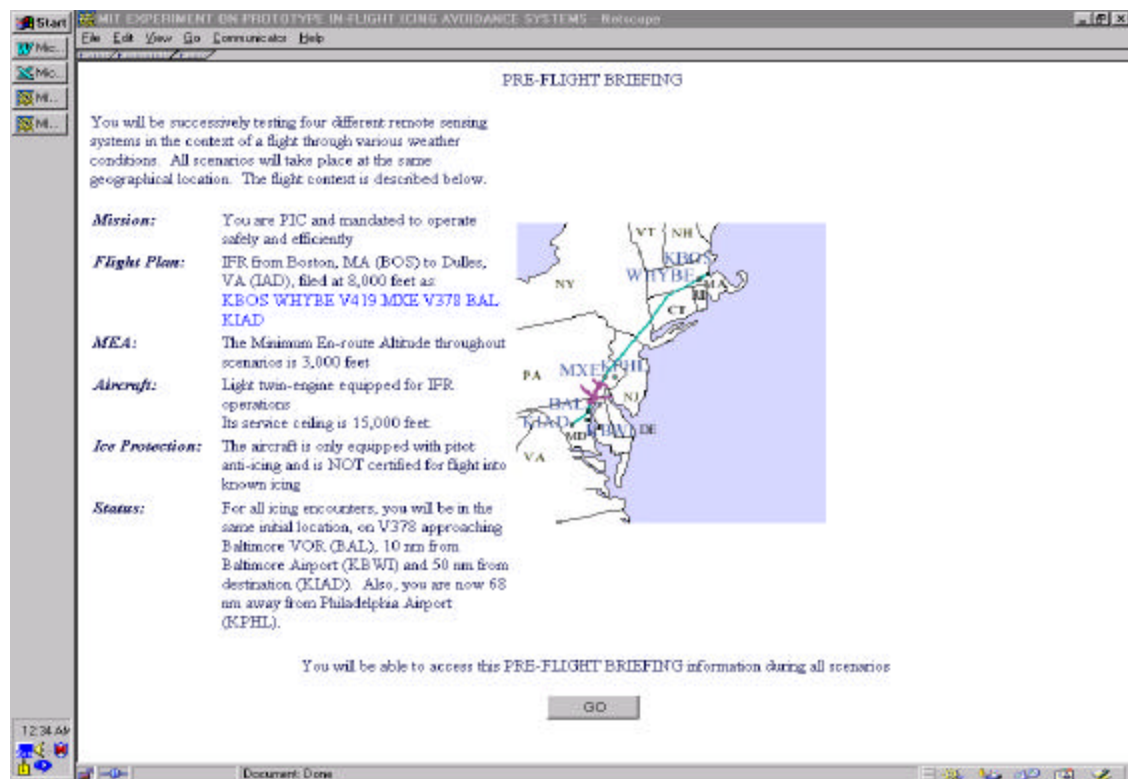
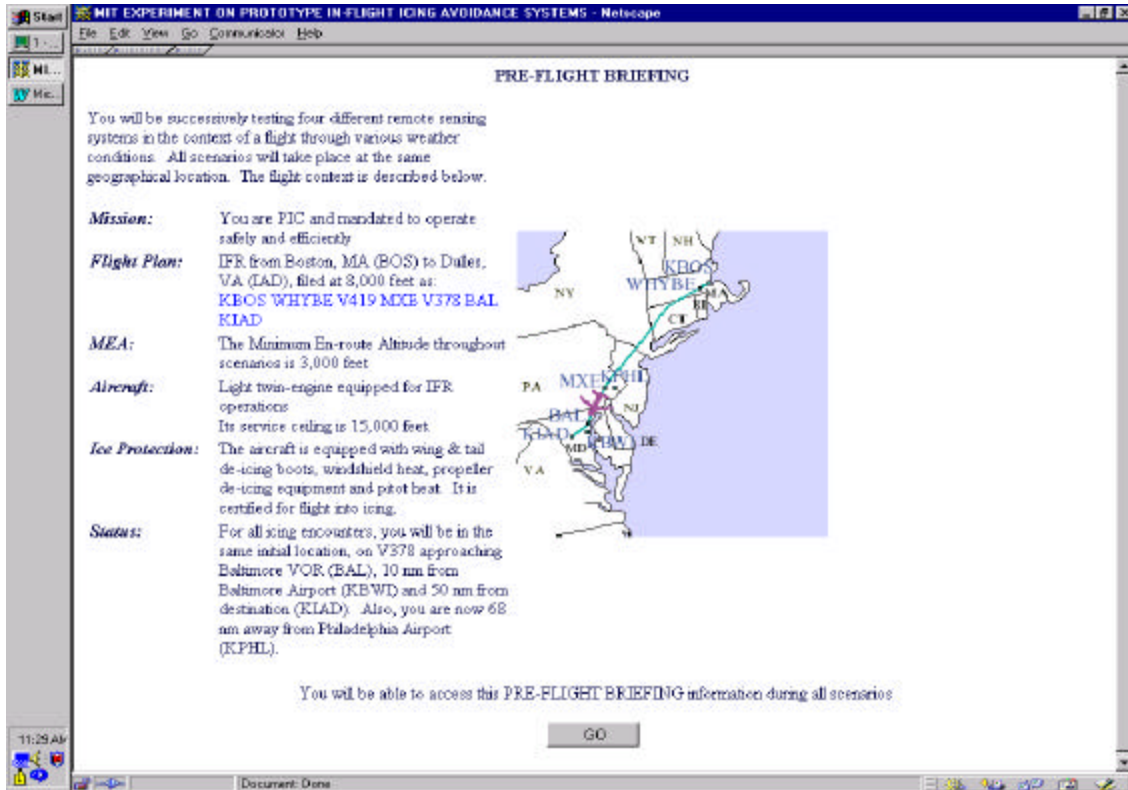
Age:

Previous | Next

Document Done

Start Microsoft Word - Thesis D... Microsoft Excel - Book1 1-ATHENA_DIALOG [AT... MIT EXPERIMENT ON P... 12:29 AM

Sample Pages

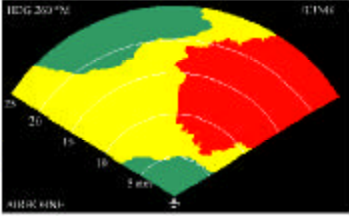


Pre-Flight Briefing for Equipped (above) and Non-Equipped Pilots (below)

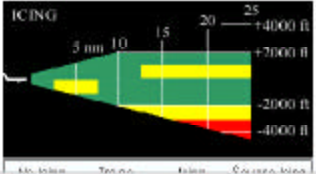
**PRE-FLIGHT BRIEFING
AIRBORNE ICING REMOTE SENSING SYSTEM**

In the next four scenarios, you will be provided information from an airborne system which remotely detects icing conditions ahead of the aircraft over a range of 25 nm. Based on sensing of liquid water content (LWC), droplet size spectra (DSD) and droplet temperature (T), this system provides pilots with graphical icing severity information on both plan view and profile displays, as presented below. Both plan view and profile displays have 10 second update rates.

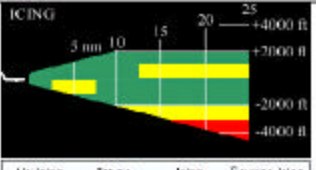
Plan View Display:
Similar to airborne weather radar, this airborne icing system senses icing within a specified vertical angular range and depicts the most severe icing conditions sensed within this range on its plan view display.



Profile Display:
The profile icing display is based on the scan of a thin vertical slice of atmosphere in front of the aircraft. As depicted, it covers a vertical range of ±4,000 feet at maximum range of 25 nautical miles.



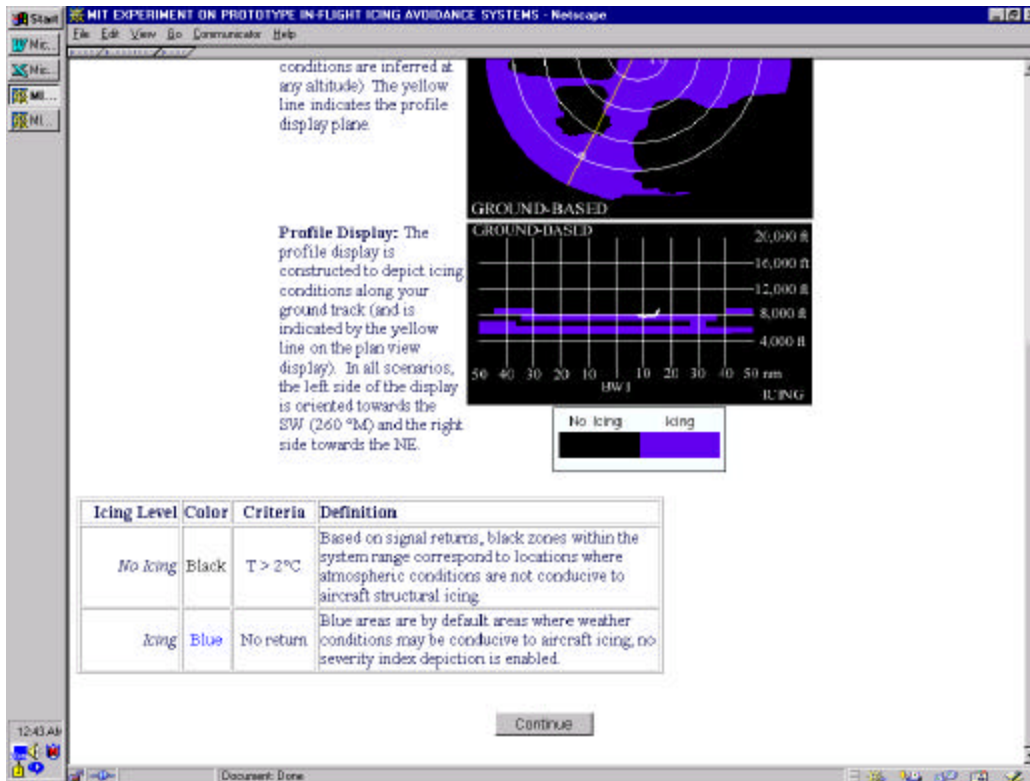
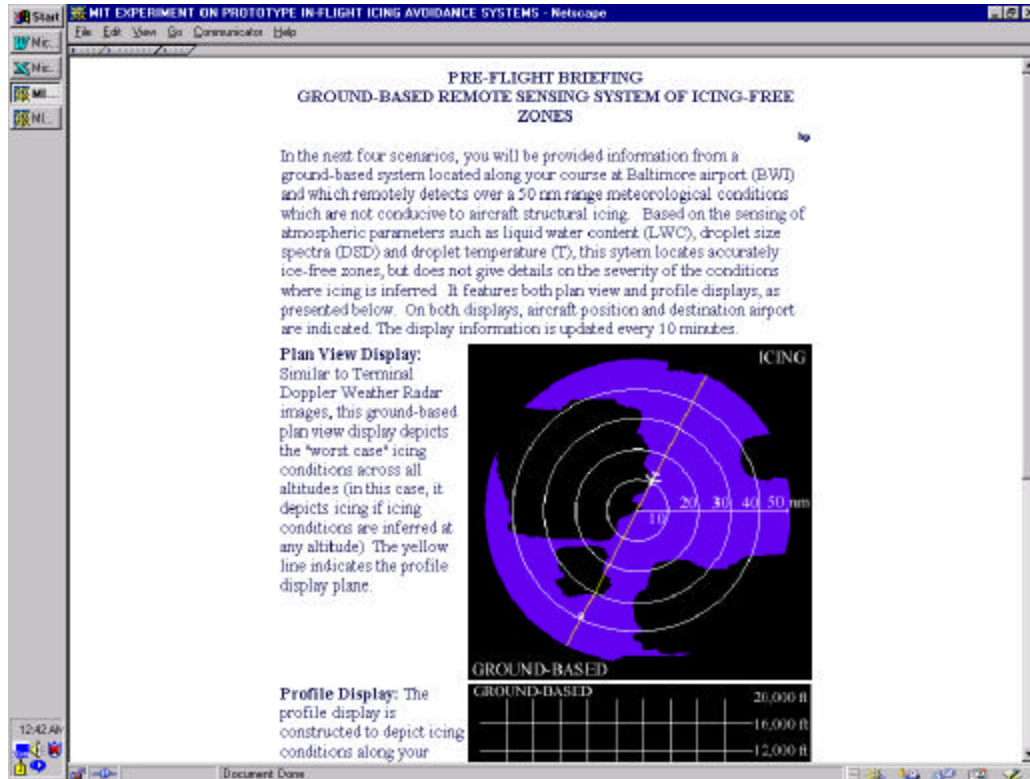
Profile Display:
The profile icing display is based on the scan of a thin vertical slice of atmosphere in front of the aircraft. As depicted, it covers a vertical range of ±4,000 feet at maximum range of 25 nautical miles.



