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# Enhanced Turbulence (E-Turb) Hazard Prediction Algorithm

## An Overview

**ATR-2007-17WP13**

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# 1 Introduction

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Ever had a significantly bumpy ride during air travel or experienced a sudden heave in your stomach as an aircraft drops in flight without warning?

Nearly every day, turbulence has an adverse effect on aircraft operations and capacity of the National Air Space (NAS). In fact, 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. The cost of these injuries, operational inefficiencies, and unscheduled maintenance to the airline industry is over \$150 million per year. A Department of Transportation study even estimates that this cost could be in the billions of dollars. Both NASA and the FAA have goals to reduce turbulence injuries, but how can these turbulence injuries, operational inefficiencies, and unscheduled maintenance be reduced?

## 2 The Problem

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A large contributing factor to the injuries and unplanned costs caused by turbulence encounters is that flight crews do not have sufficient awareness of the location and severity of the turbulence hazards. Upwards of 80% of aircraft turbulence encounters occur in and around convective activity (thunderstorms, cold and warm fronts).

Most commercial aircraft currently possess an airborne weather radar, which they use to detect convective weather activity based on reflectivity. Many of these weather radars have a turbulence mode function designed to display regions of turbulence. The problem is that, due to the currently implemented processing techniques used to identify the turbulence, this turbulence function produces numerous false turbulence detections and sometimes does not even identify turbulence that actually exists.

These false and missed detections have resulted in many pilots not trusting the turbulence function. In fact, many pilots have stated that they just leave the turbulence function off. This results in the aircrew receiving no turbulence warning information from the onboard weather radar. Instead they rely on attempting to remain clear of the stronger radar reflectivity returns to avoid the worst of the convective turbulence. Research has shown that the location and severity of turbulence do not correlate with reflectivity, so this method of turbulence avoidance is also inaccurate and potentially both unsafe and inefficient to flight operations.

## 3 The Need

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Since so many turbulence accidents occur in and around convection where airborne Doppler weather radars can make measurements, there is a need to provide pilots with reliable predictions of turbulence severity. These predictions should reflect the turbulence hazard to their specific aircraft at its current flight conditions and should be presented far enough ahead to allow some action to be initiated. With enough forewarning, the pilots may be able to avoid the encounter or at a minimum prepare the cabin and its occupants. Also, in order to increase pilots' confidence in the detections, it is important to reduce the number of false detections ("nuisance detections") and the missed detections which plague the current system.

AeroTech's Enhanced Turbulence (E-Turb) Hazard Prediction Algorithm for airborne weather radars goes a long way toward addressing these needs as described below.

## 4 What is the E-Turb Radar Hazard Prediction Algorithm?

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Recognizing the need to provide more reliable and relevant turbulence information to the cockpit, AeroTech Research (ATR) developed the Enhanced Turbulence (E-Turb) Hazard Prediction Algorithm for aircraft weather radars.

The current turbulence mode function in weather radars relies on analyzing the measurement processed from the radar returns. The measurement, known as the “second moment”, is the measure of the second spectral moment estimate from the weather radar signal processor providing a reflectivity-weighted variance of the radial velocities. The overall result is a measure of the shear or turbulence within the resolution volume.<sup>1</sup>

A small second moment indicates that most of the particulates (e.g., raindrops) are moving with the same speed and direction – i.e., smooth air. A large second moment indicates a large variation in the particulates’ velocities – i.e., turbulence. In current radars, if the second moment value is greater than a defined threshold value, a region of magenta is shown on the display to indicate an area of potential turbulence. The problem with this technique is that the turbulence metric does not differentiate between aircraft types or various configurations – 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.”<sup>2</sup>

AeroTech’s E-Turb Hazard Prediction Algorithm, when implemented as software in Predictive Wind Shear radar systems (Figure 1), scales the radar second moment based on the aircraft’s current configuration (type, weight, altitude, speed, etc.) and calculates real-time estimates of predicted g-load (in the form of  $\sigma_{An}$ )<sup>3</sup>. These predicted g-loads are then provided to the radar display processor and can be translated, using various thresholds, onto the display as multiple levels of turbulence, scaled to the aircraft’s configuration and flight conditions. From these indications the aircrew can easily assess the impact that turbulence will have on their aircraft.

