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AeroTech Research (U.S.A.), Inc.

Concept of Operations for an Integrated Turbulence Hazard Decision Aid for the Cockpit

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1. Scope

The scope of this document is defined to be a conceptual description of how an Integrated Turbulence Hazard Decision Aid for the Cockpit that combines Turbulence Auto-PIREP System (TAPS®) with the Enhanced Turbulence Radar (E-Turb) and how it would apply in 14 CFR Part 121 Air Carrier operations. However, it is important to note that the potential benefits of the technologies could also apply to other classes of aircraft and other types of operations, such as regional air carriers, cargo carriers, charter operators, military operations, and business aircraft operations. Since some of these other types of operations may not have the meteorological and dispatch support infrastructure of the scheduled air carriers, real-time turbulence data could represent enhanced value for them. Also, as equipage grows into other classes of aircraft and other types of operations, the turbulence database would also grow over a broader range of airspace and altitudes, thus offering more options for deviations and route changes by all aircraft. While it is beyond the scope of this document to discuss the implementation of TAPS and E-Turb Radar technologies in an integrated Decision Aid for these other classes of aircraft and airspaces, such expansion is highly likely and would significantly enhance the overall value of the system.

It should also be noted that, while this Concept of Operations (CONOPS) document has been developed assuming domestic operations in U.S. Airspace much of the discussion and conclusions would also be applicable to oceanic and other international airspace.

Section 1 provides an overview of the CONOPS document and the functional area to which it applies.

1.1 Identification of the Technology

The goal of the National Aeronautics and Space Administration (NASA) Aviation Safety and Security Program (AvSSP) was to develop technologies that address the causal factors of historical fatal aviation accidents, as well as to develop proactive, system-wide risk detection technologies to prevent future accidents and mitigation technologies to reduce their severity. The AvSSP conducted research into pre-emptive identification of aviation system risk, into accident severity mitigating technologies, and into accident prevention technologies across four causal factor areas. The causal factor areas include limited visibility operations, unseen weather hazards, aircraft component failures, and human errors.

Both the TAPS and E-Turb technologies were developed under the AVSSP, and both have, separately, achieved a significant level of adoption in the industry. ATR with its industry partner Weather Services International, Inc. (WSI) have installed the TAPS software on over 500 commercial aircraft worldwide. The TAPS information is incorporated into WSI's Fusion™ dispatcher decision support tool.

The E-Turb radar technology has been adopted by the FAA as the standard for airborne radar turbulence detection. The FAA has produced a Technical Standards Order (TSO) defining the Minimum Operational Performance Standard (MOPS) for certification of this capability (References [20] and [21]).

This CONOPS document addresses the incorporation of both TAPS and E-Turb technology in an integrated Decision Aid for the cockpit. The CONOPS is intended be a living document, to the extent that the concepts presented may need to be modified to ensure continued applicability in light of advances in the technology, integration with other technologies, maturation of other technologies that support or enhance the operability of the subject technology, changes to the system in which the technology is suggested for insertion, or other factors. This revised version of the CONOPS is intended to communicate an understanding of the aviation stakeholders' needs for and expectations of the proposed technologies to potential users and/or developers. It represents an understanding of how commercial products based on the proposed technologies will operate to fulfill those expectations.

1.2 Document Overview

The CONOPS is written in compliance with NASA's AvSSP Products CONOPS Guide, which was developed by the Technical Integration Project of the AvSSP as part of the Systems Engineering effort. The guide was developed through consideration of a variety of existing Concept of Operation documents, as well as a number of Concept of Operation development guides published by standards organizations and commercial entities. The guide most closely follows the IEEE Draft Standard, *IEEE Guide for Concept of Operations Document v3.1*, from January 1998, with modifications to the outline and content to ensure applicability within aviation products as opposed to software product development, and NASA's AvSSP-specific content requirements. The AvSSP CONOPS Guide also incorporates the *AIAA Guide for the Preparation of Operational Concept Documents* definition of a system as "a collection of hardware, software, people, facilities, and procedures organized to accomplish some common objectives."

At a high level the CONOPS describes the current system, justifies changes to it, and describes the resultant system, presenting scenarios to illustrate the proposed system operations.

The audience for the CONOPS includes those within the aviation industry, NASA, and the Federal Aviation Administration (FAA) or other regulatory agencies that play a role in the operation of the aviation system segment addressed by the CONOPS. The likely audiences will range from subsystem designers to aircraft manufacturers, air carriers, pilots, air traffic controllers, researchers, and regulators.

Section 1 of the document establishes the scope and provides an overview of the document, its purpose, and structure.

Section 2 of the document lists referenced documents and sources of further descriptions of details contained within this text.

Section 3 of the document describes the current system and discusses the limitations of that system.

Section 4 of the document provides justification for changing the current system.

Section 5 of the document provides an overview of a proposed new system that incorporates new turbulence technologies, and discusses how these technologies could make airline operations safer and more efficient.

Section 6 of the document details linkages between the proposed technologies and plans, policies, and programs that the FAA and others have published.

Section 7 of the document discusses two operational scenarios that illustrate how the proposed new system would actually work in practice.

Section 8 of the document discusses limitations of the proposed system and alternative concepts that were considered. Also presented are supporting and enhancing processes, procedures and other technologies that enhance the proposed application.

Section 9 of the document presents summary conclusions and recommendations, including follow-on plans to increase the NASA Technology Readiness Level or further refine the concept of operations.

1.3 System Overview

Aircraft encounters with turbulence are the leading cause of injuries in the airline industry and result in significant human, operational, and maintenance costs to the airline community each year. A large contributor to the above injuries and costs is that flight crews do not have sufficient situational awareness of the location and severity of potential turbulence hazards to their aircraft. Improvement to pilots' situational awareness of turbulence hazards can be accomplished by developing an integrated, graphical cockpit Decision Aid incorporating turbulence hazard information scaled to their specific aircraft's configuration. This display would remove the need for inference that is required to interpret current turbulence information. With better knowledge of turbulence hazards' severity and location, pilots would be able to avoid turbulence encounters or prepare for them by having all occupants seated with seatbelts on, thereby avoiding injuries.

It is envisioned that the integrated Decision Aid for the cockpit will provide pilots with improved turbulence hazard information allowing them to operate more efficiently and safely. Significant reductions in flight delays and cancellations, fuel waste and costs associated with injuries due to turbulence are expected to be major commercial drivers for this system. The primary market for this display is all Part 121 carriers (both domestic and international) with the secondary market moving towards business and general aviation aircraft.

2. Referenced Documents

[1] Federal Aviation Administration, Aeronautical Information Manual, Official Guide to Basic Flight Information and ATC Procedures, February 16, 2006.

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[3] Federal Aviation Administration, Advisory Circular No: 120-88A, *Preventing Injuries Caused by Turbulence,* January 19, 2006.

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[19] Paul A. Robinson, Bill K. Buck, Steven G. Velotas, and Jason B. Prince, "*Concept of Operations for an Integrated Turbulence Hazard Decision Support Tool for Controllers and Dispatchers*", AeroTech Research, ATR-2014-12044, Newport News, Virginia, October 2014

[20] "*Airborne Weather Radar Equipment*", FAA TSO-C63d, 12/28/12.

[21] Roland L. Bowles, Bill K. Buck, "*A Methodology for Determining Statistical Performance Compliance for Airborne Doppler Radar with Forward-Looking Turbulence Detection Capability*", NASA Contractor Report Series, NASA/CR-2009-215769, Newport News, Virginia, June 2009.

3. Current System Description

In current operations, a pilot's total "picture" of turbulence hazards is achieved by mentally integrating information from a variety of disparate sources including commercial weather products, preflight briefing information, pilot reports uplinked on ARINC Communications Addressing and Reporting System (ACARS) or verbally transmitted from Flight Service Stations, ride reports available on Air Traffic Control (ATC) frequencies, and communications with airline dispatch personnel. Additionally, pilots infer the possibility of convective-related turbulence by referring to reflectivity indications on their airborne weather radars. No means exist for inferring the existence of Clear Air Turbulence from radar information in today's environment. This "mental integration" process may be different from pilot to pilot, based on experience and training, and can vary significantly depending upon the class of aircraft and type of operation, equipage, and support infrastructure.

The current system will be discussed in the following subsections in terms of radar-based and non-radar-based technologies in order to allow direct contrasting of today's system with a model of a future system described in Section 5 that incorporates TAPS and E-Turb Radar technologies, which are non-radar and radar-based, respectively.

A similar CONOPS has been developed for an integrated turbulence hazard display tool for controllers and dispatchers which is intended to be completely complementary to the CONOPS herein (Reference [18]).

3.1 Background, Objectives, and Scope

Today's air traffic control system serves a wide variety of users, all of whom have an interest in identifying and avoiding atmospheric turbulence. The relative priority that avoiding turbulence takes in comparison to other considerations, such as fuel conservation or maintaining schedule, varies between users. However, virtually all users are interested in avoiding severe turbulence and most are interested in avoiding moderate turbulence. Severe turbulence can represent both a structural and a controllability hazard for aircraft, and moderate turbulence can represent a safety issue for unconstrained passengers or cabin crews. While all operators clearly have a stake in turbulence avoidance, the scope of the discussion in this section will be limited to 14 CFAR Part 121 air carrier operators except where inclusion of other operators or other classes of aircraft is necessary to understand the context of turbulence avoidance systems or procedures.

Atmospheric turbulence is generally characterized within the aviation system as convective turbulence, clear air turbulence (CAT), or wake turbulence. The scope of this document will be limited to discussions of convective and clear air turbulence only. Other research programs are addressing wake turbulence identification and avoidance and its inclusion is beyond the scope of this document.

Modifications to commercial weather systems and the forecast products of the aviation weather system are also beyond the scope of this document. Potential changes to these elements of today's system will not be discussed except as background or as they are necessary to understand the use and limitations of today's system. Discussion will focus primarily on how pilots obtain actual in situ turbulence data and how they use that data.

3.1.1 Non-Radar Information Sources

Pilots normally begin building their integrated "picture" of atmospheric turbulence by reviewing the general weather synoptic situation 12 to 24 hours before their planned departure time. Typically they may access commercial weather products, such as the Weather Channel™ or one or more of the many commercial weather sources available via the Internet, or obtain an "Outlook" briefing from one of the FAA's official weather sources known as Direct User Access Terminal Service (DUATS). Some larger air carrier operators provide sufficient internal or contract weather services that their flight crews can depend solely on their company systems for weather information. However, smaller operators and pilots operating out of airfields where no company dispatch or meteorological functions exist may rely more heavily on commercial weather services.

Immediately prior to departure pilots must obtain, by regulation for this class of operations, a formal weather briefing. This briefing would include forecast information concerning regions of turbulence applicable to the pilot's planned route and altitude, and formal pilot reports (PIREPs) that have been logged into the aviation weather system through FAA or National Weather Service (NWS) facilities. PIREPS relating to turbulence include the aircraft location, time of occurrence, turbulence intensity, whether the turbulence occurred in or near clouds, altitude, type of aircraft, and duration of the turbulence.

Once a flight has departed, pilots submit pilot reports at their discretion to the facility with which they are maintaining radio communications, usually an air traffic facility. If desired, the facility personnel can submit such pilot reports for encoding into the formal PIREP system. Most often, however, the reports are simply received by other aircraft on the frequency, or relayed by the controller to new aircraft checking in, as a "ride report".

Pilots may also elect to enter formal PIREPS into the FAA system by contacting a Flight Service Station or "Flight Watch" on designated frequencies. They may also elect to send the information back to their company dispatch organization via ACARS or ARINC voice frequencies. Information sent in this manner is generally only available to other company aircraft unless dispatch decides to enter the information into the FAA system. Workload considerations in air traffic facilities, the cockpit, and dispatch facilities generally result in most ride reports not being entered into the formal PIREP system, which significantly limits the value of the system.

Pilots receive ride reports, a form of real-time turbulence reports, from aircraft in their immediate area by monitoring air-to-ground communications on their current ATC sector frequency, or they can obtain information for other geographical areas by contacting "Flight Watch". They can also contact their company dispatch personnel if preferred. Some company dispatchers will also provide ride reports to flight crews via ACARs messages but, like FSS information, these reports may be difficult to interpret.

3.1.2 Airborne Weather Radar-Based Information Sources

Another source of in-flight weather hazard information is the aircraft weather radar, first introduced over 50 years ago. At the time of its introduction and for many years thereafter, this radar could only sense the presence of water vapor or water droplets and was primarily used to avoid thunderstorms based on moisture content, displayed on the radar scope as "reflectivity". Modern airborne weather radars still display reflectivity, but have automated some tasks such as gain and tilt control to provide an improved reflectivity picture. Reflectivity information from airborne weather radars can only be used to infer the existence of turbulence. Radar engineers and pilots have developed many useful techniques for maximizing the value of reflectivity information, but in the end it is still only a secondary indication of turbulence.

Modern Doppler weather radars are also capable of measuring the along-path motion of water droplets and from this information derive an indirect measure of turbulence. However, the turbulence identified by this Doppler technology is very limited in range and is not generally well accepted by pilots. More importantly, this information is not scaled to the measuring aircraft and thus the implications of the measured particle motion is difficult to interpret depending on the type, size, weight, speed, etc. of each aircraft. Furthermore, this information is only available in the presence of water particles and thus provides no protection against clear air turbulence hazards and the turbulence outside of thunderstorms.

Considering both non-radar and radar information sources in today's system, flight crews and airline meteorologists and dispatchers have very little timely, reliable information about actual turbulence encounters and only rudimentary information about the turbulence fields in front of the aircraft. For these reasons, pilots are forced to make larger deviations than are perhaps necessary, costing time and fuel, and exposing both passengers and cabin crews to the possibility of undetected and unreported turbulence encounters which can lead to the possibility of injuries and their associated costs.

3.2 Operational Policies and Constraints

Because turbulence is the most frequent cause of in-flight injuries, the operational policies of both the FAA and the US air carriers have attempted to extract the maximum amount of protection possible from the existing system of turbulence forecasting, pilot reporting, and Doppler radar usage. Pilots and controllers are both encouraged to report turbulence hazards by their respective operational guidelines and ride reports are a common element in most ATC communications. However, fundamental limitations of the system limit the value of the available data as a viable tool for turbulence identification and avoidance.

This section will discuss some of these operational policies and the associated limitations as it relates to turbulence in the cockpit.

3.2.1 Non-Radar Information Sources

Due to constraints on workload, combined with the manual nature of the formal PIREP system, the number of formal turbulence PIREPs is generally very limited. The NWS provides a geographical overlay of these PIREPS on its aviation weather website and a quick glance on any given day will confirm the scarcity of data. Also, this data is only available in graphical form on the ground, so flight crews can use it only as background information during preflight planning. Additionally, turbulence PIREPS are very subjective. For example, the reported severity can be dependent upon the type of aircraft, the state parameters of the aircraft at the time of the turbulence encounter, and aircrew experience.

"Ride reports", a form of real-time turbulence pilot reports, are more ubiquitous but generally limited to the sector airspace in which the aircraft is operating. Ride reports are also subjective in nature and dependent upon aircraft type, size, weight, speed, etc.

While there have been significant improvements in turbulence forecasting in recent years the current tools still provide only general guidance for planning turbulence-minimized flight paths. These tools usually identify relatively large areas of airspace where turbulence is possible and thereby reduce their effectiveness for routine use as practical flight planning tools for the airlines. As an example, Figure 1 shows the coverage of turbulence Airman's Meteorological Advisory (AIRMETs) issued by the National Weather Service for October 6, 2014.

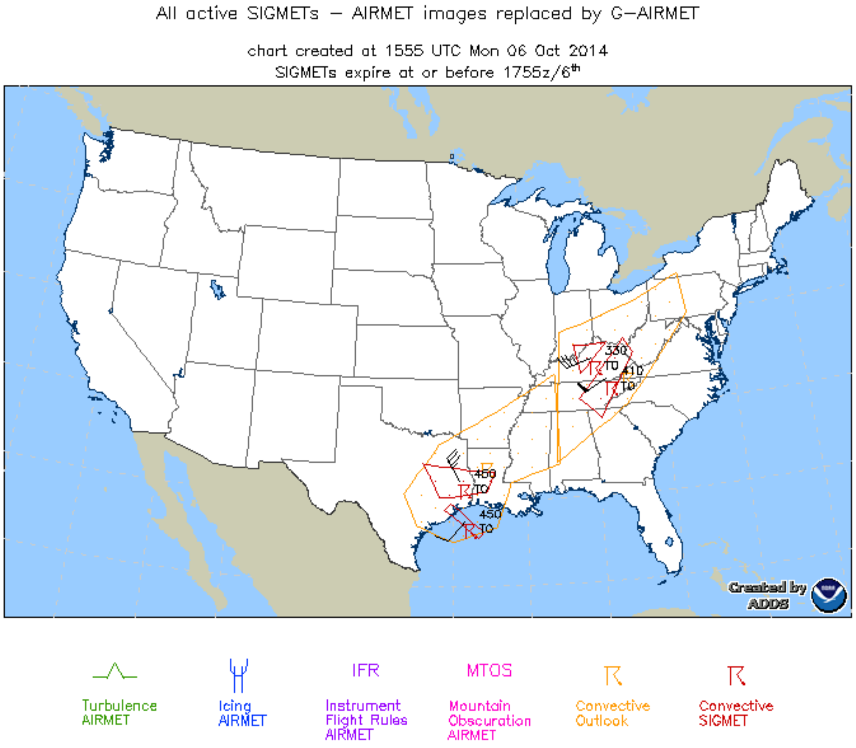


Figure 1: Sample Turbulence AIRMET

As illustrated, the AIRMETs cover greater than 50% of CONUS and also are valid from altitudes in the mid-20,000 foot range to Flight Level (FL) 410, which covers most of the band of desirable altitudes for airline operations.

Figure 2 shows the formal turbulence PIREPS that were entered into the National Oceanic and Atmospheric Association (NOAA) Aviation Digital Data Service (ADDS) for this same day. While this PIREP data has known limitations with data density, scaling, and timeliness, the data available implies that the AIRMET information may not have been entirely representative of the actual turbulence experienced by aircraft.

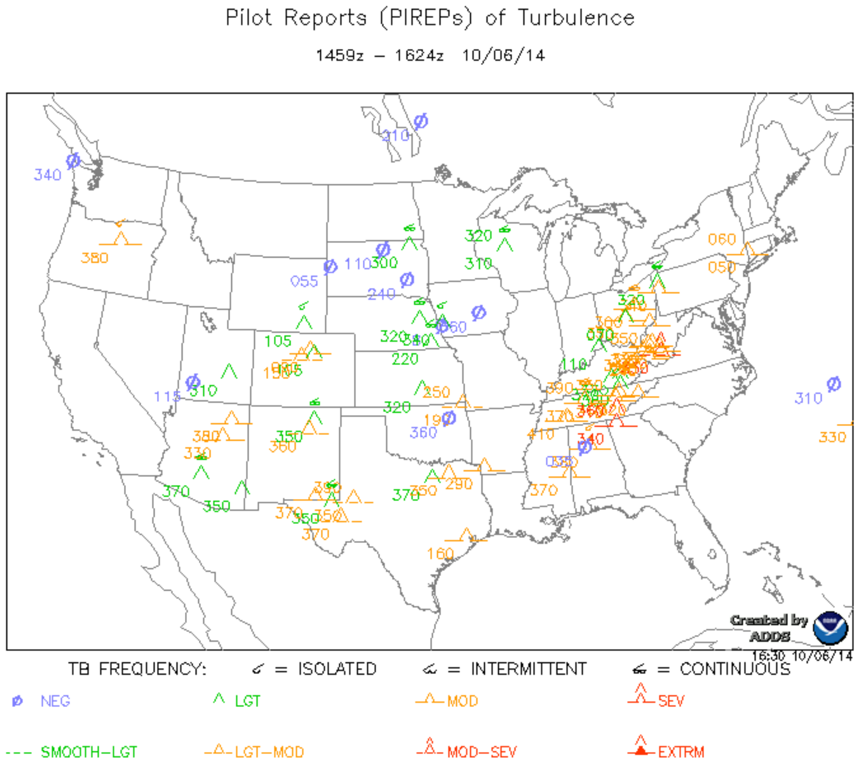


Figure 2: PIREP Data Corresponding to AIRMET Data in Figure 1

A better turbulence-forecasting tool that recently became operational for meteorologists and dispatchers is the Graphical Turbulence Guidance (GTG) chart. This chart combines forecast data with PIREPS and Eddy Dissipation Rate (EDR) data to create a more robust turbulence prediction chart. The GTG for Oct. 6, 2014 is shown in Figure 3.

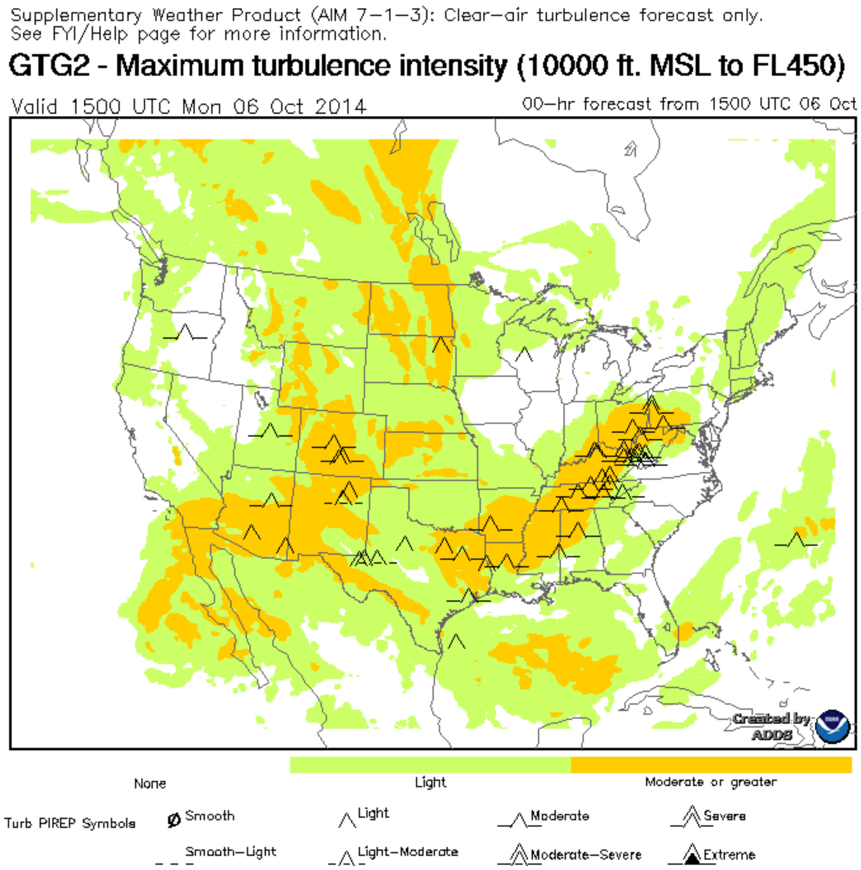


Figure 3: GTG Chart Corresponding to AIRMET and PIREP Data in Figure 1 and Figure 2

Although the current system has serious operational limitations and is of limited value in avoiding hazardous turbulence, the FAA and the airlines try to mitigate these limitations by operational policies that encourage pilots, especially air carrier pilots, to report turbulence and other hazards whenever encountered. For example, Federal Aviation Regulation (FAR) 121.561 states:

121.561 Reporting potentially hazardous meteorological conditions and irregularities of ground facilities or navigation aids.

