Severe Winds in the Dallas/Ft. Worth Microburst Measured from Two Aircraft

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Advanced analytical methods are applied to the digital flight data and air traffic control radar records from two airliners, Delta flight 191 and American flight 539, that penetrated a microburst at the Dallas/Ft. Worth Airport on August 2, 1985. The results for Delta 191 (which crashed) show that the aircraft encountered a strong downburst followed by a strong outflow accompanied by large, rapid changes in the vertical wind. The rapid changes in the vertical wind detected near the ground are attributed to vortex-induced turbulence. The next aircraft, American 539, made a go-around 110 s after Delta 191 and traversed the microburst at an altitude of about 2500 ft above the ground. The measured winds during this go-around indicate a broad pattern of downflow in the microburst, with regions of upflow at the extreme edges. The combined results indicate a microburst that was increasing in size with vortex-induced turbulence embedded in a strong outflow near the ground. These wind measurements provide a realistic description of the microburst wind environment that can be used in simulator studies and pilot training and provide a standard of comparison for ongoing experiments and modeling of microbursts involving vortex rings.

Introduction

LOW-LEVEL microbursts are a continuing problem that must be better understood in the interest of aircraft safety.[1] One way to investigate the nature and cause of severe microburst encounters is through analysis of airline flight records. Previous wind-shear accidents (Table 1) have primarily involved airliners with the older metal-foil flight recorders that do not record enough information to uniquely determine the winds. In one previous case, however, an L-1011 with an on-board digital recorder made a go-around through a microburst at the John F. Kennedy Airport (JFK) on June 24, 1975. Also, some foreign airliners with on-board digital recorders have penetrated microbursts. More recent microburst encounters have involved modern airliners with digital flight data recorders (DFDR's). As described in Ref. 2, advanced analytical methods have been developed to utilize the digital flight records, along with air traffic control (ATC) radar tracking data, to measure the time history of the wind vectors in severe turbulence encounters.

In cooperation with the National Transportation Safety Board (NTSB), these advanced analytical methods have been applied to the digital flight records from two aircraft, Delta 191 and American 539, that penetrated the microburst at the Dallas/Ft. Worth Airport (DFW) on August 2, 1985. Delta 191, an L-1011, encountered the microburst on final approach and contacted the ground about 1 mile short of the runway. Some background about the Delta 191 accident and the measured winds is presented in Refs. 2–7. Most recently, the advanced data analysis methods have been applied in a further analysis of the flight and ATC radar data from American 539, which was the following aircraft. American 539, an MD-80, made a go-around 110 s after the Delta 191 accident and traversed the microburst at an altitude of about 2500 ft above the ground.

This paper first outlines the method used to analyze the digital flight data and then presents the measured winds from the two aircraft at DFW. These measured winds along the different flight paths are compared and discussed in relation to previous findings about the microburst phenomenon.

Presented as Paper 87-2340 at the AIAA Guidance, Navigation and Control Conference, Monterey, CA, Aug. 17–19, 1987; received Feb. 5, 1988; revision received Oct. 3, 1988. This paper is declared a work of the U.S. Government and is not subject to copyright protection in the United States.

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Analysis Method

Airliners that have been certified since 1969 are equipped with DFDR's that record an extensive set of variables (Table 2). These digital flight records, along with ATC tracking records, can be used to determine the time histories in the three components of the winds along the aircraft flight path. In this analysis, the accelerations measured on board the aircraft are integrated to determine the time history of the flight-path–matching ATC radar position data.[2] The wind velocity is computed as the difference between the vehicle inertial velocity and its velocity with respect to the air mass. Figure 1 shows a block diagram of the overall analysis procedure.