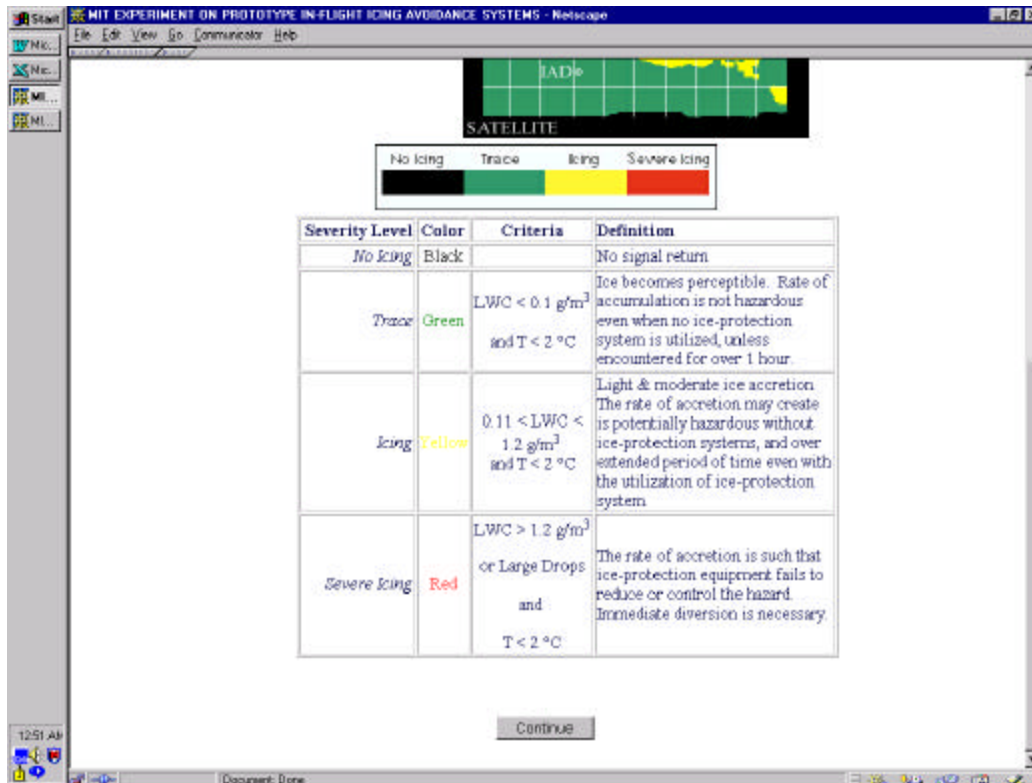
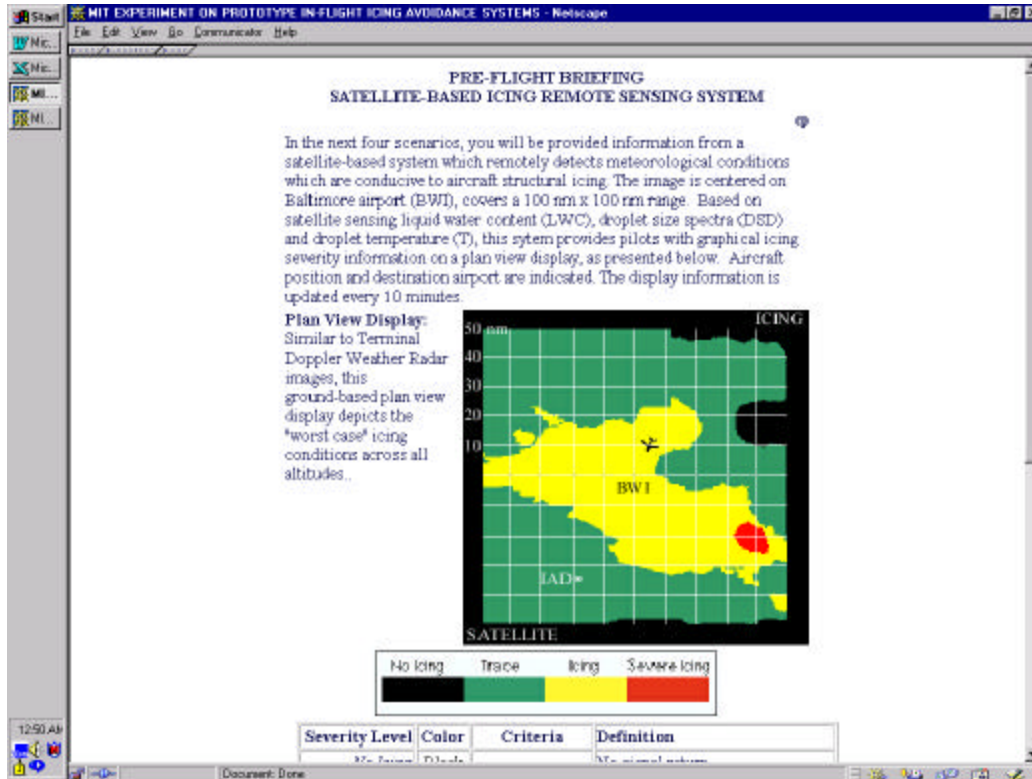
Severity Level	Color	Criteria	Definition
No Icing	Black		No signal return
Trace	Green	$LWC < 0.1 \text{ g/m}^3$ and $T < 2 \text{ }^\circ\text{C}$	Ice becomes perceptible. Rate of accumulation is not hazardous even when no ice-protection system is utilized, unless encountered for over 1 hour.
Icing	Yellow	$0.11 < LWC < 1.2 \text{ g/m}^3$ and $T < 2 \text{ }^\circ\text{C}$	Light & moderate ice accretion. The rate of accretion is potentially hazardous without ice-protection systems, and over extended period of time even with the utilization of ice-protection system.
Severe Icing	Red	$LWC > 1.2 \text{ g/m}^3$ or Large Drops and $T < 2 \text{ }^\circ\text{C}$	The rate of accretion is such that ice-protection equipment fails to reduce or control the hazard. Immediate diversion is necessary.

Continue

Description Page of Display B (3D, Min. Range, 3 Levels)



Description Page of Display C (3D, Max. Range, 1 Level)



Description Page of Display D (2D, Max. Range, 3 Levels)

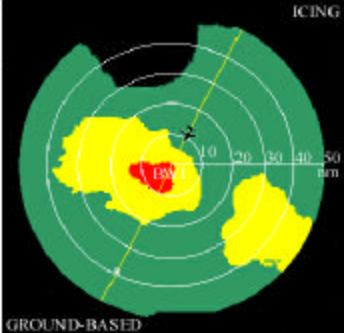
MIT EXPERIMENT ON PROTOTYPE IN-FLIGHT ICING AVOIDANCE SYSTEMS - Netscape

File Edit View Go Communicator Help

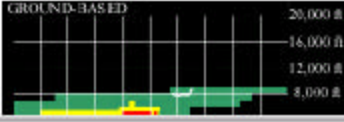
PRE-FLIGHT BRIEFING GROUND-BASED ICING REMOTE SENSING SYSTEM

In the next four scenarios, you will be provided information from a ground-based system located along your course at Baltimore airport (BWI) and which remotely detects over a 50 nm range meteorological conditions which are conducive to aircraft structural icing. Based on the sensing of atmospheric parameters such as liquid water content (LWC), droplet size spectra (DSD) and droplet temperature (T), the system provides pilots with graphical icing severity information on plan view and profile displays, as presented below. On both displays, aircraft position and destination airport are indicated. The display information is updated every 10 minutes.

Plan View Display: Similar to Terminal Doppler Weather Radar images, this ground-based plan view display depicts the "worst case" icing conditions across all altitudes. The yellow line indicates the profile display plane.



Profile Display: The profile display is constructed to depict icing conditions along your ground track (and is indicated by the yellow line on the plan view display). In all



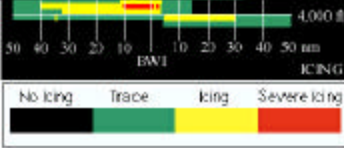
12:55 AM

Document Done

MIT EXPERIMENT ON PROTOTYPE IN-FLIGHT ICING AVOIDANCE SYSTEMS - Netscape

File Edit View Go Communicator Help

use plan view display. In all scenarios, the left side of the display is oriented towards the SW (260 °M) and the right side towards the NE.



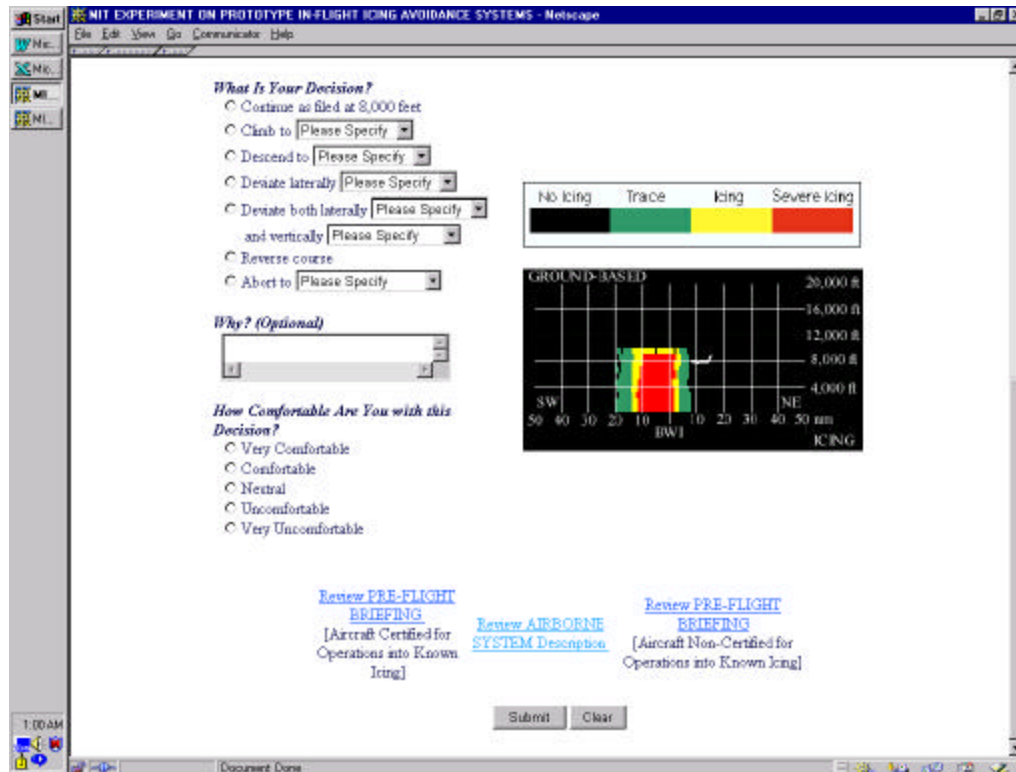
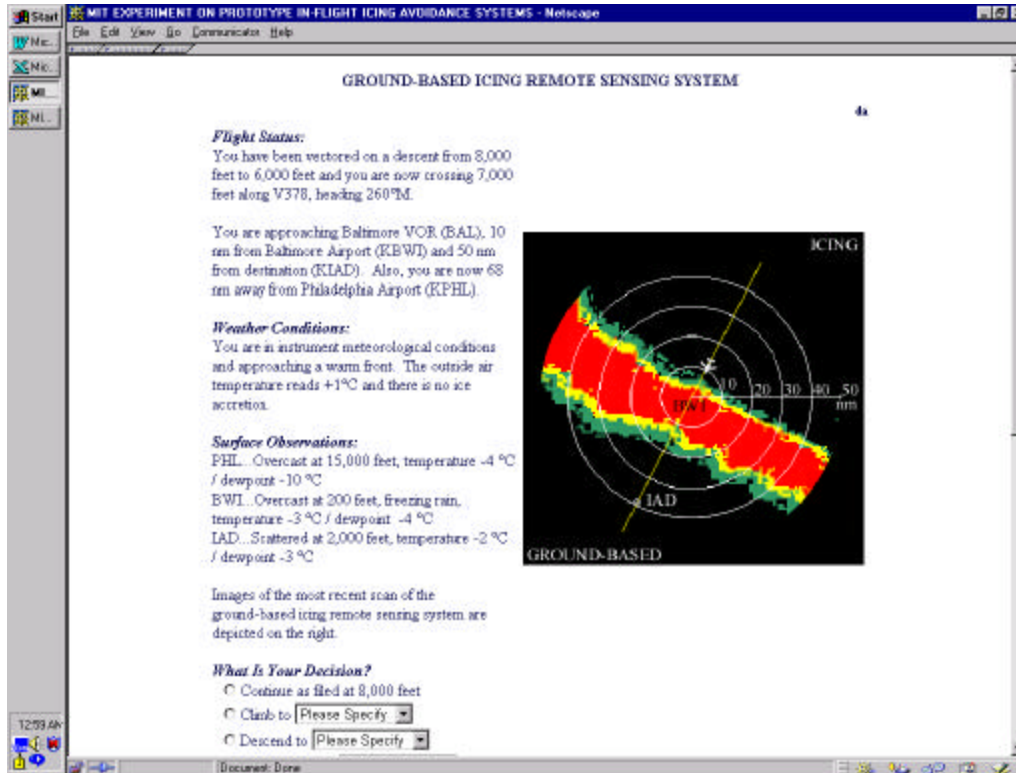
Severity Level	Color	Criteria	Definition
No Icing	Black		No signal return
Trace	Green	$LWC < 0.1 \text{ g/m}^3$ and $T < 2 \text{ }^\circ\text{C}$	Ice becomes perceptible. Rate of accumulation is not hazardous even when no ice-protection system is utilized, unless encountered for over 1 hour.
Icing	Yellow	$0.11 < LWC < 1.2 \text{ g/m}^3$ and $T < 2 \text{ }^\circ\text{C}$	Light & moderate ice accretion. The rate of accretion may create is potentially hazardous without ice-protection systems, and over extended period of time even with the utilization of ice-protection system.
Severe Icing	Red	$LWC > 1.2 \text{ g/m}^3$ or Large Drops and $T < 2 \text{ }^\circ\text{C}$	The rate of accretion is such that ice-protection equipment fails to reduce or control the hazard. Immediate diversion is necessary.

