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Aircraft Turbulence Detection and Display from the Professional Pilot's Perspective

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To the Graduate Council:

I am submitting herewith a thesis written by Leslie Owen Kagey entitled "Aircraft Turbulence Detection and Display from the Professional Pilot's Perspective." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aviation Systems.

Richard Ranaudo, Major Professor

We have read this thesis and recommend its acceptance:

Ralph D. Kimberlin, Charles T. N. Paludan

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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Anne Mayhew
Vice Chancellor and
Dean of Graduate Studies

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AIRCRAFT TURBULENCE DETECTION AND DISPLAY FROM THE PROFESSIONAL PILOT'S PERSPECTIVE

A Thesis

Presented for the Master of Science Degree

The University of Tennessee, Knoxville

Leslie Owen Kagey

August 2004

DEDICATION

This thesis is dedicated to my wife, Sandra Kagey, whose support over the years kept me focused on the goals that I have been seeking, and to my parents, Owen Kagey and Myrtie Kagey, for setting a climate in my life to seek after excellence and integrity.

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ABSTRACT

The purpose of this study was to investigate the detection and display of weather avoidance information to commercial airline, business aircraft, and general aviation aircraft cockpits from the perspective of the professional pilot.

A flight campaign was conducted over a period of three years. Convective weather detection was attempted utilizing an experimental airborne weather radar installed on NASA's Airborne Research Integrated Experiments Systems (ARIES) Boeing 757. Additionally ground-based Next Generation Radar (NEXRAD) information and textual data was linked to the aircraft for correlation. It was determined after encountering several heavy turbulence events that radar detection and conventional displays alone were inadequate to provide the types of data needed by the professional flight crew in order to make informed decisions concerning weather avoidance. The NASA King Air B200 and Cessna 206 were also used to evaluate the human factors issues concerning cockpit displays for these classes of aircraft, which are also flown by some professional pilots.

In addition to convective weather avoidance associated with thunderstorms or frontal activity, the study also explored clear air turbulence detection techniques. The detection of these events and the communication of this information to other aircraft in an automated Pilot Report format are being used to display danger areas to other pilots.

PREFACE

The purpose of this thesis is to provide a professional pilot's perspective on weather avoidance information detection and display. Most developmental work in this area has been originated at the engineering level with sometimes insufficient early discussion and coordination with pilots as to their desires and needs for the provision of weather information in the cockpit. By becoming involved at the start of these investigations, it was possible to guide the researchers toward the goal of meaningful and easy-to-use displays. The scope of the study was focused on turbulence phenomena detection and providing displays and early warning tools that could allow for safe deviations from threatening conditions. The future safety of crews, passengers, and aircraft are at stake.

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NOMENCLATURE

AIRMET	Airman's Meteorological Information
ARIES	Airborne Research Integrated Experiments Systems
AvSP	Aviation Safety Program
AWIN	Aviation Weather Information Network
CAT	Clear Air Turbulence
CORRAL	Correlation of Radar Reflectivity And Lightning
COWS	Convective Weather Sources
EWXR	Experimental Weather Radar
FAA	Federal Aviation Administration
ITFA	Integrated Turbulence Forecasting Algorithm
LIDAR	Light Detection and Ranging
METAR	Meteorological Actual Report
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NEXRAD	Next Generation Radar
NWS	National Weather Service
RMS	Root-Mean-Square
SIGMET	Significant Meteorological Information
TPAWS	Turbulence Prediction and Warning System
WARP	Workload and Relative Position Experiment
WINCOMM	Weather Information Communications
WxAP	Weather Accident Prevention Program

Introduction

One of the most widely recognized global issues in the area of Aviation Safety has been the significant impact that weather phenomena have on aircraft operations. Many individuals are injured or even killed as a result of aircraft encounters with severe weather events in-flight (*Aviation Operations,* 1999). Turbulence, thunderstorms, convective weather, lightning, and high winds have plagued aviators since the time of the Wright Brothers (Landsberg, 1996). Weather affects all users of the airspace from small single-engine General Aviation (GA) aircraft through the largest airliners and military transports (Aircraft Owners and Pilots Association, 2002). These issues still are a significant threat to air travel today (*Aviation Operations*, 1999; Landsberg, 2001; AOPA, 2002). "Weather is a factor in approximately 30% of aviation accidents. Weather is responsible for approximately two-thirds of air carrier delays - a four billion dollar cost, of which 1.7 billion dollars are considered avoidable." (Latorella, 2003). Turbulence associated with convective weather and clear air turbulence (CAT), not only constitute dangers to individuals in aircraft, but also to the aircraft itself. Characterization of the effects of turbulence on aircraft structural integrity and airframe fatigue life are essential to the design of new aircraft and to the continued safety of aging aircraft (Fuller, 1997). Hardware and avionics have been developed in response to these threats to safety in order to provide better turbulence and weather situational awareness. Continuing progress in detection and display are necessary to meet the goals of reducing weather impact on flight safety. The focus on scientific investigation of these issues was escalated when the White House Commission on Aviation Safety and Security was

established in 1996 by President Clinton to study, among other aviation topics, the topic of weather effects upon aviation safety. (Exec. Order No. 13015, 1996). The report of the Commission recommended that studies be conducted to reduce accident and incident rates in civil aviation. (Gore, 1997). Congressional testimony was taken as well with regard to turbulence-related incidents and accidents (*Aviation Operations,* 1999). As a result of this impetus, NASA's Administrator, Mr. Daniel Goldin, established the NASA Aviation Safety Program (AvSP) at NASA, in conjunction with the FAA, to address accident reduction (Croom, 2003a).

Chapter 1: The Weather Accident Prevention Project of the NASA Aviation Safety Program

Weather Accident Prevention

This thesis addresses the NASA Langley Research Center Weather Accident Prevention (WxAP) flight experiments conducted between 2000 and 2003, specifically with regard to the emphasis that the experiments have had on cockpit weather display development. Additionally, a short look is taken at the proposed follow-on studies scheduled for 2004.

The Weather Accident Prevention project was created as a subset of the NASA Aviation Safety Program (AvSP) to address the weather portion of the aviation safety goals, as stated by Croom, (2003c):

> The objective of the Weather Accident Prevention (WxAP) Project is to develop and foster the implementation of technologies that will reduce the role of atmospheric conditions in aviation fatal accidents, incidents, and injuries. Hazardous atmospheric conditions include those generally attributed to weather and turbulence. The Project will provide weather information, avoidance and mitigation technologies. (p. 1)

The NASA Langley Research Center in Hampton, Virginia is leading the Aviation Safety Program (Green, Tsoucalas, & Tanger, 2003). This program has as its ultimate goal to reduce fatal accidents by a factor of five by the year 2007 (Croom, 2003a). Although the overall program management of the AvSP is led by the Langley Research Center, the Weather Accident Prevention Project portion of the AvSP at NASA is headed by and coordinated from the NASA Glenn Research Center (GRC) in

Cleveland, Ohio (Green et al., 2003; Banks, 2003a). Some of the in-flight research, therefore, is conducted from Cleveland, while some is flown out of Langley Air Force Base in Hampton, Virginia. The focus of the WxAP flight effort at Glenn is related primarily to cold weather and icing investigations. Ultimately the emphasis of the Langley studies is to provide necessary and timely weather information to the flight deck by way of easily interpreted display technology.

Since the 1940's and into the present day, several in-depth studies have been performed especially in the United States, Canada, and Europe to provide methods of detection and warning to crewmembers prior to entering areas of suspected dangerous weather conditions (Tolefson, 1947; Press & Binckley, 1948; Thompson & Lipscomb, 1949; Scanlon, 1994; Fuller, 1997; Ferris, 1999). The National Aeronautics and Space Administration (NASA), the Federal Aviation Administration (FAA), the National Oceanographic and Atmospheric Administration (NOAA), and the military have been the primary sources of government-funded research into these various phenomena in the United States (Scanlon, 1994; Gallon, 1997; Banks, 2003a). Additionally, several universities and private corporations have done additional research concerning weather detection and display (Rockwell-Collins, 2003a; *Projects,* 2003).

WxAP subareas of research. The WxAP aircraft flight research work at Langley Research Center (LaRC) in Virginia is focused on Aviation Weather Information (AWIN), Weather Information Communications (WINCOMM), and Turbulence Prediction and Warning Systems (TPAWS) (Banks, 2003a). AWIN is a technology aimed at providing improved and timely displays of textual and graphical data to the cockpit flight crew. WINCOMM provides the communications connectivity and data

links to provide data to the crews of aircraft and to interested ground stations (Banks, 2003b). TPAWS is a system designed to provide turbulence warning information to the cockpit through the WINCOMM connectivity links (Banks, 2003a). Especially emphasized at Langley for the last several years have been commercial and business aviation issues, primarily with respect to convective weather, wind shear, and turbulence, as well as, runway friction on icy runways. In order to assess the impact of weather on real-world airline crews and equipment, the WxAP investigations at NASA were designed to put comparable aircraft and seasoned aircrews into flight scenarios that would closely replicate airline and business aviation operations (McAdaragh, 2002). These pilots included airline captains, FAA pilots, Boeing Company pilots, and NASA pilots, who have military, airline, and corporate piloting backgrounds.

The approach taken by this project was to:

- Improve weather forecast and "nowcast" capabilities.
- Revolutionize aircraft-ground, and aircraft-aircraft information exchange.
- Use aircraft as airborne weather data collectors. (Croom, 2003c)

In order to provide the data required for the development of this information display technology, a series of flight investigations was carried out over three separate flight periods. A team of scientists, meteorologists, engineers, and research pilots from NASA Langley Research Center conducted these investigations of turbulence prediction and convective weather avoidance. The NASA ARIES Boeing 757 research aircraft, the NASA Raytheon Beech King Air B200 corporate class aircraft, and the NASA Cessna 206 general aviation aircraft were employed as the in-flight research platforms for these experiments.