> *(a) Whenever he encounters a meteorological condition or an irregularity in a ground facility or navigation aid, in flight, the knowledge of which he considers essential to the safety of other flights, the pilot in command shall notify an appropriate ground station as soon as practicable.*

The Aeronautical Information Manual [1] also states in Chapter 7-1-24 a. *"When encountering turbulence, pilots are urgently requested to report such conditions to ATC as soon as practicable."*

The FAA also encourages controllers to solicit pilot reports of turbulence and other meteorological hazards. For example, FAA Order 7110.65R [2] "Air Traffic Control" states:

2−6−3. PIREP INFORMATION *Significant PIREP information includes reports of strong frontal activity, squall lines, thunderstorms, light to severe icing, wind shear and turbulence (including clear air turbulence) of moderate or greater intensity, volcanic eruptions and volcanic ash clouds, and other conditions pertinent to flight safety.*

> ***a.*** *Solicit PIREPs when requested or when one of the following conditions exists or is forecast for your area of jurisdiction:*

> ***1.*** *Ceilings at or below 5,000 feet. These PIREPs shall include cloud base/top reports when feasible.*
> ***2.*** *Visibility (surface or aloft) at or less than 5 miles.*
> ***3.*** *Thunderstorms and related phenomena.*
> ***4.*** *Turbulence of moderate degree or greater.*

In addition to the operational policies affecting the pilot and controller, in Part 121 operations a ground-based dispatcher monitors flights in progress and plays an important role in the safety and efficiency of these flights. The FAA's operational policies regarding the role of the dispatcher in turbulence identification and avoidance can be summed up by stating that hazard avoidance, including turbulence avoidance, is the joint responsibility of both the pilot-in-command and the dispatcher. This policy is confirmed by FAR 121.533, which states:

121.533 Responsibility for operational control: Domestic operations.

> *(b) The pilot in command and the aircraft dispatcher are jointly responsible for the preflight planning, delay, and dispatch release of a flight in compliance with this chapter and operations specifications.*

Additionally, FAR 121.601 states:

> *(b)Before beginning a flight, the aircraft dispatcher shall provide the pilot in command with all available weather reports and forecasts of weather phenomena that may affect the safety of flight, including adverse weather phenomena, such as clear air* ***turbulence****, thunderstorms, and low altitude wind shear, for each route to be flown and each airport to be used.*
>
> *(c) During a flight, the aircraft dispatcher shall provide the pilot in command any additional available information of meteorological conditions (including adverse weather phenomena, such as clear air* ***turbulence****, thunderstorms, and low altitude wind shear), and irregularities of facilities and services that may affect the safety of the flight.*

As a further measure to attempt to mitigate the injuries associated with atmospheric turbulence encounters, the FAA recently published an Advisory Circular entirely dedicated to preventing such injuries [3]. This Advisory Circular covers training, procedures, roles and responsibilities, attitudes, and a host of other topics that could help avoid turbulence-related injuries. This Advisory Circular also provides a review of available and evolving turbulence forecasting and data collection efforts.

Despite these well-intended policies, fundamental constraints of the current system non-radar turbulence products still result in pilots not having reliable and timely turbulence data in a format that they can understand and use. These limitations can be summarized as:

- Data latency – Formal PIREPS can take a long time to file and can be as much as 12 hours old.
- Data quantity – The manual nature of the current PIREP system combined with pilot, controller, and dispatcher workloads during times when route and altitude deviations are necessary to avoid turbulence result in a very limited turbulence data set.
- Compartmentalization – Ride reports, which circumvent the data latency problem of formal PIREPS, are generally limited to the sector in which the aircraft is operating. This prevents flight crews from forming a "big picture" of the turbulence fields in which they are operating, and limits them generally to tactical avoidance. This process works fairly well in localized convective situations, but not very well in CAT situations.
- Communications bandwidth – Constraints on available frequencies limit the quantity and quality of data that can be transmitted to aircraft in flight. This limitation is particularly constraining in the transmission of graphical products, which would be necessary to give pilots good spatial orientation with regard to turbulence information.

- Sensors – Air traffic control radars are optimized for aircraft detection not weather detection and thus cannot provide direct indications of atmospheric turbulence. There are no operational ground-based or airborne systems that can detect turbulence not associated with water vapor, such as turbulence outside of thunderstorm cells or CAT.

3.2.2 Airborne Weather Radar-Based Information Sources

The current air carrier fleet has a mix of airborne weather radar equipage. Some older aircraft have non-Doppler radars that can only provide an indication of water droplet density, known as reflectivity. In older mechanical display aircraft, such as early Boeing 737s, DC-8s, DC-9s, etc. this information is presented to flight crews on a separate display that has to be mentally overlaid with navigation information to try to form a mental picture of the aircraft's spatial relationship to the reflectivity information, and any turbulence that can be inferred from this reflectivity. Over the years, pilots have developed many unique approaches for manipulating the radar controls and for interpreting the radar data but, at best, these techniques are mostly "rules of thumb" and can vary significantly from pilot to pilot. Very little formal radar training is provided to pilots, even at the air carrier level.

More modern aircraft, beginning with the first generation electronic cockpit aircraft such as the Boeing 757, 767, MD-11, etc., generally are now equipped with airborne radars that can not only process reflectivity data but can also measure the along-track Doppler shift of the water particles and thereby infer some information about turbulence. Unfortunately, no methodology exists for translating this Doppler information into a level of hazard for each aircraft and the maximum range for processing the Doppler returns is about 40 nautical miles, or about 5 minutes, in front of the aircraft. Reflectivity data is available beyond 200 nautical miles., but the data can be very misleading at times due to unavoidable limitations of the radar, such as attenuation and shadowing. The most modern radars also incorporate software algorithms that automate the tilt and gain functions to optimize the radar for weather avoidance.

The more modern aircraft also are equipped with electronic navigation displays, or Electronic Horizontal Situation Indicators (EHSIs), that allow the reflectivity and turbulence information from the radar to be overlaid directly on the aircraft's navigation path. This greatly facilitates the building of the mental picture of the spatial relationship between the radar information and the aircraft.

Despite the capabilities of modern radars and electronic displays, there are still fundamental constraints on the use of this equipment to identify and avoid atmospheric turbulence. These constraints may be summarized as follows:

- Presence of particulates – The radars primarily sense the presence, and in the case of Doppler radars, the motion of water particles. This means that the pilots can only *infer* the existence of turbulence from reflectivity data and the radars can only measure turbulence (unscaled to the measuring aircraft) within the limits of the Doppler signal processing capability, which is about 40 nautical miles. This limitation is a signal-to-noise measurement and thus cannot be easily improved upon with advanced processing. Most hazardous turbulence encounters occur around convective cells while aircraft are deviating, or in optically clear air, and these situations cannot be detected by even the most modern radars due to the lack of particulates in these situations. This constraint makes radars useless in detecting CAT.
- Attenuation – The radar signal attenuates differently in clear air, in water vapor, in water droplets, and in frozen or partially frozen water particulates. Consequently, when there are water particles present the radar can only get an accurate picture of the water particle density nearest the radar. What lies beyond may be different than the radar picture, especially if the water droplets in the near field are large and dense.
- Range – Range is limited by attenuation. Reflectivity information, from which turbulence may be inferred, is available out to several hundred miles, subject to the attenuation effects discussed above. Doppler turbulence information is only available out to approximately 40 nautical miles,

or 5 minutes at cruise speeds, which allows insufficient time for planning, clearing with ATC, and executing significant route or altitude deviations.

- Vertical resolution/interpretation – Downward tilt of the radar beam creates backscatter problems from the ground which limits the ability to process returns from lower altitudes. At long ranges curvature of the earth causes the beam to sense particles at increasing altitudes for a given tilt level causing the displayed data to be a mix of ranges and altitudes. Adding to this problem is the fact that current aircraft displays have no provisions for a vertically formatted radar presentation.
- Scaling – The turbulence data currently presented to the pilot is nothing more than an indication of the motion of the water particles in front of the aircraft. There is no scaling or processing of this data to take into account other important parameters that determine how this motion will affect aircraft response, such as the aircraft's weight, speed, and configuration. Currently pilots must estimate the expected effect of the turbulence represented by a radar return on their particular aircraft, based primarily on the pilot's experience with the radar in individual aircraft installations
- Confidence – As a combined consequence of all of the constraints above, pilots have low confidence in the turbulence information currently presented on their displays. Many simply turn the turbulence function off to reduce display clutter. This is one of the key contrasts between today's system and the system that will be discussed in Section 5.

3.3 Description of and Modes of Operation for the Current System

For purposes of this document, the current system is described in two modes of operation:

- Convective Turbulence Avoidance
- Non-convective (CAT) Turbulence Avoidance

Each mode is subdivided into discussions of non-radar sources of information and airborne radar-based sources of information. This structure will facilitate the discussions of the new technologies proposed for the new system in Section 5. Note that the radar information source is not included in the clear air turbulence mode discussions because "clear air" turbulence implies the absence of particulates; which, in turn, nullifies the airborne radar as a viable sensor.

3.3.1 Convective Turbulence Avoidance Mode

Figure 4 illustrates the information flow and decision-making processes that might be used by an airline crew to avoid convective-related turbulence in today's system.

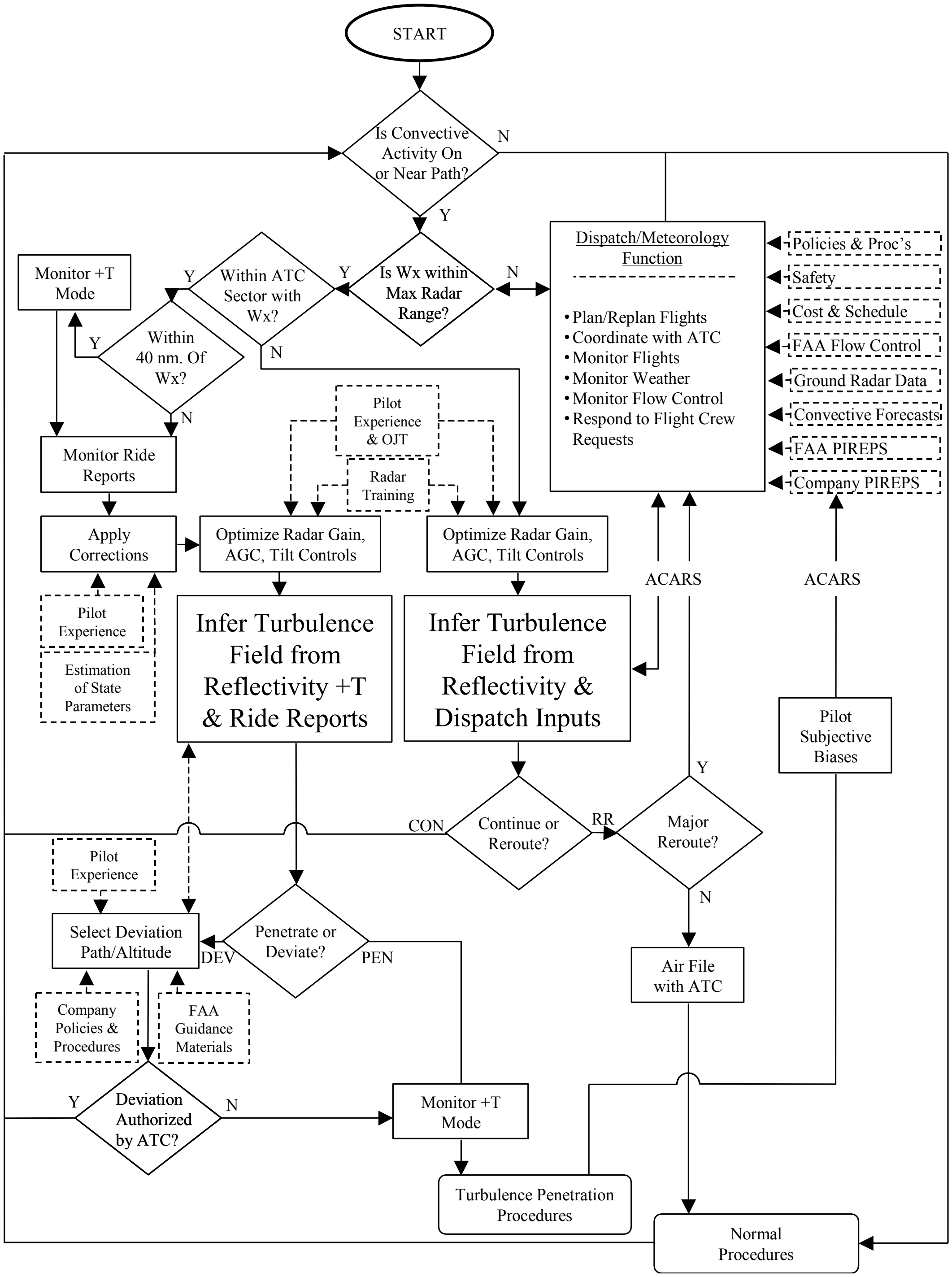


Figure 4: Decision-Making Processes for Current System – Convective Turbulence

3.3.1.1 Non-Radar Information Sources

Convective turbulence is generally characterized by rapid change, both spatially and temporally. A typical thunderstorm cycle can last from 20 minutes to 1.5 hours [4]. During this cycle updrafts can reach 6000 ft/min and downdrafts can reach 2500 ft/min inside the storm cell. Potentially hazardous turbulence can be induced outside of the cell for distances up to 20 nautical miles.

Thunderstorm cells associated with fronts or mesoscale complexes can last much longer and even reach stable states of existence. Atmospheric turbulence associated with these systems can be even more hazardous and cover greater volumes of airspace.

Only one non-radar information source is of any real value in avoiding convective turbulence in today's system, that source being "ride reports". Formal PIREPS are generally too old to be of any real value and getting a spatial picture of the turbulence from these textual reports is very difficult at best. Convective forecast products and graphical depictions of radar reflectivity from ground-based radars have generally lost their value in the time interval between preflight and the time the aircraft arrives at the location of the convection unless the convective area is at or near the departure airport.

A general depiction of the flow of information in the convective mode of operation is presented in Figure 5. The flow includes two elements of the Air Traffic Control System, controllers and flow managers, the flight crew and, in airline operations, the dispatcher. The communications channel between the flight crew and the dispatcher, and between the control facility and the flow management facility, are generally used during flight planning. Flow control may block out areas of airspace and dispatch may alter flight plans based on turbulence forecasts or PIREP data. However, since convective activity is generally very dynamic, most flights are planned for optimum fuel use and schedule considerations and then the flight crew avoids turbulence as a tactical exercise.

Thus, most of the real turbulence avoidance in this mode of operation in today's system occurs in the communications channels between the flight crews and controllers. Pilots provide ride reports on the sector frequency and the controllers relay this information with location information to other pilots who use the information to make route change or deviation decisions and then provide ride reports of their own. While this system helps pilots avoid or prepare for turbulence, it also has many limitations as discussed in Section 3.2.1.

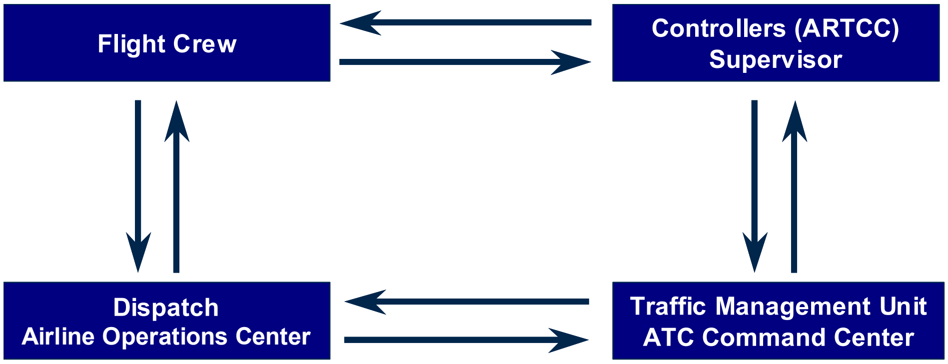


Figure 5: Current Turbulence Information Flow

3.3.1.2 Radar-Based Information Sources

The onboard weather radar can be separated into three categories of operation: long-range reflectivity only, short-range reflectivity only, and short-range reflectivity with turbulence mode.

The long-range reflectivity only mode is currently used for detecting convection at significant distances ahead of the aircraft. Depending on the radar system and the type and extent of the convection, reflectivity returns from convective cells up to 320 nautical miles (typical) ahead of the aircraft can be displayed or "painted." Color-coding is based on the reflected signal strength, and separated into regions of green, amber, and red. Beam broadening and other radar system attributes can make the identification of cell tops and location difficult to resolve at long distances. This display will not give the location of turbulence, but will only identify the regions containing the appropriate particulates in the air (hydrometeors). At typical cruise speeds, 320 nautical miles can be 40 minutes ahead of the aircraft.

During this time convection may grow, decay, or advect significantly. Therefore, reflectivity information is best used at long ranges for general awareness and making penetration vs. rerouting decisions.

The next identified category of operation, short-range reflectivity only, is currently used for tactical maneuvering around convective cells. Range settings for the radar reflectivity display are typically 80 nautical miles or less. This mode would commonly be used after a decision is made to penetrate a region of convective activity. The reflectivity display is used to keep the aircraft clear of higher reflectivity areas (yellow or red), as well as to identify strong reflectivity gradients, and particular shapes in the reflectivity returns, which may indicate strong turbulence. Thus, from short range reflectivity information flight crews infer that turbulence may exist or not exist in a given region and operate the aircraft and warn flight attendants and passengers accordingly. The radar antenna may be tilted manually to try to pick up reflectivity images above and below the aircraft's flight path in order to identify cell tops and rising cells respectively, but such manipulation can also increase the probability of misinterpretation of returns, such as mistaking ground returns for strong cells. Also, attenuation of the radar signal by hydrometeors closest to the aircraft can mask the intensity of cells beyond, giving flight crews potentially misleading information about the strength of reflectivity regions in the shadows of the closer cells. Given these limitations and radar characteristics the flight crew must not only infer the existence of turbulence, but they must do it from very imperfect information. Frequently, the safest solution is just to avoid all areas of convection by large margins, which can unnecessarily waste time and fuel.

The last category of operation, short-range reflectivity with turbulence, paints the reflectivity patterns as well as regions of solid magenta indicating areas of predicted turbulence. These regions primarily occur within the boundaries of reflectivity mappings although it is theoretically possible to map some turbulence outside of regions of particulate concentrations. The range of the turbulence prediction is limited to approximately 40 nautical miles, providing about 5 minutes of warning for typical cruise speeds. As discussed above, the combined consequence of all of the constraints on current radars, these predictions are not widely trusted. Also, since turbulence indications usually appear in the vicinity of areas of high reflectivity that flight crews are already avoiding, they are usually avoided as a secondary effect of avoiding the hazardous reflectivity itself.

3.3.2 Non-Convective Turbulence Avoidance Mode

Figure 6 illustrates the information flow and decision-making processes that might be used by an airline crew to avoid CAT-related turbulence in today's system.

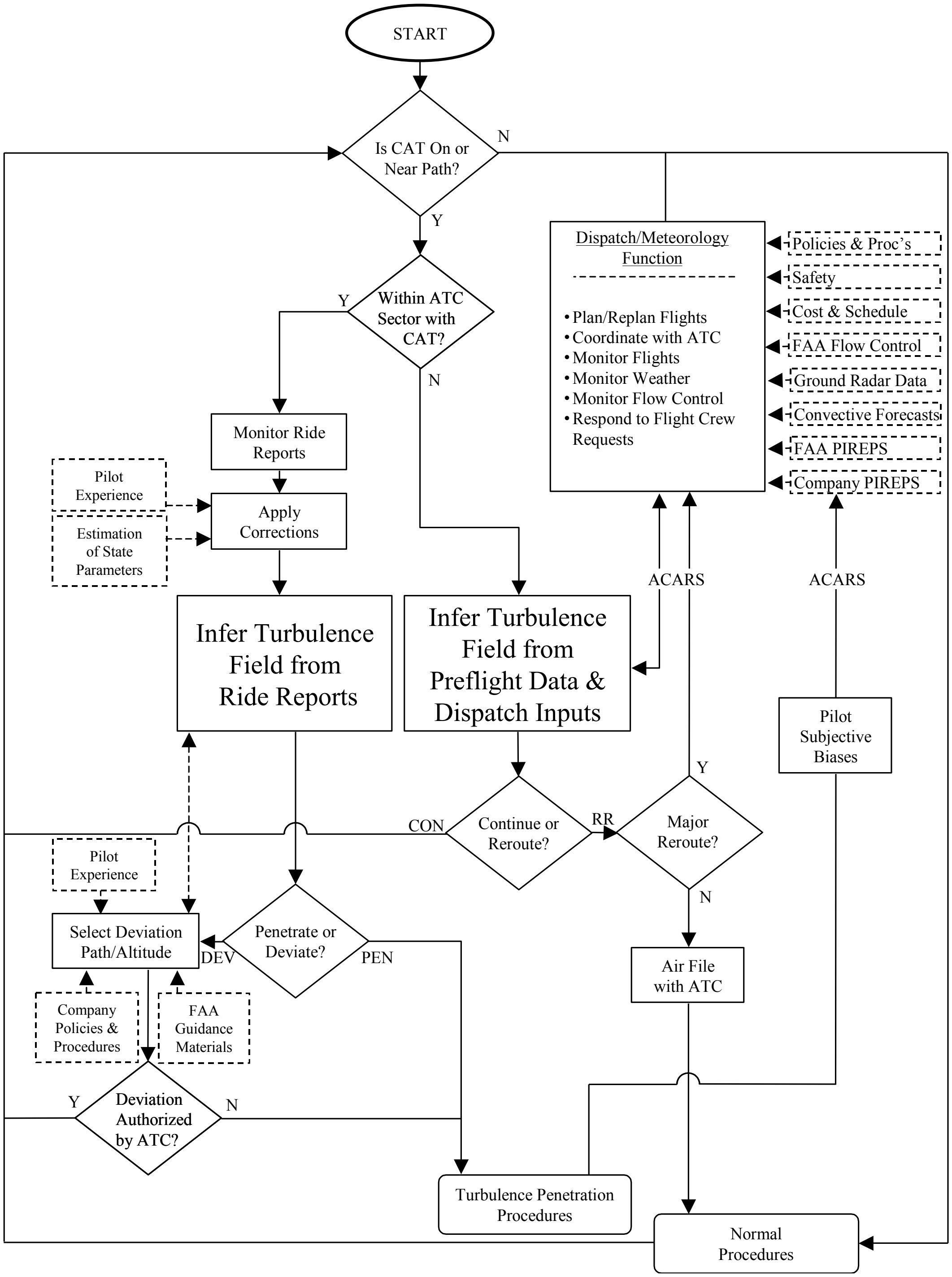


Figure 6: Decision-Making Processes for Current System – Clear Air Turbulence

3.3.2.1 Non-Radar Information Sources

In non-convective or CAT mode, today's system works very differently from convective mode. Since CAT phenomena are generally stable and persist over many hours, sometimes days, the value of the different forms of turbulence-related information change.