The equations of motion are in an Earth frame with the x axis pointing north, the y axis pointing east, and the h axis vertical:

$$\ddot{x} = a_x \cos\theta \cos\psi + a_y(\sin\phi \sin\theta \cos\psi - \cos\phi \sin\psi) + a_z(\cos\phi \sin\theta \cos\psi + \sin\phi \sin\psi)$$

$$\ddot{x} = a_x \cos\theta \sin\psi + a_y(\sin\phi \sin\theta \sin\psi + \cos\phi \cos\psi) + a_z(\cos\phi \sin\theta \sin\psi - \sin\phi \cos\psi)$$

$$\ddot{h} = a_x \sin\theta - (a_y \sin\phi + a_z \cos\phi) \cos\theta - g$$

Table 1 Low-level wind-shear encounters

Date	Location	Aircraft	Recorder
	Accidents		
6/24/75	JFK	B-727	Foil
8/7/75	Denver	B-727	Foil
6/23/76	Philadelphia	DC-9	Foil
6/3/77	Tucson	B-727	Foil
8/22/79	Atlanta	B-727	Foil
7/9/82	New Orleans	B-727	Foil
6/1/84	Denver	B-727	Foil
6/13/84	Detroit	DC-9	Foil
8/2/85	DFW	L-1011	Digital
	Go-arounds		
6/24/75	JFK	L-1011	Digital
8/2/85	DFW	MD-80	Digital

where a_x, a_y, and a_z are the body-axis accelerations, and ϕ, θ, and ψ are the body-axis Euler angles. Integration of these differential equations provides estimates of inertial velocity $(\dot{x},\dot{y},\dot{h})$ and position (x,y,h). A set of initial conditions and bias corrections is determined by matching the calculated x and y time histories to ATC radar position data and by matching the calculated h time history to the DFDR altitude data.

The wind vector is computed as the difference between the vehicle inertial velocity and its velocity with respect to the air mass:

$$W_x = \dot{x} - V \cos\psi_a \cos\gamma_a$$

$$W_y = \dot{y} - V \sin\psi_a \cos\gamma_a$$

$$W_h = \dot{h} - V \sin\gamma_a$$

where the true airspeed V is computed from the flight records and the wind-axis Euler angles (γ_a, ψ_a) are computed using the identities

$$\sin\gamma_a = \cos\alpha \cos\beta \sin\theta - C \cos\theta$$

$$\tan(\psi_a - \psi) = \frac{\sin\beta \cos\phi - \sin\alpha \cos\beta \sin\phi}{\cos\alpha \cos\beta \cos\theta + C \sin\theta}$$

$$C = \sin\alpha \cos\beta \cos\phi + \sin\beta \sin\phi$$

Table 2 Digital flight data recorder measurements

Variable	Measurement rate, per s L-1011	Measurement rate, per s MD-80
Normal acceleration	4	8
Lateral acceleration	4	4
Longitudinal acceleration	4	4
Roll angle	1	1
Pitch angle	1	1
Heading angle	1	1
Angle-of-attack vanes	2	a
Pressure altitude	1	1
Indicated airspeed	1	1
Elevator deflection	1	1
Rudder deflection	2	2
Engine thrust	1/4	1

[a]Not included.

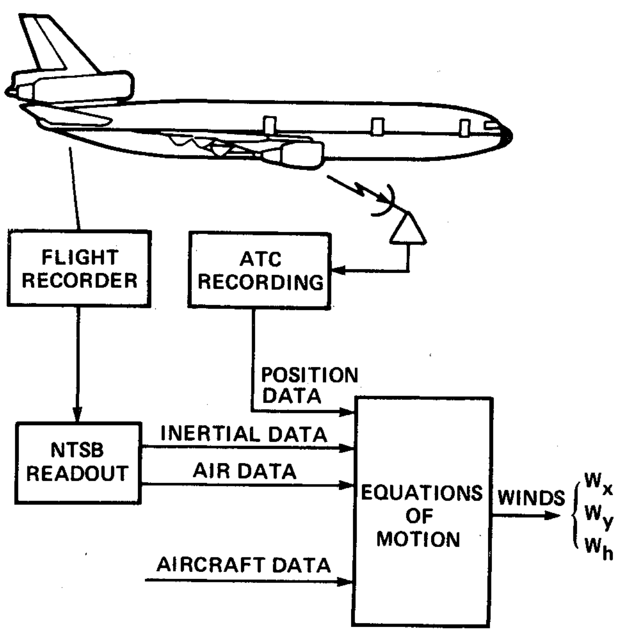

Fig. 1 Estimation of winds from flight and ATC records.

where α is the angle of attack and β is the angle of sideslip.