Chapter 2: Weather Detection and Display Needs From the Professional Pilot's Perspective

Professional Pilot Perspective

This thesis provides a focus, from the professional pilot's perspective, on the impact that providing improved weather information and turbulence predictions could have on commercial airline, business aircraft, and general aviation flight crews. Of interest was the exploration of how modern technologies could improve the safety and reliability of air travel. During these experiments, evaluations by human factors engineers and psychologists were included in order to appraise the ease of use and effectiveness of the communicated information. Much of the literature related to the weather avoidance issue is focused on the science and technology of weather avoidance systems as interpreted by engineering organizations, with limited discussion of the needs and desires of the professional pilot. This is not an intentional oversight, but, from the view of the professional pilot, the practical needs of these pilots have often been overlooked to a large extent by many of the studies done in the past. For example, Bass and Minsk (2001) found that:

> Another issue is that most weather products are designed by and for meteorologists. However, the goal here is to communicate information so that it is relevant to pilots. Pilot-centered metrics are required. A more pilot-centered approach to the display and management of real-time and forecast weather information is clearly needed. (pp. 3, 4)

Often a new weather avoidance system is developed by engineers or meteorologists based on their perceptions of the needs of the pilot. Although some of these engineers and

scientists may have had some exposure to the flight environment as private pilots, they often assume knowledge of operations that is more likely only gained through years of extensive commercial or military operation in all weather and air traffic control regimes. When professional expertise and experience of professional pilot crews is not actively sought and utilized prior to the commencement of a research study, then the display tools developed by industry that are provided to the pilots in the weather avoidance scenario may not fully satisfy their needs. In most programs, prototype designs are developed in engineering laboratories with little or no professional pilot input at this stage of design. The pilot is often brought in to review the design during the prototype-testing phase after the design is well along in development. This is not always the most ideal method of development. Often the hardware design is already established, thus limiting the ability to significantly affect the human-machine interface issues. Personal experience, as a NASA Research Pilot, former corporate jet pilot, military pilot, and engineer working in commercial industry, has made it clear that a more effective developmental approach is to involve a group of professional air crewmen early in the design process. This process is properly incorporated in the Mission Analysis Phase of systems integration (Weiner & Nagel, 1988). Bauer (1996), in his study of military cockpit design, echoes this same perspective:

> The physical and attentional resources of the aircrew must be understood and accommodated by those designing the cockpit and other workstations. Aircrew members who are knowledgeable of, and experienced in, the intended mission must be involved in the design process from the earliest phases of concept definition.

Real-world experiences in flying often include learning how to avoid many weather events that impact the ability to continue safely on a planned route to an intended destination. The professionals have gained experience and knowledge of these events such that they have a perspective on the types of data that are desired for appropriate decision-making. The decisions they have had to make over the years in weather situations have often required significant deviations from planned routes or even diversion to alternate airports. These occurrences were often accomplished with inadequate information or inappropriate displays. From a pilot's viewpoint, much of the avionics systems, and the software to drive them, are developed and go to market with little real world understanding of the needs of the flight crew. This is especially true when it comes to interpretation of the data displayed and the proper response by aircrews to those displayed data (Bass & Minsk, 2001). Often inadequate emphasis is placed on human factors and the design of interfaces that are effective and intuitively usable (Keel et al., 2000). Therefore the focus of this NASA research was to determine the limitations of existing weather avoidance systems and to evaluate these systems implementations from an experienced professional pilot's viewpoint.

Inadequacies of Current Weather Information Systems

There have been previous studies of airline crew decision-making with regard to weather, such as the simulation study of Bass, Jones, & Castaño (2000), as well as, reviews of actual weather encounters by air transport aircraft and crews (Ferris, 1999; *Aviation Operations,* 1999; Kaplan et al, 2002). These studies have been useful in documenting types of weather that crews are willing to penetrate or that they will avoid based on the sensor information presented to them (Newton, 1989). These studies have

been primarily a review of crew response to airborne weather radar displays. However, it is well known that crews have continued flights through areas of severe weather, which have resulted in crashes because of poor sensory information availability or unsatisfactory interpretation of that data in the cockpit. (Rhoda & Pawlak, 1999; *Aviation Operations,* 1999; Castaño & Bass, 2000; Kaplan et al, 2002). In most cases, this has pointed out the inadequacy of airborne weather radar alone as an adequate weather avoidance tool. Airborne weather radar primarily detects precipitation or high moisture content in clouds. The display of this data is normally calibrated to provide color differentiation based on the dBz levels of the received reflected energy from the water droplets in the air. These levels may not necessarily correlate directly to the severity of turbulence in these precipitative regions. In recent years some effort has been made to address these inadequacies, such as the introduction of lightning detection sensors. Although the primary purpose of such systems is to keep aircraft from being struck by lightning, a secondary purpose is to avoid thunderstorms and their associated turbulence. This assumes that turbulent air columns are present in the vicinity of lightning. This is known to be a factor in lightning development. However, it is also known that the currently available accuracy of lightning detection systems is not adequate to pinpoint turbulence areas in every case (McDonnell-Douglas, 1997). Although these systems have provided some improvement to situational awareness of weather issues in the cockpit, they do not provide the other information that crews could readily use. It is also known that turbulence is not necessarily associated with precipitative weather returns on radar or with electrical activity displayed on lightning detection systems (McDonnell-Douglas, 1997; Hamilton & Proctor, 2002). When the provided cockpit information is

incomplete or poorly correlated, improper decisions ensue, thus jeopardizing the safety of the aircraft and the persons on board. As will be discussed in greater detail, this became very clear to the research team in the CY2002 flight events.

Types of Weather Information Desired by Professional Pilots

From the perspective of professional pilots, the types of data that are useful for severe weather avoidance should include:

- displays of precipitation
- potential wind shear
- clear air turbulence
- convective weather (including associated turbulence)
- turbulence area predictions and pilot reports (PIREPs)
- lightning
- altitudes of cloud developments ahead of the aircraft's planned flight path

(*Avoiding "Bumps",* 2002)

Also ready availability of destination and alternate weather observations and forecasts while airborne is essential to safe determination of route selection. Several of these data are available in the modern cockpit through commercially available uplink systems (Newton, 1989; Chamberlain & Latorella, 2001). Although much of this information is available from ground sources or the Internet today, it is not widely distributed to most aircraft in flight, because of the lack of necessary reception and display equipment installations on these aircraft (Newton, 1989; Chamberlain & Latorella, 2001; McAdaragh, 2002; *Turbulence,* 2003; Wynbrandt, 2003a, 2003b). Another factor is that there has been no government mandate for the inclusion of these systems into aircraft

cockpits, even among airline operations. In fact, corporate aircraft are more likely to be better equipped than airliners. They usually have the most modern equipment installed because of the personal interest of company executives in their own safety and the ability of corporations to equip a smaller fleet more inexpensively. Airline companies are faced with much larger capital outlays if they were to retrofit all of their aircraft. Thus safety enhancement is balanced against fiscal reality. Therefore, the airlines tend to take a phased approach to the installation of this type of equipment. Most of their upgrades occur during initial procurement of new aircraft and then on a gradual basis on their remaining airframes, as their financial situations allow. New aircraft are often brought on the line with some of these features as standard equipment. Depending on the remaining useful life of the older aircraft, those older aircraft may never be slated for modification or upgrade.

When these upgraded systems are incorporated, they should include:

• Well-designed man-machine interfaces to reduce workload

• Intuitive operation of controls and switches

• Accurate correlation of data with the outside world

• Timely sharing of information with other aircraft and users.

Chapter 3: Studies to Quantify the Needs of Professional Aircrews

Cognitive Task Analysis (CTA)

The coordinated cognitive analysis of flight crews, based on the use of real-time modern electronic displays of approaching weather hazards, had not been thoroughly explored prior to these series of NASA Langley WxAP flight tests.

> Cognitive task analysis (CTA) differs from traditional task analysis by focusing on operators' cognitive processing and knowledge base, or experience. CTAs are typically used when tasks are complex, or ill structured; and when these tasks occur in dynamic, uncertain, multi-tasking, real-time operational domains [Gordon & Gill 1997]. To conduct a CTA, one uses knowledge acquisition tools to elicit and represent general and specific knowledge. Typically researchers use these methods with highly knowledgeable and experienced operators that are considered subject matter experts (SMEs). The knowledge elicitation phase of CTA uses a set of interview techniques to explore these experts' decision-making processes. (Latorella, Pliske, Hutton, & Chrenka, 2001).

Flight tests were planned in order to focus on these identified display needs. The planned tests included intentional flight into areas of predicted moderate turbulence and associated convective weather activity. This was especially true of the test planning related to altitudes, airspeeds, and locations where turbulence events occur. Direct involvement as the NASA Research Project Pilot at the earliest planning sessions provided the team of researchers with informed insight into the existing limitations of current and proposed systems. This allowed for the consideration from the pilots' perspective of the value of proposed enhancements to existing hardware and avionics

display systems. These flight test data are expected to be used to provide useful inputs to the subsequent design process in the preliminary planning stages of proposed commercialized system enhancements. In the course of the flight research events, potential improvements to systems that would enhance weather and situational awareness were to be evaluated. Preliminary design reviews were used to set the focus for needed areas of avionics improvement. These were followed by critical design reviews, which evaluated the design proposals and both positive and negative aspects of the systems from the pilot crew perspective. It was anticipated that the research pilots would be able to provide an evaluation of a given display system in a subjective manner and, also, through quantitative data collection, correlation, and reduction. Coordination and liaison with air traffic control facilities and participating aircraft was included in the planning. One of the research team members was an experienced air traffic controller, who was very familiar with established procedures in the Air Route Traffic Control Centers (ARTCC).

Weather Avoidance Doctrine

The Federal Aviation Administration Advisory Circular AC 00-30B (1997) contains the official government guidance for operation of aircraft in the vicinity of turbulence. This document does not provide definitive guidance for transport aircraft standoff distances or other methods of dealing with potential severe turbulence within the context of large transport aircraft operations. However, the McDonnell-Douglas-developed "Turbulence Education and Training Aid" (1997), which was produced under the auspices of the FAA and the Air Transport Association (ATA), has been published and distributed to all American air carriers, with FAA approval and concurrence. This

document is also known as the "Turbulence Guide," and was adopted as the underlying standard for our weather flight operations. It provided the basis for the limiting set of restrictions in the original WxAP Flight Test Operations and Safety Report (FTOSR) (NASA Langley Research Center, 2000) to be used for operational boundaries, standoff distances, and safety tolerances for the NASA flight operations in the vicinity of convective weather activity. Potential hazards to flight were identified and controls were developed (Weathered, 2000). These identified hazards assessments were included as an appendix in the NASA-required FTOSR (NASA, 2000). The proposed flight test plans were presented to the Aviation Safety Review Board (ASRB) for safety review and flight release authorization. Each year's operations and each new FTOSR (NASA, 2001, 2002, & 2003) contained the McDonnell-Douglas (1997) recommendations as guidance for standoff parameters and were reviewed by the Langley ASRB and Aviation Safety Officer. Included each year were hazard assessments that were reviewed and updated to meet the changing risks of the experimental data flights (Weathered, 2001, Kagey & Weathered, 2002; Beaton & Kagey, 2003).

Chapter 4: Data Collection Campaigns

CY2000 Flight Campaign: Experimental Weather Radar Evaluation

The CY2000 flight campaign with the NASA Boeing 757 ARIES research aircraft was flown from NASA Langley Research Center located at Langley Air Force Base in Hampton, Virginia. This campaign consisted of two major components. The principal test component was the evaluation and refinement of the experimental turbulence prediction weather radar (EWXR) (see Figure A.1) installed in the ARIES aircraft. The other component of the test runs was the evaluation of the AWIN display technology provided to the flight crew and the determination of their display needs and desires.

