CONVECTIVELY INDUCED TURBULENCE ENCOUNTERED DURING NASA'S FALL-2000 FLIGHT EXPERIMENTS

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1. INTRODUCTION

Aircraft encounters with atmospheric turbulence are a leading cause of in-flight injuries aboard commercial airliners and cost the airlines millions of dollars each year. Most of these injuries are due to encounters with turbulence in and around convection. In a recent study of 44 turbulence accident reports between 1990 and 1996, 82% of the cases were found to be near or within convective activity (Kaplan et al. 1999). According to NTSB accident reports, pilots' descriptions of these turbulence encounters include "abrupt", "in Instrument Meteorological Conditions (IMC)", "saw nothing on the weather radar", and "the encounter occurred while deviating around" convective activity. Though the FAA has provided guidelines for aircraft operating in convective environments, turbulence detection capability could decrease the number of injuries by alerting pilots of a potential encounter.

The National Aeronautics and Space Administration, through its Aviation Safety Program, is addressing turbulence hazards through research, flight experiments, and data analysis. Primary focus of this program element is the characterization of turbulence and its environment, as well as the development and testing of hazard-estimation algorithms for both radar and *in situ* detection. The ultimate goal is to operationally test sensors that will provide ample warning prior to hazardous turbulence encounters. In order to collect data for support of these activities, NASA-Langley's B-757 research aircraft was directed into regions favorable for convectively induced turbulence (CIT). On these flights, the airborne predictive wind shear (PWS) radar, augmented with algorithms designed for turbulence detection, was operated in real time to test this capability.

Prior to these experiments, attempts have been made to identify regions of CIT with ground-based radar. In early studies, Press and Binkley (1948) and Thompson and Lipscomb (1949) found that avoiding radar echo regions could reduce turbulence encounters near thunderstorms. However, avoiding these regions is not always possible. With the introduction of Doppler radar, turbulence may be detected from the spectrum width (Doviak and Lee 1985; Lee 1977). Lee has shown that there is a good agreement between the spectrum width from ground-based radar and aircraft penetration measurements of turbulence when the aircraft was within 1 *km* of the radar resolution volume. Furthermore, Lee found that within regions of "moderate" or "severe" turbulence the spectrum width exceeded 5 ms^{-1}. However, the spectrum width calculations may not be accurate if the radar reflectivity (RRF) is weak or if the event is greater than 60 *km* from the radar (Brewster 1984).

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Older technology airborne weather radars are limited in their capability to detect and quantify aircraft turbulence hazards. However, current generation radars with PWS capability offer new opportunities. Bowles (1999, 2000) has provided a technical basis for relating aircraft root mean square (RMS) normal loads to airborne radar observables. Similar to Lee, this technique utilizes the velocity spectrum width to predict the intensity of the turbulence ahead of the aircraft. However, signal-to-noise ratios (SNR) must be relatively high to provide a reliable detection. The SNR ratio is dependent on the returned power, i.e. RRF levels associated with the turbulence "patch".

At the moment, the RRF "floor" for the current system requirement is set at 15 *dBz*. If a hazard is detected when the RRF is below this threshold an alert will not be presented to the pilots, since the SNR may be too small to provide a reliable detection.

In this paper, we present the results of two research flights when turbulence was encountered. Described is an overview of the flights, the general radar performance, and details of four encounters with severe turbulence.

2. THE FLIGHT EXPERIMENTS

The initial flight experiments were conducted during the fall of 2000. The aircraft, a Boeing-757, was equipped with *in situ* sensors for wind, temperature and acceleration measurements, and an airborne Doppler radar for forward-looking turbulence detection. Direct penetrations into regions where RRF > 35 *dBz* were purposefully avoided at all times during the flights. Commercial carriers routinely avoid these regions, as well.

Flight days were chosen based on the likelihood of CIT somewhere within flight range of NASA Langley. General locations favorable for CIT were chosen based on real-time weather predictions from the Mesoscale Atmospheric Simulation System (MASS, Kaplan et al. 2000). MASS was run on a NASA owned workstation and provided key indices for real-time turbulence prediction.