By definition, clear air turbulence phenomena, such as mountain waves and jet streams, are virtually invisible to the flight crew and to airborne radars. Occasionally such phenomena can be associated with particular forms of clouds, such as lenticular clouds, but the lack of hydrometeors makes the phenomena undetectable by current airborne radars. Other sensors, such as lasers, show promise as CAT detectors, but no such systems are operational at this time or are expected in the near future.

Despite the fact that no CAT sensors exist, the long-lived nature of the phenomena means that forecast turbulence products and formal PIREPS have more value than in convective operations. However, as in convective operations, CAT phenomena are generally large in scale thus making rerouting not always a viable option. As in convective operations, tactical avoidance by the flight crew again becomes the most common method of coping.

In the flow chart of Figure 6 the dispatch and traffic management functions play a larger role in the overall avoidance scheme because more data is available during preflight to plan turbulence-minimized routes. However, just as in convective mode, the real turbulence avoidance has to take place once the aircraft has reached the region of turbulence. As in the convective mode, ride reports thus become the primary means of communicating real-time in situ turbulence information. In Figure 6, this emphasizes the communications flow between the air traffic controller and the flight crew.

Also, as in the convective mode, all of the limitations and constraints associated with ride reports now come into play, with one additional disadvantage. Since CAT phenomena are generally large in scale compared to sector sizes and larger deviations in altitude or route may be necessary to minimize turbulence effects, the limited geographical reach of ride reports is more of a problem in non-convective situations. This means controllers must pass information across sector and facility boundaries to provide turbulence information to pilots in time to plan and execute these larger deviations.

3.3.2.2 Radar-Based Information Sources

The radar information source is not included in the clear air turbulence mode discussions because “clear air” turbulence implies the absence of particulates; which, in turn, nullifies the airborne radar as a viable sensor.

3.4 Users and Stakeholders

The following section will describe the users and stakeholders and their interactions. Note that the interactions may vary slightly depending upon whether the operational mode involved is convective or non-convective turbulence avoidance.

3.4.1 Organizational Structure

Three major organizations / users have been identified that will contribute to, and are involved in, the flow of turbulence information within the current system:

1. Pilots - The flight crew is one of the end users of turbulence information and has a direct interaction with the traveling public while flying. They also are responsible for the safety of the cabin crews who spend much of their time in the air unrestrained.
2. Air Traffic Service providers - These consist of the FAA Traffic Management Unit (TMU) and the FAA Air Traffic Controllers and Supervisors. The air traffic service providers will have an initial role in managing traffic flows around turbulent areas and also in approving turbulence-related changes in the routing of an aircraft.
3. Airline Dispatchers - The dispatch control desk works with the flight crew and air traffic control for initial turbulence-minimized flight plans and then changes to flight plans as flights progress.

The interaction of the major organizations and users is explained further in Section 3.4.3.

3.4.2 Profiles of Users and Stakeholders

The flight crew is generally employed and managed by the airline operator and may be considered the primary end user of turbulence information. The flight crew is responsible for the collection and application of turbulence data, but the cabin crew is the group most affected by any flaws in the collection, distribution, and decision-making processes. The flight crew also has direct interaction with, and is responsible for the safety of the traveling public while flying.

Air traffic controllers and the supervisors who interface with the Traffic Management Unit also have an important role in collecting and distributing turbulence data. Controllers are tasked primarily with maintaining separation between aircraft, but also generally serve as clearinghouses for turbulence-related ride reports for aircraft operating within their jurisdictions.

There is a Traffic Management Unit at each Air Route Traffic Control Center (ARTCC) and an ATC Command Center that meters traffic on a national scale when necessary. The former handles flow issues within each ARTCC, and the latter takes each Center's inputs and formulates national plans for airspace usage.

Dispatchers perform initial flight planning, brief flight crews, file flight plans, release flights, and monitor and support flights in progress. Dispatchers can provide turbulence information that they receive from company flights in progress, AIRMETs, Significant Meteorological Advisory (SIGMETs), and other weather products via ACARS. Dispatchers also perform other duties such as interfacing with ATC flow control functions and implementing flow control restrictions within their airline's operations.

3.4.3 Interactions Among Users

As mentioned above, the current system requires the collaboration and interactions of dispatchers, controllers, and flight crews. The information present in the following table summarizes these interactions and the actions taken by each user class in the information flow of the current system. References to the various interactions refer back to Figure 6. It will be noted that these descriptions reflect current practices. The interactions between each of the users are illustrated in Table 1.

Table 1: Turbulence-Related Interactions Among Users

Interaction	Turbulence Information Provided / Gathered	Decisions to be Made	Actions
Pilot to Controller	Provide turbulence PIREPs and ride reports (usually verbally). Request for ride 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.
Controller to Pilot	Request ride reports. Receive and disperse ride reports.	Path deviation clearances. Altitude change clearances. Reroutes	Approve/disapprove pilot-requested clearances

Interaction	Turbulence Information Provided / Gathered	Decisions to be Made	Actions
Pilot to Dispatcher	Occasional verbal/text turbulence PIREPs (as workload permits). Request ride reports from other company aircraft. Request for reroute recommendations. Request for altitude recommendations. Request updated weather information.	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)	Optimize flight plan and schedule from an overall airline perspective.
Dispatcher to Pilot	Receive occasional verbal/text turbulence PIREPs from other aircraft. Ride report requests from company aircraft. Reroute recommendations. Altitude recommendations.	Decide whether the identified regions of weather (convection, turbulence, etc) are a threat to the safety of flights being followed, and communicate flight plan change recommendations	Notify company aircraft of safety hazards. Recommend route or altitude changes based on meteorological information and reports from other company aircraft.
Dispatcher to Traffic Management Unit/National Flow Control	Provide airline flight planning information and internal turbulence reports from company aircraft.	Optimize airline schedules and routing (from nominal) given adverse conditions (e.g., regions of turbulence, convection, etc.). Provide airline plan – reroute schedule. Receive national flow plan.	Request for route availability. Request for changes based on “restrictive flow program.” Execute national flow plan (reschedule/cancel flights accordingly).
Traffic Management Unit/National Flow Control to Dispatcher	Receive flight plan information from airlines based on their internal information sources including turbulence reports.	Define a national flow plan, including: - miles in trail - reroutes - ground stops	Communicate with airlines and execute plan.

Interaction	Turbulence Information Provided / Gathered	Decisions to be Made	Actions
Controller (supervisor) to Traffic Management Unit	Turbulence impacts on normal routing based on verbal turbulence reports received. If the controller's ability to maintain the airspace capacity will be affected the supervisor will be notified who will in turn raise the issue with the TMU.	Macro-level changes to the traffic flow around the region. This may entail decreasing the number of aircraft or rerouting them around the disturbance. This decision must be made in a strategic sense and in accordance with other traffic flow considerations (other centers, airline operations, etc.).	Raise issue to TMU and expect a flow plan. Execute flow plan.
Traffic Management Unit to Controller (Supervisor)	Provide weather (including turbulence) information that may not be in the ARTCC airspace, or a given supervisor's sectors, but will affect operations in that airspace. Define the nature of the hazard and provide forecasts of intensity and movement.	Develop a flow plan for the next 2, 4, and 6 hours based on weather information.	Pass national flow plan to controllers for execution.

3.4.4 Other Involved Personnel

In addition to the users and stakeholders discussed in the previous sections, the airline operator is also involved in the day-to-day operation of the current system. The airline develops policies and procedures, and enforces constraints on its employees based on information feedback from various sources, including internal departments of marketing, finance, and safety. A typical policy that an airline operator is closely involved in is the operation of an aircraft near and in turbulent regions. Some airlines change altitudes and routes with a very conservative approach to avoid large blocks of airspace if there is a potential for significant turbulence. This is primarily due to a lack of sufficient tools to identify the location and intensity of turbulence within a given region of the national airspace. The result is erring on the side of safety at the cost of higher fuel consumption during the operation of a flight within one of these regions.

3.5 Support and Maintenance

Since the current method of making turbulence PIREPs relies so much on human interaction, the support and maintenance issues do not apply. However, the radar is an integral piece of equipment, identified on the Minimum Equipment List. Its performance is clearly defined by the FAA (in its Minimum Operational Standards) and the airlines and vendors perform its maintenance.

4. Justification for and Nature of Changes

This section of the CONOPS describes the shortcomings of the current system or situations that motivate development of a modification of the existing system. The proposed changes to overcome these issues are also covered.

4.1 Justification for Changes

Table 2 identifies, based on the type of information source, the current deficiencies and limitation of today's system and lists the justifications for changing and improving these deficiencies. The identification of each component of the turbulence prediction or reporting system enables an understanding of the justification for changes to be introduced. It is the goal of the proposed work to produce a system that will increase safety, reduce injuries, and increase operational efficiency in airline operations in and around turbulence.

Table 2: Current System Deficiencies and Justification for Change

Information Source	Deficiencies / Limitations of Current System	Justification for Change
Long-range reflectivity only	No direct indication of the location, altitude and severity of turbulence hazards. Lack of information on which to make the long-range tactical decisions for turbulence avoidance. Fundamental radar limitations, such as attenuation, shadowing, and ground returns become worse at long ranges.	Increased safety in turbulence hazard avoidance. Improved efficiency in operations around hazardous weather. Improved situational awareness of turbulence hazards will allow for the minimization of route or flight level deviations and maximize on the operational and airspace efficiencies. Need to include improved turbulence information specifically relevant to the aircraft in question; i.e., its type, location, and flight path. The addition of the new information may require new functional capability to the display to allow the pilot to interact with available information in order to realize the benefits.

Information Source	Deficiencies / Limitations of Current System	Justification for Change
Short-range reflectivity only	No direct indication of the location, altitude and severity of turbulence hazards. Fundamental limitations of radar, such as attenuation, shadowing, and ground returns. Lack of information on which to make the short-range tactical decisions for turbulence avoidance. In the short-range mode (less than 80nm), the aircraft will be in the vicinity of convection, and the pilot's expectation for turbulence encounters will be high. The need for good turbulence hazard information in this environment is critical. The lack of information or the existence of misleading information makes the need for improvement greatest.	Increased safety in turbulence hazard avoidance. Improved efficiency in operations around hazardous weather. Improved situational awareness of turbulence hazards will allow for the minimization of route or flight level deviations and maximize on the operational and airspace efficiencies. Need to include improved turbulence information specifically relevant to the aircraft in question; i.e., its type, location, and flight path. The addition of the new information may require new functional capability to the display to allow the pilot to interact with available information in order to realize the benefits.
Short-range reflectivity and turbulence mode	Current turbulence mode is not scaled to ownship state parameters and thus cannot predict the hazard level that can be expected for each individual aircraft. The current turbulence mode has too many false, missed, and nuisance detections.	Need reliable quantification of turbulence hazard free from inference and subjective interpretation. Turbulence information needs to be specifically relevant to each individual aircraft.
Combination of turbulence hazard information in a graphical form.	Turbulence information provided to the pilot in several forms: aurally or textually (from controllers/dispatchers), visually (from the radar display). The pilot is required to assimilate these data into a mental "picture" of the hazardous areas. Combining information may be difficult if the turbulence hazards are quantified in different ways; e.g., how does the radar's current magenta turbulence information correspond to verbal PIREPs of moderate turbulence?	Standardization of the turbulence hazard metric will allow combination of the systems information. Graphical display of PIREPs will allow combination with graphical radar display. Combined graphical display will provide an integrated picture of the turbulence hazard.

4.2 Description of Desired Changes

Desired changes to the existing system based on the technologies to be integrated are described below in Table 3. It should be noted that many of the changes listed under the columns labeled "Radar Turbulence

Detection" and "Non-Radar Information Sources" are changes that have already been developed and evaluated in the Turbulence Prediction and Warning System element of NASA's Aviation Safety and Security Program. These changes will need to be adopted within a real-time integrated turbulence Decision Aid implementation in order to perform the integration of the candidate data sources. The changes proposed in this work are those identified in the last column on the right of the table. Also identified in the table are those changes that are essential to the success of a real-time display, and therefore must be provided by the new or modified system. If these features were not to be included, the effectiveness of the system would be compromised. They will be discussed in further detail in the next section.

The changes presented in Table 3 are based upon the current system as described in Section 3 of the CONOPS. The changes are broken into the following major headings:

1. Capability Changes – Description of the functions and features to be added, deleted, and modified in order for the new or modified system to meet its goals and objectives.
2. Operational Changes - Description of changes to the users' operational policies, procedures, methods, or routines caused by the above changes.
3. Personnel Changes – Description of changes in personnel, if any, caused by new requirements, changes in user types, or both.
4. Interface Changes – Description of the changes in the system that will cause changes in the system interfaces.
5. Support Concept Changes – Description of changes in the support concept caused by changes in the system functions, processes, interfaces, or personnel.
6. Other Changes – Description of other changes that will impact the users, but which do not fit under any of the above categories.

Table 3: Proposed System Changes

Area of Influence	Radar Turbulence Detection	Non-radar Information Sources	Integrated Turbulence Hazard Decision Aid
Capability	Ability to scale the radar turbulence measurement to predicted load based on aircraft type and configuration. (E-Turb) **This is an essential change**	Ability to make quantitative turbulence reports, automatically pass the reports to dispatchers, ATC, and other aircraft, and to scale the reports to different aircraft types and configurations. (TAPS) **This is an essential change**	Ability to deliver both E-Turb radar information and TAPS reports to the same display and interface hardware. **This is an essential change**
Operational	Information is advisory in nature, but pilot's confidence in the product should be increased. There will also be two levels of turbulence severity depicted.	Information is advisory in nature. TAPS reports will improve turbulence forecasting models.	Information is still advisory in nature.
Personnel	Training on new system	Training on new system	Training on new system

Area of Influence	Radar Turbulence Detection	Non-radar Information Sources	Integrated Turbulence Hazard Decision Aid
Interface	No changes in interface. Newer radars utilize automatic antenna controls, which automatically provide a better 3-dimensional picture of the weather.	The interfaces to provide the pilot with a clear display of the automatic turbulence reports will require interface development. This is currently underway in NASA/AvSSP for a TAPS-only cockpit display. **This is an essential change**	Interfaces will need to be developed that maintain a clear and uncluttered display without an increase in pilot workload. Preference will be given to Electronic Flight Bag implementations. **This is an essential change**
Support Concepts	None	None	None
Other	None	None	None

4.3 Priorities among Changes

There are several “essential changes” required as shown in Table 3. Those essential changes in the “Radar Turbulence Detection” and the “Non-radar Information Sources” columns are those changes that have been made or are currently being developed under other NASA and FAA programs. Only those changes in the right-hand column are those that would be made based on the current Integrated Turbulence Hazard Decision Aid work.

It will be essential that both the TAPS and E-Turb information be delivered to the same display. This is a critical integration/implementation issue that has been accomplished in the Phase II research efforts. Inability to do so will make it impossible to realize the integrated system within the cockpit.

Suitable interface changes will need to be made. If the interfaces cannot be configured correctly the system may be cumbersome or difficult to use. This was also a key area of focus within the Phase II research effort with pilots and avionics integrators.

4.4 Assumptions and Constraints

This section describes assumptions or constraints that have been identified as applicable to the changes and new features identified within this section of the CONOPS. This includes assumptions and constraints that will affect users during operation of the modified system.

Three key assumptions have been identified during the initial research of a Turbulence Hazard Decision Aid for the Cockpit that integrates TAPS and E-Turb Radar technologies. The first assumption is that the Enhanced Turbulence radar will produce an improved turbulence hazard prediction for the end users of the system technology. An In Service Evaluation on a Delta Air Lines aircraft has provided valuable positive feedback, both quantitative and qualitative, on this portion of the system (Reference [14]). It is evident that the E-Turb Radar product is superior to the previous prediction capabilities available and that pilots are using it in their decision-making processes.

A second assumption for the proposed system is that an operational TAPS system will provide turbulence information as described in Section 5, and that the information can be transmitted to the cockpit, the ATC system, and airline operations centers for display. TAPS reports from Delta aircraft have already been shown to be useful in Delta’s dispatch and meteorology departments. TAPS reports have also been integrated into the WSI’s Fusion^{TM} Dispatcher Decision Support Tool.

A final assumption is that there will be suitable cockpit display implementation approaches available for the integration of the proposed technologies into a real-time display within the cockpit environment. Research has shown that a Class III Electronic Flight Bag (EFB) display that fully integrates reflectivity, TAPS, and E-Turb Radar information in a track up ownship-centered display overlaid with navigation and flight plan information substantially enhances flight crew situational awareness relative to turbulence hazards (Reference [18]). Further research will be required to mitigate minor issues and ensure a suitable display implementation of the TAPS and E-Turb Radar information.

An identified constraint of the proposed system includes the need to address regulatory issues associated with integrated cockpit turbulence displays. Resolution of these issues will require an ongoing effort during the development of such displays. The action has been taken to keep policy makers informed of the work being conducted and to request guidance in developing safe certifiable displays.

5. Proposed System Concepts

This section will describe a proposed system that results from the desired changes specified in Section 4 of the CONOPS. The proposed system concept is an integrated approach using existing and modified aircraft sensors, data links, automation, and integrated displays to provide significant improvements in, and eliminate many of the constraints of today's turbulence detection and avoidance systems. The proposed system will achieve the stated goals by making improvements in the following system elements:

- Forecasting – The proposed system will allow better turbulence forecast models to be developed by the federal agencies responsible for turbulence forecasting which, in turn, will lead to improvements in efficiently avoiding hazardous turbulence by better preflight planning and improved pilot/dispatcher/ATC coordination.
- Reporting – Automatic quantitative turbulence (TAPS) reports will improve the density of turbulence data, remove the workload constraints on reporting the data, and remove the subjective element of the data, while also reducing turbulence-related ATC communications.
- Displaying – New displays, or new overlays for existing displays will be developed that allow pilots, dispatchers, and ATC personnel to have intuitive 4-dimensional displays that provide much improved situational awareness with respect to turbulence locations and severity.
- Airborne Weather Radar – The Enhanced Turbulence Radar will provide improved predictions of turbulence hazards for up to 40 nautical miles ahead of the aircraft. The scaling of the turbulence information to the pilot's own aircraft conditions and configuration will ensure that crew confidence reaches levels where the information is actively used to tactically avoid turbulence.

As in Section 3, the discussion of the proposed system concept will be in terms of non-radar and radar-based technologies so that a direct contrast can be made with the current system. Also, the scope of the discussion will be limited to air carrier operations except where inclusion of other operators or classes of aircraft is necessary to understand the proposed new approach to turbulence identification and avoidance. Convective and non-convective modes of operation will be discussed separately.

5.1 Background, Objectives, and Scope

Aircraft encounters with turbulence are the leading cause of injuries in the airline industry. In a ten-day period in August 2003 alone, over 30 passengers and crew were hurt, some seriously, in turbulence encounters. In addition to the human costs, the airlines have numerous unplanned operational and maintenance costs associated with turbulence encounters.

Previous studies have been conducted in an attempt to develop a conceptual turbulence warning system based on aircraft reports. In 1996, Search Technology, Inc. [5], working under a NASA Small Business Innovative Research (SBIR), tried to develop a real-time turbulence warning system based on automated turbulence reports from other aircraft. Their final system was not realized due to limitations in the measurement algorithms, lack of a suitable communications infrastructure, and a lack of integration with the onboard systems. In addition, the work did not focus on specifying the turbulence hazard to the aircraft. Instead, the system reported an "aircraft independent" turbulence value from which the pilot was required to infer a turbulence hazard.

As part of their SBIR work, Search Technology polled 272 active commercial airline pilots to discover requirements for a turbulence reporting system [5]. These pilots were asked to rate various forms and capabilities of a turbulence reporting system. Based on their responses, a better understanding of the user requirements of such a system was gained. The findings are briefly summarized below.

- In flight turbulence information sources were rated the most important source of turbulence information for pilots.
- Over 95% of pilots said they would want a display showing real-time turbulence indices of aircraft in the vicinity.
- Over 60% of pilots wanted that information within ± 4,000 ft of their flight level.
- Over 60% of pilots wanted the information within at least an 80 nautical mile range.

Search Technology conducted a second study using surveys of commercial airline pilots to investigate further the usability and implementation of a turbulence reporting system [6]. Some findings were:

- Pilots consistently stated a need for turbulence information in the cockpit from other aircraft in the vicinity.
- The pilots wanted a dynamic display with the capability to filter out "clutter".
- Most pilots would prefer the information on a dynamic navigational display.

These results illustrate clear and unambiguous preferences and requirements on the part of flight crews. The efforts described in References [5] and [6] were unable to achieve an operationally viable system, but the collected feedback from flight crews has provided a useful source of requirements upon which the proposed system design is based.

The objective of the proposed system concept is to address and resolve known problems with the current system and earlier system concepts using three unique elements:

- The first conceptual element involves automatically detecting, classifying, and reporting turbulence information from aircraft in flight – essentially using enroute aircraft as automated sensors. While this approach has been proposed before, the key technology in the new system concept is that this quantitative information is then scaled to generate an automated turbulence "hazard" index that is unique to each aircraft receiving the data.
- The second element involves the integration of similar algorithms that scale, based on an aircraft's current type, weight, altitude, speed, etc., the second moment data from airborne weather radar Doppler returns to develop a similar, but completely independent, prediction of turbulence hazard.
- The third key element of the proposed system is the integration and fusion of the turbulence data from other aircraft (key element #1) with the onboard weather radar second moment data (key element #2) into a useful and easily interpretable cockpit display that will allow flight crews to easily use the data in real-time to identify and avoid turbulence.

