In-Service Evaluation of the Turbulence Auto-PIREP System and Enhanced Turbulence Radar Technologies

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Nomenclature

Acronym	Description
A/C	Aircraft
ACARS	Aircraft Communications Addressing and Reporting System
ACMS	Aircraft Condition Monitoring System
ADS-B	Automatic Dependent Surveillance – Broadcast
AIM	Aeronautical Information Manual
AIRMET	Airmen's Meteorological Information
AOA	ACARS Over Aviation VHF Link Control
AOC	Airline Operations Control
ARINC	Aeronautical Radio Incorporated
ATC	Air Traffic Control
ATCSCC	Air Traffic Control Systems Command Center
ATR	AeroTech Research (U.S.A.), Inc.
AvSSP	Aviation Safety and Security Program
CAT	Clear Air Turbulence
CCFP	Collaborative Convective Forecast Product
CONOPS	Concept of Operations
DAL	Delta Air Lines
DFDR	Digital Flight Data Recorder
EFB	Electronic Flight Bag
E-Turb	Enhanced Turbulence
FAA	Federal Aviation Administration
FDR	Final Design Review
FL	Flight Level
FOQA	Flight Operations and Quality Assurance
GCS	Ground Clutter Suppression
HF	High Frequency
ICAO	International Civil Aviation Organization
IRU	Inertial Reference Unit
ISE	In-Service Evaluation
LIDAR	Light Detection And Ranging
METAR	aviation routine weather report

MOPS	Minimum Operational Performance Standards
NASA	National Aeronautics and Space Administration
NEXRAD	Next-Generation Radar
NOAA	National Oceanic and Atmospheric Administration
NTSB	National Transportation Safety Board
ORR	Operational Readiness Review
PDF	Probability Distribution Function
PDR	Preliminary Design Review
PIREP	Pilot Report
R/C	Rockwell Collins
R/T	Receiver / Transceiver
RMS	Root Mean Square
SATCOM	Satellite Communications
SIGMET	Significant Meteorological Information
SNR	Signal to Noise Ratio
STC	Supplemental Type Certificate
TAPS	Turbulence Auto-PIREP System
TMU	Traffic Management Unit
TPAWS	Turbulence Prediction and Warning System
TSO	Technical Standard Order
UAL	United Airlines
VHF	Very High Frequency
WebASD^{SM}	Web Aircraft Situation Display
WX+T	Weather plus Turbulence
WxAP	Weather Accident Prevention

Symbol	**Description**
E(y|x)	Expected value of y given x
HA	Alternative Hypothesis
HO	Null Hypothesis
I_{VV}	Inertial Vertical Speed
p	Probability
r^2	Correlation Coefficient
V_T	True Airspeed

w_g	Vertical Wind Component
x	Peak Radar $\sigma_{\Delta n}$
y	Aircraft Measured peak $\sigma_{\Delta n}$
$\hat{y}$	Estimate of y
α_B	Body Angle of Attack
β	Slope of the Regression Model
$\hat{\beta}$	Estimate of β
Δn	Vertical Acceleration
ε	Error of the Residuals
μ_e	Mean Error
ϕ	Roll Angle
σ_e	Standard Deviation of Error
$\sigma_{\Delta n}$	Running Windowed Root Mean Square of Vertical Acceleration
θ	Pitch Angle

1. Introduction

Since 1998, AeroTech Research has contracted with the National Aeronautics and Space Administration (NASA) to research and develop turbulence detection and avoidance systems. The contracts were in support of NASA's Aviation Safety and Security Program's (AvSSP) overall goal to "develop and demonstrate technologies that contribute to a reduction in aviation accident and fatality rates." From 1998 to 2003, AeroTech (and other NASA partners) developed the concepts and initial algorithms of various safety-related technologies under the NASA Turbulence Prediction and Warning System (TPAWS) element of the Weather Accident Prevention (WxAP) Program within AvSSP. The WxAP Program's three objectives to support the goal of the AvSSP were:

1. Develop technologies and methods that will provide pilots with sufficiently accurate, timely, and intuitive information during the en-route phase of flight, which, if implemented, will enable a 25-50% reduction in aircraft accidents attributable to lack of weather situational awareness.

2. Develop communications technologies that will provide a 3- to 5-fold increase in datalink system capacity, throughput, and connectivity for disseminating strategic weather information between the flight deck and the ground, which, if implemented along with other supporting technologies, will enable a 25-50% reduction in aircraft accidents attributable to lack of weather situational awareness.

3. Develop turbulence prediction technologies, hazard metric methods, and mitigation procedures to enable a 25-50% reduction in turbulence-related injuries.

The Turbulence Auto-PIREP System (TAPS) and the Enhanced Turbulence (E-Turb) Radar came to the forefront as technologies that were realizable and significant contributors to meeting the TPAWS goal to "provide airborne centric technologies for detecting and reporting of hazardous turbulence" that when developed would "enable about a 50% reduction in injuries attributable to the lack of turbulence situational awareness." These two systems were further developed and evaluated both in simulations and flight experiments onboard NASA's B757-200 ARIES Research Aircraft.

Engineering issues with the NASA B757 aircraft in late 2003 caused the cancellation of the NASA flight experiments for the TAPS and E-Turb Radar technologies. Realizing the importance of the research and needing a way to properly evaluate the technologies, NASA and AeroTech sought collaboration within the aviation industry.

In August of 2003, a two-month feasibility study was initiated to develop the content and structure of potential In-Service Evaluations (ISE) of the TAPS and E-Turb Radar technologies. The results of that study established separate, two-year ISEs of the technologies with the participation of Delta Air Lines (DAL), Rockwell Collins, and Aeronautical Radio Incorporated (ARINC), as outlined in Figure 1. This report provides an overview and summary of the efforts, analyses, and results of the ISEs of these technologies.

The objectives of the TAPS and E-Turb Radar ISEs were:

1) Develop, implement into commercial aircraft and ground station systems, and evaluate algorithms that would automatically produce reports of aircraft encounters with turbulence and show the reports on ground station displays, and

2) Implement and integrate E-Turb Radar algorithms into a weather radar onboard a commercial aircraft and evaluate the effectiveness of the enhanced radar.
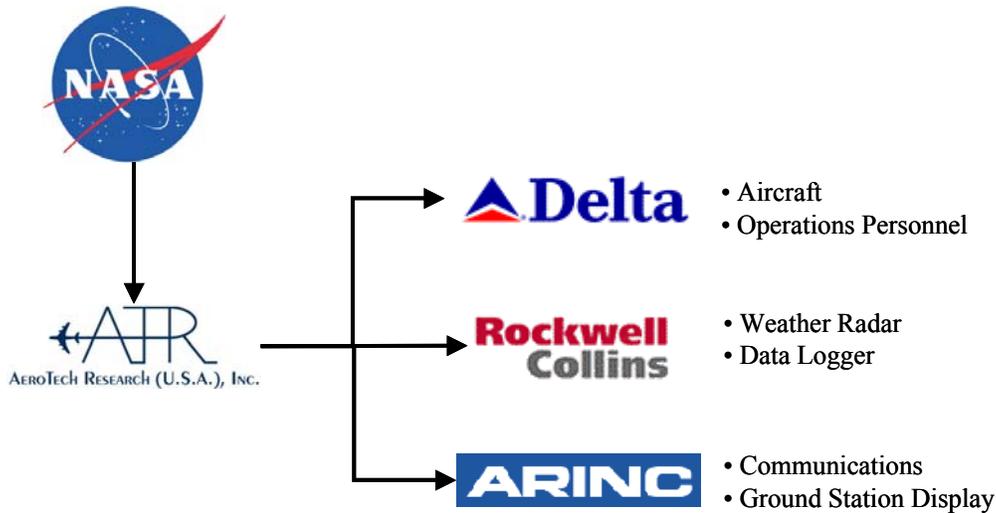
Figure 1: In-Service Evaluation Collaboration

2. Turbulence Hazard Metric

Early in the TPAWS Program, there was an effort to identify a metric to quantify the turbulence hazard to a commercial transport aircraft. The primary requirements were that:

1. It should unambiguously represent the intensity of the turbulence hazard based on accelerations, which result in injuries and damage to an aircraft.

2. It should not depend on the atmospheric phenomenon that produce the effect on the aircraft

3. It could be related to measurements or observables made by various forward-looking airborne sensors (e.g., radar, lidar, etc.).

4. It would be measured by sensors onboard an aircraft; thereby, providing a "truth" measurement to assess the performance of the sensors.

5. It could be readily scaled from one aircraft to another based on accepted physics.

The metric that was decided upon was a running 5-second windowed root mean square (RMS) of the vertical acceleration, denoted by $\sigma_{\Delta n}$. The metric was refined in simulations and several sets of flight experiments on NASA's B757-200 research aircraft under TPAWS. There is plausible justification for this choice of metric given the longitudinal response characteristics and operating speeds of transport category aircraft. The selection of five seconds was based on two key considerations:

- The need to balance between 1) a sample window small enough to adequately resolve small scale turbulence that affect aircraft through induced g-loads and 2) an accelerometer measurement sample size large enough to calculate an RMS with acceptably low random error; and

- Five seconds corresponds to the one-kilometer spatial average used by the E-Turb Radar turbulence processing, based on typical cruise airspeeds. Therefore, there was consistency between the forward-looking airborne sensor and the in situ accelerometer measurements.

By using the same hazard metric, TAPS and the E-Turb Radar outputs can be directly compared on a one-to-one basis as will be seen in Section 5. The $\sigma_{\Delta n}$ parameter can also be related to the peak accelerations experienced by an aircraft. Figure 2 shows turbulence encounters from historical flight data; including data collected during previous NASA flight tests, National Transportation and Safety Board (NTSB) accident investigations, and several other airline incidents and accidents. A linear regression applied to

this data yields a correlation of 95%. This data clearly demonstrates that the $\sigma_{\Delta n}$ parameter can be used as a surrogate for peak loads.
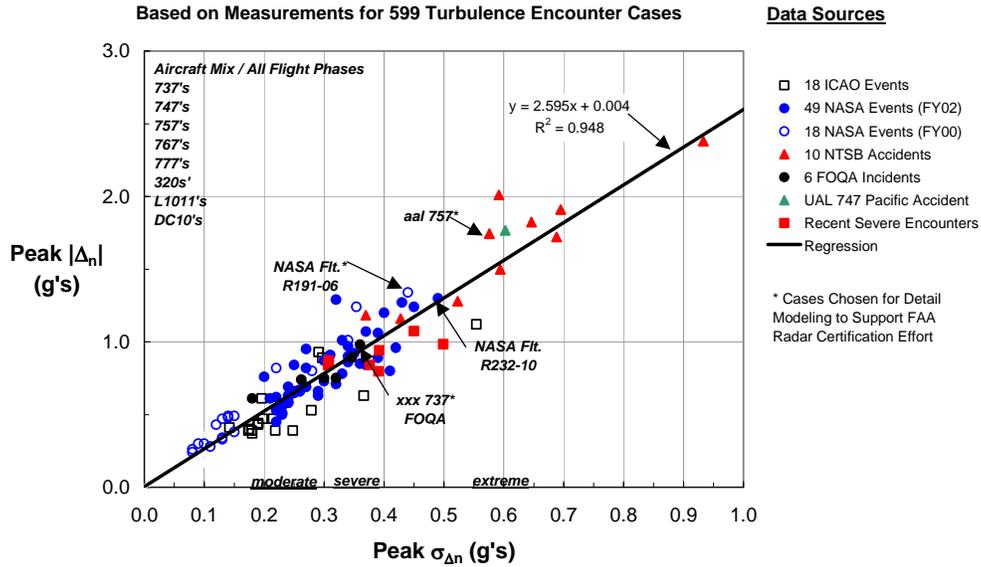
Figure 2: Correlation Between Peak Load and Peak $\sigma_{\Delta n}$ (5 sec. window)

Analyses were conducted to select thresholds of $\sigma_{\Delta n}$ that could be used to define the various levels of turbulence intensity. The selection of thresholds was hampered by the lack of clear, objective data relating the $\sigma_{\Delta n}$ parameter to the usual subjective descriptions of light, moderate, and severe turbulence. The Federal Aviation Administration (FAA) Aeronautical Information Manual (AIM) states that during severe turbulence, items in the cabin become weightless. Based on this, a threshold of $\sigma_{\Delta n}$ = 0.3g was conservatively chosen as the lower limit of severe turbulence. These data are consistent with thresholds defined in the Forecasting Guide on Turbulence Intensity[1]. It is important to note that there is neither a need nor ability to be exact in the categorizations of the turbulence intensities. The need is for thresholds that can be used as a basis for warning pilots and dispatchers of potential hazards, as opposed to attempting a highly accurate scientific quantification of the effect. From this threshold analysis and an assessment of the $\sigma_{\Delta n}$ experienced by NASA research pilots during the NASA B757 flight experiments, the following threshold scheme was adopted and used for both the TAPS and E-Turb Radar ISEs:

$$0.1g \leq \sigma_{\Delta n} < 0.2g \qquad \text{Light Turbulence}$$

$$0.2g \leq \sigma_{\Delta n} < 0.3g \qquad \text{Moderate Turbulence}$$

$$0.3g \leq \sigma_{\Delta n} \qquad \text{Severe Turbulence}$$

3. Turbulence Auto-PIREP System

TAPS is an autonomous system that generates and provides real-time, objective reports of aircraft turbulence encounters in order to improve pilots', dispatchers', and air traffic controllers' situational awareness of potential turbulence hazards. TAPS is a combination of non-flight critical software applications residing on an aircraft's computer system and ground station computers that:

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[1] "In-flight Aviation Weather Advisories", NOAA National Weather Service Directive ND229107, May 22, 1991.

1) Automate the reporting of all significant encounters with turbulence (regardless of convective, clear air, mountain wave classification, or any other source),

2) Enable the scaling/interpretation of the turbulence reports for dissimilar aircraft, and

3) Display the turbulence information for use in the cockpit or for use by ground-based personnel.

The TAPS reporting algorithms consist of three components: hazard metric ($\sigma_{\Delta n}$) calculation, reporting logic, and report generation. The hazard metric is continuously calculated during flight. The reporting logic determines when a TAPS report should be generated. When the value of the hazard metric exceeds a particular threshold, a TAPS report is generated containing information on the time, location, aircraft flight conditions, and maximum accelerations experienced during the turbulence encounter. The report also contains a parameter that may be used to scale reports to other aircraft to determine the potential hazard to that aircraft. An additional benefit of TAPS is that the system would report any encounters when the aircraft exceeded the vertical load acceleration limits, defined by the aircraft maintenance manual, that require an airplane structural examination. A graphical depiction of the overall TAPS architecture is shown in Figure 3.
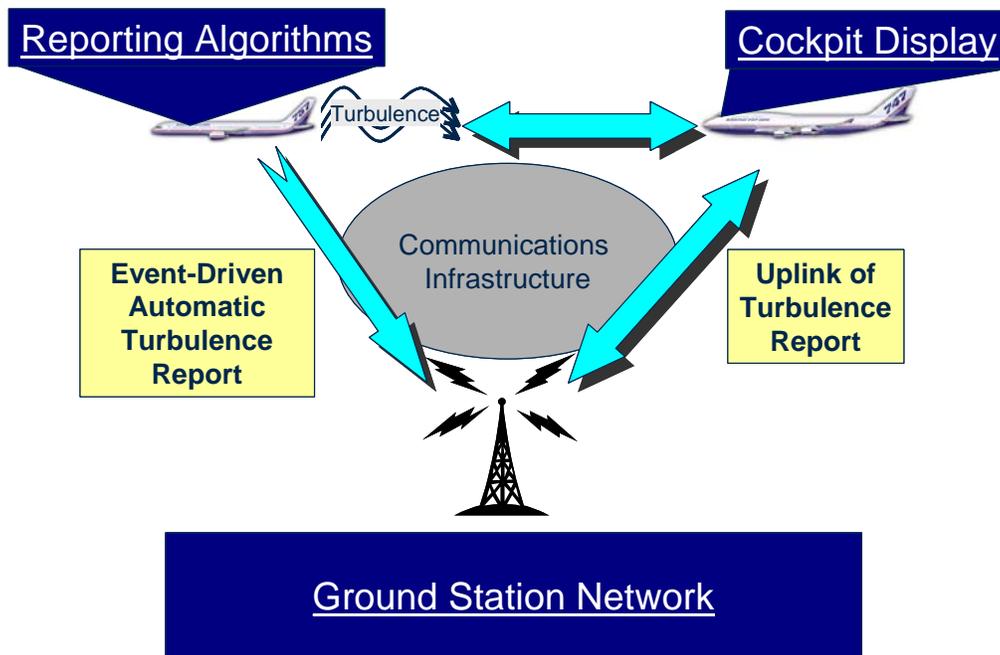
Figure 3: TAPS Architecture

3.1 TAPS In-Service Evaluation Overview

The TAPS ISE began in December 2003 with the development of the TAPS reporting software for the Delta B737-800 (B738) aircraft. The installation of the TAPS algorithms on the B737-800 fleet of 71 aircraft was completed at the end of September 2004. In FY05, an additional 52 Delta aircraft were equipped with TAPS: 31 B767-300ER (B763) and 21 B767-400ER (B764). Figure 4 shows the history of the technology development from initiation of the research through the end of the ISE.
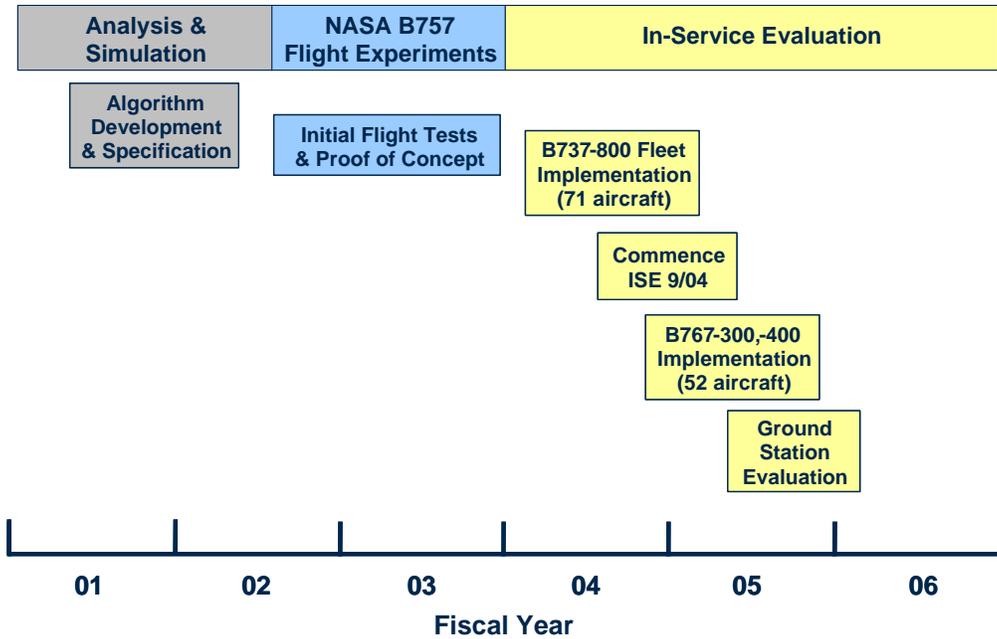
Figure 4: TAPS Chronological Development

3.1.1 Organization

The TAPS ISE was a collaborative effort, with significant in-kind support, between NASA, AeroTech Research, Delta Air Lines, and ARINC. AeroTech held the prime contract with NASA for the TAPS ISE and subcontracted Delta and ARINC to provide resources, expertise, software development, and assistance in the analysis and evaluation. The organizational roles and responsibilities of the various participants are outlined in Figure 5.

Figure 5: TAPS ISE Organizational Structure

3.1.2   Aircraft Selection and TAPS Implementation

During the feasibility study (discussed in Section 1), several Delta departments were approached to determine their needs, uses, and information requirements regarding a turbulence encounter.   After several iterations, the final form of the TAPS report was realized. The information included in a TAPS report and the individual departments' user requirements are summarized in Table 1.

Table 1: TAPS Report Content and Delta Air Lines User Requirements

TAPS Report Parameter	Units	Delta Air Lines Department				
		Maintenance	Flight Safety	Flight Ops	Dispatch	Meteorology
Time	hh:mm:ss	✓	✓	✓	✓	✓
Position, Latitude & Longitude	deg		✓	✓	✓	✓
Altitude	ft/100	✓	✓	✓	✓	✓
Gross Weight	klbs	✓	✓		✓	
True Airspeed	ft/s	✓	✓			
Hazard Metric	g	✓	✓	✓	✓	✓
TAPS Scaling Parameter	--			✓	✓	
Wind Speed	kts		✓		✓	✓
Wind Direction	deg		✓		✓	✓
Peak Vertical Acceleration	g	✓	✓			
Peak Lateral Acceleration	g	✓	✓			
Outside Air Temperature	deg C		✓		✓	✓
Flap Position	deg	✓				
Flap Handle Position	deg	✓				
Indicated Airspeed	kts	✓				
Maintenance Flag	--	✓				

Delta Air Lines' B737-800 fleet was selected for the initial TAPS implementation since it provided a large number of similarly equipped aircraft with significant coverage of the continental United States. These aircraft were also chosen because of the ease of coding and installation of the TAPS software. Delta Tech Ops developed the software code based on AeroTech's specifications and performed the code installation at their facilities.

Prior to a fleet-wide implementation, the coding and installation of the TAPS algorithms were verified on a single aircraft. This verification and validation process was critical because it ensured that the software was working correctly during normal flight operations, the communication of the TAPS reports to the ground via the Aircraft Communications Addressing and Reporting System (ACARS) was working properly, and validated that the TAPS reports broadcast to the ground station contained the correct turbulence and aircraft parameter information. The procedure for implementing the TAPS algorithms on the Delta aircraft involved a four-step process:

1. Development of the code for the TAPS algorithms based on the specifications provided by AeroTech.

2. Installation of the developed code on a single aircraft for a 30-day evaluation.

3. Verification of the correct implementation using received TAPS reports and flight data.

4. Implementation of the TAPS software on the remaining fleet aircraft.

The software was loaded on the Aircraft Condition Monitoring System (ACMS) of the Digital Flight Data Acquisition Unit on the aircraft during scheduled maintenance. Ground testing of each of the reporting algorithms components was performed while the evaluation aircraft was in the maintenance hangar. This

testing used data from the aircraft databus to ensure there was total functionality of the software. There was no requirement that maintenance be performed on an aircraft specifically for the purpose of installing the TAPS algorithms. Once satisfactory ground testing was completed, the aircraft was returned to service.

Beginning June 10, 2004, the first TAPS-equipped aircraft was flown in revenue service for a 30-day period to check the performance of the installed software. TAPS reports were generated when the aircraft encountered turbulence, transmitted to the ground via ACARS, and logged at ARINC. By July 10, 2004, a total of 31 TAPS reports were generated from 14 separate flights. Analysis was performed using Flight Operations Quality Assurance (FOQA) data from seven of these flights in which 14 TAPS reports were generated. TAPS reports were 'generated' post-flight using the FOQA data and compared to the real-time reports. The comparison checked that the correct number of reports was generated, at the correct time, and that the information gathered in the TAPS report was correct. After the successful verification of the TAPS software installation on a single aircraft, fleet-wide implementation began. The full B737-800 fleet implementation was completed by September 21, 2004.

Following a successful five-month period with TAPS on the B737-800 aircraft fleet, it was requested by Delta that a subsequent installation of TAPS on the 52 B767-300ER/400ER aircraft should be performed. This additional fleet implementation provided an increased worldwide coverage since these aircraft service Hawaii, South America, Europe, and Asia. The same TAPS implementation procedure used with the B737-800 aircraft was followed for the installation of TAPS on the B767 aircraft except that Digital Flight Data Recorder (DFDR) data was used for the verification of the B767-300ER aircraft, as they are not FOQA-equipped. Further comparative analysis directed towards spot-checking particular aircraft was performed during the fleet-wide implementation for additional verification of the functionality of the software.

Figure 6 shows the timeline for the installation of the TAPS software on the Delta aircraft. The dates used in determining the exact installation of the algorithms on a particular aircraft coincide with the date of the first TAPS report received by that aircraft.
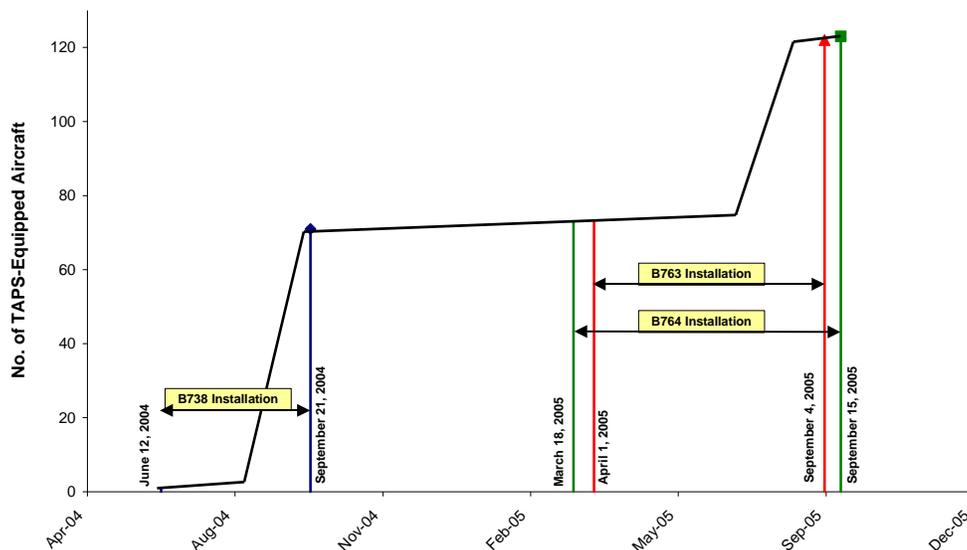
Figure 6: TAPS Installation Timeline

3.1.3 *Report Handling and Ground Station Display*

The objective of the ground station display effort was to develop a baseline display with functional interfaces to assess how dispatchers would utilize real-time, quantitative, objective turbulence encounter information in their day-to-day operations. The communication and routing of TAPS reports utilized ARINC's air-ground communications system as the primary infrastructure for air-ground communications, ground data processing, and data display for dispatchers and engineers. ARINC's communications system consisted of three parts:

1. GLOBALink^{SM} air-ground datalink system,

2. Web Aircraft Situation Display (WebASD^{SM}) application, and

3. Hosted Messaging System Application.

GLOBALink^{SM} is ARINC's worldwide air-ground datalink network. This network is a seamless, end-to-end datalink system that enables aircrews and onboard aircraft systems to communicate and exchange information with ground crews and airline host systems anywhere in the world without interruption. GLOBALink^{SM} is the primary technology behind the ACARS used for airline operational control and, increasingly, air traffic control communications around the world. GLOBALink^{SM} provides clear, accurate, unambiguous data communications.

ARINC's WebASD^{SM} exhibits the real-time location of aircraft based on FAA and other air traffic control system radar position reports. Worldwide tracking is achievable for aircraft that provide their position via datalink. WebASD^{SM} can display multiple groups of aircraft along with flight data, map overlays, Next-Generation Radar (NEXRAD) weather overlays, satellite infrared weather imagery, airport weather information including terminal area forecasts, aviation routine weather report (METAR), Digital-Automatic Terminal Information Service, and Terminal Weather Information for Pilots, navigational aids, estimated time of arrival, and flight lists that track arrival times and sequence. WebASD^{SM} can be integrated with other automation and decision-support applications and can be used with a wide range of computers using a standard Internet browser.

ARINC's Hosted Messaging System (OpCenter^{SM}) is designed as a low-cost, user-friendly, easily configurable system to enable airlines to exchange datalink messages with their aircraft, with Air Traffic Service Provider Organizations, and with their remote operations sites. OpCenter^{SM} is accessed through a web-browser interface. Messages received through OpCenter^{SM} can be reformatted for input directly to existing application systems. Because it is web-based, the user interface can be tailored to the specific needs of individual customers. This message management tool, in conjunction with WebASD^{SM}, makes up a significant part of an airline's dispatch suite. OpCenter^{SM}'s purpose within the TAPS program is three-fold. First, it receives and identifies downlinked TAPS reports from the aircraft. Next, it parses and reformats those reports as necessary prior to forwarding them to WebASD^{SM}. Lastly, OpCenter^{SM} is able to receive uplinked turbulence information from WebASD^{SM} and format it for delivery to the ground-air network.

Figure 7 provides an illustration of ARINC's TAPS Air-Ground Communications System architecture. Aircraft downlink TAPS reports to ARINC's ground network via one of several media (i.e., Very High Frequency (VHF), ACARS Over Aviation VHF Link Control (AOA), High Frequency (HF), Iridium, or Satellite Communications (SATCOM)). These reports are then forwarded to the ACARS Central Processor, which then routes them to the appropriate ground application. In the case of TAPS, these reports are forwarded to the OpCenter^{SM} Hosted Messaging System, which extracts the TAPS information from the downlink, reformats the message, and forwards it to the WebASD^{SM} application. WebASD^{SM} processes this information into a form that can be displayed to the dispatcher and analyzed by engineering. Both dispatchers and engineers can access the WebASD^{SM} application from the Internet or through dedicated ground circuits.
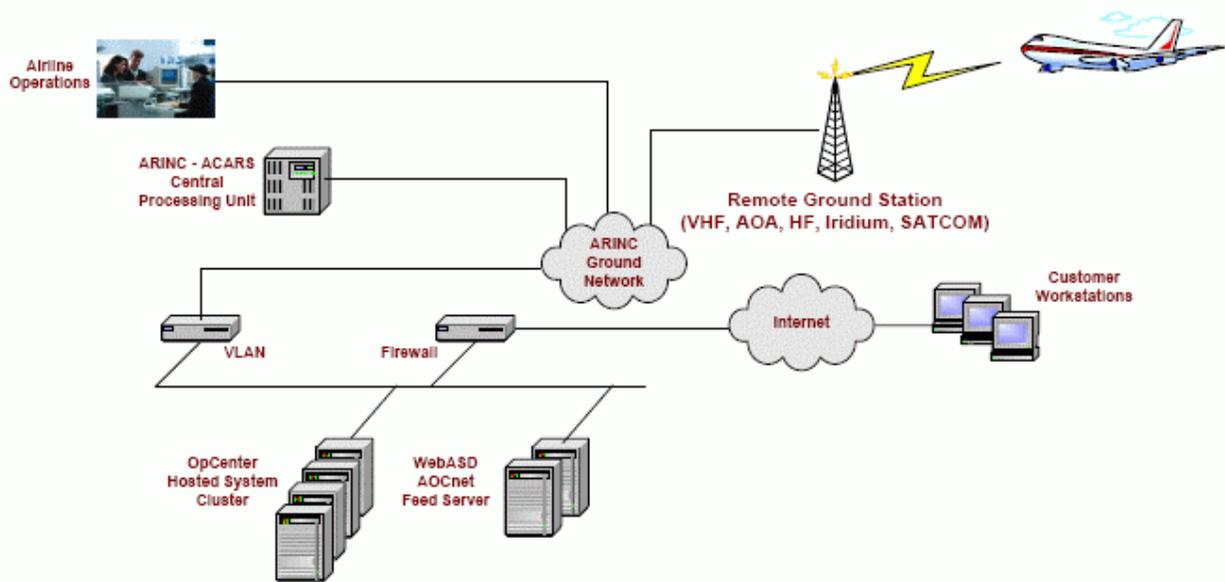
Figure 7: ARINC TAPS Air-Ground Communications System Architecture

The TAPS reports were represented on WebASD^{SM} by icons consistent with the International Civil Aviation Organization (ICAO) symbology for turbulence pilot reports (PIREP). Table 2 shows the levels of turbulence intensity reported by TAPS with the corresponding display icon, hazard metric value range, and associated AIM guidelines for reporting turbulence. The reporting logic used by TAPS allows the generation of reports at a $\sigma_{\Delta n}$ value less than the light threshold of 0.1g. Even though these 'less than light' reports were not significant for the reporting aircraft, they could prove important to other aircraft when scaled accordingly. There are no corresponding AIM guidelines for this level of turbulence.

Table 2: Turbulence Reporting Criteria

Turbulence Intensity	Icon	Hazard Metric ($\sigma_{\Delta n}$)	Aircraft Reaction	Reaction Inside Aircraft
Less Than Light		< 0.1g	No AIM guidelines.	No AIM guidelines.
Light		0.1g to < 0.2g	Turbulence that momentarily causes slight, erratic changes in altitude and/or attitude.	Occupants may feel a slight strain against seatbelts or shoulder straps. Unsecured objects may be displaced slightly. Food service may be conducted and little or no difficulty is encountered in walking.
Moderate		0.2g to < 0.3g	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.	Occupants feel definite strains against seatbelts or shoulder straps. Unsecured objects are dislodged. Food service and walking are difficult.
Severe		≥ 0.3g	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.	Occupants are forced violently against seatbelts or shoulder straps. Unsecured objects are tossed about. Food service and walking are impossible.

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Using ARINC's WebASD[SM], Figure 8 and Figure 9 show snapshots of the display showing TAPS reports, aircraft, and various weather products and TAPS reports covering a wide geographic area, respectively. During the ISE, reports were received from aircraft over India, the Middle East, Europe, the North Atlantic, the continental United States, the Eastern Pacific (to Hawaii), Central and South America, and the Caribbean.

From March 2004 to February 2005, fourteen Delta dispatchers were interviewed to gain feedback about functional interfaces that would be useful in a TAPS display. This feedback led to the development of the interactive capabilities on WebASD[SM] that were specific to the TAPS implementation. The functionalities incorporated into the initial release of TAPS on WebASD[SM] were:

- Temporal Filtering - users could filter reports based on the age of the report, from real-time to the previous twelve hours.

- Turbulence Intensity Filtering - users could filter reports based on the intensity of the reported turbulence.

- Altitude Filtering - users could filter reports based on a specific altitude range.