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<sup>1</sup> Doviak, Richard J. and Znić, Dušan S. *Doppler Radar and Weather Observations*, 2<sup>nd</sup> Edition. Dover Publications, Inc., Mineola, New York, 2006

<sup>2</sup> Croft, John, “*Truer Pictures of Turbulence*,” *Aerospace America*, April 2005, pg. 36.

<sup>3</sup>  $\sigma_{An}$  is a running 5-second windowed root mean square (RMS) of the vertical acceleration that can be related to and used as a surrogate for the peak accelerations (loads) experienced by an aircraft. The  $\sigma_{An}$  metric was evaluated and verified using historical flight data from NASA flight tests and National Transportation Safety Board (NTSB) accident investigations.

Figure 1

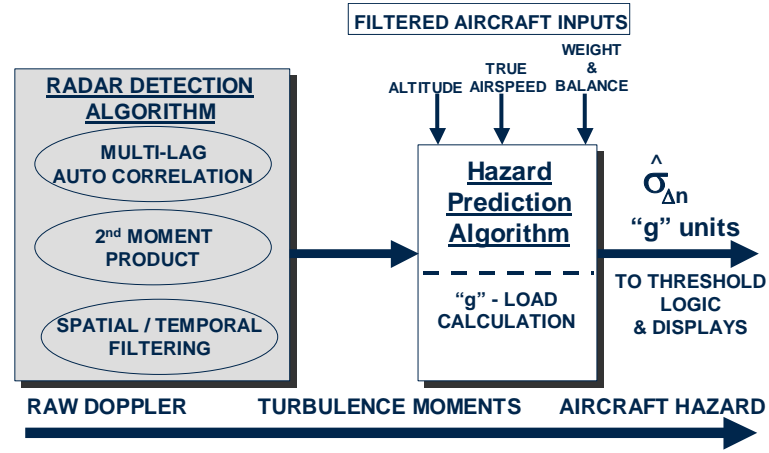


Table 1 shows the real-time inputs and outputs of the Hazard Prediction Algorithm. The inputs to the algorithm come directly from the 429 bus or the airborne weather radar itself.

Table 1

Algorithm Inputs	Algorithm Outputs
<ul style="list-style-type: none"> <li>- Aircraft Gross Weight</li> <li>- Aircraft True Airspeed</li> <li>- Aircraft Altitude (baro-corrected)</li> <li>- Radar derived Second Moment or <math>\sigma_{og}</math></li> </ul>	<ul style="list-style-type: none"> <li>- <math>\sigma_{\Delta n}</math> (RMS of Normal Load [predicted g-load])</li> </ul>

## 5 Some Examples of E-Turb Radar Displays

The following figures show some examples of the E-Turb Radar display that can be produced using the predicted g-load output from the AeroTech Hazard Prediction Algorithm and established thresholds for the levels of turbulence to be displayed. The examples are taken from actual recordings of the E-Turb Radar used in the NASA Turbulence Prediction and Warning System (TPAWS) program In-Service Evaluation with Rockwell Collins and Delta Air Lines. Somewhat different from the current turbulence mode magenta display available in commercial radars is Rockwell Collins' display of two-levels of turbulence hazard: speckled magenta representing a region of light turbulence and solid magenta representing a region of moderate or greater turbulence (the type of magenta displayed is based on the predicted g-load and the threshold values). The green, yellow, and red regions are the standard display of reflectivity measured by the airborne weather radar. In the examples, the dotted line represents the actual flight path of the aircraft through the region.