Continue

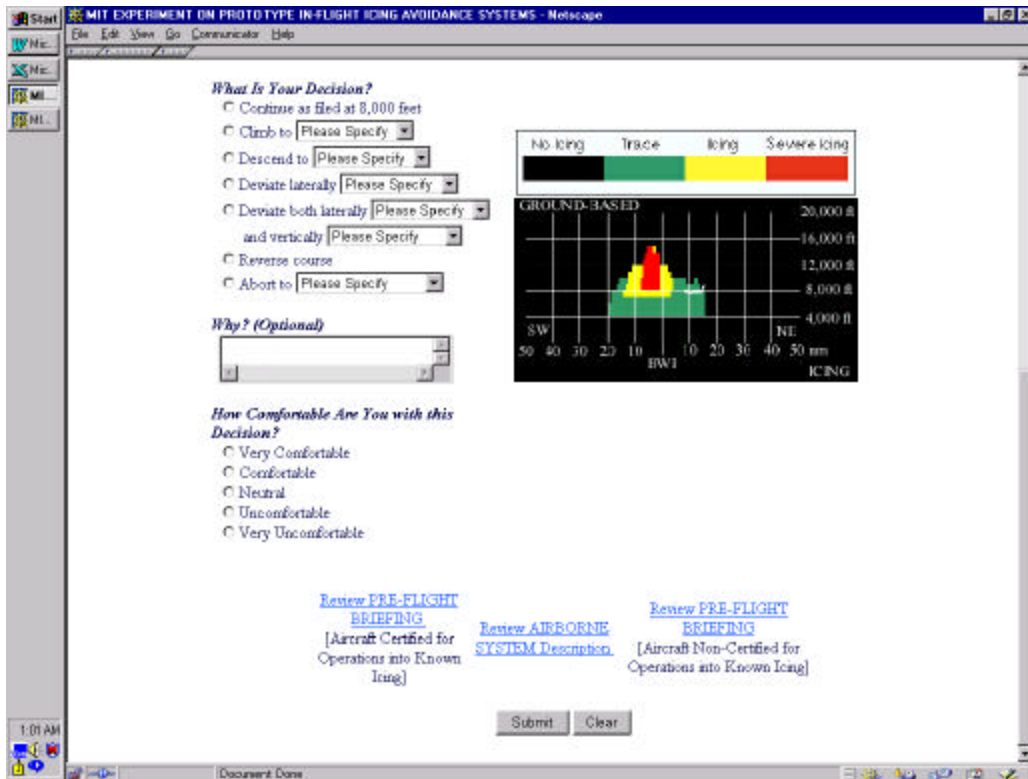
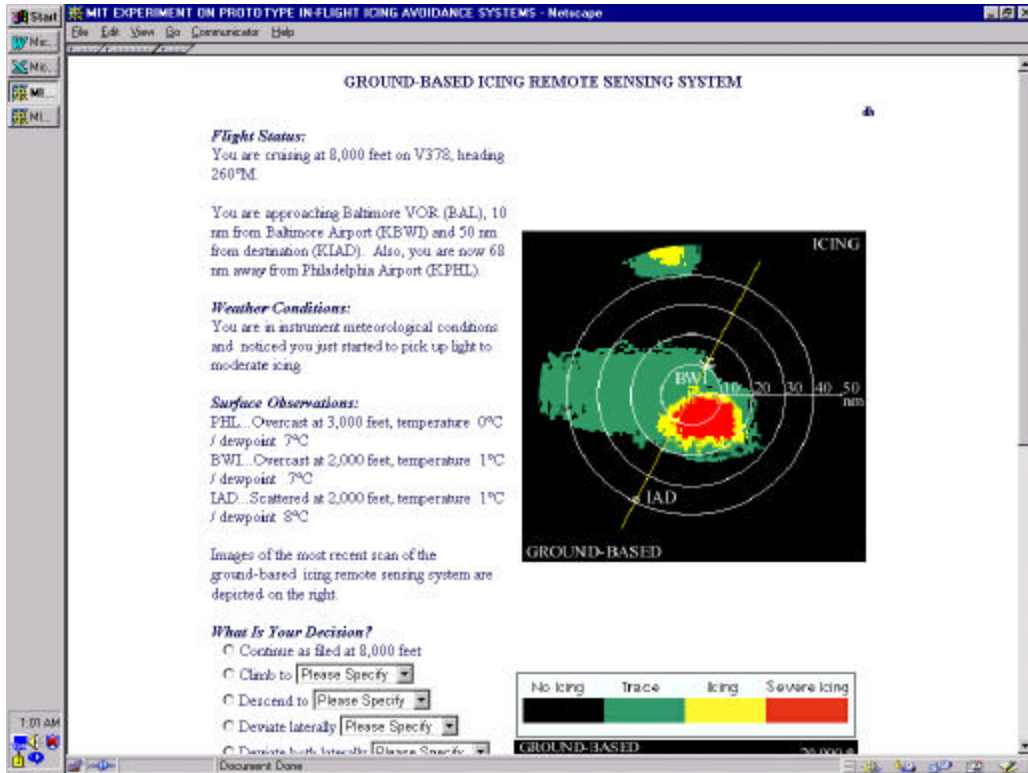
12:55 AM

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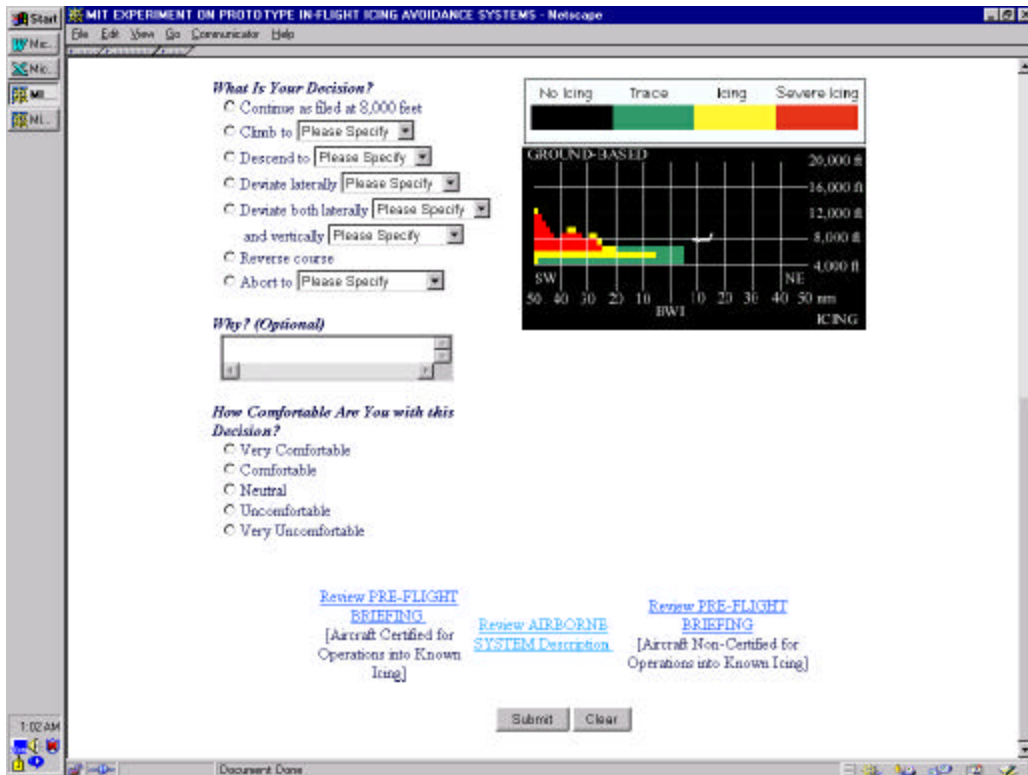
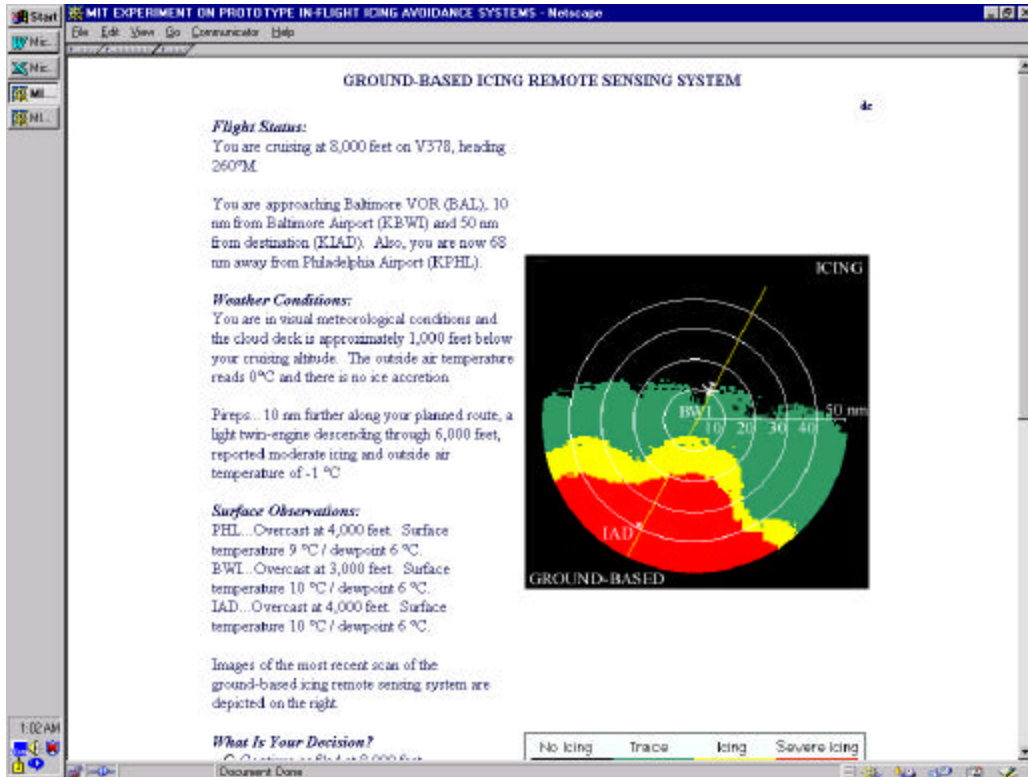
Description Page of Display E (3D, Max. Range, 3 Levels)