These filtering capabilities allowed the dispatchers to focus on the TAPS reports of interest. Additional functionalities were integrated to identify aircraft that may be affected by available TAPS report information, but the ISE ended before these functions could be completely evaluated.
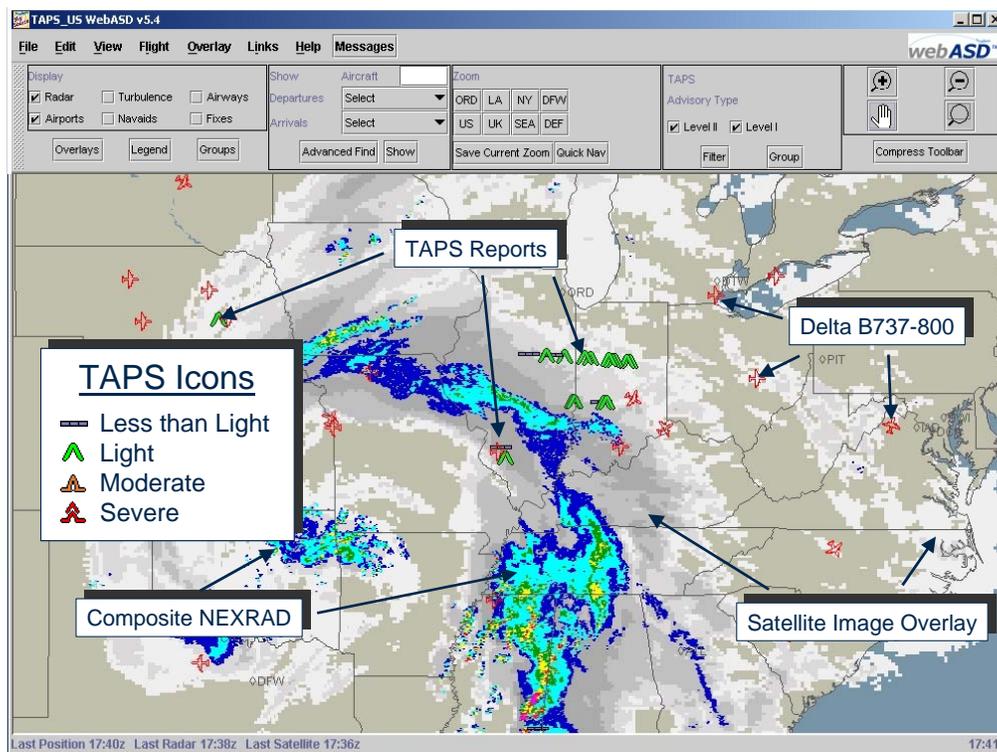
Figure 8: TAPS-WebASD[SM] Display
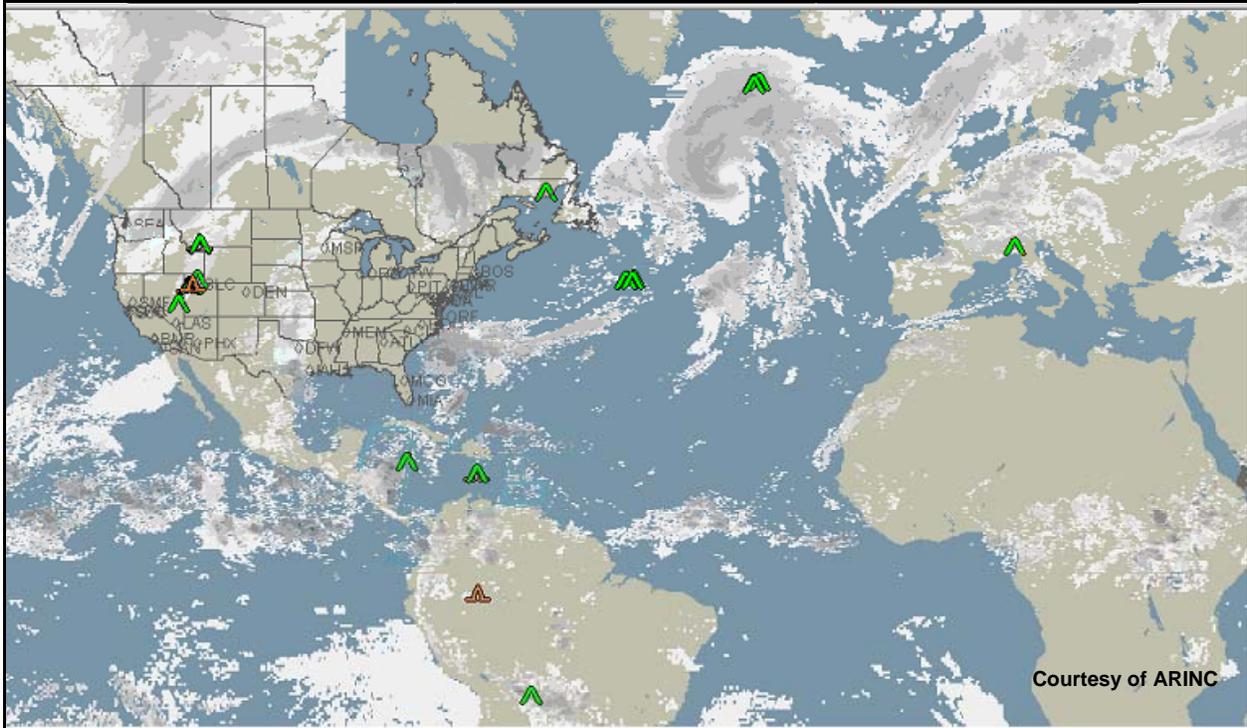
Figure 9: TAPS-WebASD^{SM} Worldwide Coverage

3.1.4   Uplink of TAPS Reports to Aircraft

A major component of the final architecture of TAPS is to provide the TAPS information to pilots. Preliminary groundwork to reach this goal was developed during the ISE by demonstrating the ability to automatically uplink multiple TAPS reports to specified aircraft via a ground station in real-time. Since the hardware capability to perform a true aircraft-to-aircraft data transfer, such as Automatic Dependent Surveillance – Broadcast (ADS-B), did not exist on Delta aircraft, all reports had to be routed through the ground station network. The automatic relaying of information (and confirmation thereof) was the focus of this part of the ISE. The turbulence information uplinked to the aircraft was not displayed to the pilot.

This part of the evaluation was an effort to develop and integrate algorithms, also known as "routing rules", that would automatically determine and transfer TAPS reports to appropriate aircraft as necessary and enable the reception and interpretation of the transferred TAPS reports on the receiving aircraft using a standard ACARS datalink. The main components on the receiving aircraft included:

1. Receiving Algorithm – decoded the uplinked TAPS information for use in the interpretation algorithm and return receipt generation.

2. Interpretation Algorithm – scaled the received TAPS information and determined if the report represented a potential hazard to the receiving aircraft.

3. Return Receipt Packet Generation – combined the TAPS report information and interpretation algorithm results to be downlinked for algorithm verification and validation.

The routing rules included the logic by which the ground station could determine if a TAPS report should be routed to another aircraft within the vicinity. The factors used to make this determination included the range of the aircraft from the location where the TAPS report was generated, the intensity level of the report, and the capability of any particular aircraft to receive the rerouted TAPS report. The initial implementation was designed to emulate the capabilities of ADS-B, which meant that an equipped aircraft had to be within 100 nautical miles of the TAPS report for the uplink message to be sent. Due to

the limitations of the ACMS on the Delta aircraft, only five parameters from the original TAPS report could be uplinked at one time.

Delta Tech Ops personnel developed the software code for the aircraft based on specifications provided by AeroTech. ARINC developed the ground station code, based on the routing rules specified by AeroTech, and incorporated it into their communications system. Beginning in May 2005, the software was installed on a total of seven aircraft: 3 B737-800, 2 B767-300ER, 2 B767-400ER.

3.1.5 Vertical Wind Estimator

Over the years, there has been significant interest in trying to determine the effectiveness of using commercial transport aircraft as atmospheric sensors. AeroTech has worked with NASA in the past to implement a vertical wind estimator on several of its research aircraft. In 2005, with a successful initial implementation of TAPS on the B737-800 already accomplished, NASA decided that, as part of the Delta B767-300ER/400ER implementation, a non aircraft-specific vertical wind estimator would be incorporated into the software loaded onto the aircraft. The vertical wind estimation was calculated by:

$$w_g = -I_{VV} - V_T\left(-\cos\alpha_B \sin\theta + \sin\alpha_B \cos\phi\cos\theta\right) \tag{3-1}$$

where w_g = vertical wind component [m/s]

I_{VV} = inertial vertical speed [m/s]

V_T = true airspeed [m/s]

α_B = body angle of attack [rad]

θ = pitch angle [rad]

ϕ = roll angle [rad]

The vertical wind estimation was continuously calculated in flight on a total of 52 aircraft. A 5-second moving window RMS of the vertical wind estimation (σ_w) was also calculated and included in the TAPS report generated from B767-300ER/400ER aircraft.

3.2   TAPS In-Service Evaluation Process

There were several components to the analyses for the TAPS ISE, namely:

1. Statistical analyses of TAPS reports: all TAPS reports were accumulated into logfiles, and statistical analyses on the reports were performed from the data within the logfiles.

2. Comparison of TAPS reports to "manual" PIREPs: typically, manual PIREPs are made either verbally or via ACARS text messaging. Either approach incorporates the pilots' subjective assessment of the intensity of the turbulence encounter. The analyses highlighted the variability of the quality of these manual PIREPS relative to the TAPS reports.

3. The use of TAPS for severe loads maintenance inspections: typically, the captain initiates a severe loads maintenance inspection. For TAPS-equipped aircraft, the number of severe loads inspections was tracked and the need for an inspection, based on TAPS reports, was assessed.

4. Effectiveness of TAPS uplink software: the effectiveness of the uplink algorithms was tracked based on reports sent up to aircraft and the automatic acknowledgment sent back from the aircraft.

5. Effectiveness of the vertical wind estimator: the σ_w estimations reported in the TAPS reports were accumulated, and a quantification of the reasonableness of the estimations was determined.

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6. Feedback from TAPS users: over the period of the ISE, dispatchers, pilots, and other Operations Control Center (OCC) personnel were interviewed regarding their use of TAPS, and their assessment of the effectiveness of the technology.

7. Development of a TAPS Concept of Operations (CONOPS) for dispatchers: dispatchers from several airlines participated in developing the uses and applications of TAPS in their daily tasks.

Results from each component of the analysis are presented in the next section.

3.3 Summary of Results

3.3.1 Statistical Analysis of TAPS Reports

Every TAPS report generated was collected into a comprehensive database so that the information could be analyzed depending on the research needs. More than 77,000 TAPS reports were broadcast from the 123 Delta B737-800, B767-300ER, and B767-400ER aircraft from June 2004 to August 2006. Delta discontinued the forwarding of messages to ARINC on August 16, 2006. Figure 10 shows the location of every TAPS report generated during the ISE. The distribution of TAPS reports by turbulence intensity is shown in Figure 11. Just over 3% of the reports were of moderate or greater intensity. Figure 12 through Figure 14 show the distribution of TAPS reports for each aircraft fleet.
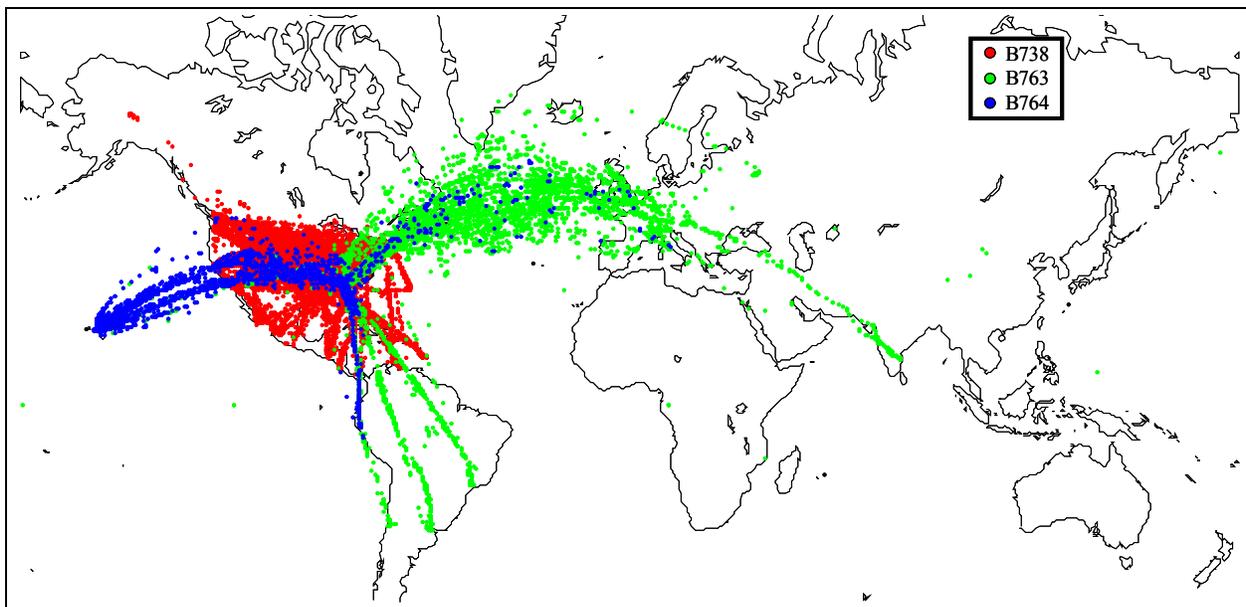
Figure 10: Geographic Distribution of TAPS Reports

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Period Covered: June 10, 2004 - August 16, 2006
Total # of Reports from All Aircraft: 77942
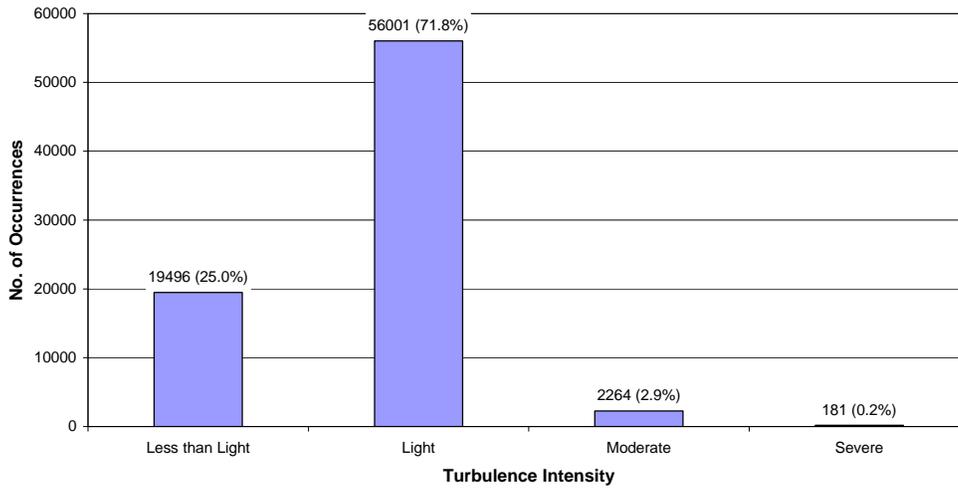
Figure 11: Summary of All TAPS Reports Based on Turbulence Intensity

Period Covered: June 12, 2004 - August 16, 2006
Total # of B738 Reports: 65355
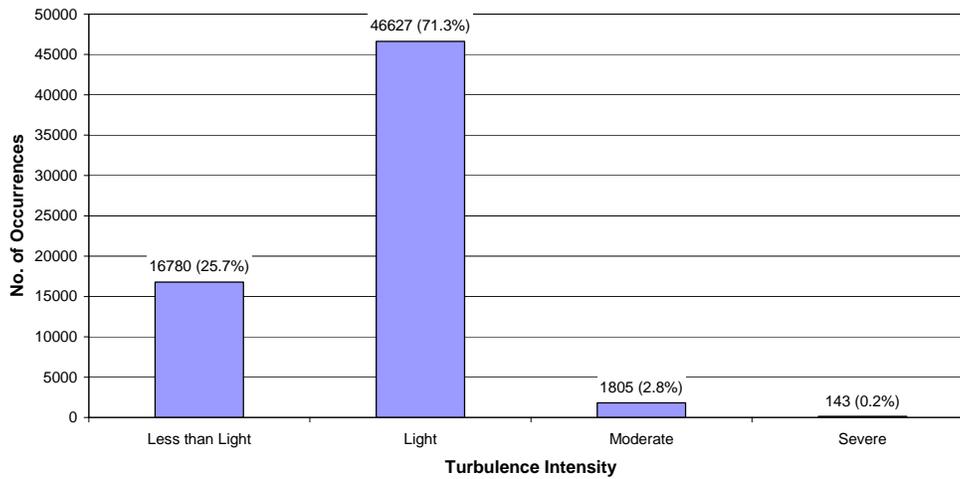
Figure 12: Summary of B737-800 TAPS Reports Based on Turbulence Intensity

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Period Covered: April 1, 2005 - August 16, 2006
Total # of B763 Reports: 8174
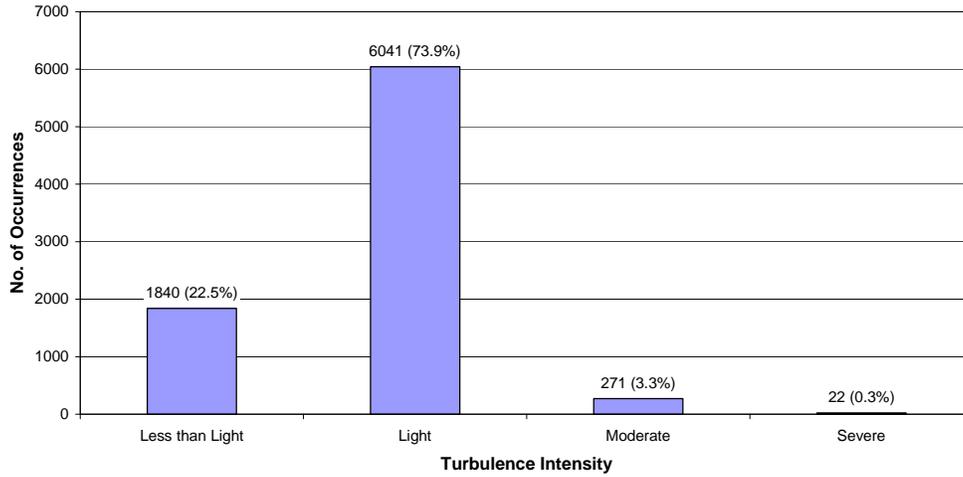
Figure 13: Summary of B767-300ER TAPS Reports Based on Turbulence Intensity

Period Covered: March 21, 2005 - August 16, 2006
Total # of B764 Reports: 4414
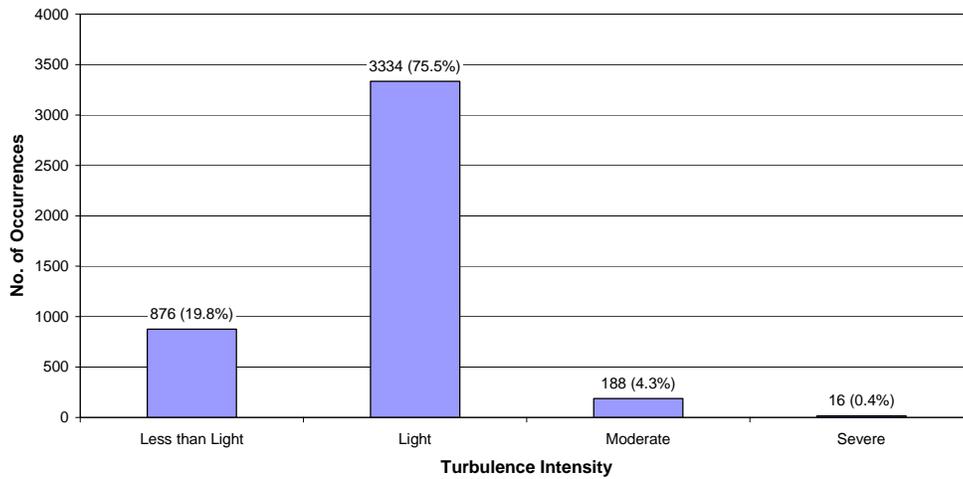
Figure 14: Summary of B767-400ER TAPS Reports Based on Turbulence Intensity

To understand the communications requirements for an aircraft equipped with TAPS, the number of reports per aircraft was tracked on a monthly basis. Figure 15 through Figure 17 show the number of reports generated each month normalized by the number of TAPS-equipped aircraft for each aircraft type. The number of TAPS-equipped aircraft is also provided. On average over all aircraft types, a TAPS-equipped aircraft generated 32 TAPS reports per month. Each TAPS report is less that one kilobit (kb); this translates to less than 32kb per aircraft per month.

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In 2002, ARINC stated that for its customers, 20 million messages were being sent per month for 6,000 aircraft[2]. This averages to approximately 110 messages per aircraft per day. A comparison of bandwidth requirements was not possible since the size of these messages was unknown but in relation to traffic volume, TAPS reporting during the ISE was negligible compared to typical ACARS traffic today.
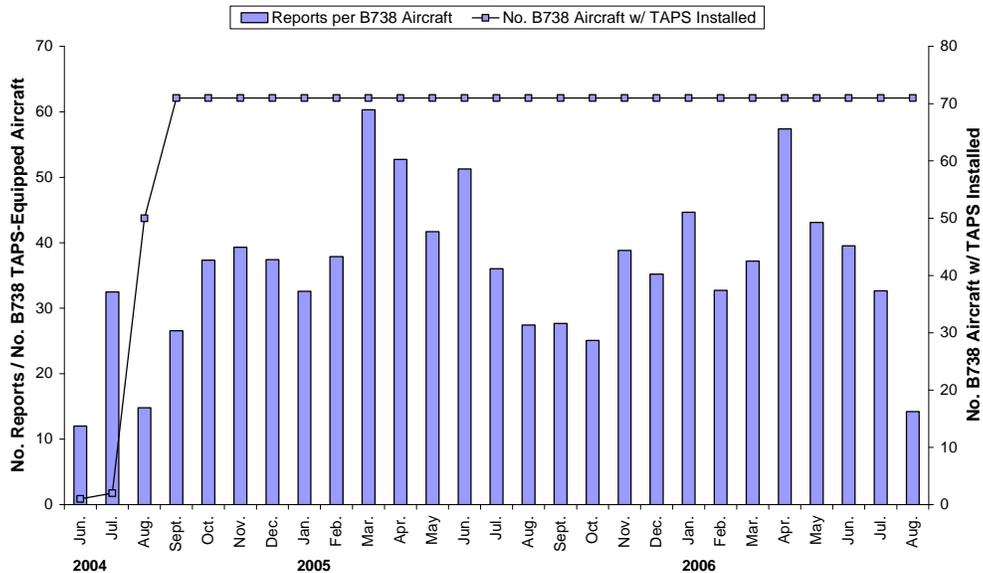
Figure 15: Monthly TAPS Reporting for B737-800 Aircraft
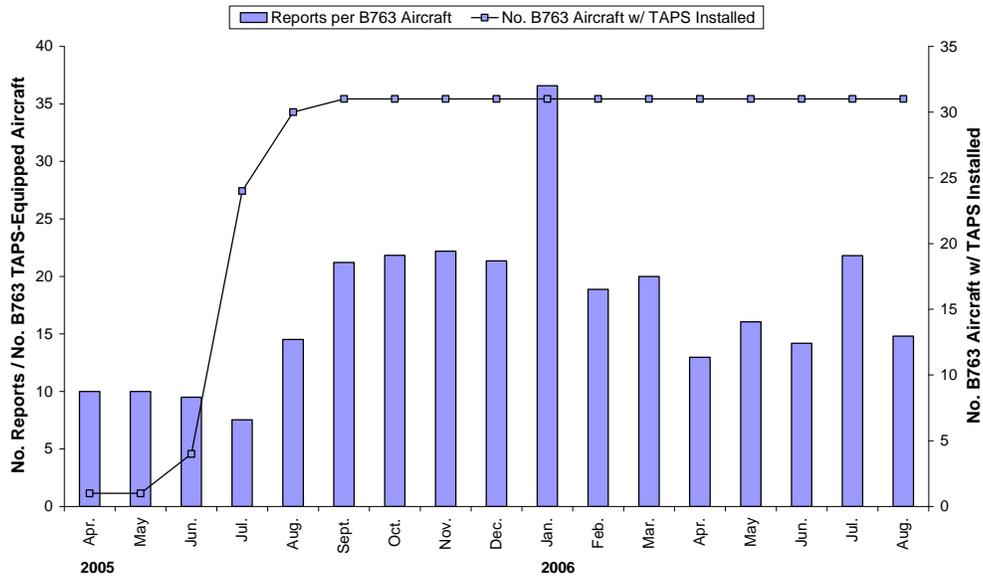
Figure 16: Monthly TAPS Reporting for B767-300ER Aircraft

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[2] Homans, Al, "The Evolving Role of the Communication Service Provider", Integrated CNS Technologies Conference and Workshop, May 1, 2002.
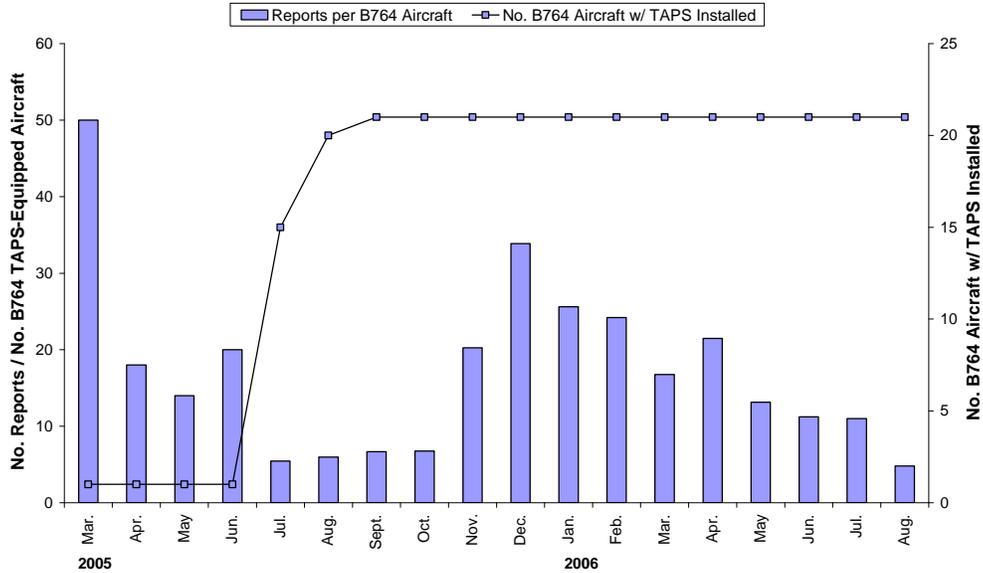
Figure 17: Monthly TAPS Reporting for B767-400ER Aircraft

For the ISE, the TAPS reporting threshold was set at 0.1g, which corresponds to an encounter of at least light turbulence. The reporting threshold may be lowered to provide ride quality information if so desired by the industry. This will not alter TAPS structurally, but will lead to an increase in the overall number of reports generated by TAPS-equipped aircraft and therefore, an increase in communications costs. The following example estimates the impact on TAPS reporting if the reporting threshold was lowered to 0.05g. This value has no particular technical significance and was used for illustrative purposes only.

Less than light TAPS reports were generated due to a reporting "deadband" about 0.1g. Although the reports themselves were valid, they do not constitute a full population of the RMS range from 0.05g to 0.1g and are excluded from this analysis. The data presented in Figure 11 (excluding the less than light reports) were re-sampled into 0.01g "bins" from 0.1g to 0.4g and is shown in Figure 18. An exponential curve fit was applied, and data were extrapolated to the nominal lower threshold of 0.05g.

Summing the number of reports for each bin from 0.05g to 0.1g, it is estimated that an additional 168,000 TAPS reports may have been generated, which yields a 387% increase in the total number of reports. Using the timeframe of the ISE for which TAPS reports were collected, this averages out to an additional 53 TAPS reports per aircraft per month. Combining the extrapolated data with the ISE results, if the TAPS reporting threshold had been lowered from 0.1g to 0.05g, a TAPS-equipped aircraft may have generated approximately three TAPS reports per day. This volume of TAPS reporting is negligible when compared to the amount of data currently downlinked daily.
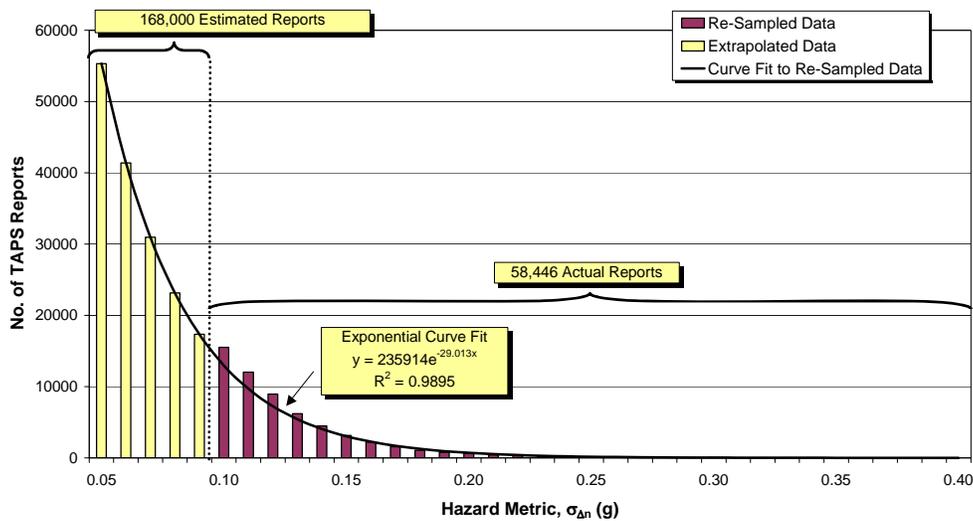
Figure 18: Curve Fit Applied to Re-Sampled TAPS Report Data

Additional characterization of the data gathered during the ISE is presented below. Figure 19 through Figure 21 show the number of reports generated by time of day for each aircraft type. Figure 22 through Figure 24 show the number of reports generated by flight level for each aircraft type. These figures represent just a presentation of the data collected during the ISE, and no definitive conclusions could be drawn from these results since information about scheduling, traffic volume, etc., was available.
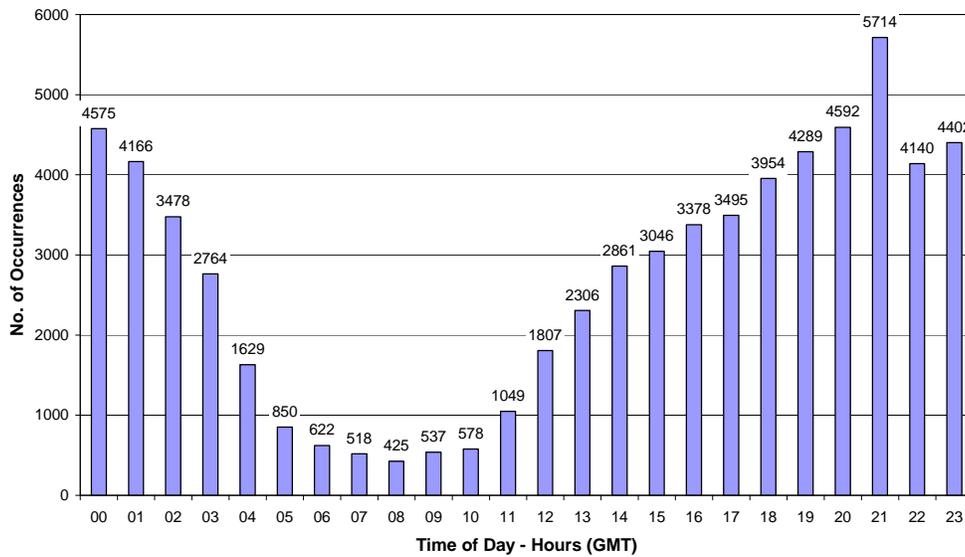
Figure 19: Summary of B737-800 TAPS Reports Based on Time of Day