The genesis of the first element of this new approach came from AeroTech Research (ATR) while working under contract to the NASA. As part of NASA's aviation safety technology program ATR developed the Turbulence Auto-PIREP System or TAPS. TAPS is designed to improve pilots', dispatchers' and controllers' situational awareness of the location and severity of turbulence hazards without increasing their existing workload. TAPS accomplishes this by automating the reporting of all significant aircraft encounters with turbulence and providing the pilots, dispatchers, and controllers a display of relevant, quantitative turbulence hazard information from which they can quickly and easily understand the impact that reported turbulence may have on their aircraft.

The genesis for the second element of this new approach also came from ATR while working under contract to the NASA. As part of NASA's aviation safety technology program ATR developed and evaluated the algorithms for the Enhanced Turbulence Radar, which provide more reliable and relevant radar-derived turbulence information to the cockpit.

The third element of the proposed system also had its genesis at ATR, sponsored by NASA. An integrated Decision Aid for the cockpit concept was developed as Part of a Phase II SBIR. This display has been successfully tested in laboratory and cockpit simulation environments and is the primary subject of this CONOPS document.

5.1.1 Non-Radar Information Objectives

The fundamental objectives of the proposed system concept are to improve safety and increase operational efficiency. Major elements of the safety improvement goal include reducing injuries to personnel and reducing damage to aircraft. The operational efficiency goal of the proposed system is to help airlines and air traffic decision makers operate more efficiently by providing maximum utilization of airspace at an equivalent level of safety to today's system. While safety is the primary driver for the proposed improvements, the economic impact resulting from efficiency improvements and increased airspace capacity could also be significant.

A large contributor to the turbulence injury problem is the fact that flight crews do not have sufficient situational awareness regarding the location and severity of potential turbulence hazards, particularly clear air turbulence hazards. Without this situational awareness flight crews are not able to avoid hazardous turbulence and are not always able to provide adequate warning to passengers and cabin attendants allowing them to be seated with seatbelts on and stow loose articles and equipment.

The inability of the current system to give pilots sufficient data to distinguish between safe levels of turbulence and unsafe levels can result in unscheduled aircraft inspections and delays. This is both a safety and a cost issue for airlines. The proposed TAPS system will help pilots avoid situations that may result in unplanned structural inspections and will help airlines determine when such inspections are really needed and not needed. In today's system such decisions are entirely subjective based on the Captain's assessment of the turbulence severity encountered. Data has shown that these assessments are not always accurate.

The uncertainties about turbulence locations and severity in today's system have the net effect that aircraft are rerouted and deviate around entire regions of potentially hazardous turbulence, which costs the airlines time and fuel and adds unnecessarily to system delays. With better knowledge of turbulence locations and severity the magnitude of such reroutes and deviations can be reduced while still maintaining safe levels of turbulence exposure.

5.1.2 Airborne Radar-Based Information Objectives

The current turbulence mode function in airborne weather radars relies on analyzing the Doppler information processed from airborne radar returns. The measurement, known as the "second moment", is a measure of the velocity distribution of particulates (e.g., raindrops) – which indicates whether the moisture is or is not moving as a homogenous entity. A small spectrum width indicates that most of the particulates are moving with the same speed and direction – i.e., smooth air. A large spectrum width indicates a large variation in the particulates' velocities – i.e., turbulence. In current radars, if the spectrum width 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 – 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 second moment to induce a severe turbulence encounter than would 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.” [7]

The E-Turb Radar hazard prediction algorithms proposed as the second element of the new approach are implemented as software within Predictive Wind Shear radar systems. The algorithms scale the radar second moment based on the aircraft’s current configuration (type, weight, altitude, speed, etc.) and provides the aircrew a display of the predicted turbulence hazard. From these indications they can easily assess the impact that turbulence will have on their aircraft.

The objective of this element of the proposed system is to provide flight crews with real-time scaled turbulence information that can be used to tactically avoid turbulence fields in front of the aircraft and/or to provide sufficient warnings to passengers and cabin attendants if turbulence penetration is unavoidable. This will result in decreased passenger and crew injuries and reduced airline costs due to reductions in airframe loads and maintenance/inspection requirements. Another contribution of this technology is expected to be increased confidence of flight crews in the turbulence information presented on their cockpit displays based on better matching of their experiences with turbulence to the displayed information.

An additional objective is to allow mutual confidence building between the TAPS element of the concept and the E-Turb element by overlaying both sets of data on a common display, which will allow direct comparison of the two sources of data and a filling in of the TAPS data fields with E-Turb Radar data providing improved coverage and timeliness of the data.

5.1.3 Scope

As in Section 3, the scope of the discussion in this section will be limited to 14 CFAR Part 121 air carrier operators except where inclusion of other operators or other classes of aircraft is necessary to understand the context of the proposed new turbulence avoidance systems or procedures. The scope of this section will be also be limited to discussions of convective and clear air turbulence only, since wake turbulence is being studied extensively under other programs.

5.2 Operational Policies and Constraints

This section describes the operational policies and constraints that would likely apply to the proposed system concept. Operational policies are predetermined management decisions regarding the operation of the new or modified system, in the form of operating specifications, operational use limitations, certification limitations, or regulations that prescribe the system’s operational use and proscribe certain other uses. Operational constraints are limitations placed on the operations of the proposed system. Several operational policies have been identified that will likely apply to the proposed system concept.

5.2.1 Non-Radar Information

The existing operational policies of the airlines and the FAA, as outlined in Section 3, would not likely need to be changed to accommodate the proposed TAPS system element. The automatic measurement and reporting features of the proposed system would, in fact, allow enhanced compliance with the existing policies that require reporting of turbulence data and the communication of this data to other aircraft that may be affected. Also, since the automatically collected turbulence data would be displayed to dispatchers as well as pilots, compliance with the policies requiring dispatcher involvement in flight planning and flight monitoring would be enhanced. Likewise, the availability of TAPS data to ATC flow management functions would enhance real-time decision making concerning the overall flow of the ATC system as well as the metering of flows in individual ARTCCs.

A key element in the new system concept is the presentation of TAPS data on a cockpit display that will provide flight crews with the situational awareness regarding turbulence locations and severity that they lack today. New operational policies may need to be developed to ensure that the TAPS data presented to flight crews, ATC personnel, and dispatchers does not interfere with the performance of other duties and is not presented in a way that is confusing or prone to misinterpretation.

Certification guidelines for electronic cockpit displays for 14CFR Part 25 aircraft are contained in Advisory Circular AC 25-11A [8], *"Electronic Flight Deck Displays"*. These guidelines will likely be adequate for certifying a TAPS application as an additional functionality for an electronic primary navigation display. However, reengineering display generators, interface control panels and software to filter and display TAPS icons may not be a simple or inexpensive task, especially as a retrofit application to existing electronic display aircraft.

Certifying a TAPS application as part of an Electronic Flight Bag display may be a simpler and less expensive course of action. Certification guidelines for certifying Electronic Flight Bags are contained in Advisory Circular AC 120-76A [9], *"Guidelines for the Certification, Airworthiness, and Operational Approval of Electronic Flight Bag Computing Devices"*. Guidelines for certifying cockpit weather displays are contained in Advisory Circular AC 00-63 [10], *"Use of Cockpit Displays of Digital Weather and Operational Information"*. These guidelines will likely be adequate for certifying a limited TAPS application that overlays TAPS information on geographical maps. However, in order for the full potential of TAPS to be realized it will be necessary to display the data on a track-up, ownship-centered display with range control and a variety of filters, with overlays for navigation and weather radar data. This type of application will likely require updated guidelines.

It is likely that new training courses and documentation will need to be developed to assist operational personnel in understanding and using TAPS data. This is especially true with regard to identifying and avoiding CAT since there are presently no systems that can graphically present CAT turbulence data.

It is anticipated that when TAPS automatic reporting capability reaches high levels of equipage in the military, cargo, regional carrier, and business aircraft markets, as well as the airlines, that management of the turbulence report database in the cockpit will become a pressing but manageable issue. Operational policies will need to be developed that control when and how much of the TAPS database can be displayed to ensure that such data does not mask other important information, such as Traffic Alert and Collision Avoidance System (TCAS) or Terrain Awareness and Warning System (TAWS) data. Likewise, policies will be needed to ensure that high-priority safety-related dispatcher functions and ATC management and control functions are not derogated by the presentation of turbulence data. Research to date has shown that it is possible to develop algorithms that can automatically or manually filter TAPS data to allow the display of only that data that is necessary and useful in managing the flight path of the aircraft, or monitoring and control of specific aircraft.

Likely constraints on the proposed TAPS system element will be determined by the results of further research. One known limitation of the proposed TAPS system element is that a lack of TAPS reports can have two meanings; either TAPS-equipped aircraft have passed through the airspace of interest but the air is smooth, or no TAPS-equipped aircraft have passed through the airspace and the state of the turbulence is therefore unknown. This issue has been addressed by adding a "heartbeat" TAPS message into the data stream. This message is sent out at regular intervals regardless of the turbulence the aircraft encounters. This allows awareness of where TAPS equipped aircraft have travelled. If no TAPS turbulence reports were emitted by these aircraft, the air can be assumed to have been below the TAPS reporting threshold.

Another possible constraint on this proposed system element could be communications bandwidth issues. While the communications bandwidth required to send individual TAPS reports is very small, the bandwidth required to uplink large numbers of reports to each aircraft could be an issue unless filtering is applied or links with large bandwidths are used. Presently, limited numbers of reports are being successfully downlinked and uplinked using the ARINC ACARS system, but widespread equipage with

TAPS could strain limited bandwidth systems of this type. As new technologies are implemented that make more efficient use of bandwidth, or more bandwidth becomes available, this constraint is expected to stay very manageable.

5.2.2 Airborne Radar-Based Information

There will be very few operational differences between the proposed E-Turb equipped radar and current-generation turbulence radars except that E-Turb equipped radars will perform better and earn back flight crew confidence in the turbulence indications. Minimum Operational Performance Standards (MOPS) for the E-Turb Radar function on advanced airborne weather radars have been developed are will be included in Technical Standard Order (TSO) C63d (References [20] and [21]).

The primary operational constraint on the E-Turb Radar element of the proposed system is its limited range. Research studies with simulated E-Turb equipped radars have indicated that pilots would like more time to plan turbulence avoidance maneuvers, which implies range capabilities beyond 40 nautical miles. However, such an extension will require a technology breakthrough in radar processing capabilities, which may have been achieved by the radar manufacturers. For this CONOPS, a maximum E-Turb range of 40 nm is assumed.

An additional operational constraint on the E-Turb Radar element of the proposed system is that the E-Turb Radar data will only be available to the flight crew and thus cannot be used in the flight planning and rerouting functions exercised by ATC and dispatchers. While consideration has been given to filtering, compressing, and downlinking E-Turb Radar data, the technical and bandwidth issues with such an application make this extension unlikely in the foreseeable future.

5.3 Description of the Proposed System

Two new sources of scaled turbulence hazard information and a new integrated display concept underpin the proposed system. The two new sources of turbulence information are:

1. The Turbulence Auto-PIREP System, which automatically transmits and receives turbulence encounter information from aircraft [11], and
2. The Enhanced Turbulence Mode Radar [12].

Both of these technologies have been operationally evaluated under NASA's Turbulence Prediction and Warning System element of the Aviation Safety and Security Program, and are currently being used in operational service with airlines worldwide. The turbulence hazard measurements made by both technologies have been designed to be entirely consistent in terms of the metrics and scaling used. In addition, TAPS includes an estimate of EDR – an atmospheric state parameter favored by the weather and forecast communities.

The new integrated display concept is the key to fusing these two new sources of turbulence information together into a display that can be used to operationally reduce or eliminate hazardous turbulence encounters. The focus of the display development effort has been the development of an Electronic Flight Bag implementation that integrates the turbulence information from TAPS and E-Turb Radar with navigation, flight plan and airborne radar reflectivity information to provide flight crews with a level of turbulence awareness and spatial orientation never before realized.

Key concepts integral to the proposed system include:

1. The system is user-centric in that both turbulence products are designed to provide turbulence data in a manner that is readily usable by those engaged in air carrier operations, whether as a flight crew, a dispatcher, or ATC personnel. Current turbulence products are more meteorologist-centric and require a good deal of study to draw conclusions about severity and develop a mental picture of the spatial distribution of the turbulence.

2. The focus of the system is on quantifying the hazard's effect on each individual aircraft, removing the need for pilots or others to infer the expected turbulence severity from either subjective PIREPs or from weather radar reflectivity returns.
3. The system, for the first time, provides a real-time operational methodology for identifying and avoiding clear air turbulence, the hidden danger in airline operations.
4. The system has provisions to allow flight crews to know what the system is predicting and then actually experience it, which will build confidence and acceptance over time.
5. The two sources of scaled turbulence hazard information are fused and integrated into an intuitive graphical cockpit display that allows simple filtering of the information to minimize clutter and maximize the utility of the data for the planned flight path.

In addition to the obvious safety advantages of providing better turbulence information to flight and ground personnel, it has been estimated that turbulence-related costs to the airline community amount to \$150 to \$500 million per year (Reference [13]). These costs are incurred due to injuries, as well as operational inefficiencies and unplanned maintenance requirements. The proposed system has the potential to significantly lower these costs as the airlines see a decrease in injuries, required maintenance due to turbulence, and improved operational efficiencies.

The end goal of the proposed system is not just the creation of the infrastructure to allow real-time scaled turbulence data to be collected and distributed. Rather, the end goal includes providing this data in meaningful formats that allow operational personnel on the ground and in the air to increase their situational awareness of turbulence hazards. This goal will be achieved by providing them with processed displays of turbulence hazard information from which they can quickly and easily understand the impact that reported turbulence will have on their aircraft (in the case of flight crews), or aircraft they are monitoring (in the case of dispatchers or flow controllers).

The true innovation in this concept is that the displayed turbulence information is scaled to each aircraft, so that crews and ground personnel do not have to infer the probable effects of measured turbulence on individual aircraft in flight. With this improved situational awareness pilots and others will be able to make informed decisions about avoiding turbulence or preparing the passengers and cabin crews if turbulence cannot be avoided. Ground and flight crews will also be able to better predict the impact of turbulence-related decisions on both safety and costs for their individual airlines.

5.3.1 Non-Radar Information Sources

The conceptual design of the non-radar element of the proposed system (TAPS) is illustrated in Figure 7. An aircraft in flight (such as Aircraft #1, Figure 7) encounters some form of turbulence. Turbulence measurement algorithms on board the aircraft compare the turbulence measured with predetermined thresholds and, if these thresholds are exceeded, transmit a report. When a report is sent, it includes a packet of data with the aircraft's position, the time of occurrence, the load experienced, and various aircraft parameters from the onboard systems. This data packet is transmitted to the ground, stored in a database, and displayed on ground station networks where it can be used by meteorologists, dispatchers, ATC personnel, or flight crews performing preflight planning.

The data packet is then retransmitted to other aircraft (such as Aircraft #2, Figure 7). The receiving aircraft, using a turbulence prediction algorithm, scales and interprets the data for its aircraft type and flight conditions creating a hazard display that represents how that turbulence is likely to affect that aircraft. This information is then displayed to the flight crew on a graphical display as "light", "medium", or "severe" icons with time and altitude tags that allow the quick building of a mental picture of the turbulence field. With this situational awareness the flight crew can then decide how to avoid the turbulence, or when to prepare the cabin for it. Note in Figure 7 that an air-to-air link is also proposed to allow the direct transmission of turbulence information between aircraft, both inside and outside of airspace not served by terrestrial data links, such as oceanic airspace. Due to the efficiency with which the data can be organized into small digital packets, such direct transmission to other aircraft is operationally viable even with today's level of communications technology

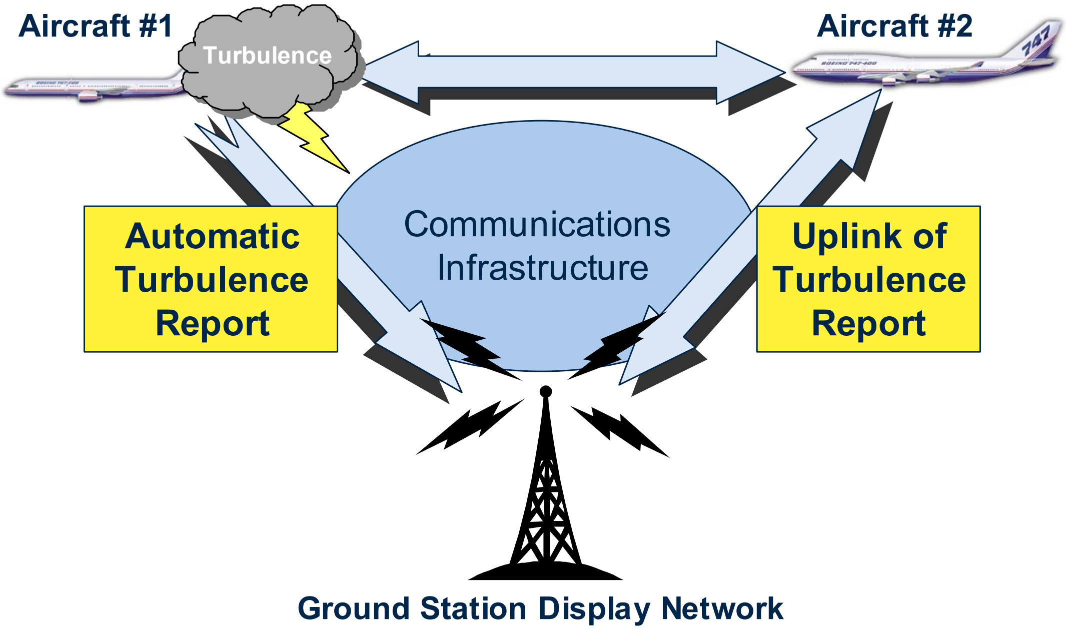


Figure 7: TAPS Architecture

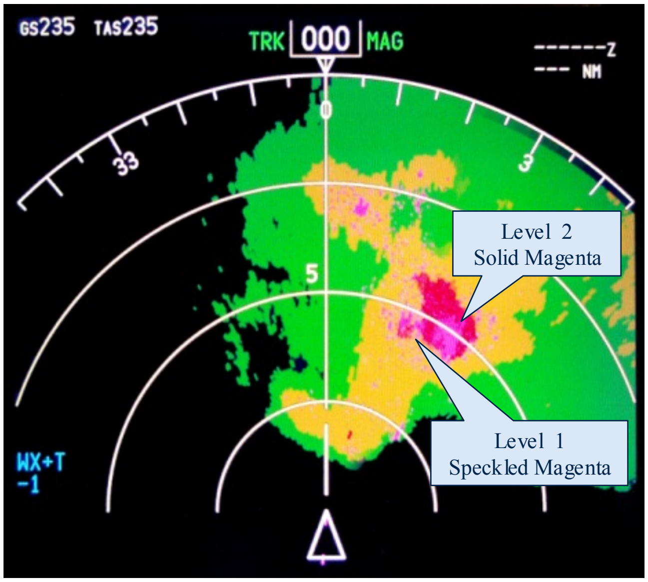
The turbulence measurement algorithms were successfully validated on the NASA Boeing 757-200 research aircraft and on more than 176 commercial transport aircraft (both Boeing and Airbus design) from multiple airlines in revenue operations. During an operational evaluation on Delta Air Lines B-737-800, B767-300ER, and B767-400ER aircraft in revenue operations, TAPS reports were successfully transmitted to a ground station network via the ACARS messaging system. The reports were graphically displayed to Delta dispatchers and retransmitted up to other aircraft where they were received and interpreted, but not displayed in the cockpit. [14]

Currently, AeroTech and its partner WSI have integrated TAPS into WSI's Total Turbulence Product suite, including the Fusion^{TM} dispatcher display tool. TAPS reporting software has been implemented on over 500 aircraft worldwide with more aircraft implementations in process.

5.3.2 Airborne Weather Radar-Based Information Sources

The second major data source of turbulence information in the proposed system comes from the E-Turb. Developed under the NASA Aviation Safety & Security Program, this radar is an existing airborne Doppler radar that has been modified using software algorithms that translate the second moment of the Doppler return into a turbulence "hazard index" based on the aircraft's current state parameters, such as weight, airspeed, configuration, etc. Current airborne Doppler weather radars can detect and display Doppler data, but do not translate this Doppler data into an accurate indication of the turbulence hazard for each aircraft. An example of E-Turb Radar data overlaid on radar reflectivity information is illustrated in Figure 8.

The E-Turb Radar enhances pilots' awareness of turbulence hazards scaled to their aircraft by converting the weather radar's measurement into predicted loads on the aircraft. The E-Turb Radar provides these locations and severity of turbulence hazards 3 – 5 minutes ahead of the aircraft, giving the flight crew useful information with which to maneuver the aircraft when already in turbulent regions. With the Enhanced Turbulence Radar, aircraft are better able to avoid hazardous convective turbulence by deviating tactically around patches of turbulent air. Like the TAPS system described in Section 5.3.1, this can lead to a reduction in injuries and maintenance costs due to turbulence encounters.



Level 2
Solid Magenta

Level 1
Speckled Magenta

Figure 8: Cockpit Presentation of Turbulence by the E-Turb Radar

The E-Turb hazard algorithms were initially integrated with experimental radar on the NASA B-757-200 and flight-tested in 2002. More recently, the turbulence hazard algorithms have been integrated into a Rockwell Collins' Multiscan^{TM} radar and operationally evaluated for more than 6,000 flight hours on a Delta B-737-800. Delta pilots reported that the correlation of the E-Turb Radar turbulence indications with actual turbulence is much better than a Doppler radar without this capability [14]. Certification standards have been developed and published (References [20] and [21]).

5.3.3 Integrated Display

A key element of the proposed system that does not currently exist in the current system, other than in prototype form, is an integrated display that allows the overlay of real-time measured turbulence information on other important operational information. In the proposed system the turbulence information may be filtered and overlaid on terrestrial or Instrument Flight Rules (IFR) navigation maps for dispatchers. It may be overlaid on other graphical weather data for meteorologists. It could be overlaid on ATC radar displays or flow control displays for ATC planners. Finally, and perhaps most importantly, it can be overlaid on cockpit navigation displays to allow flight crews to avoid, or penetrate intelligently, turbulence fields affecting their aircraft.