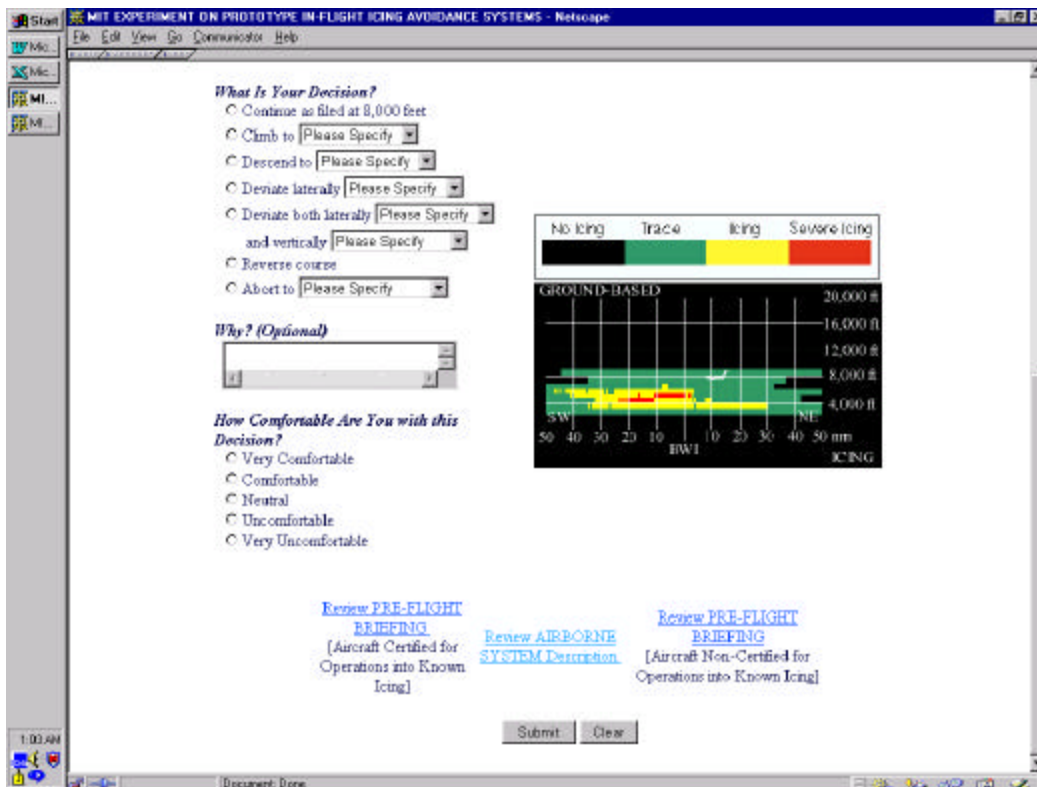
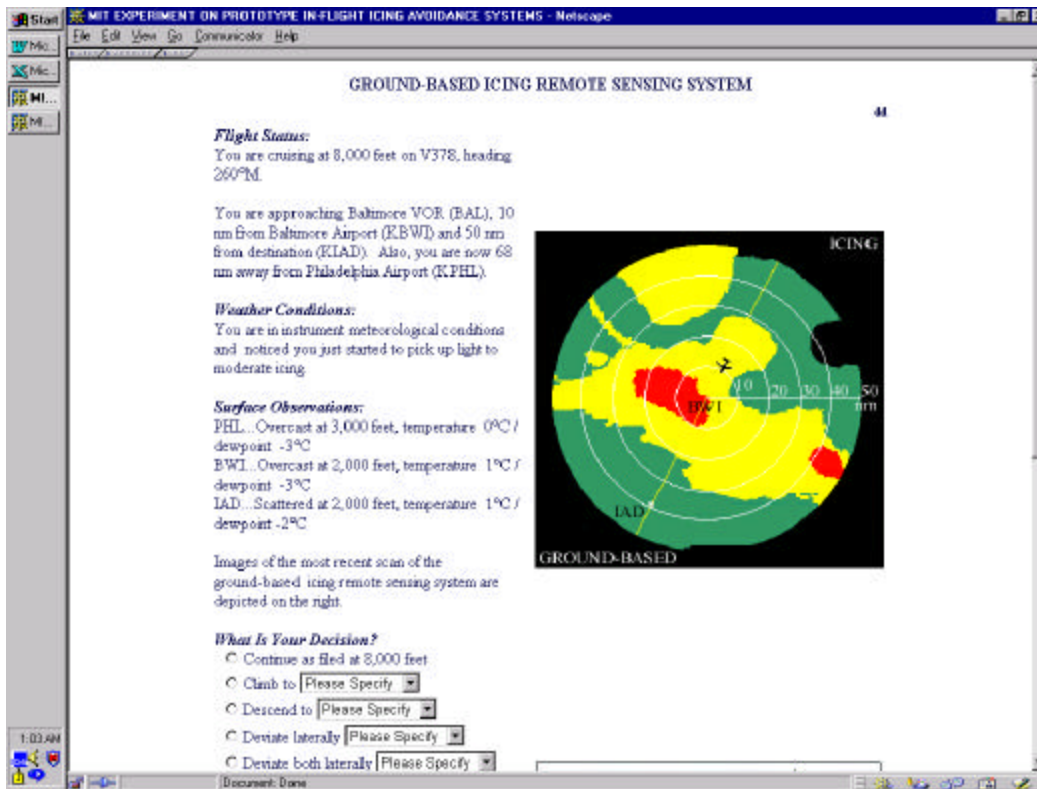
Sample Page of Scenario 1(with Display E)



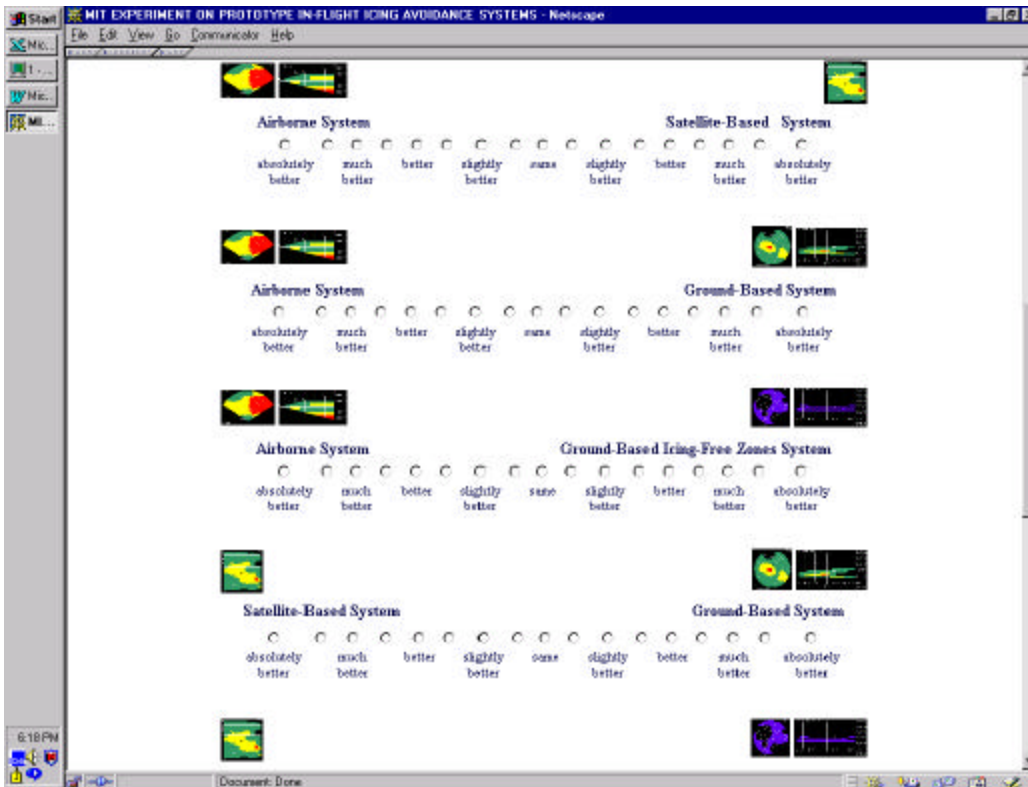
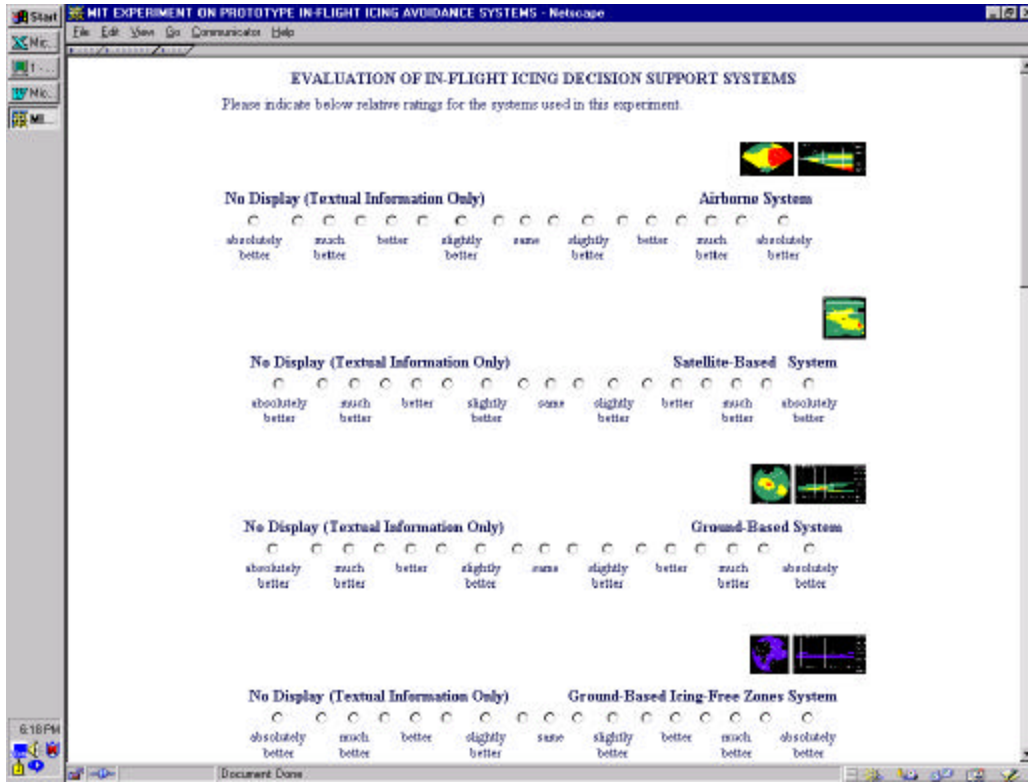
Sample Page of Scenario 2 (with Display E)



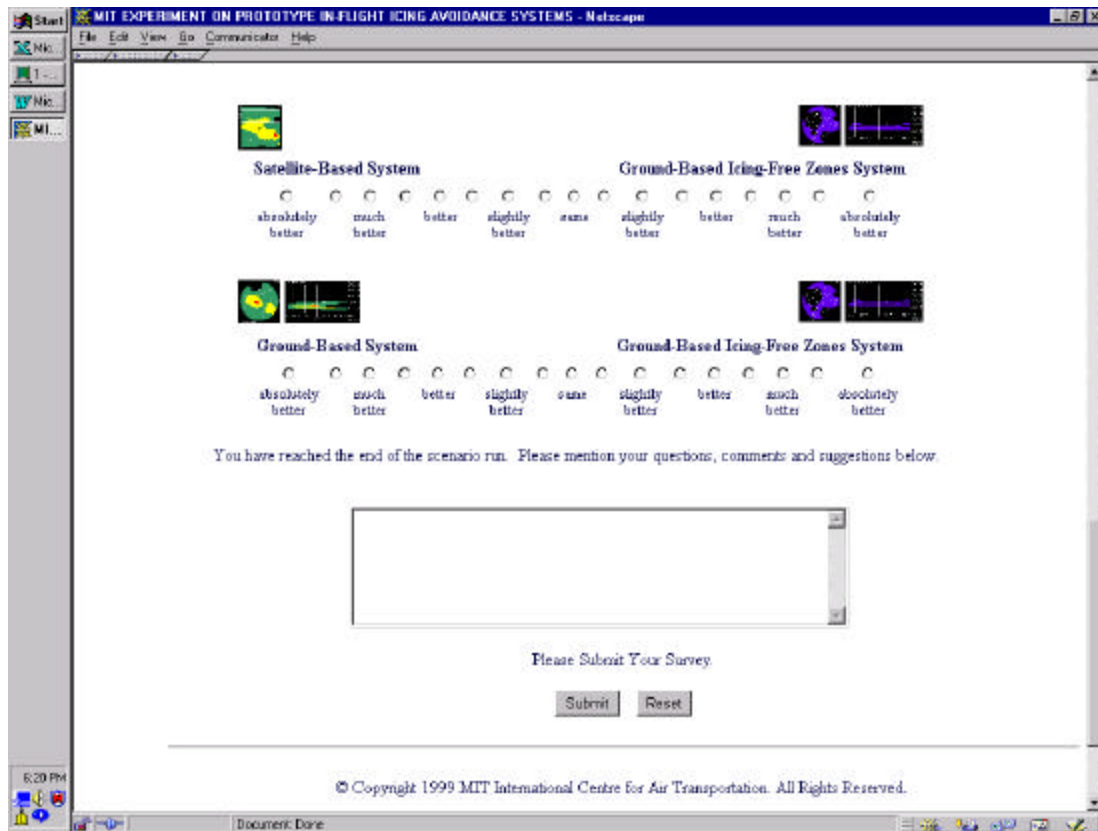
Sample Page of Scenario 3 (with Display E)