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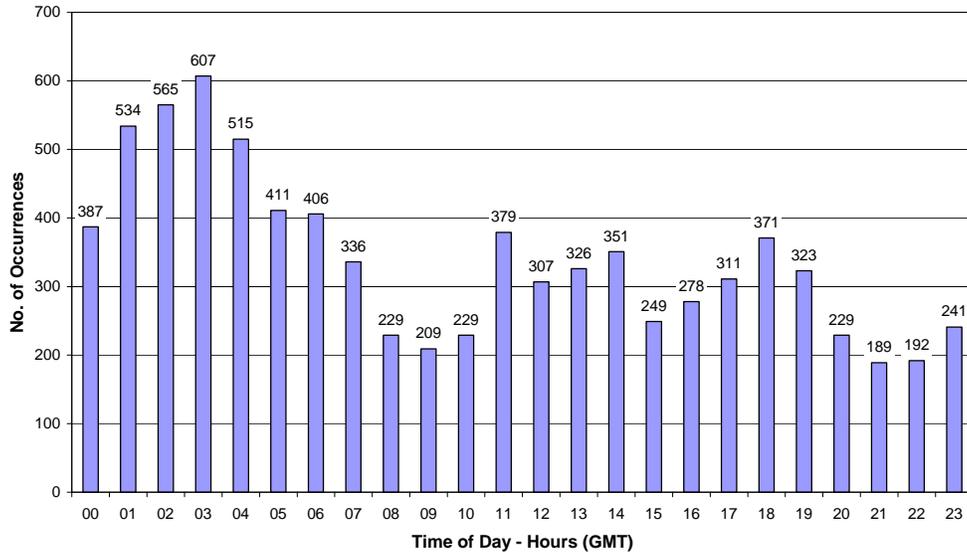
Figure 20: Summary of B767-300ER TAPS Reports Based on Time of Day
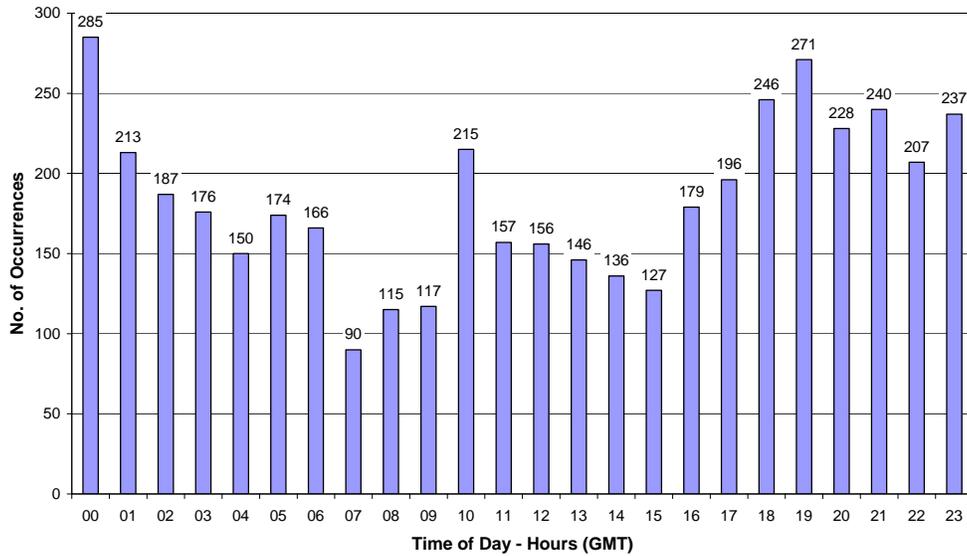
Figure 21: Summary of B767-400ER TAPS Reports Based on Time of Day
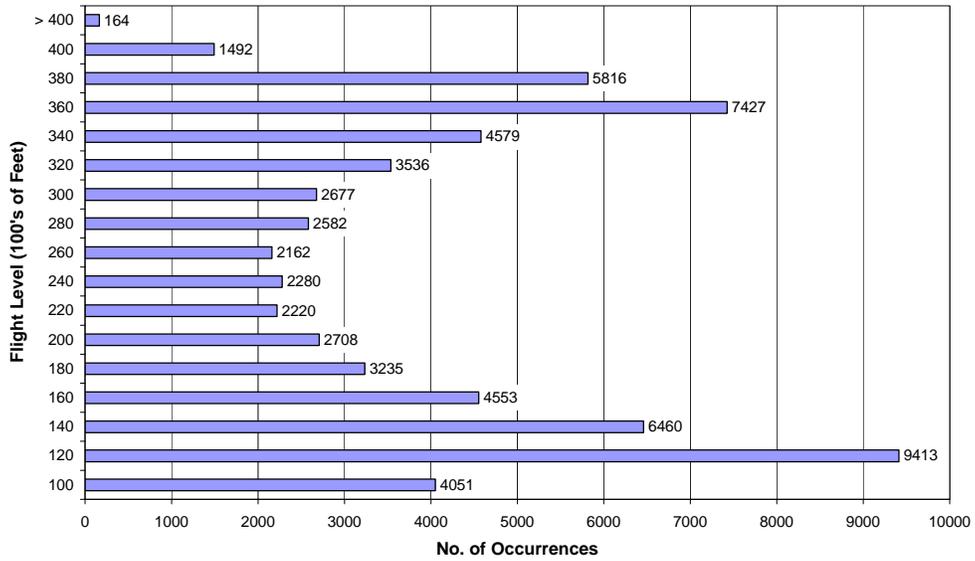
Figure 22: Summary of B737-800 TAPS Reports Based on Flight Level
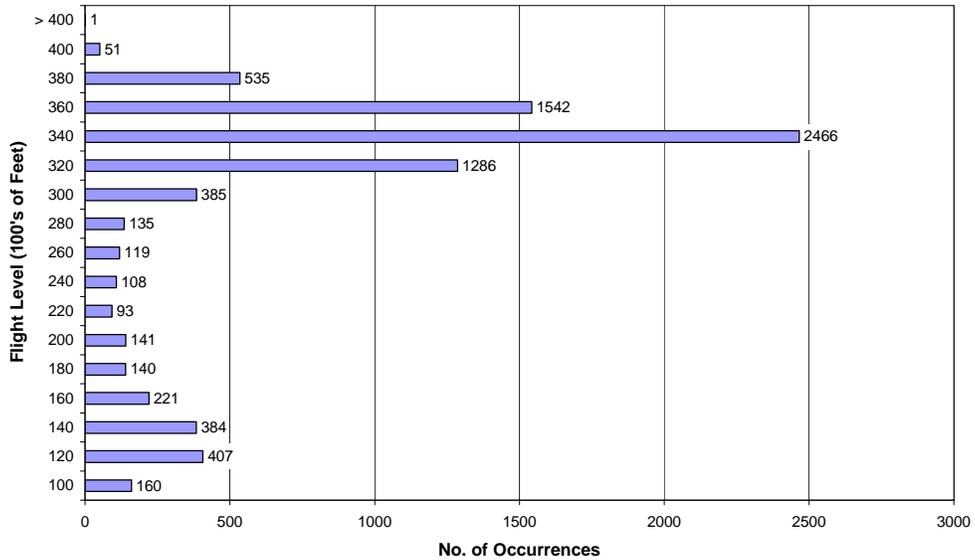
Figure 23: Summary of B767-300ER TAPS Reports Based on Flight Level
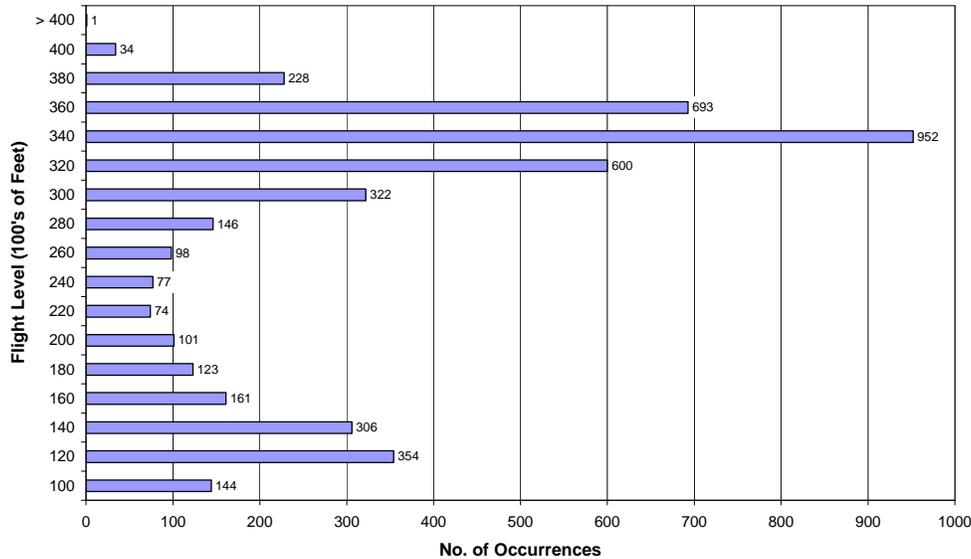
Figure 24: Summary of B767-400ER TAPS Reports Based on Flight Level

3.3.1.1 Spurious TAPS Reports

During the course of the ISE, unforeseen issues arose regarding the quality of the input data being provided to the TAPS algorithms that, in turn, caused the generation of TAPS reports that did not represent an encounter with turbulence or severe loads. These spurious TAPS reports were determined to be from one of two separate sources: databus dropouts and incorrect sensor data.

A method was developed and implemented on the ARINC ground station that would identify these types of reports and reject them from being displayed on WebASD[SM]. If a report contained data representative of a problem with the aircraft's databus or sensor, the information was provided to airline maintenance about the occurrence. Examples of these issues are provided in more detail below.

A databus dropout may occur intermittently and was defined by a spike in a particular parameter in the flight data. A dropout could occur in multiple parameters but not consistently in the same parameters. Since the vertical acceleration is an important parameter of interest for the TAPS algorithms, analysis was focused on instances when there was a dropout in this parameter. Figure 25 and Figure 26 show examples of erroneous data in the vertical acceleration and other parameters.

Incorrect sensor data also may occur intermittently and ranged from offsets or biases to unreasonable data (e.g., UTC time greater than 23:59:59, true airspeed equal to zero, etc.) to problems attributed to sensor wiring issues. Figure 27 shows an example of the vertical acceleration from a B767-300ER aircraft. From 1500 seconds to 1900 seconds, the accelerometer appeared to be functioning correctly even though the mean acceleration seemed to decrease. Between approximately 1920 seconds and 2075 seconds, the mean acceleration noticeably decreased by 0.02g. Dropouts in the accelerometer measurements could also been seen at 1950 and 2070 seconds. Following the second dropout, the mean acceleration had decreased by almost 0.1g and the signal continued to deteriorate. Eventually, the signal recovered to proper operation but this phenomenon frequently occurred throughout this flight. A clear explanation of the cause of this error was never determined. The identification of these issues resulted in improved awareness of the aircraft system's performance, since many of these sensor and databus problems would possibly have gone unnoticed until the aircraft's next scheduled maintenance.
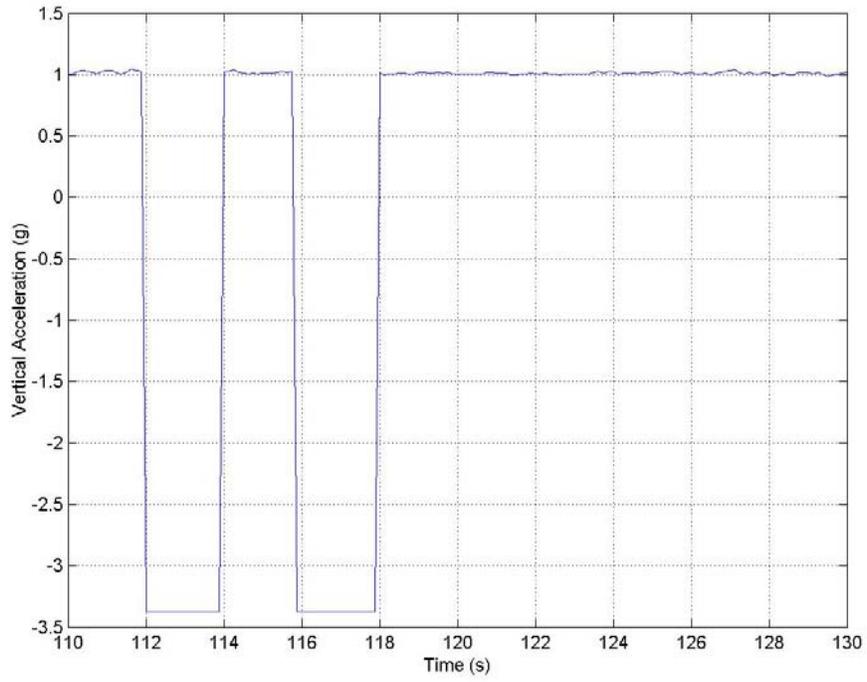
Figure 25: Databus Dropout in Vertical Acceleration
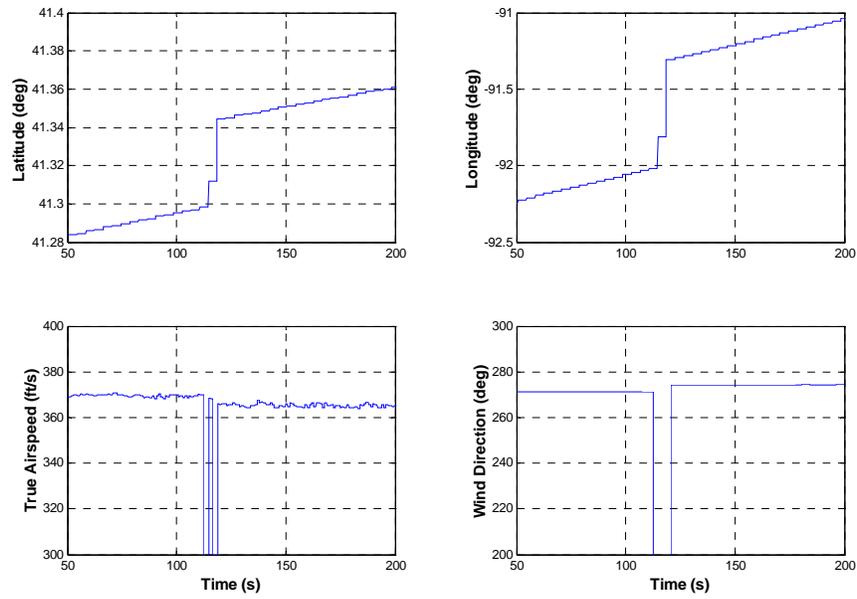
Figure 26: Databus Dropout Examples
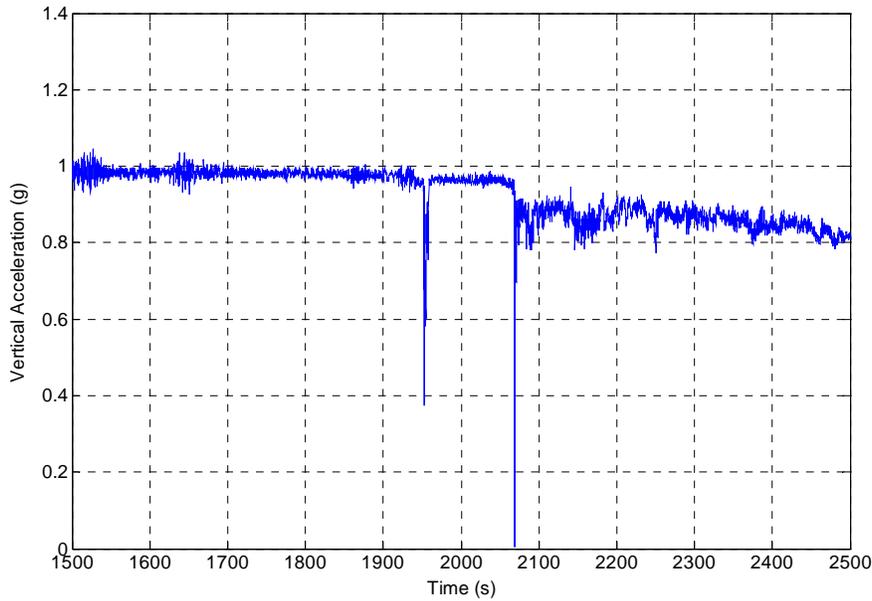
Figure 27: Example of Erroneous Sensor Data (Vertical Acceleration)

3.3.2   Comparison of TAPS Reports to Manual Reports

As part of the TAPS evaluation, Delta pilots of B737-800 aircraft were asked to provide feedback via ACARS or e-mail about encounters with turbulence that they deemed as moderate or greater. This data was compiled and compared to any associated TAPS reports from that particular flight. Feedback from a total of 91 events is summarized in Table 3.

Table 3: Comparison of Reported Turbulence Intensity between PIREPs and TAPS Reports

No. of Events	% Total Events	Description	
21	23.1	• PIREP and TAPS reported turbulence intensity agreed.	
35	38.5	• PIREP reported turbulence intensity greater than TAPS intensity.	*Overestimation*
11	12.1	• PIREP with no corresponding TAPS report.	
5	5.5	• PIREP reported turbulence intensity less than TAPS intensity.	*Underestimation*
19	20.8	• TAPS report with no corresponding PIREP.	

From the feedback gathered, a quarter of the events showed a correlation between the turbulence intensity reported by the pilots and TAPS. The remaining events were represented by either an overestimation or underestimation of the turbulence intensity. A majority of the overestimations were when the pilot classified the turbulence as "moderate chop" and only a light TAPS report was generated. For all five cases of an underestimation with a PIREP, the PIREP stated either "moderate" or "moderate plus" turbulence when a severe TAPS report was generated. For the other 19 underestimation cases, follow-up conversations with the flight crews confirmed the existence of some level of turbulence. It was difficult to correlate the perceived turbulence intensity due to the amount of time between the flight and when the interview occurred. However, it was determined all were in the vicinity of convective activity.

Examples of the range of traditional PIREP subjectivity are illustrated in Figure 28 and Figure 29. These figures show the processed g-loads data for flights in which TAPS reports were generated along with a

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traditional PIREP. The trace represents the level of turbulence that particular aircraft experienced in flight.

Example 1: PIREP Underestimation vs. TAPS Reports

Figure 28 shows data from a flight in which the pilot reported a moderate turbulence encounter. This PIREP was sent approximately one hour after the actual encounter. It was also reported that the flight crew was investigating a possible passenger injury due to the turbulence. TAPS reported moderate and severe turbulence. Since the manual PIREP was made an hour after the encounter, it becomes less useful in improving the situational awareness of other aircraft in the vicinity. These aircraft could have possibly traversed that same region without ever being aware that a flight ahead of them encountered this level of turbulence.
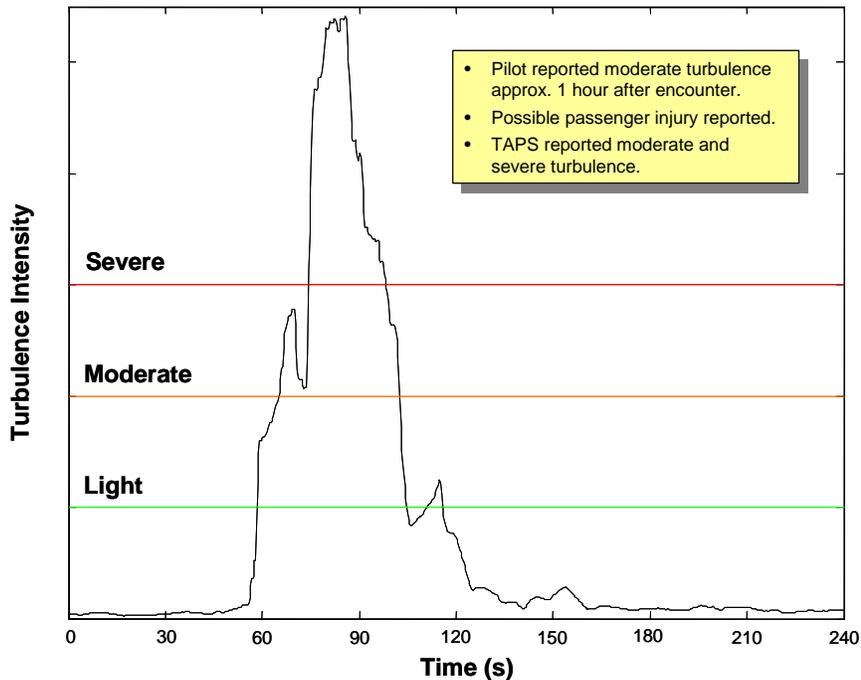
Figure 28: PIREPs vs. TAPS Underestimation

Example 2: PIREP Overestimation vs. TAPS Reports

Figure 29 shows a reported moderate to severe turbulence encounter. The pilot made a PIREP approximately 5-10 minutes after the encounter. The pilot also requested that an aircraft inspection be performed. Maintenance personnel were not available to perform the inspection until hours after the aircraft landing, which subsequently cancelled the next flight. TAPS generated a report of only light turbulence, meaning no inspection was necessary. Based on cost estimations from a 2005 Volpe Center study, a flight cancellation (with an inspection) costs the airlines approximately $10,000 per occurrence for a narrow-bodied jet and upwards of $150,000 per occurrence for a wide-bodied jet.[3] If the information was integrated into an airlines' decision-making process, TAPS could have potentially saved the airline money in maintenance costs and the flight cancellation.

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[3] Campbell, Britney, "Safety & Business Benefit Analysis", Volpe Center, March 9, 2005.
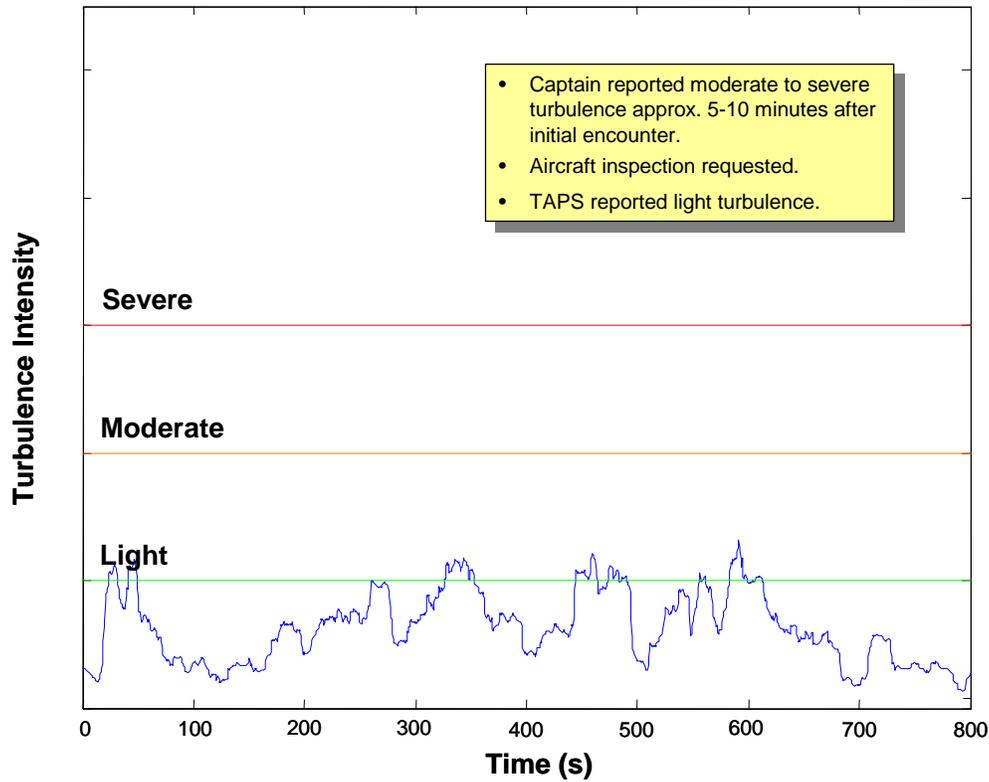
Figure 29: PIREPs vs. TAPS Overestimation

3.3.3   The Use of TAPS for Severe Loads Maintenance Inspections

Another benefit of TAPS is the real-time reporting of the peak loads experienced by the aircraft from either a turbulence encounter or abrupt maneuvering. As previously shown, maintenance inspections from severe turbulence can prove costly (in time, dollars, and operational impact) to an airline, especially if they are unnecessary. The TAPS report contains a specific flag that provides a notification when the aircraft has encountered severe loads as per the maintenance manual guidelines.

Delta provided information concerning the number of inspections performed from 2002 to 2005. Table 4 shows the number of inspections performed from September 2004, when all B737-800 aircraft were equipped with TAPS, to February 2006. The first row shows that 35 severe loads inspections were performed in that period over the entire Delta fleet aircraft. The following rows show the number of inspections carried out on the three TAPS-equipped aircraft types. Based on the TAPS information, no maintenance inspections due to severe loads exceeding the manufacturer's limits occurred during this timeframe.

Table 4: Maintenance Inspection Comparison

Aircraft Type	No. Inspections	Needed Per TAPS
All	35	-
B737-800	5	0
B767-300ER	3	0
B767-400ER	0	0

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3.3.4   Effectiveness of TAPS Uplink Software

AeroTech developed and integrated algorithms on the aircraft and ground station that would automatically transmit TAPS reports generated from one aircraft to another within a specified range. Seven aircraft were installed with software that enabled the reception and interpretation of the transmitted TAPS reports. This evaluation tested the process of providing TAPS information to the aircraft in real-time for future development of displays in the cockpit.

Based on the aircraft's proximity to a TAPS report, the ground station software automatically determined when to uplink the TAPS report information. When an aircraft received an uplinked report, an acknowledgement packet was generated and downlinked. This receipt contained the original uplinked report information and specific calculations performed by the onboard algorithms. The purpose of this receipt was to ensure the report was uplinked to the correct aircraft and validate the processing of the uplinked report onboard the aircraft. On average, the transmission time interval was less than two minutes from when the initial TAPS report was generated to when the receiving aircraft generated the return receipt, which corresponds to approximately when the interpreted information would be available to the pilots.

This system was able to successfully provide TAPS information to aircraft within a range of distances from 1000 nautical miles (to test system operation) to 100 nautical miles. The latter distance approximates the maximum expected range of an ADS-B air-to-air datalink. Table 5 lists the number of uplinks sent to the respective aircraft type along with the number of return receipts received.

Table 5: Comparison of Uplink and Return Receipt Reports

Aircraft Type	No. of Uplinks	No. of Return Receipts
B737-800	1048	334
B767-300ER	96	33
B767-400ER	333	189

The results in Table 5 show there was significant difficulty in consistently performing this uplink. With the help of Delta engineers, several potential reasons for this inconsistency were identified; however, no definitive source was determined before the conclusion of the ISE. One potential source of data loss was attributed to the limitations of the aircraft's ACMS, which could not process uplinked data in close succession. To improve the fidelity of the uplink reception, multiple uplinks to an aircraft would need to be separated by at least 30 seconds. This delay was not accounted for in the routing rules on the ground station. However, it can be concluded that there is no inherent difficulty in uplinking TAPS reports to an aircraft using ACARS, but a refinement of the ground station routing rules would be required to accommodate known avionics limitations.

3.3.5   Vertical Wind Estimation

During the B767 evaluation, whenever an aircraft encountered turbulence, a TAPS report was downlinked containing the maximum $\sigma_{\Delta n}$ experienced and maximum σ_w calculated. A total of 12,545 TAPS reports generated from the B767-300ER/400ER aircraft fleets were used for this analysis. All of these reports are shown in Figure 30. A linear regression was applied to the data, and a weak correlation is evident between the measured $\sigma_{\Delta n}$ and estimated σ_w.
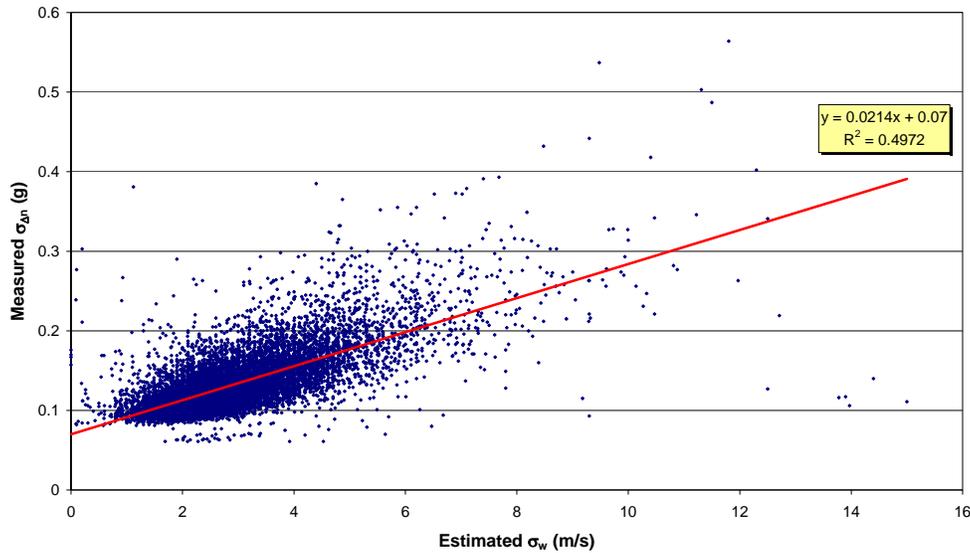
Figure 30: Comparison of Measured $\sigma_{\Delta n}$ to Estimated σ_w

Further insight can be gained in the quality of the reported σ_w by relating it to the $\sigma_{\Delta n}$ experienced by the aircraft. Theory[4] provides a proportional relationship of σ_w to $\sigma_{\Delta n}$:

$$\sigma_{\Delta n} = f(\text{Weight, Altitude, True Airspeed, Aircraft Response})\sigma_w$$

In practice, the function f is difficult to realize due to the complexity of representing modern aircraft response and control systems. Using simulator data, AeroTech has developed a technique to estimate f for the B767 aircraft across its flight envelope. Weight, altitude, and true airspeed are known for each data point since they were included in the TAPS report. Therefore, each σ_w data point can then be scaled to an estimated $\sigma_{\Delta n}$ (Figure 31). A linear regression was applied to the data yielding an R^2 of 0.5059.

Results of the analysis show significant variability between the measured and estimated $\sigma_{\Delta n}$. For example, an estimated $\sigma_{\Delta n}$ of 0.1g is seen to correspond to a range of measured $\sigma_{\Delta n}$ from 0.08g to over 0.3g. Possible sources of this error include:

1. The data rates of the parameters used in calculating w_g are too low to capture the frequencies containing the energy to produce the full $\sigma_{\Delta n}$. This would result in estimated $\sigma_{\Delta n}$ values significantly lower than the actual measured. Most of the points lie above the line of perfect agreement indicating that this may be a significant effect.

2. The angle of sideslip may not be zero, due to a turning flight or turbulence.

3. The TAPS software did not check to ensure that the reported σ_w was the actual value associated with the reported maximum $\sigma_{\Delta n}$. Checking for this condition is a complex process, especially in regions of continuous turbulence. There may be occasions when the reported σ_w did not correspond to the peak $\sigma_{\Delta n}$.

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[4] Houbolt, John C. "Design Manual for Vertical Gusts Based on Power Spectral Techniques," Air Force Flight Dynamics Laboratory Technical Report AFFDL-TR-70-106, December 1970.

This analysis suggests that an atmospheric parameter such as σ_w would not suffice as a surrogate for $\sigma_{\Delta n}$. AeroTech did not receive any flight data from Delta to investigate this further, and it was not possible to estimate the magnitude of the error.

Figure 31 plot with axes: y-axis "Measured $\sigma_{\Delta n}$ (g)" from 0 to 0.7, x-axis "Estimated $\sigma_{\Delta n}$ (g)" from 0 to 0.7. Labels "Perfect Agreement", "y = 0.7935x + 0.0702", "$R^2 = 0.5059$".
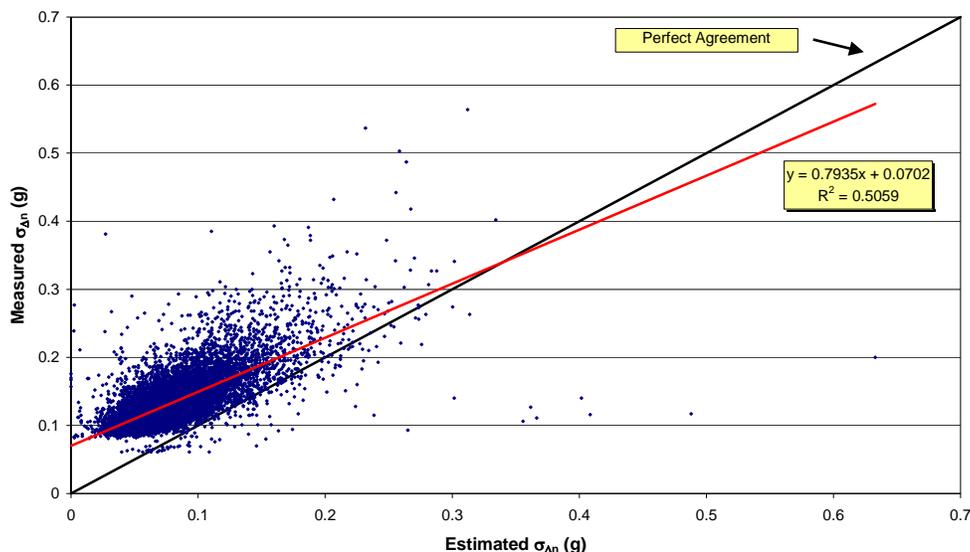
Figure 31: Comparison of Measured $\sigma_{\Delta n}$ to Estimated $\sigma_{\Delta n}$

3.3.6   Dispatcher Anecdotal Feedback

Solicited and volunteered feedback was collected concerning the use of TAPS information by dispatchers in an operational environment. The feedback encompasses the active and post-event use of TAPS corresponding to 16 separate turbulence encounters. Table 6 summarizes the feedback from different users based on dispatcher utilization of the TAPS information. The four examples of use listed in Table 6 are summarized below.

Table 6: Summary of TAPS Usage Feedback

Type	# Events	Examples of Use
Turbulence Encounter *Active Use*	8	• Pilots requesting real-time TAPS-related information about an encounter.
	2	• Maintenance including TAPS reported loads in severe turbulence logbook entry.
Turbulence Encounter *Post-Event Use*	3	• Dispatcher informing flight crews about TAPS information once aware of the encounter.
	3	• Flight Safety using TAPS report information in an NTSB injury investigation.

Example 1: Pilots Requesting Real-Time TAPS-Related Information About An Encounter

In November 2005, an aircraft generated a severe TAPS report at flight level 360. Ten minutes after the initial encounter, the pilot informed the dispatcher of a "moderate plus" turbulence encounter between flight levels 320 to 380, lasting approximately four minutes. There were six TAPS reports generated over a three-minute period: 1 light, 3 moderate, and 2 severe. In a subsequent ACARS message to dispatch, the pilot queried if a TAPS report had been generated for the encounter and requested the peak g-loads reported. This is an excellent example of the increased accuracy and timeliness of TAPS over manual PIREPS. It may also indicate the beginning of reliance by dispatchers and pilots on TAPS reports for

turbulence encounter information and quantification. TAPS provides timely loads information that is currently not available to the dispatcher, pilots, etc., until sometimes days or weeks after the encounter.

