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An evaluation of real-time aviation turbulence metrics

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San Jose State University

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**AN EVALUATION OF REAL-TIME AVIATION
TURBULENCE METRICS**

A Thesis

Presented to

The Faculty of the Department of Meteorology

San Jose State University

In Partial Fulfillment

of the Requirement for the Degree

Master of Science

by

William Chan

May, 1995

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A handwritten signature in black ink, appearing to read "P. F. Lester", written over a horizontal line.

Dr. Peter F. Lester

A handwritten signature in black ink, appearing to read "Ralph E. Bach, Jr.", written over a horizontal line.

Dr. Ralph E. Bach, Jr.

A handwritten signature in black ink, appearing to read "Douglas M. Sinton", written over a horizontal line.

Dr. Douglas M. Sinton

APPROVED FOR THE UNIVERSITY

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ABSTRACT

AN EVALUATION OF REAL-TIME AVIATION TURBULENCE METRICS

by William Chan

This thesis addresses the problem of aviation turbulence and proposes a method to minimize severe turbulence encounters based on direct turbulence measurements (metrics) by commercial aircraft. An ideal onboard metric for this purpose should be quantitative, aircraft independent, maneuver independent, and comprehensive. This study selected and tested six practical turbulence metrics.

A review of the literature revealed four appropriate candidate metrics: vertical loads, airspeed fluctuations, derived gust velocity, and eddy dissipation rate. Two additional metrics related to the turbulent kinetic energy (TKE) were developed during the course of this study. Wingrove turbulent kinetic energy was selected as the most appropriate turbulence metric because it has the most characteristics of an ideal turbulence metric. The other five metrics, vertical loads, airspeed fluctuations, derived gust velocity, eddy dissipation rate, and Wingrove parameter have a number of shortcomings.

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LIST OF SYMBOLS

a_n	Vertical load.
a_x	Aircraft body axis acceleration along body fixed x axis.
a_y	Aircraft body axis acceleration along body fixed y axis.
a_z	Aircraft body axis acceleration along body fixed z axis.
c	Kolomogorov's constant for the inertial subrange.
$\bar{c}$	Mean geometric chord.
f_c	Filter cutoff frequency.
f_r	Filter rolloff frequency.
g	Acceleration due to gravity.
h	An axis on Earth coordinate system with positive h pointing vertical.
$\dot{h}$	Inertial velocity along h axis.
$\ddot{h}$	Inertial acceleration along h axis.
i	Data point index.
k	Wavenumber.
k_{lo}	Low wavenumber limit.
k_{hi}	High wavenumber limit.
K_g	Gust alleviation factor.
m	Finite wing lift curve slope (1/rad).
N	Number of data points in a ten second period.
n	Total number of data points.
S	Wing area.
TKE_{wi}	Wingrove turbulent kinetic energy per unit mass.
U_{de}	Derived gust velocity.
u	Northward wind speed.
V_e	Equivalent airspeed.
V_t	True airspeed.
V_{xy}	Horizontal aircraft velocity.
v	Eastward wind speed.
W	Aircraft weight.
Wi	Wingrove parameter.
w_{xy}	Horizontal wind velocity.
w_h	Vertical wind speed.
x	An axis on Earth coordinate system with positive x pointing true north.
$\dot{x}$	Inertial velocity along x axis.
$\ddot{x}$	Inertial acceleration along x axis.

LIST OF SYMBOLS (Continued)

x'	An axis on the aircraft coordinate system along the aircraft body axis.
y	An axis on Earth coordinate system with positive y pointing east.
$\dot{y}$	Inertial velocity along y axis.
$\ddot{y}$	Inertial acceleration along y axis.
y'	An axis on the aircraft coordinate system perpendicular to the aircraft body axis.
z	An axis on the aircraft coordinate system with positive z upwards.
z'	An axis on the aircraft coordinate system with positive z' downwards.
ε	Eddy dissipation rate.
$\Delta\sigma^2$	Variance of airspeed or windspeed under the PSD curve.
Δt	Time increment between recorded data points.
λ	Wavelength.
μ_g	Aircraft mass ratio.
ρ_0	Sea level air density.
ρ	Air density at flight altitude.
$\phi(k)$	Power spectral density.
θ	Aircraft body axis Euler angle, pitch.
ψ	Aircraft body axis Euler angle, heading.
ϕ	Aircraft body axis Euler angle, roll.
θ_w	Wind axis Euler angle, pitch.
ψ_w	Wind axis Euler angle, heading.
$()'$	High-pass filtering.
$()^*$	Deviation from a mean value.
$\overline{()}$	Average or mean.

I. INTRODUCTION

A. BACKGROUND

Turbulence was already a problem for pilots many years before the Wright Brother's first flight. For example, in 1896 Otto Lillienthal was fatally injured when his glider pitched up and stalled due to a turbulent gust (Lieurance, 1969). Early in the history of aircraft development, it became apparent that designers needed quantitative information about the statistical and physical characteristics of turbulence. Organized research began about 1915 when the National Advisory Committee For Aeronautics (NACA) published its very first report "Theory of an Aeroplane Encountering Gusts" (Wilson, 1915).

In 1924, NACA was one of the first agencies to use accelerometers to quantify the turbulence experienced by aircraft and airships (Burgess, 1924; Doolittle, 1924). Aviation turbulence research by NACA and other agencies continued through World War II and into the late 1950's (e.g., Binckley and Funk, 1937; Rhode and Donely, 1944; Byers and Braham, 1949; McDougal et al., 1953; Holmboe and Klieforth, 1957; Press and Steiner, 1958; Endlich, 1964). At the same time, a number of turbulence studies were also being conducted outside of the United States (e.g., Yudin, 1946; Hislop, 1951; Alaka, 1960; Reiter, 1962). In the late 1960's, the United States Air Force sponsored the Critical Atmospheric Turbulence (ALLCAT) program which was conducted to obtain a compre-

hensive sample of atmospheric turbulence data between sea level and 70,000 feet. Data sampling was concentrated in regions of clear air turbulence (CAT). The data were primarily used to establish gust design criteria for aerospace vehicles (Loving, 1969).

In the 1980's, the National Aeronautics and Space Administration (NASA) conducted the Measurement of Atmospheric Turbulence (MAT) program. Its goal was also the acquisition of atmospheric data for the improvement of aircraft design. Data from instrumented research aircraft were used to determine turbulence power spectra under a variety of meteorological conditions in the boundary layer, jet stream, mountain waves, and (in contrast to ALLCAT) in thunderstorms. Research flights were conducted over an altitude range from near sea level to about 65,000 feet (Murrow, 1986).

In conjunction with the efforts to quantify turbulence for aircraft design, there has been extensive work in turbulence avoidance. This effort has been concentrated in three primary areas: forecasting, remote sensing, and direct turbulence measurements.

Early research to improve forecasting of turbulence identified synoptic and mesoscale wind, temperature and clouds associated with turbulence (e.g., George, 1960; Endlich, 1964; Reiter and Nania, 1964; Vinnechenko et al., 1980; Ellrod, 1985). Together with sparse, qualitative pilot reports, pattern identification techniques have been the foundation of short period turbulence forecasting for many years. For larger periods (6-12 hours)

turbulence forecasting using numerical weather prediction models has also been explored. Although model resolution is improving, infrequent, qualitative observations, poor communications, and large distances between observation sites do not provide adequate input data required for precise turbulence forecasts (Hopkins, 1977; Lester, 1993a). It is clear that for turbulence forecasts to improve, observations need to be enhanced both spatially and temporally in order to resolve the microscale features of turbulence (Hopkins, 1977).

Given the imprecision of forecasts, the attention of engineers and scientists has focused on the development of remote sensing devices that will allow detection and subsequent avoidance of turbulence. The ideal sensor should be capable of detecting all significant turbulence in the path of the aircraft. It should detect turbulence far enough ahead of the aircraft to allow necessary course changes. Current sensors include infrared radiometers, doppler RADAR, and doppler LIDAR. Radiometers rely on thermal differences in the atmosphere to infer turbulence which may not always be present resulting in missed turbulence events or false alarms (Lenschow, 1986). Doppler RADAR is being used on-board aircraft to detect turbulence; however, airborne radar has insufficient power to detect turbulence in the absence of precipitation particles (Lester, 1993). More success has been found in the development of doppler RADAR sensors to detect downbursts (Staton, 1994).

Doppler LIDAR has a shorter range than RADAR (it cannot penetrate clouds) but has a higher image resolution (Lenschow, 1986). However, LIDAR is not useful in regions where aerosols or cloud particles are absent. These conditions are common at the high altitudes where CAT is normally encountered. Research on an onboard LIDAR sensor for clear air turbulence (CAT) continues at NASA-Dryden (Bogue, 1994). Because of current shortcomings in the available airborne sensors and in turbulence forecasts, pilot reports (PIREP) of turbulence intensity will remain the primary data source for turbulence avoidance.

Standard PIREPs of turbulence intensity are based on the International Civil Aviation Organization (ICAO) criteria shown in Table I.1. These turbulence intensity observations are subsequently relayed via voice communication to air traffic control (Pocock, 1980).

Although the turbulence criteria in Table I.1 have been used for many years, their application has some serious problems. They are subjective and aircraft dependent. The subjectivity arises because reports are based on an individual pilot's interpretation of events. Also, in some turbulence cases, the pilot or autopilot will attempt to maneuver the aircraft through the turbulence region. This maneuvering may actually change the severity of the turbulence encounter. Additionally, turbulence reports are relayed at the aircrew's convenience often affecting timeliness of the report.