Figure 2

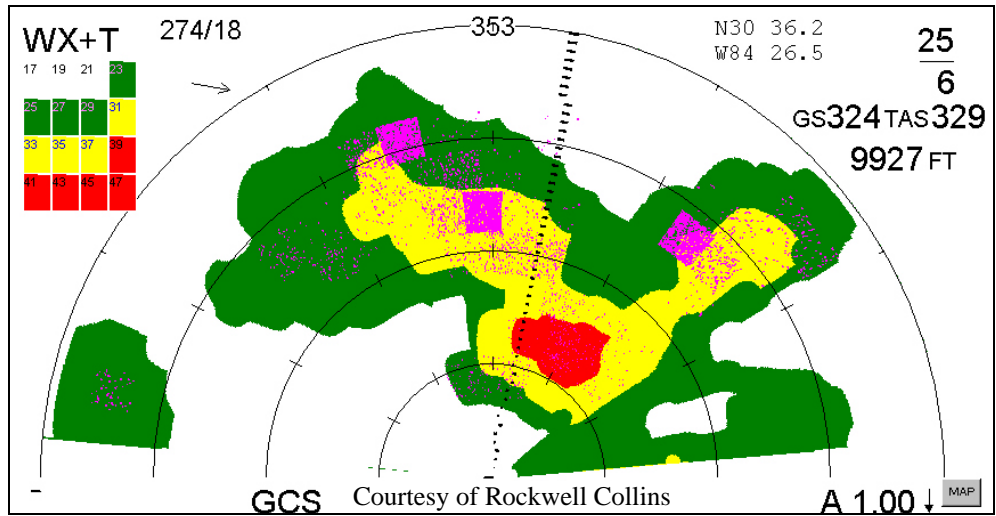


Figure 3

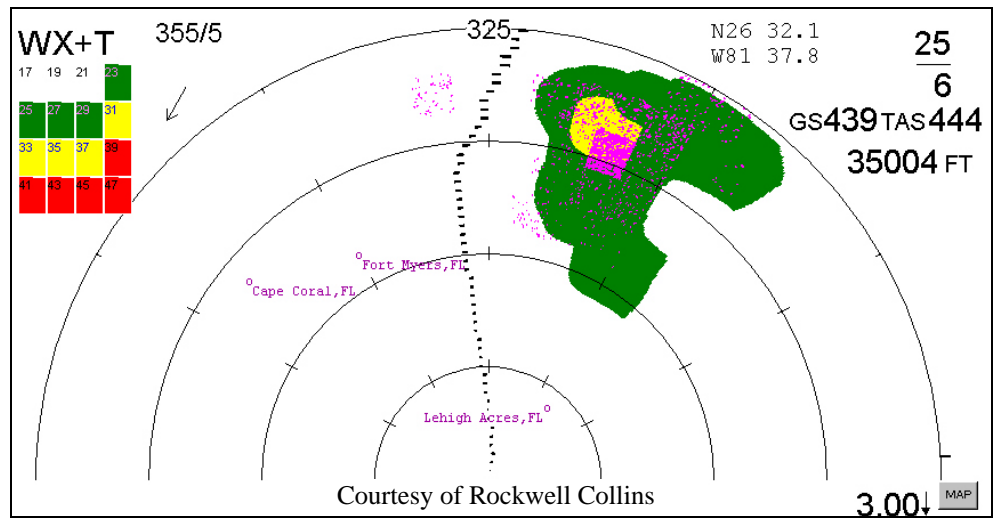


Figure 4

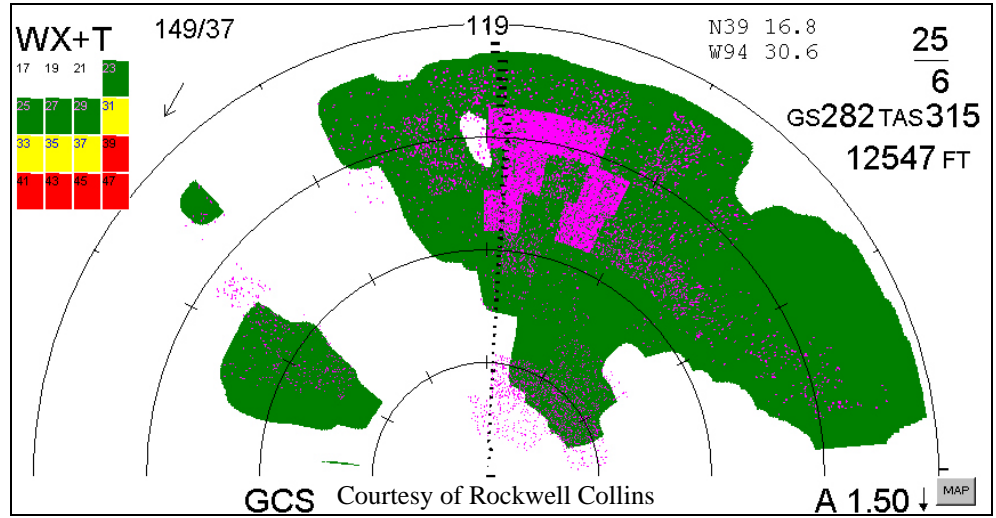
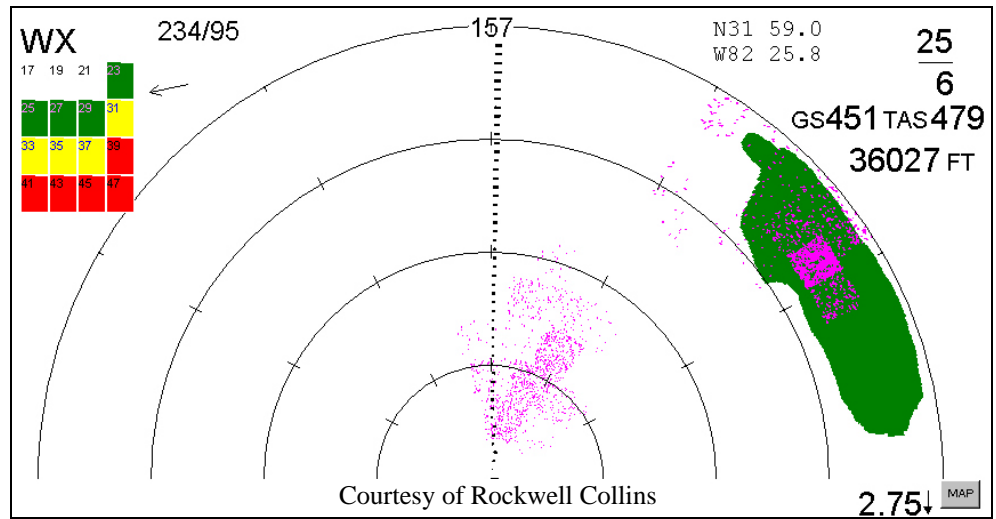


Figure 5



## 6 E-Turb Radar Certification

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The E-Turb Radar Hazard Prediction Algorithm is currently considered at Technology Readiness Level 7: system prototype has been demonstrated in an operational environment.<sup>4</sup> The algorithm completed Level 7 through tests onboard the NASA B757-200 research aircraft (FY2000-2003) and since August 2004, the E-Turb Hazard Prediction Algorithm has been operating successfully within a Rockwell Collins WXR-2100 Multiscan™ Radar, which is onboard a Delta Air Lines B737-800 aircraft.<sup>5</sup> The algorithm and E-Turb Radar have logged over 6,000 continuous flight hours of operation.

The FAA is currently developing Minimum Operating Performance Standards (MOPS) for Enhanced Turbulence Radars. These MOPS will be incorporated into a Technical Standard Order (TSO) for Enhanced Turbulence equipped weather radars. The performance capabilities of AeroTech's E-Turb Hazard Prediction Algorithm that were documented during the evaluation in the Rockwell Collins's WXR-2100 exceed the minimum requirement of the MOPS being developed.