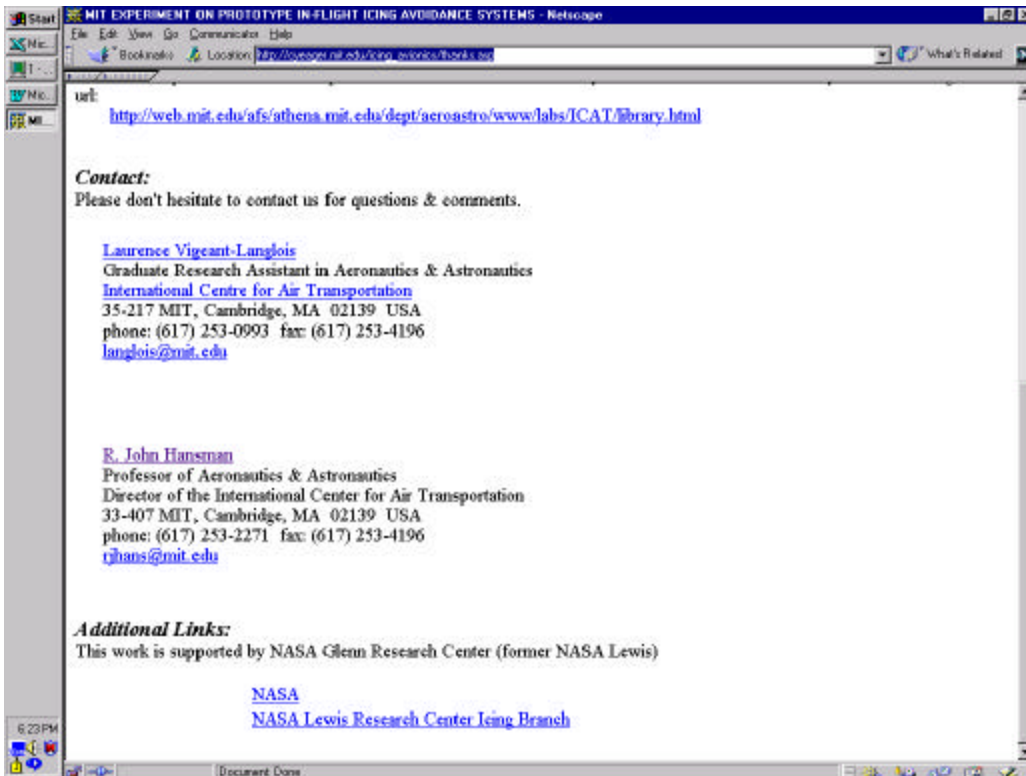
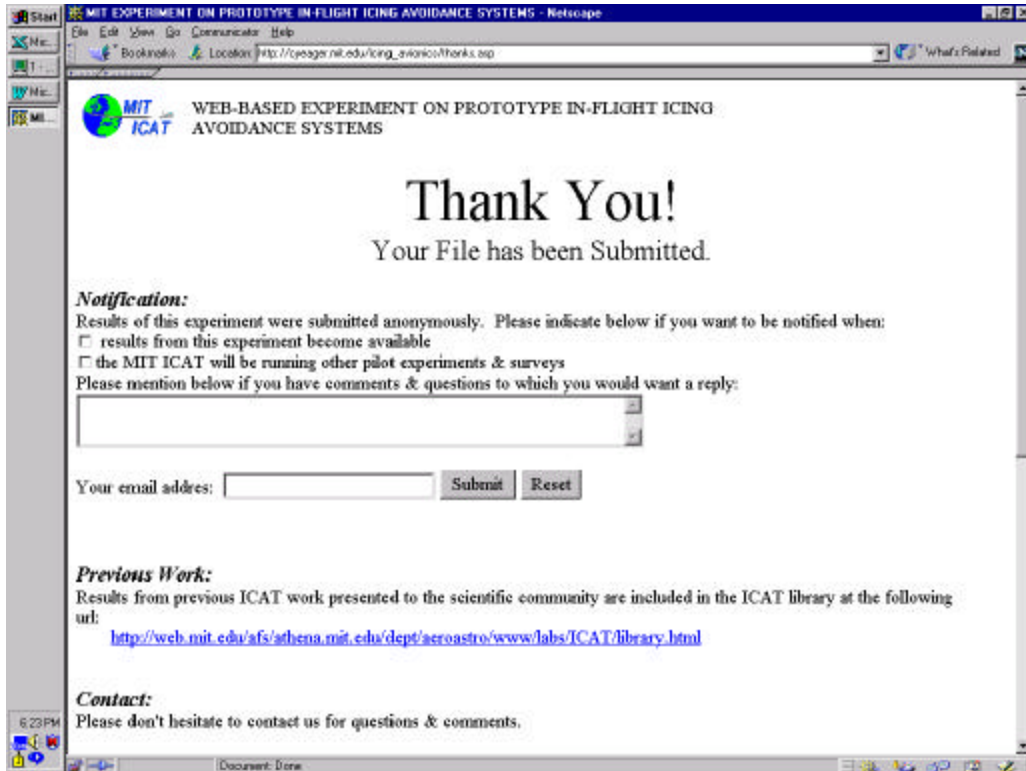
Sample Page of Scenario 4 (with Display E)



Sample Page Relative Display Evaluation

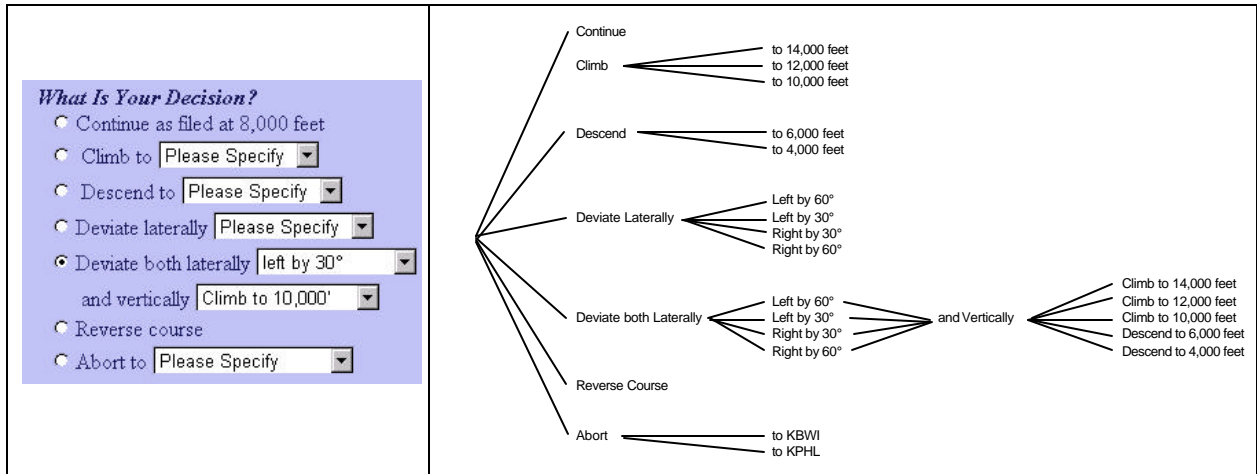


Sample Page Relative Display Evaluation



Sample Conclusive Page

APPENDIX C – PILOT ROUTING DECISION QUALITY RATING ANALYSIS



Decision Space			
L 60°	L 30°	14,000	R 30° R 60°
L 60°	L 30°	12,000	R 30° R 60°
L 60°	L 30°	10,000	R 30° R 60°
L 60°	L 30°	8,000	R 30° R 60°
L 60°	L 30°	6,000	R 30° R 60°
L 60°	L 30°	4,000	R 30° R 60°
		Abort to KBWI	
		Reverse Course	
		Abort to KPHL	

- Continue
- Climb
- Descend
- Deviate laterally
- Deviate both laterally and vertically
- Reverse course
- Abort

SCENARIO	Icing Severity Zone Rating				Icing Presence Zone Rating			
	No Icing		Trace	Icing	Severe	No Icing		Icing
SCENARIO 1	L 60° L 30°	14,000	R 30° R 60°		L 60° L 30°	14,000	R 30° R 60°	
	L 60° L 30°	12,000	R 30° R 60°		L 60° L 30°	12,000	R 30° R 60°	
	L 60° L 30°	10,000	R 30° R 60°		L 60° L 30°	10,000	R 30° R 60°	
	L 60° L 30°	8,000	R 30° R 60°		L 60° L 30°	8,000	R 30° R 60°	
	L 60° L 30°	6,000	R 30° R 60°		L 60° L 30°	6,000	R 30° R 60°	
	L 60° L 30°	4,000	R 30° R 60°		L 60° L 30°	4,000	R 30° R 60°	
	Abort to KBWI Reverse Course Abort to KPHL				Abort to KBWI Reverse Course Abort to KPHL			
SCENARIO 2	L 60° L 30°	14,000	R 30° R 60°		L 60° L 30°	14,000	R 30° R 60°	
	L 60° L 30°	12,000	R 30° R 60°		L 60° L 30°	12,000	R 30° R 60°	
	L 60° L 30°	10,000	R 30° R 60°		L 60° L 30°	10,000	R 30° R 60°	
	L 60° L 30°	8,000	R 30° R 60°		L 60° L 30°	8,000	R 30° R 60°	
	L 60° L 30°	6,000	R 30° R 60°		L 60° L 30°	6,000	R 30° R 60°	
	L 60° L 30°	4,000	R 30° R 60°		L 60° L 30°	4,000	R 30° R 60°	
	Abort to KBWI Reverse Course Abort to KPHL				Abort to KBWI Reverse Course Abort to KPHL			
SCENARIO 3	L 60° L 30°	14,000	R 30° R 60°		L 60° L 30°	14,000	R 30° R 60°	
	L 60° L 30°	12,000	R 30° R 60°		L 60° L 30°	12,000	R 30° R 60°	
	L 60° L 30°	10,000	R 30° R 60°		L 60° L 30°	10,000	R 30° R 60°	
	L 60° L 30°	8,000	R 30° R 60°		L 60° L 30°	8,000	R 30° R 60°	
	L 60° L 30°	6,000	R 30° R 60°		L 60° L 30°	6,000	R 30° R 60°	
	L 60° L 30°	4,000	R 30° R 60°		L 60° L 30°	4,000	R 30° R 60°	
	Abort to KBWI Reverse Course Abort to KPHL				Abort to KBWI Reverse Course Abort to KPHL			
SCENARIO 4	L 60° L 30°	14,000	R 30° R 60°		L 60° L 30°	14,000	R 30° R 60°	
	L 60° L 30°	12,000	R 30° R 60°		L 60° L 30°	12,000	R 30° R 60°	
	L 60° L 30°	10,000	R 30° R 60°		L 60° L 30°	10,000	R 30° R 60°	
	L 60° L 30°	8,000	R 30° R 60°		L 60° L 30°	8,000	R 30° R 60°	
	L 60° L 30°	6,000	R 30° R 60°		L 60° L 30°	6,000	R 30° R 60°	
	L 60° L 30°	4,000	R 30° R 60°		L 60° L 30°	4,000	R 30° R 60°	
	Abort to KBWI Reverse Course Abort to KPHL				Abort to KBWI Reverse Course Abort to KPHL			