Example 2: Maintenance Including TAPS Reported Loads in Severe Turbulence Logbook Entry

In January 2006, a TAPS researcher working at Delta observed on the TAPS ground station display an aircraft that had generated four TAPS reports at flight level 350: 1 light and 3 moderate. The researcher reviewed the ACARS message traffic for this aircraft and found that the pilot reported "light chop" in a standard turbulence PIREP followed by a PIREP stating moderate turbulence with occasional severe chop at flight level 350. The pilot also said that maintenance should be notified of a 10-knot overspeed and that a severe turbulence encounter should be entered into the logbook. The maintenance coordinator confirmed the overspeed and severe turbulence encounter with the pilot. The dispatcher then informed the pilot that meteorology believed that the aircraft was likely on the fringes of forming mountain waves and that the remainder of the flight should be uneventful. The maintenance coordinator followed up with the pilot to determine if they were requesting a structural inspection, which the pilot declined; no inspection was performed and the aircraft continued in service. In an interview with the researcher, the dispatcher stated they were pleased with the information provided to them by TAPS and that they had provided to the pilot the classification of the encounter and the peak loads experienced by the aircraft per the TAPS report. The maintenance coordinator also told the researcher that they appreciated the information from TAPS and included the g-loads from the TAPS report in the maintenance log. The researcher then provided a summation of the encounter to Delta's flight safety department.

Example 3: Dispatcher Informing Flight Crews About TAPS Information Once Aware Of The Encounter

In September 2005, a TAPS researcher working at Delta solicited feedback from a dispatcher handling a flight that had generated a moderate TAPS report. The dispatcher had not been monitoring the TAPS ground station display at the time of the encounter and stated that no PIREP had been received from the flight crew. The dispatcher was convinced by the information being provided by TAPS and immediately relayed this information to an aircraft that was approaching the region where the report was generated. Even though flight operations personnel were not always using TAPS in real-time due to screen space limitations, once they were made aware of the TAPS information being provided to them, they could immediately benefit from the use of TAPS.

Example 4: Flight Safety Using TAPS Report Information In An NTSB Injury Investigation

In October 2005, Delta's flight safety department contacted a TAPS researcher about a prior incident that occurred in which the pilot reported brief moderate turbulence with an injury to a flight attendant. The researcher provided a log of the three TAPS reports generated during that flight: 2 light and 1 severe. After reviewing the TAPS reports, the flight safety department agreed that the encounter should have been classified as severe based on the g-loads experienced, even though an aircraft inspection would not have been necessary based on the peak g-loads in the TAPS reports. TAPS data was then provided to the NTSB for its injury investigation essentially as a substitute for DFDR data. This expedited the release of the DFDR back to Delta for examination by flight safety.

3.3.7 TAPS Dispatcher Workshop Summary

On January 9th and 10th 2007, AeroTech Research convened a workshop whose purpose was to further refine an industry-wide needs assessment of turbulence information for dispatchers, to identify how TAPS information may benefit dispatchers and rectify current system deficiencies in day-to-day operations, and to refine the TAPS CONOPS for dispatchers. Attendees included seven persons with dispatch experience (4 active, 1 retired, and 2 airline operations center managers) from six different airlines (American, American Eagle, Delta Air Lines, Frontier Airlines, Pinnacle Airlines, and US Airways). The dispatcher

attendees had an average of 20 years experience. Other attendees included two NASA representatives, an FAA representative, an American Airlines pilot, and an ARINC representative.

The first discussions examined the current state-of-the-art of turbulence information and products available to dispatchers and the perceived problems or deficiencies with this information from an airlines' and individual dispatchers' point of view. Some significant findings included:

- Without a clear understanding of the location of turbulence, dispatchers may flight plan using the limited turbulence forecast information available and leave the tactical maneuvering to the pilot and controllers. Information sources may include convective Significant Meteorological Information (SIGMET) and Airmen's Meteorological Information (AIRMET), turbulence forecasts and nowcasts (e.g., Collaborative Convective Forecast Product (CCFP)), and company PIREPs.

- The threat of injury due to turbulence is a major concern to all the airlines represented. All agreed that there is inadequate information available to reduce the impact to operations from injuries. The number of flight crew man-hours lost due to turbulence injuries is important to management and a key motivator in the adoption of new technologies.

- Pilot reports of turbulence to dispatchers (verbal or via ACARS) usually remain internal to the airline of the reporting aircraft and are not shared between airlines.

- Air Traffic Control (ATC) and Traffic Flow Management do not have better tools for identifying the location of turbulence than dispatchers.

- There is a clear disconnect between the quantity and quality of information being used internally by airlines and the information received by sector controllers in ATC. ATC receives more verbal turbulence information than airlines, particularly in regions of dynamic weather.

- Occasionally, the FAA will close a region of airspace in which aircraft have encountered severe turbulence. An additional concern of dispatchers is when and where to safely re-enter that region of airspace once it has been re-opened.

The next portion of the workshop reviewed the ISE of TAPS with Delta Air Lines, including a presentation of the TAPS ground station development efforts. The discussions transitioned into understanding the operational phases in which TAPS would prove useful for dispatchers: flight planning and flight following. The discussions focused on refining the roles, responsibilities, and interactions of the dispatchers for each phase and understanding the underlying tasks performed during each phase and how integrating TAPS information might enhance operations. This was accomplished by presenting example scenarios that dispatchers commonly encounter and understanding their current practices, then discussing how their decision-making may differ with the integration of TAPS information. The details of these discussions have been incorporated into the CONOPS (Section 3.3.8); however, some key findings included:

1. Flight Planning.

   - Dispatchers would use TAPS as one of the tools in flight planning for selection of routes; moderate or greater TAPS reports would initiate a search for alternate routes.

2. Flight Following: Aircraft Approaching Convection.

   - Dispatchers are primarily a third party information source for aircraft approaching or entering regions of convection. With TAPS reports from aircraft transiting a convective region, dispatchers could provide quantitative turbulence information and improved re-route recommendations to aircraft.

3. Flight Following: Severe Turbulence Encounters.

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- If a severe TAPS report were generated without a corresponding pilot report (or report of lower intensity), dispatchers would make decisions based on the TAPS report.

- Pilots may decide that an airframe inspection is necessary based on their experience and use any corresponding TAPS report for real-time comparison and verification.

4. Flight Following: Turbulence on Arrival Path.

- Dispatchers would provide TAPS information prior to the top of descent. Typically, pilots prefer not to communicate with dispatchers below 10,000 ft.

- Only severe TAPS reports would trigger a response or closure of an arrival corridor. Flights would then either hold or divert, an airline would not allow aircraft to traverse region of reported severe turbulence.

The workshop concluded with a discussion about the near-, mid-, and long-term future development of the TAPS (and E-Turb Radar) technologies. Near-term applications may be realized within a year and included the communication of TAPS information to the flight crew via an ACARS textual message. Mid-term applications involved the displaying of TAPS information to the flight crew in aircraft equipped with an electronic flight bag (EFB). Long-term goals would be the integration of TAPS cockpit displays, TAPS ground station displays, the E-Turb Radar, and the participation of ATC. Overall, there was an extremely positive response to the two technologies and their potential use for enhancing flight safety and increasing operational efficiency.

3.3.8   Summary of the TAPS Concept of Operations for Dispatchers

A Concept of Operations presents an understanding of the needs for and expectations of a proposed technology to potential users. This CONOPS summarizes the incorporation of TAPS into flight operations for dispatchers.

3.3.8.1   Current System Description

A dispatcher's complete understanding of turbulence hazards is attained by listening to or reading turbulence reports from pilots and searching through various weather data sources. The level of meteorological knowledge varies among dispatchers, even though most have had some training in understanding weather phenomenon and forecasting. However, since there are insufficient means of integrating the available turbulence information into a logical, usable source, it becomes incumbent upon the dispatchers themselves to assimilate the information and accurately portray this information to the flight crew.

Pilot reports of turbulence are intended to provide information concerning existing flight conditions to dispatchers and ATC. Verbal PIREPs are sent to dispatchers and controllers by radio and the ACARS datalink system is used for textual reports. Turbulence reports that are passed to the Flight Service Station are displayed on the Aviation Digital Data Service website. Currently, there is no automated method of making these reports, and the flight crew must perform this duty manually as time permits.

Since pilots must be involved in the generation of the turbulence reports in today's environment, the resulting report will always be based on their subjective interpretation of the turbulence encounter. No formal measure of the true aircraft response or g-loads caused by the turbulence is reported. The reported location is not always reflective of the altitude and geographic region of the actual encounter. Hence, several altitude levels can essentially be eliminated from the available airspace by a few non-descriptive reports of a rough ride.

Turbulence encounters are also under-reported, especially in regions of convection that are rapidly developing and for which turbulence is expected. In such cases, the pilot's workload may be high from making tactical decisions to avoid the convective hazards in a busy region where all aircraft are

requesting route deviations from ATC. The pilot may be unable to make timely and accurate turbulence PIREPs, especially to the dispatchers, for dissemination to other company aircraft.

For ground personnel, high workloads may lead to reports not always being formally entered into the FAA database. This has resulted in an almost exclusive reliance on radio transmissions and internal company-mandated PIREPs to identify areas of turbulence. There are limited methods to communicate and display the turbulence information to the various users. Therefore, the lack of shared information between ATC controllers, dispatchers, and pilots limits the degree of interaction the users can have when making decisions regarding turbulence. Dispatchers must rely on NEXRAD reflectivity images, airmets/sigmets, CCFP, and inputs from pilots to understand the potential turbulence threat to an aircraft.

3.3.8.2   Users

Five categories of organizations are involved in the flow of information within the current turbulence information system: flight crew, Airline Operations Control (AOC), Air Traffic Controller, the Traffic Management Unit (TMU), and the Air Traffic Control Systems Command Center (ATCSCC). For the purpose of these discussions, the flight crew will represent the pilots exclusively. Figure 32 illustrates the connectivity among the different users and organizations within the current system. It should be noted that the AOC structure might differ between airlines and most airlines lack an internal meteorological departments but may have on-site contractor support; however, the general communication requirements are similar.
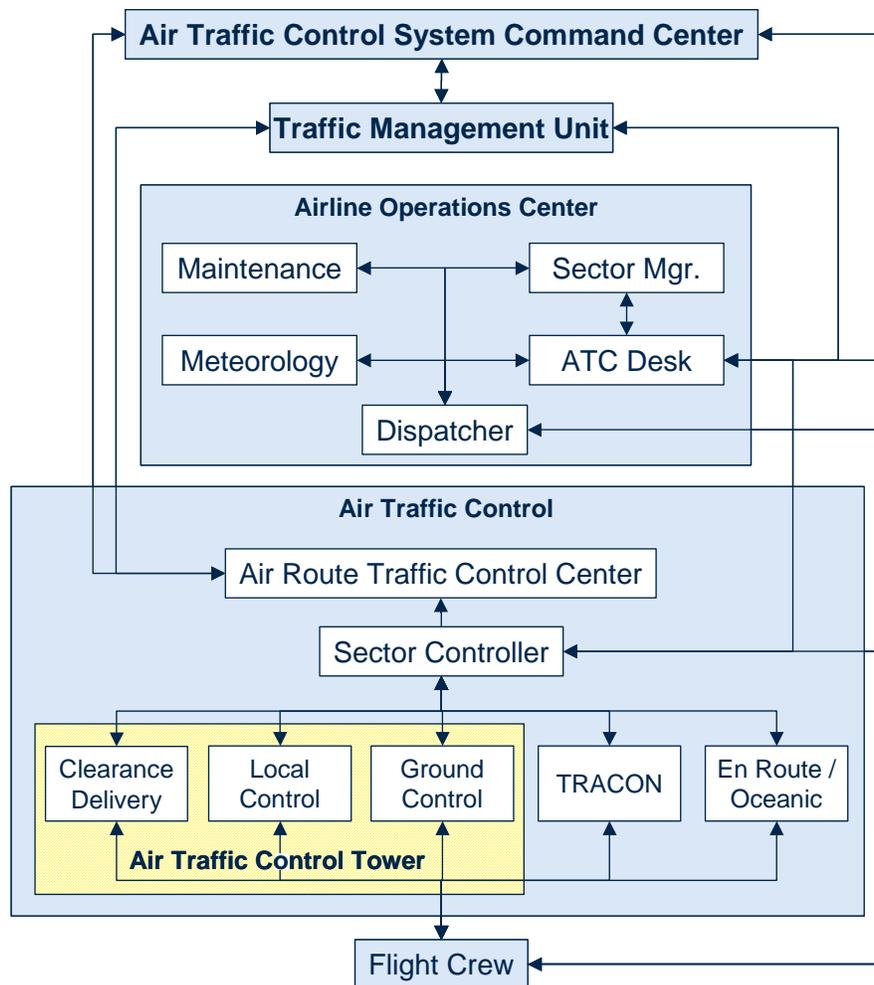
Figure 32: User Connectivity Diagram

3.3.8.3 Interaction Among Users

The existing system for the communication of turbulence information between key role players is complex. A simplified overview of the participants and their communications paths is illustrated in Figure 33. The current system requires the collaboration and interactions among various users, and the type of interaction depends on the task at hand and parties involved. The information presented in Table 7 summarizes and generalizes these interactions and the actions taken by each user class in the information flow of the current system. These descriptions reflect current practices.
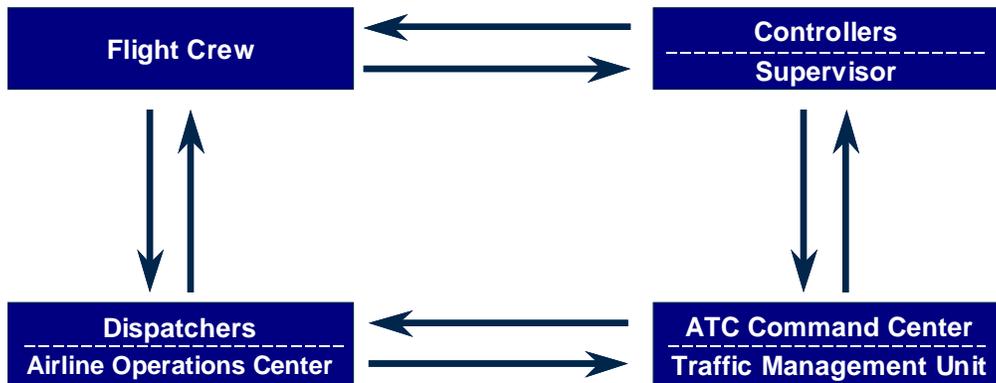
Figure 33: Current Turbulence Information Flow

Table 7: Summary of Interactions Among Users

Turbulence Information Provided/Gathered	Decisions to be Made	Actions
Interaction: Flight Crew to Controller		
Provide turbulence PIREPs (usually verbally). Request for ride quality reports ahead (as made from other aircraft) or at other altitudes. Pilot's view of weather radar reflectivity and turbulence display provides tactical hazard information.	Request for deviation based on the information received and seen on the radar. Request for altitude change based on information received and seen on the radar.	Change route around region of convection. Change altitude (climb/ descend). Prepare cabin for possible turbulence encounter.
Interaction: Controller to Flight Crew		
Request for ride quality PIREPs. Receive ride quality reports.	Deviation clearance. Altitude change clearance.	Respond to ride reports from other aircraft. Initiate PIREP distribution by providing information to supervisor.
Interaction: Flight Crew to Dispatcher		
Provide occasional verbal/text turbulence PIREPs (as workload permits). Request for ride reports ahead from other company aircraft. Request for deviation recommendations. Request for altitude recommendations.	In collaboration with dispatcher, decide whether a region of weather (convection, turbulence, etc) should be avoided. If it is to be avoided, what is the preferred deviation (altitude, flight path, both).	Get recommended routing and performance data for reroute negotiation with ATC. Execute deviation. Prepare cabin for turbulence, if necessary.
Interaction: Dispatcher to Flight Crew		
Receive occasional verbal/text turbulence PIREPs from other aircraft. Ride quality requests from company aircraft. Deviation recommendations. Altitude recommendations.	Decide whether the identified regions of weather (convection, turbulence, etc) are a threat to the safety of flights being followed, and are the affected aircraft far enough away to be able to route around/over/under the region. If so, decide on the best route to optimize safety.	Notify company aircraft of potential threat(s). Recommend route deviations or altitude change based on meteorological information, and reports from other company aircraft.
Interaction: Dispatcher to Traffic Management Unit		
Provide relevant weather information based on meteorological information and turbulence PIREPs.	Optimize airline schedules and routing (from nominal) given adverse conditions (e.g., regions of turbulence, convection, etc.). Provide airline plan – reroute schedule.	Request for route availability. Request for changes based on "restrictive flow program."
Interaction: Traffic Management Unit to Dispatcher		
Receive relevant weather information from airlines based on their internal information sources including turbulence PIREPs.	Define a national flow plan, or, if the weather is contained within a center the flow plan can be defined within that center only. The plan will consist of defining: miles in trail, reroutes, and ground stops	Communicate with airlines and execute plan.

3.3.8.4   Current System Deficiencies and Justification for Change

The dynamic nature of turbulence requires flexibility by the users to plan for and navigate aircraft around regions of significant weather. In order to provide recommendations to improve the quality and communication of turbulence information, it is important to understand where the deficiencies exist and to provide a justification for improving these deficiencies. The operational environments identified in which TAPS will prove beneficial to dispatchers are flight planning and flight following.

The increased situational awareness provided by TAPS will allow dispatchers to plan accordingly for the safety of the passengers and the aircraft they are monitoring. TAPS will function as supplemental information that the user has at their disposal for making decisions about the condition and future planned route of the aircraft.

Flight Planning

The aircraft dispatcher is responsible for selecting a route that most complies with safety, passenger comfort, economy, and available National Air Space requirements, including restricted airspace, etc. In many congested areas and very short stage lengths, routes are limited to only a few options based on ATC preferred routes. During periods of adverse weather, available and/or mandatory routes may be selected by ATC, thus limiting the selection capabilities of the dispatcher. If the dispatcher deems the ATC identified routes as unacceptable, a negotiation for a new routing through the ATC coordinator is initiated. Flight plan development is usually accomplished 1-2 hours prior to departure with only limited knowledge, based solely on vague forecasts, of when and where turbulence might exist. The dispatcher may reassess the route due to weather, turbulence, or other constants and modify these via computer automation up to 45 minutes prior to flight planned departure time. Any changes desired within the 45-minute limit must be coordinated with the TMU. Table 8 provides examples of the deficiencies of the current system for flight planning.

Table 8: System Deficiencies - Flight Planning

Deficiencies of Current System	Justification for Change
A dispatcher has limited knowledge of the location and intensity of turbulence along the planned flight path and cruise altitude.	Observations of turbulence conditions, in conjunction with forecasts, can be very useful in planning to avoid regions of turbulence. However, since flights are planned up to 1-2 hours in advance of take-off, the turbulence information generated in this process will be speculative.
No or inaccurate turbulence information may cause dispatcher and pilot to agree on insufficient fuel to circumnavigate turbulence, especially during congestion.	Improved awareness of enroute constraints might require additional fuel to be considered to safely avoid turbulent regions.

Flight Following

Flight following involves the largest amount of operational time. The dispatcher is responsible for monitoring the progress of the flight and providing significant weather updates to the flight crew based on changes to forecasts and turbulence PIREPs. Even though small deviations around turbulent areas are usually negotiated between the pilot and ATC controller, the dispatcher may recommend amendments to the planned flight path to comply with fuel and aircraft performance capabilities. Table 9 provides examples of the deficiencies of the current system for flight following.

Table 9: System Deficiencies - Flight Following

Deficiencies/Limitations of Current System	Justification for Change
Pilots' decisions to navigate around convection are based on their airborne radar reflectivity maps in the cockpit. More than 80% of all turbulence accidents occur in the vicinity of convection. When approaching convection, currently there is no indication of the location and intensity of the turbulence hazards.	As pilots navigate in and around convection, they may provide turbulence PIREPs to the sector controller and other aircraft in the vicinity as their workload allows. As previously mentioned, these reports may be inaccurate and, in many situations, lead to requests for deviations increasing radio frequency congestion. In addition, if the convective region spans several sectors, pilots may not be aware of the turbulence PIREPs until they switch to the next sector frequency because controllers rarely provide information about other sector conditions.
	If the turbulence information was reported and disseminated automatically, dispatchers may use this information to communicate with company aircraft whose routes will take them through the affected regions, and may use the information, in conjunction with forecast products, to plan future flights around the region if necessary.
If a region of airspace has been closed due to severe weather, there will come a time when the airspace must be reopened to air traffic. In order to do this, a "pathfinder" aircraft is required. Currently, this aircraft will be entering a region where there are no PIREPs, and there is only NEXRAD and airborne radar information.	Opening the region of airspace should be based on knowledge of the turbulence hazards. A "pathfinder" aircraft equipped with TAPS would be the perfect candidate to penetrate such a region of airspace. TAPS will provide other aircraft, controllers, and dispatchers with immediate reports of the turbulence encountered by that aircraft. Based on information from the "pathfinder" aircraft, other aircraft may be routed into the region safely and quickly.
If the pilot perceives that the aircraft has experienced severe turbulence, a request for an inspection will be made to the dispatcher. PIREPS made in this manner are known to be very subjective and inaccurate, and may not always be provided in a timely manner due to the circumstances of the event. In addition, the PIREP may not necessarily be distributed throughout the system to all users.	There is a need for immediate, accurate, and automatic reporting of severe loads events. It is important to understand when an aircraft has encountered severe loads so that appropriate planning may be accomplished for maintenance to inspect the structural integrity of the aircraft and return the aircraft to service. This immediate information would allow for improved turn around time or preparation for a change of equipment and possibly reduce a delay.
The filed flight plan for all flights includes a designated arrival routing plan (Standard Terminal Arrival Route). This arrival plan transitions the aircraft from high altitude sectors to low and approach sectors. In most cases (unless provided by the Dispatcher) turbulence information is not available before descending and switching to radio frequencies for the lower sectors and/or Terminal Radar Approach Control.	Prior information of turbulence conditions that pose a hazard on the arrival path may allow the pilot and dispatcher to develop alternate safer plans in advance of the actual encounter, such as airborne holding, reroute to another arrival fix or diversion to an alternate airport.

3.3.8.5   Integration of TAPS into Current System

TAPS will enhance a dispatchers' situational awareness of the location and intensity of turbulence by providing real-time, quantitative turbulence encounter information downlinked from aircraft. TAPS will remove the need for inference that is currently required to interpret turbulence information and enhance tactical and strategic decision-making for airspace usage and aircraft routing by enabling users to predict the effect of the reported turbulence on their aircraft. Table 10 summarizes how TAPS would enhance dispatcher operations for certain common scenarios.

Table 10: TAPS Enhancements to Flight Operations

Operational Scenario	Enhancements Using TAPS
Flight Planning	TAPS information (in conjunction with forecasts and observations) utilized to select route and altitudes to minimize turbulence impact on a flight. Light turbulence reports would be evaluated for passenger comfort, while moderate or greater reports would be perceived as possible safety issues.
Aircraft Approaching Convection	With TAPS reports, a dispatcher has improved situational awareness of location and intensity of turbulence encounters and may scale received information to determine potential impact to aircraft being monitored. TAPS reports allow dispatchers to develop improved reroute recommendations.
Aircraft Encounters Severe Turbulence	Dispatcher presented with objective information of severe turbulence encounters with supporting flight data. TAPS report information quickly supplied to maintenance to facilitate aircraft inspection and analysis.
Turbulence On Arrival Path	With TAPS information, dispatchers are capable of identifying turbulent and non-turbulent arrival paths. Information on arrival corridor conditions may be provided to the pilots. Dispatchers may also understand which arrival paths could be closed, due to severe turbulence reports, and plan accordingly in case their aircraft may have to hold or divert.

The automatic reporting of turbulence encounters by TAPS enhances and improves the overall turbulence information flow. The objective reporting based on g-loads and the timely transmission of these reports to a ground station from reporting aircraft provides additional information to the user that may previously have been subjective, late, and/or unavailable. The automatic transmission of reports decreases the need for interactions and streamlines communications between the reporting aircraft's flight crew, ground controllers, and company dispatchers. With the sharing of information, TAPS will provide a common picture of potential turbulence hazards to all users.

The integration of TAPS information into a ground station display will not eliminate any existing capabilities present within the user's current toolset; this integration will enhance them. The full potential of TAPS will only be realized by the continued development and usage of the TAPS display tools, and this same turbulence information becoming accessible (either textually or graphically) by pilots and controllers.

4. Enhanced Turbulence Radar

Recognizing the need to provide more reliable and relevant turbulence information to the cockpit, AeroTech Research, under contract to NASA, developed an enhanced turbulence algorithm that takes the radar estimate of 2nd moment[5] and calculates real-time estimates of predicted g-load. That information is then translated onto the radar display in two levels of turbulence, presented in magenta, scaled to the aircraft's configuration and flight condition.

The current turbulence mode function in weather radars relies on analyzing the measurement processed from the radar returns. A small 2nd moment indicates that most of the particulates are moving with the same speed and direction – i.e., smooth air. A large 2nd moment indicates a large variation in the particulates' velocities – i.e., turbulence. In current radars, if the 2nd moment value is greater than a defined threshold value, a region of magenta is shown on the display to indicate an area of turbulence. The problem with this technique is that the turbulence metric does not differentiate between aircraft types, e.g. a Boeing 737 would display the same magenta picture as a Boeing 777, when in fact these aircraft would react much differently to the turbulence. Typically, a smaller aircraft would require a smaller 2nd moment to induce a severe turbulence encounter than a larger aircraft. "The indirect and often incorrect assessment of turbulence has led many pilots to believe the systems were unreliable for warnings of rough skies ahead."[6]

4.1 E-Turb Radar In-Service Evaluation Overview

Under the NASA TPAWS Program, AeroTech Research, with subcontractors Rockwell Collins and Delta Air Lines, implemented the E-Turb Radar software into a Rockwell Collins WXR-2100 "Multiscan™" airborne weather radar. Together with the capabilities of the Multiscan™ radar, the enhanced turbulence feature is particularly helpful in detecting turbulence within areas of low reflectivity, where the radar display is showing either black (less than 20 dBz) or green reflectivity levels while in Weather and Turbulence (WX+T) mode. Such situations often occur in areas perceived as "holes," where low radar reflectivity between convective areas may mask rapid convective development and significant turbulence. In areas of convection, the result is a well-defined area of magenta that truly and objectively represents the hazards that could lie ahead for that particular aircraft. For the ISE version of the E-Turb Radar, full functionality existed at a maximum distance of 25 nautical miles.

Three goals were established for the evaluation of the E-Turb Radar. They were 1) to demonstrate a realizable and reliable turbulence detection system in operational environments, 2) evaluate the system's performance using data downloaded from the aircraft, and 3) solicit subjective pilot feedback.

The history of the E-Turb Radar system technology development is depicted in Figure 34. The development of the concept algorithms began in 1998 with simulations and feasibility concept evaluations. The E-Turb Radar algorithms were subsequently implemented within the radar onboard NASA's B757-200 Research Aircraft and flown in a series of flight experiments.

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[5] 2nd Moment is the measure of the second spectral moment estimate from the radar signal processor providing a reflectivity-weighted variance of the radial velocities. This is a measure of the shear or turbulence within the resolution volume. Source: Doviak, Richard J. and Zrnić, Dušan S. *Doppler Radar and Weather Observations*, 2nd Edition. Dover Publications, Inc., Mineola, New York, 2006.

[6] Croft, John. "Truer Pictures of Turbulence,*" Aerospace America*. April 2005, pg. 36.
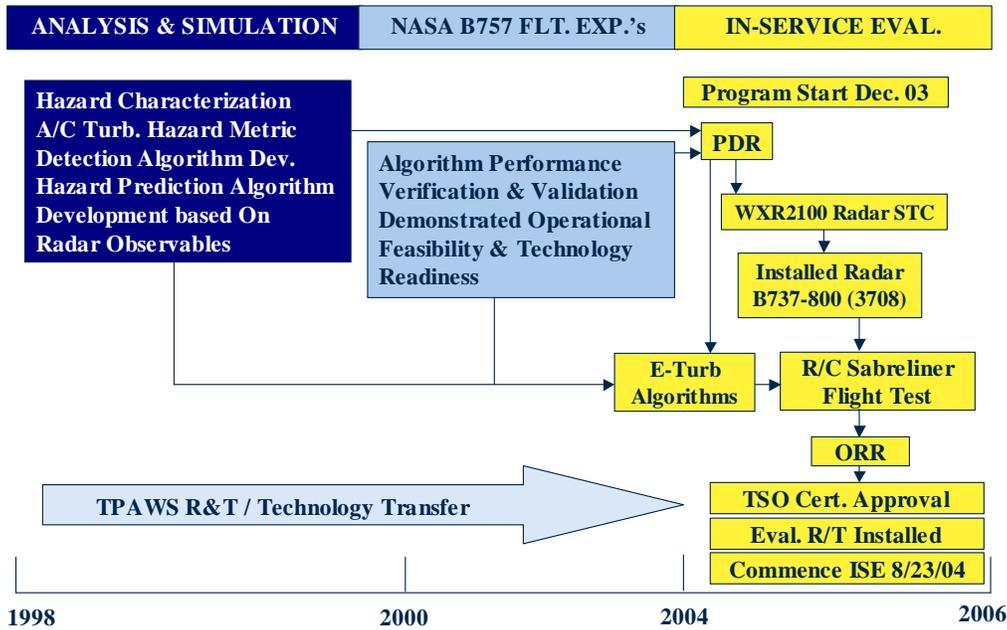
Figure 34: History of E-Turb Radar Technology Development

Following the start of the ISE in December 2003, a Preliminary Design Review (PDR) was conducted to define the design of the E-Turb Radar system installation on Delta Air Lines' B737-800, ship number 3708 (DAL 3708). The approval process for a Supplemental Type Certificate (STC) for the installation of a Rockwell Collins WXR-2100 Multiscan™ radar onboard a B737-800 was completed on March 28, 2004. Following the STC approval, the Multiscan™ radar was installed on DAL 3708 without the E-Turb Radar algorithms implemented, although the software for these algorithms was being written during this period. A series of flights were conducted with the Rockwell Collins' Sabreliner 50 flight test aircraft to test and evaluate the hardware and the software for implementation on the Delta aircraft. An Operational Readiness Review (ORR) was conducted on August 11, 2004, to review and assess the readiness of the E-Turb Radar system for final aircraft implementation. Technical Standard Order (TSO) certification was approved on August 23, 2004, allowing for commercial operational service with the E-Turb Radar algorithms installed on DAL 3708. The E-Turb Radar system has been operating in revenue service onboard DAL 3708 since August 2004.

4.1.1 Organization

The E-Turb Radar ISE was a collaborative effort, with significant in-kind support, between NASA, AeroTech Research, Rockwell Collins, and Delta Air Lines. AeroTech held the prime contract with NASA for the E-Turb Radar ISE and subcontracted Rockwell Collins and Delta Air Lines to provide resources, expertise, software development, and assistance in the analysis and evaluation. The organizational roles and responsibilities of the various participants are outlined in Figure 35.