The angle of attack α was derived from measured vane angles for the analysis of Delta 191. (It should be noted that there were short intervals during the microburst encounter when these vanes were rate-limiting.) The vane angles were not recorded for American 539; in that case, α was determined from the equation

$$C_L = C_L(\alpha,\delta_F) + C_{L_{\delta e}} + C_{L_q}(\bar{c}q/2V)$$

where $C_L(\alpha,\delta_F)$, $C_{L_{\delta e}}$, and C_{L_q} are based on the aircraft aerodynamics. The measured lift coefficient C_L, flap position δ_F, elevator position δ_e, and pitch rate q were derived from the flight recorder data, leaving the α as the solved variable. (This method of deriving unmeasured flow angles is discussed further in Ref. 8.)

In a similar manner, the angles of sideslip β for Delta 191 and American 539 were determined from the equation

$$C_Y = C_{Y_\beta}\beta + C_{Y_{\delta_r}}\delta_r + C_{Y_r}(br/2V)$$

where C_{Y_β}, $C_{Y_{\delta_r}}$, and C_{Y_r} are based on the aircraft aerodynamics. The measured side-force coefficient C_Y, rudder position δ_r, and yaw rate r were derived from the flight recorder data, leaving β as the solved variable.

Further details about the general analysis procedure and previous applications are given in Refs. 9 and 10.

Results and Discussion

The results obtained from the analysis of the Delta 191 and American 539 data are compared in Figs. 2 and 3. In these figures, the data for the two aircraft are presented as functions

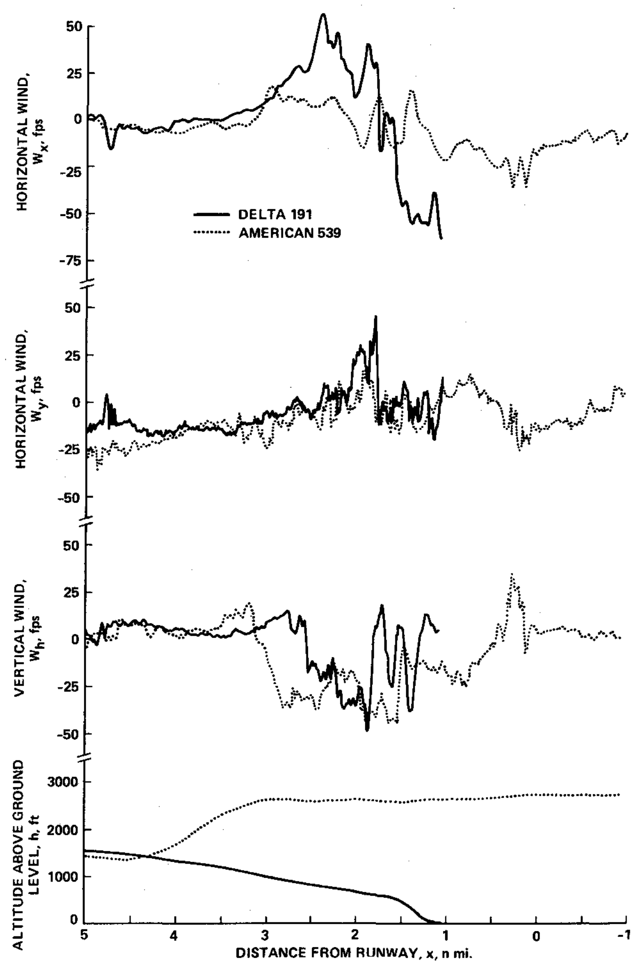

Fig. 2 Measurements from Delta 191 and American 539 encounters with a microburst at DFW (August 2, 1985).