This campaign required the aircraft to approach large convective cumulonimbus cloud build-ups from the upwind side of a weather front and the subsequent approach to the edges of these cells (Hamilton & Proctor, 2002a & b). This upwind technique was based on the recommendations of the "Turbulence Guide" (1997) and the associated FTOSR (2000). The goal was to correlate the predicted turbulence levels from the radar with the actual accelerative "in-situ" loads encountered by the aircraft (Proctor, Hamilton, & Bowles, 2002). Returns from the radar were to be correlated with the accelerometer data recorded aboard the aircraft. Root-mean-square (RMS) and peak vertical acceleration values were recorded. Although the EWXR display was initially tested in 2000, the display of the EWXR during those tests was not presented or available to the cockpit flight crew during the flight experiment. Only the standard weather radar information was available in the cockpit (Latorella, 2004).

Flight tests of 13 and 14 December 2000 (Flights 190 and 191). This dedicated flight test campaign consisted of flights over a 20-day period. Although several missions were flown to capture turbulence data, two particular flights stand out.

Flight 190. On December 13, 2000, the NASA Boeing 757 ARIES aircraft was flown into a known area of convective weather over the southeast United States where significant turbulence was encountered (known as Flight 190). Figure A.2 shows an overview of the weather situation in the general area of that event. Figure A.3 shows the flight path of the aircraft. This also shows the ground-based radar returns from the Fort Polk, Louisiana ground radar site. The red returns are related to the greatest reflectivity normally associated with precipitation and high moisture content in the clouds. The amber returns are less reflective, with green being of even lesser reflectivity. This ground-based information was not available to the cockpit crew at the time of the weather penetration. It should be noted that the ground-based radar has the ability to look upward into the cloud region, scanning all altitudes. In contrast, the installed aircraft weather radar uses a narrow pencil beam propagation pattern, which only provides a look at a very shallow band of altitudes. It is also sensitive to the pilot's selection of proper antenna tilt adjustments to maximize the return. The aircraft radar in this particular event showed no return greater than a moderate amber return, even though Figure A.3 illustrates that the aircraft actually transited areas of red as detected by the ground station. Hamilton and Proctor (2002b) stated:

> The turbulence encounters resulted from the penetration of the turrets located upwind of the large thunderstorm. Snow and ice crystals within the turrets went nearly undetected by the airborne radar and was later confirmed by the radar at

> POE *(Fort Polk, Louisiana; my italics)* to have weak reflectivity with values generally less than 10 dBz. Event 190.6 was the first of two severe turbulence encounters of the day. Maximum radar reflectivity with these cells was less than 15 dBz. The aircraft entered the plume and experienced three updraft/downdraft pairs, each increasing in strength. The third plume exhibited an updraft/downdraft couplet with a horizontal wind shear in the vertical wind exceeding 12 m/s over 170 m. The gradient led to a normal load acceleration (Δn) of –0.81 g. The maximum RMS normal load during the event was 0.33g, which is considered severe. Event 190.7 was the strongest event of the day. The incurred peak load (Δn) measured during the event was –1.22g and the RMS normal load peaked at just over 0.35, which again rates as a severe encounter. (pp. 4, 6)

The aircraft radar proved to be inadequate for accurate determination by the flight crew of the severity of the turbulence embedded in the convection. This highlights the way the conventional aircraft weather radar is used by professional flight crews. Since crews have found through experience that the radar returns are not always indicative of the severity of turbulence, they tend to use the radar as a weather avoidance tool, rather than a weather penetration tool. In fact, this is the crux of the guidance found in AC00-30B (FAA, 1997) and the McDonnell-Douglas "Turbulence Guide" (1997). Current generation aircraft weather radars provide returns of precipitation ahead of the aircraft, which the crew then must subjectively evaluate, through experience gained in years of operation in weather, in order to predict their ability to safely continue or to deviate from

a path of flight. This has proven to be only moderately successful (Wynbrandt, 2003a, 2003b; Latorella et al., 2001).

Flight 191. Flight 191, flown the next day, 14 December 2000, proved to be the most severe flight of the season. Hamilton and Proctor (2002b), who were the meteorology researchers aboard these flights, reported that:

> The most severe encounter with turbulence during the fall deployment was Event 191.3. Associated with Event 191.3 were horizontal changes in vertical winds of up to 27 ms^{-1} within a distance of 100 *m*. RMS normal loads ($\sigma\Delta n$) of 0.44 *g* and peak normal load (Δn) of –1.4 *g* were associated with 191.3, and rank relatively high with regards to previous accident cases. (p. 10).

Comparison to known turbulence accident data. Hamilton and Proctor (2002b) also stated:

> The factors that caused the turbulence during the NASA fall deployment could be considered as factors in previous turbulence accidents [described by Pantley (1989), Pantley and Lester (1990), and Wingrove and Bach (1994)]. Similarities between the NASA flight experiments and reported accident accounts are as follows:
>
> 1) Event duration was typically less than 30 seconds and coincided with time spent within the cloud.
> 2) Consistent with pilot reports, events occurred inside cloudy regions where radar reflectivity levels were low (< 20 *dBz*). Furthermore, the events occurred outside of high reflectivity regions (> 35 *dBz*) associated with the most intense thunderstorm cells.

3) The most severe events occurred within the sharp gradient between a strong updraft and a downwind downdraft. (p. 10)

Note that the data associated with documented accidents of aircraft were very similar to the same levels of turbulence as were experienced by the NASA Boeing 757 during Events 190.6, 190.7 of Flight 190 and event 191.3 of Flight 191. Also Hamilton and Proctor (2002a, 2002b) found that the aircraft weather radar returns did not correlate in any usable way with the actual in-situ accelerometer data recorded during the turbulence events. This was seen as an extremely important finding, providing impetus to further research into turbulence prediction and reporting. It was understood that the amplitude of radar returns displayed to the pilots were set at dBz thresholds related to precipitation levels, since prior to these tests these thresholds were assumed to be sufficiently correlated to the associated turbulence levels expected in vertical air columns within the cumulonimbus turrets. On the contrary, as can be seen in Figures A.4 and A.5, it was found that there was inadequate resolution of differences in the return data to allow the aircrew enough discrimination between returns to allow for turbulence avoidance.

As was shown by Hamilton and Proctor (2002b), the events were poorly correlated with the pilot's displays:

> During the flights, the aircraft avoided high levels of radar reflectivity (> 35 dBz). Continuous turbulence was experienced while flying within convection and associated precipitation (Instrument Meteorological Conditions) but smooth conditions were present when flying outside of those regions (Visual Meteorological Conditions). In all cases, radar reflectivity levels were low

> (< 35 dBz), and at times, lower than the detection ability of the airborne radar. However, the airborne radar did detect the hazardous turbulence along the flight path when radar reflectivity levels were relatively large, i.e. between 20 and 33 dBz. (pp. 9-10)

Color-coding of the radar displays is inadequate. These data demonstrated a need for additional study of the display techniques used for turbulence avoidance. The EWXR has the ability to detect turbulence through Doppler detection. It was determined that color-coding of the radar returns at the appropriate dBz levels associated with turbulence, therefore, rather than correlation to levels of precipitation, would make the display more valid for turbulence avoidance. It was suggested that the colors should correspond in some way to the standard levels of turbulence normally reported in PIREPs by aircrews. These standard PIREPS in the classic FAA turbulence definition are placed in four categories: Extreme, Severe, Moderate, and Light (see Table A.1). This information is also available to military and government pilots in the Flight Information Handbook (National Imagery and Mapping Agency, 2003).

Aviation Weather Information (AWIN) evaluation. The second test component of the CY2000 campaign was the AWIN (Aviation Weather Information) system (Jonsson, 2002). During this phase of the AWIN testing, a flat panel color display was positioned on the left side windshield panel (see Figure A.6) with a presentation of various up-linked weather data products. These products included meteorological data in text form, known a Meteorological Actual Reports (METARs) and Next Generation Radar (NEXRAD) ground radar displays (Latorella, 2003). Several 757 pilots, unfamiliar with the AWIN system, were placed in the left seat of the cockpit. The pilots were asked to use the

display to make informed decisions, based on the data presented, concerning adverse weather ahead of the aircraft, with a subjective evaluation of the effectiveness of the data being made available, and their intentions for aircraft deviations from course to avoid the weather (Jonsson, 2002). This display was not correlated with the on-board ship's radar display during the CY2000 campaign. Rather it was independently evaluated from a human factors perspective for utility and effectiveness, using the NASA Task Load Index (NASA-TLX) method. This method rates human-machine interface issues in a subjective fashion using six subscales. The subscales are: mental demands, physical demands, temporal demands, own performance, effort, and frustration (Hart & Staveland, 1988). The pilots' assessments are being used to determine the validity of data products from a pilot's subjective perspective and to fine-tune the way the products are displayed. The AWIN studies were incomplete at this point and were continued in the next years' campaigns.

The CY2000 flight campaign ended in December in order to make preparations for a very ambitious AvSP flight program in CY2001.

CY2001 Flight Campaign: Clear Air Turbulence (CAT)

The CY2001 campaign was initiated in the summer of the year. Boeing 757 flights were flown from Colorado Springs, Colorado. The main thrust of these events from the weather perspective was to explore clear air turbulence (CAT) predictions and observe and record the data first-hand from the aircraft. CAT has been identified as a major threat to passenger and crew safety since the 1960's (Stough & Martzaklis, 2002). As jet-powered passenger aircraft came into service in the late 1950's and early 1960's,

the higher cruising altitudes of these aircraft exposed them to a much greater incidence of clear air turbulence than earlier propeller-driven aircraft had encountered.

CAT data collection flights. Our operations in Colorado provided an opportunity to search for CAT in order to obtain accelerative data. The Rocky Mountain region is notorious for producing CAT, especially due to mountain wave phenomena. (Miller, 1999). Also CAT is usually associated with the upper level jet stream. (Ferris, 1999; Bass, Jones, & Castaño, 2000). The ARIES aircraft was flown at high altitude above 30,000 feet on two dedicated weather flights during this deployment and ten joint operation flights in this region in conjunction with another NASA AvSP research project. Additionally, weather and turbulence data from convective cumulus cell build-ups were obtained during the transits to and from Colorado Springs. These convective turbulence data collections were accomplished using the "upwind edge" technique used in CY2000. Additionally, in-situ accelerometer-derived turbulence data was being recorded during those flights. The first dedicated CAT flight during the deployment period was planned to detect reported CAT over southern Colorado and northern New Mexico. Coordination was made with the Denver Air Route Traffic Control Center (ARTCC) meteorologist prior to flight. Also a team of NASA meteorologists was embarked on the ARIES aircraft and was able to obtain real-time reports from ground support personnel on potential areas of CAT. The flight path originated in Colorado Springs and then proceeded over southern Colorado and Albuquerque, New Mexico. Reports were obtained from the Albuquerque Center that alerted us to other areas of turbulence reported by airline crews. Therefore, we turned east and continued over Oklahoma City, then headed north over Nebraska, with subsequent return to Colorado Springs. The most

intense CAT encountered in that flight was found over southern Colorado and was related to mountain wave and thermal activity. Visible lenticular clouds were observed in the area. These are classic indicators of uplift associated with mountain wave conditions. The second dedicated flight was launched in response to predictions of CAT over Wyoming. The flight again originated in Colorado Springs with the first leg proceeding over the Eagle County area of Colorado and then turning toward the northeast with most of the CAT encountered over the region between Casper and Cheyenne, Wyoming. This CAT correlated to forecast jet stream-induced turbulence. Approximately one-and-a-half hours were spent in this area with several east-west runs collecting "in-situ" data. On both of these flight events, the turbulence data encountered during a turbulence event were detected by recording vertical accelerations measured by accelerometers. The data obtained were recorded for use in "in-situ" algorithms in order to provide quantified RMS values for accelerative loadings encountered in aircraft operations (Sharman & Cornman, 1998; *Projects,* 2003). The data collected is to be used in the development of the TPAWS experiment now scheduled for CY2004. CAT encountered during the dedicated Rocky Mountain flights was "Light" to "Moderate" in intensity, with occasional peak values approaching "Severe."

