Simulated Flight Through JAWS Wind Shear

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The Joint Airport Weather Studies (JAWS) Project was designed to investigate low altitude wind shear of the type believed to have caused several recent air carrier accidents, including the crash of Pan Am Flight 759 in New Orleans in 1983 Approximately 70 microbursts and numerous gust fronts have been identified by Doppler radar, the primary instrument used in JAWS, and several have been chosen for high-resolution, three dimensional wind field reconstruction using multiple Doppler radar techniques Of these, one case in particular has been investigated with a six degree of-freedom "piloted" numerical aircraft model

Several approach to landings and takeoffs were made through this case to investigate landing and takeoff phase aircraft flight dynamics through the different wind shears Results indicate that apparently similar wind structures within the same weather feature, separated by only a few hundred meters, can produce radically different flight paths Methods of incorporating these data into training and research flight simulators are presented and discussed

Introduction

THE Joint Airport Weather Studies (JAWS) field experiment, conducted near Denver in 1982, provided spatial and time-dependent (four-dimensional) velocity fields of microbursts Details on JAWS can be found in Refs 1 and 2. Velocities were measured with three Doppler radars—CP-2, CP-3, and CP-4—located relative to Stapleton International Airport as shown in Fig 1 Processing of the dual and triple Doppler returns resulted in a rectangular grid array of the three Cartesian velocity components of the wind The origin of the $(x,y\ z)$ coordinate system to which the grid is referenced is located at CP-2 The x coordinate is measured positive toward the east, the y coordinate positive toward the north, and the z coordinate positive upward All wind velocities are absolute; that is, relative to a fixed-Earth coordinate system with no storm motion removed An analysis of aircraft performance in the three dimensional wind field is presented in this paper; the fourth dimension of time is not specifically considered The purpose of the analysis is to prepare computer models of microburst wind shear from the JAWS data sets for input to flight simulators and for research and development of aircraft control systems and operational procedures

The paper first describes the data set and the method of interpolating velocities and velocity gradients for input to the six degree-of-freedom equations governing the motion of the aircraft [3] The results of the aircraft performance analysis are then presented and the interpretation of the results as to regions of severe, moderate, and weak shears is described Paths through the 5 August 1982 severe microburst are then recommended for training and operational applications Selected subregions of the flowfield defined in terms of planar sections through the wind field are given for application to simulators with limited computer storage capacity; that is, for computers incapable of storing the entire array of variables needed if the complete wind field is programmed

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Data Description

Figure 2 illustrates the grid system For the August 5 microburst data set, the total volume element probed by the Doppler radar was 12x12 km in the horizontal plane and 2 km

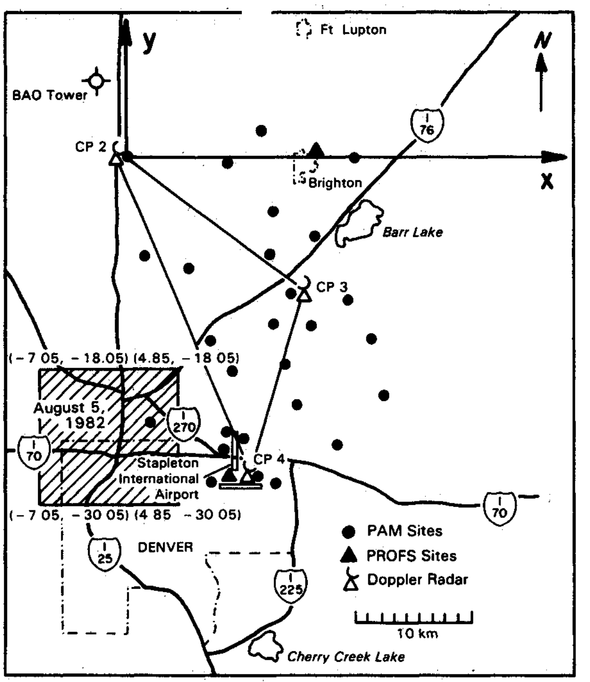

Fig 1 Location of Doppler radars CP 2, CP 3, and CP 4 The origin of the xyz coordinate is located at CP 2 The location of the August 5, 1982 data set is indicated by the shaded area

in the vertical direction The three Cartesian velocity components (W_x W_y W_z) are computed on a grid with 150 m spacing in the horizontal and 250 m spacing in the vertical [4] Thus, the total number of grid points for the data set is 81x81x9 or 59,049 Since there are three velocity components at each grid point, the total number of variables to be stored is 177,147; approximately 692K bytes of memory are required for real time data storage alone This is an excessive amount of storage for some flight training simulators Thus, to minimize data storage requirements, subsets of the full data set volume have been selected and will be described later