Icing Severity (Left) and Icing Presence (Right) Indices for Routing Decisions

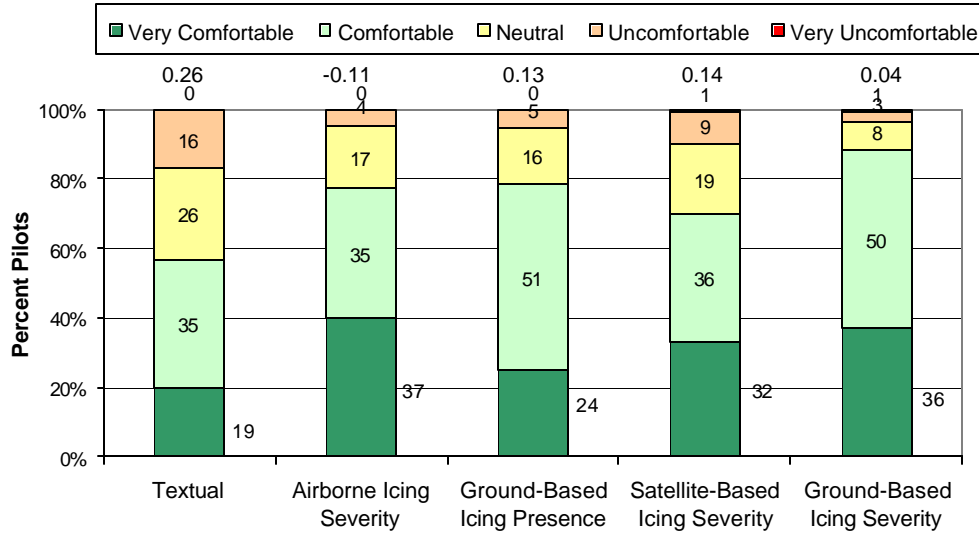
Scenario	Decision Rating (Non-Equipped)				Decision Rating (Equipped)			
	Good	Acceptable	Poor		Good	Acceptable	Poor	
SCENARIO 1	L 60°	L 30°	14,000	R 30° R 60°	L 60°	L 30°	14,000	R 30° R 60°
	L 60°	L 30°	12,000	R 30° R 60°	L 60°	L 30°	12,000	R 30° R 60°
	L 60°	L 30°	10,000	R 30° R 60°	L 60°	L 30°	10,000	R 30° R 60°
	L 60°	L 30°	8,000	R 30° R 60°	L 60°	L 30°	8,000	R 30° R 60°
	L 60°	L 30°	6,000	R 30° R 60°	L 60°	L 30°	6,000	R 30° R 60°
	L 60°	L 30°	4,000	R 30° R 60°	L 60°	L 30°	4,000	R 30° R 60°
								Abort to KBWI
								Reverse Course
								Abort to KPHL
SCENARIO 2	L 60°	L 30°	14,000	R 30° R 60°	L 60°	L 30°	14,000	R 30° R 60°
	L 60°	L 30°	12,000	R 30° R 60°	L 60°	L 30°	12,000	R 30° R 60°
	L 60°	L 30°	10,000	R 30° R 60°	L 60°	L 30°	10,000	R 30° R 60°
	L 60°	L 30°	8,000	R 30° R 60°	L 60°	L 30°	8,000	R 30° R 60°
	L 60°	L 30°	6,000	R 30° R 60°	L 60°	L 30°	6,000	R 30° R 60°
	L 60°	L 30°	4,000	R 30° R 60°	L 60°	L 30°	4,000	R 30° R 60°
								Abort to KBWI
								Reverse Course
								Abort to KPHL
SCENARIO 3	L 60°	L 30°	14,000	R 30° R 60°	L 60°	L 30°	14,000	R 30° R 60°
	L 60°	L 30°	12,000	R 30° R 60°	L 60°	L 30°	12,000	R 30° R 60°
	L 60°	L 30°	10,000	R 30° R 60°	L 60°	L 30°	10,000	R 30° R 60°
	L 60°	L 30°	8,000	R 30° R 60°	L 60°	L 30°	8,000	R 30° R 60°
	L 60°	L 30°	6,000	R 30° R 60°	L 60°	L 30°	6,000	R 30° R 60°
	L 60°	L 30°	4,000	R 30° R 60°	L 60°	L 30°	4,000	R 30° R 60°
								Abort to KBWI
								Reverse Course
								Abort to KPHL
SCENARIO 4	L 60°	L 30°	14,000	R 30° R 60°	L 60°	L 30°	14,000	R 30° R 60°
	L 60°	L 30°	12,000	R 30° R 60°	L 60°	L 30°	12,000	R 30° R 60°
	L 60°	L 30°	10,000	R 30° R 60°	L 60°	L 30°	10,000	R 30° R 60°
	L 60°	L 30°	8,000	R 30° R 60°	L 60°	L 30°	8,000	R 30° R 60°
	L 60°	L 30°	6,000	R 30° R 60°	L 60°	L 30°	6,000	R 30° R 60°
	L 60°	L 30°	4,000	R 30° R 60°	L 60°	L 30°	4,000	R 30° R 60°
								Abort to KBWI
								Reverse Course
								Abort to KPHL

Decision Quality Space for Ice-Protection

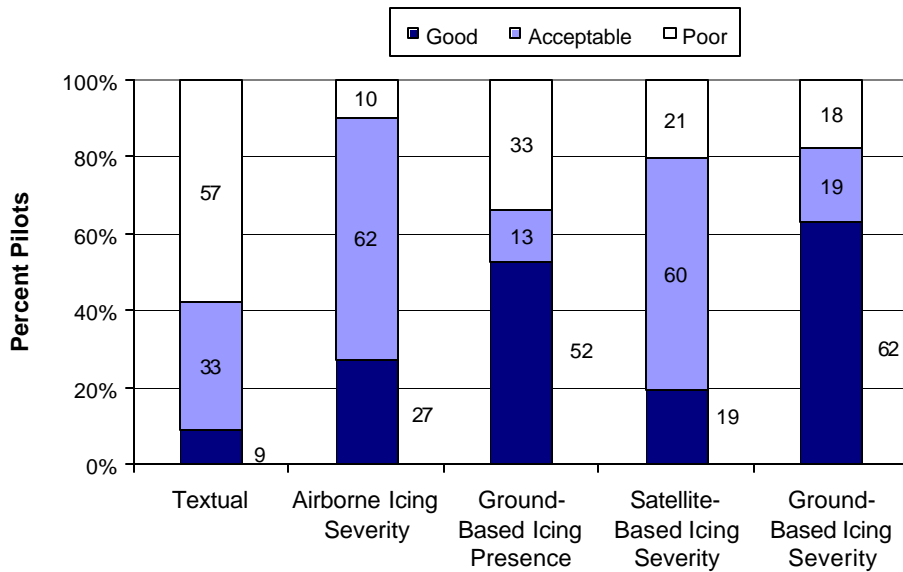
Equipped (Right) and Non-Equipped Operations (Left)

APPENDIX D – EXPERIMENTAL RESULTS

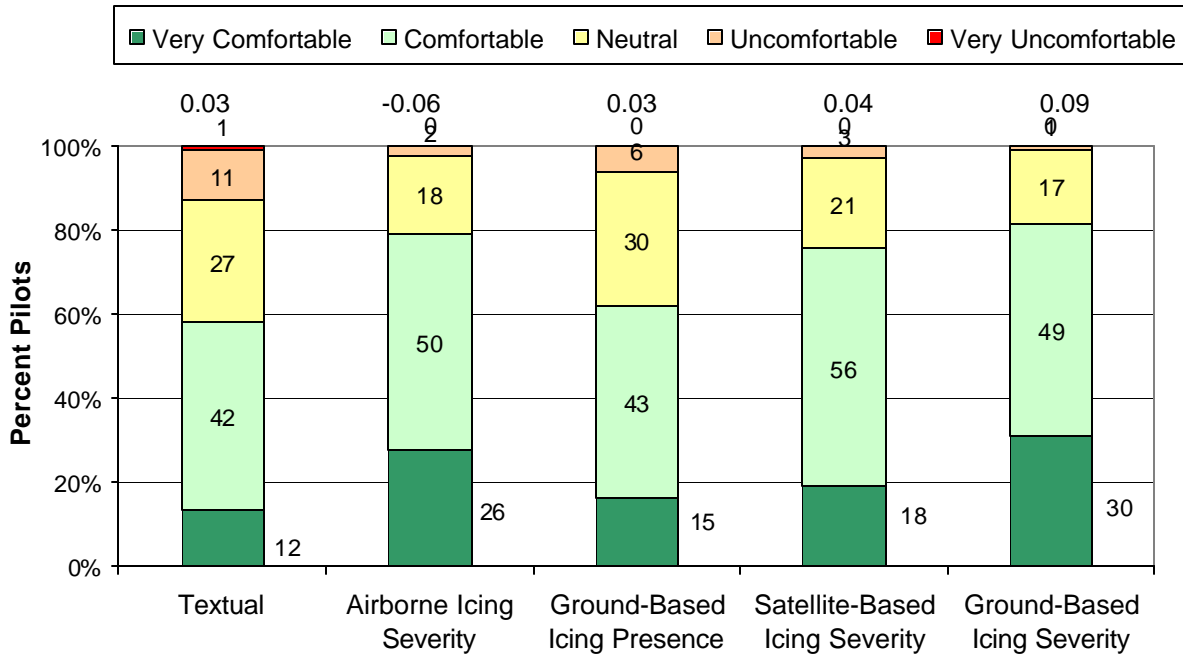
**Comfort Level - Warm Front Avoidance (Scenario 1)
Operations without Ice Protection Equipment
141 Subjects**



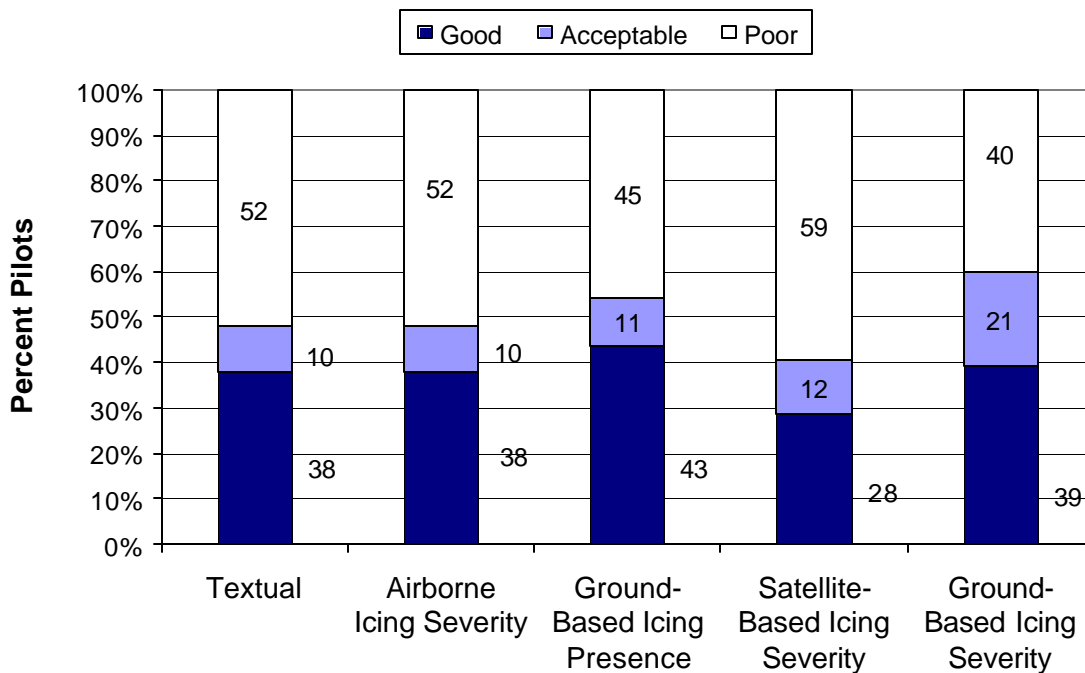
**Decision Quality - Warm Front Avoidance (Scenario 1)
Operations without Ice Protection Equipment - 141 Subjects**



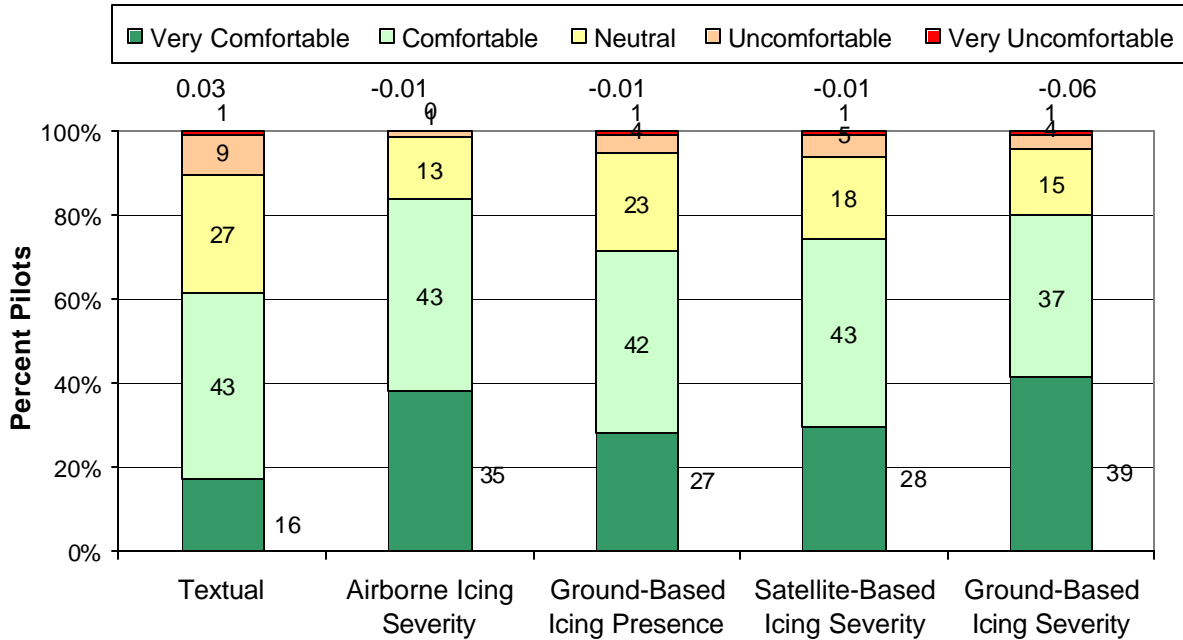
Comfort Level
Embedded Convective Weather Avoidance (Scenario 2)
Operations without Ice Protection Equ. - 141 Subjects