Turbulence forecasting algorithms. Cornman has said that these subjective categories, although of some use in aviation safety, are not adequate to quantify turbulence among the atmospheric science community. (Cornman, in Gallon, 1997). The atmospheric science community has been attempting to obtain turbulence data and correlate it in such a way that PIREPs and other data transmission methods will have

universal relevance to aircrews independent of the aircraft platform and of the crews' subjective judgments. According to Sharman and Cornman (1998),

> Current turbulence forecasts have in general shown poor performance, missing detected turbulence while over-predicting its occurrence. This is due in part to the fact that turbulence in the atmosphere is a result of a variety of ill-understood complex and non-linear processes and also to the fact that the spatial and temporal scales [*that are*] characteristic of atmospheric turbulence are not adequately observed. (p. 1).

Additionally, the National Center for Atmospheric Research (NCAR), in its studies in the late 1990's to better quantify turbulence levels and appropriate reporting, developed a forecasting product known as Integrated Turbulence Forecasting Algorithm (ITFA).

> The integrated turbulence detection and forecasting product provides two capabilities: (1) detecting and reporting turbulence, and (2) forecasting regions of likely turbulence. (Sharman & Cornman, 1998, p. 1).

As stated by Sharman and Cornman (1998), the detection method used by ITFA relied on accelerometer measurements, which included maneuvering accelerations due to turns, climbs, and descents. The reporting of collected data was accomplished through broadcasting of real-time data via standard airline equipment used in the Aircraft Communications and Reporting System (ACARS) data system, which was installed on commercial airliners operating in the United States. The forecasting methodology used by ITFA incorporated a fuzzy logic approach, where several algorithms are integrated to obtain a final forecast. Furthermore, it used focused algorithms dependent on the anticipated regions of turbulence generation.

Expanded collection of AWIN data. In anticipation of the need for improved graphical presentation of weather products, the AWIN portion of the WxAP project attempted to broaden its usefulness to the profession. Since professional pilots are employed in the piloting of all types and sizes of aircraft, it was identified that the AWIN-type of study should, therefore, encompass all types of aircraft. General aviation, including business and small civil aircraft, may be the biggest benefactors of improved weather displays, since they may not be equipped with radar or lightning detection systems. Latorella and Chamberlain (2001) stated that:

> General aviation is particularly affected by convective weather. A survey of GA accidents from1982 to 1993 revealed that while only 3.5% of these accidents are directly attributed to thunderstorms, a large percentage of these accidents, 66%, resulted in fatalities. Convective weather is challenging because it can be characterized by reduced ceiling and visibility defined by instrument meteorological conditions (IMC) as well as including severe to extreme turbulence, gusts, hail, icing, lightning, and possibly severe downdrafts and microbursts. Such concomitant weather phenomena were analyzed separately in this accident analysis. Therefore the incidence of GA accidents attributed to convective activity, and the fatalities resulting from such weather systems is *(sic)* likely under-represented by the percentages cited for thunderstorm effects. (p. 1)

Workload and Relative Position Experiment (WARP). These identified issues, therefore, led to a study known as the Workload and Relative Position Experiment (WARP) study. It was initiated as a subset of the AWIN project. It focused on the use of up-linked data to a General Aviation (GA) aircraft (Cessna 206) with evaluation to be

performed by instrument-rated pilots. The Graphical Weather Information System (GWIS) is the system of information used to display these data to the pilots. It consists of the same types of information that was previously displayed to the 757 pilots in the previous test campaign. These included NEXRAD ground-based weather radar, METAR and other textual weather data, PIREPS, and SIGMETS/AIRMETS. Since there are charter operators operating GA-class aircraft with a single professional pilot in commercial operations under FAR Part 135, this study looked at workload increases for a single-piloted aircraft when the enhanced weather display technology is provided. A flight series was conducted using the NASA Cessna 206 to observe and evaluate general aviation aircraft professional pilot workload issues when presented with graphical weather data in the cockpit. Again the NASA-TLX method of obtaining qualitative pilot information was used. After this post-run questionnaire was completed, a usability questionnaire was also provided to the pilot for assessment. Accordingly, the overall result of the study was the recognition of the insufficiency of data currently available to the aircrew. (Chamberlain, Burt, Jones, & Coyne, 2002; Latorella & Chamberlain, 2001 & 2002).

Convective Weather Sources (CoWS) experiment. In order to study the impact of this AWIN data on larger business aircraft and higher performance GA aircraft operations, and to study alternative presentations of the weather information, the NASA King Air B200 aircraft was also employed in a study of the decision-making tasks of licensed subject pilots who were asked to compare what was received on the GWIS with the visual situation viewed from the front cockpit (see Figure A.7). This experiment was known as the Convective Weather Sources (CoWS) experiment (Croom, 2003d). The

GWIS provided the subject with near real time data-linked weather products, including a weather radar mosaic superimposed on a moving map with a symbol depicting the aircraft's present position and direction of track (Chamberlain & Latorella, 2001)

Pilots were seated within the aircraft either in the cockpit or in the rear cabin using a tethered flat panel display in order to compare the effect of being able to view outside weather on decision-making processes. A series of questions was then presented to the subject pilot for their response. Subjective data were collected from the pilots concerning their preferences for the format of the displayed data. These flights were flown at altitudes in the vicinity of 14,000 feet in order to stand off at a distance from any visible convective cells and to allow strong radar returns to be "painted" by the ship's radar. The up-linked data was not integrated into the aircraft system or radar display during this period, but was evaluated independently on the research display. Since the aircraft was not required to penetrate any convective weather, the research display information was not made available to the NASA safety pilot during the research flights. It was determined that a necessary part of making this detected data valuable to a cockpit crew would require additional studies of the human-machine display interface in the cockpit. An integrated approach was seen as necessary to meet the previously identified needs of the commercial cockpit crew to make proper on-the-fly weather decisions. Latorella and Chamberlain (2001) found that:

> Subjects reported the need for significant additional weather information sources when only supported by the aural cues available to subjects today. (p. 5)

They also found that:

> NASA-TLX results demonstrate that subjects believed their performance is significantly varied according to the cues available, and trends suggest that both external visual cues and those provided by the GWIS improved their perceived performance. (p. 5)

In other words, on the whole, the interviewed subject pilots agreed that the additional visual and textual data presented during the experiment flights improved their ability to make rational decisions concerning in-flight weather.

CY2002 Flight Campaign: Boeing 757 Convective Turbulence Data Collection Flights

Flights flown in CY2002 in support of the WXAP program included flights in the NASA Boeing 757 ARIES research aircraft. In previous flight campaigns, data was individually catalogued and displayed to the researchers at the research pallets in the cabin of the aircraft, but had not been correlated in an integrated fashion for presentation to the pilot crew. However, the focus of the CY2002 campaign was the coordination of data to provide an integrated test program that would bring together the previous findings in a coordinated way.

Most of the Boeing 757 flights during this season were conducted along the South Carolina and Georgia coastlines and, also, in the vicinity of northern Alabama, western Tennessee, Arkansas, and eastern Missouri. The purpose of the flights in the B-757 aircraft was to obtain correlative data related to observed turbulence and from radar predictions from within convective frontal and air mass cumulus cloud build-ups.

WINCOMM connectivity/data transfer tests. Additionally, ground-based weather products, such as NEXRAD radar returns were data-linked to the aircraft for display at the research pallet in the cabin of the aircraft. Due to technical reasons, the full

NEXRAD suite was not displayed in the cockpit. Additionally, direct communication was maintained with ground observers who were able to track the aircraft and its position with respect to frontal weather systems. A data link path (see Figure A.8) was utilized using the WINCOMM equipment (Banks, 2003b). This path was found to be unreliable during this period due to satellite communication equipment malfunctions. Therefore, it was necessary for alternate connections to be made through a slow 2400 baud rate link using the "Skyphone", which is a VHF downlink system originally designed for voice transmission. Only one Skyphone was available and could only be used in one mode at a time—either voice alone or data alone. This caused sizeable delays in the reception of strategic and tactical weather information.

Convective weather penetration. The initial intention for obtaining convective weather data was to find established lines of convective or thunderstorm weather along a well-defined frontal system. Initial storm location was obtained from ground sources, either through the data link or through voice transmission from ground observers at NASA Langley Research Center. Normal implementation of the ship's weather radar was used to select a suitable entry point to attempt weather penetration within the constraints of the approved Flight Safety Release and FTOSR (NASA, 2002). Visual confirmation of size and shape of cloud build-ups was then used to steer the aircraft on a path that was expected to provide turbulence events within the moderate levels sought by the experimenters. Such weather phenomena were initially probed and the turbulence levels encountered during those events were determined to approach levels too severe to safely provide for routine penetration. This especially was evident when the aircraft was struck by lightning near the South Carolina coast, causing damage to the radome of the

aircraft. It became clear that the use of the radar alone, even with ample visualization of the cloud by experienced professional pilots, was inadequate to accurately predict the levels of turbulence or electrical activity in these building clouds. In CY2000, Hamilton and Proctor (2002) had determined that turbulence did not always directly correlate with radar returns in a meaningful way. Their data had not been published at the time of this campaign, however, leading the pilots to trust in their own experience, which obviously was not foolproof. Even such innovations as lightning detection systems are not without error. Since they are based on detection of low-frequency static noise, they are notoriously inaccurate in relation to range, although they have been found to relatively valid in the azimuth.