Figure 35: E-Turb Radar ISE Organizational Structure

4.1.2   E-Turb Radar System Implementation

The evaluation of the new radar technology involved several new key features. The program saw the insertion of a new, highly automated WXR-2100 Multiscan™ transceiver technology that provides improved performance with many automated features and a 2nd moment detection algorithm with performance characteristics equivalent to the one successfully demonstrated in NASA flight experiments. The ISE is a direct transfer of the NASA hazard prediction algorithm technology and related hazard tables tailored to B737-800 commercial operations. Additionally, real-time estimation of the aircraft's weight was interfaced with the radar system to support g-load prediction. A graphical depiction of the overall E-Turb Radar system architecture is shown in Figure 36.
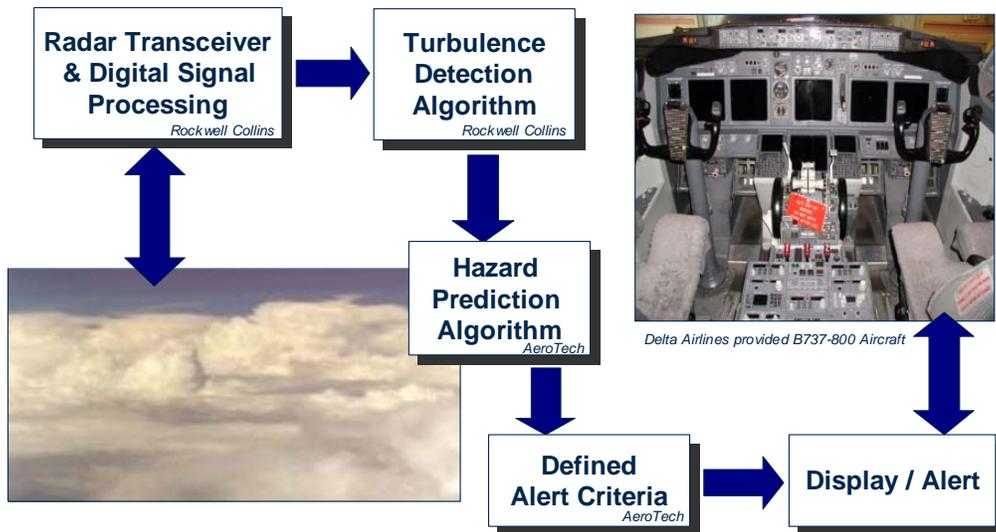
Figure 36: E-Turb Radar System Architecture

Figure 37 shows a diagram of the E-Turb Radar system concept. For the ISE, the E-Turb Radar platform uses Rockwell Collins proprietary multiple-lag autocorrelation algorithms optimized for specific signal to noise ratios to improve the detection reliability of the radar. Real-time values of the aircraft's altitude,

airspeed, and weight are used in the hazard prediction algorithm to scale the 2nd moment to a predicted $\sigma_{\Delta n}$. The E-Turb Radar features include a presentation of the predicted turbulence impact as a $\sigma_{\Delta n}$ (the same hazard metric used for TAPS).
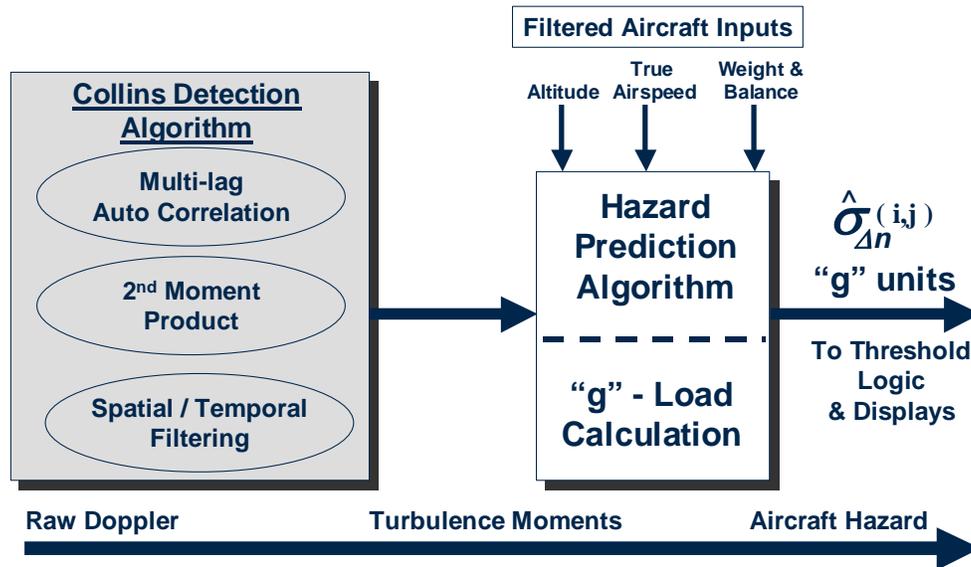
Figure 37: E-Turb Radar Technology System Concept

The cockpit display of the turbulence detected by the E-Turb Radar is presented in two intensity levels. The thresholds for these two levels are defined as:

- Level 1 (Speckled Magenta) $0.093\ g \leq \sigma_{\Delta n} < 0.156\ g$

- Level 2 (Solid Magenta) $\sigma_{\Delta n} \geq 0.156\ g$

Figure 38 illustrates the two-level threshold presentation of the detected turbulence to an aircraft's crew.
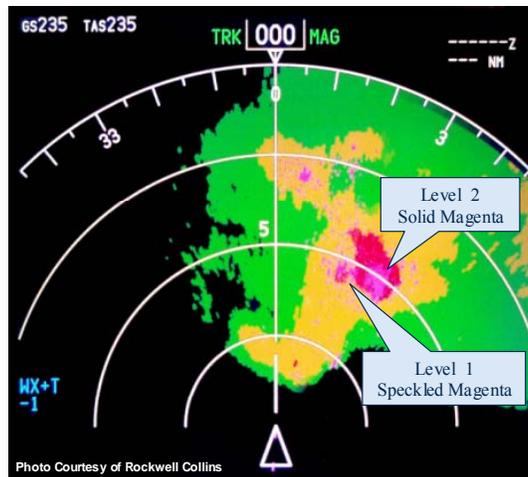
Figure 38: Cockpit Presentation of Turbulence by the E-Turb Radar

As part of the initial feasibility study conducted in August 2003 with Honeywell and Rockwell Collins, the Rockwell Collins WXR-2100 Multiscan^{TM} radar was selected for the E-Turb development and the ISE. The components of the WXR-2100 Multiscan^{TM} radar are presented in Figure 39.
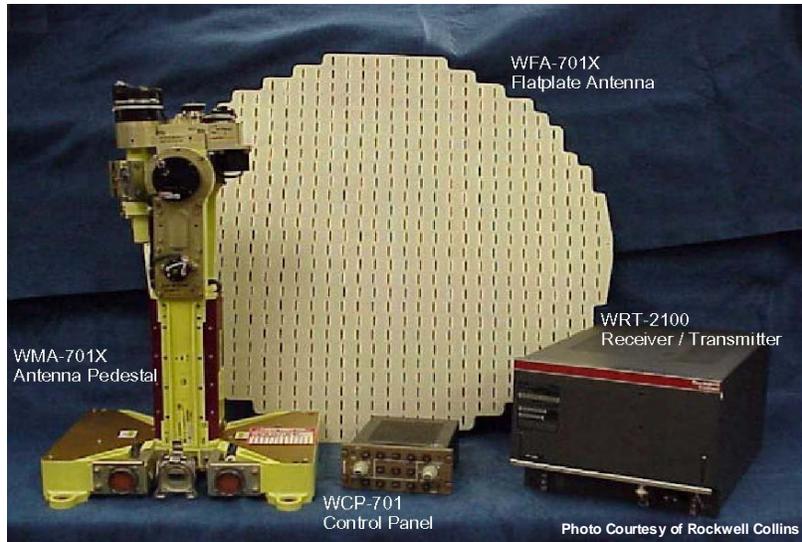
Figure 39: Rockwell Collins WXR-2100 Multiscan^{TM} Radar

4.1.3 Summary of Rockwell Collins Sabreliner Flight Tests

As part of the E-Turb Radar System Technology Evaluation Program, flight tests were conducted in 2004 using an engineering radar unit onboard a Rockwell Collins' Sabreliner 50 flight test aircraft shown in Figure 40. The Sabreliner aircraft is configured with two engineering stations. The first engineering station controls the recording of radar In-phase and Quadrature phase (I and Q) data, aircraft ARINC 429 data, and radar display data from the ARINC 453 display bus. The other engineering station has the capability to control the radar and monitor it during flight operations. The purpose of these flight tests was to test and evaluate the hardware and the software for implementation on the Delta aircraft. An initial assessment of the E-Turb Radar algorithms and the accompanying hazard table was also performed.

Figure 40: Rockwell Collins Sabreliner Flight Test Aircraft

Eleven flights were conducted from April 14, 2004 to July 8, 2004. Table 11 lists further details about each of the individual test flights, their purpose, and the resulting changes to the radar hardware and software configuration. The final flight used a radar hardware and software configuration functionally equivalent to the system provided to Delta Air Lines for the E-Turb Radar ISE. During this flight, many convective penetrations were carried out to collect corresponding in situ acceleration data for evaluation of the radar detection performance. For this flight, 19 event recordings were made, seven of which were

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suitable for an initial assessment of the radar performance yielding 15 individual data points. There was no indication from the results that changes would be required to the hazard tables for the B737-800 installation. Additionally, results of the flight test indicated a reasonable correlation between the prediction of the radar and the in situ measurement below a $\sigma_{\Delta n}$ of 0.2g. Results and lessons learned from the Sabreliner flight test were used in the refinement and implementation of the WXR-2100 with the E-Turb Radar technology on a Delta B737-800 aircraft.

Table 11: Summary of Sabreliner Flight Tests[7]

Date	Location	Flight Purpose	Results
4/14/2004	Cedar Rapids to Western Iowa and back	No weather available. Purpose is to evaluate turbulence algorithm against ground returns and to evaluate ability to change detection thresholds.	Validated ability to detect/display turbulence and to change detection thresholds.
4/20/2004	Cedar Rapids to central Indiana and back.	Evaluate turbulence algorithm against weather targets.	Saw erroneous returns, which lead to discovery of error in off-axis beam broadening compensation algorithm. Saw erroneous spreading of turbulence detections in range, which lead to correction in range filter.
4/22/2004	Cedar Rapids to southwester Missouri and back.	Evaluate turbulence algorithm against weather targets and to check off axis beam broadening compensation.	Several small weather encounters. Some correlation between predicted and in situ turbulence. Storms were relatively weak.
4/23/2004	Cedar Rapids to southern Missouri and back.	Evaluate turbulence algorithm against weather targets and to check off axis beam broadening compensation.	Saw noise building during low reflectivity regions due to over flight hold. Changed Signal to Noise Ratio (SNR) thresholds to prevent erroneous turbulence detection in low SNR conditions.
4/29/2004	Cedar Rapids to Little Rock. Refueled at Little Rock, Arkansas	Test new thresholds on SNR. Test alien filter (first time alien filter is operational on E-Turb Radar). Test modification to reject turbulence detection in areas where second range returns are detected.	Penetrated strong weather cells with good correlation between predicted and in situ turbulence. Saw erroneous detections close to ground on landing.
4/29/2004	Little Rock to Cedar Rapids	Test new thresholds on SNR. Test alien filter (first time alien filter is operational on E-Turb Radar). Test modification to reject turbulence detection in areas where second range returns are detected.	Penetrated strong weather cells with good correlation between predicted and in situ turbulence. Saw erroneous detections close to ground on takeoff. Turbulence "spoking" problem was traced to error where ground clutter suppression code was being executed in manual mode. Discovered sign error with drift angle due to erroneous position of turbulence shadows near strong isolated storm cells.
5/27/2004	Cedar Rapids to Central Missouri and back	Test fixes for ground clutter suppression and drift angle.	

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[7] Tabular Data Courtesy of Rockwell Collins and continued onto the following page.

Table 11: Summary of Sabreliner Flight Tests (con't)

Date	Location	Flight Purpose	Results
6/08/2004	Cedar Rapids to southern Illinois and back.	Test fixes for ground clutter suppression and drift angle.	Several strong storm penetrations with good correlation between predicted and in situ turbulence.
6/18/2004	Cedar Rapids to northwestern Arkansas and back.	Test event logger.	Tested event logger acceleration triggers by inducing normal acceleration with stick pumping. Observed several radar resets during flight which was eventually traced to chip select line control during data logging.
7/02/2004	Cedar Rapids to eastern Nebraska and back.	Test issues with event logger triggers and other minor threshold issues with detection algorithm. Test new chip select code, which should prevent radar resets. Evaluate detection algorithm at intermediate altitudes.	No radar reset issues detected. Had good correlation between in situ and predicted turbulence at cruise and intermediate altitudes down to 19,000 ft.
7/08/2004	Cedar Rapids to central Missouri and back	Test final software build.	Had several encounters with Level 2 turbulence and numerous smaller encounters. Had good correlation between in situ and predicted turbulence. Data logger worked correctly. No resets observed.

4.1.4   Aircraft Selection

The aircraft selected for evaluating the E-Turb Radar was a Delta B737-800 aircraft. DAL 3708 (shown in Figure 41) was selected since it was already equipped with a Rockwell Collins radar. Additionally, it was one of the aircraft equipped with the TAPS reporting software, which allowed for a crosscheck of the two technologies during the ISE.

Figure 41: Delta Air Lines Ship 3708

4.1.5   Data Logger Implementation

A key feature in the assessment of the performance of the E-Turb Radar during the ISE was the recording of data on the radar unit for events triggered during flight operations. Event data was recorded during all phases of flight from weight-off-wheels to weight-on-wheels and was accessed and downloaded from the aircraft via an RS-232 port. An Integrated Radar Data Logger, developed by Rockwell Collins, could store approximately 4.8 hours of reflectivity and turbulence scan data, as shown in Figure 42. In addition to this radar sweep data, aircraft information regarding position, orientations, accelerations, and radar

mode data were recorded for accurate data evaluations. The spatial resolution of the radar display information (turbulence and reflectivity) was reduced in comparison to that displayed on the aircraft due to the memory limitations of the data logger hardware.
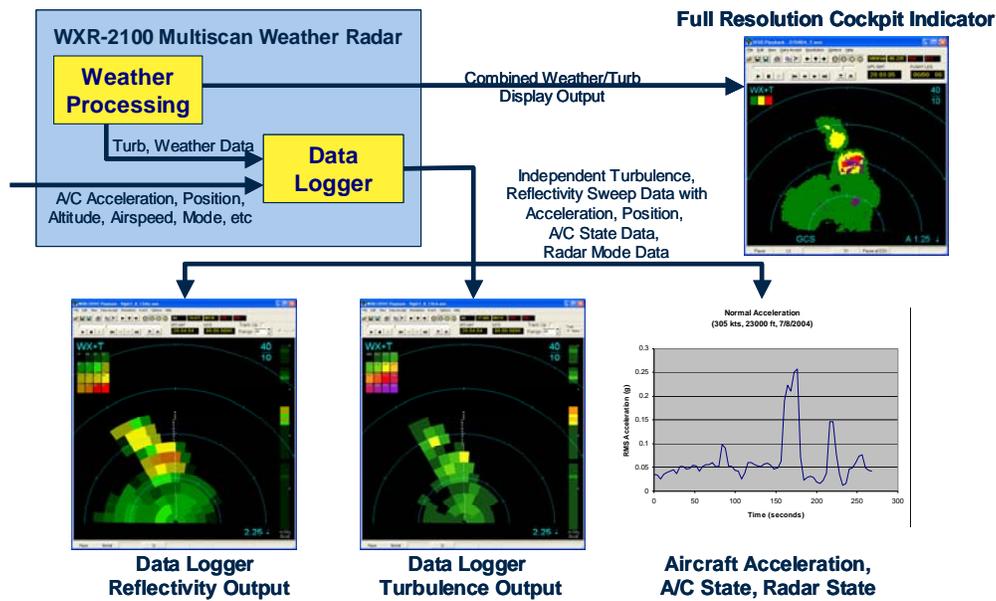
Figure 42: Integrated Radar Data Logger Stores Reflectivity and Turbulence Scan Data

The data logger has programmable trigger thresholds for automatic recordings based on actual turbulence encounters or radar predicted turbulence. There are four triggers that can initiate a data recording of the E-Turb Radar data stream utilizing the data logger:

- Magnitude of Peak Inertial Reference Unit (IRU) Acceleration, $\Delta n \geq 0.5$ g

- 5-second Windowed RMS IRU Acceleration, $\sigma_{\Delta n} \geq 0.156$ g

- Radar Predicted RMS Load, $\sigma_{\Delta n} \geq 0.093$ g

- Manual Activation by Crew

4.2   E-Turb Radar In-Service Evaluation Process

The components of the E-Turb Radar ISE analyses are:

1. Playback of events using the data logger download data: actual events, as seen in the cockpit, could be replayed and snapshots of the display gathered.

2. Pilot feedback: using solicited and volunteered reports from pilots, general feedback and comments were accumulated. A brief summary is included in Section 4.3.2.

3. Statistical analysis of radar performance using the flight data: using data downloaded from the data logger, a statistical analysis of the radar estimation capability was performed.

Results from each component of the analysis are presented in the next section.

4.3   Summary of Results

4.3.1   Playback of Events Using the Data Logger Downloads

The Turbulence Event Playback Tool was used for display and analysis of turbulence events recorded by the Rockwell Collins' Enhanced Turbulence Multiscan[TM] weather radar software. Using the Rockwell Collins' replay tool and data recorded by the data logger, it was possible to review what the radar display was showing during encounters recorded in flight, albeit at a reduced resolution. The replay tool is capable of providing the following functions: reading the archived event data file that is downloaded from the aircraft, displaying the recorded reflectivity data, displaying the recorded turbulence data, displaying in situ aircraft data, monitoring the health of the radar, route plotting, and charting of in situ acceleration and radar turbulence. A selection of representative "snapshots" illustrates the results and capabilities of the system. In the figures shown below, the black background color has been removed to allow the turbulence regions to be seen more clearly. In the cockpit, these regions would be black.

Figure 43 shows the recorded radar display from a DAL 3708 flight. There are convective cells in the vicinity of the aircraft (denoted by the green region in the bottom left). The dotted line is the aircraft's subsequent flight path superimposed on the image. The radar has detected regions of light to moderate turbulence (speckled magenta – Level 1), and a region of greater turbulence intensity (solid magenta – Level 2). These regions were detected in areas of reflectivity less than 20 dBz, which is where normal radars show black or no reflectivity. In fact, in this case the reflectivity in the region of solid magenta was 4 dBz. This event is representative of historical accident cases where the pilot does not see a reflectivity signature on the radar display yet encounters significant turbulence. The E-Turb Radar was capable of detecting these types of hazards. Although the predicted region is not corroborated by the aircraft's penetration of the area, the statistical analysis presented later provides a significant level of confidence in this enunciation.
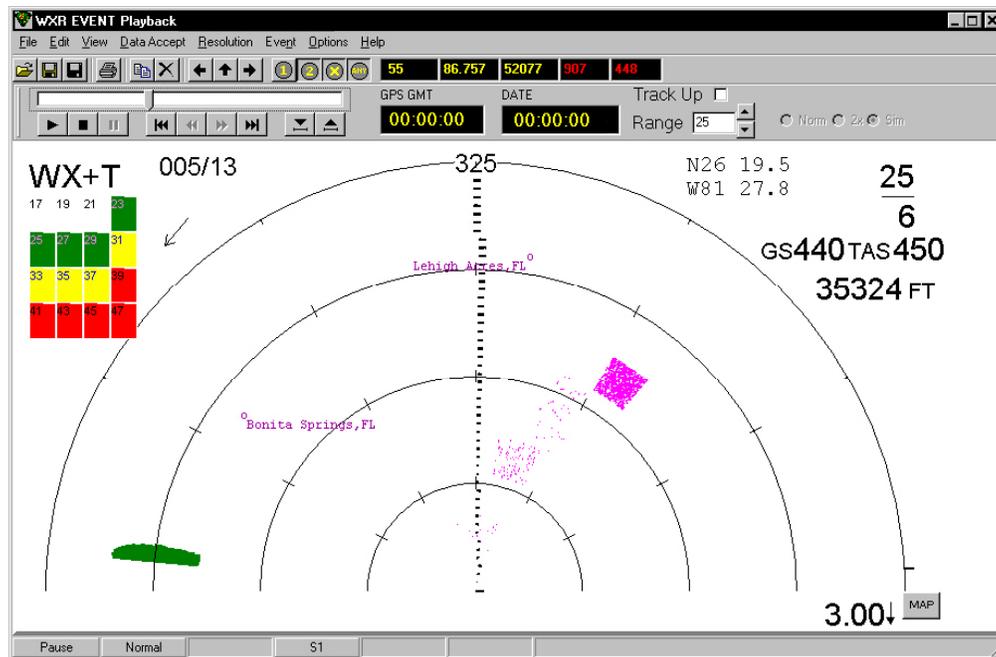
Figure 43: Representative DAL 3708 Encounter, Scan 55

Figure 44 below shows the aircraft's flight path deviating to the left to avoid a convective area clearly depicting turbulence directly ahead. Also depicted are regions of light to moderate turbulence (speckled magenta), one of which lies in the flight path. It was surmised (and supported by pilot feedback) that the pilot deviated around that region to avoid the encounter.
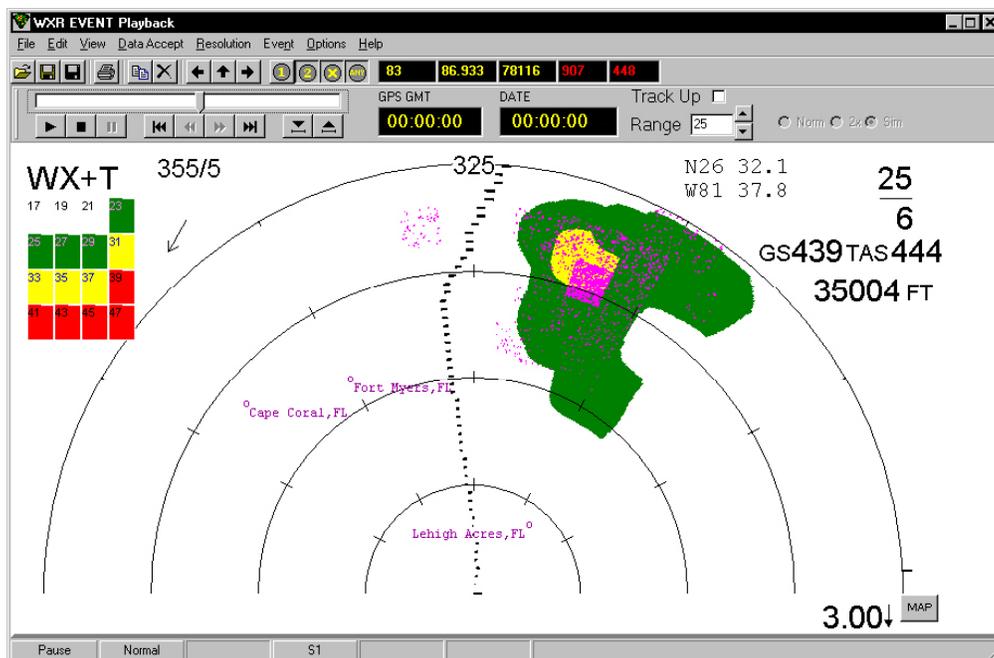
Figure 44: Representative DAL 3708 Encounter, Scan 83

4.3.2 Pilot Feedback

Feedback was elicited from pilots from interviews after the flights, onboard questionnaires, and jump seat observations. Twenty-eight detailed accounts are presented in the Appendix. Dates, flight numbers, and personnel names have been removed from the narrative to preserve confidentiality. It should be noted that the feedback summaries began in May 2004, following the installation of the Rockwell WXR-2100, and before the installation of the E-Turb Radar software; subsequently, feedback and comments did not begin on the E-Turb Radar capabilities until after the upgrade of the onboard software in late August 2004. The following is a summary of the feedback received.

During the evaluation process, the flight crews identified several issues concerning the use of the E-Turb Radar. These issues include a suggested adjustment for setting the lower turbulence threshold regarding ride quality versus safety. In some instances, according to the flight crews, some light turbulence was shown within the display as magenta, but other experienced light turbulence was not displayed during the flight. The pilots felt that both encounters were about the same level of intensity. This possibly indicates a need for an education and training process for future users of the system. Lastly, many pilots requested that turbulence information be provided at ranges greater than 25 nautical miles. The operational range for the production version of the E-Turb Radar is expected to be approximately 40 nautical miles.

In summary, pilots generally agreed that the displayed E-Turb Radar magenta correlated well to experienced turbulence. Of those that disagreed, most either felt that the E-Turb Radar did not provide them awareness of light chop in clouds where they expected it, or that the magenta was only painted where a pilot would expect to find it based on reflectivity. It should be noted that no corresponding TAPS reports were transmitted from DAL 3708 during incidents for which pilots disagreed that E-Turb Radar correlated with experienced turbulence.

Response to the E-Turb Radar has been positive in many respects. Many comments by flight crews have noted that the display of turbulence (magenta) was shown in areas of little to no reflectivity and that the E-Turb Radar product depicts a better definition of magenta than existing weather radars. Most users of the E-Turb Radar have stated that there was sufficient correlation with the turbulence experienced by the aircraft.

4.3.3 Statistical Analysis of Radar Performance Using the Flight Data

Data collection for the ISE of the E-Turb Radar began on August 23, 2004. Since then, twenty-one downloads of the data logger have been made. Table 12 lists information for the date of the download from the aircraft, the date range covered within the data file, and the total number of data logger identified events captured.

Table 12: Summary of E-Turb Radar Data Logger Downloads

Download No.	Download Date	Time Span Covered	Total # of Events
1	08/25/2004	08/23/2004 – 08/25/2004	28
2	09/02/2004	08/25/2004 – 09/02/2004	61
3	09/17/2004	09/11/2004 – 09/17/2004	29
4	09/29/2004	09/17/2004 – 09/28/2004	45
5	10/12/2004	09/30/2004 – 10/11/2004	30
6	10/26/2004	10/16/2004 – 10/25/2004	32
7	12/02/2004	10/27/2004 – 11/25/2004	82
8	12/16/2004	12/02/2004 – 12/05/2004	29
9	02/11/2005	12/17/2004 – 02/10/2005	66
10	03/31/2005	02/12/2005 – 03/24/2005	92
11	05/12/2005	03/31/2005 – 04/23/2005	89
12	07/14/2005	05/12/2005 – 06/02/2005	96
13	08/30/2005	07/14/2005 – 07/25/2005	97
14	10/14/2005	08/30/2005 – 09/25/2005	99
15	11/14/2005	10/16/2005 – 11/14/2005	87
16	02/10/2006	11/14/2005 – 12/31/2005	87
17	04/01/2006	02/11/2006 – 03/31/2006	84
18	09/05/2006	04/01/2006 – 04/21/2006	96
19	10/26/2006	09/05/2006 – 09/15/2006	117
20	11/20/2006	10/26/2006 – 11/02/2006	32
21	12/07/2006	11/22/2006 – 12/04/2006	26

The first step in the processing of the downloaded radar data was to categorize the recorded encounters. Rockwell Collins performed the initial analysis and categorization of the data with subsequent refinement and finalization performed by AeroTech Research. In summary,

- 1,435 turbulence events were triggered and recorded between August 23, 2004 and December 7, 2006,
- 347 events were determined to be invalid data and subsequently discarded, and therefore
- 1,088-recorded events were admissible for analysis.

Invalid criteria causing recording of the radar data stream may have come from several sources, including:

- Touchdown "bumps."
- Radar operated in manual or stand-by mode by the pilot.
- Flight at low altitude with the antenna pointing at ground in manual mode (possibly clutter induced).
- Inadvertent manual triggers by pilots.

The 1,088 data events identified for analysis were separated into three distinct groups for further statistical analysis. Figure 45 presents the distribution of the events between the three categories. The first group represents data recordings triggered by the IRU accelerometer with no display of turbulence by the radar. This may have been indicative of Clear Air Turbulence (CAT) and was the group with the lowest number of occurrences. The second group, represented by the hatch pattern within the pie diagram, was triggered by the radar detecting regions of turbulence of significant magnitude; however,

the aircraft did not traverse these areas, and the accelerometer data could not verify the presence of turbulence. The final group, represented by the solid section of the diagram, was the accumulation of event data recordings when the radar displayed areas of predicted turbulence, the aircraft's flight path traversed the affected areas, and the presence of turbulence was verified by the IRU accelerometer. This final group of 495 events was used for the detailed statistical data analysis.
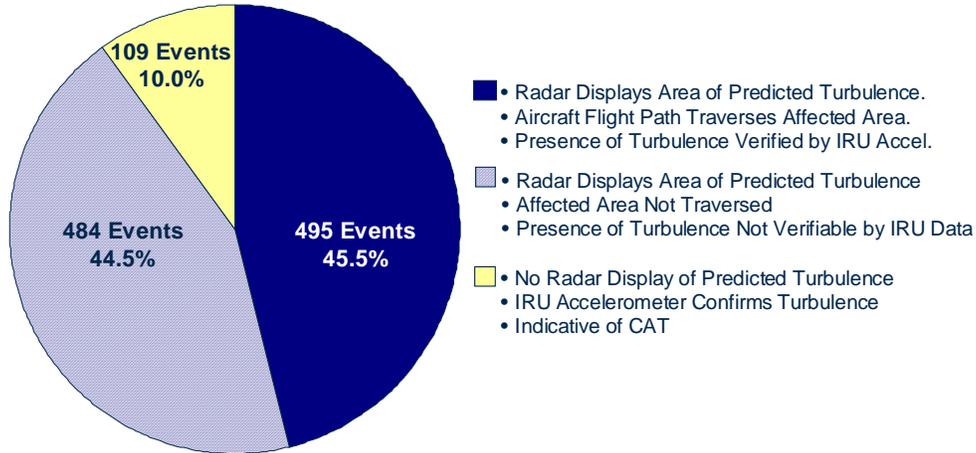
Figure 45: Event Categorization for the E-Turb Radar Analysis

For these 495 cases, an analysis was conducted to determine the correlation between radar predicted and experienced g-loads. Figure 46 shows the linear regression between the peak radar predicted $\sigma_{\Delta n}$ and peak measured $\sigma_{\Delta n}$. To minimize notational complexity in the subsequent text, we define x as peak radar $\sigma_{\Delta n}$ and y as aircraft measured peak $\sigma_{\Delta n}$.
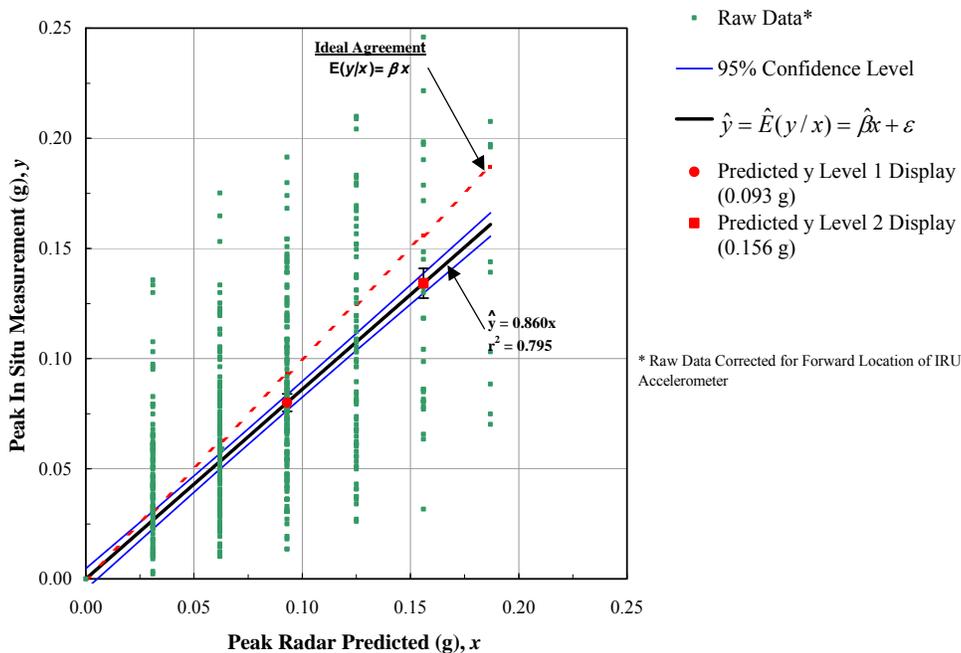
Figure 46: Correlation of Radar Predicted & In Situ Peak $\sigma_{\Delta n}$

The linear regression for the 495 turbulence event data sample produces a trend line with a slope of $\hat{\beta} = 0.860$ and a correlation coefficient $r^2 = 0.795$. Information presented in Figure 46 indicates that the radar

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prediction explains 79.5% of the variation in the actual experienced g-loads, with a general tendency for the radar to overestimate the in situ measurements (since $\hat{\beta}$ is less than one relative to the line of ideal agreement of $\beta = 1$). For an accurate assessment of the loads on the aircraft, the recorded in situ accelerometer data was corrected for the difference between the forward location of the IRU accelerometer and the center of gravity location. The correction required is 23.1 feet forward relative to the typical center of gravity for B737-800 operations. The results show that the linear estimator for in situ accelerometer response $\hat{y}$, based on radar observables (2nd moment) x, is of the form $\hat{y} = \hat{\beta} \cdot x + \varepsilon$ where ε is defined as the error residuals and $\hat{\beta} = 0.860$.

A standard two-tailed t-test was conducted to establish a 95% confidence interval, illustrated in Figure 46, for the "true" slope – the estimator β. The results strongly reject the null hypothesis (HO: $\beta = 0$) as opposed to an alternative hypothesis (HA: $\beta \neq 0$) with an inference that there is convincing statistical evidence to indicate that radar predictions provide reliable estimates of in situ experienced g-loads. In fact, for a 95% confidence interval the data indicate $\beta = 0.860 \pm 0.0385$. Also shown in Figure 46 are two data markers highlighting the display threshold values for Level 1 and Level 2 turbulence predictions.

Estimating the mean values of y (actual g-load) for a given specific value of x (radar predicted g-load) is an important practical problem; as well as finding a confidence interval for $E(y|x)$, the expected value of y given a radar x. Based on the 495-event data sample, two confidence intervals as defined below were calculated:

> **Case I:** Find a 95% confidence interval for the estimated mean in situ g-load for a radar predicted $x = 0.093$ g, which provides the Level 1 display threshold for speckled magenta. Direct calculation of the confidence interval results in 0.0765 g $\leq E(y|x = 0.093$ g$) \leq 0.0835$ g with a probability of $p = 0.05$ that this result was due to chance.

> **Case II:** Same as Case I except the radar predicted $x = 0.156$ g, which provides the Level 2 display threshold. Direct calculation results in 0.130 g $\leq E(y|x = 0.156$ g$) \leq 0.139$ g with a probability of $p = 0.05$ that this result was due to chance.

The above results clearly indicate a general tendency of the radar to overestimate the experienced in situ g-loads due to turbulence. The overestimates range from 10-18% for the speckled magenta threshold ($\sigma_{\Delta n} = 0.093$ g) to 11-17% for the solid magenta threshold ($\sigma_{\Delta n} = 0.156$ g) based on 95% confidence intervals. This performance was considered acceptable given all the sources of variability inherent in the system.