TURBULENCE REPORTING CRITERIA TABLE			
Intensity	Aircraft Reaction	Reaction Inside Aircraft	Reporting Term-Definition
<u>Light</u>	Turbulence that momentarily causes slight, erratic changes in altitude and/or attitude (pitch, roll, yaw). Report as <u>Light Turbulence</u> .* or Turbulence that causes slight, rapid and somewhat rhythmic bumpiness without appreciable changes in altitude or attitude. Report as <u>Light Chop</u> .	Occupants may feel a slight strain against seat belts or shoulder straps. Unsecured objects may be displaced slightly. Food service may be conducted and little or no difficulty is encountered in walking.	Occasional-Less than 1/3 of the time. Intermittent-1/3 to 2/3. Continuous-More than 2/3.
<u>Moderate</u>	Turbulence that is similar to Light Turbulence but of greater intensity. Changes in altitude and/or attitude occur but the aircraft remains in positive control at all times. It usually causes variations in indicated airspeed. Report as <u>Moderate Turbulence</u> .* or Turbulence that is similar to Light Chop but of greater intensity. It causes rapid bumps or jolts without appreciable changes in aircraft altitude or attitude. Report as <u>Moderate Chop</u> .	Occupants feel definite strains against seat belts or shoulder straps. Unsecured objects are dislodged. Food service and walking are difficult.	<u>NOTE:</u> 1. Pilots should report location(s), time (UTC), intensity, whether in or near clouds, altitude, type of aircraft and, when applicable, duration of turbulence. 2. Duration may be based on time between two locations or over a single location. All locations should be readily identifiable.
<u>Severe</u>	Turbulence that causes large abrupt changes in altitude and/or attitude. It usually causes large variations in indicated airspeed. Aircraft may be momentarily out of control. Report as <u>Severe Turbulence</u> .*	Occupants are forced violently against seat belts or shoulder straps. Unsecured objects are tossed about. Food service and walking are impossible.	<u>EXAMPLES:</u> a. Over Omaha, 1232Z, Moderate Turbulence, in cloud, Flight Level 310, B707. b. From 50 miles south of Albuquerque to 30 miles north of Phoenix, 1210Z to 1250Z, occasional Moderate Chop, Flight Level 330, DC8.
<u>Extreme</u>	Turbulence in which the aircraft is violently tossed about and is practically impossible to control. It may cause structural damage. Report as <u>Extreme Turbulence</u> .*		
* High level turbulence (normally above 15,000 feet ASL) not associated with cumuliform cloudiness, including thunderstorms, should be reported as CAT (Clear Air Turbulence) preceded by the appropriate intensity, or light or moderate chop.			

Table I.1. ICAO turbulence criteria. Standard turbulence intensity symbols are on the left (Lester, 1993).

In addition to the subjectivity of the application of the criteria in Table I.1, the reaction of an aircraft depends on the aircraft design and airspeed. Reports of turbulence will vary from aircraft to aircraft because turbulence of a given magnitude produces a more noticeable effect on a small, light-weight aircraft than on large transports due to a different wing loading. Another shortcoming with the data in Table I.1 is that the criteria do not base turbulence intensity on the phase of flight such as takeoff, cruise and landing. Due to the proximity of the aircraft to the ground, a light turbulence encounter during takeoff or landing is potentially more hazardous than light turbulence encountered during high altitude cruise.

Despite the long history of experimental, theoretical, and practical studies, turbulence continues to be a serious hazard for aircraft nearly 100 years after Lillenthal's death. The most dramatic evidence of this problem are accidents due to unexpected turbulence. For example, between the years of 1964 and 1975, 183 (25%) of 729 US air carrier accidents were turbulence-related (Etkin, 1981). From 1981 to 1984, turbulence contributed to 24% of all accidents involving large commercial carriers and 54% of all weather-related accidents (McLean, 1986). In addition to the obvious impact of aircraft accidents, turbulence has some more subtle yet important, impacts on aircraft operations. These include increased costs due to late arrivals and inflight diversions, passenger discomfort and crew fatigue, and inflight injuries (Redington, 1985; Wingrove, 1987; Ellrod, 1993).

Until turbulence forecasts become more precise and/or onboard remote sensors become more dependable, improvements in turbulence avoidance can only be found in better and more frequent inflight turbulence measurements. As noted above, there is much room for improvement in the subjective and quantitative turbulence reporting system currently in use. The development of objective, quantitative turbulence measurements is not a new idea. In 1964, MacCready discussed the use of a real-time turbulence severity index that not only was objective and quantitative, but also was independent of aircraft type. Several other such measures have been previously developed, but they have been used strictly for research or aircraft design applications. The technology now exists so that many of these turbulence measurements can be computed objectively in real-time from available aircraft data (Wingrove et al., 1989). In addition to improvements in onboard measurements of turbulence, technology has also progressed such that rapid dissemination of turbulence data is now possible. A prime example of a modern communications system capable of transmitting real-time turbulence measurements to other pilots, air traffic controllers and forecasters is the Meteorological Data Collection and Reporting System (MDCRS).

MDCRS is currently able to collect, decode, store and disseminate aircraft meteorological information through Aircraft Communication, Addressing and Reporting System (ACARS) (Martin et al., 1993). ACARS is a Very High Frequency (VHF) data link that has been developed by Aeronautical Radio, Incorporated (ARINC) for transmitting on

board meteorological measurements (Bisoux et al., 1983). ACARS can be used to automatically transmit data routinely during flight and can also transmit data when requested from receiving stations. Currently, ACARS provides air-to-ground coverage throughout North America and to over 500 airports worldwide (Campbell et al., 1993). In 1993, the airlines that were participating in MDCRS were Delta, Northeast and United. The number of MDCRS observations is expected to increase from a current 8,000 per day (1993) to 45,000 per day with the addition of several new airlines (Martin et al., 1993). MDCRS offers an exceptional opportunity to standardize the regular measurement, reporting and rapid dissemination of aircraft turbulence reports. It will provide frequent, automated, quantitative turbulence data that will be useful to forecasters and aircraft designers. Forecasters will be able to use the aircraft data to relate turbulence to meso- and synoptic scale features to improve forecasting techniques. These data will also give designers more insight into the loads experienced by aircraft to help in future designs.

It is clear that the technology to rapidly measure, compute and disseminate aircraft turbulence data is now available. Furthermore, there is a need to improve current turbulence measurement and reporting techniques to enhance aircraft safety. Therefore, the application and standardization of real-time measures aboard commercial aircraft should be explored.

B. OBJECTIVE

The purpose of this study is to identify and/or develop a practical, objective turbulence measure (metric) that can be easily automated and disseminated. In Chapter II, a number of candidate metrics are selected; algorithms are developed to compute each metric; and the experimental data base is described. Results are presented in Chapter III followed by a discussion of the results in Chapter IV. Concluding remarks and recommendations for future study are given in Chapter V.

II. METHODOLOGY

Four promising candidates for a practical real-time turbulence metric have been identified from the literature. These include vertical loads, airspeed fluctuations, derived gust velocity and eddy dissipation rate. In addition, two other turbulence measures, the Wingrove parameter and the Wingrove turbulent kinetic energy have been developed in the course of this study. In this chapter, these six metrics are defined and historical background is presented. Additionally, a description of the test data base is presented and algorithms for metric computations are given and evaluation procedures are discussed.

A. METRICS

1. VERTICAL LOADS

Fluctuations in airflow (gusts) produce changes in vertical loads on an aircraft. A vertical load, a_n , is defined as the incremental change of the measured vertical acceleration, a_z , from normal gravity (1.0 g),

$$a_n = a_z - 1. \quad (1)$$

For this study, a_z is referenced to an aircraft body coordinate axis which has $+z$ pointing vertically. This is opposite to the standard aircraft coordinate system where $+z'$ on the

aircraft body axis is pointing downward (See Fig. II.3). Vertical loads have been used for many years to quantify turbulence. NACA began measuring vertical loads with accelerometers in the 1920's (Burgess, 1924; Doolittle, 1924). Accelerometers were also being used by Soviet researchers by 1948 in turbulence studies using civilian airliners (Pao and Goldberg, 1969). Vertical load data were also collected in the 1960's during the comprehensive ALLCAT program described in the previous section. From 1960 to 1980, NASA conducted an extensive aviation turbulence study using airspeed (V), vertical load (G) and pressure altitude (H) (VGH) records from airliners. The VGH program collected more than 42,000 hours of turbulence data from 105 aircraft during this 20 year period (Morrow, 1986).

Vertical loads continue to be used by researchers as a quantitative metric in the study of commercial airline accidents (e.g., Parks et al., 1985; Lester et al., 1988; Lester et al., 1991; Lester, 1994). Vertical load has proven to be a useful metric because it is a direct measure of the bumpiness experienced in flight and is easily interpreted. Additionally, it is widely measured aboard commercial airliners and it is one of the fastest sampled parameters aboard airliners. The sample rate allows resolution of the important small scales of atmospheric turbulence. A scale relating vertical loads to turbulence intensity has been developed and is widely accepted by many the aviation community (Table II.1).

Turbulence Intensity	a_n (g)
Light	0.20 - 0.49
Moderate	0.50 - 0.99
Severe	1.0 - 1.99
Extreme	≥ 2.00

Table II.1. Turbulence intensity based on vertical loads (Lester, 1993).

2. AIRSPEED FLUCTUATIONS

Airspeed fluctuations, V_i^* , are the differences between the instantaneous airspeeds, V_i , and the airspeed averaged over some time interval, $\bar{V}_i$, that is,

$$V_i^* = V_i - \bar{V}_i. \quad (2)$$

Changes in airspeed affect the lift on an aircraft resulting in vertical loads. Airspeed fluctuations and bumpiness in flight can be caused by both (atmospheric) turbulent eddies and by strong wind shear in the absence of atmospheric turbulence. Turbulent eddies can cause airspeed fluctuations (Vinnichenko et al., 1980) and have been shown to be proportional to the intensity of the turbulence (e.g., Poellot et al., 1991). For example, V_i^* was used in early studies of CAT by European researchers (Hislop, 1951) and, more recently, similar data were used to help quantify turbulence during the NASA VGH program (Morrow, 1986). The relationship between turbulence intensity and airspeed fluctuations is shown in Table II.2.

Turbulence Intensity	V_i^* (Kts)
Light	5 - 14.9
Moderate	15 - 24.9
Severe	≥ 25
Extreme	

Table II.2. Turbulence intensity and airspeed fluctuations (Lester, 1993).