After the lightning encounter, the radome was replaced. It was decided that prior to the next flight, future convective weather would be sought only in isolated cells, which it was assumed, would be less likely to be fully developed enough to have a significant risk of lightning or severe levels of turbulence. There was concern that this change in data collection methodology would not allow RMS levels of acceleration of >0.2g to be achieved. These levels were required by the test plan to provide proper correlation with the experimental radar color display thresholds. However, when probing these isolated cells, an interesting finding was that vertical velocities of air columns within the building cells were often as high as that found in developed frontal build-ups (*NASA In Situ,* 2003). These isolated cells were found to be potentially as severe in terms of turbulence as fully developed cells previously experienced in frontal or squall lines. Most of the cells probed in the vicinity of fronts were at the southwestern end of frontal development and this allowed the aircraft to go from cell to cell as they spawned and moved toward

the northeast and combined into a more organized frontal system. Flight operations were restricted to predicted turbulence levels of “Moderate” or less. This was accomplished by avoiding areas of predicted severe weather formations, as defined in the FAA Advisory Circular, AC 00-30B (FAA, 1997), and by relying on the experience of the pilots in the use of the color weather radar installed in the nose of the aircraft. Any radar returns of “red” were completely avoided. During this CY2002 campaign, an additional experimental radar display was made available to the aircrew. This had a revised display regime to provide a better view of turbulence within cloud build-ups. This display was limited in range to approximately 5 km, however. The Flight Safety Release by the NASA Aviation Safety Review Board also mandated that only certificated ship’s system radar be used for actual flight path determination. The experimental display was to only be consulted to compare its effectiveness in comparison to the standard wind shear weather radar, and not for navigation or weather avoidance. Therefore, when on a weather research flight, the normal ship’s radar display was active. On April 30, 2002, while flying in the vicinity of Birmingham, Alabama, a large turbulence event (see Figure A.9) was encountered by the B757 at levels that were unexpected within an isolated cell. Figure A.9 shows the radar return levels available at the radar receiver for display from the ship’s radar in the top two frames (which are only 12 seconds apart in time) and the experimental displays in the lower two frames (which were not available to the pilots for weather avoidance purposes) (Croom, 2003b). The lower two frames consist of the prototype EWXR radar system information combined with superimposed in-situ acceleration data. The information available from the radar at levels less than “Green” is not displayed on the pilots’ cockpit display. Therefore, it can be seen that the

information displayed in both of the top views of Figure A.9 would not have alerted the pilots to impending turbulence. Also note the short time in which the intensity of the turbulence associated with the vertically rising air columns developed in severity. This turbulence caused the aircraft to climb approximately 1000 feet in altitude within approximately 5 to 6 seconds, followed by an immediate loss of altitude of about 1200 feet within less than 5 seconds. The aircraft almost immediately then exited the cloud and it was determined at that time to abort the flight and return to base. A peak delta vertical acceleration of approximately 1.6 g was encountered in this upward acceleration. The design certification limit of the Boeing 757 is +2.5g at the maximum gross weight of 230,000 pounds per Federal Air Regulation (FAR) Part 25 certification. The NASA aircraft was operating at approximately 200,000 pounds on these research flights. This large excursion and the acceleration associated with it was uncomfortable to the crew and in a normal airline operation could have easily resulted in bodily injury to anyone not safely strapped in. It resulted in an impulsive acceleration that could have exceeded a certification limit. FAR Part 25 gust load certification requirements are complicated and require an extensive dynamic response analysis. They consist of both discrete and continuous gust load criteria. The discrete load requirement assumes a "1-cosine" gust load shape and the continuous gust requirement assumes a statistical distribution (see 14 C.F.R. 25.341, 1996). Essentially the aircraft was designed to be able to withstand, as a minimum, about a 100 ft/s maximum vertical velocity or about 6000 ft/min at 33,000 feet (see 14 C.F.R 25, Appendix G). The event encountered exceeded this considerably (in excess of 10,000 ft/min for a short duration).

Re-evaluation of future weather penetration methods. Although the 757 ARIES aircraft sustained no structural damage, this finding led to a re-evaluation of the risks to which this type of weather could subject the Boeing 757 in the future. With the flight crew basing decisions for weather entry on the types of radar displays, as seen in the top panels of Figure A.9, which appeared to be relatively benign, it was decided to rethink the way the Boeing 757 aircraft would be employed in subsequent weather research scenarios. Based on concerns about the potential impact to the structure of the aircraft, such as addressed by Fuller (1997), it was decided that future flights in the Boeing 757 would not intentionally penetrate weather of that severity. Visual avoidance would be employed, rather than using the ship's radar for such avoidance, until it was shown that more effective display technology could be presented to the pilots and that it would be authorized for use in weather penetration and avoidance. However, our experiment showed that if the experimental radar displays, as seen in the lower views of Figure A.9, had been presented to the pilots this moderate-to-severe encounter could have been avoided. Reveley (2002) showed that if the WxAP equipment had been available to the pilots, the probability of avoidance was 0.875 with 2 minutes of warning and a probability of avoidance of 1.0 with 3 minutes of warning. In fact it is ironic that the pilots could have used this information if they had been allowed to select this display in the cockpit. However, since it had not been authorized to be used by the pilot crew for actual weather avoidance, they did not select that display until the aircraft was already in the cloud and encountering the turbulence event. As Croom, (2003b) states:

> The research radar was operated on 20 flights in 2000 through 2002, and a total of 43 radar data files of moderate or greater turbulence encounters were collected.

> Data analysis (using human judgment) indicates excellent performance with probability of detection of severe turbulence (equal to or greater than 0.2 RMS g) with a lead-time greater than 30 seconds at 81%, and a nuisance alarm rate at 11%. Reflectivity in several cases was at or slightly lower than 15dBz. Improved algorithms for estimation of turbulence were developed and shown to work in real-time in an experimental prototype radar, based on current-generation commercial radar technology. This approach is intended to enable retrofit of current wind shear capable X-band radar systems for transport aircraft to provide substantial improvements in turbulence detection, and to add hazard estimation relevant to the particular class of airframe. Radar reflectivity and hazard maps from NCAR post-processing (with in-situ overlay) of data collected on B-757 ARIES, demonstrates X-band radar detection of hazardous levels of turbulence at ranges greater than 5 km ahead of aircraft and (*with*) no significant reflectivity indicated on standard weather radar. (Croom, 2003b)

It should be noted that even with this display available and the speed of the Boeing 757 of about 10 km/min, the pilots have only about a maximum of 30 seconds from the first detection of the severe radar return to turn away. With the relatively slow turning response of large airliner aircraft such as the Boeing 757, this warning is really not adequate for all situations. This is especially clear when comparing the returns on the left of Figure A.9 with those on the right. There is only a 12 second difference between these two views. It also clearly indicates the rapid increase in air column velocity in such clouds.

CY2003 Campaign

The CY 2002 in-situ accelerometry data, along with the experimental radar information that had been available at the research pallet (see Figure A.9), was demonstrated to be valid and, if it had been presented to the pilots could have provided some level of early warning of the potentially dangerous turbulence event. The CY2003 campaign thus was designed to bring all these technologies together in a display format, when coordinated with the AWIN and WINCOMM systems, would meet the previously identified desires for weather avoidance information needed by the professional aircrew (Stough, 2002). The campaign for CY2003 with the Boeing 757 had been planned to focus on the Turbulence Prediction And Warning System (TPAWS) and AWIN (Rickard, 2003; Green, Tsoucalas, & Tanger, 2003). It had been scheduled to be conducted from Billings, Montana. Billings was chosen due to its proximity to jet stream-induced CAT in late summer and the relatively low traffic density in that part of the country. Due to several scheduling issues and unscheduled maintenance requirements that occurred on the Boeing 757 aircraft, the planned CY2003 campaign was postponed and is now planned to be flown in the late summer or fall of CY2004.

Because of the difficult scheduling issues previously mentioned, the only weather–related flights accomplished in 2003 by NASA Langley were aboard the NASA King Air B200 aircraft. These flights were in support of a small portion of the WxAP project related to business and general aviation aircraft display concerns. This project was known as the Correlation of Radar Reflectivity and Lightning (CORRAL) study. The NASA King Air B200 was used to gather some lightning detection and correlation

information in the vicinity of Kennedy Space Center, which will be used in future, integrated WxAP display technologies.

Planned Follow-On CY2004 Campaign

Turbulence Prediction and Warning System (TPAWS) experiment. The CY2004 program of research for WxAP is primarily focused on TPAWS with some integration with AWIN displays (Horne, 2003; Nadell, 2003). The TPAWS portion of the project will build on the previous work accomplished in the previous campaigns collecting in-situ data. This data incorporated the recording of accelerative g-loading on the aircraft in both convective and clear air environments (Green et al, 2003). The purpose of this experiment will be to use this in-situ information to provide predictive transmissions by data link of turbulence encountered along a route by a preceding aircraft (Feinberg & Tauss, 1999; *Projects*, 2003). It was also recognized that CAT was a much more difficult problem than convective weather turbulence.

> Although more rare than convectively induced turbulence caused by thunderstorms or other cumuliform clouds, CAT is also more difficult to predict and avoid. Progress in clear-air turbulence prediction has been slow to date. The introduction of in-situ quantitative measurements of turbulence intensities together with precise positional information will replace the qualitative and unreliable PIREPs. This should dramatically improve now-casting capabilities. But it also should lead to improvements in turbulence forecasts, as well. (Sharman & Cornman, 1998, p. 4).

Coordinated flight test. To accomplish this task, the NASA Boeing 757 ARIES aircraft is still planned to be flown in coordination with the NASA Glenn Research

Center Learjet in the skies over Montana. Montana was chosen as the deployment location to take advantage of the low level of air traffic through this region and the ability to climb to altitude essentially unrestricted. The Learjet, due to its limited fuel capacity and fuel burn rates, needed to be able to quickly climb from the departure airport and reach the test area with minimal transit time. It is limited to approximately a two-hour flight window per sortie, whereas the B-757 can remain airborne in excess of 7 hours, if necessary. The two aircraft will be flown in regions of jet stream activity in the 30,000 to 40,000 foot regime. Detected turbulence information obtained from each aircraft will be filtered and transmitted to the other participating aircraft through a data link and communicated as a potential turbulence threat area. This will allow the trailing aircraft to avoid transiting through the area of heavy turbulence (see Figure A.10). Since turbulence along a route can be changeable and time-dependent (Miller, 1999), the aircraft will be spaced at different intervals from 10 nautical miles to possibly as much as 200 nautical miles. The initial plan is for the Boeing 757 to launch from Billings to a pre-determined rendezvous location based on predicted CAT opportunities obtained from the National Weather Service, the FAA, and the commercial airlines. Once the 757 has reached the rendezvous point, the Learjet will depart Billings and will enter a pre-briefed holding pattern within block altitudes reserved by Salt Lake City ARTCC. Coordination with Air Traffic Control authorities will ensure safe separation and avoid any collision hazard with other aircraft. The FAA Center at Salt Lake will provide positive separation. Each aircraft will act as the lead and trailing aircraft, alternately.

WINCOMM evaluation. The Learjet will be data-linking with the Boeing through ground stations using satellite and VHF ground links. This test is not only a chance to

obtain and display turbulence data between aircraft in an automatic pilot reporting system (Auto-PIREP) (Robinson, 2003), but it will provide an opportunity to evaluate and investigate the viability of various communication connectivity resources (see Figure A.10).