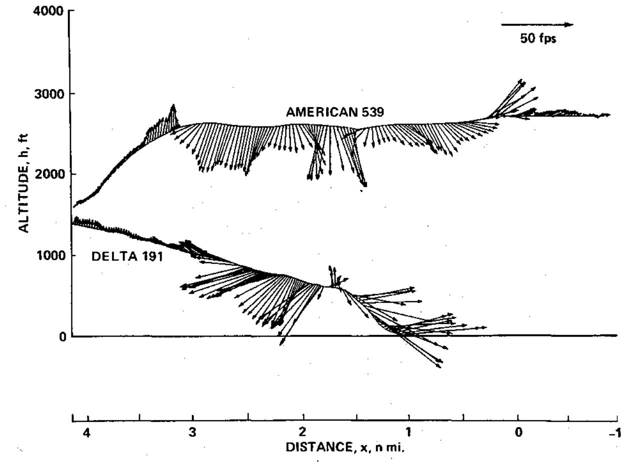

Fig. 3 Wind vectors along the flight paths of Delta 191 and American 539.

of position with respect to the runway. Figure 2 shows the height above ground along with the three components (W_x, W_y, W_h) of the measured winds. Figure 3 shows the profile of the wind vectors (W_x and W_h) in the vertical plane.

As Delta 191 descended through 1000 ft approaching the runway, the results show it was experiencing an updraft and increasing head wind. The vertical wind component W_h increased to about 15 ft/s, and the horizontal wind component W_x increased to over 50 ft/s. The aircraft next encountered a strong downflow followed by a rapid change in vertical wind direction, followed by further changes that occurred about 5 s apart. In the period of major downflow, the aircraft experienced vertical winds of the order of -10 to -40 ft/s. During that time, there was a change to a tail wind of over 50 ft/s. Delta 191 contacted the ground about 360 ft to the left of the approach path and about 6300 ft short of the runway.

American 539, the following aircraft, executed a go-around at 1400 ft above the ground and then climbed to an altitude of 2500 ft, where it penetrated the microburst. The results show that the aircraft first experienced an updraft of about 15 ft/s and a head wind of 15 ft/s. The aircraft next encountered a strong downflow over a fairly large distance, followed by a strong updraft. In the period of major downflow, the aircraft experienced vertical winds of the order of -10 to -40 ft/s. During this time, there was a change to a tail wind of 25 ft/s.

In comparing the measured winds we note that the overall changes from head winds to tail winds occur in nearly the same location over the ground. This would suggest that the center of the microburst had not appreciably changed location during the time when these two sets of measurements were made. American 539 passed through the center of the microburst about 110 s after Delta 191.

It can be observed that the region of the downflow measured for American 539 was larger than that for Delta 191. The results indicate that American 539 entered the region of the downflow about 0.5 n.mi. farther out from the runway than Delta 191. Also, the data from American 539 indicate that portions of the downflow had extended to near the end of the runway. The total region of downflow measured by American 539 was about 3 n.mi. in diameter. This appearance of an expanding microburst is consistent with meteorological data gathered at DFW[3] and with a numerical simulation of the DFW downburst.[7] These previous studies indicate that the storm had reached the end of the runway and that its diameter had expanded to about 3.7 n.mi. near ground level during the time that American 539 traversed the microburst.

In comparing the magnitudes of the changes in the horizontal winds W_x, we can observe that Delta 191 was closer to the ground and experienced the stronger outflow from the microburst. The results for Delta 191 indicate that there was a head-wind/tail-wind change of 100 ft/s; for American 539 this change was 40 ft/s. In these two cases, the rate of change in the horizontal winds shows significant differences. For Delta 191, the change in horizontal wind occurred over a 26-s period, corresponding to a rate of change of -3.85 ft/s^2. For American 539, the change in horizontal wind occurred over a 50-s period, corresponding to a rate of change of -0.80 ft/s^2.