Advantages of V_i^* as a turbulence metric are its simplicity and widespread use (all aircraft measure airspeed). Also, V_i^* is aircraft-independent; that is, all aircraft flying through the same turbulence will measure the same airspeed fluctuations, although the aircraft will not necessarily have similar reactions.

3. DERIVED GUST VELOCITY

The derived gust velocity, U_{de} , is a turbulence metric based on a simple one degree of freedom aircraft model. The assumptions made in the derivation of U_{de} are as follows:

- The airplane is rigid and constrained to motions in the vertical direction only.
- Various aircraft configurations have similar gust responses.
- The gusts are uniform along the wingspan.
- Unsteady aerodynamics for airplane motion and gust penetrations are included.
- The gusts encountered are discrete and have a one-minus cosine profile.

The derived gust velocity is defined as

$$U_{de} = \frac{2a_n W}{m \rho_0 S V_e K_g}, \quad (3)$$

where

$$K_g = \frac{0.88 \mu_g}{5.3 + \mu_g} \quad \mu_g = \frac{2W}{m \rho \bar{c} g S}.$$

In Eqn. 3, W is the aircraft weight, m is the finite wing lift curve slope, ρ_0 is air density at sea level, S is the surface area of the wing, V_e is the equivalent airspeed, K_g is the gust alleviation factor, μ_g is the aircraft mass ratio, ρ is the air density at flight altitude and $\bar{c}$ is the mean geometric chord length. K_g is used to account for the reduction of lift due to several factors. One of these is the motion of the aircraft in pitch and vertical translation. During a gust encounter, the aircraft pitches and translates with the gust which will reduce the angle of attack and thus alleviate the loads produced by the gust. The correction made using the gust alleviation factor implies that the vertical acceleration for all aircraft is affected by the aircraft motion to about the same degree. This assumption is valid for aircraft with a conventional configuration and with reasonable flying qualities (Turner, 1985; Pratt and Walker, 1954). An aircraft with “reasonable flying qualities” allows a pilot to control the airplane through various maneuvers without undue effort. These qualities are defined by military regulations such as MIL-F-8785B (Roskam, 1979).

The derived gust velocity is computed from vertical loads caused by a symmetrical, wave-shaped gust with a wavelength equivalent to $25\bar{c}$ (Pratt and Walker, 1954). Wavelengths less than $25\bar{c}$ do not develop fully around the wing and thus lift due to the gust is not maximized. For gusts with wavelengths greater than $25\bar{c}$ the aircraft has time to pitch and translate and alleviate the gust by decreasing its angle of attack.

In the early 1950's, U_{de} was used widely in aircraft design. For example, U_{de} can be used to relate the peak acceleration experienced by an aircraft to the peak accelerations to be expected on another aircraft flying through the same turbulence. With regard to turbulence, in 1954, NASA adopted U_{de} as a standard turbulence metric (Donely, 1950). U_{de} replaced an earlier metric (the effective gust velocity) by integrating a revised standard gust alleviation factor, K_g (Pratt and Walker, 1954). Since 1954, U_{de} has been used by researchers in many turbulence studies (e.g., Press and Steiner, 1958; Zalovcik, et al., 1977; Turner, 1985). The relationship between turbulence intensity and U_{de} is shown in Table II.3.

An advantage of U_{de} as a turbulence metric is that it can be easily calculated from the parameters that are normally measured aboard commercial aircraft. Also, based on its assumptions, this metric is approximately aircraft independent; that is, all aircraft traveling through the same turbulent region will measure the same U_{de} .

Turbulence Intensity	Derived Gust Velocity (U_{de}) ($m s^{-1}$)
Light	1.5 - 6.1
Moderate	6.2 - 10.7
Severe	10.8 - 15.2
Extreme	≥ 15.3

Table II.3. Turbulence intensity based on derived gust velocity (Ehrenberger, 1980).

4. EDDY DISSIPATION RATE

The eddy dissipation rate, ϵ , is a turbulence metric that is proportional to the rate of turbulent kinetic energy (TKE) transfer. It is derived from a direct estimate of the intensity of atmospheric turbulence rather than from the effects turbulence produces on an aircraft. Therefore, it is aircraft independent. In addition, estimations of ϵ are relatively simple and many investigators have found it to be a promising turbulence intensity parameter. One of the reasons for this is that TKE requires the measurement of winds along three axes while ϵ can be computed from wind measurements along only one of the wind axes.

Modern measurements of ϵ are based on the work of Kolmogorov (1941). He recognized that kinetic energy is transferred from large to small eddies and then to heat through a spectral cascade process. He hypothesized the existence of a subrange within the TKE

spectrum where the shape of the spectrum depends only on ε and the wavenumber, k (inertial subrange). The following equation shows this relationship

$$\phi(k) = c\varepsilon^{2/3} k^{-5/3} \quad (4)$$

where $\phi(k)$ is the power spectral density (PSD) and c is the dimensionless Kolmogorov constant. The $-5/3$ power law through the inertial subrange is illustrated in a schematic of the atmospheric energy spectrum in Fig. II.1. The inertial subrange is estimated to include the wavenumbers from 0.01 rad m^{-1} (100 meters) to 10 rad m^{-1} (0.1 meters) (Lenschow, 1986).

Figure II.1. Schematic of turbulent atmospheric spectrum. The $-5/3$ power law is shown to be valid for the inertial subrange and portions of the energy containing and dissipation range (Lenschow, 1986).

In order to compute ε , Eqn. 4 can be rewritten as

$$\varepsilon = \left[\frac{\phi(k)}{c} \right]^{3/2} k^{5/2}. \quad (5)$$

In this case, $\phi(k)$ is measured at a given k within the inertial subrange to estimate ε . $\phi(k)$ is the PSD estimated from airspeed or wind speed. An alternative method to compute ε entails the integration of Eqn. 4 (Nastrom and Gage, 1985). This is shown below.

$$\varepsilon = \left[\frac{2}{3} \frac{\Delta\sigma^2}{c(k_{lo}^{-2/3} - k_{hi}^{-2/3})} \right]^{3/2} \quad (6)$$

where $\Delta\sigma^2$ is that portion of the variance of airspeed or wind speed (area under the PSD) in the range of k_{lo} to k_{hi} (within the inertial subrange).

MacCready (1964) first suggested that ε should be used as a real-time turbulence metric. Subsequently, ε has been applied in several studies to quantify turbulence (e.g., Lilly et al., 1974; MacPherson and Isaac, 1977; Kennedy and Shapiro, 1980; Cornman et al., 1994; Tank, 1994). On the basis of these studies, a number of turbulence intensity scales based on ε have been suggested. The scale suggested by Ehrenberger (1980) is shown in Table II.4. Others have similar values (e.g., Poellot et al., 1991).

Turbulence Intensity	Eddy Dissipation Rate($\varepsilon^{1/3}$) ($m^{2/3} sec^{-1}$) $\times 10^2$
Light	3.7 - 8.87
Moderate	8.88 - 21.00
Severe	21.01 - 50.00
Extreme	≥ 50.01

Table II.4. Turbulence intensity based on eddy dissipation rate (Ehrenberger, 1980).

5. WINGROVE PARAMETER

The Wingrove parameter, Wi , is a turbulence metric that quantifies the intensity of atmospheric turbulence only in those scales that affect aircraft in flight. It is defined as:

$$Wi \equiv \overline{w_h'^2} \quad (7)$$

where w_h is the vertical wind speed, $(\)'$ indicates a high-pass filter, and $(\overline{\ })$ indicates an average along the aircraft track.

The concept of Wi evolved from work done by Wingrove and Bach at NASA-Ames over the last ten years. They showed that good estimates of w_h can be made from airliner Digital Flight Data Recorder (DFDR) data (Wingrove and Bach, 1983; Bach and Wingrove, 1989). Wingrove (1991) suggested a turbulence metric be based on the application of “....a high-pass filter-smoother.....to eliminate long term waves in the vertical wind that do not contribute to turbulence G-loads”. Based on Wingrove’s suggestion, a high-pass filter was developed to isolate the vertical winds that contribute to turbulence. Additionally, the filtered wind was squared in order to emphasize the differences between small and large turbulence values. The result was averaged to provide a stable statistic of the turbulence along the aircraft track.

Assuming accurate wind estimates, Wi is not affected by maneuvering and is aircraft independent. All aircraft will measure the same Wi , but may not have similar reactions. This metric also has a simple and useful physical interpretation.

6. WINGROVE TURBULENT KINETIC ENERGY

Turbulent kinetic energy (TKE) is defined as

$$TKE = \frac{1}{2} (\overline{u'^2} + \overline{v'^2} + \overline{w_h'^2}) \quad (8)$$

where u' , v' and w_h' are deviations of the northward, eastward and vertical wind from their respective mean values (e.g., Stull, 1991). For example, u' is given by

$$u' = u - \bar{u} \quad (9)$$

where $\bar{u}$ is computed over some arbitrary time interval. The quantities v' and w_h' have similar definitions. TKE has found wide use within the study of atmospheric turbulence. It has been used for both boundary layer studies (e.g., Stull, 1991) and in some aviation turbulence studies (e.g., Dutton, 1968; Lester, 1972; Lester and Fingerhut, 1974). TKE has an advantage over previous parameters because it also includes horizontal gusts. However, it is somewhat problematic as a turbulence metric because the selection of the

averaging period is arbitrary; that is, it is often includes gusts on large scales that do not contribute to bumpiness in flight.

In order to overcome this problem, the Wingrove turbulent kinetic energy (TKE_{wi}) was introduced as

$$TKE_{wi} \equiv \frac{1}{2} (\overline{u'^2} + \overline{v'^2} + \overline{w_h'^2}) \quad (10)$$

where u is the northward wind speed and v is the eastward wind speed. All other symbols have the same definition as in the Wingrove parameter. The major difference between Eqns. (8) and (10) is that the determination of the deviations (Eqn. (9)) are replaced with a high-pass filter of the original data. As with Wi , the filter eliminates those long period oscillations that do not contribute to bumpiness in flight.