Two flight days that include four severe turbulence encounters are discussed. Information from airborne and Nexrad radars, as well as data collected from the *in situ* sensor is presented. Nexrad data (WSR-88D) for Fort Polk, Louisiana (POE) and for Tallahassee, Florida (TLH) were acquired for the first and second days, respectively. The *in situ* turbulence measurements were quantified in terms of the peak normal load acceleration, Δn, and the RMS normal load acceleration, $\sigma_{\Delta n}$, where 0.20 $g \leq \sigma_{\Delta n} \leq$ 0.30 g is "may alert" and $\sigma_{\Delta n} > 0.30$ g is "must alert". A measurement of $\sigma_{\Delta n}$ exceeding 0.3 g is equivalent to a Δn exceeding one g, and represents severe turbulence (Pantley 1989). An event was classified as significant turbulence if it was moderate or worse, i.e. $\sigma_{\Delta n} \geq 0.20$. Details of wind recovery methods and load estimations from the *in situ* recorder can be found in Robinson et al. (2000).

Table 1. Summary of Significant Turbulence Events

Event	Peak In Situ Turbulence (g's)			Peak Vertical Wind (ms^{-1})		Horizontal Scale (*km*)/ Duration of Event (*sec*)	Peak RRF near path airborne/Nexrad
	$\sigma_{\Delta n}$	Δn_{max}	Δn_{min}	Max	Min		
190.1	0.25	0.41	-0.49	6.85	-4.48	2.2 / 10	16 / 13
190.2	0.24	0.47	-0.68	4.58	-5.73	6.0 / 28	12 / 13
190.3	0.20	0.41	-0.49	3.50	-4.19	6.5 / 30	12 / 8
190.4a	0.24	0.44	-0.58	7.01	-5.34	3.2 / 15	16 / 13
190.4b	0.28	0.48	-0.77	8.06	-6.71	3.7 / 17	16 / 18
190.4c	0.26	0.56	-0.44	12.15	-6.53	5.0 / 23	16 / 18
190.5	0.21	0.53	-0.36	9.71	-2.30	2.2 / 10	16 / 2
190.6	0.33	0.48	-0.81	9.48	-3.37	2.6 / 12	16 / 8
190.7	0.35	0.51	-1.22	11.18	-6.23	2.4 / 11	8 / 8
190.8a	0.20	0.63	-0.33	7.30	-4.45	1.5 / 7	8 / 8
190.8b	0.22	0.57	-0.46	9.56	-0.62	2.2 / 10	12 / 8
190.8c	0.22	0.69	-0.26	10.42	0.49	2.0 / 9	16 / 13
190.8d	0.25	0.62	-0.50	8.49	-1.89	3.7 / 17	12 / 18
191.1a	0.34	0.95	-0.58	6.05	-15.0	4.2 / 18	12 / NA
191.1b	0.25	0.54	-0.87	8.36	-8.05	2.8 / 12	20 / NA
191.1c	0.24	0.78	-0.48	9.32	-2.63	3.4 / 15	16 / NA
191.2	0.20	0.54	-0.50	6.82	-5.93	18.9 / 80	12 / NA
191.3	0.44	0.83	-1.40	18.41	-14.9	5.2 / 22	28 / 33

NA – Not Available

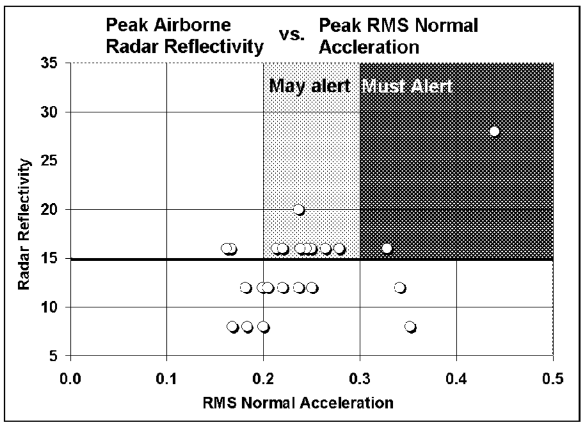

Figure 1. Comparison between $\sigma_{\Delta n}$ and airborne RRF for 23 NASA turbulence events. RRF values greater than or equal to 15 *dBz* and $\sigma_{\Delta n}$ > 0.20 are alert threshold considerations for FAA radar certification.