In comparing the pattern in W_h, we observe that Delta 191 was nearer to the ground and experienced the more rapid changes in the vertical winds (Fig. 2). The results for Delta 191 show several rapid, large changes in the vertical winds; for American 539, the changes in vertical winds are less extreme and appear primarily at the edges of the downflow. Previous studies have indicated that microbursts might involve vortices that induce variations in the observed pattern of the winds.[11-15] These previous studies indicate that, when a vortex nears the ground, its vorticity increases, providing a mechanism for the large changes in vertical wind that are observed near the ground. The changes in the vertical winds near the ground, such as those Delta 191 experienced, appear to be induced by vortices embedded in the outflow.[3,5] The changes in the vertical winds observed higher above the ground, such as with Delta 191 entering the downflow at 1000 ft and American 539 traversing the downflow at 2500 ft, are consistent with the hypothesized ring vortex at the front of the expanding microburst.[3,5,7]

These combined results for two aircraft penetrating the microburst at different altitudes indicate that the more significant outflow winds and the more rapid, larger changes in the vertical winds occur near the ground. For Delta 191, the major control problems occurred near the ground. The aircraft was well-controlled until it was about 600 ft from the ground, at which altitude the major wind changes were encountered. The aircraft was buffeted by wind changes in the lateral axes, experienced a rapid change in angle of attack, and a decrease in airspeed. The results show that at this time (near 600 ft above the ground) the peak-to-peak magnitude of the rapid changes in wind were over 70 ft/s along the W_h axis and over 45 ft/s along the W_x and W_y axes. As the aircraft descended further, the results indicate that it encountered additional turbulence and an increasing tail wind.

These results are important in considering the control of aircraft in microburst encounters. With the change from head wind to tail wind that is inherent in microburst encounters, it has been suggested that control might be accomplished by a trade off of decreasing altitude to increase airspeed. The results presented here indicate that this proposed strategy could lead to additional problems. By allowing the aircraft to descend near the ground, it will penetrate the region of strongest outflow, and, as these results show, near the ground are rapid changes in the winds that can cause short-period control problems.

The results from Delta 191 appear to be the first substantial evidence from flight records to show the large and rapid changes in the wind that can be encountered during microburst encounters. In one previous instance (June 24, 1975), an L-1011 with a digital flight data recorder made a go-around through a microburst at JFK. In comparison with the Delta 191 results, these previous L-1011 data[4] suggest similar changes in the vertical winds that occurred at about 5-s intervals, but those changes were of less magnitude than those that Delta 191 encountered. The available flight data in other wind-shear encounters (Table 1) are from metal-foil recorders. As mentioned earlier, the limited data available from these foil recorders cannot be used to determine with certainty any rapid changes in the winds or in the associated turbulence environment.

Conclusions

Wind measurements obtained form the digital flight records on board modern airliners provide a detailed description of the turbulence in a severe microburst. The measured winds for Delta 191 show that the aircraft encountered a strong downflow followed by a strong outflow accompanied by large, rapid changes in the vertical winds. The measured winds during the subsequent go-around of American 539 indicate a broad pattern of downflow with regions of upflow at the extreme edges. These results indicate a microburst that is increasing in size with vortex-induced turbulence embedded in a strong outflow near the ground.

The measured winds provide a realistic description of microburst-induced turbulence that can be used in manned flight simulators and in aircraft control studies to better understand the operating problems that can be encountered in low-level microbursts. Also, these wind data can be used as a standard of comparison in ongoing experiments and modeling of microbursts involving vortex rings.

Acknowledgment

The authors thank Jeffrey Gorney, Dennis Grossi, Gregory Salottolo, and others on the staff at the National Transportation Safety Board, Washington, D.C., for their aid in obtaining the data used in this report.

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