Assuming accurate wind estimates, TKE_{wi} is not affected by maneuvering and includes lateral gusts. It is also aircraft independent. Similar to Wi , all aircraft will measure the same TKE_{wi} but may experience different reactions. Additionally, TKE_{wi} has a simple and useful physical interpretation.

B. THE NASA-AMES TURBULENCE STUDY

Airliners certified in 1969 or later are equipped with DFDR equipment that provide aircraft time histories of parameters such as inertial acceleration and altitude. This information has provided researchers with a low cost method of investigating turbulence incidents (e.g., Wingrove et al., 1989). Although the data are less accurate than those gathered from specially instrumented research aircraft, they do offer good quantitative estimates of turbulence on scales that were previously unresolvable from PIREPs especially when that turbulence is significant (moderate or greater) (Lester et al., 1991). Since 1980, researchers at NASA-Ames Research Center, in cooperation with the National Transportation Safety Board (NTSB), have been able to acquire DFDR data sets from 23 turbulence incidents (Table II.5). These data have been analyzed to better understand turbulence-producing mechanisms and their effects upon aircraft.

DFDR data sets sometimes do not contain all the necessary aircraft information to complete a satisfactory turbulence analysis. In order to merge the information from these limited DFDR data sets with other data sources (e.g., Air Traffic Control RADAR), an aircraft state estimation program is used. A state estimation program called SMACK (SMoothing for AirCRAFT Kinematics) was developed at NASA-Ames for use in flight-test analyses and turbulence investigations. It has been useful in computing unknown aircraft

parameters such as Euler angles, aircraft ground track and estimates of the winds along the aircraft flight path (Bach, 1991).

DFDR data are not immediately useful because of data dropouts and erroneous data.

Several steps of data pre-processing are required for later calculations. These steps

Date	Flight Number	Location	Aircraft	Altitude (feet.)	Disturbance	DFDR
6/75	-	JFK, NY	L-1011	Go-around	Microburst	
11/75	TIA	Calgary, Canada	DC-10	33,000	Clear air turbulence	X
4/81	UA012	Hannibal, MO	DC-10	37,000	Turbulence near thunderstorms	X
7/82	-	Morton, WY	DC-10	37,000	Clear air turbulence	
10/83	AA676	Near Bermuda	DC-10	37,000	Convective turbulence	X
11/83	-	Offshore So. Carolina	L-1011	37,000	Clear air turbulence	
1/85	PAA125 (1)	Over Greenland	B-747	33,000	Mtn. wave turbulence	X
2/85	PAA125 (2)	Over Greenland	B-747	33,000	Mtn. wave turbulence	X
2/85	-	Offshore CA	B-747	41,000	Wind shear	
8/85	AA539	Dallas/Fort Worth, TX	MD-80	Go-around	Microburst	X
8/85	DAL191	Dallas/Fort Worth, TX	L-1011	Landing	Microburst	X
11/85	-	Over Greenland	B-747	33,000	Clear air turbulence	
3/86	-	Offshore HI	B-747	33,000	Clear air turbulence	
4/86	SA534	Jamestown, NY	DC-10	40,000	Wind shear/ maneuvering	X
7/86	-	West Palm Beach, FL	A-300	20,000	Convective turbulence	
9/87	EA924	Near Bermuda	L-1011	31,000	Turbulence near thunderstorms	
11/87	PAA217	Near Bermuda	A-310	33,000	Turbulence near thunderstorms/ maneuvering	X
1/88	AA350	Chicago, IL	B-767	25,000	Clear air turbulence	X
3/88	AA550	Cimarron, NM	B-767	33,000	Mtn. wave turbulence	X
1/90	AA689	Near Puerto Rico	DC-10	-	-	X
5/91	USA1002	Memphis, TN	B-767	-	Undetermined	X
3/93	JA046	Anchorage, Alaska	B-747	3,000	Mtn. wave turbulence	X
4/93	CEA583	Near Shemya, Alaska	MD-11	33,000	Mechanical failure	X

Table II.5. DFDR data of turbulence incidents investigated at NASA-Ames. Data sets that are still available are marked with an "x".

include removing erroneous data points and synchronizing all the parameters sampled at different data rates to a common rate. These procedures are discussed thoroughly by Wingrove et al. (1989). After removing any erroneous data points or “wildpoints”, the data are interpolated to 64 Hz with a digital filtering algorithm to take into account the different recording rates and offset in data sampling of each recorded parameter (see Table II.6). After this interpolation step, the sample rate for each parameter is reduced to the highest rate found in the DFDR. For example, in the case of L-1011 data, that would be 4 Hz.

After the data pre-processing, the next step, as shown in Fig. II.2, is to combine the DFDR data with the ATC radar data whenever the radar data are available. Prior to performance calculations or wind estimation, computations of air data are performed. These include calculations of Mach number, dynamic pressure, and true airspeed. Performance calculations include the derivation of force coefficients determined from DFDR data. For example, a force coefficient such as the lift coefficient can be used to estimate angle of attack, α , whenever the angle of attack is not included in the DFDR data set. The angle of attack, which is shown in Fig. III.3, is essential in determining vertical winds in any investigation of severe turbulence encounter.

Parameter	Measurement Rate (per sec)				
	L-1011	DC-10	MD-80	B-767	B-747
Normal acceleration	4	4	8	4	4
Lateral acceleration	4	4	4	4	4
Longitudinal acceleration	4	1	4	1	4
Roll angle	1	1	1	1	1
Pitch angle	1	1	1	1	1
Heading angle	1	1	1	1	1
Angle-of-attack vanes	2	-	-	2	-
Pressure altitude	1	1	1	1	1
Indicated airspeed	1	1	1	1	1
Elevator position	1	1	1	1	1
Rudder deflection	2	2	2	2	2
Static air temperature	0.5	0.5	1	1	-

Table II.6. Typical Digital Flight Data Recorder measurements for various commercial aircraft (Wingrove et al., 1989).

Figure II.2. Airliner data processing procedure (after Bach and Wingrove, 1989).

Figure II.3. Aircraft attitude angles and axes used in equations for computing winds along the aircraft track. In this case, x' is along the aircraft body axis, y' is perpendicular to the aircraft body axis and z' is positive in the downward direction

After data pre-processing, wind estimation is accomplished with a state estimation program called SMACK (Wingrove and Bach, 1989). In this program, aircraft motions are governed by a six-degree-of-freedom model, referenced to a flat, nonrotating Earth. The model is considered to have six degrees of freedom because of the three axes of movement and rotation about those three axes (see Fig. II.3). The following wind estimation procedure is summarized from Bach and Wingrove (1989) where the aircraft accelerations are expressed with the x -axis pointing north, y -axis east, and h -axis vertical as:

$$\begin{aligned}
 \ddot{x} &= a_x \cos\theta \cos\psi \\
 &\quad + a_y (\sin\phi \sin\theta \cos\psi - \cos\phi \sin\psi) \\
 &\quad + a_z (\cos\phi \sin\theta \cos\psi + \sin\phi \sin\psi) \\
 \ddot{y} &= a_x \cos\theta \sin\psi \\
 &\quad + a_y (\sin\phi \sin\theta \sin\psi - \cos\phi \cos\psi) \\
 &\quad + a_z (\cos\phi \sin\theta \sin\psi + \sin\phi \cos\psi) \\
 \ddot{h} &= a_x \sin\theta - (a_y \sin\phi + a_z \cos\phi) \cos\theta - g
 \end{aligned} \tag{11}$$

where (a_x, a_y, a_z) are onboard measurements of body axis accelerations, (ϕ, θ, ψ) are onboard measurements of Euler angles and g is the acceleration of gravity. Integration of these differential equations lead to estimates of inertial velocities $(\dot{x}, \dot{y}, \dot{h})$ and position (x, y, h) . The resulting estimates of inertial positions need to be compared to independently derived positions (e.g., from RADAR) to determine the biases in the position estimates. These inertial estimates of position and velocity are crucial in the accurate determination of winds along the aircraft flight path. The wind velocity is calculated as the

difference between the vehicle inertial velocity and its velocity with respect to the air mass. The wind components in the Earth frame are computed as:

$$\begin{aligned} u &= \dot{x} - V_i \cos\theta_w \cos\psi_w \\ v &= \dot{y} - V_i \cos\theta_w \sin\psi_w \\ w_h &= \dot{h} - V_i \sin\theta_w \end{aligned} \quad (12)$$

where the true airspeed V_i is computed from the flight recorder and the wind axis Euler angles (θ_w, ψ_w) are found using the identities

$$\begin{aligned} \sin\theta_w &= \cos\alpha \cos\beta \sin\theta - C \cos\theta \\ \tan(\psi_w - \psi) &= \frac{\sin\beta \cos\phi - \sin\alpha \cos\beta \sin\phi}{\cos\alpha \cos\beta \cos\theta + C \sin\theta} \\ C &= \sin\alpha \cos\beta \cos\phi + \sin\beta \sin\phi \end{aligned} \quad (13)$$

where β is the angle of sideslip. Estimates of the error in the calculation of the wind velocity were determined based on the assumption that the measurements are statistically independent and the angles, α, β, ϕ , and θ are small (Lester et al., 1989). In this case, the error in the horizontal wind velocity component is given by

$$\delta w_{xy} \approx \sqrt{(\delta^2 V_{xy} + \delta^2 V_i + V_i^2 \delta^2 (\psi + \beta))} \quad (14)$$

where δV_{xy} is the error in the horizontal aircraft velocity component. Similarly, the error in the vertical wind component is given by

$$\delta w_h \approx \sqrt{(\delta^2 \dot{h} + V_i^2 \delta^2 (\theta - \alpha))} \quad (15)$$

A summary of the errors are listed in Table II.7. An additional loss of accuracy in the computation of horizontal winds sometimes results from a lack of ATC radar data as estimates of aircraft track have to be computed from aircraft inertial data. However, this has little effect on the vertical wind calculations. In many cases, the effects of the missing ATC radar data fixes can be reduced with independently determined initial conditions such as ground fixes and bias corrections for each parameter (e.g., drift).