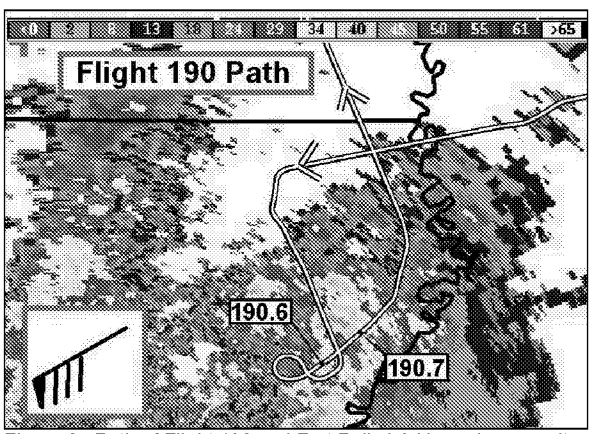

Figure 2. Path of Flight 190 and Fort Polk, LA Nexrad composite RRF (*dBz*) at 18:57:48 UTC. Flight level wind vector (*knots*) is in the inset. Bold black lines represent state borders of LA, MS, and AR. Severe turbulence encounters indicated on flight path.

3. RESULTS

Details of 18 significant turbulence events are listed in Table 1. These events were located within either rising cumulus plumes or precipitation shafts, and were characterized by large, horizontal gradients of vertical velocity. The aircraft encounters with the turbulence lasted several seconds to a minute. Smooth conditions prevailed in the clear air surrounding these events.

For all events, airborne RRF values were weak with peak values ranging from 8 to 28 *dBz* (Table 1). The Nexrad radars showed similar values for RRF near the path of each event. Note from the values in Table 1 and the comparison in Fig. 1 that *no correlation exists between the RRF level and* $\sigma_{\Delta n}$. Figure 1 contains the events from Table 1 and an additional 5 events of light turbulence ($\sigma_{\Delta n}$ < 0.20) encountered during the two flights. If the present reflectivity "floor" of 15 *dBz* were implemented, nearly half of the events in Fig. 1 would not have generated an alert. These eleven 'no-alert' events included two severe turbulence encounters.

3.1 *Flight 190*

On December 13, 2000, NASA's B-757 investigated a thunderstorm complex in northeastern Louisiana. Early in the morning, moderate turbulence had been reported over Louisiana in the vicinity of rapidly building thunderstorms. Description of the prevailing meteorological conditions can be found in Hamilton and Proctor (2002). The path for Flight 190 relative to the Fort Polk, Louisiana (POE) radar composite is shown in Fig. 2. The aircraft was operating in mostly visual meteorological conditions (VMC) at 7.3 *km* mean sea level (MSL), well beneath the anvil outflow of the thunderstorm (13.7 *km* MSL) complex. Cumulus turrets containing ice crystals and light snow emanated from a stratiform cloud region that was present at lower elevations (6.7 *km* MSL). The turbulence encounters resulted from the penetration of cumulus turrets located on the upwind flanks of two large convective systems. Data traces during two severe turbulence encounters for Flight 190 are shown in Figs. 3 and 4 and are discussed below.

Event 190.6 occurred about 43 *km* upstream of the main thunderstorm cell. Prior to the encounter, the aircraft was operating in VMC. At 18:54:33 UTC the aircraft entered the first of three cumulus turrets (see Fig. 3). Maximum RRF with these three turrets, as deduced from both airborne and Nexrad radars, was less than 15 *dBz*. An updraft/downdraft couplet, located on the downwind side of the third plume, exhibited an along track wind shear in the vertical wind exceeding 12 ms^{-1} over 170 *m*. This gradient was associated with a Δn of -0.81 *g* and a peak $\sigma_{\Delta n}$ of 0.33 *g*.

Event 190.7 was the strongest event of the day. The aircraft, operating in VMC prior to this event, encountered a growing cumulus plume (see Fig. 4). Although snow was present within the cloud, RRF was weak at 8 *dBz*. Similar to Event 190.6, the aircraft encountered a sharp updraft/downdraft interface located near the downwind side of the plume. The incurred peak Δn at this interface was –1.22 *g* with a $\sigma_{\Delta n}$ for the event at just over 0.35 *g*, which again rates as a severe encounter.