The Hazard Prediction Algorithm and the display threshold criteria must be installed into the software of a pulsed Doppler capable weather radar. The Hazard Prediction Algorithm must be able to, in real-time, access aircraft ship system information including aircraft altitude, weight, and true airspeed. If two levels of magenta are required, the radar display generation program would require modification in order to display both speckled and solid magenta.

## 7 Benefits of E-Turb Radar

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The Enhanced Turbulence Radar with AeroTech's Hazard Prediction Algorithm benefits airlines, flight crews, flight attendants, passengers, the air carrier, and Air Traffic Control (ATC) in several ways:

### 7.1 Safety

- Reduced injuries to flight attendants and passengers due to enhanced turbulence awareness by flight crews, avoidance through flight deviations, and turbulence preparation (e.g., passengers and flight attendants seated with seatbelts fastened and loose items secured).
- Ability to accurately detect turbulence hazards to the aircraft in areas of low reflectivity (below the threshold for reflectivity display on current weather radar).

### 7.2 Operations

Increased situational awareness of turbulence hazards in the National Air Space for pilots. This situational awareness:

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<sup>4</sup> DODI 5000.2 Acquisition System Guidebook, DOD (2004).

<sup>5</sup> "In-Service Evaluation of the Turbulence Auto-PIREP System and Enhanced Turbulence Radar Technologies," J. B. Prince, B. Buck, P. A. Robinson, and T. Ryan, NASA/CR-2007-214887, July 2007.

- Enhances pilots' ability to route aircraft around regions of potentially hazardous turbulence.
- Enables more judicious use of airspace and can lead to potential savings in fuel and reductions in flight delays.
- Provides ATC a better equipped pathfinder aircraft for airspace previously closed to severe weather.

### 7.3 Maintenance

- Potentially less unscheduled maintenance, fewer severe loads inspections, less overall stress on the aircraft structure, and longer airframe life due to ability to avoid turbulence.

## 8 Summary

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Hazardous turbulence continues to take a significant toll on aircraft, the airlines, passengers, flight crew, and the efficient use/capacity of the air space. NASA has recognized that just telling passengers to buckle up and maintaining the current method of providing turbulence information to flight crews will not reduce the injuries to flight crews and passengers, nor increase efficiency in the use of air space.

NASA's Associate Administrator's March 16, 2005 testimony to Congress reaffirmed the need to adopt a solution to this issue.

*Protecting air travelers and the public is the focus of the Aviation Safety and Security Program which develops technologies for both National Aviation System and aircraft that are aimed at preventing ...unintentional events that could cause damage, harm, and loss of life; and minimizing the consequences when these types of events occur. Aviation safety focuses on technologies that can reduce aircraft accident rates and reduce aviation injuries and fatalities.*

*Turbulence is a leading cause of in-flight injuries and costs the airlines at least \$100 M per year. To address this issue, AvSSP has designed and is performing in-service evaluations of a turbulence prediction and warning system with a major airline that gives flight crews the advanced warning needed to avoid turbulence or advise passengers to sit down and buckle up to avoid injury.....*

AeroTech's Enhanced Turbulence Hazard Prediction Algorithm and methodology will enhance pilots' situational awareness of hazardous turbulence in and around convection, result in a reduction in turbulence related injuries and maintenance costs, extend aircraft service life, improve operational efficiency, and enhance the efficient use of airspace. Because the algorithms are not limited to certain types of aircraft, the system can be integrated into nearly any aircraft with a PWS radar. With the integration of the Enhanced Turbulence system, aviation safety and operations efficiency will take an important step forward in the 21<sup>st</sup> century. AeroTech's E-Turb Hazard Prediction Algorithm is a proven product that is currently flying and has flown over 6,000 hours on a Rockwell Collins WXR-2100 Multiscan<sup>TM</sup> radar onboard a Delta Air Lines B737-800 in revenue operations. E-Turb Radar could be in your aircraft and enhancing your operations and safety.

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