Multiple runs with varying initial conditions can be made to minimize errors between a known parameter and an estimated parameter calculated using SMACK. Also, biases can be identified and corrected with a comparison with local observations.

δw_{xy}		δw_h	
Error source	Error (m s ⁻¹)	Error source	Error (m s ⁻¹)
δV_y	1.0	$\delta \dot{h}$	1.0
δV	1.0	$V\delta(\theta - \alpha)$	2.0
$V\delta(\psi + \beta)$	2.0		

Table II.7. RMS errors of wind estimates (Lester et al. 1989).

C. TURBULENCE CASES

The following seven cases were selected from the NASA-Ames case archive (Table II.5). They represent a range of aircraft, flight profiles, and turbulence phenomena. A brief description of each case follows.

UA012 United Airlines flight 012, Hannibal, MO, April, 1981.

On April 4, 1981, near Hannibal, MO, a DC-10 encountered severe turbulence while cruising from Los Angeles to New York at about 37,000 feet. Prior to the incident, the aircraft passed through thin cirrus clouds and lightning could be seen around the aircraft. The aircraft continued through the cirrus and entered another cloud where the aircraft suddenly experienced several severe jolts. This incident resulted in 29 injuries to passengers and crew members (Pantley, 1989).

PAA125 Pan American Airlines flight 125, Over Greenland, January, 1985.

On January 22, 1985, over southern Greenland, a B-747 encountered a series of increasingly violent vertical oscillations over a period of a few minutes while cruising in a westerly direction at 33,000 ft. The turbulence event ended with the aircraft suddenly gaining 1000 ft. Analysis of the flight and meteorological data strongly suggests the aircraft traversed the trough of a mountain lee wave over the western slopes of the Greenland icecap. This incident resulted in 13 injuries (Lester et al., 1988).

SA534 Sabena Airlines flight 534, Jamestown, NY, April, 1986.

On April 7, 1986, over Jamestown, NY, a DC-10 encountered severe turbulence just after it began descending from a cruising altitude of 41,000 ft. Analysis of the meteorological data showed as the aircraft descended, the headwind decreased. Then the headwind suddenly increased, forcing the autopilot to pitch the aircraft up in order to maintain airspeed. The aircraft was forced to continue pitching up until it stalled. After the stall, there were additional sharp downward elevator control inputs leading to additional pitch angle changes and high vertical loads. Vertical loads caused by atmospheric turbulence (if any) were greatly exaggerated by maneuvering and led to twelve injuries (Lester et al., 1991).

EA924 Eastern Airlines flight 924, Near Bermuda, September, 1987.

A Lockheed L-1011 encountered severe turbulence while flying from San Juan, Puerto Rico to New York's Kennedy airport. The aircraft was flying at an altitude of 33,000 feet and dropped several thousand feet into the vicinity of a thunderstorm. This turbulence near thunderstorm incident resulted in injuries to four passengers and one flight attendant (Anonymous, 1987).

PAA217 Pan American Airlines flight 217, Near Bermuda, November, 1987.

On November 11, 1987, an Airbus A-310 encountered severe turbulence at an altitude of 33,000 feet over the Atlantic Ocean while flying from New York, NY to Caracas, Vene-

zuela. Preliminary analysis indicates that the aircraft encountered turbulence near or in thunderstorms (TNT) resulting in 35 injuries. However, DFDR analysis suggests this incident was induced by pilot or autopilot maneuvering (Lester et al., 1991).

AA350 American Airlines flight 350, Chicago, IL, January, 1988.

On January 20, 1988, a B-767 encountered severe turbulence during descent from 35,000 feet to 24,000 feet. DFDR analysis showed the aircraft intersected a patch of clear air turbulence (CAT) embedded in a strongly sheared stable layer in the vicinity of a jet stream. Two injuries resulted (Lester, 1994).

AA550 American Airlines flight 550, Cimarron, NM, March, 1988.

On March 24, 1988, a B-767 encountered severe turbulence while cruising at 33,000 ft enroute from Phoenix, AZ to Chicago, IL. The upset was due to mountain wave activity produced in the lee of the Sangre de Cristo mountains. Three injuries were reported (Lester, 1989).

A summary of the seven cases described above is shown in Table II.8. Five of the seven turbulence events were primarily due to atmospheric phenomenon while the turbulence in the SA534 and PAA217 incidents were contaminated by maneuvering.

Date mo./yr.	Flight Number	Location	Aircraft	Disturbance
4/81	UA012	Hannibal, MO	DC-10	Turbulence near thunderstorms
1/85	PAA125	Over Greenland	B-747	Mountain wave turbulence
4/86	SA534	Jamestown, NY	DC-10	Wind shear/maneuvering
9/87	EA924	Near Bermuda	L-1011	Turbulence near thunderstorms
11/87	PAA217	Near Bermuda	A-310	Turbulence near thunderstorms/maneuvering
1/88	AA350	Chicago, IL	B-767	Clear air turbulence
3/88	AA550	Cimarron, NM	B-767	Mountain wave turbulence

Table II.8. Summary of turbulence cases used in this study.

D. ALGORITHMS

1. VERTICAL LOADS

This metric was simply computed based on Eqn. 1, rewritten below,

$$a_n(i) = a_z(i) - 1 \quad (16)$$

where i is an index for each data point with $i = 1 \dots n$ and n is the total number of points.

All the data are in units of g's.

2. AIRSPEED FLUCTUATIONS

In this study, instantaneous airspeed fluctuations were computed relative to the average airspeed over the previous ten seconds as shown below.

$$V_i^*(i) = V_i(i) - \frac{1}{N} \sum_{i=N}^i V_i(i) \quad (17)$$

where N is the number of data points within ten seconds equal to $10\Delta t$ and Δt is the data sampling rate. The ten second moving average was used to mimic the mental process that is employed by pilots when using this metric. A ten second moving average was chosen to provide sufficient detail in airspeed fluctuations.

3. DERIVED GUST VELOCITY

Instantaneous derived gust velocity for each data point was computed based on Eqn. 3 for each time step as shown below,

$$U_{de}(i) = \frac{2a_n(i)W}{m\rho_0SV_e(i)K_g(i)} \quad (18)$$

where

$$K_g = \frac{0.88\mu_g(i)}{5.3 + \mu_g(i)} \quad \mu_g = \frac{2W}{m\rho(i)cgS}.$$

Generally, parameters such as ρ_0 , ρ and V_e are not available on DFDRs. These parameters were computed based on pressure altitude and static air temperature as discussed in Dunlap and Porter (1971). Aircraft weights, W , were considered constant and were sometimes available in NTSB accident reports or estimated based on available informa-

tion. Geometric parameters such as $\bar{c}$ and S were available from manufacturer supplied information or Jane's All the World's Aircraft (1993). The finite wing lift curve slope, m , was estimated based on finite airfoil theory presented in Anderson (1991).

4. EDDY DISSIPATION RATE

Eddy dissipation rate estimates require determination of the vertical wind PSD, $\phi(k)$. $\phi(k)$ was estimated using Matlab[®] which incorporates the Welch method with overlapping Hanning windows. This technique is discussed by Oppenheim and Schaffer (1975) as well as Cooley et al. (1967) and is summarized as follows.

The data are partitioned into individual sections and a Hanning window was applied. The windowing procedure is required to remove any discontinuities at the end of the data section that cause errors in the PSD estimate (Brault and White, 1971). In order to facilitate the use of the Fast Fourier Transform (FFT), the number of data points within the section correspond to a power of two. Successive estimates of $\phi(k)$ were made for each overlapping data section. An average estimate of $\phi(k)$ was then computed by summing up all individual estimates of $\phi(k)$ and dividing by the number of estimates. As noted by

Oppenheim and Schafer (1975), this method of PSD estimation smooths the spectrum and reduces the variance of the estimate.

The eddy dissipation rate, ε , was computed over the turbulent region of each case based on Eqn. 6 which is repeated for convenience,

$$\varepsilon = \left[\frac{2}{3} \frac{\Delta\sigma^2}{c(k_{lo}^{-2/3} - k_{hi}^{-2/3})} \right]^{3/2}.$$

In this application, $\Delta\sigma^2$ is the variance of the vertical wind speed within a wavenumber band defined by k_{lo} and k_{hi} (i.e., $\Delta\sigma^2 = \int_{k_{lo}}^{k_{hi}} \phi(k) dk$) and Kolmogorov's constant, c , was selected as 0.20 for vertical wind speed (Tank, 1994). $\Delta\sigma^2$ was determined by approximating the integral numerically using the midpoint rule (a form of the rectangular method). The turbulent region was defined as that portion of the record which includes all measurements of $|a_n| > 0.2g$ (i.e., the threshold for light turbulence). The wavenumber band was chosen for each case where the -5/3 power law was valid.

A common wavenumber band used to compute $\phi(k)$ for all cases is bounded by k_{lo} and k_{hi} at $0.0065 \text{ rad m}^{-1}$ (967 m) and 0.02 rad m^{-1} (314 m), respectively. The lower wavenumber band was selected based on work performed by Lilly et al. (1974) and Tank (1994) where they found the -5/3 power law was valid for vertical wind wavelengths $\leq$

1000 m. The upper wavenumber limit of 0.02 rad m^{-1} was the highest wavenumber which fit the $-5/3$ power law for most cases.

5. WINGROVE PARAMETER

The computational form of Eqn. 7 is

$$Wi = \frac{1}{N} \sum_{i=1}^N w_h'^2(i) \quad (19)$$

where N is the number of data points within a ten second portion of the record.

The evaluation of the RHS of Eqn. 19 was accomplished as follows. The vertical wind data were detrended to remove any biases and improve subsequent filtering results at the endpoints of the data record.