Integration of display technologies. Additionally, this campaign will integrate the display of AWIN data with other sensors (Horne, 2003; Green et al., 2003). The turbulence information will be displayed to the B-757 crew in a format that will include the type, altitude, and path of the preceding aircraft. This display will be color-coded to alert the trailing aircraft to any areas of severe turbulence encountered by the lead aircraft (*Projects,* 2003). The turbulence information for this experiment is not planned to be displayed in the Learjet cockpit, however it will be available to the researcher aboard the Learjet. This is related to the avionics processing and display limitations of the Learjet. If additional funding becomes available, such displays could be provided to the Learjet.

It is anticipated that FAA and industry participation in these experiments will lead to a certificated system such as had been proposed by AeroTech Research and others (*Products-Simulation Examples,* 2003; *Products-TAPS,* 2003; *Products-TPAWS,* 2003).

Conclusion

Detection Inadequacies

The WxAP investigations, including the flight evolutions, clearly revealed inadequacies in current aircraft weather information availability. Although very significant advancements have been and continue to be made in cockpit displays, much work is still necessary to meet the needs of the professional pilot with regard to weather situational awareness. Wind shear detection radar, lightning detection, and weather display and text uplinks all help to improve the weather awareness of the aircrew. During these studies, the weather needs of professional flight crews in various classes of aircraft were reviewed. It was determined early in the program that current display technology and availability are inadequate for weather avoidance decision-making, even in the best-equipped aircraft. The AWIN studies conducted in all three aircraft revealed a common theme. The pilots, as a whole, said that they would prefer to have:

- Well-designed man-machine interfaces to reduce workload
- Intuitive operation of controls
- Accurate correlation and compliance of displayed information with the outside world
- Timely sharing of information with other aircraft and users.

In order to seek out the best human factors solutions to reach those desires, the WxAP team will continue to conduct cognitive task analyses in order to evaluate the efficacy of weather products and display systems provided.

Radar Improvements

There has been significant progress in recent years in improving radar products by adding wind shear detection to cockpit radars through the use of Doppler effects detection. An example of a production system that has gained from the NASA turbulence and wind shear studies is the recently released Rockwell Collins WXR-2100 Multiscan radar (Rockwell-Collins, 2000a; 2000b). It is a production radar whose technology was partially tested and enhanced as a result of the CY2000 campaign. It is a sophisticated turbulence detection and wind shear detection radar operating in the X-band. Wind shear returns, with their potential for turbulence, are displayed as a magenta color. It also goes into a wind shear mode when approaching the ground below 2,300 feet, such as on an approach for landing. New enhancements to such radars will likely include the types of displays, as shown in Figure A.9, which include the overlay of in-situ data and improved display algorithms, in addition to the display of NEXRAD ground radar. This significantly increases weather situational awareness and it is anticipated that such information will be displayed in the next generation of airborne weather radar systems.

Need for Accurate Turbulence Level Determination

Post-flight simulation, using the data obtained from the December, 2000 flights, allowed Proctor, Hamilton, and Bowles (2002) to more thoroughly analyze the accelerations encountered using NASA supercomputers. They found that the RMS accelerations encountered during the most severe event were at a level of .44g, which is considered to border just below the level of "Extreme." This correlated to a peak delta value of -1.4 g. Although the simulation provided an evaluation of "Severe," the actual

experienced reactions in the cockpit coincided with the description of "Moderate," as set forth in the FAA guidance seen in Table A.1. Here we had a situation where standard pilot subjective determination of turbulence levels grossly underestimated the potential for structural damage to the aircraft. The Boeing 757 is certificated under FAR Part 25 for 2.5 g loading, while in this previous instance the peak g imposed on the airframe was 2.4 g, a level that would seem to correlate with a value much larger than "Moderate." This post analysis was not completed prior to our CY2002 campaign. Therefore, no effort was made to re-evaluate the hazard analyses used in CY2002. As a result, initial penetrations into weather yielded lightning strikes and severe turbulence loads were applied to the B-757 airframe. In the CY2002 flight campaign, we discovered that we had encountered a peak g of 2.6, which is in excess of the certificated allowable g-loading for the B-757 at maximum gross weight. Our aircraft was not at full gross weight, however. As with most airliners the B-757 does not have a g-meter installed in the cockpit. Additionally, due to the size of the aircraft, g-meter readings in the cockpit would not necessarily display the peak accelerations that the airframe would sustain in a localized area of the structure. This made it obvious that something much better than seat-of-the-pants subjective evaluation of turbulence is needed. It became clear to the professional research pilots that there is a need to be provided with a future turbulence detection system. This system would objectively quantify turbulence categories electronically for both convective and clear air turbulence.

Test Restriction Criteria Limited Pilot Evaluation of Systems

One of the situations that adversely affected the full evaluation of the radar detection and display technologies were the significant test restrictions placed on the

cockpit crew. Authorization for the research aircrews to actually view the displays in the cockpits during flight as a weather avoidance tool has not been granted. Additionally there has been a tendency to keep research displays segregated from the cockpit because the researchers did not see that the pilots' viewing of the displays directly assisted in their data collection. I believe this limits the value of the test, since pilot feedback as to its usefulness is not being considered during the research events. There has been resistance to allowing this use because it has been the policy at NASA Langley that only certificated avionics equipment could be used for navigation and weather avoidance by the research aircrews. The difficulty for the NASA research flight crew is that even though pilot inputs are now being heard and considered in the early developmental stages of a weather program, there are still other test restrictions established which could hinder full system evaluation. The research review process at NASA Langley Research Center has yet to take the recommended inputs from the NASA project pilots, as well as, industry pilot inputs that some research equipment, such as the experimental turbulence display, should be available for use during data collection flights. As was seen in the CY2002 campaign, this contributed to the crew entering severe vertical velocity spectra unwittingly, even though the display was available on the aircraft, which could have given warning of the impending danger. These issues are cultural in nature with a safety-of-flight aspect, as well. Additionally study is needed at the management level to evaluate the differences in risk that may be encountered by allowing the use of the experimental display, compared to the degree of risk of requiring certificated displays alone. Also, even though NASA research pilots are engineers, as well as, pilots, they have not normally been invited to

participate in the post-processing and data reduction phases of the research. Therefore, their inputs into future experiment design are not consistently obtained or utilized.

Turbulence Detection and Reporting Is Imperative

Effective clear air turbulence technologies have yet to be perfected, along with an adequate early detection of vertically accelerating air columns associated with severe convective turbulence. Until predictions of potentially severe events can be detected and communicated effectively, weather-related accidents and injuries will continue to occur. This is an area of research in which NASA continues to make strides with the assistance of its industry partners and contractors. Not only are improved display technology and color-coding regimes necessary, but also timeliness of the information was demonstrated to be of utmost importance. We saw this in the very short detection distances available in the improved experimental radar algorithms and this will become especially important in the refinement of turbulence detection and prediction technologies. The in-situ accelerometry data that was collected over the three flight seasons will become the foundation of the TPAWS turbulence prediction system and Auto-PIREP system, as illustrated in Figure A.10. Data link and display of potentially hazardous turbulence on a map view will alert crews of impending danger with adequate time to successfully deviate.

Industry and Government Partnership

In order to meet the NASA Aviation Safety Program milestones with respect to weather detection and display, it will be important for government and industry to continue their partnership in development of technologies, which will allow timely and adequate warning to flight crews of impending danger. Systems, such as AWIN, with its

ability to display real-time "big picture" weather information will help to meet those minimum needs requested by the professional pilot. These data will be made available through the use of faster more reliable weather information communication uplinks as will be demonstrated by the WINCOMM system. Also systems, such as TPAWS, have the potential, through turbulence prediction, detection, and relay of such information to other aircraft in the area, to significantly reduce the risks to aircraft and crews from severe turbulence events.

Professional Aircrew Involvement Is Necessary for Effective Cockpit Technology

Acceptance of the need and desire for professional experience to be included in system development processes has allowed for improved displays, development of Auto-PIREP technologies, better understanding and implementation of radar displays, and improved weather product downlinks. This early involvement by the pilots is paying off in the research results and eventually will yield significant gains for the professional flight crews in the field. It will become more crucial in the future to include the professional flight crews in all phases of aircraft development projects to ensure that useful and effectiveness information is displayed to future aircrews.

The Weather Reporting System Professional Pilots Need

The ultimate goal of the weather reporting system and associated displays for the professional pilot is to be able to effectively avoid the dangers to passengers, crew, and aircraft associated with turbulence and other forms of severe weather hazards. I would propose development of an integrated data system, which would incorporate the features of a system, such as illustrated in Figure A.10, in which professional flight crews in all classes and types of aircraft will be able to obtain a complete picture of the weather issues

they are facing in flight. Instead of having to rely on subjective determination of turbulence effects, a quantified output would be available to cockpit crews. The data from ground-based detection sources, such as NEXRAD radar, wind and precipitation reports, correlated with the detected turbulence data from airborne accelerometry, Light Detection and Ranging (LIDAR) (which is a sensor capable of detecting some types of CAT), and modern wind shear Doppler-based airborne radars would provide the inputs to the system. Additionally, the potential exists for the detected turbulence algorithms to be used to provide active controls/mitigation schemes that could provide for automated reduction of structural loads to the aircraft. The onboard accelerometers, if outfitted throughout the aircraft fleet, could provide real-time turbulence detection information to aircraft operating in similar areas and altitudes through active data links. These turbulence detections would be properly scaled to take into account the sizes of the aircraft encountering the turbulence. This would provide for accuracy in the Auto-PIREP display so that, for example, a detection of "Light" turbulence by an airline transport category aircraft, such as the Boeing 757, would be displayed as "Moderate" on the display of a turboprop business aircraft, such as a King Air B200. The detections would be displayed with a tag attached to the aircraft denoting the type, altitude, and relative position of the transmitting aircraft, similar to existing displays in Traffic Collision Avoidance Systems (TCAS) used today. Displays must be designed so as to minimize workload effects on the pilots and also be designed to provide for ease of interpretation of the displays.