Underlying the statistical influences as discussed above was a key assumption that the residual errors defined as $y - \hat{y}$ have a standard normal distribution (Gaussian) and were independently distributed with a mean of zero. Figure 47 presents a combination of the calculated normal probability distribution function (PDF) and a normalized histogram for the 495 events considered.
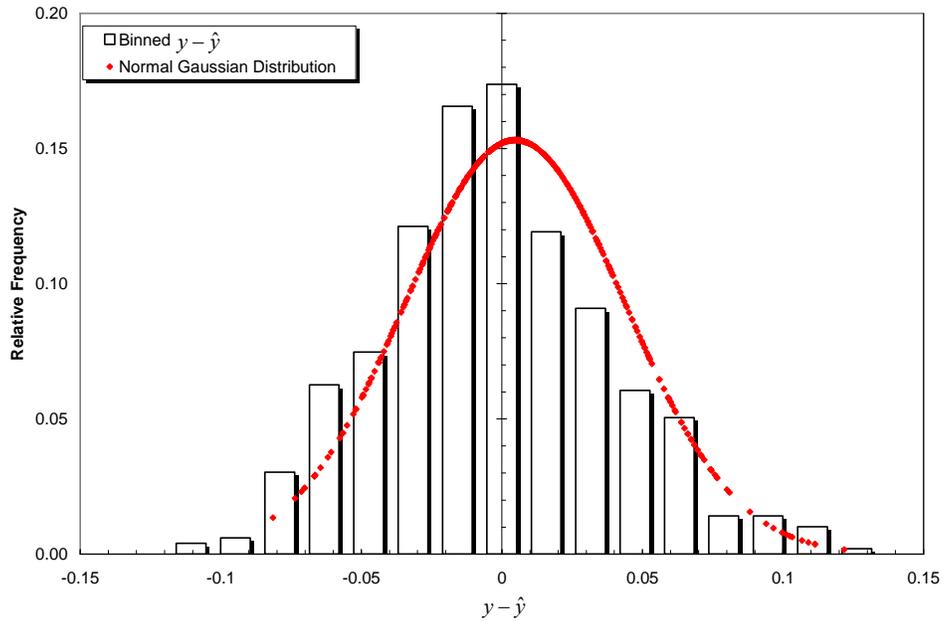
Figure 47: PDF Distribution of Statistical Data

Based on the data, the mean error was $\mu_e = 0.004687$ g with a standard deviation of $\sigma_e = 0.0391$ g. Figure 47 readily demonstrates the errors to be Gaussian in nature. A diagnostic that more clearly demonstrates the Gaussian nature of the error residuals is provided by a Quantile-Quantile plot, shown in Figure 48.
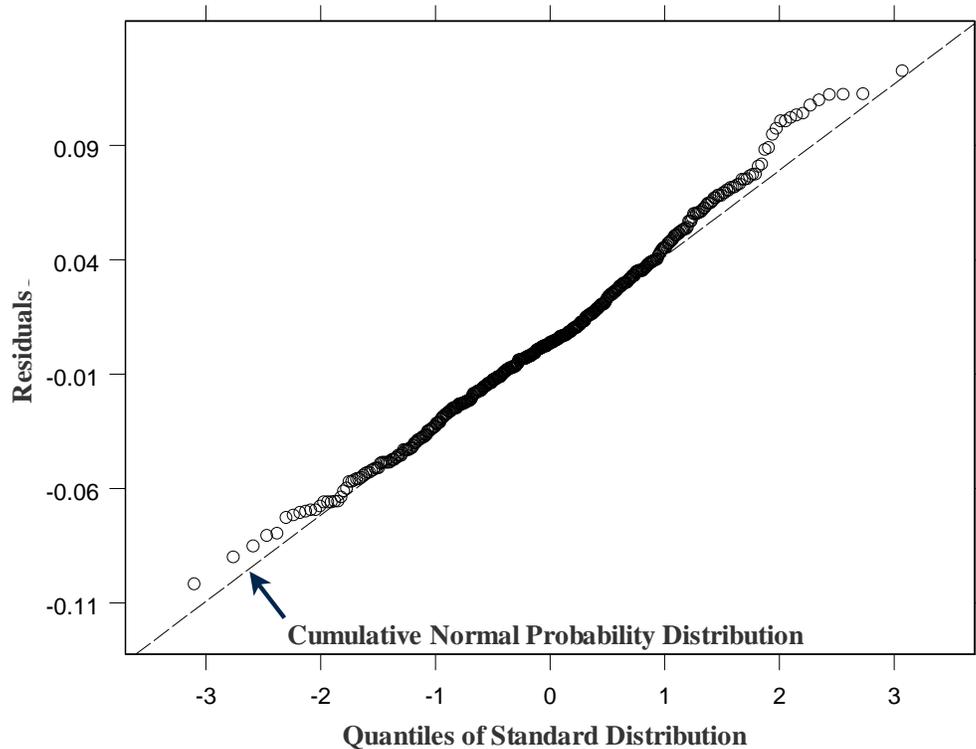
Figure 48: Quantile-Quantile Plot of Residual Errors vs. Standard Normal

If the data points of the Quantile-Quantile plot were to fall close to the straight line (representing the cumulative normal probability distribution) as shown, the conjectured distribution (assumed to be Gaussian) was a reasonably good model for the data. Breakup along the tails was expected given reduced samples available from the data recordings at high levels of turbulence. As presented in Figure 48, the Quantile-Quantile diagnostic gave no reason to doubt that the error residuals are approximately normally distributed and the underlying assumption of the earlier analysis was supported.

A final key result of the statistical analysis of the radar download data was the correlation of measured peak loads with the peak $\sigma_{\Delta n}$ for individual events, as shown in Figure 49. The RMS of the recorded load values was calculated in real-time onboard the ship's computers and uses a 5-second buffering window. For additional comparison, the contents of the ISE were augmented with other historical flight data including data collected during previous NASA flight tests, NTSB accident investigations, and several other airline incidents. A linear regression was also applied to this data yielding a correlation coefficient of 94.8%. This indicated that the data collected during the ISE from DAL 3708 was consistent with other accident and flight test data. The relationship of the peak loads to the peak $\sigma_{\Delta n}$ values could prove useful in future analyses.

Figure 49: Correlation of Peak Load With Peak $\sigma_{\Delta n}$ (5 sec. window)
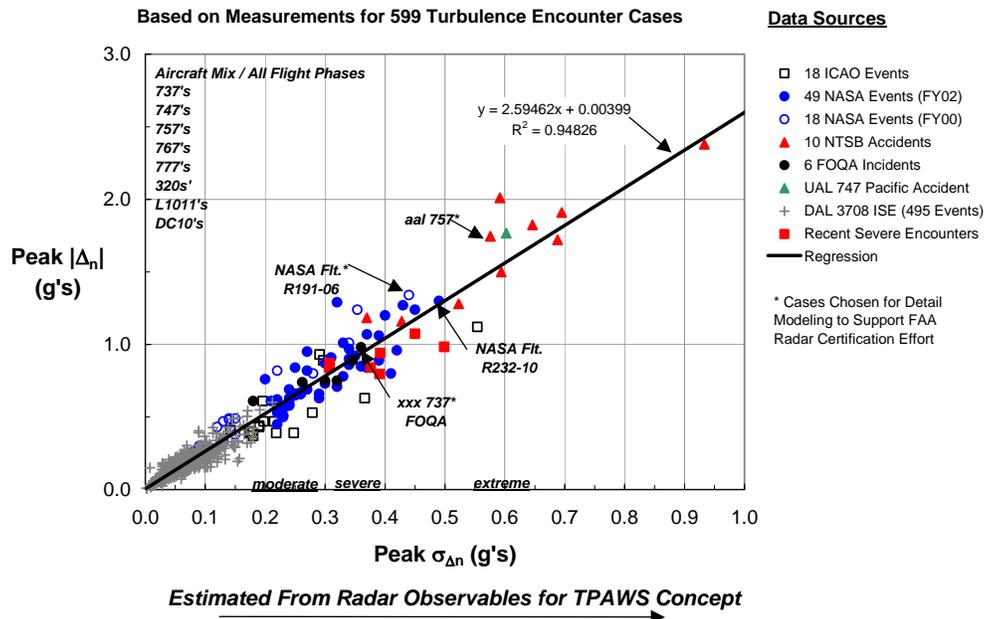
Based on the analysis of the 21 downloads from the data logger, a summary of the statistical results was performed. The detection of turbulence by the radar provided a reliable prediction of the subsequent measured g-loads with a high degree of confidence. It can also be summarized from the statistical analysis that the linear prediction model explains about 79% of the variation in the observed g-loads. An analysis of the residual error diagnostics provided a strong indication that the residuals are approximately normally distributed – a key theoretical assumption to support the statistical analysis approach taken.

It can therefore be summarized that the E-Turb Radar performed as per design and its intended function. Based on collected data, there was convincing evidence that crews were using E-Turb Radar to avoid indicated moderate to severe turbulence. The data also indicated strong correlation between radar predicted loads and experienced loads when avoidance was not possible.

4.4 FAA Certification of E-Turb Radar

The turbulence mode function on current airborne weather radars was not covered in the FAA's airborne radar certification document TSO-C63[8]; therefore, no performance standards for this function have been established. This may be a contributing factor to the unreliability of the function on existing radars. The successful development and demonstration of radar turbulence detection technology from TPAWS and the successful ISE with Delta established the technical criteria to develop the Minimum Operational Performance Standards (MOPS) for the turbulence functionality. In 2005, the FAA decided to develop MOPS for the enhanced turbulence capability. The MOPS would be incorporated into a revised TSO-C63 for which future airborne weather radars with turbulence functions must be certified. To this end, the FAA convened a group of government and industry representatives to define the certification process and MOPS for the E-Turb Radar capability. This group, the Airborne Turbulence Detection Systems (ATDS) Working Group, is tasked with producing the MOPS for the E-Turb Radar by September 2007.

In addition, the FAA included in Section 17 of Advisory Circular 120-88[9] the actions air carriers could take to support emerging technologies.

Air carriers support development and implementation of emerging technologies when they:

- *Retrofit current predictive wind shear equipped aircraft with enhanced turbulence detection radar*

- *Assist in certification of enhanced radar*

- *Conduct in-service flight trials to determine the effectiveness of new onboard radar systems in detecting turbulence, and the feasibility of using them…*

5. E-Turb Radar / TAPS Event Correlation Case Studies

The installation of both the TAPS and E-Turb Radar onboard a single aircraft provided the ability to do a comparative analysis of the two technologies while both were in operational service. The following sections present examples of turbulence encounters by DAL 3708 that were detected by both the E-Turb Radar and TAPS, enabling the correlation of the magnitudes of the radar predictions and TAPS measured detections.

A comprehensive comparative analysis of a large ensemble of events was precluded due to a lack of a time value recorded within the radar data logger file. This was due to a software anomaly, and this missing parameter prohibited developing an automated process for the comparison of the turbulence encounters based on time. It was therefore necessary to use aircraft position records in conjunction with the scan time to correlate the two data sources. The time between stored radar scans within the data logger files is known to be 4.4 seconds. This process was time consuming and limited the number of cases that could be fully analyzed.

TAPS and E-Turb Radar were both installed on the DAL 3708 in August 2004; however, due to the recording limitations of the data logger, available E-Turb Radar information was limited in quantity and considered a subset of the total time span covered by TAPS reports. The distribution of TAPS reports for Delta Air Lines' Ship 3708 is presented in Figure 50. The volume of potential recorded events was limited since the event data file fills the available memory storage space preventing further data recordings until it was manually downloaded, resetting the storage space available. In the next section,

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[8] "Airborne Weather and Ground Mapping Pulsed Radars", TSO-C63c, August 18, 1983.

[9] "Preventing Injuries Caused by Turbulence", FAA AC120-88A, January 19, 2006.

the data reduction method will be explained, leading to the selection of three candidate dates for a correlation study between the E-Turb Radar and TAPS technologies.

Period Covered: August 28, 2004 - August 16, 2006
Total # of Reports: 1190
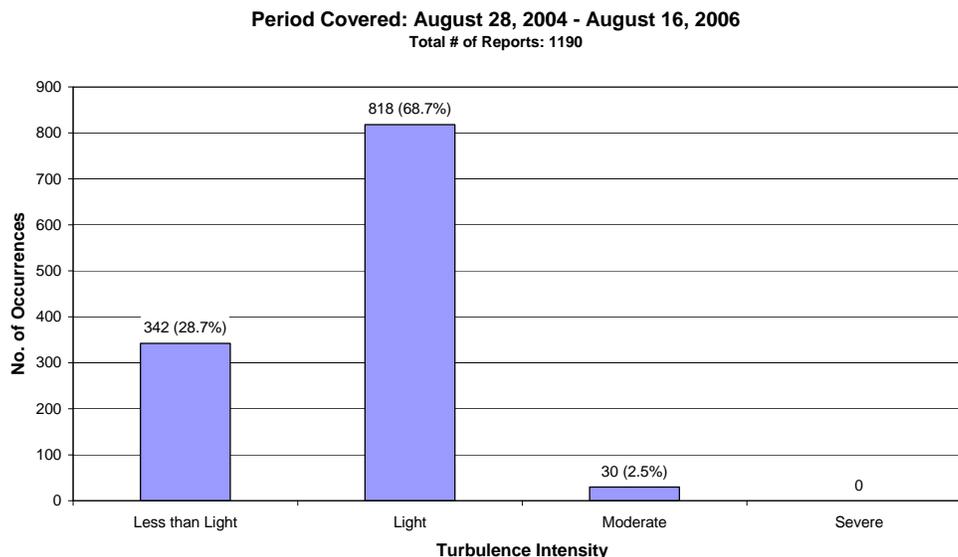
Figure 50: Distribution of TAPS Reports for DAL Ship 3708

5.1   Data Reduction Method

The process to find suitable cases for correlation analysis used the entire TAPS and radar data set obtained between August 23, 2004, and December 7, 2006. The process was as follows:

1. Determine candidate days when both E-Turb Radar and TAPS turbulence encounters were recorded. Although this process identified the days of recorded encounters, it did not guarantee that the same event was recorded by both systems.

2. Determine the total number of events recorded by each system to begin the process of determining potential "high value" dates. The assumption was made that dates chosen with a high count of both E-Turb Radar and TAPS would yield encounters that may produce good correlation in space and time.

3. Determine if any recorded turbulence encounters resulted in moderate or severe TAPS reports with corresponding E-Turb Radar data recordings. A filter of the TAPS database of DAL 3708 reports was searched, looking for instances of dates when DAL 3708 encountered turbulence and made TAPS reports of moderate or greater intensity level ($\sigma_{\Delta n} \geq 0.20$ g). To date, no severe encounter has been reported by TAPS for DAL Ship 3708. Nineteen different encounters were identified with a $\sigma_{\Delta n} \geq 0.20$ g over 14 different days. Of these encounters, only one day included TAPS data with a $\sigma_{\Delta n} > 0.20$ g and a radar prediction of $\sigma_{\Delta n} > 0.156$ g. For this identified date, there were no collocated TAPS reports and E-Turb Radar data logger recordings. Therefore, there was no matching recorded data by both systems that identifies turbulence encounters of moderate or greater intensity.

4. Select days to perform the manual process of comparing the recorded E-Turb Radar data with the TAPS reports from DAL 3708. Days were chosen based on a high count of either of TAPS or E-Turb Radar recorded encounters. This process resulted in ten candidate days; three were admissible for a more in-depth analysis that is included in subsequent sections. The other days were eliminated after reviewing plots of the aircraft's track, recorded during the E-Turb Radar event, and the location of TAPS reports. Reasons for elimination included a lack of alignment in

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space between the TAPS report and the E-Turb Radar data logger data for a particular day, poor radar management (no Ground Clutter Suppression (GCS) or Automatic Mode (AUTO) selected), painting of the ground, and clear air turbulence encounters (i.e., no radar returns).

5. With the available dataset narrowed, each day's events were reviewed for correlation between available TAPS reports and recorded E-Turb Radar scan data from DAL 3708.

5.2   DAL 3708 Turbulence Encounters

Following the above outlined process, three candidate dates, out of 83 potential days, were identified and are listed below with the number of recorded TAPS reports and E-Turb Radar events indicated. The actual dates of the turbulence encounters have been replaced by an arbitrary identifier within the subsequent text to preserve Delta Air Lines' data confidentiality. The selected dates for the detailed comparison are:

- Turbulence Encounter Day A-11 with 7 TAPS reports and 4 E-Turb Radar recorded events,

- Turbulence Encounter Day A-14 with 7 TAPS reports and 7 E-Turb Radar recorded events, and

- Turbulence Encounter Day A-20 with 12 TAPS reports and 13 E-Turb Radar recorded events.

For each of the encounter days presented in the following analysis, an overview figure is provided. An example is shown below in Figure 51. This figure is a representation of all the events of interest for that day. The domain was defined by the aircraft's path during that period (from position data within the data logger). Unfortunately this resulted in the events and the individual TAPS reports being very compressed and hard to differentiate. However, each event is presented in expanded form in the subsequent text. The solid lines represent the E-Turb Radar recorded flight paths with event numbers (as determined by the data logger software) called out. The length of an event (and hence the length of the line shown) was determined by the length of time that the radar detects a hazard. For example, the hazard was very short-lived in Event 44 below, but longer in Event 41. The multiple TAPS reports are represented within these figures by the various markers with the magnitude of the $\sigma_{\Delta n}$ value of the report listed within the legend. From the information presented within each figure, it was possible to see which radar recorded events align with the TAPS reports for each particular date.
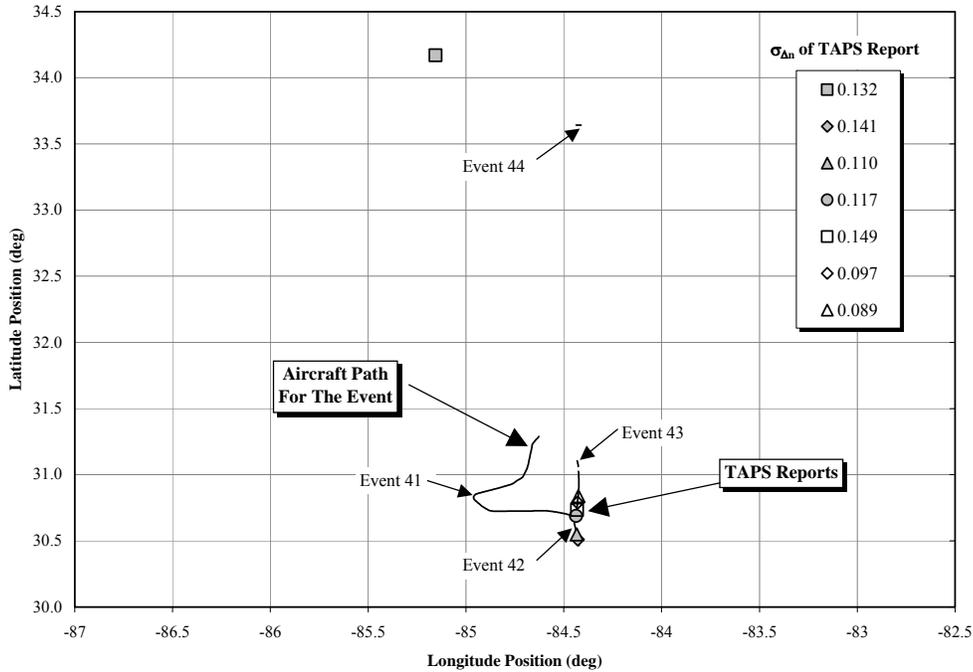
Figure 51: Example of a Turbulence Encounter Day Summary

Following a brief explanation of each day's turbulence encounters, a detailed view of a particular event(s) is presented. Within the detailed view figures, the TAPS reports, represented by diamond markers in both the main figure and the insets, are labeled as light (***L***) and less than light (***LTL***) as per the categorization scheme previously defined in Section 3.1.3. The inset plots show the aircraft's altitude in thousands of feet in relative position as well as a time history plot of $\sigma_{\Delta n}$ as recorded by the E-Turb Radar data logger and the individual TAPS reports. Information in these figures will allow attention to be focused more on detailed scans of the weather reflectivity and predicted turbulence as captured by the data logger software.

5.2.1 Turbulence Encounter Day A-11

The majority of events for this day were centered on a close region around Hartsfield-Jackson Atlanta International Airport (ATL) with the concentration of TAPS reports occurring within one particular portion of the departure of DAL 3708 from the airfield. During this portion of the flight, a large convective weather system was approaching the northern Georgia area from the southwest. At the time of the aircraft's departure, only the leading edges of the storm system were approaching the area, with the heavier, more dense convection still several hours away. Figure 52 presents the path of the aircraft during the E-Turb Radar data recordings and the TAPS reports made from the ship during these particular encounters.
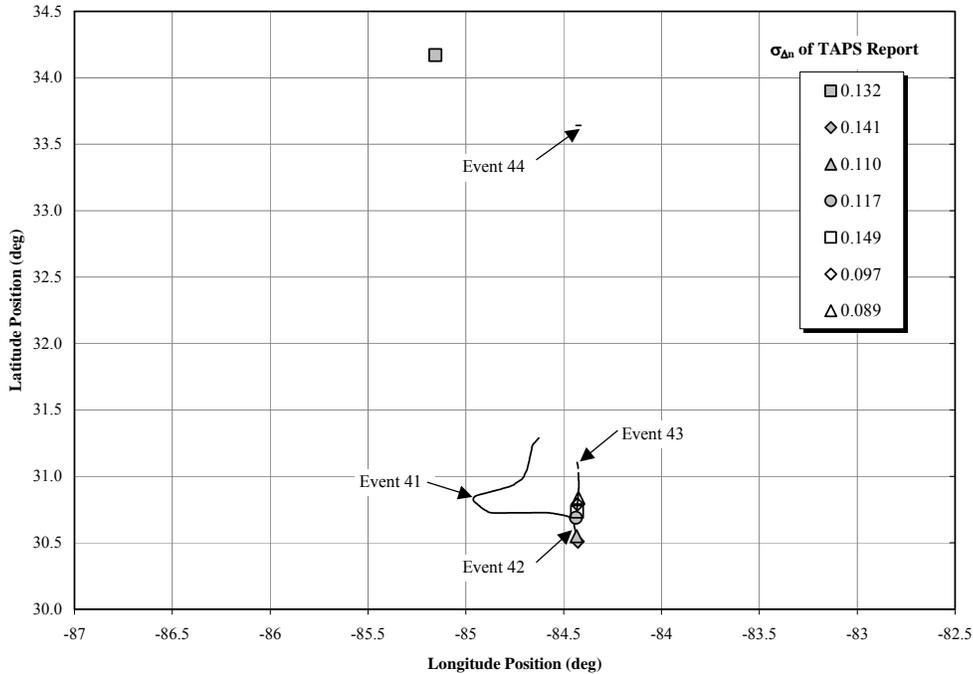
Figure 52: DAL 3708 Turbulence Encounter Day A-11 (E-Turb Radar Recorded Events & TAPS Reports)

From Figure 52, Event 42 is the only event containing both E-Turb Radar data and TAPS reports. This event is examined in this section. For Event 42, a closer view of the flight path of DAL 3708 and the TAPS reports is presented in Figure 53. Shown are two separate groupings of turbulence encounters by the aircraft as it was climbing out from ATL. The first group occurs as the aircraft passed between five and ten thousand feet and the second group occurs after a brief leveling off at ten thousand feet before continuing. Each of the TAPS events reported did not exceed the light magnitude category for the TAPS reporting system.

Within Figure 53 (as well as the subsequent Figure 58 and Figure 63), it is apparent that there is a difference in the $\sigma_{\Delta n}$ trace and the $\sigma_{\Delta n}$ of the TAPS reports. The difference in magnitudes was caused by the two separate software algorithms onboard DAL 3708 using two separate sources of the aircraft vertical acceleration. Misalignment of a particular TAPS report with peaks presented within the trace of $\sigma_{\Delta n}$ was attributed to the fact that the positional information within a TAPS report marks the beginning of incremental 30-second reporting window, not the position of the peak value of $\sigma_{\Delta n}$.

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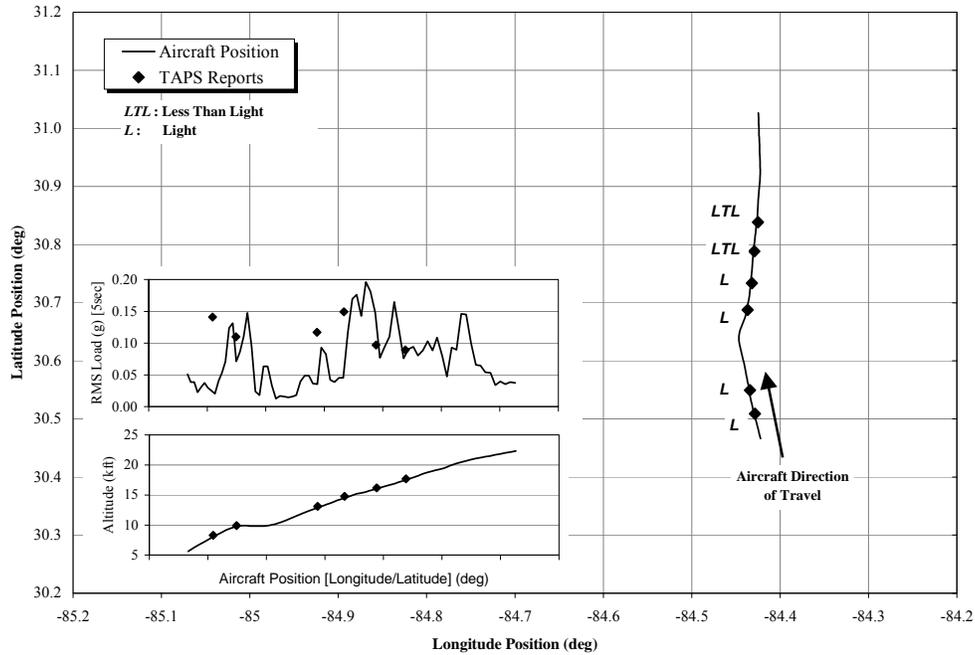
Figure 53: DAL 3708 Turbulence Encounter Day A-11, Event 42 Detailed View

Event 42, as recorded by the E-Turb Radar data logger, begins just after the aircraft passes 5,000 feet on climb out. The first two TAPS reports for this day were immediately visible within six nautical miles of the aircraft position, as shown in Scan 2 presented in Figure 54. Additional lead in time to the event was not available for a full assessment of the first two TAPS reports because none of the four predefined triggers within the data recording software were met.

Starting with Scan 1 of Event 42, the aircraft was near convection north of ATL. A comparison of the predicted turbulence from the E-Turb Radar, albeit within a six nautical mile range, showed a good correlation of a Level 1 prediction to the TAPS report transmitted by DAL 3708. The remaining four TAPS reports are present at a distance greater than 12 nautical miles from the current position. The first two reports within this line have good agreement with the Level 1 predicted turbulence in this area.

58
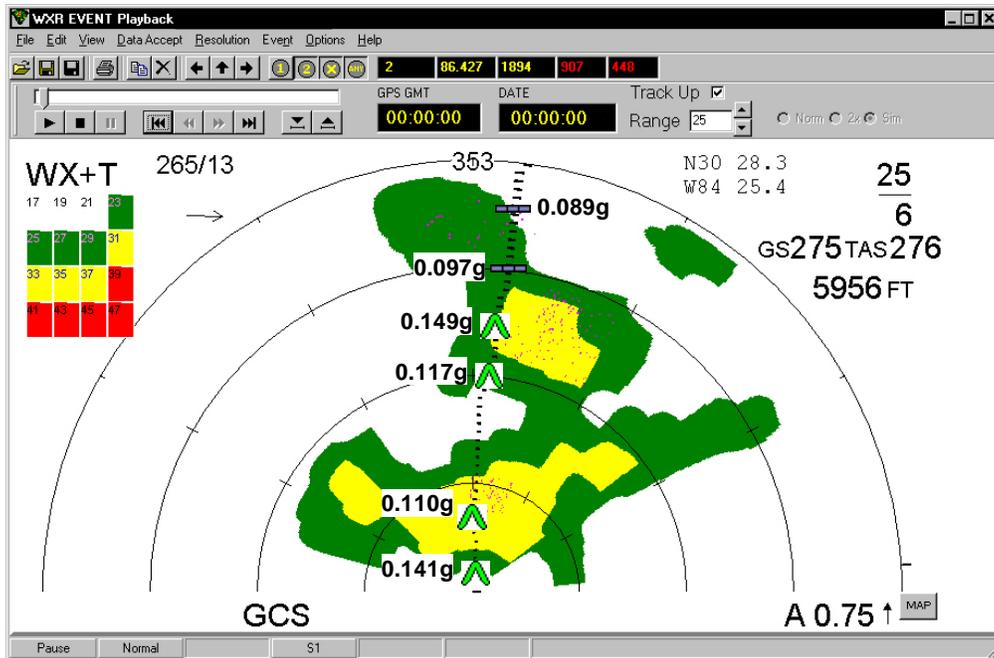
Figure 54: DAL 3708 Turbulence Encounter Day A-11, Event 42, Scan 2

Early during the playback of Event 42, an intense convective cell with red reflectivity remained present through most of the scans to the right of the intended flight path of the aircraft. Small areas surrounding this region were highlighted by a Level 1 prediction. The recorded flight path of DAL 3708 shows the aircraft just passing the left edge of this region.

Scan 11, shown in Figure 55, occurs approximately 40-seconds after Figure 54. The aircraft was approaching 9,000 feet with the radar in automatic mode with a tilt of one-half degree down. Scan 11 highlights several areas of Level 1 turbulence predicted along the flight path. Figure 55 also clearly captures the potential for turbulence with the remaining four TAPS reports. The areas highlighted with Level 1 predicted turbulence continue to persist over several more scans as the aircraft transits the region.
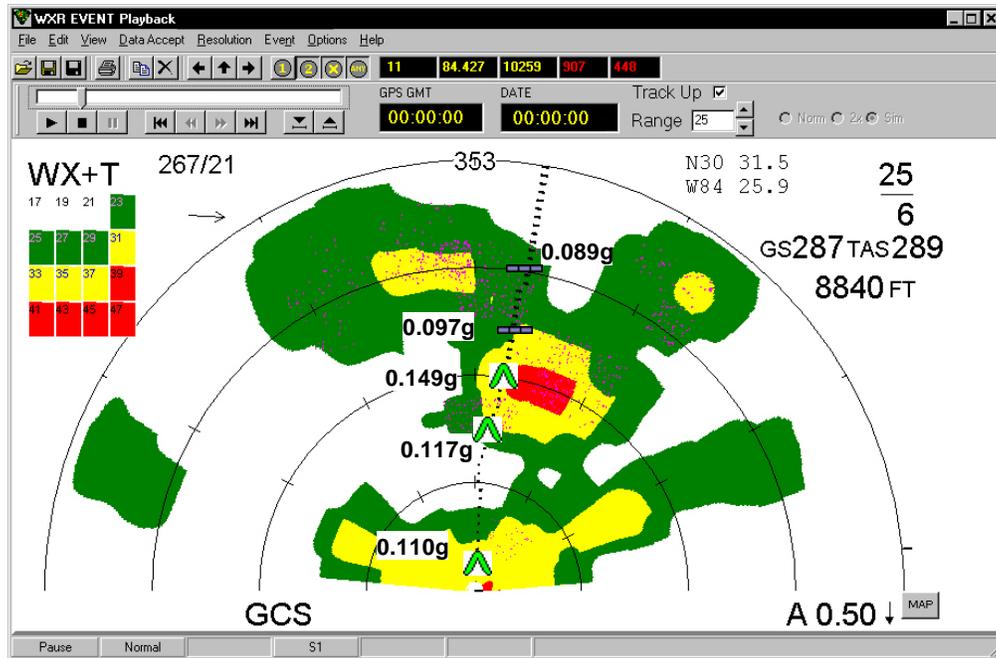
Figure 55: DAL 3708 Turbulence Encounter Day A-11, Event 42, Scan 11

Beginning in Scan 13, recorded data indicated a region of Level 2 predicted turbulence to the left of the intended flight path. Convection was still present in the area for the aircraft's ascent. The Level 2 area was located within moderate (yellow) reflectivity, not in the high (red) reflectivity and is a further illustration of the lack of correlation between turbulence intensity and radar reflectivity. This region of predicted turbulence continued to persist for many scans during the event playback.

Figure 56 shows Scan 23 of the playback of Event 42. The first two TAPS reports have passed with the remaining four present within areas of high reflectivity. The E-Turb Radar predicted multiple areas of Level 1 turbulence with some areas of Level 2 shown at farther distances to the left and right of the aircraft's flight path. The spacing of the TAPS reports' 30-second window aligns well with the reduced resolution of the predicted E-Turb Radar product as shown with the playback tool. The aircraft encountered light and less than light turbulence as indicated by the TAPS reports and predicted by the E-Turb Radar. During the remainder of the flight for Event 42, the radar remained in automatic mode, with the antenna tilted down.
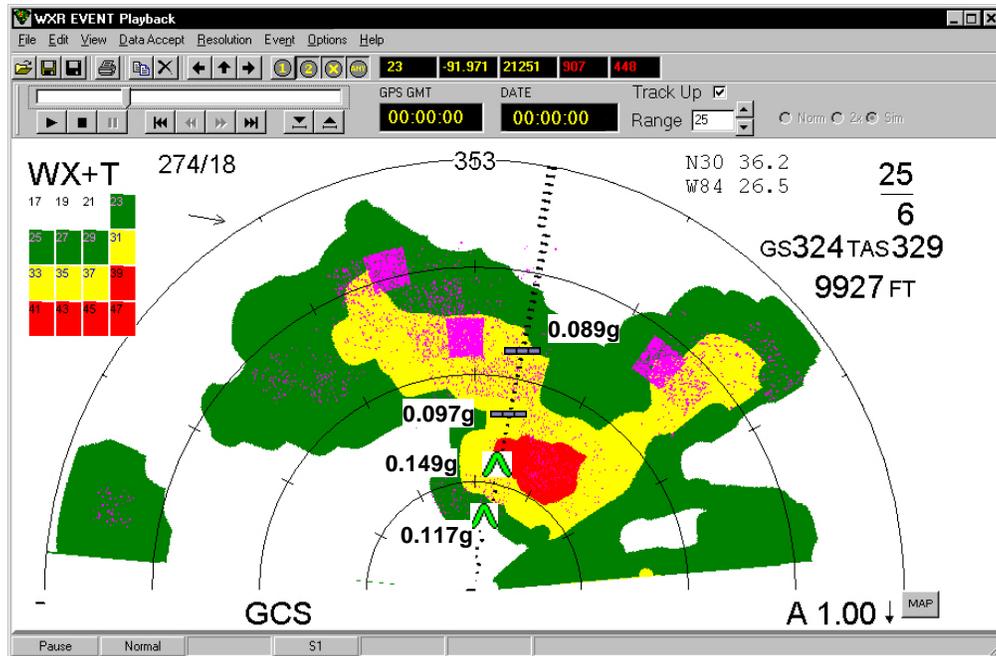
Figure 56: DAL 3708 Turbulence Encounter Day A-11, Event 42, Scan 23

By the time Scan 45 was reached, the aircraft was in the process of exiting the convective region. Level 1 predicted turbulence was still indicated on the flight path. Additionally, an area of Level 2 turbulence was indicated on the right within moderate reflectivity that persisted over several more scans.