A high-pass filter was then applied to isolate the vertical wind scales that contribute to significant vertical loads. The filter was designed based on experimental and theoretical studies of the response of large multi-engine aircraft to gusts at the aircraft's center of gravity. From these studies, 2500 m (0.1 Hz) was estimated to be the largest dimension (e.g., wavelength) that could contribute to significant turbulence (See Fig. II.4). This frequency cutoff varies slightly from case to case because it depends on average airspeed.

A fourth order Butterworth high pass filter was selected for its simplicity and filter characteristics. The filter is defined by two characteristic frequencies; the cutoff frequency, f_c and rolloff frequency, f_r . The cutoff frequency is the desired filter cutoff and the rolloff frequency is required for a well behaved filter. The filter used for the AA350 case is shown in Fig. II.5 as an example of a typical filter used in this study. The filter has a f_c

Figure II.4. Calculated and experimental center-of-gravity vertical acceleration frequency responses for a large swept-wing airplane (Houbolt et al., 1964).

Figure 11.5. Vertical wind high-pass filter frequency response for AA350. f_r is the rolloff frequency and f_c is the cutoff frequency.

of about 0.09 Hz (≈ 2500 m) and a f_r at 0.07 Hz (≈ 1950 m). At f_c and f_r the signal is attenuated at 3 dB and 15 dB, respectively. Although this fourth order filter does not have an extremely sharp cutoff, it is devoid of the Gibbs Phenomenon apparent with higher order filters. The filter was applied symmetrically to the data in the forward and reverse direction eliminating all phase distortion. Passing the data through the filter twice essentially attenuates the amplitude of the signal by 6 dB at f_c , the product of two filters. The result was squared and averaged over ten seconds yielding Wi corresponding to the last data point of that ten seconds. A running average was then used until the end of the data set was reached. The purpose of averaging is to provide a stable statistic of the turbulence intensity along the aircraft track.

6. WINGROVE TURBULENT KINETIC ENERGY

The method used to compute this metric is similar to the technique used to compute the Wingrove parameter except this metric includes horizontal wind information. Equation 10 is rewritten below,

$$TKE_{wi} = \frac{1}{2} \left(\frac{1}{N} \sum_{i=1}^N u'^2(i) + \frac{1}{N} \sum_{i=1}^N v'^2(i) + \frac{1}{N} \sum_{i=1}^N w_h'^2(i) \right) \quad (20)$$

where the symbols have their usual meanings. To compute TKE_{wi} , the northward, eastward and vertical wind data were initially detrended. The vertical wind filter used for this metric is identical to the one used for computing Wi . A high-pass filter was also applied to the horizontal winds to isolate horizontal wind scales that contribute to significant lateral loads. Research has shown that there is an increased response in roll, yaw and sideslip of large conventional aircraft to horizontal gusts smaller than approximately 1600 meters (Eggleston et al., 1960; Lichtenstein, 1974). Based on those studies, a fourth order Butterworth high-pass filter with a designed cutoff at about 0.135 Hz (1600 m) was applied to the horizontal wind data. This cutoff varies from case to case since it is computed based on the average airspeed. The horizontal wind filter used for the AA350 case is shown in Fig. II.6 as an example of a typical filter used for this metric. The filter has a cutoff f_c of about 0.14 Hz (≈ 1600 m) and a f_r at 0.089 Hz (≈ 1020 m).

III. RESULTS

In order to study the relationship between the following metrics and turbulence, an appropriate indicator of turbulence was needed. Aviation turbulence can be simply defined as bumpiness in flight (Reiter, 1962). Vertical load, a_n , is the bumpiness felt by the aircrew and it identifies turbulent regions. Therefore, a_n is used here to determine if significant values of a metric are associated with the region where bumpiness occurs.

A. VERTICAL LOADS

The turbulence experienced and reported by aircrews (“bumpiness in flight”) is captured objectively and quantitatively by the measurement of vertical loads (a_n). In the present section, Figs. III.1 through III.3 show time-histories of a_n for all cases. In following sections, a_n time-histories for the seven cases are presented to indicate the turbulent regions. In agreement with Lester et al. (1991), the turbulence for all cases is intermittent and “burst-like” with severe turbulence being only a small portion of the entire turbulence event. The vertical loads record for SA534 in Fig. III.2 shows short period oscillations prior to the turbulence event. This appears to be noise contaminating the record. This noise is followed by a smooth transition to large vertical loads which correspond to the autopilot induced change in pitch which was initiated to decrease the airspeed. Figure

III.2 also shows two distinct regions when AA350 descended through the two strongly sheared layers.

Extreme vertical loads for all cases are listed in Table III.1 with corresponding turbulence duration which was defined previously. The cases are listed in descending order according to the extreme absolute values of vertical load, $|a_n|$. All cases are categorized as severe turbulence based on Table II.1. Reported turbulence severity from the crew is also included. Intensities marked with a “*” are determined based on injuries alone. These reported turbulence intensities are in agreement with this metric.

However, Lester et al. (1991) have concluded two of these severe turbulence cases, SA534 and PAA217, were due to maneuvering. This illustrates a disadvantage of this metric in its inability to separate turbulence induced vertical loads from maneuvering induced vertical loads.

Case	Reported Turbulence Intensity	Extreme a_n (g)	Turbulence Duration (sec.)
UA012 (Hannibal)	Severe	0.83, -1.91	41
PAA125 (Greenland)	Severe*	1.72, -1.04	30
PAA217 (Bermuda)	Severe	1.00, -1.54	30
SA534 (Jamestown)	Severe*	0.84, -1.38	79
EA924 (Bermuda)	Severe	0.78, -1.36	55
AA350 (Chicago)	Severe	0.50, -1.14	329
AA550 (Cimmaron)	Severe	0.73, -1.04	73

Table III.1. Summary of vertical loads. Asterisk indicates those cases specified as severe on the basis of passenger injuries alone.

Figure III.1. Vertical load time histories for UA012, PAA125, and PAA217. Positive values indicate the aircraft was accelerated upwards.

Figure III.2. Vertical load time histories for SA534, EA924, and AA350. Positive values indicate the aircraft was accelerated upwards.

Figure III.3. Vertical load time history for AA550. Positive values indicate the aircraft was accelerated upwards.

B. AIRSPEED FLUCTUATIONS

Figures III.4 through III.6 show airspeed fluctuations and vertical loads for all cases. These figures show there are large V_t^* associated with large a_n . However, there are also some regions of large V_t^* in regions of small a_n . For example, Fig. III.6 shows an airspeed deviation for SA534 of about 6.5 knots from 245 seconds to 275 seconds. This is a significant airspeed deviation compared to the maximum V_t^* of 7.0 knots. This could be attributed to either additional maneuvering or a wind shear without turbulence.

Extreme values of V_t^* , associated turbulence intensities and reported turbulence intensities are shown in Table III.2. Cases are listed in descending order of extreme values according to the absolute value of airspeed fluctuations, $|V_t^*|$. The two maneuvering cases, PAA217 and SA534, were some of the least intense turbulence cases. This is in contrast to Table III.1 where a_n values indicated they were some of the most intense turbulence events. Additionally, there are some inconsistencies between the turbulence intensity computed by this metric and reported by the aircrew. EA924 and the two maneuvering cases were reported as severe turbulence but these computations indicate only moderate turbulence.

The lower than expected turbulence intensity for EA924, PAA217 and SA534 may be due to the relatively slow sampling rate of airspeed (1 Hz). At a sampling rate of 1 Hz, the average distance traveled by these aircraft in between samples is approximately 250 meters (750 feet). This may not be sufficient resolution to capture turbulence extremes.

Case	Reported Turbulence Intensity	Extreme V_t^* (knots)	Turbulence Intensity
PAA125 (Greenland)	Severe*	32.6, -35.2	Severe
UA012 (Hannibal)	Severe	31.8, -31.7	Severe
AA550 (Cimmaron)	Severe	28.4, -15.0	Severe
AA350 (Chicago)	Severe	18.0, -25.1	Severe
PAA217 (Bermuda)	Severe	6.9, -18.1	Moderate
EA924 (Bermuda)	Severe	6.5, -16.5	Moderate
SA534 (Jamestown)	Severe*	7.0, -12.1	Moderate

Table III.2. Summary of airspeed fluctuations. Asterisk indicates those cases specified as severe on the basis of passenger injuries alone.

Figure III.4. Airspeed fluctuation and vertical load time histories for PAA125, UA012, and AA550. Positive vertical loads indicate the aircraft was accelerated upwards

Figure III.5. Airspeed fluctuation and vertical load time histories for AA350, PAA217, and EA924. Positive vertical loads indicate the aircraft was accelerated upwards.

Figure III.6. Airspeed fluctuation and vertical load time histories for SA534. Positive vertical loads indicate the aircraft was accelerated upwards.

C. DERIVED GUST VELOCITY

The records of derived gust velocity for each case are presented in Figs. III.7 through III.9. Extreme values of U_{de} , corresponding turbulence intensities, and reported turbulence intensities are presented in Table III.3. The cases are listed in descending order according to extreme absolute values of U_{de} , $|U_{de}|$.

As expected, there is a close relationship between the time histories of U_{de} and a_z since U_{de} is proportional to a_z . The U_{de} values in this study are similar to those found by other turbulence researchers. The maximum $|U_{de}|$ presented by Pratt and Walker (1954) is 25 ms^{-1} . In a study conducted by Zalovick et al. (1977), they computed a maximum $|U_{de}|$ of 14.6 ms^{-1} with a corresponding a_z of $1g$. This result by Zalovick et al. (1977) closely agrees with the $|U_{de}|$ computed for AA550 (12.1 ms^{-1}) which had a corresponding $|a_z|$ of $1.04g$.