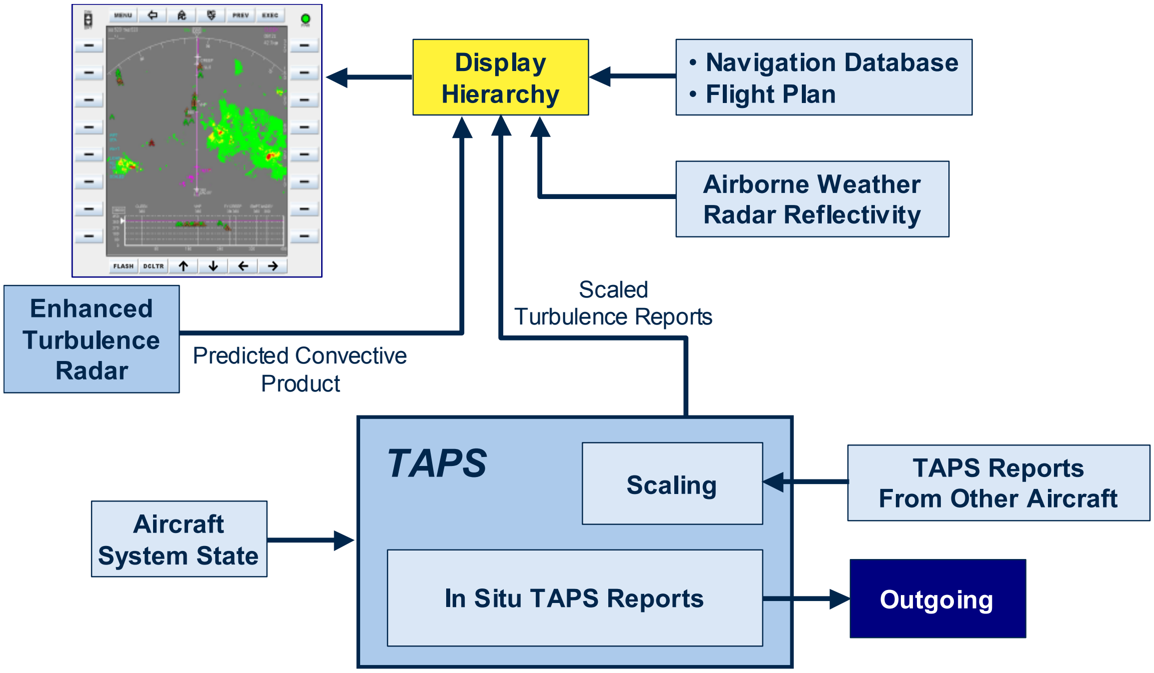


Figure 9: Integrated Turbulence Hazard Decision Aid System Concept Diagram

The cockpit display is the only display that is presently proposed for the fusing of TAPS and E-Turb Radar data in an integrated display format. A diagram illustrating how this concept would work is shown in Figure 9. As discussed in Section 5.2.1, the display could be an evolutionary form of the existing primary navigation display with TAPS and E-Turb Radar data as an additional functionality, or it could be some form of auxiliary display, such as a Class 3 EFB [9]. In either case, research has shown that the data must be overlaid with route and navigation information and have extensive filtering capability to provide a useful tool for improving flight crew situational awareness.

A prototype display that achieves this goal has been developed and evaluated by active airline pilots in both workshop and simulator environments. The advanced version of the display presents the turbulence hazard information in a track-up, ownship-centered format that also includes navigation, flight plan, and vertical profile information. This display has received high praise from evaluation pilots. A more primitive version of this display that meets current FAA criteria for EFBs is being prepared for flight evaluation in the near future, but the realization of the full potential of the proposed system concept will require the development and certification of more advanced display formats.

5.4 Modes of Operation

The proposed system would operate in two primary modes – a convective turbulence mode that requires integration of TAPS and E-Turb Radar data, and a CAT mode that uses only TAPS data. However, even the convective mode will make heavy use of the TAPS element of the system to identify and avoid turbulence outside of areas of reflectivity where E-Turb Radar protection will be minimized due to the lack of the aerosol particles necessary to allow a Doppler radar to function.

5.4.1 Convective Mode

The convective mode of operation will offer the following advantages over today's system:

- The proposed system will provide turbulence information in the clear air surrounding convective buildups where aircraft are maneuvering to avoid flying through areas of reflectivity.

- The regions offering smoother rides will be able to be identified without congestion-adding verbal ride reports, although such reports could still be available as an additional aid if needed.
- The TAPS data will be automatically scaled to the flights crew's own aircraft eliminating the need to mentally compensate for the aircraft type, probable weight, airspeed and altitude, etc. from aircraft giving ride reports.
- A 4-dimensional (counting age function) mental picture of the turbulence field will be easy to build and update as the aircraft proceeds through an area of convection.
- If penetration of an area of reflectivity is chosen or forced, a true turbulence-minimized path through that region can be flown tactically using E-Turb Radar with confidence that sudden, unexpected turbulence will not hazard the aircraft of it's occupants.
- Flight crews will be able to build confidence in both the TAPS and E-Turb Radar elements of the system, and monitor the continuing performance of the systems, by having the ability to compare the output of their own TAPS reports and E-Turb Radar indications with the turbulence actually experienced.

When operating in convective mode, it is anticipated that TAPS data will initially be used by airline staff meteorologists and dispatchers to plan turbulence-minimized flight plans for evaluation/acceptance by flight crews. Should turbulence avoidance conflict with other airline objectives, such as schedule or fuel conservation, more intelligent tradeoffs between turbulence avoidance and these other objectives will be possible using TAPS data. However, research to date has indicated that turbulence avoidance using actual reported data is generally more time and fuel conservative than similar planning with only forecast products and formal PIREPS.

Once a flight has departed and an area of convection reached, the proposed system will allow flight crews to update their "picture" of the turbulence field in and around the region of reflectivity shown on their onboard radar. At ranges of approximately 100 nautical miles or greater from the turbulent region TAPS will allow flight crews and dispatchers, operating from a common turbulence data base but perhaps overlaid with different types of other information, to make informed decisions about reroutes, diversions, or penetrations. This type of planning will allow significant improvements in the system-wide coordination of flights of individual airlines and improvements in ATC flow control. Additionally, it will help flight crews develop an improved understanding of reroute or diversion decisions that may seem non-optimal from an individual aircraft perspective, but are in fact optimal from an overall airline or system perspective.

If a decision is made to penetrate a region of reflectivity, avoiding areas of significant turbulence tactically, the E-Turb Radar element of the system becomes the primary avoidance tool. While other aircraft that are also tactically avoiding turbulence in the same region will likely be leaving TAPS reports that will be useful in tactical decision-making, these reports have some time latency that will make them less useful than E-Turb while actively maneuvering. However, by judicious use of the "age" filter provided in the integrated display, the pilots will be able to readily distinguish those TAPS reports that are new enough to be useful during tactical maneuvering.

The key to successful use of the proposed system in a convective environment is the careful fusion of TAPS and E-Turb Radar data into a single integrated display that allows the data to be referenced to reflectivity and other navigation and route information.

The information flow and decision processes that an airline crew might use in the proposed system to avoid convective turbulence are illustrated in Figure 10 and Figure 11. Figure 10 assumes that the aircraft is equipped with an Electronic Flight Bag display that operates independently of the ship's navigation display and therefore the crew is not restricted to the range and map limitations of the navigation display. Figure 11 assumes the TAPS and E-Turb Radar data are displayed on an integrated display that is subject to the range and map limitations of the navigation display.

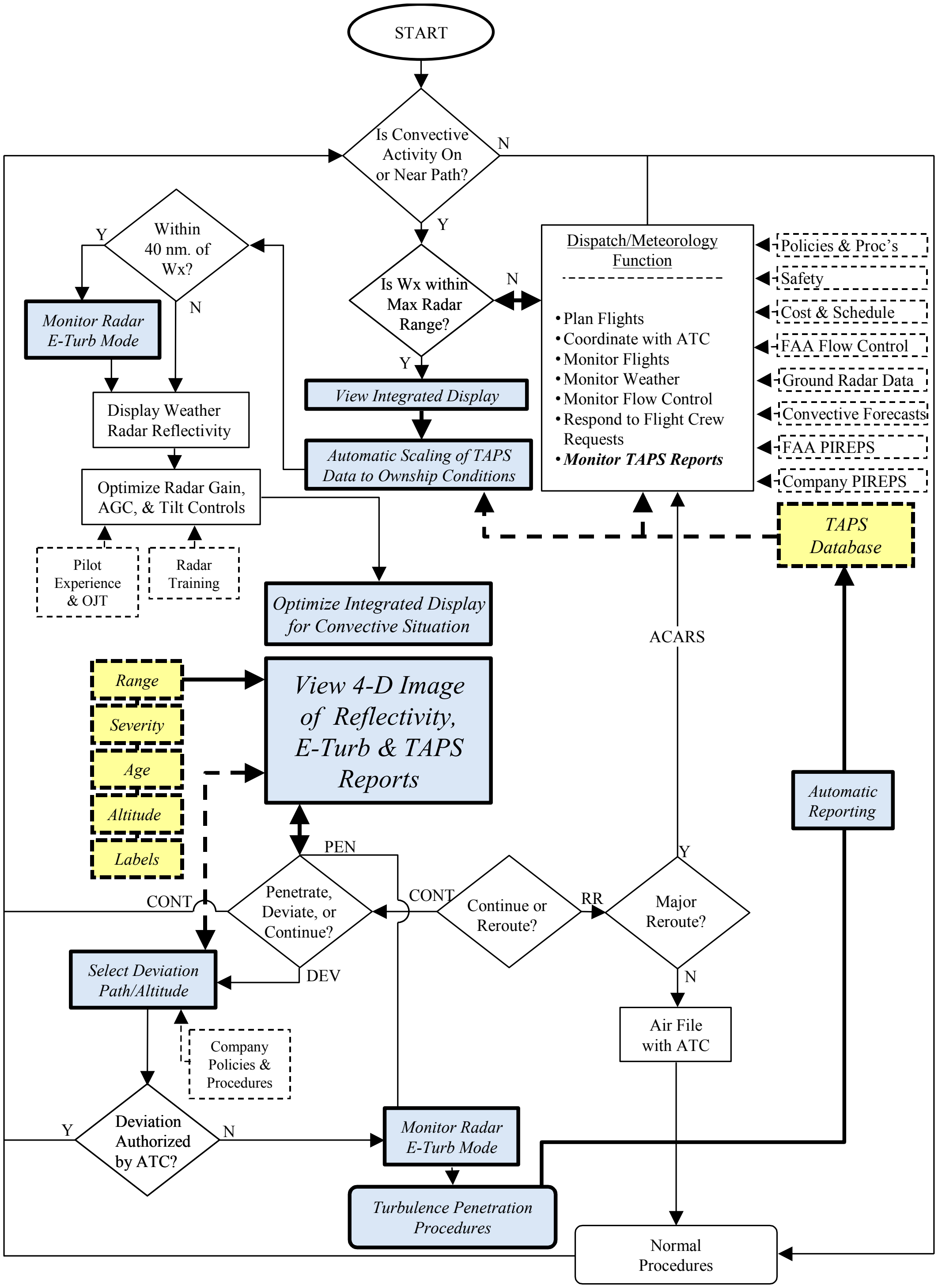


Figure 10: Decision-Making Processes for Proposed System – Convective Turbulence, EFB Display

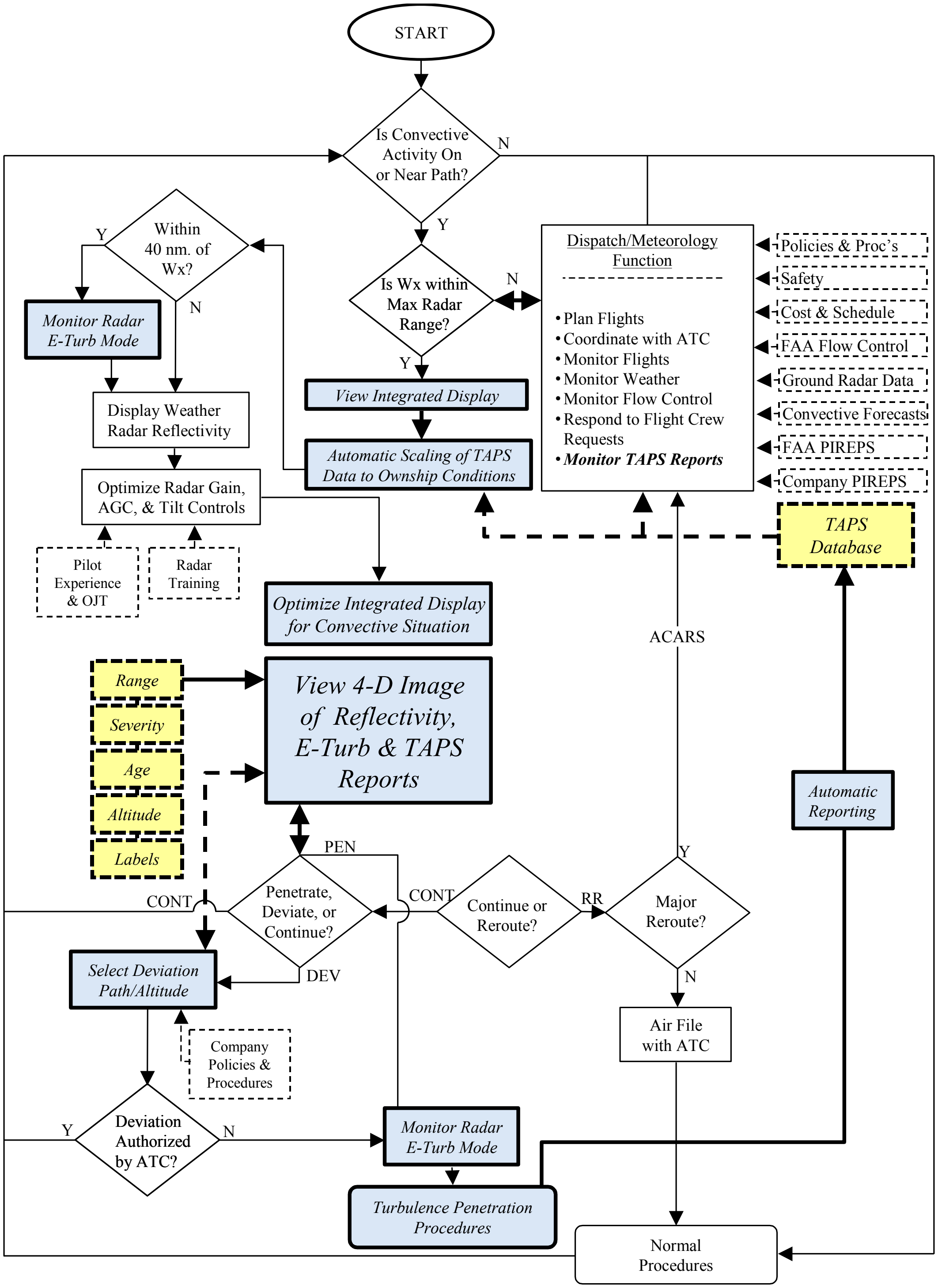


Figure 11: Decision-Making Processes for Proposed System – Convective Turbulence, Int. Display

5.4.2 Non-Convective (CAT) Mode

The CAT mode of operation will offer the following advantages over today's system:

- Real-time, quantitative clear air turbulence data will be available to ground and flight personnel for developing turbulence-minimized flight plans.

- Fuel and time savings will likely result from airlines being able to avoid areas of actual moderate and severe CAT without unnecessarily large reroutings that avoid entire regions of airspace that are just forecast to have CAT or where occasional reports of turbulence have shown up in the formal PIREP system.
- The turbulence reports will be scaled to each individual aircraft so that flight and ground personnel will no longer have to infer the likely effects of the measured turbulence field on individual aircraft.
- Ground and flight personnel will be able to filter and study the turbulence reports to develop a better understanding of the physical phenomenon causing the turbulence and thereby develop better avoidance strategies.
- Real-time scaled turbulence data will be available in flight allowing flight crews to update their avoidance strategies as the turbulence field ages and advects.
- Continuous mapping and updating of the turbulence field by enroute aircraft will virtually eliminate the surprise element in clear air turbulence that most often results in passenger and flight attendant injuries.

When operating in CAT mode, it is likely that airline staff meteorologists and dispatchers will use TAPS data to plan routes that are optimized with respect to turbulence exposure as well as schedule and fuel conservation. Since CAT tends to persist over long periods of time preflight planning using measured data is a valuable option not present in today's system. Airline meteorologists and dispatchers will be able to use data that is up to several hours old to define the spatial dimensions of the turbulent region and develop flight plans that avoid moderate and severe turbulence with minimal deviations from fuel optimal paths. Once participation in the TAPS system grows to include cargo carriers who operate primarily at night, TAPS data should be available for flight planning even early morning passenger flights.

Once a flight has departed, continuous updating of TAPS data will allow dispatchers to monitor CAT development and keep enroute aircraft informed regarding any recommended changes in routes or altitudes. Such early planning will enable early coordination of any flight plan changes with ATC, thus reducing ATC controller workload and allowing better optimization of flow control strategies.

Depending upon the maximum range of the cockpit display in the aircraft, flight crews should be able to begin direct monitoring of TAPS data in the CAT region when within approximately 300 nautical miles. At this time the availability of a common TAPS database to both flight crews and dispatchers should allow fine-tuning of the deviation or penetration plan.

As the aircraft approaches the CAT region the flight crew will be able to filter out older TAPS data and make last minute adjustments to their avoidance strategies using the most recent data. If the strategy includes penetrating a region of light turbulence, TAPS data can help to define a minimum exposure path through the turbulent field and allow early preparation of the cabin for turbulence. Such early preparation will reduce the probability of unexpected aircraft reactions that can injure passengers and cabin crews. The availability of TAPS data will also help flight crews know when they are clear of the turbulent field and can resume normal cabin service and safely turn off the seat belt sign.

The information flow and decision processes that an airline crew might use in the proposed system to avoid clear air turbulence are illustrated in Figure 12 and Figure 13. Figure 12 assumes that the aircraft is equipped with an Electronic Flight Bag display that operates independently of the ship's navigation display and therefore the crew is not restricted to the range bin or map limitations of the navigation display. Figure 13 assumes the TAPS data are displayed on an integrated display that is subject to the range and map limitations of the navigation display.

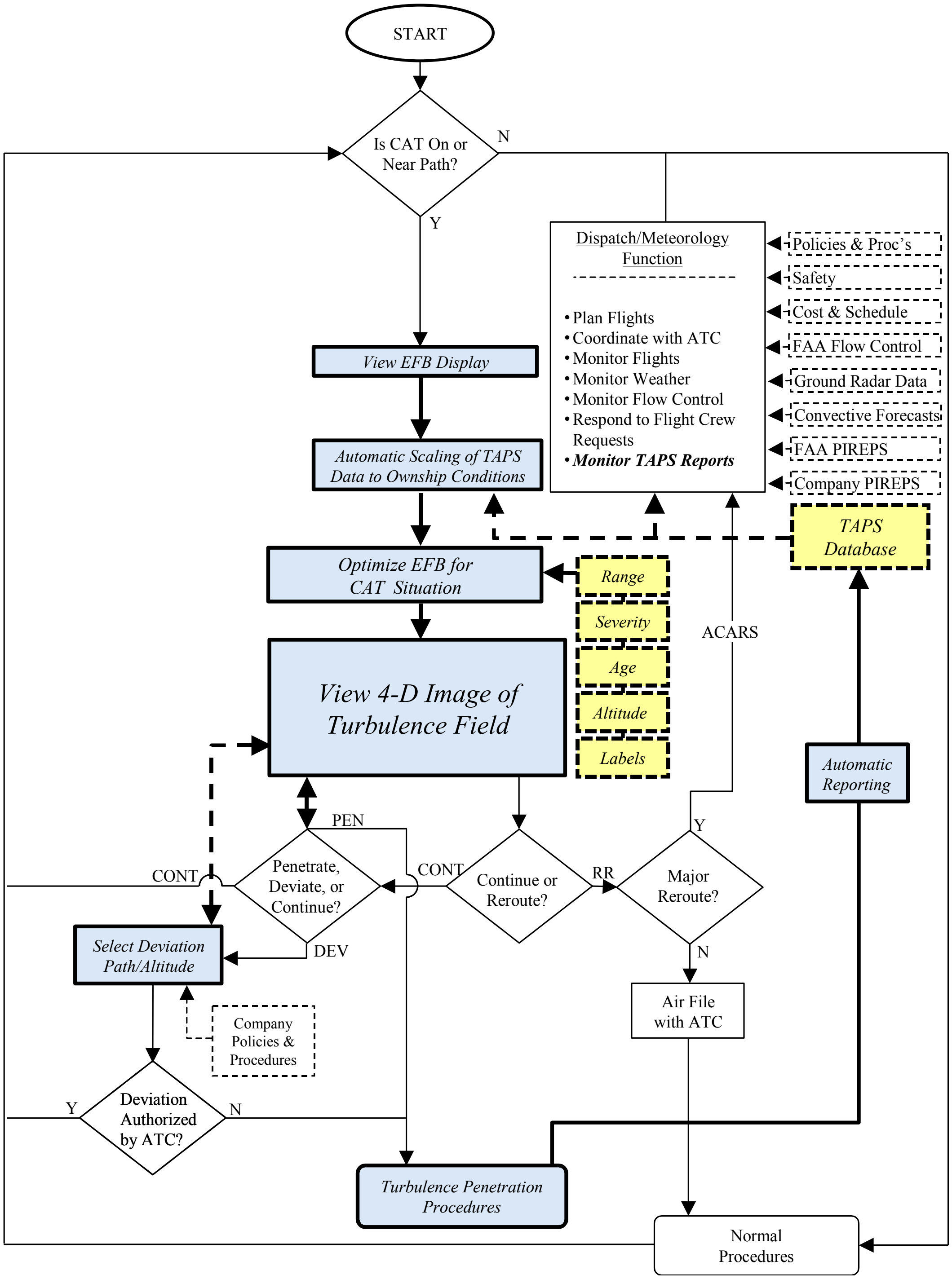


Figure 12: Decision-Making Processes for Proposed System – Clear Air Turbulence, EFB Display

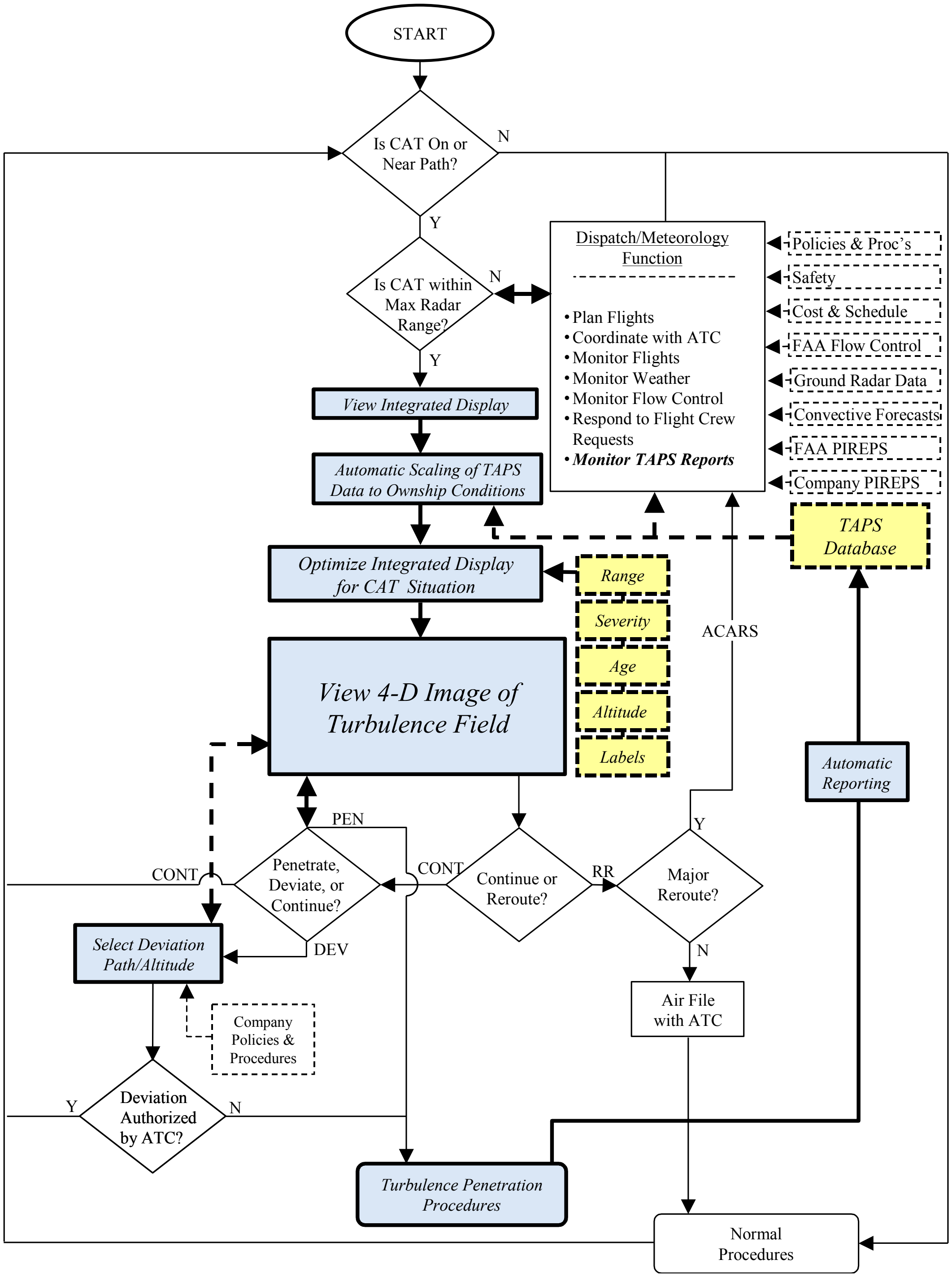


Figure 13: Decision-Making Processes for Proposed System – Clear Air Turbulence, Int. Display

5.5 Users and Stakeholders

The following section will describe the users and stakeholders that may be involved with the proposed system concept described within this CONOPS.