5.2.2   Turbulence Encounter Day A-14

On the encounter day A-14, a large weather system moved through the central plains of the United States. Late in the day, most of the heavy storm activity had moved out of the Kansas City, Missouri area. Figure 57 presents several encounters recorded by the E-Turb Radar and TAPS on DAL 3708 in and around this area. The spatial distribution of the E-Turb Radar recordings covered areas near Kansas City, Missouri (MCI), eastern portion of Texas, and the northwestern portion of Georgia (approaching the Hartsfield-Jackson Atlanta International Airport). TAPS reports were only present for the E-Turb Radar recorded event number 68. More detail on this particular event is presented below.

61
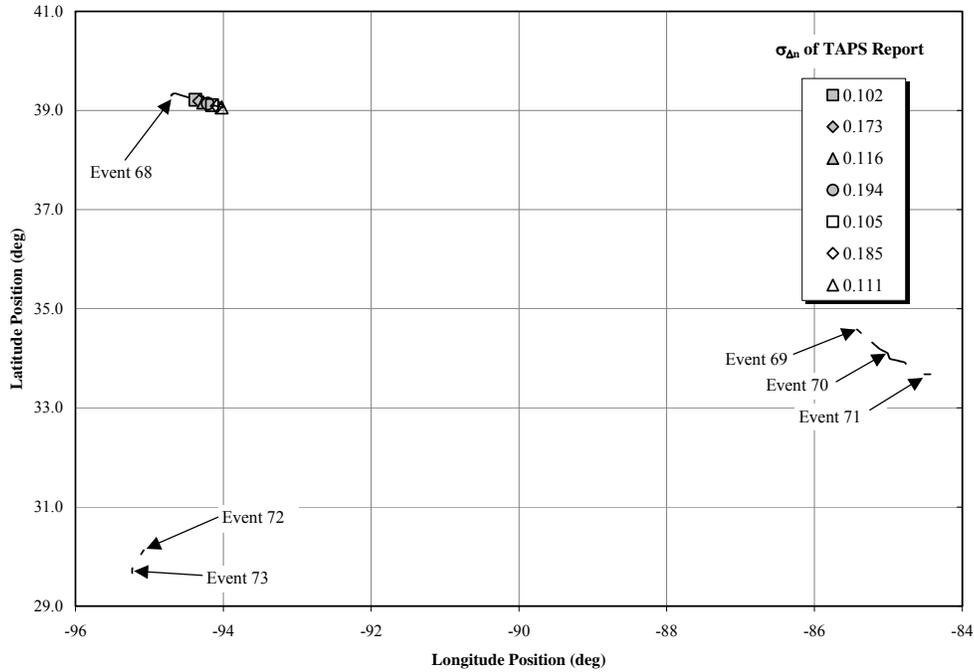
Figure 57: DAL 3708 Turbulence Encounter Day A-14 (E-Turb Radar Recorded Events & TAPS Reports)

Focusing on Event 68, DAL 3708 was on departure from MCI and began encountering light turbulence as reported by TAPS near 17,000 ft. In Figure 57 and Figure 58, this was indicated by the even spacing of the TAPS reports along the flight track history and a review of the report contents; showed the turbulence was continuous in nature causing a TAPS report to be generated every 30-seconds. The turbulence did not subside until after the aircraft leveled off at flight level (FL) 250. It should again be noted that the difference with the inset for Figure 58 was caused by the position information as captured by the TAPS report and the two separate sources of vertical acceleration used for the $\sigma_{\Delta n}$ calculation.
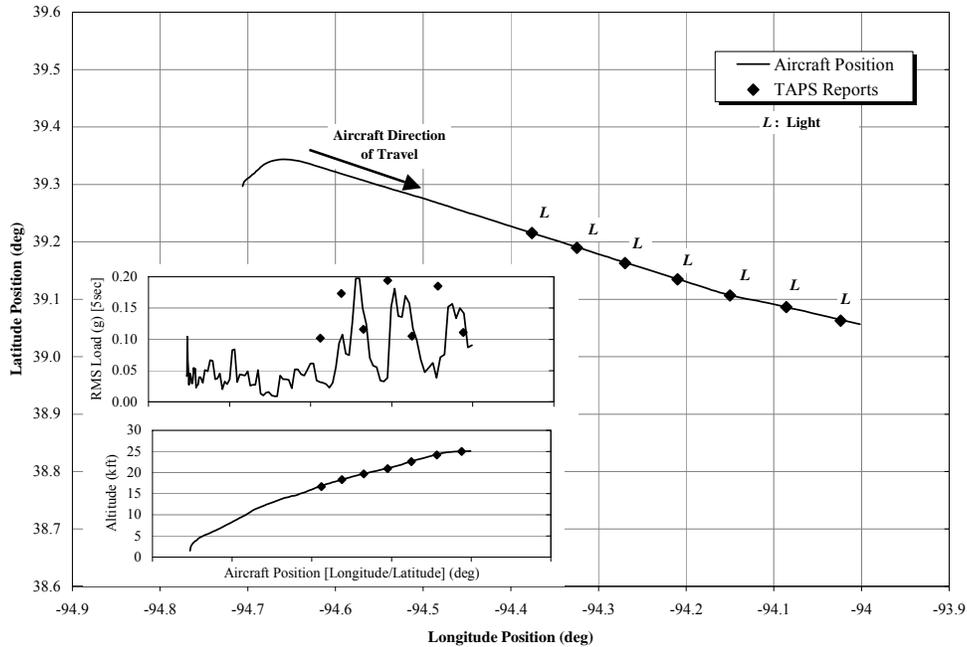
Figure 58: DAL 3708 Turbulence Encounter Day A-14, Event 68 Detailed View

For this encounter, the E-Turb Radar was in Automatic Mode with Ground Clutter Suppression on. The first indication by the radar of turbulence was on Scan 32. The aircraft was near 8,200 feet when a high density of Level 1 turbulence was indicated to the right of the intended path. Scan 34 shows predictions along the flight path for more than 12 nautical miles. The radar configuration was still in Automatic Mode with a tilt of 0.25 degrees down. Level 2 turbulence was later predicted in Scan 37 to the right of the flight path. The more intense turbulence region persisted for several more scans and was located in regions of weak (green) reflectivity.

Approximately six to twelve nautical miles to the right of the aircraft's position, Level 2 regions of predicted turbulence were indicated within the data recording before and after Scan 41, shown in Figure 59. A region of Level 2 prediction at a distance greater than 20 nautical miles was also present but changed as the aircraft continued to climb out. The contents of Figure 59 indicate that the aircraft continued to penetrate the region of weak reflectivity and would potentially encounter light turbulence as shown by the speckled Level 1 turbulence product. An overlay of the TAPS reports confirms that in subsequent minutes to follow, DAL 3708 did encounter light turbulence on climb out.
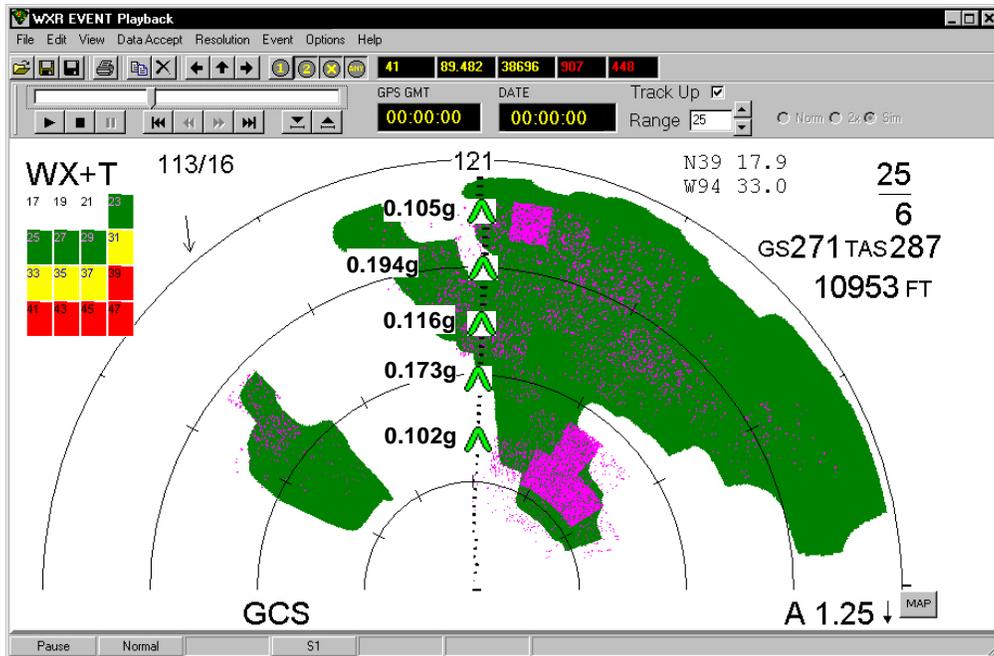
Figure 59: DAL 3708 Turbulence Encounter Day A-14, Event 68, Scan 41

Figure 60 captures the radar display seconds after the image presented in Figure 59. Turbulence in the area within the weak reflectivity regions was intensifying at 15 to 20 nautical miles from the aircraft's position. The aircraft continued to climb as well as increase its airspeed. The Level 1 prediction from the E-Turb Radar continued to cover most of the viewing area in and around the convective cell. The first TAPS report was made approximately six nautical miles from the current aircraft position and the weather radar was tilted 1.75 degrees down with GCS on.
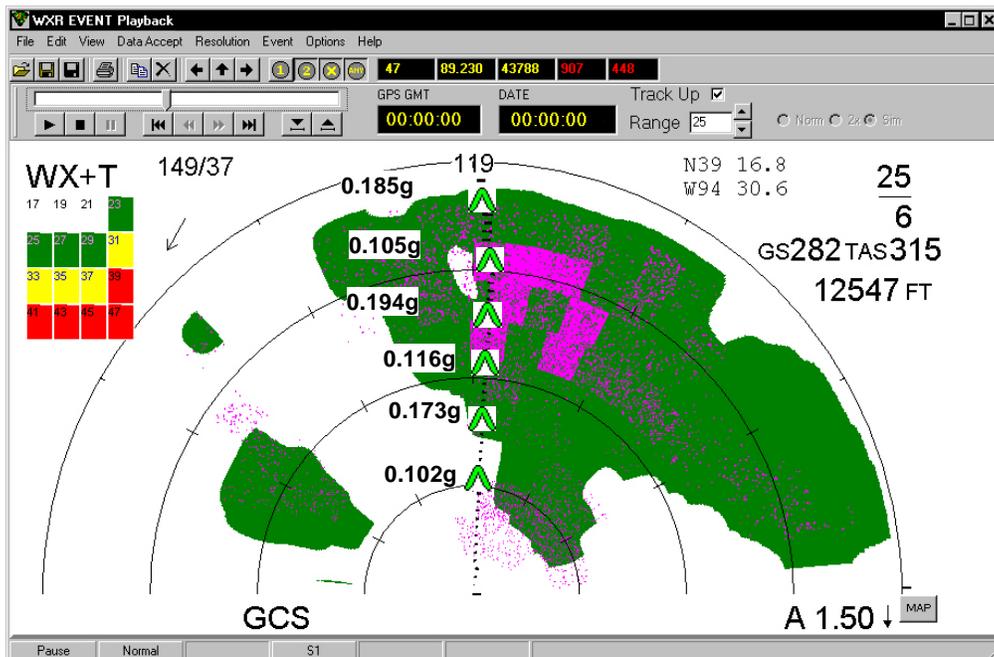
Figure 60: DAL 3708 Turbulence Encounter Day A-14, Event 68, Scan 47

As the aircraft continued its climb out, Scan 57 (not shown, but similar to Figure 60) was representative of the Level 1 prediction present along the flight path and only green reflectivity was in the area. The Level 2 predicted regions of turbulence within the direct path of the aircraft persists over many scans and links spatially to the 0.194g TAPS report. The aircraft did not deviate and continued the climb.

As the aircraft continued the climb out, the earlier predicted area of turbulence changed. The region of Level 2 turbulence prediction persisted as the aircraft traversed the area. Figure 61 shows that the aircraft encounters the predicted Level 2 region in less than ten nautical miles and experienced a $\sigma_{\Delta n}$ of 0.194g, as noted within the TAPS report. This was a light TAPS report that was well correlated with a Level 2 prediction by the E-Turb Radar technology. The intensity of the continuous turbulence remained for the next several minutes until the aircraft exited the region, past the end of the data logger event file.
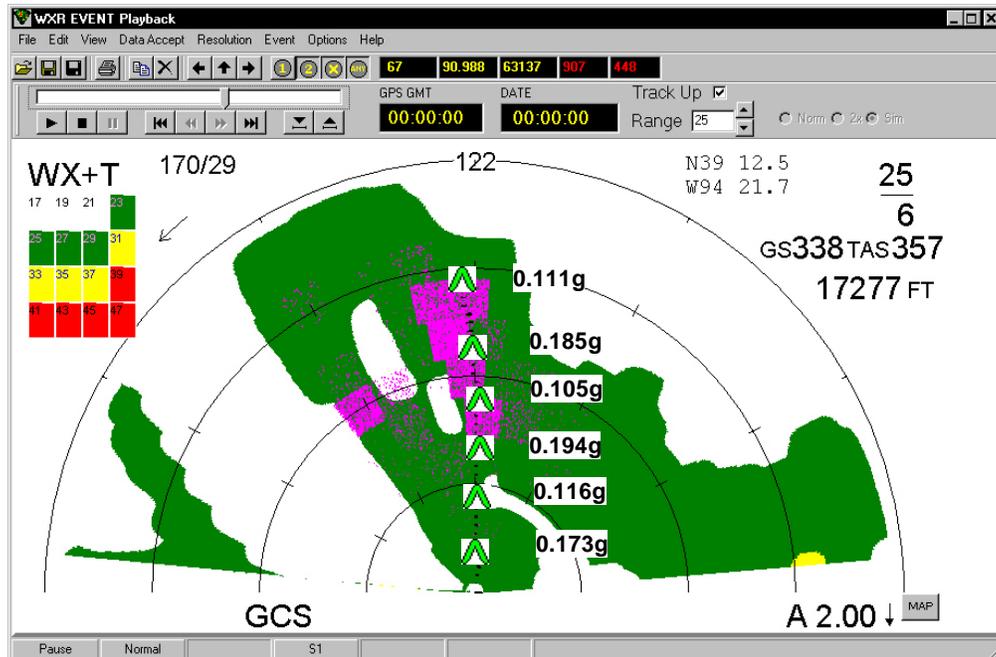
Figure 61: DAL 3708 Turbulence Encounter Day A-14, Event 68, Scan 67

With the aircraft exiting the region, Scan 80 indicated moderate reflectivity in conjunction with a Level 2 prediction in proximity to the 0.194g TAPS report, i.e. less than six nautical miles out.

5.2.3   Turbulence Encounter Day A-20

The turbulence encounters recorded from DAL Ship 3708 on the A-20 date, were the most numerous for an individual day out of the dataset of possible candidates examined. On this particular date, a large storm system from the central portion of the United States was moving quickly through the southern states. The size of the weather system increased throughout the day and during the time of the majority of the TAPS reports made by DAL 3708. The weather system was centered over western Georgia, stretching from the Gulf of Mexico north to Tennessee and back towards Missouri.

Figure 62 is a summary plot of the position of DAL Ship 3708 during various recordings by the E-Turb Radar data logger with reported TAPS reports for the day overlaid on the positional grid. The majority of events presented in Figure 62 were located within the states of Georgia and northern Florida. Events 78 and 79 with the associated TAPS reports were selected for further investigation due to the number of TAPS reports in close proximity to one another.
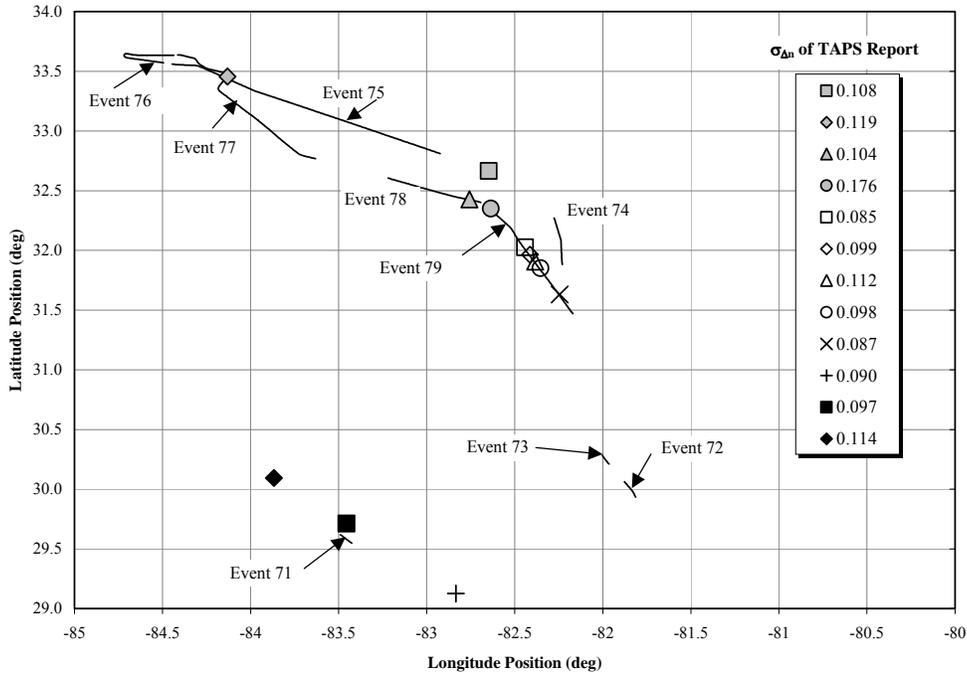
Figure 62: DAL 3708 Turbulence Encounter Day A-20 (E-Turb Radar Recorded Events & TAPS Reports)

Further analysis for Encounter Day A-20 will include sequential Events 78 and 79. One TAPS report is located at the end of Event 78 and the remaining six reports are contained in Event 79. As shown in Figure 63, a series of TAPS reports align with the flight track history of the aircraft as it was traversing the airspace in the direction of Jacksonville, FL. The aircraft was in a cruise condition at/near FL360.
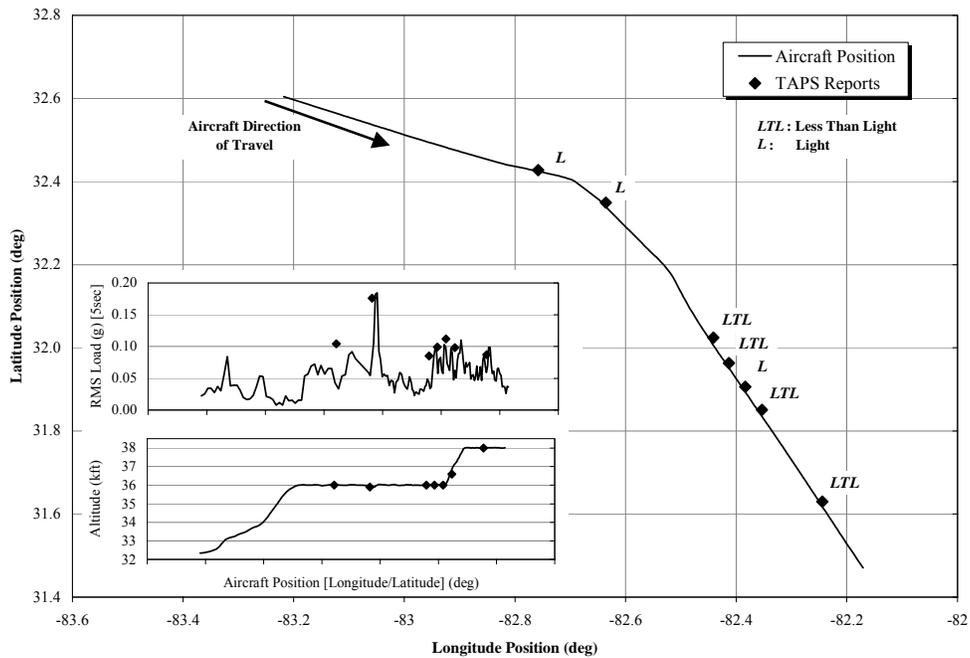
Figure 63: DAL 3708 Turbulence Encounter Day A-20, Events 78 and 79, Detailed View

A review of both events using the recorded scan data indicated that no significant areas of reflectivity were displayed within the direct path of the aircraft. However, a convective area (containing weak to moderate reflectivity) was displayed to the right of the aircraft track within the recorded events. Focusing on the playback of scan data from Event 79, the second TAPS report, measuring 0.176g, was present (Figure 64) within a region of Level 1 prediction by the E-Turb Radar in Scan 2. The 30-second window used by the TAPS calculation would place the TAPS report directly in the middle of the predicted area. As the aircraft progresses, the next four TAPS reports made by DAL 3708 came into view. Beginning with Scan 35, playback data showed each of the reports within dense areas of predicted turbulence. The prediction persists for several more scans with an estimated warning distance of 12 nautical miles.
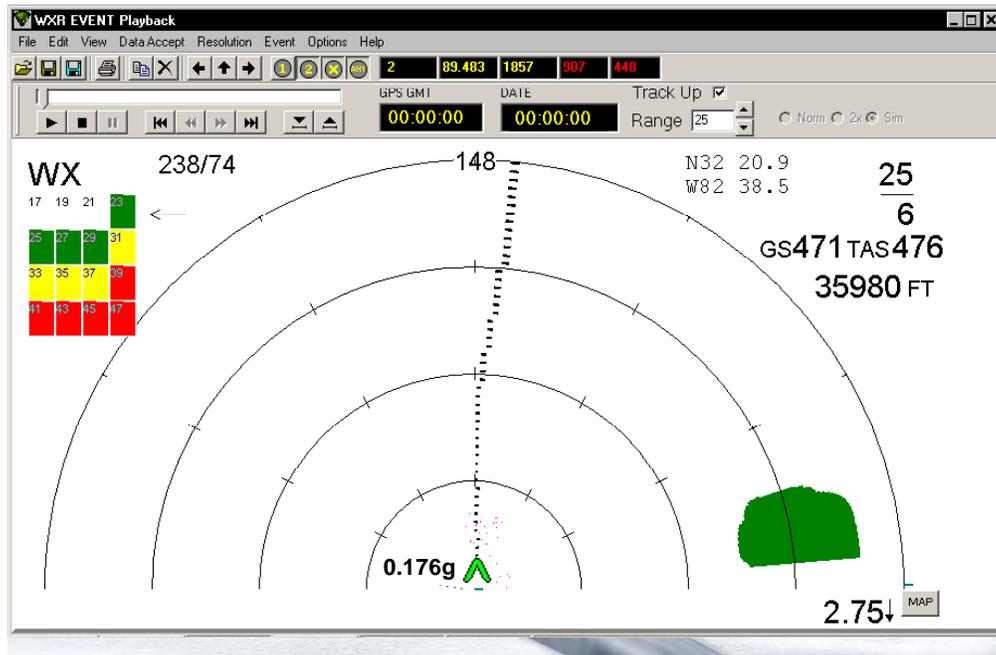
Figure 64: DAL 3708 Turbulence Encounter Day A-20, Event 79, Scan 2

Figure 65 illustrates Scan 39 from the recorded E-Turb Radar data with the location of four TAPS reports overlaid post-flight within the image. The last TAPS report of this region was outside of the 25 nautical mile range of Figure 65 by only a few scans. The first encounter as recorded by TAPS had already passed. Level 1 predicted turbulence was indicated through the first 12 nautical miles of the display, with the majority of the advisory region located to the right of the flight path with the wind (direction indicated in the upper left corner of Figure 65) causing advection of the air mass across the aircraft's flight path. The E-Turb Radar indicated the potential for Level 1 turbulence ($\sigma_{\Delta n} \geq 0.093$ g) for the next 12 nautical miles. The predicted region persisted for several scans before and after the image shown in Figure 65. Placement of the TAPS reports made by DAL 3708 from the flight indicated a mix of less than light and light turbulence was encountered in this region.

67
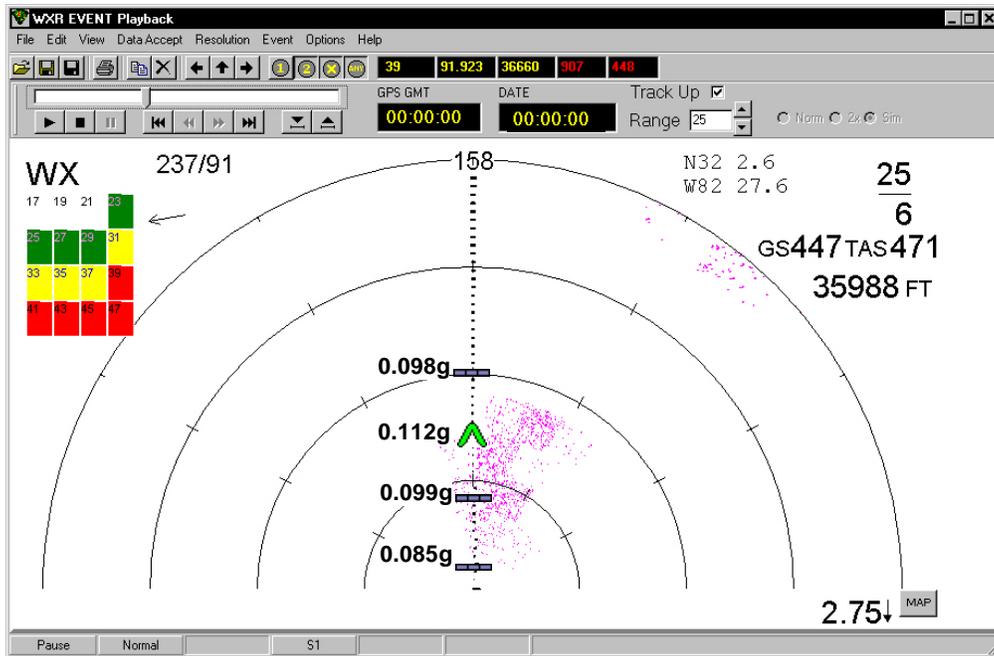
Figure 65: DAL 3708 Turbulence Encounter Day A-20, Event 79, Scan 39

Figure 66 continues to indicate a region of speckled (Level 1) magenta. The TAPS reports overlaid in Figure 66 clearly match the Level 1 criteria ($\sigma_{\Delta n} > 0.093$ g) for the E-Turb Radar. The last TAPS report for the series of recorded radar events was now visible within the scan range; however, it should be noted that the radar was still configured for manual mode with a tilt of 2.75 degrees down. Figure 66 is an example of the E-Turb Radar's capability to detect turbulence in regions of weak reflectivity (less than 20 dBz).
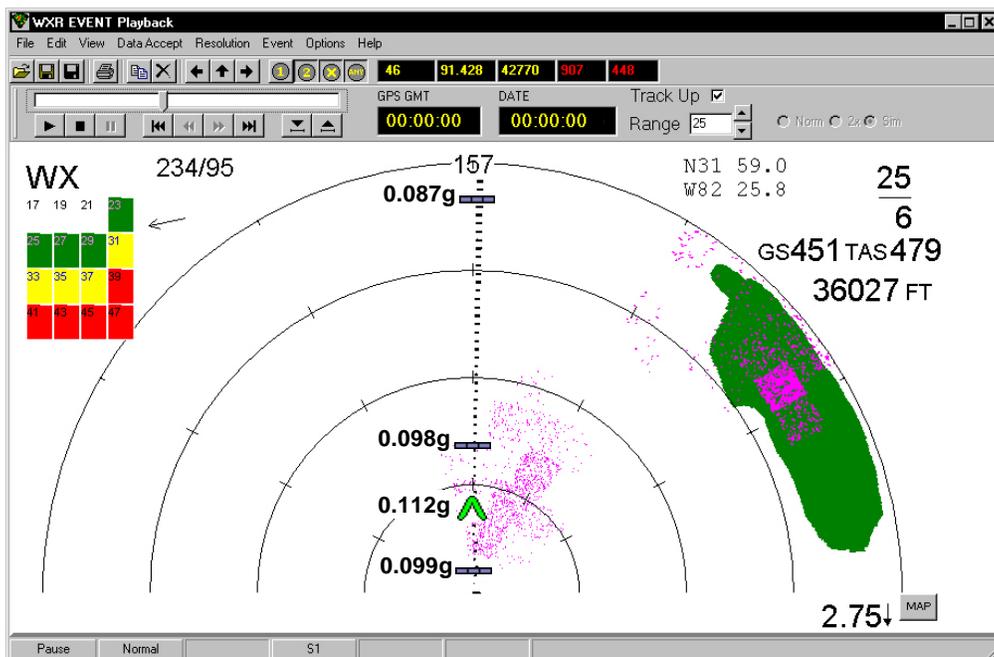
Figure 66: DAL 3708 Turbulence Encounter Day A-20, Event 79, Scan 46

68

Continuing the review of Event 79, areas of Level 2 prediction appeared near the flight path in scans 50 and 51. This was about six nautical miles from the aircraft's position. A similar area repeats the scenario; closer to the aircraft in scans 56 and 58.

As shown in Figure 67, Scan 56, Level 2 turbulence was predicted along the flight path for several scans. The reduced resolution of the data logger's capture of the event did not allow for a clear estimate of the position of the predicted region relative to the flight path six to eight nautical miles out. The scans following Figure 67 indicated (as shown by the altitude position readout in the right hand portion of the figure) that the aircraft was beginning a change in altitude from FL360 to FL380, possibly in an effort to avoid the turbulent region indicated by the radar. The only radar reflectivity present at altitude was located off on the right of the aircraft's flight path. The E-Turb Radar predictions in Figure 67 were made in areas of weak reflectivity.
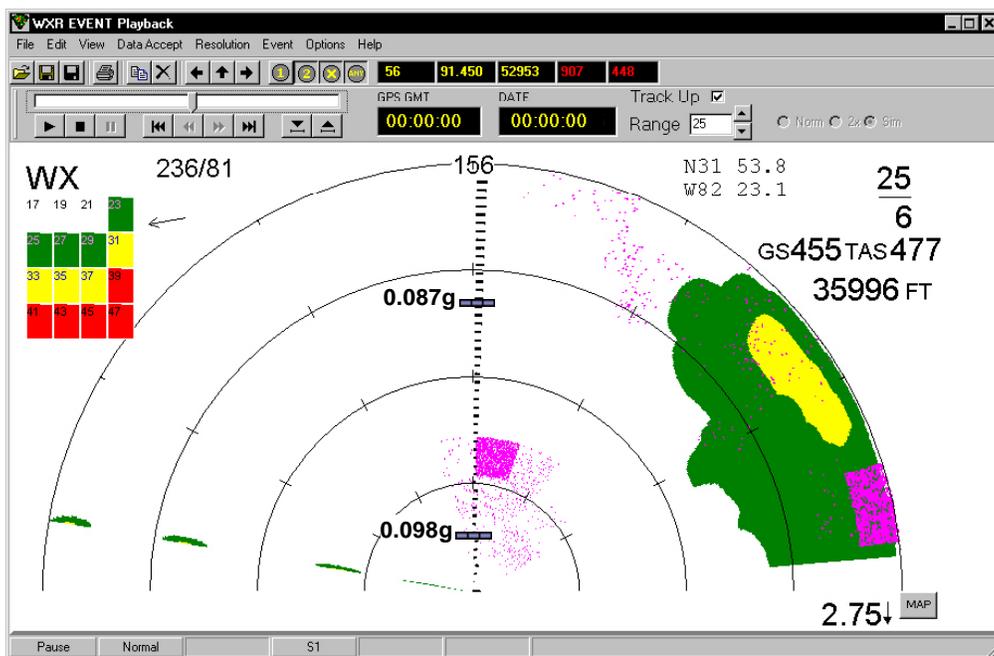
Figure 67: DAL 3708 Turbulence Encounter Day A-20, Event 79, Scan 56

The aircraft's course continued to hold steady on its flight path but the aircraft climbed 2,000 feet as the turbulence persisted. As the aircraft climbs, the predicted amount of turbulence decreases as well as what was encountered by the aircraft. The aircraft leveled out at FL380 and encountered turbulence (reported as less than light by TAPS) that was detected by the E-Turb Radar in scans 84 through 87, but only three to four nautical miles out from the aircraft's current position. During the flight level change, the radar was continuously tilted 2.75 degrees down with Automatic Mode off.

6. Summary and Conclusions

From August 2003 to December 2006, In-Service Evaluations of two technologies developed in NASA's Turbulence Prediction and Warning System element of its Aviation Safety and Security Program were conducted. The two technologies were the Turbulence Auto-PIREP System and Enhanced Turbulence Radar. NASA and AeroTech Research established an industry team comprising AeroTech, Delta Air Lines, Rockwell Collins, and ARINC to conduct the ISEs. The technologies were installed on Delta aircraft and their effectiveness was evaluated in day-to-day operations. The TAPS and E-Turb Radar ISEs represent an extremely efficient and successful collaboration of government and industry. Cost-sharing by all participants greatly leveraged the resources provided by NASA and led to a wealth of data

and significant results obtained in a "real-world" operational environment. This report documented the establishment and conduct of the ISEs and presented results and feedback from various users.

Between 1998 and 2003, as part of the work performed in the TPAWS program, a turbulence hazard metric was developed, tested, and validated in simulations and flight tests. This loads-based hazard metric ($\sigma_{\Delta n}$), which is used by both TAPS and the E-Turb Radar, quantifies the intensity of the turbulence effect on an aircraft. Prior to the ISEs' commencement, analysis demonstrated that $\sigma_{\Delta n}$ was a suitable surrogate for peak loads, and the data collected during the ISE further solidified that correlation. The FAA, in its E-Turb Radar certification requirements, has also adopted this hazard metric.