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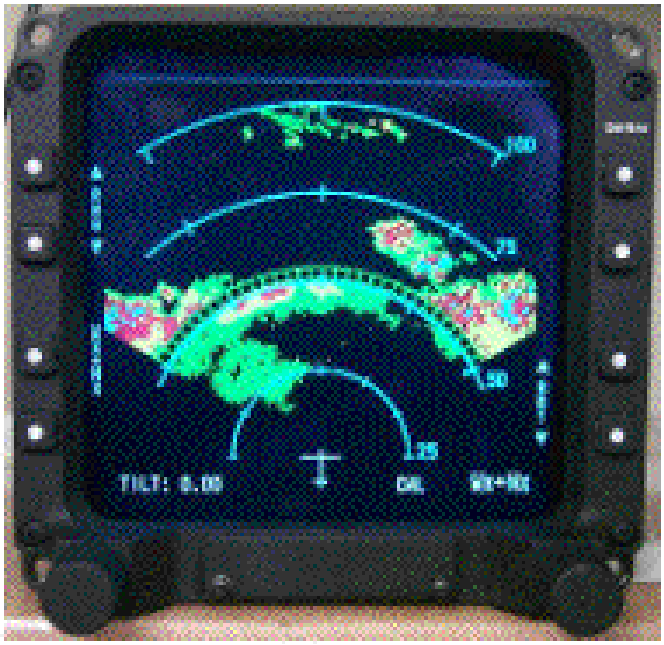
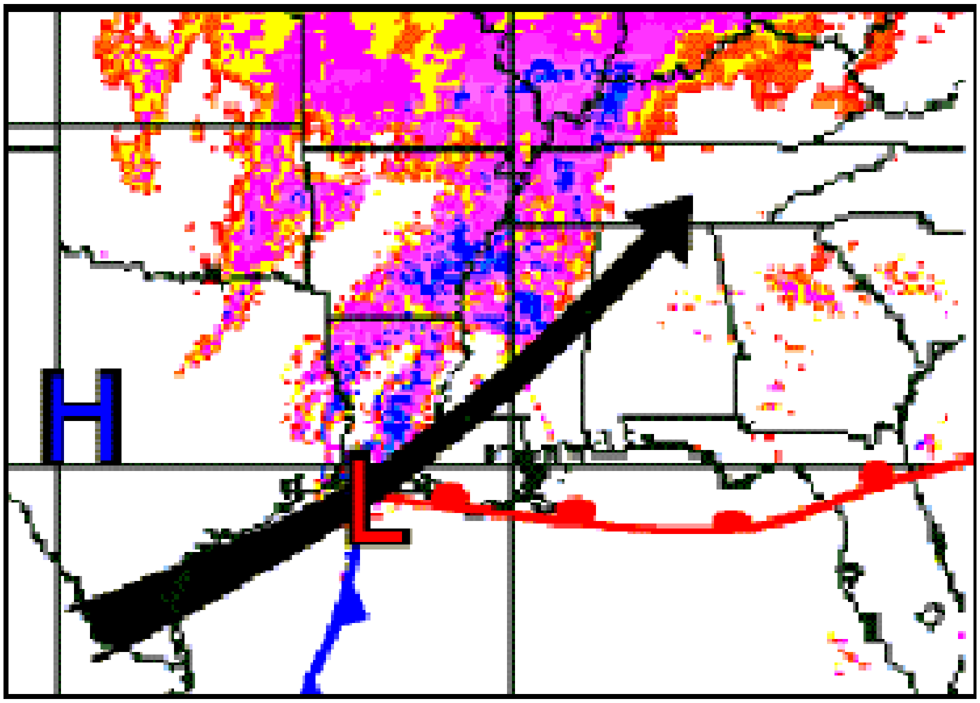
APPENDIX A:

Figures and Table



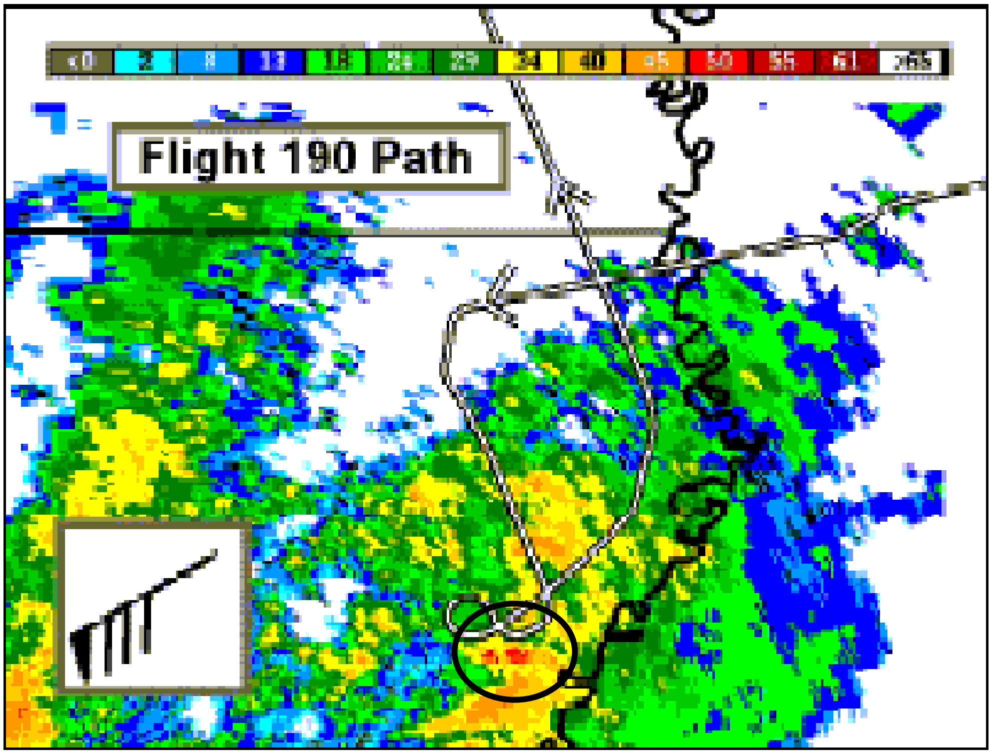
(NASA Photo)

Figure A.1. A typical view of the EWXR on-board radar display. Note the dotted line "fence" at 50 miles. NEXRAD uplink is available for view beyond 50 miles when ranges are selected above 50 mile setting.



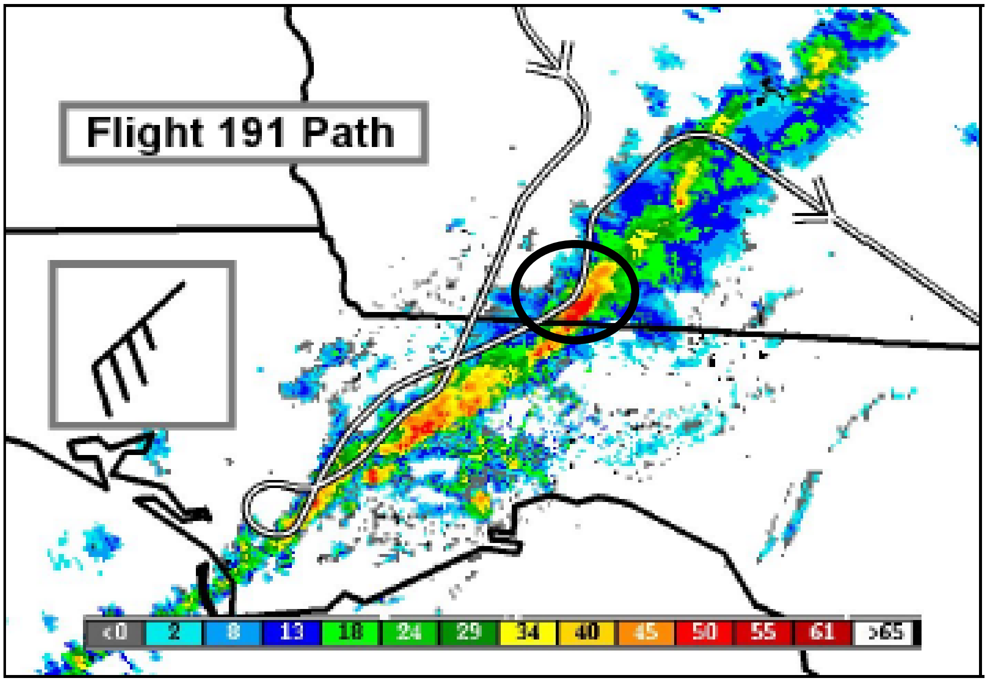
(Hamilton & Proctor, 2002a)

Figure A.2. Weather depiction for December 13, 2000 flight. Depiction shows surface fronts, National Weather Service radar composite (shading), and jet stream position (bold arrow).



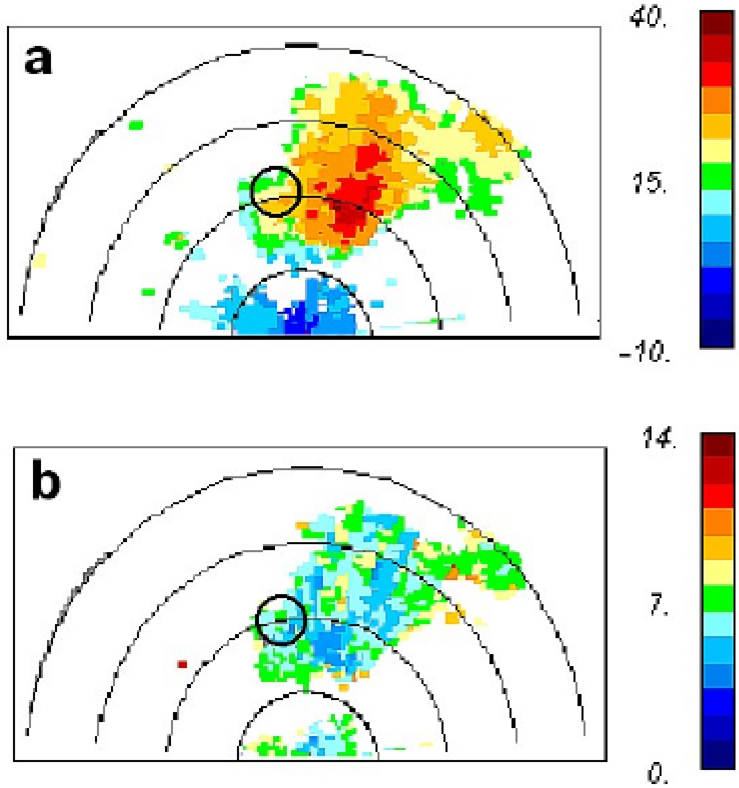
(Hamilton & Proctor, 2002a)

Figure A.3. Radar returns from December 13, 2000 NASA Boeing 757 flight. Obtained from Ft. Polk, LA Ground Weather Radar Station. Wind was from the southwest at 85 knots at the aircraft's altitude. Area of dangerous turbulence is circled.



(Hamilton & Proctor, 2002a)

Figure A.4. Path of Flight 191. Ground based composite radar reflectivity (dBz) from the Tallahassee, FL ground radar at 18:44:21 UTC, 14 December 2000. Flight level wind vector (35 knots) is in the inset. Note that the aircraft is avoiding the heaviest radar returns. The circled area is the location of Event 191.3.



(Hamilton & Proctor, 2002a)

Figure A.5. Radar images from the B-757 onboard radar on December 14, 2000. Images are for:

(a) radar reflectivity (dBz), and

(b) spectrum width (ms^{-1}).