5.5.1 Organizational Structure

Three top-level organizations have been identified that will contribute to the use of the proposed system concept as described within this CONOPS. They are the airline operators (American Air Lines, United Air Lines, Southwest Airlines, etc), the air traffic service providers (FAA ATC), and the traveling public. Users within the airline operators will have direct interaction with the proposed displays and information contained within them. The air traffic service providers will be a part of the approval process for changes in the routing of an aircraft and should have access to similar information contained within such a display. And finally, the traveling public has an indirect use of the display through their flights on equipped aircraft and their experiences or lack of experiences of turbulence during those flights. The significance of the traveling public is emphasized by the fact that the airlines typically take a very conservative approach in avoiding turbulence regions to provide a smooth ride for the passengers at the expense of time and money for the airline. Should fuel prices continue to rise, airlines may be forced to make different tradeoffs between smooth rides and most efficient routes.

Within the airlines there are two primary groups identified: pilots and dispatchers who have a shared responsibility for the safety of the flight from a company perspective. The air traffic provider has a dual responsibility of efficient and safe guidance within the subject airspace through the use of controllers and the ATC Traffic Management Unit. The passenger is the economic driver of the air transport system. The other two groups must provide not only a safe and efficient mode of transportation, but they have to consider the comfort factor since the consumer might choose another air carrier if they are not satisfied with the flight. Unfortunately, there are not many timely and accurate reports of turbulence in today's environment because of the constraints in the system. Currently, all PIREPs are subjective, based on FAA guidance, concerning control of the aircraft and movement of objects in the airplane. The current organizational structure does not support efficient and timely handling of PIREPs since both the controllers and pilots are usually busy with higher priority duties when the occasion arises to report turbulence.

If timely and accurate PIREP information is made available to the users of the system, there could be dramatic changes in the way these groups perform their jobs. Such data would allow them to make real-time decisions, which not only improve safety, but also allow a more efficient and expanded use of the national airspace.

5.5.2 Profiles of Users and/ or Stakeholders

The primary user of the proposed system in this CONOPS document is the flight crew of a Part 121 air carrier aircraft. The display of turbulence information, the TAPS data, and the Enhanced Turbulence Radar information must all meet the user's needs, but those needs are directly related to the requirement of the dispatchers and controllers that may interact with the aircraft. The pilots and dispatchers are managed by the airlines; which set the standards for the operation of the flight. It can be assumed that as new tools are developed that better perform the job of identifying turbulence regions, that the various constituents such as marketing, finance, operations, and safety within the airline will adjust their policies accordingly. Externally, the management for the controllers will similarly adjust their policies and procedures especially in light of growing airspace capacity problems and limitations.

5.5.3 Interactions Among User Classes

As mentioned earlier, this environment requires the collaboration of pilots, dispatchers, controllers, and the Traffic Management Unit of ATC. Because of this, the information concerning turbulence must be compatible for the displays of the users that interact with the flight crew. The individual design of each system must take into account the needs and requirements of the other systems. The sharing of information between the different user classes must provide the same picture of a turbulence region of interest although different user classes may have differing display scales to accommodate their individual responsibilities.

5.5.4 Other Involved Personnel

In addition to the users and stakeholders discussed in the previous sections, the airline operator is also involved in the operation and acceptance of the proposed system. This is exemplified by the turbulence policy of the operating airline. Airlines change altitudes and routes with a very conservative approach to avoid large blocks of airspace if there is potential for significant turbulence. This is primarily due to a lack of sufficient tools to identify the location and intensity of turbulence within a given region, thereby resulting in significantly higher fuel consumption during the operation of a flight within one of these regions. If new tools were available, such as those proposed within this CONOPS, an airline internal team, consisting of marketing, finance, operations, and safety, could discuss and elect to accept a safe level of turbulence to reduce fuel usage and increase airspace utilization by managing the expectations of the customer.

5.6 Support and Maintenance

The display of automatic turbulence reports and weather radar within the cockpit environment is supported directly by the integration of the TAPS and E-Turb Radar technologies into the cockpit. TAPS relies on an electronic data link to supply information packets to and from an aircraft. The display of this information relies on a combination of the TAPS reports and existing hardware within the cockpit. Because new hardware is not being installed solely for the display of TAPS information, support and maintenance of such devices would fall under normal operations and preventive inspections.

The storage of up linked TAPS reports can be handled by existing equipment and systems within the aircraft, and data in the database will be purged routinely based upon the time stamp associated with TAPS reports. Maintenance and operational requirements for the proposed system will need to be developed although, since the system is intended to be advisory in nature, these requirements will not likely be any greater than those for the aircraft systems which host the TAPS and E-Turb capabilities.

6. System Introduction

This section will discuss the introduction of the proposed technologies within the current system, highlighting the relationships between the proposed technologies and the planned changes to the National Airspace System (NAS). A range of dependencies for the proposed technologies is presented, including the performance level expected of the proposed technologies. Also, issues associated with certification, procedures and partial and mixed equipage environments are discussed.

6.1 Relationship to Modernization Plans

The proposed system, including the Integrated Turbulence Hazard Decision Aid for the Cockpit, fits directly with modernization plans of both the FAA and various airlines. The FAA's Flight Plan (or Strategic Plan) identifies three goals that the FAA is striving for during their current modernization efforts [15]:

1. Safety – reduce fatal aviation accident rates by 80% in 10 years
2. Security – prevent security incidents in the aviation system, and
3. System Efficiency – provide an aerospace transportation system that meets the needs of the users and applies resources efficiently.

The proposed system with the Integrated Turbulence Hazard Decision Aid for the Cockpit will add value in the reduction of aviation accidents and the enhancement of the National Airspace System (NAS) by increasing the pilots' situational awareness of turbulence hazards to their aircraft. This will enable the pilots to more efficiently negotiate and collaborate with air traffic controllers and dispatchers to avoid potential injury-producing turbulence encounters and potentially enable pilots to use more of the existing airspace. Currently large areas of airspace are periodically closed due to convective activity or CAT and the potential for hazardous turbulence. By providing the pilots, dispatchers, and ATC personnel enhanced situational awareness of where the turbulence hazard to their aircraft exists, less of the airspace needs to be closed for air travel. These outcomes will assist the FAA in meeting some of their Free Flight Phase II goals as well.

The airlines are also interested in increased aviation safety. In fact the reduction/elimination of injuries to aircrew and passengers is one of their primary goals. Any technology that can assist in reducing the costs due to injuries is highly sought after in this day of financial tightening. The airlines also see value in making more efficient use of the NAS. One hour of flight for a modern aircraft can cost nearly $10,000 in fuel and other operational costs.

The FAA and the airlines have also been working on various initiatives to get weather information into the cockpits of aircraft. Within the FAA's NAS Architecture 5 there are five Operational Improvements [16] related to providing better weather information to aircraft and pilots:

1. Deploy Flight Information Service - Broadcast (FIS-B) Nationally
2. Improve En Route Weather Products
3. Improve Oceanic Weather Products
4. Provide Automatic Hazardous Weather Alert Notification
5. Support Collaborative Decision Making (CDM) with Simultaneous Hazardous Weather Notification

All of these Operational Improvements would benefit from the addition of the proposed system and the Integrated Turbulence Hazard Decision Aid for the Cockpit.

The overall process of getting weather information to the cockpit has proceeded much more quickly for General Aviation and Business Jet aircraft. The proposed system enables both the FAA and the commercial airlines to make greater strides in getting weather in the cockpit and focuses on weather that could have a significant safety impact on the aircraft.

6.2 Enabling, Dependent and Enhancing Elements

6.2.1 Enabling Elements

The display capabilities and current software of Multifunction Displays (MFDs) and the Electronic Flight Bags (EFBs) are enablers to the proposed system. The turbulence hazard information and the corresponding display software could easily be integrated into either an EFB or a MFD. The Integrated Turbulence Hazard Decision Aid for the Cockpit software could take advantage of the mapping software and some of the standard display functions that has already been developed and are currently being used by EFBs and/or MFDs.

6.2.2 Dependent Elements

Two key turbulence information sources for the Integrated Turbulence Hazard Decision Aid for the Cockpit are the TAPS and Enhanced Turbulence radar software. Both technologies were developed by AeroTech under the Turbulence Prediction and Warning System element of NASA's Aviation Safety and Security Program and have been fielded commercially.

The Integrated Turbulence Hazard Decision Aid will not likely be commercialization-ready on this same timetable. However, development and refinement of several integrated display concepts is underway and this work is providing the technology basis and risk reduction necessary for commercialization. The certification basis for a simple integrated display is available, but this basis will need to be updated to accommodate the full EFB-based Integrated Turbulence Hazard Decision Aid described in this document.

6.2.3 Enhancing Elements

During the initial investigation of turbulence information sources, two technologies were discovered that performed airborne remote sensing and warning of turbulence: RADAR and Light Detection and Ranging (LIDAR). The fundamental principle of making Doppler measurements of wind is common to the two techniques. The radar uses pulsed radio frequency energy to make the measurements, and the LIDAR uses pulsed laser energy. Both technologies rely on particulate matter in the air reflecting the energy to make the measurements. The frequency shift caused by the movement of these particles is used to estimate the velocity of the surrounding atmosphere. Unlike the weather radar, the LIDAR requires much smaller hydrometeors, which are invisible to the naked eye. This makes the LIDAR an intriguing option because it is able to make measurements in "clear air"; however, the LIDAR technology is much less mature than the radar and its hardware is very expensive. Also, no LIDAR system has shown that it can make useful turbulence measurements at cruise altitudes. Swan International of Sydney Australia has recently patented a laser-based wind-shear detection system for small aircraft (Reference [17]), but little information is known concerning evaluation results from any simulations or proto-type systems. If this technology is proven, its capabilities will be complementary to those of the E-Turb Radar for operations in "clear air." Continued monitoring of developments in the field of LIDAR technology and especially Swan International will be required.

6.3 Transition Periods and Mixed Equipage

The value of TAPS data increases with the density of the turbulence reports in the TAPS database. As airlines initially equip their aircraft with TAPS technology the TAPS database will be relatively small and may be localized according to each airline's route structure. The value of TAPS will increase proportionately with the equipage level in the airlines.

The value of TAPS will also be enhanced by equipage outside of the airline community. As the technology expands into other segments of aviation (e.g. military, business, general aviation) the spatial and temporal limits of the TAPS database will also grow, providing enhanced benefit to all participating elements.

E-Turb Radar technology, unlike TAPS, is not dependent on high equipage levels. When an aircraft is equipped with E-Turb Radar technology it immediately benefits fully from the new capability. The only mixed equipage issue with E-Turb Radar in an airline environment would be the training associated with flight crews operating aircraft that may or may not be equipped. However, airlines are experienced with transitioning new technologies into their airline fleets so this should not hinder the technology transition.

Transition and mixed equipage issues will be minimal for the Integrated Turbulence Hazard Decision Aid for the Cockpit. Mixed equipage could occur when first installing the display software if the aircraft do not have all of the turbulence inputs for the display – TAPS and the E-Turb Radar. Installing the display without the inputs will not be a problem – the software will just display those turbulence inputs that it does receive. As aircraft become equipped with TAPS and the E-Turb Radar, the turbulence inputs will begin appearing on the Integrated Turbulence Hazard Decision Aid for the Cockpit. Each turbulence input (TAPS reports, E-Turb Radar information, etc.) is independent of the others; therefore, just having one or two of the inputs will not be an issue. The display will present the turbulence information that the aircraft has available. If an aircraft is upgraded with other turbulence information sources in the future that can provide information to the display in a suitable hazard metric, the integrated display should be readily capable of presenting that information.

Pilots will need to be aware of what turbulence information sources a particular aircraft has for the Integrated Turbulence Hazard Decision Aid for the Cockpit, so that they do not expect to get certain information when it is unavailable to that aircraft. Throughout the transition period, detailed documentation of the turbulence sources available on any particular aircraft should be a top priority. The display will also be able to inform the flight crew of what turbulence information is available based on installed turbulence sources.

As an airline installs the display and associated software on its various aircraft, no unusual technical issues are expected. The display is an enhancement for the aircraft that it resides on and the presence or lack of a display will not affect the operations of other aircraft within a specific airline or organization. There may be a difference in the way that pilots of an equipped aircraft communicate with dispatchers and controllers due to the increased situational awareness of turbulence. With increased turbulence awareness, pilots will have a clearer idea of what they would like the dispatcher and/or the controller to do for them – new flight plan, deviation, new altitude, etc. – before communicating with the dispatcher or controller. The standard operating procedures for the flight crew will not change based on the presence of the display.

6.4 Performance Measures

The performance level of the standard radar’s reflectivity information is presently known. The performance level of the turbulence mode of current Doppler radars is also known and its correlation with actual aircraft upsets leaves room for improvement.

The E-Turb Radar’s turbulence prediction and the TAPS reports’ measurements/scaling have been shown to correlate well with individual aircraft upset during research and development flights [14]. However, both technologies will have to reach acceptance by line flight crews correlating what they see on their integrated display with the aircraft motions they experience. This “performance measure” will dictate whether the technologies ultimately pass or fail.

It is likely that failure detection will be built into production versions of the display software, so the pilots will be notified when there is a loss of input from any of the various sources of turbulence information. Because the display is intended to be advisory in nature, the loss of the turbulence inputs to the display would only return the crew to the current level of turbulence awareness and methods of turbulence avoidance.

6.5 Procedure Changes

Integrating the proposed system into the existing system will not likely require significant changes to operational policies, as stated in Section 5. However, in order to take advantage of the proposed system’s new capabilities some changes in procedures within those policies may be needed. For example, the integration of TAPS data into the preflight briefing format for dispatching Part 121 flights may need changing. Procedures used by dispatchers to determine when aircraft need to be contacted, and procedures for handling TAPS data within the meteorology and dispatch departments may also need updating.

Flight crew procedures may also have to be updated to ensure that flight crews handle TAPS and E-Turb Radar data in the cockpit in standardized ways. This would ensure that individual flight crew members can continue to be mixed without safety issues arising, and would ensure that crews do not, for example, become overly focused on the new integrated display to the derogation of other duties.

While changes to ground and flight procedures may be desirable, such changes should be relatively easy to implement. The airline community does this on a routine basis as their airline equipment, systems, route structure, etc. evolve. The FAA has already begun to produce guidelines for the integration and use of Electronic Flight Bag displays and has many regulations and guidelines for other cockpit displays. These documents will form the basis for any procedural changes that may be necessary.

6.6 Certification, Regulatory and/ or Standards Issues

As with any new software/display introduced into the cockpit, the FAA certification issues must be addressed. Turbulence information presented on the display to flight crews is intended to be advisory in nature. The information presented will be for situational awareness purposes ***only*** – and not intended for navigation. In addition, it is fully the intention of the design that failure of the turbulence inputs to this display will result in flight crews reverting to the turbulence avoidance procedures in place today with no reduction in safety over today's methods of turbulence avoidance.

Given the history of other systems such as TCAS and Ground Proximity Warning System (GPWS), it is possible that over time, as confidence in the proposed system and the integrated display builds, that some safety-related rules or guidelines could develop that go beyond "advisory". Should such evolution take place, it would be under the strict control of the FAA and performed in accordance with accepted practices for making such changes.

The Integrated Turbulence Hazard Decision Aid for the Cockpit is only software that could theoretically reside on any number of on-board displays (multifunction display, Electronic Flight Bag, Electronic Flight Instrument System (EFIS), etc.). The systems that provide inputs to the display will need to be certified. TAPS utilizes the existing aircraft hardware infrastructure – communications, sensors, and data buses. The display of the TAPS information will be required to follow current regulations. During the In Service Evaluation of the E-Turb Radar system, a Supplemental Type Certificate (STC) was issued for a Boeing 737-800 aircraft in August of 2004. For these reasons, it is believed that the proposed system software will not confront the considerable certification issues that can face the introduction of hardware or flight critical software into the cockpit. As previously noted, the industry has developed MOPS for the E-Turb Radar function and are included in TSO C63d.

The FAA will be involved in the development and implementation process. Research has identified the Federal Aviation Regulation (FAR) 23 (Airworthiness Standards: Normal, Utility, Acrobatic, and Commuter Category Airplanes) and 25 (Airworthiness Standards: Transport Category Airplanes), specifically Subpart F (Equipment), sections 1303, 1309, 1311, 1322, and 1397, as well as the various SAE publications, Department of Transportation documents, and various air and mil standards regarding color and aviation displays. It will be required that these regulations are abided by in the development of the display software and the presentation of any icons/graphics.

Development of the implementation issues arising in the introduction of weather products and displays in the cockpit should be followed. Participating in various working groups addressing these issues will be the key to a successful commercialization; the Radio Technical Commission for Aeronautics (RTCA) Working Group 95, and the Airline Transport Association's Digital Display's Working Group. Additionally, issues currently faced by the industry in the introduction of Electronic Flight Bag technologies will be monitored, as well as following the issues being addressed under the FAA's Advisory Circular AC-120-76A and Department of Transportation document DOT-VNTSC-FAA-03-07.

7. Operational Scenarios

Two operational scenarios are presented. Each scenario will emphasize one of the two primary operational modes of the proposed system – convective and non-convective operations. Within each scenario an end-to-end flight will be discussed that utilizes the proposed system through all phases of a typical airline flight, beginning with preflight planning and ending with landing at destination.

As each flight proceeds sample flow charts will be used to illustrate how decision-making would take place in the proposed system, and sample screenshots of a hypothetical cockpit display will be used to illustrate how turbulence data could be filtered and manipulated to assist the flight crew with the decision-making process.

The convective operational scenario will illustrate the fusion of information from three primary sources – airborne radar reflectivity data, airborne radar E-Turb Radar data, and TAPS data. The non-convective scenario will illustrate how TAPS data alone can be used to identify and avoid clear air turbulence where radar reflectivity is too low to support any type of radar data.

Details of the functions and features of the proposed system can be found in Section 4 of this document and in Reference [18].

7.1 Convective Scenario

7.1.1 Overview

The context for the convective operational scenario will be a revenue passenger flight from Minneapolis-St. Paul International Airport (KMSP) to Miami International Airport (KMIA) at 31,000 feet (FL 310). The route of flight will take the aircraft over Nodine Vortac (ODI) to BRIBE Intersection, then direct to Roberts Vortac (RBS), direct to Louisville Vortac (IIU) and then via the preferred high altitude routing to Miami. A large area of convective activity exists along a line oriented from southwest to northeast across Arkansas, Illinois, and Indiana. Severe thunderstorms associated with this region of convection have spawned tornadoes and generated damaging winds on the ground. The relationship between the route of flight and the convective weather is illustrated in Figure 14.