During the ISE, TAPS was successfully implemented on three Delta aircraft fleets (B737-800, B767-300ER, and B767-400ER). The content of the TAPS reports was established early in the evaluations based on stated needs from multiple Delta users (dispatchers, pilots, flight safety, maintenance, and meteorology). The TAPS-WebASD^{SM} display facilitated the evaluation of the TAPS information and functions by Delta Air Lines operations personnel. The display was available via the Internet and access was provided to 135 Delta dispatchers and other Operations Control Center personnel. The ability to automatically uplink TAPS reports to aircraft, which is a component of the future architecture of TAPS, was demonstrated using an ACARS datalink. In summary, the results of the TAPS ISE are:

- TAPS has flown onboard 123 Delta aircraft for more than 600,000 flight hours. More than 77,000 TAPS reports were generated during the ISE.

- TAPS reports were received by aircraft over four continents.

- On average, 32 TAPS reports were generated per month per aircraft. Each TAPS report was less than one kilobit.

- A method was developed to identify spurious reports generated from databus dropouts and incorrect sensor data.

- Significant differences were documented between a pilots' perception of experienced turbulence and the actual measured accelerations. The latency in which verbal turbulence pilot reports was provided to dispatchers was also observed.

- For the entire evaluation period, no TAPS-equipped aircraft generated a TAPS report that indicated a need for a severe loads maintenance inspection, although many of these aircraft were inspected at the request of the captain.

- For the uplinking of TAPS report information, the average transmission time from when the initial TAPS report was generated to when the information was interpreted on the receiving aircraft was less than two minutes.

- A vertical wind estimator, using validate calculation techniques, was implemented on 52 TAPS-equipped aircraft. The estimation of aircraft loads from calculated vertical winds using standard ship-system data yielded poor correlation.

- A TAPS Concept of Operations for dispatchers was developed. Dispatchers from seven airlines participated in its development, and the results reflected a broad consensus of industry needs and how the integration of TAPS would improve operations.

The ISE proved that TAPS could automatically provide timely, objective loads-based turbulence encounter information to both the Operations Control Center and to other aircraft. TAPS can increase a dispatchers' situational awareness concerning the location and intensity of turbulence hazards to aircraft and potentially assist in avoiding turbulence and in the prevention of injuries from encounters with turbulence. The volume of TAPS reports generated per aircraft is negligible when compared to the totality of data downlinked routinely today. The identification of spurious TAPS reports improved the awareness of the aircraft system's performance, since many of these issues might have gone unnoticed until the next scheduled maintenance. Results validate and quantify the historical understanding that

verbal PIREPs of turbulence do not accurately reflect the turbulence in intensity due to the subjective interpretation. There is no inherent difficulty in uplinking TAPS reports to an aircraft using ACARS datalink from a data management and throughput perspective. However, some aircraft avionics suites have software limitations that can impede multiple uplinks of data. Installation and use of TAPS on commercial aircraft can enable a significant reduction in maintenance man-hours, costs, and impact on operational schedule by providing real-time, quantitative notifications to airline maintenance of the need for severe loads inspections. Typical commercial airliners are not suitably equipped to make reliable estimates of vertical wind. Dispatchers from a variety of airlines acknowledged that TAPS would enhance the current turbulence information flow by providing timely information, streamlining communications and interactions among users, and presenting a common picture of potential turbulence hazards through shared information. The sharing of TAPS information would provide improved situational awareness of turbulence encounters for all participating airlines.

During the ISE, the E-Turb Radar algorithms were successfully implemented on a Rockwell Collins WXR-2100 radar and the system was installed on one Delta B737-800 aircraft, which was also equipped with TAPS. In a departure from the conventional magenta turbulence regions display on current radars, the ISE E-Turb Radar display presented two-levels of magenta turbulence indications. Light-to-moderate turbulence was indicated by speckled magenta regions, and moderate or greater turbulence by solid magenta. In summary, the results of the E-Turb Radar ISE are:

- Delta Air Lines Ship 3708 flew over 6,000 flight hours with the E-Turb Radar.

- The E-Turb Radar functions and performance received very positive feedback from pilots. Anecdotal and measured data indicated that pilots developed confidence in the turbulence indications and were using the radar to avoid detected turbulent regions.

- Over the course of the E-Turb Radar ISE, 1435 events were recorded and downloaded from Delta Air Lines Ship 3708. Applying a data assessment and reduction process, 495 events were suitable to be used for the statistical analysis of the radar's performance because in these events the radar displayed areas of predicted turbulence, the aircraft flight path traversed the affected areas, and the presence of turbulence was verified by the on-board accelerometer.

- From the statistical analyses, it was shown that there was a general tendency for the radar to overestimate the experienced in situ g-loads due to turbulence. The overestimates range from 10-18% for the speckled magenta threshold (0.093 g $\leq \sigma_{\Delta n} < 0.156$ g) to 11-17% for the solid magenta threshold ($\sigma_{\Delta n} \geq 0.156$ g) based on 95% confidence intervals. This performance is considered acceptable given all the sources of variability inherent in the system and the fact that it provides a more conservative estimate of the turbulence intensity.

- Based on the positive performance and acceptance of this system, NASA, Rockwell Collins, and AeroTech are participating in the FAA's Airborne Turbulence Detection Systems working group to develop Minimum Operating Performance Standards for FAA Technical Standards Order C-63. Performance of the E-Turb Radar evaluated in the ISE has met and surpassed the draft MOPS criteria.

- The E-Turb Radar was able to detect and provide turbulence hazard awareness in areas of weak reflectivity (below the threshold for reflectivity display on current weather radars).

- Several events are presented in this report where there were radar detections of turbulence and subsequent TAPS reports made by the aircraft. These events showed strong correlation between the radar's indication and subsequent TAPS reports made.

The E-Turb Radar is a stable and useful product for flight crews to mitigate the potential effects from turbulence encounters. Recorded data and discussions with pilots indicate that E-Turb Radar enhances pilots' situational awareness of turbulence hazards to their specific aircraft. The E-Turb Radar provides information that pilots can use to make tactical deviations to avoid potentially hazardous turbulence. It is

highly likely that the improved situational awareness of turbulence and the ability to avoid some convective induced turbulence could lead to a reduction in flight attendant and passenger injuries. Expanding the turbulence detection capability from 25 to 40 nautical miles is desired by users and supported by industry and could improve the usefulness of the technology for deviations and avoidance of turbulence, and therefore improve flight safety and efficiency. The use of a common hazard metric ($\sigma_{\Delta n}$) allowed for direct comparisons to be made between the turbulence detected by the E-Turb Radar and encountered turbulence identified by the TAPS. The two forms of turbulence information can be used together to further extend (beyond 40 nautical miles) and improve pilots' situational awareness of turbulence.

The Turbulence Auto-PIREP System and Enhanced Turbulence Radar worked as designed and achieved favorable feedback from users. The adoption and utilization of these technologies could enhance dispatchers' and pilots' situational awareness of hazardous turbulence. The improved situational awareness could result in a reduction in turbulence related injuries and maintenance costs, extend aircraft service life, and improve operational efficiency. Due to their success in the ISEs, both TAPS and E-Turb Radar are technologies recommended for airline implementation by the FAA, as stated in Advisory Circular 120-88. With the integration of these technologies into aircraft and ground station systems, aviation safety and operations efficiency will take an important step forward in the 21st century.

7. Future Work

7.1   Integrated Cockpit Display

One of the most significant findings of the ISEs was the compatibility and comparability of the hazard metric ($\sigma_{\Delta n}$) from both TAPS and E-Turb Radar. As discussed in Section 2, the calculation of $\sigma_{\Delta n}$ in TAPS uses a temporal window of five seconds and E-Turb Radar uses a spatial window of one kilometer. One of the reasons for the choice of these windows was to be able to compare the two data products directly, within the constraints of the measurement methods (temporal vs. spatial). Despite selecting compatible windows, the assumption was that the difference in measurement techniques did not guarantee compatibility. Results in Section 5 confirmed this assumption, and the compatibility was demonstrated.

These findings also lead to the prospect that data products from TAPS and E-Turb Radar could be integrated into a single cockpit display of turbulence hazard. Such a display would provide the pilot with turbulence hazard information out to an unlimited range. The long-range display of TAPS reports would provide indications to the pilot of turbulence-affected regions (in conjunction with weather forecast products). As the aircraft approaches and enters the region, the display of TAPS reports from other aircraft in the vicinity will provide real-time information of the turbulence to be expected in those locations. Within 40 nm, the E-Turb Radar would provide the "super-tactical" information for the pilots (within the limitations of radar detection ability in the atmosphere).

NASA is currently funding AeroTech to develop and evaluate such a display under a Phase II SBIR. This work is being carried out in such a way that, as other turbulence detection systems become available (e.g., Light Detection And Ranging (LIDAR), ground-based radars, infra-red sensors, etc.), the approach can be readily extended to include that data.

7.2   Next Generation Airspace System

Together, the TAPS and E-Turb Radar technologies represent a step in the FAA's vision that each aircraft be an information "node in a network", by providing and sharing real-time turbulence information to other aircraft and ground operations. In the future, there may be technology developed to enable aircraft to "share" the E-Turb Radar detected turbulence hazards with other aircraft, dispatchers, air traffic controllers, and traffic flow managers. This is an important concept in the FAA's Next Generation Airspace System for which turbulence is identified as an important consideration.

Appendix

Delta Air Lines' Flight Crew Feedback on E-Turb Radar ISE

The following is a listing of feedback received from DAL 3708 flight crews and ISE jump seat observers (Delta project personnel). These data were gathered by the Delta project personnel and passed along to the NASA TPAWS program. Pilot feedback was typically provided within several days of a flight on DAL 3708, either by means of a questionnaire or follow-up interview conducted with Delta project personnel. From these "raw" data, presented without amendments or additional annotation, the overall conclusions presented in Section 4.3.2 of this document were drawn.

ID:1	**Source:** Pilot Feedback
	Flew 3708 (Multiscan ship) a couple nights ago from SFO to JFK around significant weather in the mid-west; it was nighttime and the radar was needed. I was very impressed by the multi-scan capability. It lived up to the billing – much better than the normal 737NG radar! A definite safety benefit in the information presented and ability to analyze returns.
ID:2	**Source:** Pilot Feedback
	All positive feedback, not one negative review of any kind
ID:3	**Source:** Jump Seat Observation
	Conditions: encountered several cells over the Midwest, did not enter IMC at any point while deviating 1. Both pilots were very pleased with the Multiscan's automated capabilities 2. Weaving between cells, the captain remarked that he did not "buy" a particularly sharp gradient in reflectivity within one echo. 3. Pilots were impressed by the much better defined magenta available in WX+T mode compared with other radar units. In this case, magenta was painted only within the most reflective portion of the cells
ID:4	**Source:** Jump Seat Observation
	Conditions: encountered a few isolated cells enroute, deviation not necessary at any time 1. Positive comments about system capabilities and special features 2. On climb out from SFO, in auto mode, first officer remarked that he saw exactly what he wanted to see on the radar screen given some small buildups east of the Sierra Nevada mountains 3. First officer remarked that the gain control had better credibility than previous systems. On other units, changing the gain did not always result in the echoes showing proportionally more or less reflectivity 4. Painted magenta in areas of little or no reflectivity near Atlanta (but did not transit areas) 5. Despite a few small, distant cells enroute, overall basis for evaluation was disappointing due to scanter than expected convection around Atlanta
ID:5	**Source:** Pilot Feedback

	I used the new radar and liked what I saw under the conditions that I used it on. I came back to ATL on a day with a lot of cells in the area and the auto feature was great. When I was above developing cells that were close by the radar would never over scan them and when I descended below the bottoms of some of the cells it did a nice job of showing me, even though I was below them, where they where located. I have clearly defined cells displayed that matched what was outside.
ID:6	**Source:** Pilot Feedback
	I used the new radar going to CCS. It is extremely sensitive and displayed even minor weather as heavy. Had we not switched back and forth between traditional settings and the new self scan, we would have deviated a long way around weather that was either well below us or minor. Perhaps if we had more information it would be a better tool. Overall it is too sensitive (just my opinion).
ID:7	**Source:** Pilot Feedback
	First leg with AC3708 with new test radar. We were deviating for weather in JAX center airspace on freq 127.87. Jax directed us to go direct to a fix on the RDU arrival. We were painting a strong isolated cell on the requested course and stated we could not accept that routing. JAX then directed 15 degrees left for traffic. The cell was too close to this turn and we said we were unable to comply. The controlled then became agitated and asked us if we were using our emergency authority to contradict an ATC directive. I replied with an affirmative response. We were able to take his original requested course within 10 to 15 miles after passing the cell. A contributing factor was this radar with auto tilt. It tends to tilt lower and paint a lot more weather than I normally see at cruise. After switching to manual tilt with a 0 tilt angle, the strong cell almost disappeared from our display.
ID:8	**Source:** Jump Seat Observation
	Pilot said that the [Rockwell Collins] WXR700 (conventional unit on 737NGs) tends to be too sensitive. Often, it will paint red in a certain spot, and when crews have to penetrate the area they find only light-moderate precipitation. Interestingly, and in contrast to some other feedback received on the Multiscan, he said he did not encounter this problem during either of the two flights that he was aboard ship 3708 with the Multiscan radar installed. To him, it showed a much more realistic picture than the previous radar.
	Important unknowns in this kind of feedback are the gain settings that were used on both the Multiscan unit and the conventional WXR700 radar. During previous jump seat rides, I noticed the gain setting on the Multiscan unit spun to its highest level of sensitivity, particularly at higher altitudes. Awareness of the Multiscan's automatic gain feature, which automatically compensates for reduced reflectivity at higher altitudes and colder temperatures, may be lacking. Further emphasis on setting the gain to "CAL" and leaving it there may be needed. This potential variation in gain settings may be a leading cause of the kind of anecdotal feedback regarding radar sensitivity currently being received.
ID:9	**Source:** Pilot Feedback
	When asked where the gain was set during the event mentioned in the crew report, the captain stated that it was at CAL in auto mode, where it remained when put in manual mode. The pilot cited the automatic gain, as well as OverFlight protection features as factors in the reduced reflectivity that resulted when the radar was placed back in manual mode. The captain further

stated that as soon as he denied the controller's clearance by exercising his emergency authority, the controller asked other Delta aircraft (presumably transiting the area that the radar had predicted as hazardous, though there's no way to be certain) for ride reports. All aircraft responded that the ride was smooth, and after about one minute of deviating, the captain accepted direct to the fix where he'd previously been asked to proceed. When asked if the aircraft penetrated the area where the radar had painted high reflectivity, the captain responded that they skirted the edge of that area but did not penetrate the "core."

It was explained that his issue underscores a broader, more fundamental change in terms of what the new radar is communicating versus previous radars. That is, raw returns are being replaced by hazard assessments, and the E-Turb will enhance that effect even more.

Assessing the particular situation with which the captain was confronted, the other Delta aircraft that were in the vicinity of the cell could have been just above (or just past) something that was about to give them a very rough ride, as predicted by the Multiscan. Since the captain deviated, we'll never know. Also, conditions were IMC, so there was no way to visually verify the top of the cell in question.

The other possibility, of course, is that perhaps the radar is too sensitive, as has occurred in the past with the introduction of GPWS and TCAS systems.

ID:10	**Source:** Jump Seat Observation

While in AUTO mode with the gain set to CAL, a cell with strong echoes was detected ahead and to the left of the flight path. At the time, the aircraft was in IMC at FL330. Taking the radar out of AUTO mode and leaving the gain at the same setting, the cell nearly disappeared, showing green and a hint of yellow with the tilt at 0 degrees, -1 and then -2. The cell essentially blended in with other light echoes all around. Cranking the gain to the highest setting was required to display the same reflectivity as in AUTO mode at that altitude, and the captain remarked that he normally would leave the gain alone (at the calibrated setting) on the previous radar, adjusting the tilt downward to detect the hazard instead. Again, operating the radar in this fashion yielded very benign echoes, and both pilots remarked that, without the advisory information provided by the Multiscan's automatic functionality, they would have had no reservations about transiting the area where the radar had painted nasty weather while in AUTO mode.

We weren't really certain what to make of the system at this point, wondering whether the unit was in fact too sensitive.

ATC then issued a clearance to FL410, at which time we popped out on top of the cirrus. At the same time, the top of the echo that the Multiscan had detected as hazardous became visible, ending in an anvil at about FL430 or 440.

ID:11	**Source:** Pilot Feedback

I had the opportunity to use the new wx radar from LAX-SLC. The new wx radar is a big improvement over the older radar system on the 800 fleet. The auto-tilt feature significantly reduces crew workload in a convective weather environment and the wx display is much more accurate in terms of where the actual cells are located and what degree of convective activity they contain. The new radar provided the crew with very accurate wx/turb information minimizing the disruption to cabin service and the chance for turbulence related injuries to the crew and pax. It's a great system and I hope when economic conditions improve, this system can be retrofitted on the remainder of the 800 fleet.

ID:12	Source: Pilot Feedback

Paraphrased from actual crew report: Liked the Multiscan radar, and felt it did an excellent job of distinguishing cells at long range. Very dissatisfied with the turbulence feature, however, which did not show the continuous light chop that was experienced in cumuliform clouds at mid-altitudes (15,000-25,000 feet). Turbulence was painted in cells, but that should be fairly obvious. Did not feel that the feature was of any value, since the turbulence was painted only where one would expect to find it, and did not correlate with the light turbulence that was experienced.

ID:13	Source: Jump Seat Observation

Despite very little weather reflectivity throughout the flight, magenta was painted in one area near Atlanta while it was not present in a cumuliform cloud that the pilot felt would be turbulent. Upon entering the cloud in question, the turbulence was relatively smooth.

ID:14	Source: Jump Seat Observation

Context: Rome Arrival into Atlanta, lots of convection and turbulence associated with the northeast quadrant of Hurricane Ivan. An unprecedented number of TAPS reports on this arrival, with several moderates as the day progressed (including one moderate from ship 3708 on flight 954, ATL-LGA). A request for ride reports yielded "moderate turbulence all the way in until turning final."

Multiscan Performance: The Multiscan automated functionality worked flawlessly throughout, significantly reducing pilot workload in some very challenging airspace.

E-Turb Performance: Descending from 27,000 to 23,000 feet, speckled (but sparsely distributed) magenta began being depicted in areas of very low and nil reflectivity. When we transited the area, the bumps were very, very light, not unlike turbulence we had been encountering for some time in similar IMC conditions. Because of building weather over ERLIN intersection, ATC then vectored us 20 degrees left of course, which brought us directly into an area of more concentrated speckles. Recognizing this, the first officer asked for 20 degrees right of course as an alternative, which would have taken us very close to the heavier reflectivity at ERLIN but avoided turbulence (since there was none predicted in that area). ATC denied the request, and there was good correlation between the speckles and what we experienced. A glance at the altimeter during this encounter read 19,300 feet (in the course of a descent).

During the remainder of the descent, which included a few minutes in VMC between layers, very little if any magenta was depicted. Throughout this period, the flight crew and I felt that the turbulence experienced was just as intense as the area where concentrated speckles had been displayed previously.

Additionally, ATC advised traffic on frequency of a microburst 1 mile to the northeast of runways 8L and 8R (on the north side of the field). A speck of magenta was apparent in this vicinity while on final.

ID:15	Source: Jump Seat Observation

Observed isolated cells, separated primarily by VMC conditions, at altitude. The captain remarked that the Multiscan did an outstanding job of painting the cells as they actually appeared, including the overhang typical of thunderstorm tops. Using the previous radar, this overhang went virtually undetected.

Despite coming within 25 nautical miles of the storms, no magenta was depicted within these cells.

Also, both pilots had flown ship 3708 previously, and were very impressed with the Multiscan's capabilities. The captain mentioned a flight in August from LAX to GDL (Guadalajara, Mexico) during which the new system was especially helpful. While descending into GDL, the crew's workload was significantly reduced thanks to the cancellation of ground returns in the vicinity of thunderstorms and mountainous terrain.

However, the captain also mentioned a flight during which strong returns were painted even though the tops were well below the altitude of the aircraft. He recounted that the aircraft was cruising at about FL350, and estimated that the cell tops in question were at approximately FL200, 80-100 nautical miles distant. Despite the distance of the cells from the aircraft, he confidently asserted that the cells topped out well below the aircraft altitude.

ID:16	Source: Jump Seat Observation

Observed isolated cells over New Mexico and the Texas panhandle. Both pilots had flown ship 3708 previously, and saw the system as a very significant improvement vs. the previous radar.

Despite coming within 25 nautical miles of the storms, no magenta was depicted within these cells.

ID:17	Source: Jump Seat Observation

Leg 1: PHX-CVG

Context: Lots of rain with embedded convection ahead of a cold front pushing through the Ohio Valley throughout the day. Indianapolis Center had descended every CVG arrival from the west very early due to airspace restrictions associated with the weather. TARNE3 arrival to runway 18R, solid IMC all the way to about 800 feet.

Multiscan Performance: Excellent

E-Turb Performance: Patch of speckled magenta encountered at FL290 within an area of relatively low reflectivity (green), and all felt that the correlation between the turbulence predicted by the magenta and the turbulence actually experienced was very good. At first, the captain commented that perhaps this area had been a false warning, since the magenta began to disappear behind us while the ride remained smooth. Before he could finish this sentence, the bumps occurred.

Also had good correlation between a patch of speckled magenta encountered just after leveling at FL230, and skirted the right side of an area of concentrated speckles to the east and north of TARNE intersection.

Similar turbulence encountered in areas where speckles were very sparsely distributed (from about 10,000 to 5000 feet, and particularly around 9,000 feet). This may have merely been turbulence just below the threshold established for the speckled magenta, but such experiences can be confusing and may underscore the need for significant education on the system once it is deployed more widely.

Leg 2: CVG-LGA

Relatively smooth with just a few speckles of magenta depicted during the climbout. Otherwise smooth, and no significant weather to LGA.

ID:18	**Source:** Jump Seat Observation

Context: After a modified holding pattern at Henderson VORTAC (HNN) due to a line of storms over the CVG airport, vectored to the north, then west, then south for a landing on 18L. Storms containing the highest reflectivity had largely moved south and east before being cleared from HNN, but lots of rain and turbulence still remained for the arrival.

Multiscan Performance: Excellent

E-Turb Performance: From 11,400 feet until about 9,000 feet, an area of predicted turbulence (concentrated speckles) within relatively low reflectivity correlated very well against what was experienced. Initially, the low reflectivity (green and nil returns) made both pilots skeptical about the existence of the turbulence, but after transiting the area, they agreed that the magenta had in fact told the truth.

For the remainder of the descent, sparsely distributed speckles appeared within areas of relatively higher reflectivity (yellows), and the turbulence was fairly smooth.

ID:19	**Source:** Pilot Feedback

MDT TURB ENCOUNTERED DP RTG ATL THRU 9000. NO MAGENTA DSPLY. ENROUTE FL310 MDT CHP NO DSPLY SEVRL RANGES.

ID:20	**Source:** Pilot Feedback

1. Were you satisfied with the presentation/design of the 2 levels of magenta (if applicable)? – **Yes**

    i. If not, what did you see as deficient (e.g. definition around the 2 levels etc.)? **Only dispersed pattern displayed**

2. Did the aircraft penetrate any area(s) where magenta was indicated? **Yes!**

    i. If so, did you feel that the magenta accurately predicted the level of turbulence experienced (if any)? **Turb was present and approached moderate**

3. Was the 25 nm range of the magenta adequate for avoidance and/or the crew's ability to secure the cabin? **More notice would be better. By the time we were able to coordinate, we were in it.**

4. Did you encounter turbulence within clouds in areas where no magenta was depicted? **N/A**

    i. If so, would you have liked to see that turbulence depicted or was it too light to be worthwhile?

Please feel free to include any other feedback in the space below.

Great to have had the little warning we did!

ID:21	**Source:** Pilot Feedback

Context: Ideal proving ground for E-Turb, with lots of convection throughout south Georgia along the route of flight. Several TAPS reports (included below with rms g levels highlighted) were made during climbout and cruise.

MESSAGE FROM DISPATCHER (prior to departure):

** PLEASE ACK ** WHEN ABLE PLEASE SEND FEEDBACK ON PERFORMANCE OF NEW RADAR, PARTICULARLY PRESENCE/ABSENCE OF MAGENTA WITH WX/T MODE SELECTED **CREW FEEDBACK:** A80 FI DL1555/AN N378DA GOT GOOD WORKOUT WITH NEW RADAR. MAGENTA TBC WORKED GREAT EVEN AT HI ALT WITH MIN MOISTURE	
ID:22	**Source:** Pilot Feedback
FROM RZC [waypoint in northwest Arkansas] TO PER [waypoint in north central Oklahoma], IN AND OUT OF CIRRUS WITH INTER LT CHOP. E TURB RADAR NOT PAINTING ANYTHING	
ID:23	**Source:** Pilot Feedback
Descending into SLC, in the vicinity of convection, the aircraft sent a string of TAPS reports, including one moderate report. After landing, the captain commented that he was very pleased with the E-Turb system's performance, which he said painted only speckled magenta. In his opinion, that correlated very well with what he experienced as turbulence "approaching moderate." Additionally, he noted that the radar issued windshear alerts during taxi-in, and the tower confirmed the presence of microbursts south of the field.	
ID:24	**Source:** Jump Seat Observation
Lots of convective activity associated with frontal system over the US mid-section. East of Memphis, while level at FL380, passed between 2 cells in clear air. Speckled magenta overlaid red reflectivity in cell to the right (north of route). No turbulence encountered. NOTE: While in Memphis Center's airspace, numerous aircraft asked if it would be possible to cut out some waypoints along their flight plan routes, since the weather system presented numerous options for tactical deviations. The response from ATC was, "There are weather routes from the Northeast into the West and Southwest, and we have been told to grant no shortcuts without first calling traffic management." Near the Oklahoma panhandle/Colorado/Kansas borders, while level at FL360, heading 290 in cirrus cloud, a speck of magenta ahead and to the left of the flight path, associated with a small circle of green reflectivity, appeared. The captain turned on the seatbelt sign. The magenta then disappeared, and the area of reflectivity also began to dissipate. Moments later, the aircraft emerged from the cirrus, revealing a small buildup that topped out just below the altitude of the aircraft. No turbulence encountered.	
ID:25	**Source:** Jump Seat Observation
Continued convective activity associated with frontal system over US mid-section.	

During taxi-out, ground control advised the crew to call clearance delivery for a re-route to the filed flight plan. Clearance confirmed that the re-route was due to weather over the mid-section of the US, and issued a drastic re-route to the north. Instead of a more or less linear due east routing to Newark (in accordance with the original flight plan), the re-route drew an arc whose top was at the upper peninsula of Michigan, adding 200 nm to the journey and resulting in an arrival that was 30 minutes late despite an on-time departure. Arrival time would have been later had the captain been less conscientious about looking for the best winds and asking for shortcuts.

Despite the radar's 320 nm range, weather was painted only once. The cells captured were 150-200 nm distant, had lots of space between them, and were just to the north of Detroit.

ID:26	**Source:** Jump Seat Observation

Lots of convection throughout the eastern U.S. associated with a low pressure system that had come ashore the prior weekend as Hurricane Cindy. All descriptions assume AUTO mode with the gain set to calibrate.

Climbing away from Atlanta at about 4500', ATC issued a vector due to weather over JCKTS intersection. This weather was depicted on the radar screen in green and yellow, and despite being within about 15 nm of the cell, there was no magenta associated with it. Due to weather west and southwest of MEI (Meridian, MS), numerous deviations were made enroute.

During descent at FL250 in IMC conditions, a few specks of magenta associated with a small patch of green reflectivity appeared ahead. Though the ride was relatively smooth in surrounding areas, only very light chop was encountered while transiting this area.

Later, while descending at FL180 and again in IMC, more specks of magenta, associated with black returns, appeared in the flight path. As the aircraft approached the area where the specks had been apparent, however, magenta disappeared.

Lots of reflectivity with speckled and solid magenta appeared to the right of course during the remainder of the descent into MSY. Due to a late descent from ATC, however, a left hand 360-degree turn was made. Magenta was not apparent in any cells during the turn, but reappeared a few seconds after rolling out and resuming the arrival towards runway 19. No areas of magenta or reflectivity were penetrated for remainder of the flight.

ID:27	**Source:** Jump Seat Observation

Upon contacting departure immediately after takeoff from runway 19, ATC issued a right hand vector to 320 degrees. Reflectivity there was green and yellow, though nil to the left. The captain requested a left hand turn to the same heading instead, and the controller denied the request citing traffic to the east and reports of a smooth ride from two Southwest B737s that had departed through the area of weather just before. In addition, no magenta was depicted in that area, and as advertised, a smooth ride was experienced.

Because of widespread thunderstorms across Mississippi, Alabama and Georgia, an ATC reroute prior to takeoff had put the flight on an enroute heading of due north towards Memphis before a right turn towards the ERLIN2 arrival into ATL. Heading 010 towards Memphis, weather was depicted at fairly long range in a northeasterly line from Jackson to Columbus, MS. The captain requested to cut the corner towards ERLIN in order to take advantage of a large hole north of the line, but was denied due to "in-trail flow restrictions" from the Traffic Management Unit. In the first officer's estimation, this routing added about 250 nm to the flight, and the FMS calculated an additional 30 minutes to Atlanta.

All was rendered moot, however, when a lingering thunderstorm over the Atlanta airport and holding at 2 locations progressively closer to the arrival necessitated a 2.5-hour diversion to Hunstville, AL.

Continuing from HSV to ATL, no significant weather close to the flight path was encountered. The top of a small cumulus buildup with no reflectivity and no magenta, however, was encountered in VMC during cruise at FL190. The captain nonetheless elected to deviate around the cloud with a quick left turn before returning to the flight plan route, and asked why he had not seen any magenta. I responded that the turbulence in the cloud probably amounted only to light chop that was below the magenta trigger, but couldn't be sure since we didn't actually go through the cloud.

ID:28	**Source:** Jump Seat Observation

Lots of convection south of the TN/GA line, associated with a stationary front draped across the southeast. While deviating left of a cell over Atlanta, windshear was forcing the temporary closure of the Atlanta airport. Thunderstorms extended through south Georgia into the Florida panhandle around Tallahassee, then quieted before picking up again along the west coast of the peninsula. The captain, who remarked that he was relatively new on the 737-800, was the pilot flying.

First cells encountered were east of Chattanooga, TN, extending south over Atlanta while at FL370. Green and yellow returns were observed with the radar in AUTO mode, and the captain deviated well left and clear. In marginal IMC conditions between Chattanooga and Atlanta, however, no magenta was observed while flying through an area of nil reflectivity, and the ride was in fact smooth.

Several more cells, showing lots of red, dotted the route south of Atlanta towards Tallahassee. The captain chose a narrow passage that avoided all reflectivity. South of Columbus, GA, the captain took the radar out of AUTO mode, demonstrating how he would normally use the conventional radar. Leaving the gain at the calibrated position and tilting at 0 and -1 degrees, reflectivity was, of course, significantly reduced, and he felt that he was getting more reflectivity in AUTO mode than was actually present. I then explained the automatic gain compensation, and after pointing out the cells as they appeared through the windows, both crewmembers somewhat grudgingly agreed that the picture painted by AUTO mode had indeed told the truth.

While green returns in AUTO mode mostly represented the edge of storms, prompting deviation, only black had been present in the same areas while in manual mode. From the standpoint of an effort to validate the magenta by getting into *some* IMC conditions, the reluctance to penetrate any reflectivity was frustrating. I wished that, in good conscience, I could have dialed down the gain while in AUTO mode to achieve better validation. Still, we did get well within 25 nautical miles of many cells showing heavy reflectivity, and, interestingly, very little magenta was observed in and around these areas. One might speculate that these storms were diminishing due to the onset of nightfall.

During the descent towards Tampa, a more or less continuous line of cells was observed left of course. While level at FL240, magenta speckles appeared in green reflectivity but left of course, 15 nm distant. Magenta was observed ahead, again left of course, descending through 15,000 feet. For no apparent reason, the captain took the gain out of AUTO mode at 8000 feet, despite no cells and VMC conditions prevailing for the remainder of the flight. After the approach was briefed, I asked to put the radar back in AUTO mode at about 6000 feet. The captain replied, "For now."

Once on the ground, I asked the captain why he had taken the radar out of AUTO mode, and he explained that due to the high workload, his newness on the 737-800, and the presence of

thunderstorms in the vicinity, his behavior almost subconsciously defaulted to the familiar. I told him I understood, but also explained – as humbly as possible – that by eliminating workload to help the crew focus on flying the airplane, that's exactly the environment in which the automation shines.

Though the Multiscan picture definitely appears more accurate than the one painted by previous generation systems, as pilots *currently conceive* using the weather radar in the en route environment, it is scaring crews to deviate much wider from storms than they might otherwise.

Meanwhile, in the terminal area, where reflectivity for the same gain setting on older systems is naturally much higher, crews are used to seeing a lot of red on the radar screen. During this flight in fact, the first officer remarked that he often sees a lot of red during the approach phase of flight, only to discover heavy rain and a fairly smooth ride. So due to the wide disparities in the picture given by a constant gain setting on legacy systems, areas of high reflectivity at low levels appear to be of much lesser concern than red returns at altitude.

With training and experience with newer radar systems, perceptions and methodologies about reflectivity and hazard are likely to change, but getting to that point will be a challenge for those used to older systems.

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14. ABSTRACT

From August 2003 to December 2006, In-Service Evaluations (ISE) of the Turbulence Auto-PIREP System (TAPS) and Enhanced Turbulence (E-Turb) Radar, technologies developed in NASA's Turbulence Prediction and Warning System (TPAWS) element of its Aviation Safety and Security Program (AvSSP), were conducted. NASA and AeroTech Research established an industry team comprising AeroTech, Delta Air Lines, Rockwell Collins, and ARINC to conduct the ISEs. The technologies were installed on Delta aircraft and their effectiveness was evaluated in day-to-day operations. This report documents the establishment and conduct of the ISEs and presents results and feedback from various users.

15. SUBJECT TERMS

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