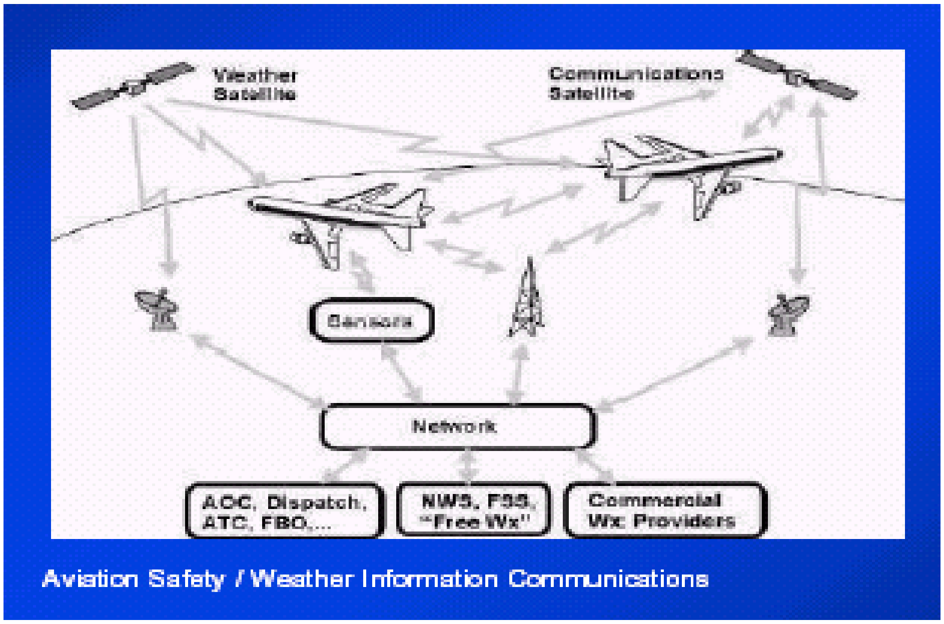
Black circle in both images denote the location of Event 191.3. Concentric circles are at 2 km intervals. Note the low dBz level of radar reflectivity and moderate Doppler levels in the area of the significant turbulence event.

(NASA Photo)

Figure A.6. The subject pilot uses the AWIN display to make decisions about weather deviation.

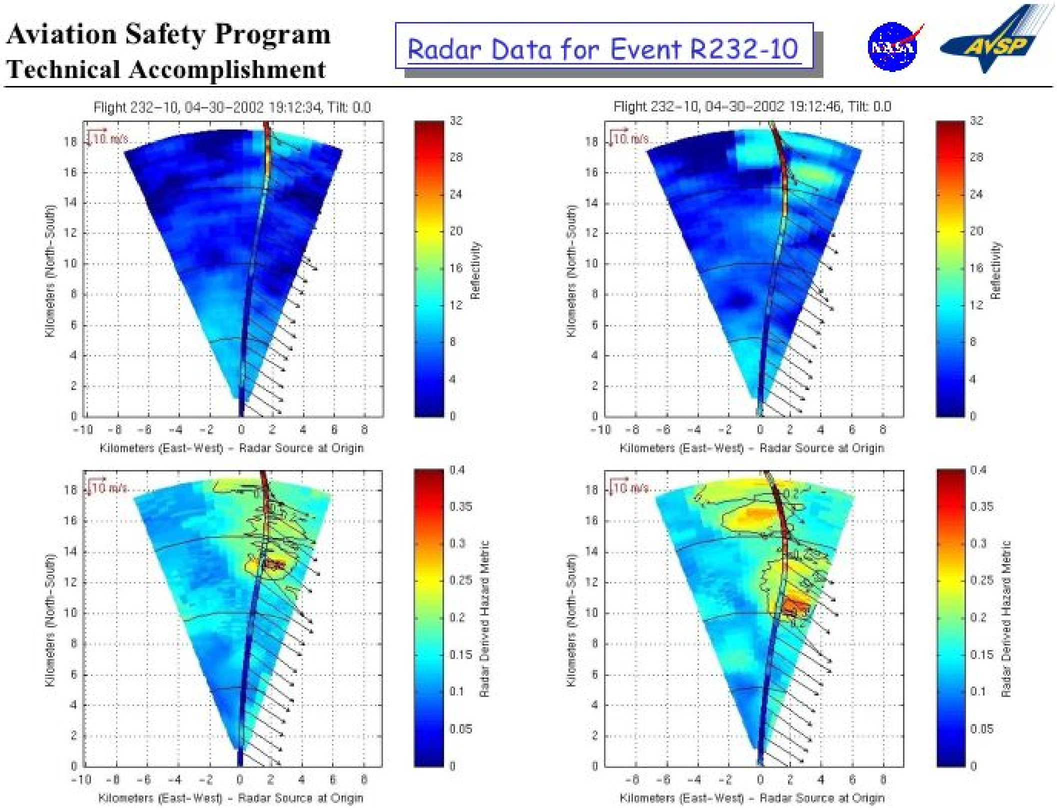
(NASA Photo)

Figure A.7. AWIN display technology has been tested and evaluated in both commercial and general aviation aircraft. This is an example of a tethered display being evaluated in the NASA King Air B200 aircraft.



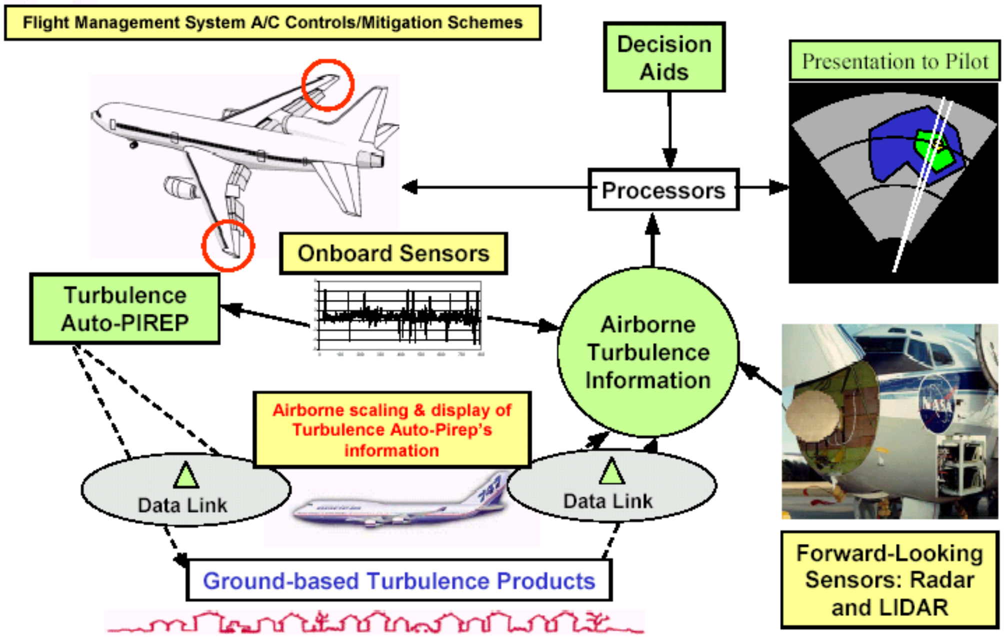
(Kerczewski, 2001)

Figure A.8. WINCOMM communications connectivity.



(Hamilton & Proctor, 2002a)

Figure A.9. The top two views display the reflectivity of building cells as displayed on a normal airborne weather radar. (Levels of return less than "Green" are not displayed to the flight crew). The bottom two views illustrate a calculated hazard level using an experimental radar detection and display algorithm. These displays were not available to the pilot crew. (Only 12 seconds separate the views on the left from those on the right.) (Croom, 2003b)



(Watson, 2002)

Figure A.10. Integrated turbulence sensors provide a display for weather avoidance. Red circles on aircraft denote potential for automated active structural load reduction from detected turbulence sensing. Severity of turbulence would be scaled to the types of aircraft detecting and receiving the data.

Table A.1. (Federal Aviation Administration, 2003)

Turbulence Reporting Criteria Table			
Intensity	**Aircraft Reaction**	**Reaction Inside Aircraft**	**Reporting Term-Definition**
Light	Turbulence that momentarily causes slight, erratic changes in altitude and/or attitude (pitch, roll, yaw). Report as **Light Turbulence;** [1] Or Turbulence that causes slight, rapid and somewhat rhythmic bumpiness without appreciable changes in altitude or attitude. Report as **Light Chop.**	Occupants may feel a slight strain against seat belts or shoulder straps. Unsecured objects may be displaced slightly. Food service may be conducted and little or no difficulty is encountered in walking.	Occasional-Less than $^1/_3$ of the time. Intermittent-$^1/_3$ to $^2/_3$. Continuous-More than $^2/_3$.
Moderate	Turbulence that is similar to Light Turbulence but of greater intensity. Changes in altitude and/or attitude occur but the aircraft remains in positive control at all times. It usually causes variations in indicated airspeed. Report as **Moderate Turbulence;** [1] or Turbulence that is similar to Light Chop but of greater intensity. It causes rapid bumps or jolts without appreciable changes in aircraft altitude or attitude. Report as **Moderate Chop.**[1]	Occupants feel definite strains against seat belts or shoulder straps. Unsecured objects are dislodged. Food service and walking are difficult.	**NOTE** 1. Pilots should report location(s), time (UTC), intensity, whether in or near clouds, altitude, type of aircraft and, when applicable, duration of turbulence. 2. Duration may be based on time between two locations or over a single location. All locations should be readily identifiable.

Table A.1. Continued. (Federal Aviation Administration, 2003)

Turbulence Reporting Criteria Table			
Intensity	**Aircraft Reaction**	**Reaction Inside Aircraft**	**Reporting Term-Definition**
Severe	Turbulence that causes large, abrupt changes in altitude and/or attitude. It usually causes large variations in indicated airspeed. Aircraft may be momentarily out of control. Report **as Severe Turbulence.** [1]	Occupants are forced violently against seat belts or shoulder straps. Unsecured objects are tossed about. Food Service and walking are impossible.	**EXAMPLES:** a. Over Omaha. 1232Z, Moderate Turbulence, in cloud, Flight Level 310, B707.
Extreme	Turbulence in which the aircraft is violently tossed about and is practically impossible to control. It may cause structural damage. Report as **Extreme Turbulence.** [1]		b. From 50 miles south of Albuquerque to 30 miles north of Phoenix, 1210Z to 1250Z, occasional Moderate Chop, Flight Level 330, DC8.

[1] High level turbulence (normally above 15,000 feet ASL) not associated with cumuliform cloudiness, including thunderstorms, should be reported as CAT (clear air turbulence) preceded by the appropriate intensity, or light or moderate chop.

VITA

Leslie Owen Kagey was born in Everett, Washington on September 10, 1949. He was raised in a Navy family and therefore attended schools throughout the United States. He attended high school in Pacific Grove, California and Waipahu, Hawaii, graduating from Waipahu High School in 1967. He served 21 years in the Navy during which time he graduated from the University of Louisville in 1975. He attended postgraduate courses at California State University-Fullerton, Florida Institute of Technology, and Oakland University prior to commencing studies at the University of Tennessee Space Institute. He received a Diploma in Aviation Safety from the U. S. Naval Postgraduate School in 2001. He is a licensed Professional Engineer in the State of Michigan.

Mr. Kagey has been involved in aviation and aeronautical research since 1975. He was a Naval Aviator and holds an Airline Transport Pilot certificate. He is currently serving as a NASA Research Pilot and Aviation Safety Officer at NASA Langley Research Center in Hampton, Virginia.