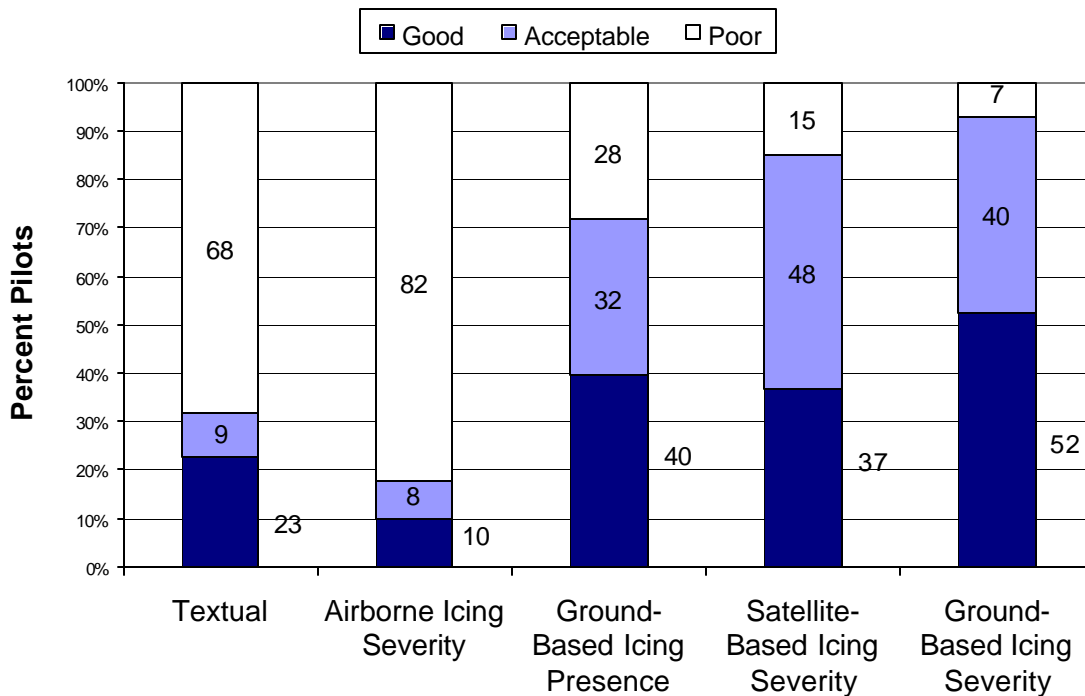
Decision Rating
Embedded Convective Weather Avoidance (Scenario 2)
Operations without Ice Protection Equipment - 141 Subjects



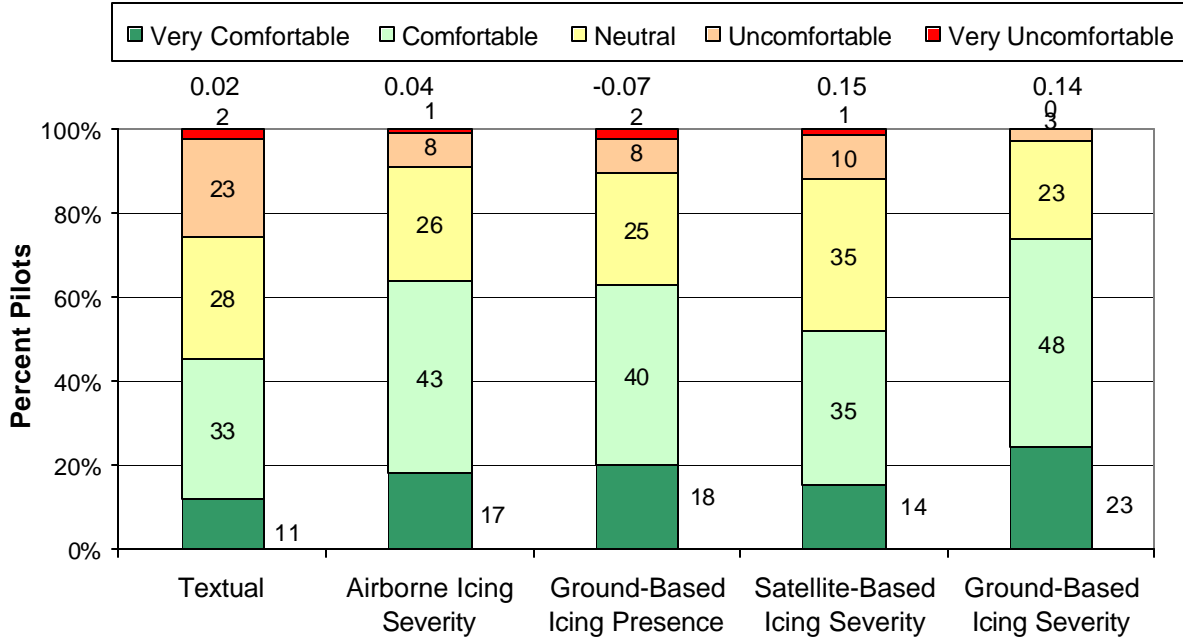
Comfort Level - VFR-On-Top Avoidance (Scenario 3) Operations without Ice Protection Equipment - 141 Subjects



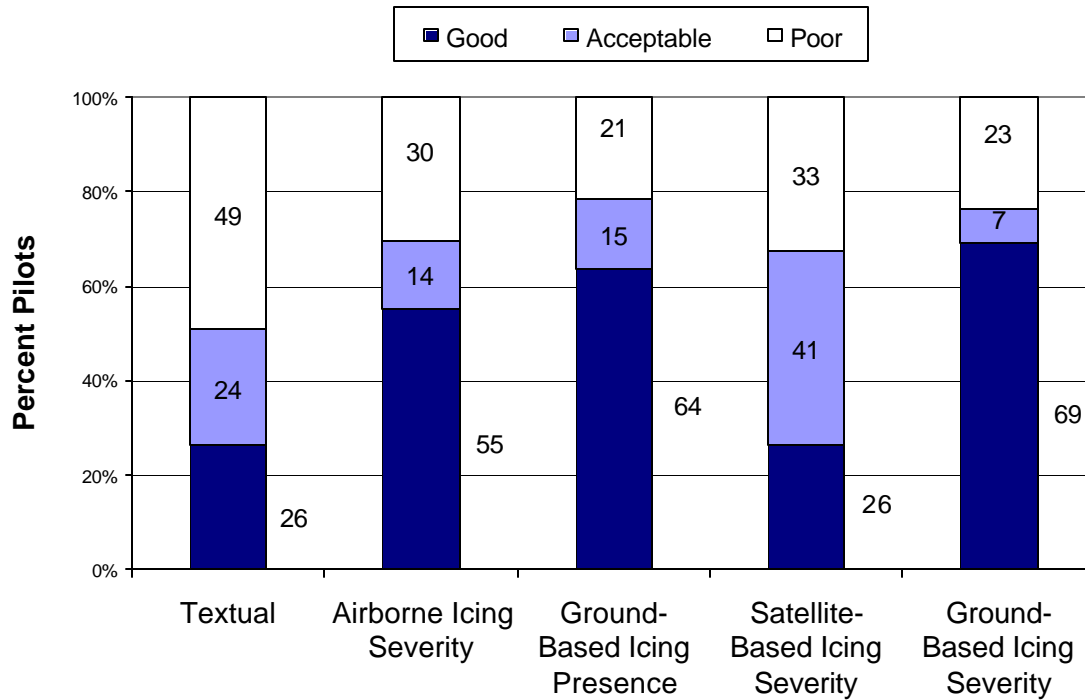
Decision Rating - VFR-On-Top Avoidance (Scenario 3) Operations without Ice Protection Equipment - 141 Subjects



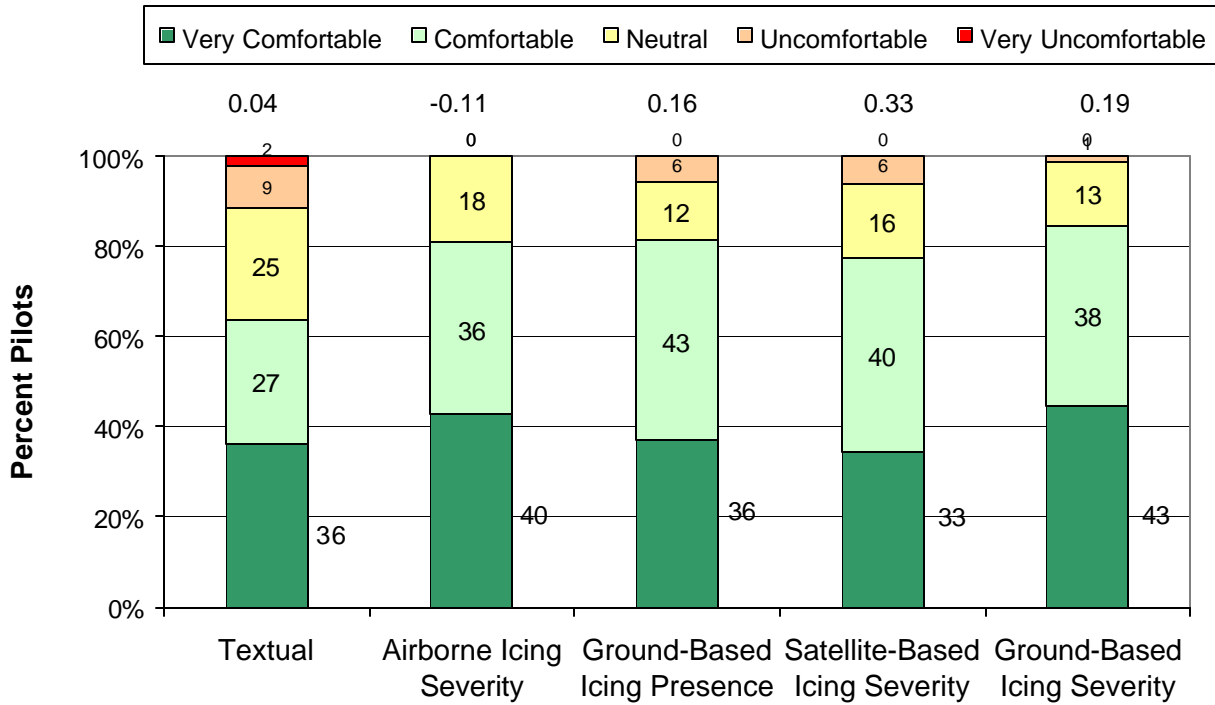
**Comfort Level - Stable Layer Escape (Scenario 4)
Operations without Ice Protection Equipment - 141 Subjects**



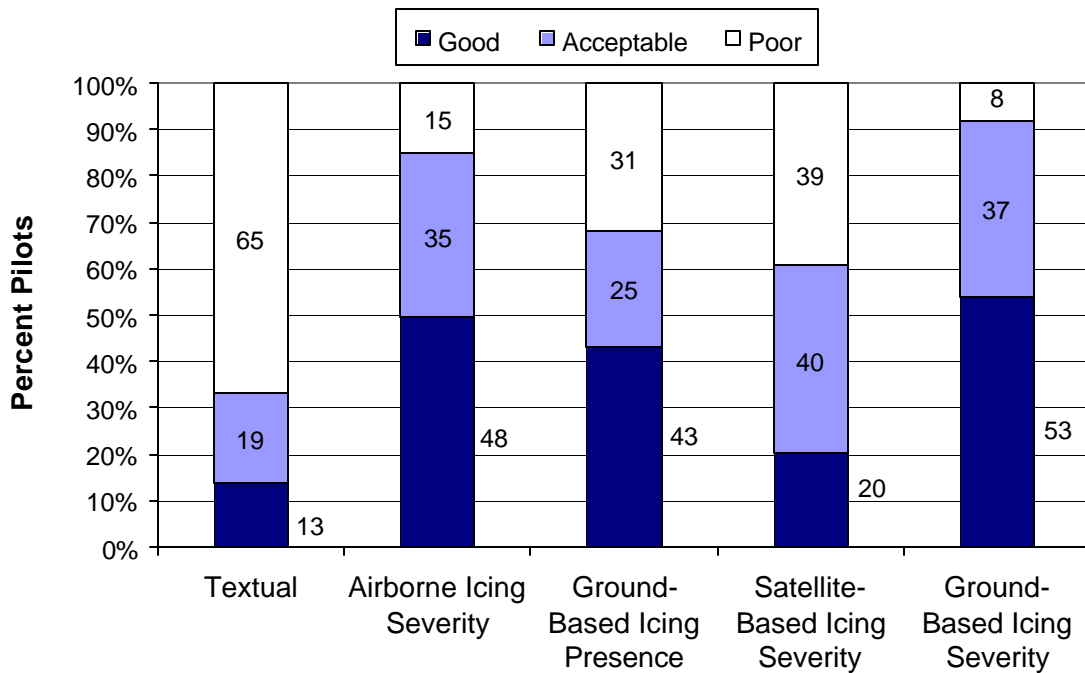
**Decision Rating - Stable Layer Escape (Scenario 4)
Operations without Ice Protection Equipment - 141 Subjects**