The order of cases in Table III.1 shows little difference compared to Table III.3 with the exception of PAA125. In Table III.1, PAA125 was the second most intense case but in Table III.3 it is the fourth most intense turbulence event. Closer analysis reveals this apparent discrepancy may be attributed a possible error in estimating the aircraft weight at the time of the incident. Information used to estimate the aircraft weight could cause the

aircraft weight to be in error by as much as 10% (i.e., 50,000 lbs too light). This variation could easily account for the lower estimate of turbulence intensity using U_{de} . This would not be a problem in real-time application because aircraft weight is constantly updated. The intensities are generally greater with U_{de} and vary over two categories of intensity (severe and extreme). This occurs because U_{de} computations attempt to account for the ability of the aircraft to alleviate gusts. U_{de} is supposed to reveal the actual strength of the gust that the aircraft encountered. However, when compared to the reported turbulence intensities, this metric appears to overestimate the intensity of the turbulence; that is, five of the seven cases indicated extreme. Also, similar to a_n , this metric cannot distinguish between atmospheric and maneuver-induced turbulence. For example, the two maneuvering cases are indicated in Table III.3 as among the three most intense turbulence cases.

Case	Reported Turbulence Intensity	Extreme U_{de} (ms^{-1})	Turbulence Intensity
UA012 (Hannibal)	Severe	11.0, -23.6	Extreme
PAA217 (Bermuda)	Severe	15.3, -23.5	Extreme
SA534 (Jamestown)	Severe*	12.8, -22.8	Extreme
PAA125 (Greenland)	Severe*	21.8, -13.3	Extreme
EA924 (Bermuda)	Severe	11.2, -20.0	Extreme
AA350 (Chicago)	Severe	5.8, -12.4	Severe
AA550 (Cimmaron)	Severe	8.3, -12.1	Severe

Table III.3. Summary of U_{de} values. Asterisk indicates those cases specified as severe on the basis of passenger injuries alone.

Figure III.7. Derived gust velocity time histories for UA012, PAA217, and SA534.

Figure III.8. Derived gust velocity time histories for PAA125, EA924, and AA350.

Figure III.9. Derived gust velocity time history for AA550.

D. EDDY DISSIPATION RATE

Table III.4 lists the cases in descending order according to maximum $\epsilon^{1/3}$. Turbulence intensities reported by the aircrew are also included. Figures III.10 through III.12 show the power spectral densities from which $\epsilon^{1/3}$ was computed for all cases.

Turbulence intensities range from light to extreme as compared to reported turbulence intensities where all cases are severe. A majority of the $\epsilon^{1/3}$ computed in this study are within their range of values computed by MacPherson and Isaac (1977). During the HICAT research project, Lilly et al. (1974) computed $\epsilon^{1/3}$ values that ranged from $8.8 \times 10^{-2} \text{ m}^{2/3} \text{ sec}^{-1}$ to $12.0 \times 10^{-2} \text{ m}^{2/3} \text{ sec}^{-1}$. More recently, Cornman et al. (1994) computed a maximum $\epsilon^{1/3}$ of $140.0 \text{ m}^{2/3} \text{ sec}^{-1}$ using the same PAA125 data analyzed in this current study. That value is almost three times larger than the value computed here. This difference can be attributed to the methods of computing $\epsilon^{1/3}$. For example, in contrast to the method used in this study (Section II.D.4), Cornman et al. (1994) used a two dimensional aircraft model to determine vertical wind speed from vertical acceleration data. This reduces some data uncertainties that arise when extracting wind information from DFDR data. Ideally, the results are better than the vertical wind estimates in this study and therefore, better spectral estimates of $\epsilon^{1/3}$ can be determined. However, no comparative studies have been made. As in the current study, their method presumes the

Case	Reported Turbulence Intensity	Maximum $\varepsilon^{1/3}$ ($\text{m}^{2/3} \text{sec}^{-1}$) $\times 10^2$	Eddy Dissipation Rate Turbulence Intensity
PAA217 (Bermuda)	Severe	62	Extreme
PAA125 (Greenland)	Severe*	50	Extreme
UA012 (Hannibal)	Severe	34	Severe
AA550 (Cimmarron)	Severe	14	Moderate
SA534 (Jamestown)	Severe*	8.8	Light
AA350 (Chicago)	Severe	8.6	Light
EA924 (Bermuda)	Severe	6.5	Light

Table III.4. Summary of eddy dissipation rates. Asterisk indicates those cases specified as severe on the basis of passenger injuries alone.

existence of an inertial subrange and homogeneous turbulence. Additionally, Cornman et al. (1994) computed $\varepsilon^{1/3}$ over ten seconds, a shorter time interval than used in this present study resulting in larger $\varepsilon^{1/3}$ values.

Table III.4 shows that the two maneuvering cases, PAA217 and SA534, have significantly different $\varepsilon^{1/3}$ values. PAA217 had a value of $62 \times 10^2 \text{ m}^{2/3} \text{ sec}^{-1}$ (extreme), while SA534 is only $8.8 \times 10^2 \text{ m}^{2/3} \text{ sec}^{-1}$ (light). It will be shown in the following section that although maneuvering clearly occurred in both cases, there is a greater contribution by atmospheric turbulence in PAA217. AA350 is also classified as light turbulence by this metric although it was reported as severe. A study by Lester (1994) showed that the turbulence was comprised of distinct turbulence patches which were primarily composed of light turbulence. Severe turbulence accounted for less than 1% of the turbulence within

the entire record. Therefore, the light turbulence classification for AA350 is due to the lack of resolution of the turbulence in the computation of $\varepsilon^{1/3}$. EA924 was another case that was categorized by this metric as light turbulence. Examination of Fig. III.12 shows the spectrum for EA924 drops off sharply at $k = 10^{-2}$ radians m^{-1} with a slope greater than $-5/3$. This is within the wavenumber region where it was assumed that the $-5/3$ power law was valid. Therefore, interpretation of $\phi(k)$ resulted in a low $\Delta\sigma^2$ which led to small $\varepsilon^{1/3}$. There are a number of possible causes for this. The most likely are errors in wind estimates due to measurements or computations. The spectral shape may simply be due to the lack of energy in that part of the spectrum (non-homogeneous, not steady state). This case clearly illustrates that the assumption of a $-5/3$ power law is not always valid for vertical winds which are extracted from DFDR data.

Figure III.10. Vertical wind spectrum for PAA217 used to compute eddy dissipation rates. A $-5/3$ slope reference line is included.

Figure III.11. Vertical wind spectrum for PAA125, UA012, AA550 used to compute eddy dissipation rates. A $-5/3$ slope reference line is included.

Figure III.12. Vertical wind spectrum for SA534, AA350, and EA924 used to compute eddy dissipation rates. A $-5/3$ slope reference line is included.

E. WINGROVE PARAMETER

Figures III.13 through III.16 show a_n , $\overline{w_h^2}$, and Wi for all cases. $\overline{w_h^2}$ is included to show the effect of omitting the high-pass filtering step. Table III.5 presents the maximum Wi and the corresponding reported turbulence intensity for each case. The table lists the cases are arranged in descending order according to maximum Wi .

In Figs. III.13 through III.16 there are several portions of the record where large values of $\overline{w_h^2}$ occur outside of the regions of large a_n . In these cases the large $\overline{w_h^2}$ are due to vertical motions on relatively large scales that do not significantly affect the aircraft as turbulence. In comparison, large values of Wi are always related to regions of significant a_n despite any maneuvering.

Maximum Wi values range from $11.70 \text{ m}^2\text{s}^{-2}$ to $76.65 \text{ m}^2\text{s}^{-2}$. The two cases with the lowest Wi are SA534, a maneuvering case, and AA350. There was no significant maneuvering in AA350 but it was characterized by a very short duration of moderate or greater turbulence (Lester et al., 1991). In this case, the ten second average used in the computation was unable to resolve the short severe turbulence burst.

Case	Reported Turbulence Intensity	Maximum Wi (m^2s^{-2})
UA012 (Hannibal)	Severe	76.65
PAA217 (Bermuda)	Severe	69.50
PAA125 (Greenland)	Severe*	66.38
AA550 (Cimmaron)	Severe	26.71
EA924 (Bermuda)	Severe	17.04
AA350 (Chicago)	Severe	11.94
SA534 (Jamestown)	Severe*	11.70

Table III.5. Summary of Wingrove parameters. Asterisk indicates those cases specified as severe on the basis of passenger injuries alone.

Similar to the results for $\epsilon^{1/3}$, Wi values versus α_n are minimized in one maneuvering case but not in the other. The high Wi value for PAA217 suggests that a significant intensity of turbulence was present. Therefore, in this case, maneuvering and turbulence contributed to the vertical loads felt by the aircrew.

Figure III.13. Vertical load, Wingrove parameter, and w_h^2 time histories for UA012 and PAA217. Positive vertical loads indicate the aircraft was accelerated upwards.

Figure III.14. Vertical load, Wingrove parameter, and $\overline{w_h^2}$ time histories for PAA125 and AA550. Positive vertical loads indicate the aircraft was accelerated upwards.

Figure III.15. Vertical loads, Wingrove parameter, and $\overline{w_h^2}$ time histories for EA924 and AA350. Positive vertical loads indicate the aircraft was accelerated upwards.

Figure III.16. Vertical loads, Wingrove parameter, and $\overline{w_h^2}$ time history for SA534. Positive vertical loads indicate the aircraft was accelerated upwards.

F. WINGROVE TURBULENT KINETIC ENERGY

TKE_{wi} and a_n for each case are shown in Figs. III.17 through III.18. Table III.6 shows the reported turbulence intensity, TKE_{wi} , $Wi/2$ and ratio of $Wi/2$ to TKE_{wi} (Wingrove ratio) for each case. The Wingrove ratio is used to show the fraction of the TKE_{wi} due to vertical motions. The cases are listed in descending order based on maximum TKE_{wi} .

Similar to the results for Wi , there are large values of TKE_{wi} near regions of significant a_n . Careful examination of the results for EA924 shows a small increase in TKE_{wi} at about 275 seconds. This is not associated with any significant vertical loads but is near a region of significant lateral loads.

Maximum TKE_{wi} values range from $6.88 \text{ m}^2\text{s}^{-2}$ to $113.64 \text{ m}^2\text{s}^{-2}$. The cases in Table III.6 are arranged in similar order as Table III.5 except for PAA125 which is categorized by this metric as the most intense turbulence event. This change in order for PAA125 reveals there were large contributions of turbulence from the horizontal gusts.