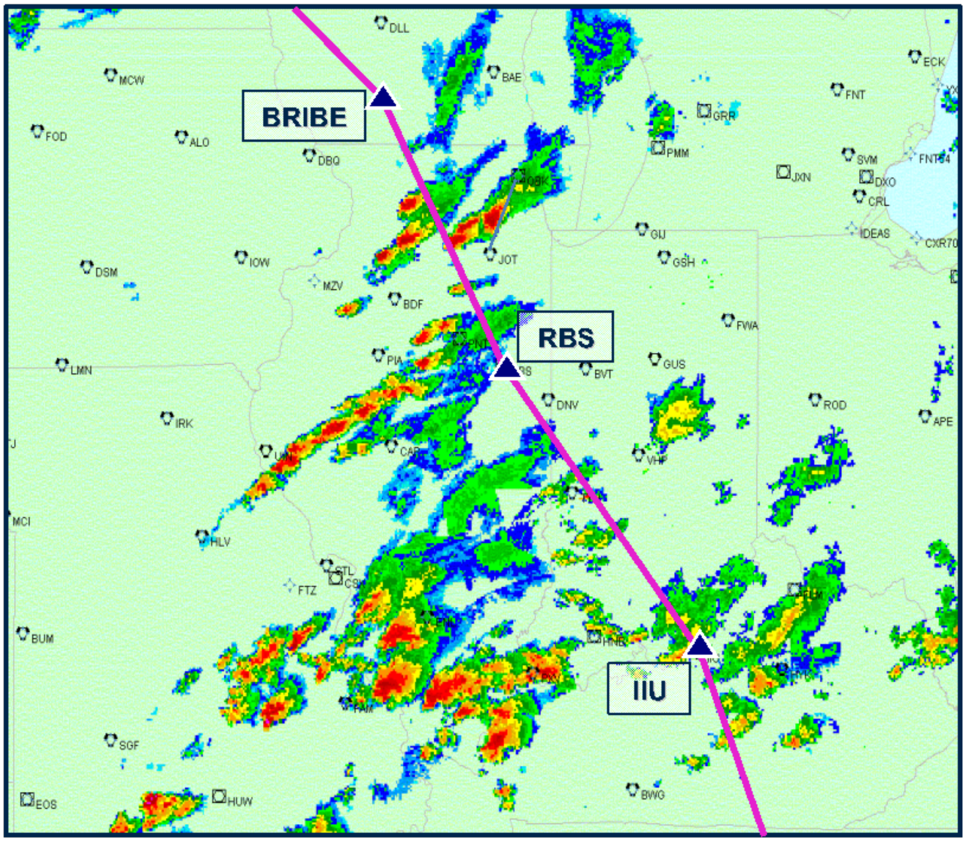


Figure 14: Convective Operational Scenario Flight Plan

This scenario is entirely fictitious with the exception of the weather, which is recorded Next Generation Radar (NEXRAD) reflectivity data from September 22, 2006. The routing, crew actions, dispatcher actions, ATC actions, and all other elements of the scenario, though typical of a routine airline flight, have been fabricated to illustrate how the proposed system might operate under real-world conditions.

7.1.2 Significant Changes from Current Operations, Procedures, or Policies

No significant changes to current operations, procedures, or policies are envisioned with the incorporation of the proposed system. The system is advisory in nature, and will not mandate a new set of requirements or actions to occur.

7.1.3 Key Assumptions

The following assumptions are made in the development of the convective scenario:

- The TAPS system for automatically sensing and reporting turbulence from enroute aircraft has been implemented in at least the majority of aircraft of the major airlines.
- TAPS data is communicated to the ground and distributed back to airline aircraft via data link, as well as made available to airline dispatchers, meteorologists, and ATC planners as a nationwide turbulence database.
- Airline aircraft have been equipped with an E-Turb Radar upgrade that provides indications for two levels of turbulence severity that have been scaled to ownship state parameters.
- An operational display has been developed that allows the dispatch community to overlay TAPS data against a wide variety of other map and graphical weather products.
- A fully integrated Class III Electronic Flight Bag cockpit display has been developed and certified that allows TAPS and E-Turb Radar data to be displayed in a track up, ownship-centered format and overlaid with reflectivity, navigation, and flight plan information.
- Ground and flight personnel have been fully trained in the features and functions of both the ground and cockpit displays.

7.1.4 Description of Proposed System Operations in a Convective Environment

The scenario begins at the airline dispatch office some two hours before scheduled departure time. Dispatchers review the reflectivity information from ground-based radars, weather reports from stations in and around the area of connectivity, and convective outlook information from the National Weather Service (NWS). The strong nature of the storms and the tendency for them to form up in squall lines argues for routing their aircraft around the entire region, which would result in delays, added fuel consumption, and missed connections at destination.

However, a review of the turbulence events actually being experienced by aircraft currently navigating in and around the convective region at high altitude indicates that acceptable flight paths through the convective area will likely be possible using TAPS data and E-Turb Radar data. ATC flow controllers also see the same picture and keep the airspace containing the convective activity open. The dispatchers file flight plans that will penetrate the region rather than circumnavigate it saving significant fleet-wide fuel and time.

Flight crews begin arriving 30 minutes to one hour before flight time and, upon viewing the ground radar depictions of the convective activity, request further information concerning why the flights were planned through rather than around the region. The dispatchers call up the TAPS data base and allow the flight crews to examine the measured data from aircraft that have recently transited the region and the flight crews agree that penetration of the region is a viable option although care will have to be taken to ensure that passengers and cabin crews are seated and belted during portions of the transit. The TAPS data will be helpful in deciding when these actions become necessary to ensure the safety of the flight.

At the departure gate the crew completes their preflight checks and is awaiting passenger emplaning. Since the weather is convective in nature, which implies a dynamically changing environment, and since the convective region will be in the early part of their flight, the crew decides to recheck the weather in the vicinity of the convection. The ship's weather radar is of no use on the ground but the EFB display can be used on the ground to uplink TAPS and other weather products. The crew calls up the NEXRAD composite weather picture and initially becomes concerned at the reflectivity picture shown on the display. However, realizing that this picture is a composite of all altitudes and multiple radars they decide to check how aircraft in the vicinity of the convection are doing. They call up the TAPS database and filter the data to show only the last 30 minutes of TAPS data and only in the altitude band in which they will be operating. The data shows aircraft are deviating, but still experiencing only light to occasional moderate turbulence while deviating.

While there are no reported thunderstorms along the planned departure path, there are layered clouds and the northern edge of a jetstream that could cause occasional bumps, so the crew elects to keep the TAPS data displayed during departure. Anticipating the normal elevated workload of a departure through high density airspace the crew decides to engage the "Climb" preselect from the integrated display filter set which optimizes the display filters for a climb segment using a single button push.

Upon reaching FL 310 the Captain and First Officer select the "Cruise" preselect and check the TAPS reports in their vicinity. The Captain selects the 160 nautical mile range scale and leaves the altitude filter at "Normal" which shows all reports within ± 3000 feet of his altitude. He sets the age filter to "60 Min", which filters the reports to only those recorded within the last 60 minutes. Seeing only occasional "light" icons the Captain turns off the seat belt sign and allows the flight attendants to begin cabin service. However, looking further out using the 320 nautical mile range selection he sees the northern edges of the reflectivity and some "moderate" turbulence icons. He therefore decides to call the flight attendants and tell them he will have to stop the cabin service and seat all of the passengers in about 30 minutes.

While the seat belt sign is off the Captain requests that the First Officer set his display range to 80 nautical mile and age to "30 Min" to monitor for recent turbulence reports from other aircraft operating in their vicinity. The captain sets his display to 320 nautical miles and begins formulating an avoidance strategy using long-range reflectivity data and TAPS reports. At this range the Captain knows the reflectivity data is only useful for a general picture of the forward edges of the storm system and places more emphasis on the TAPS data for developing a turbulence avoidance strategy.

Using the 320 nautical mile range scale the Captain's display is cluttered with TAPS icons. The Captain begins his analysis by selecting "Mod or Greater" on the severity filter and "30 Min" on the age filter, which displays only very recent moderate and severe icons. This significantly declutters the display. Now the Captain selects "Above" on the altitude filter, which displays reports in the altitude range from current altitude – 3000 feet to +9000 feet, to see whether he can minimize turbulence effects by climbing. The Captain then selects "Below" on the altitude filter to look 9000 feet below current altitude. At this time there does not appear to be an advantage to be gained by changing altitudes, so the Captain decides to stay at FL 310 for now.

About 100 nautical miles north of the area of convection the aircraft receives an ACARS message from dispatch recommending the Captain consider a reroute to the east about 100 nautical miles to avoid the region between BRIBE and RBS where squall lines have formed and severe turbulence has been reported. (Figure 15) The Captain sets his range scale to include this area and uses the "Flash" function to pull out the severe reports. There are only two. The Captain turns on the "Labels" function and selects "Absolute Alt". He notices that both of the reports are below 15,000 feet and thus were probably reported by smaller aircraft. On a hunch the Captain turns off the scaling function and immediately notices that several of the light reports turn to moderates and two moderates turn to severe, indicating that they were measured by lighter aircraft that would respond more to turbulence than his aircraft. Turning scaling back on and reexamining the data the Captain concludes that his aircraft at its current weight and speed should be able to navigate through the area of turbulence only encountering light turbulence.

At 50 nautical miles from the first indications of reflectivity the Captain stops the cabin service, turns on the seat belt sign, and makes an announcement that turbulence can be expected for the next hour or so. The Captain is just about to request the proposed reroute to the east, which would take him over Chicago and around the eastern edge of the two overlapping lines of storms when he notices a "light" TAPS report appear in an approximate 30 mile wide gap between the two lines of cells that lie across the flight path. The Captain turns off the "DCLTR" (declutter) filter and notices that several more light reports appear in a line defining a path between the lines of cells (Figure 15). Setting the altitude filter to "Norm" and the age filter to "15 min" he looks in the Vertical Profile Display (VPD) and notices that these continuous light reports are recent and come from an opposite direction aircraft at FL 300, only 1000 feet below. Based on this actual turbulence experienced by another aircraft, but scaled to his aircraft as "light", the Captain decides he can safely maneuver between the lines of cells with only slight deviations from his programmed flight path.

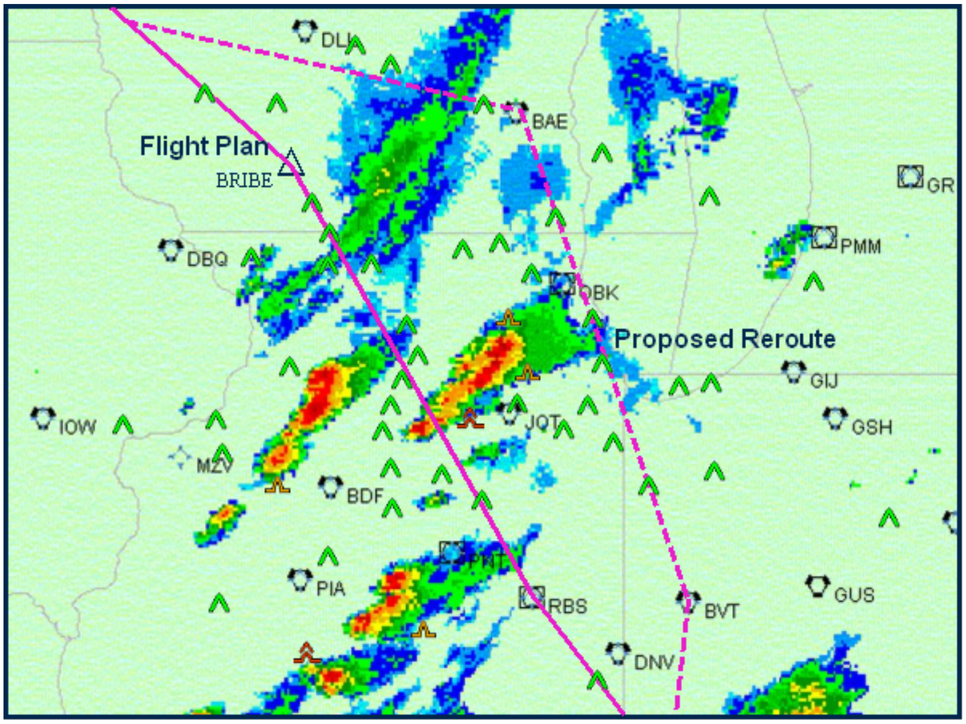


Figure 15: TAPS Information at Decision Point to Deviate Between Lines

At approximately 40 nautical miles north of the first line of cells, splotches of light magenta begin to overlay the green reflectivity around and between the storms. Dark magenta splotches overlay the yellow and red areas near the centers of the cells. The Captain requests and receives permission to deviate up to 10 miles either side of his flight plan.

As the aircraft maneuvers through the gap between the lines, a dark magenta area begins to propagate towards the aircraft's flight path from the maturing cell marking the eastern end of the first line of cells. The Captain alters his heading to provide a greater lateral margin from this cell and, clearing the western-most cell of the second line, turns southeast and re-intercepts his flight-planned route. Using the TAPS and E-Turb Radar data available to him on the integrated display the Captain is able to develop a good picture of the actual turbulence in the region surrounding these two lines of cells and is able to find a safe and efficient path through them that saves substantial fuel and time (Figure 16).

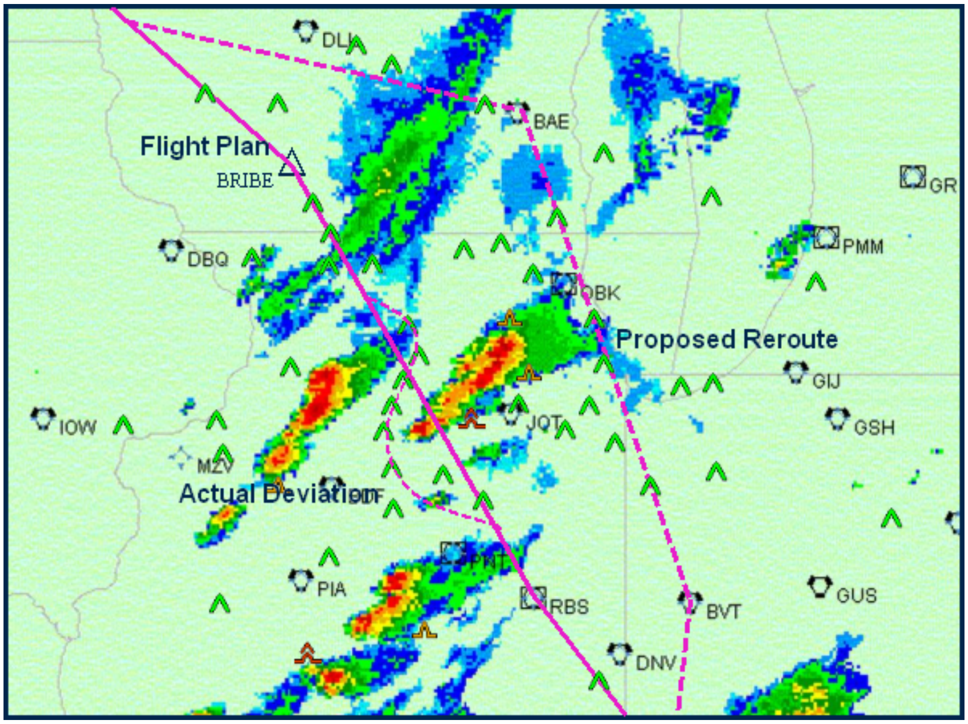


Figure 16: Deviation Path Versus Proposed Reroute Path

Once past the lines of cells the Captain checks the TAPS reports for his altitude and continued route and, seeing nothing other than occasional "light" icons, turns off the seat belt sign and resumes cabin service. Meanwhile he and the First Officer expand their range scales and begin evaluating the next area of convection that lies west of the Louisville, KY area (Figure 17). This area is moving northeastward and will cross the projected flight path. This large area of convection has no specific lines formed but many embedded cells. A SIGMET has been issued covering this area. Based upon the movement of the cells and the flight's progress the Captain determines that a reroute around the entire convective area is prudent.

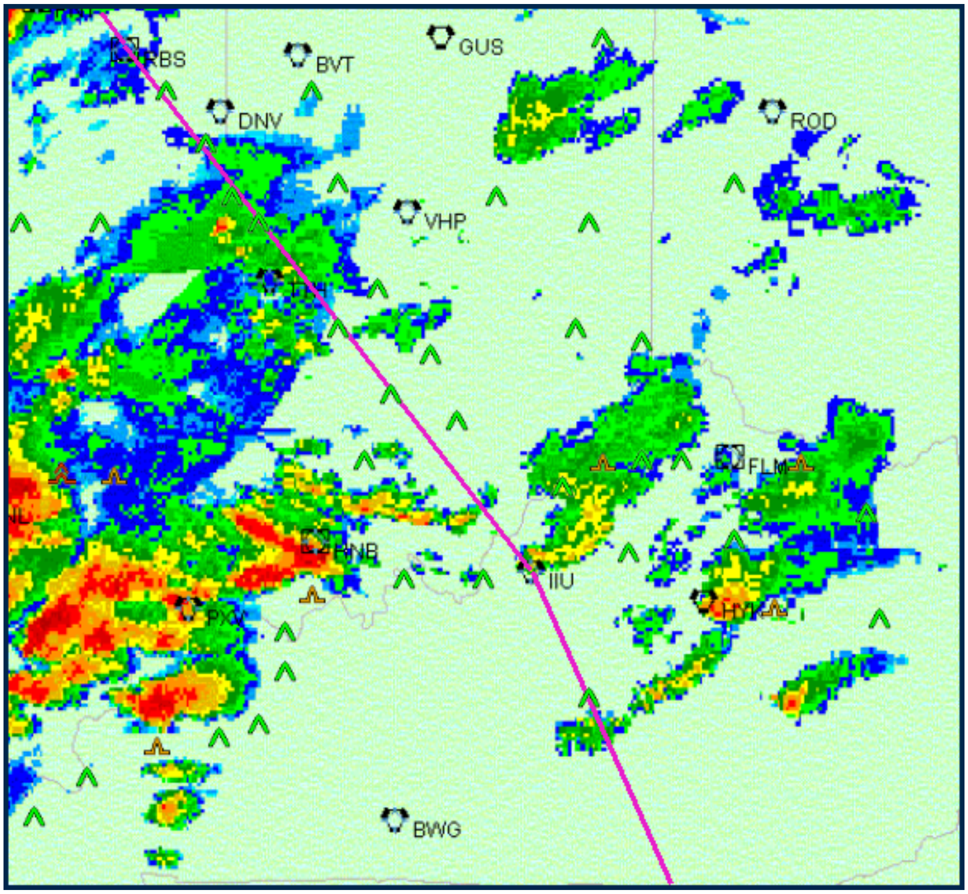


Figure 17: Convective Weather West of IIU Moving Northeastward

The Captain sends an ACARS message to dispatch asking them to check their TAPS displays and recommend a new routing. The dispatcher checks his TAPS data, along with other weather products, and determines that a rerouting is not necessary but that the crew should be able to achieve a smooth ride by a tactical deviation about 25 miles to the east where other aircraft are transmitting only "light" TAPS reports. The Captain concurs and begins watching the reflectivity and TAPS reports for the region east of his flight path as it comes within range. By proper age and altitude filtering, and reference to the VPD, he is able to obtain a good 4-dimensional mental picture of the turbulence being reported by other aircraft in the region of interest. He determines that the dispatcher recommendation was a good one and requests to deviate up to 20 miles east of his cleared routing. Using the VPD he is able to determine that two small cells just southeast of RBS are in early stages and that he will be able to safely maneuver between them at FL 310.

ATC has already been informed by flow control, which is also monitoring TAPS reports, that the preferred area for deviations is to the east of the convective area at the present time and has reconfigured airspace to accommodate more aircraft deviating to the east. The Captain receives a clearance to deviate as necessary and the flight circumnavigates the area of convection without having to stop cabin service or inconvenience the passengers (Figure 18).

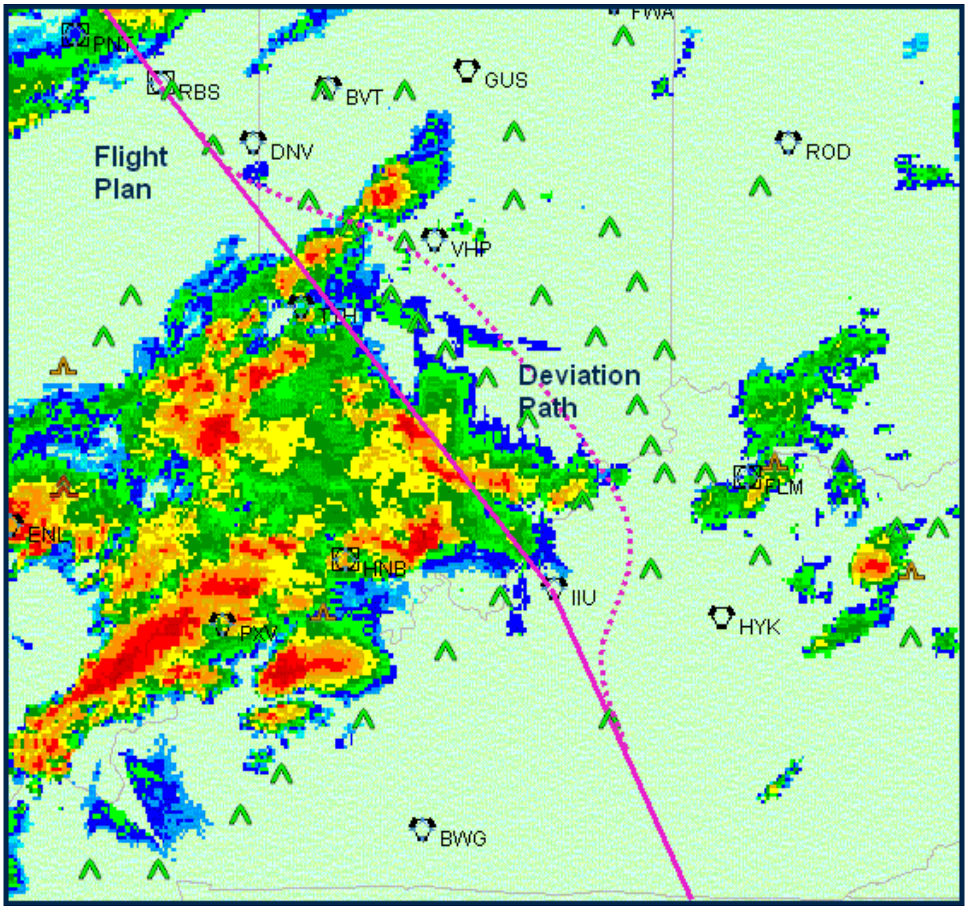


Figure 18: Deviation Path Around Louisville Convective Weather

The flight proceeds to the Miami area without further weather issues. On descent into Miami the Captain is concerned that a strong sea breeze could induce clear air turbulence over and inland of the coast. He activates the "Descent" preselect to optimize his display for the descent phase of flight and monitors the display from top of descent. No turbulence reports are indicated and the flight has a smooth arrival into KMIA.

7.1.5 Non-Normal / Rare normal Operations

No unique non/rare normal operations are expected for the proposed system. Hardware failures, such as communications link failures or radar failures could affect the utility of the system temporarily, but these occur in today's system as well. Should the data link transmitting TAPS fail or the E-Turb Radar feature of the radar fail; procedures would revert to today's verbal ride reports and avoiding convection by larger margins.

Thorough training will be necessary to ensure that the cockpit display can be easily and quickly operated and interpreted by flight crews to avoid workload and display clutter issues.