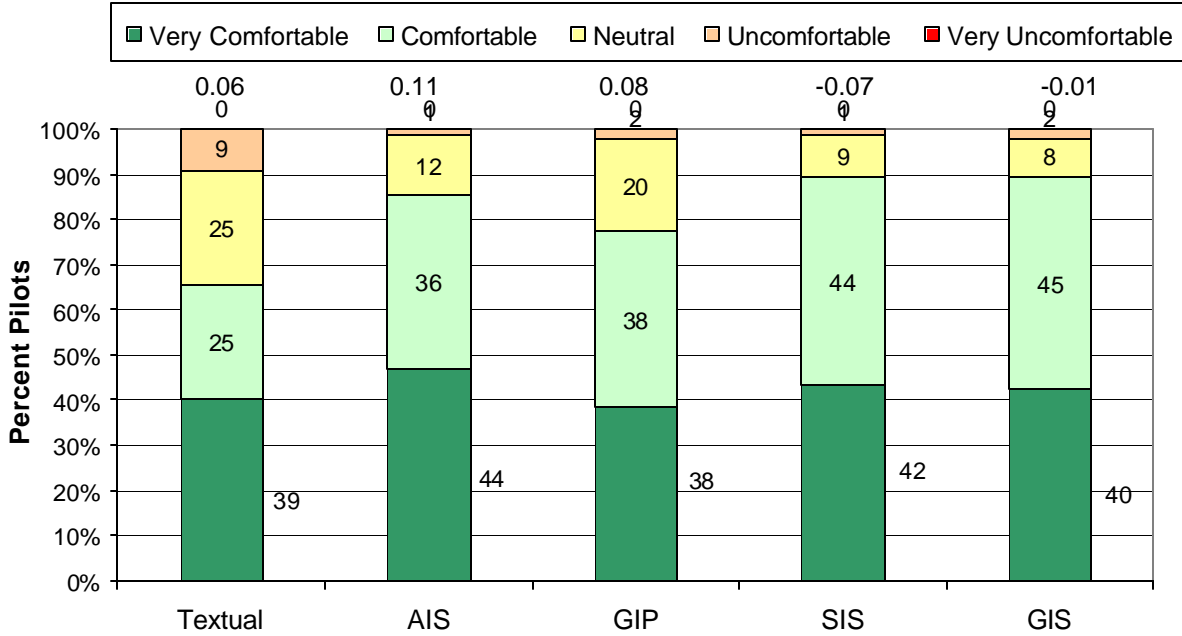
Comfort Level - Warm Front Avoidance (Scenario 1) Operations with Ice Protection Equipment - 89 Subjects



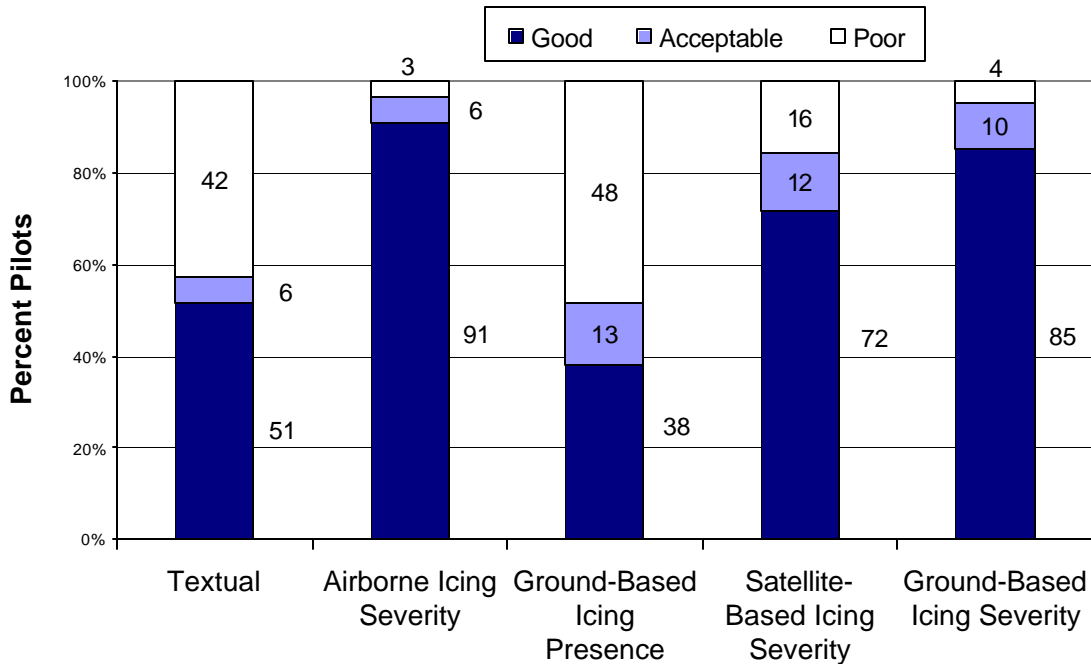
Decision Quality - Warm Front Avoidance (Scenario 1) Operations with Ice Protection Equipment - 89 Subjects



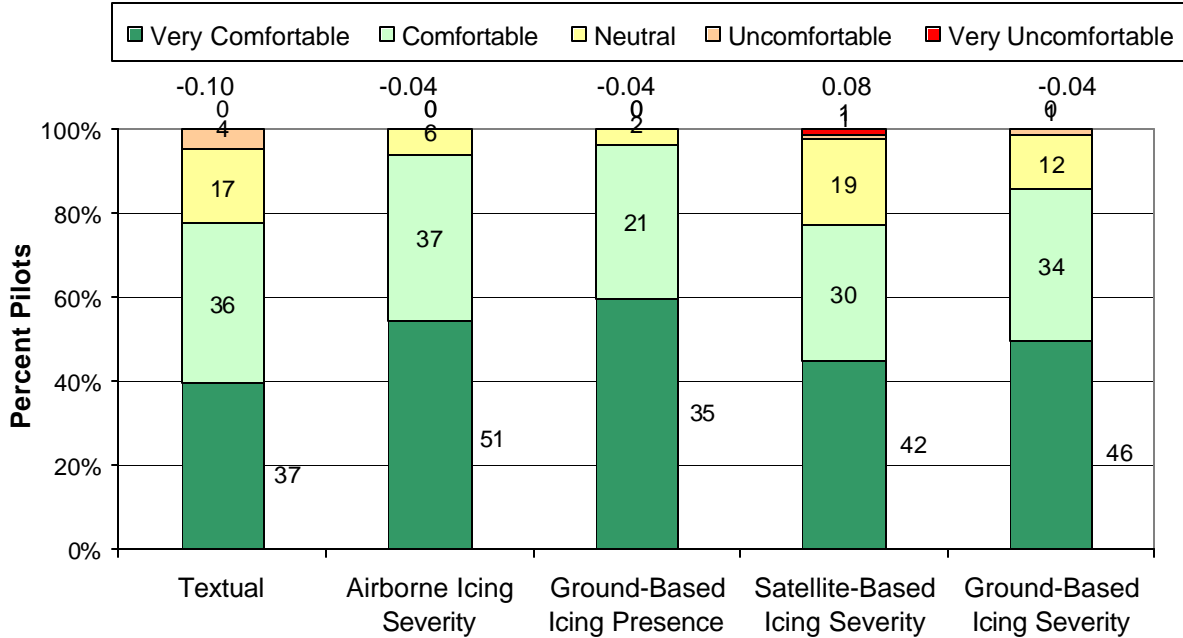
Comfort Level
Embedded Convective Weather Avoidance (Scenario 2)
Operations with Ice Protection Equipment - 89 Subjects



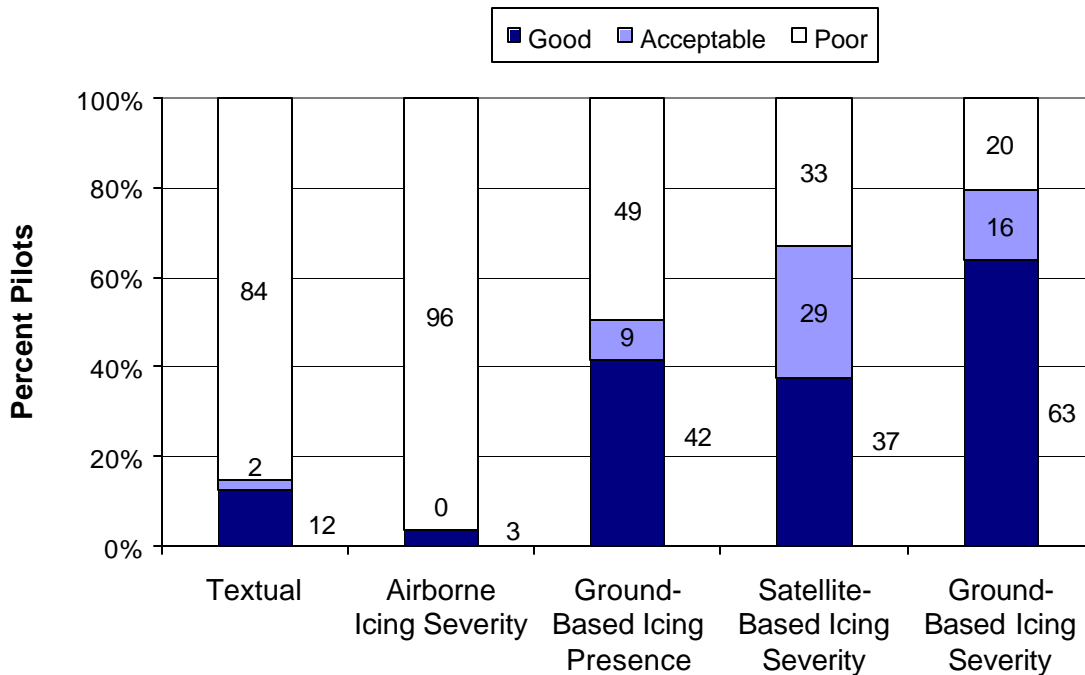
Decision Rating
Embedded Convective Weather Avoidance (Scenario 2)
Operations with Ice Protection Equipment - 89 Subjects



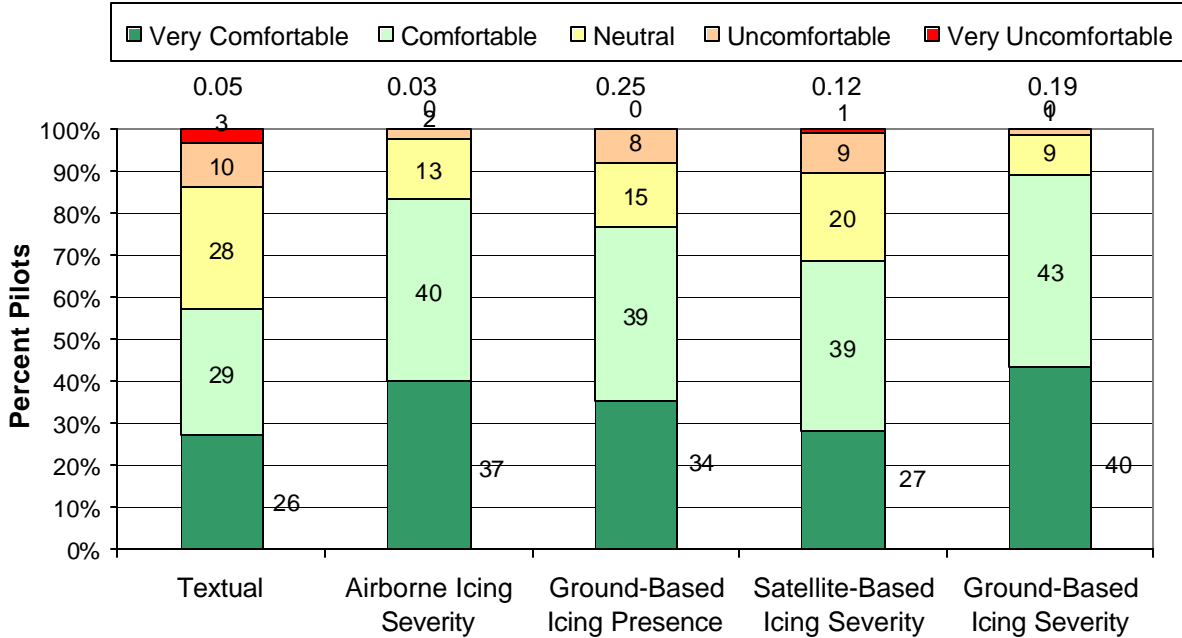
Comfort Level VFR-On-Top Avoidance (Scenario 3) Operations with Ice Protection Equipment - 89 Subjects



Decision Rating - VFR-On-Top Avoidance (Scenario 3) Operations with Ice Protection Equipment - 89 Subjects



Comfort Level
Stable Layer Escape (Scenario 4)
Operations with Ice Protection Equipment - 89 Subjects



Decision Rating - Stable Layer Escape (Scenario 4)
Operations with Ice Protection Equipment - 89 Subjects