SA534, a maneuvering case, and AA350 have the lowest values of TKE_{wi} . As previously discussed with Wi , the low value of TKE_{wi} for AA350 may be attributed to the inability of the ten second average to resolve the short turbulence burst.

The last column show Wingrove ratios range from 0.29 to 0.94. The small ratio for PAA125 emphasizes the large contribution of the horizontal gusts to the turbulence event. It is also noted that there appears to be a relationship between turbulence phenomena and Wingrove ratios. Wingrove ratios less than 0.65 are associated with stable air and gravity wave phenomena such as mountain waves. Large Wingrove ratios (≥ 0.85) are associated either with strong convection or maneuvering. Although the cases are few, this is an important result. It stresses the potential importance of horizontal gusts in certain types of flow patterns as part of the total turbulence picture.

Case	Reported Turbulence Intensity	Maximum TKE_{wi} (m^2s^{-2})	Maximum $Wi/2$ (m^2s^{-2})	$\frac{(Wi/2)}{TKE_{wi}}$
PAA125 (Greenland)	Severe*	113.64	33.19	0.29
UA012 (Hannibal)	Severe	71.86	38.33	0.53
PAA217 (Bermuda)	Severe	36.93	34.75	0.94
AA550 (Cimmaron)	Severe	22.70	13.36	0.58
EA924 (Bermuda)	Severe	9.90	8.52	0.86
AA350 (Chicago)	Severe	9.36	5.97	0.64
SA534 (Jamestown)	Severe*	6.88	5.85	0.85

Table III.6. Summary of Wingrove turbulent kinetic energy, $Wi/2$ and ratio of $Wi/2$ to TKE_{wi} . Asterisk indicates those cases specified as severe on the basis of passenger injuries alone.

Figure III.17. Vertical load and Wingrove turbulent kinetic energy time histories for PAA125, UA012, PAA217, and AA550. Positive vertical loads indicate the aircraft was accelerated upwards.

Figure III.18. Vertical loads and Wingrove turbulent kinetic energy time histories for EA924, AA350, and SA534. Positive vertical loads indicate the aircraft was accelerated upwards.

IV. DISCUSSION

Six potential turbulence metrics (a_n , V_t^* , U_{de} , $\epsilon^{1/3}$, Wi , TKE_{wi}) have been applied to seven incidents where aircrews reported severe turbulence or severe turbulence was implied from passenger injuries. Independent analyses of two of the turbulence incidents provided evidence that pilot/autopilot control inputs had caused maneuvering, accounting for most of the vertical loads that the aircrew had identified as atmospheric turbulence (Lester et al., 1991).

A summary of the results for all cases are presented in Table III.7. Vertical loads and U_{de} were not able to differentiate between atmospheric turbulence and maneuvering for the clearest maneuvering case (SA534). In contrast, computations of V_t^* , Wi , and TKE_{wi} all rated SA534, relatively, as the least intense turbulence case. In addition, $\epsilon^{1/3}$ categorized SA534 as light turbulence. The other maneuvering case (PAA217) was not clearly differentiated by any metric except V_t^* which ranked it as “moderate”. It is suspected that, although maneuvering was significant in that case, considerable turbulence was also present, accounting for its higher ranking.

Turbulence intensity scales have been available for a_n , V_t^* , and U_{de} for many years. However, it is clear that the range of values (as indicated by normalized intensities) is

quite small. In comparison, $\epsilon^{1/3}$, Wi , and TKE_{wi} have about an order of magnitude variation facilitating the creation of a turbulence intensity scale. In particular, TKE_{wi} shows important differences between cases. For example, considering only non-maneuvering cases, PAA125, which was associated with flight through a broad region of severe mountain wave turbulence, is rated more than five times as intense as AA550 which had a brief penetration of a region with severe mountain wave turbulence. Additionally, both aircraft were in similar flight conditions.

Variations between metrics also arose because of averaging over short bursts of severe turbulence. For example, averaging caused AA350 to be, numerically, much lower in intensity than PAA125 for $\epsilon^{1/3}$, Wi and TKE_{wi} . This raises an important question about the use of averaging. Pilots more often respond (and report) to the severe, instantaneous gust when reporting turbulence rather than some average gust value. However, averaging is required in the determination of $\epsilon^{1/3}$, Wi and TKE_{wi} . The determination of the turbulent state of the atmosphere should probably be quantified by both instantaneous and average values to provide a complete representation of the turbulent region. The correct averaging period is not clear, but an average of less than ten seconds may be adequate.

An unexpected result of the present study is the implication that V_t^* can differentiate between turbulence and maneuvering cases. Since this metric is so easy to measure and

is available on all aircraft, its use as a standard metric should receive attention in further research. However, as shown in Table III.8, TKE_{wi} captures many of the properties of an ideal metric which are objective, quantitative, aircraft independent, maneuver independent, and comprehensive. It is the only metric evaluated that includes the horizontal turbulence gust intensity which is apparently very important in stratified turbulence cases where mountain wave flow is present.

a_n	V_i^*	U_{de}	$\varepsilon^{1/3}$	Wi	TKE_{wi}
UA012 (S) 1.84	PAA125 (S) 2.91	UA012 (E) 1.95	PAA217* (E) 9.54	UA012 6.55	PAA125 16.52
PAA125 (S) 1.65	UA012 (S) 2.63	PAA217* (E) 1.94	PAA125 (E) 7.69	PAA217* 5.94	UA012 10.45
PAA217* (S) 1.48	AA550 (S) 2.35	SA534* (E) 1.88	UA012 (S) 5.23	PAA125 5.67	PAA217* 5.37
SA534* (S) 1.33	AA350 (S) 2.07	PAA125 (E) 1.80	AA550 (M) 2.15	AA550 2.28	AA550 3.30
EA924 (S) 1.31	PAA217* (M) 1.50	EA924 (E) 1.65	SA534* (L) 1.35	EA924 1.46	EA924 1.44
AA350 (S) 1.10	EA924 (M) 1.36	AA350 (S) 1.02	AA350 (L) 1.32	AA350 1.02	AA350 1.36
AA550 (S) 1.00	SA534* (M) 1.00	AA550 (S) 1.00	EA924 (L) 1.00	SA534* 1.00	SA534* 1.00

Table IV.1. Summary of turbulence case rankings for each metric. Turbulence intensities are indicated as light (L), moderate (M) and severe (S). The bottom number in each box is the maximum for each case, normalized by the minimum case value for that metric. Maneuvering cases are indicated with an asterisk.

The $\epsilon^{1/3}$ computations in this study were determined to be unsuitable as a turbulence metric because of the wide range of turbulence intensities and the rapid loss of energy in the vertical wind at small scales (see Fig. III.12). Other methods to compute $\epsilon^{1/3}$ have been developed which may improve the performance of this metric (Cornman et al., 1994), so a conclusive evaluation is not possible at this time. Further study is needed.

	PIREPs	a_n	V_t^*	U_{de}	$\epsilon^{1/3}$	Wi	TKE_w
Objective		x	x	x	x	x	x
Quantitative		x	x	x	x	x	x
Aircraft independent.			x	x	x	x	x
Maneuver independent					x	x	x
Includes horizontal gusts							x

Table IV.2. Desirable turbulence metric characteristics. An "x" indicates the metric includes that characteristic.

V. CONCLUSIONS AND RECOMMENDATIONS

An effort has been made to select an appropriate real-time turbulence metric. Six metrics were selected as possible candidates and applied to seven severe turbulence cases. Results have shown that for this study TKE_{wi} satisfies a majority of the characteristics of the “ideal” turbulence metric; i.e., within the limitations of the data, it is objective, quantitative, aircraft and maneuver independent. Additionally, it also captures the effects of horizontal gusts, making it more comprehensive than the other metrics.

TKE_{wi} is based on the isolation of only those turbulent motions that affect the aircraft. Large scale motions are removed by means of a high-pass filter. The filtered winds are squared; averaged over ten seconds, and divided by two yielding the TKE_{wi} . A shortcoming of TKE_{wi} is that the averaging reduces the intensity of turbulence and may lead to underestimations of the intensity of short turbulence bursts. This limitation can be overcome by selecting a shorter averaging period.

The usefulness of DFDR data has also been illustrated in this study. When processed correctly, DFDR data can be used to compute winds and other atmospheric quantities along the aircraft track. However, erroneous data and data losses are common. The problems are most often found in the measurement devices, within the DFDR, or in the transfer of

data between the measurement device and DFDR. Although these data anomalies can usually be removed manually, an automated, real time system will require that the data be edited automatically.

Current automated schemes for removing data anomalies are far from satisfactory and require future study. An obvious solution to reducing erroneous data is to improve the measurements, transfer, and recording of data. In addition, improvements in DFDR technology should include increasing the sampling rate for all parameters and include wind and inertial position information as a standard part of the DFDR data set. Increased data rates will enhance the accuracy of metrics and aid in turbulence research. The inclusion of wind information will aid in turbulence research by eliminating the need to perform wind computations. On the basis of these considerations, and the results of this study, the following recommendations can be made.

1. Develop an algorithm which is capable of detecting and correcting data anomalies.
2. Conduct research into the practical aspects of computing and transmitting metrics in real-time.
3. Explore the effects of adjusting the ten second averaging period in the computation of Wi and TKE_{wi} .
4. Apply Wi and TKE_{wi} to more cases in order to develop a turbulence intensity criteria.

5. Refine the filter cutoffs for Wi and TKE_{wi} . The filters used in this study were based on available aircraft frequency response data. The data were not for the specific aircraft used in this study but were for a large swept-wing bomber and a Lockheed L-1011.
6. Re-evaluate $\epsilon^{1/3}$ as a turbulence metric using the method proposed by Cornman et al. (1994). Their method is based on an aircraft model which can determine vertical winds from aircraft vertical accelerations. This results in more accurate computations of vertical winds and improved estimates of $\epsilon^{1/3}$.

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