3.2 *Flight 191*

On December 14, 2000 the B-757 investigated a line of convection over Southern Georgia and the Florida Panhandle. This line was a remnant of the convective complex encountered on the previous day. However, it had now weakened and manifested itself as a narrow but nearly continuous line of convection extending northeastward from the Gulf (Fig. 5). Description of the prevailing meteorological conditions can be found in Hamilton and Proctor (2002).

The path for Flight 191 relative to the TLH radar composite is shown in Fig. 5. The aircraft was operating near the top of the convective line at an altitude of 10.0 *km* MSL. Continuous turbulence, though relatively light at times, was encountered while flying within the cirrus outflow region. The strongest encounters were associated with the penetration of cumulus plumes that were rising through the cirrus outflow. *In situ* measurements from two of the events are shown in Figs. 6 and 7 and are discussed below.

Event 191.1 was a relatively long, continuous turbulence event that is split into three subevents (see Table 1). During Event 191.1, peak airborne RRF ranged between 12 and 20 *dBz* along the flight path. Unfortunately, TLH radar imagery at flight level was not available, since the event was near the radar site. For the same reason, Nexrad data was unavailable for other events during this day, as well. Event 191.1a was the strongest of the three subevents, with a peak $\sigma_{\Delta n}$ of 0.34 *g*, which is severe. The peak Δn of 0.95 occurred near the interface of a fairly broad downdraft (-15 ms^{-1}) located downwind of an updraft (6 ms^{-1}).

Event 191.3 (referred to as '191-06' in public forums; Hamilton 2001; Proctor et al. 2002) was the strongest event encountered during the two flights. Event 191.3 occurred as the aircraft penetrated the northwestern edge of an isolated cumulus plume that was ascending through the outflow region. The event was characterized by continuous moderate and severe turbulence within the plume followed by a severe 'jolt' upon exiting of the plume into the smooth clear air. The peak normal load occurred at the interface of an updraft/downdraft couplet located on the downwind side of the plume (See Fig. 7 at 18:44:21 UTC).

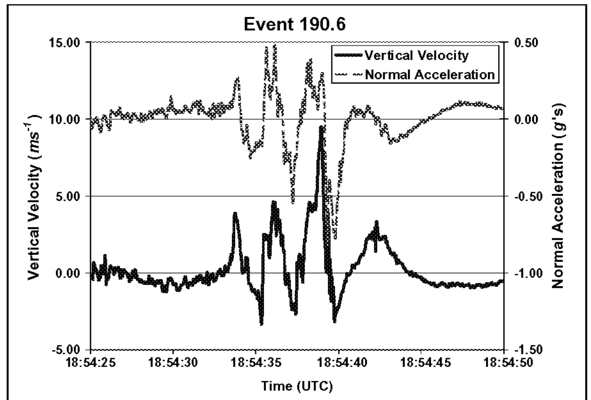

Figure 3. Plot of Vertical Velocity (solid line in ms^{-1}) and Δn (dotted line in g's) for Event 190.6.

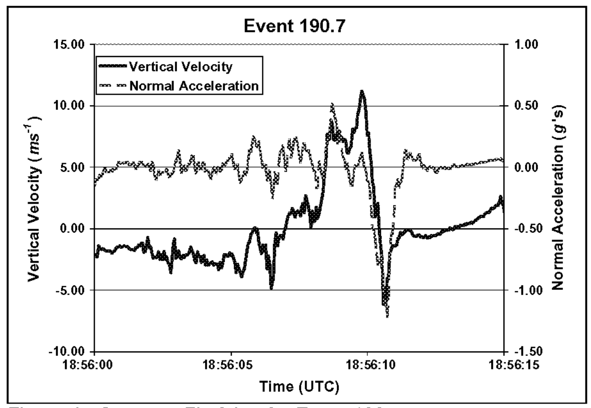

Figure 4. *Same as Fig 3 but for Event 190.7.*

Event 191.3 is of similar intensity to many of those in previous accident encounters. In an analysis of 52 turbulence accidents/incidents (Bowles, personal communication), event 191.3 ranks among accident cases investigated by the National Transportation Safety Board (refer to Figure 15 in Hamilton and Proctor 2002).