7.2 Non-Convective Scenario

7.2.1 Overview

The context for the non-convective operational scenario will be a revenue passenger flight from Dallas-Fort Worth International Airport (KDFW) to Denver International Airport (KDEN) at 38,000 feet (FL 380). The route of flight will take the aircraft over Ardmore Vortac (ADM), then J52 to ROLLS

Intersection, then direct to GAGE Vortac (GAG), then J98 to Liberal Vortac (LBL), J20 to Lamar Vortac (LAA) followed by Hugo Vortac (HGO) and Falcon Vortac (FQF), and then direct to KDEN (Figure 19). The aircraft is cleared to cross LAA at FL 300 for the descent into KDEN. A jetstream lies across this routing from just north of ADM to near HGO, as illustrated by the upper air chart overlaid on the route in Figure 19. For purposes of this scenario it is postulated that the bottom of the jetstream lies somewhere near the tropopause and the tropopause is about FL 350. Thus, at FL 380 our hypothetical flight would fly through the lower edge of the jetstream where significant shear would be occurring and turbulence would likely be significant.

This scenario is entirely fictitious with the exception of the upper air chart shown in Figure 19, which was actual weather for September 22, 2006. The routing, crew actions, dispatcher actions, ATC actions, and all other elements of the scenario, though typical of a routine airline flight, have been fabricated to illustrate how the proposed system might operate under real-world conditions.

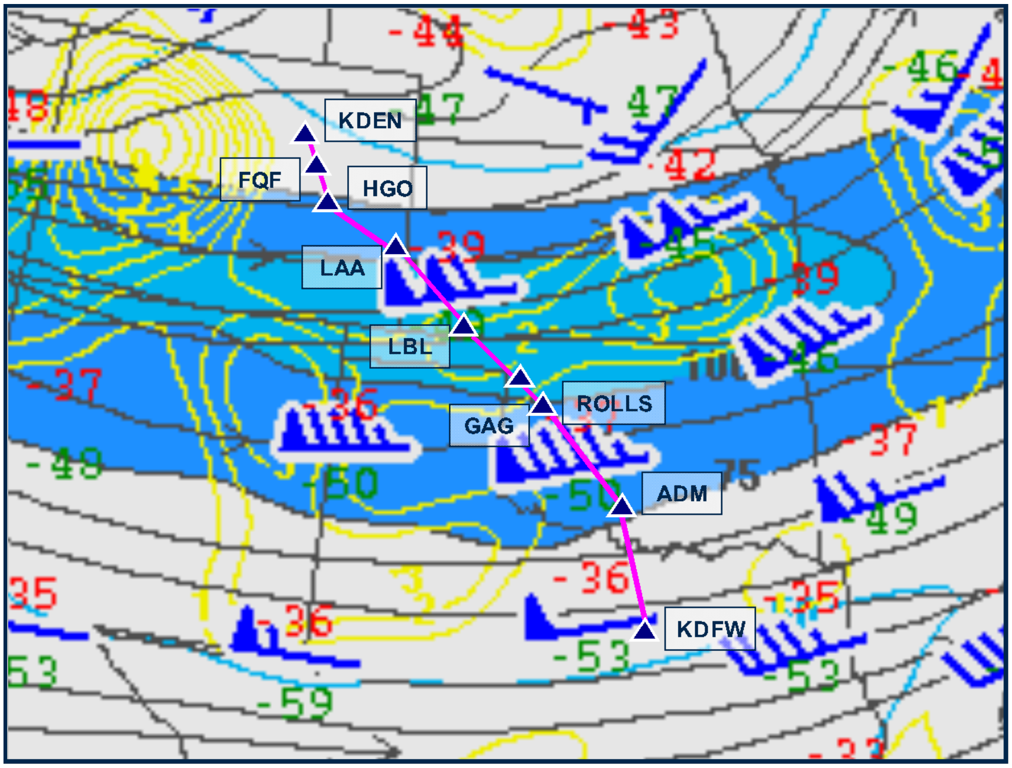


Figure 19: Non-Convective Operational Scenario Flight Plan

7.2.2 Significant Changes from Current Operations, Procedures, or Policies

The availability of graphical real-time automated quantitative turbulence data is expected to have a significant effect on those policies and procedures affecting the identification and avoidance of CAT, whether they are airline or FAA policies or procedures. Presently there are no operational sensors capable of detecting CAT, so CAT is avoided, if at all, by inference from forecast products and from monitoring ride reports, which have the limitations mentioned previously. In the proposed system, TAPS reports will allow the use of automated reports in both the preflight planning and enroute phases of flight to identify and avoid turbulence. Training will be essential regarding the correct use of the TAPS display filters to identify the type, extent, and persistence of CAT.

7.2.3 Key Assumptions

The following assumptions are made in the development of the non-convective scenario:

1. The TAPS system for automatically sensing and reporting turbulence from enroute aircraft has been implemented in at least the majority of aircraft of the major airlines.
2. TAPS data is communicated to the ground and distributed back to airline aircraft via data link, as well as made available to airline dispatchers, meteorologists, and ATC planners as a nationwide turbulence database.
3. An operational display has been developed that allows the dispatch community to overlay TAPS data against a wide variety of other map and graphical weather products.
4. A fully integrated Class III Electronic Flight Bag cockpit display has been developed and certified that allows TAPS and E-Turb Radar data to be displayed in a track up, ownship-centered format and overlaid with reflectivity, navigation, and flight plan information. This is the Integrated Turbulence Hazard Decision Aid for the Cockpit from Reference [18].
5. Ground and flight personnel have been fully trained in the features and functions of both the ground and cockpit displays.

7.2.4 Description of Proposed System Operations in a Non-Convective Environment

The non-convective (CAT) scenario begins at the airline dispatch office the day before the scheduled flight. Dispatchers and meteorologists are watching a developing southward bend of the polar jet that could affect operations the following day. TAPS reports from aircraft crossing the jet are showing occasional moderate turbulence near the boundaries of the jet and continuous light turbulence inside the jet. Flights are not being re-planned around the turbulence because the lateral and vertical extent of the jet make turbulence reroutes impractical. The TAPS data indicate that penetration of the jet will be a passenger comfort issue but will not be a safety issue if flight attendants are not allowed to offer cabin services while penetrating the jet.

An hour before flight the flight crew begins its preflight briefing. The dispatcher briefs that there is a possibility of CAT along the filed route and current TAPS reports are indicating mostly light with occasional moderate turbulence. The dispatcher shows the flight crew the lateral and vertical extent of the TAPS data to illustrate why a turbulence avoidance flight plan is not practical. The crew accepts the flight plan.

After takeoff the crew brings up the TAPS page on the Integrated Turbulence Display and activates the “Climb” preselect. Only scattered “light” icons are shown, as scaled for his aircraft, so the Captain turns off the seat belt sign and allows the cabin service to begin.

When the aircraft reaches its cruise altitude of 38,000 feet (FL 380) and approaches within 320 nautical miles of the edge of the jetstream, dense TAPS reports start showing up along an east-west line. The integrated display altitude filter is in the default “Norm” setting and the VPD is showing the turbulence icons at all altitudes shown in the display. The E-Turb Radar is showing no reflectivity in the region. The Captain briefs the flight attendants that cabin service will have to be stopped in about 30 minutes to prepare the cabin for turbulence.

The Captain sets the age filter to “120 min” and notices that the number of reports increases but the vertical and lateral boundaries of the turbulent region stay about the same. This spatial stability over a period of two hours verifies that the atmospheric phenomenon causing the turbulence is most likely a form of CAT. The east-west orientation and clear northern and southern edges of the now well-defined boundaries (due to the larger number of reports with the age filter at 120 min.) argues that the phenomenon is a jetstream rather than a mountain wave. The Captain sets the age filter back to “30 Min” to display only the most current data.

As the Captain watches the turbulence field develop he notices occasional moderates showing up in the green icons. To ensure that there is no hazard lurking in the data the Captain hits the “Flash” button and notices that a small red patch of color blinks within the multitude of green icons. The Captain now sets the severity filter to “Mod or Greater” and a number of moderate icons and one red icon are now clearly visible. The Captain checks the VPD and sees that the red icon is at his altitude and the plan view shows it is also on the inbound airway in his flight plan. The TAPS data is now indicating that the previously uncomfortable but safe ride into KDEN is now growing into a safety hazard as the jetstream strengthens. The fact that the scaling function is ON and the icon is red indicates that the turbulence field ahead could be a safety hazard for his aircraft.

Knowing that a climb over the turbulence is not an option due to the aircraft reaching the top of descent within the lateral boundaries of the turbulent field, and a lateral deviation around the jet is not an option without major rerouting including a diversion to another airport for fuel, the Captain looks to lower altitudes. He sets the altitude filter to "All" and notes that there are no moderate or severe icons shown below FL 330 in the VPD. He goes back to the severity filter and selects "Show All" and notes in the VPD that the green icons now visible stop at FL340 except for a few icons scattered at FL 330. He goes back to the preflight briefing package and notes that the KDEN temperature profile indicates that the tropopause is about FL 350. This would explain why the moderates and the one severe were near that altitude – these aircraft were flying in the mixing area at the bottom edge of the jet.

The Captain notes that by descending early to FL 300 he can avoid the turbulence field entirely and still meet his crossing restriction of FL 300 at LAA. The Captain requests and receives a clearance to a new cruise altitude of FL 300. The aircraft fuel consumption increases slightly at the lower altitude but the aircraft is no longer in harm's way and a major reroute or diversion is avoided.

7.2.5 Non-Normal / Rare normal Operations

No unique non/rare normal operations are expected for the proposed system. Hardware failures, such as communications link failures could affect the utility of the system temporarily, but these occur in today's system as well. Should the data link transmitting TAPS fail procedures would revert to today's verbal ride reports with all of the limitations inherent in that system.

Thorough training will be necessary to ensure that the cockpit display can be easily and quickly operated and interpreted by flight crews to avoid workload and display clutter issues.

8. Analysis of the Proposed System

This section provides an analysis of the benefits, limitations, advantages, disadvantages, and alternatives and trade-offs considered for the proposed system. This CONOPS has been written to help guide the process of integration and implementation of an integrated TAPS and E-Turb display within the cockpit of an aircraft. Integration and use of such a display should be simple and intuitive to reduce workload on the end user. A full evaluation of the proposed system entails the testing and refinement of concepts and features using a selected evaluation group of pilots, dispatchers, and ATC personnel. This process is now underway.

8.1 Summary of Improvements

The TAPS and the E-Turb Radar displayed within an aircraft cockpit provide a flight crew an enhancement of turbulence situational awareness previously unavailable to the users. Examples of how these operational capabilities can be employed are found in Section 7 of this document.

The automatic reporting of turbulence encounters as determined and transmitted by the TAPS enhances and augments the current method requiring user interaction. Current subjective reports, based on location and severity, are replaced by quantitative, graphical reports in the proposed system based on accurate information of g-loading and spatial location. The timely transmission of these reports to a ground station and back to the cockpit of relevant aircraft puts additional information into the user's mix of available products that previously have been late or unavailable. The transmission of reports is automatic, thereby cutting down the need of interaction between the reporting aircraft's crew, a ground controller, and the receiving aircraft's crew, thereby increasing efficiency and decreasing workload and communication chatter. The addition of TAPS information presented within a cockpit display will not eliminate any existing capabilities present within a commercial airliners' cockpit.

The addition of an Enhanced Turbulence Radar product overlay within the cockpit of an aircraft also adds to the situational awareness for a flight crew when the aircraft is within regions of convective turbulence. The current subjective inference of turbulence from reflectivity levels is replaced by a quantitative measure of the predicted turbulence level in regions of airspace within and up to 40 nautical miles of the aircraft. Scaling of the radar product to the current configuration of the aircraft makes the assessment of the potential threat accurate and meaningful to the user. Warning times of potential encounters increase with the use of the Enhanced Turbulence Radar, thereby giving the user additional time to warn cabin attendants and passengers of the forthcoming turbulence. The additional time also can provide the user the opportunity to maneuver the aircraft around potential regions if other collaborative sources and airline policies permit this. The addition of an Enhanced Turbulence Radar product presented within a cockpit display is intended to eliminate the current turbulence radar overlay provided to flight crews in Part 121 commercial aircraft, but will require additional refinements, testing, and acceptance before integration can be completed.

Most importantly, the Integrated Turbulence Hazard Decision Aid will improve flight crew situational awareness with regard to the location, altitude, and severity of turbulence that may affect their aircraft. This will be realized through the integration of TAPS, E-Turb, and other flight information on a single display.

8.2 Disadvantages and Limitations

The Turbulence Auto-PIREP System relies on the information from other aircrafts' turbulence encounters to help outline an assessment of the potential threat to the primary aircraft. Even though the sophistication of the scaling algorithms will eliminate ambiguities due to the reporting aircraft with the receiving aircraft, the lack of information due to the initial implementation of TAPS on aircraft will create "dead regions" within the reporting network. As TAPS becomes more widely deployed the "dead regions" where no TAPS-equipped aircraft are operating will diminish.

Current radar technology limits the range of the Enhanced Turbulence Radar to 40 nautical miles from the aircraft's radar antenna. Although this only provides several minutes of warning time at typical turbojet cruise speeds, this is still a significant advantage over no information whatsoever.

Training expected for use of an integrate turbulence hazard cockpit display is expected to be minimal. Any additional workload on the user will be minimized. Existing capabilities within the cockpit system will not be degraded, but enhanced by the addition of the TAPS and E-Turb Radar technology. Loss of efficiency is not expected within the cockpit environment with the inclusion of these technologies.

TAPS information presented on a navigation or display device without a VPD will require the user to interpret the symbology on a two-dimensional display and mentally construct a three dimensional image in order to gain an understanding of the potential or lack of threat to the aircraft.

The failure modes of the Turbulence Auto-PIREP System and Enhanced Turbulence Radar technology will need to be studied and the affordability and requirements for retrofitting aircraft with this technology will also require study. Standards that comply with existing mandates through ATC, FAA, and RTCA will need to be researched further and developed.

8.3 Alternatives and Trade-offs Considered

8.3.1 Alternatives

Alternatives to the proposed system include:

1. Continue using the current system.
2. Augment the current system by uplinking existing ground-based turbulence-related products.
3. Develop alternative new products.

8.3.2 Continue Using Current System

Continuing to use the current system is not a reasonable alternative because accepting the status quo with regard to turbulence-related injuries, airframe fatigue, maintenance and inspection costs, and losses of efficiency due to non-optimal trajectories are unnecessary. The system proposed in this document is one example of how existing technologies can be applied to mitigate, if not eliminate, many of the adverse consequences of turbulence. Other alternatives may exist, as discussed in the next two subsections.

8.3.3 Augment Current System with Existing Products

This alternative is really just an extension of an evolution currently underway to integrate graphical weather products into the cockpit. While such graphical products are not common in air carrier aircraft, many business jets and some higher end general aviation aircraft are already benefiting from commercially available avionics systems that bring limited graphical weather products into the cockpit. The primary limitation on this alternative is that the weather products currently available still do not give the flight crew a good 4-dimensional image of the turbulence field ahead of the aircraft. In essence this alternative is bringing the weather products discussed in Section 3.2, with all of their limitations, into the cockpit.

Examples of products that could be uplinked to the cockpit to augment the current system include:

- NEXRAD images showing reflectivity (composite and base), animation loops, cell tops and motion.
- Large-scale synoptic charts showing regions of high and low pressure, frontal regions, isobars, etc.
- Visible and infrared satellite images showing cloud tops and cloud temperatures.
- Graphical plots of AIRMETS, SIGMETS, and PIREPS.
- Graphical Turbulence Guidance plots.
- Honeywell's Weather Information Network (WINN).
- XM Satellite Weather.
- ARINC's Graphic/Text Weather Service (G/TWS).

Note that, except for PIREPS, these products do not depict actual turbulence per se, but only indications that the conditions may be present to generate significant turbulence; jet stream activity, convection, etc. PIREPS do actually depict turbulence encounters, but these reports suffer from the low data density, timeliness, and subjectivity limitations discussed in Section 3.2.

Flight crews would need to continue to infer the existence of turbulence from these products. Similar to the proposed system, flight crews would need to integrate these products with airborne weather radar reflectivity and turbulence indications. Unlike the proposed system, these weather products may not conveniently overlay such weather radar data, making interpretation and integration of the data difficult.

These weather products would be generally collected at data centers on the ground from a variety of government and commercial sources, and transmitted to the cockpit of subscribing aircraft. The receiving aircraft, in order to take advantage of the data transmissions, would need to have the necessary communications equipment with the necessary bandwidth, and appropriate display hardware and software. These requirements may be difficult to satisfy in some circumstances.

8.3.4 Develop Alternative New Products

The final alternative to the proposed system is to continue to develop alternative new technologies that actually measure, or predict with high levels of confidence, the actual existence of atmospheric turbulence. Two examples of such systems might include:

- LIDAR.
- The National Center for Atmospheric Research (NCAR) Eddy Dissipation Rate Measurement Algorithm.

Similar to an aircraft's onboard radar that uses pulsed radio frequency energy to make the measurements of the atmosphere, LIDAR uses pulsed laser energy. Both technologies rely on particulate matter in the air reflecting the energy to make the measurements. The frequency shift caused by the movement of these particles is used to estimate the velocity of the surrounding atmosphere. Unlike the weather radar, the LIDAR can use much smaller particulates, which are invisible to the naked eye. This makes the LIDAR an intriguing option because it is able to make measurements in "clear air"; however, the LIDAR technology is much less mature than airborne weather radar and it is still very expensive. Also, LIDAR technology has not yet demonstrated an ability to make reliable turbulence measurements at cruise altitudes. As this technology matures, it will offer complementary capabilities to the TAPS system for detecting turbulence in clear air situations.

EDR is a parameter related to the fluid properties of the atmosphere, and the algorithm developed by NCAR is designed to report this value from suitably equipped aircraft, regardless of its value, at intervals of one minute. The primary limitation with EDR is that it is not scaled to predict the hazard to individual aircraft and therefore requires inference on the part of the crew to estimate the level of hazard. This process is neither simple nor can it always be accomplished with data available from EDR. However, like LIDAR, the information that will come from the EDR system as it matures will complement the TAPS element of the proposed system to further improve the ability of the overall system to measure and predict atmospheric turbulence with enough lead time and reliability to allow safe and efficient operations in regions of turbulent air.

9. Conclusions and Recommendations

Aircraft encounters with turbulence are the leading cause of injuries in the airline industry and result in significant human, operational, and maintenance costs to the airline community each year. A large contributor to the above injuries and costs is that flight crews do not have sufficient situational awareness of the location and severity of potential turbulence hazards to their aircraft's configuration. Improvement to a pilots' situational awareness of turbulence hazards will be accomplished by developing an integrated, graphical cockpit display of turbulence hazard information scaled to their specific aircraft. This proposed Decision Aid will remove the need for inference that is required to interpret current turbulence information. With better knowledge of turbulence hazards' severity and location, pilots will be able to avoid turbulence encounters or prepare for them by having all occupants seated with seatbelts on, thereby avoiding injuries.

The Integrated Turbulence Hazard Decision Aid for the Cockpit is intended as a medium for advisory information concerning the location and intensity of turbulence, enabling flight crews to conduct a safer and potentially more efficient operation, from preflight to touchdown. Through the interaction with the pilot subject matter experts and the development of the CONOPS for the cockpit display, it has been shown that there is a need of and applications for a cockpit tool to provide situational awareness of turbulence hazards to the flight crew. It has also been shown that the feasibility of fusing objective turbulence hazard information from disparate sources (TAPS and the Enhanced Turbulence Radar) and displaying the information in a consistent and meaningful manner is possible. These CONOPS also show the need for and desire of flight crews for a tool that will provide them with improved situational awareness of turbulence hazards to their aircraft and accompanying software that will enable them to manipulate the data to assist them in making informed decisions regarding operation in and around turbulence.

This CONOPS is intended to be a living document throughout the development of the Integrated Turbulence Hazard Decision Aid for the Cockpit. It is envisioned that this cockpit display system will provide pilots with improved turbulence hazard information allowing them to operate more efficiently and safely. Significant reductions in flight delays and cancellations, fuel waste, and costs associated with injuries due to turbulence are expected to be major commercial drivers for this system.

Further development and research on the capabilities, impact, and benefits of an integration of a cockpit system presenting both TAPS and E-Turb information should continue.

The primary market for this display is all Part 121 carriers (both domestic and international) with the secondary market moving towards business and general aviation aircraft. When the goals of the research and development of the display are met, as stated within this CONOPS, this cockpit display and underlying system will directly contribute to the stated national goal of NASA's Aviation Safety and Security Program of a 50% reduction in aviation accidents. This work will continue to be completely aligned with other Turbulence Prediction and Warning System efforts in NASA and the FAA.

10. Appendices

10.1 Appendix A – Acronyms and Abbreviations

ACARS	ARINC Communications Addressing and Reporting System
ADDS	Aviation Digital Data Service
AIAA	American Institute for Aeronautics and Astronautics
ARINC	Aeronautical Radio, Incorporated
ARTCC	Air Route Traffic Control Center
ATC	Air Traffic Control
AIRMET	Airman's Meteorological Advisory
AvSSP	Aviation Safety and Security Program
CAT	Clear Air Turbulence
CDM	Collaborative Decision Making
CONOPS	Concept of Operations
DUATS	Direct User Access Terminal Service
EDR	Eddy Dissipation Rate
EFB	Electronic Flight Bag
EFIS	Electronic Flight Instrument System
EHSI	Electronic Horizontal Situation Indicator
E-Turb	Enhanced Turbulence Radar
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
FIS-B	Flight Information Service - Broadcast
FL	Flight Level
G/TWS	Graphic/Text Weather Service
GPWS	Ground Proximity Warning System
GTG	Graphical Turbulence Guidance
IEEE	Institute of Electrical and Electronic Engineers
IFR	Instrument Flight Rules
LIDAR	Light Detection and Ranging
MFD	Multifunction Displays
MOPS	Minimum Operational Performance Standards
NAS	National Airspace System

NASA	National Aeronautics and Space Administration
NEXRAD	Next-generation Radar
NCAR	National Center for Atmospheric Research
NOAA	National Oceanic and Atmospheric Association
NWS	National Weather Service
PIREP	Pilot Report(s)
RADAR	Radio Detection and Ranging
RTCA	Radio Technical Commission for Aeronautics
SBIR	Small Business Innovative Research
SIGMET	Significant Meteorological Advisory
STC	Supplemental Type Certificate
TAPOS	Turbulence Auto-PIREP Operational Simulation
TAPS	Turbulence Auto-PIREP System
TAWS	Terrain Awareness and Warning System
TCAS	Traffic Alert and Collision Avoidance System
TMU	Traffic Management Unit
TPAWS	Turbulence Prediction and Warning System
TSO	Technical Standard Order
VPD	Vertical Profile Display
WINN	Weather Information Network