Comparisons between the airborne and TLH radars for Event 191.3 showed nearly identical values for both RRF and spectrum width (see Figs. 13 and 14 in Hamilton and Proctor 2002). Both radars captured peak spectrum widths of 7 ms^{-1} near the downwind side of the plume, which according to Lee (1977) indicates severe turbulence.

4. Summary

This paper summarizes results from encounters with convectively induced turbulence during NASA's fall 2000 flight experiments. During the flights, NASA's B-757 avoided regions of radar reflectivity greater than 35 *dBz*. Continuous turbulence was encountered with convective clouds and precipitation, while smooth conditions existed in the surrounding air mass. In all events, RRF levels were low, with peak values along the flight path being between 8 and 28 *dBz*.

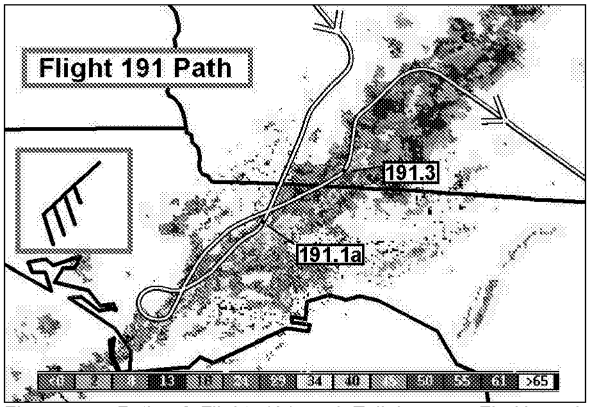

Figure 5. Path of Flight 191 and Tallahassee, FL Nexrad composite RRF (*dBz*) at 18:44:21 UTC. Flight level wind vector (knots) is in the inset. Bold black lines represent state borders of FL, GA, and AL. Severe turbulence encounters indicated on flight path.

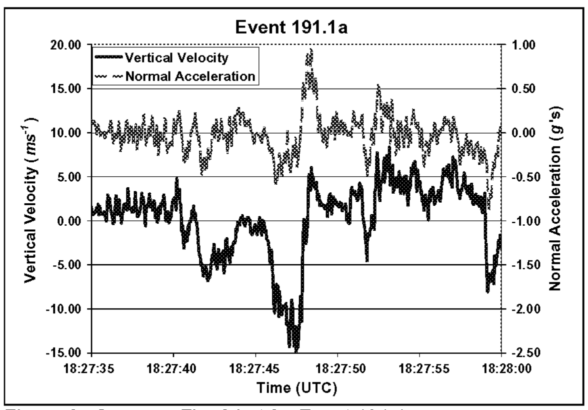

Figure 6. Same as Fig. 3 but for Event 191.1a.

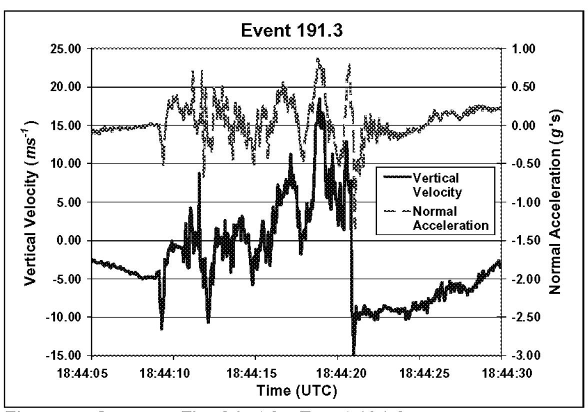

Figure 7. Same as Fig. 3 but for Event 191.3.

All of the significant encounters with turbulence were associated with an along-track shear in the vertical wind. In all severe encounters, peak normal loads occurred at the interface of an updraft/downdraft couplet located on the downwind side of the convective plumes. The most severe encounter with turbulence during the fall deployment, Event 191.3, exceeded the turbulence intensity of several accidents involving commercial aircraft.

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