To carry out analysis of the aircraft's performance, the three wind speed velocity components along with the nine derivatives must be input to the aircraft governing equations of motion Since these vary spatially, it is necessary to three dimensionally interpolate their values to any arbitrary point within the data grid when the aircraft is not at a grid point A volume weighted interpolation scheme is utilized, as illustrated in Fig 2 A volume element of the grid is assumed to have velocity $W1$, $W2$, $W3$, , $W8$ at each respective corner or nodal point of the element This volume element is then divided into eight subvolume elements through point P at which the aircraft is located Volume elements diagonal to the respective nodal points are the weighting elements for averaging Thus the value of the wind speed at point P is given by

$$W_P = \sum_{i=1}^{8} W_i V_i \Big/ \sum_{i=1}^{8} V_i$$

Utilizing the above interpolation technique, wind speed components at the 250 m level are computed and plotted in three dimensional form in Fig 3 Note that the vertical velocity is plotted with the negative values upward Thus the peaks in the three-dimensional plots represent downdrafts.

In the governing equations of motion, wind shear effects for the aircraft appear as spatial derivatives There are nine derivatives which were computed by interpolation using a similar volume averaging technique as described earlier

Selection of Wind Shear Paths and Severity

Paths through the wind fields, which represent severe, moderate or weak shears relative to airplane performance, were selected first by inspection Figure 4 shows a horizontal plane at approximately ground level through the August 5 data set The orientation of the arrows indicates the direction, while their length indicates the magnitude of the horizontal wind at each grid point in the surface plane (see scale at lower right) Coordinate values given at the corners of the plane present the x and y coordinates relative to the origin located at CP 2 The diverging outflow of the microburst is easily discernable, with the center located approximately at (−1 7 km, −24 0 km)

Paths were selected relative to the center of the microburst with the objective of finding the maximum headwind-to tailwind change in wind speed. Paths AB, YZ, and CD have approximately the maximum change in wind speed. Flight path IJ was visually selected to give a crosswind shear Finally, flights paths KL and GH were selected to provide a measure of weak but challenging wind shear

Severity of the flight paths is determined by computing aircraft performance for both approach and takeoff along both directions of each path Note that other paths were

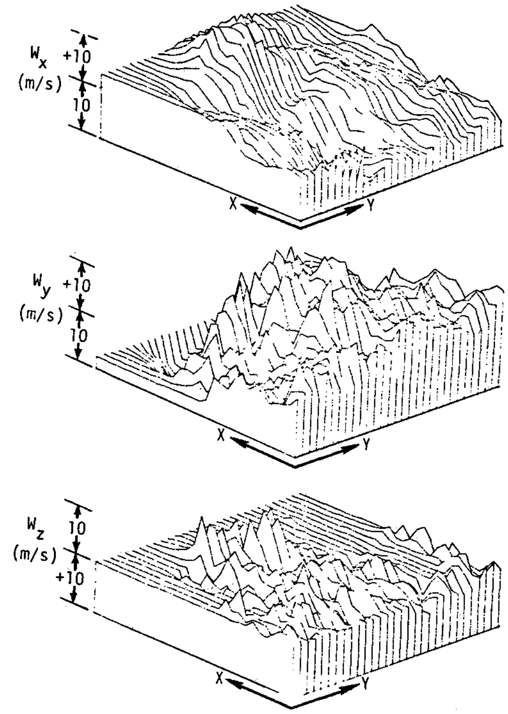

Fig 3 Wind speed components at the 250 m level

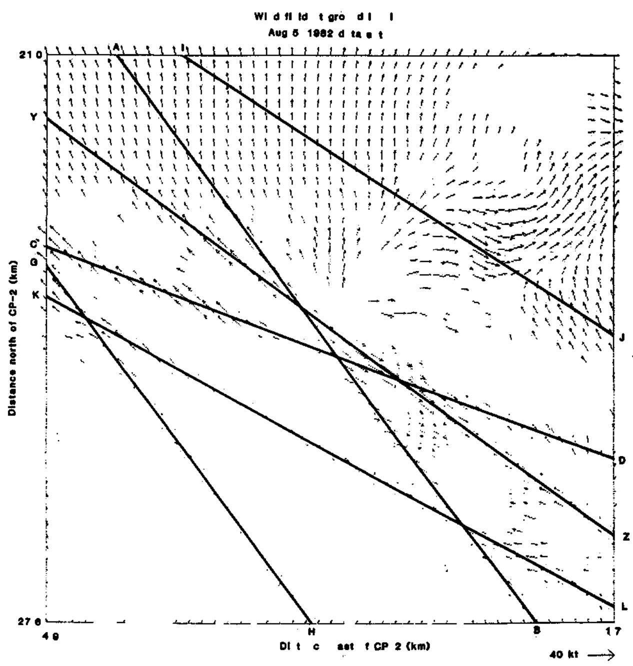

Fig 4 Flight paths overlaid on horizontal wind speed vectors

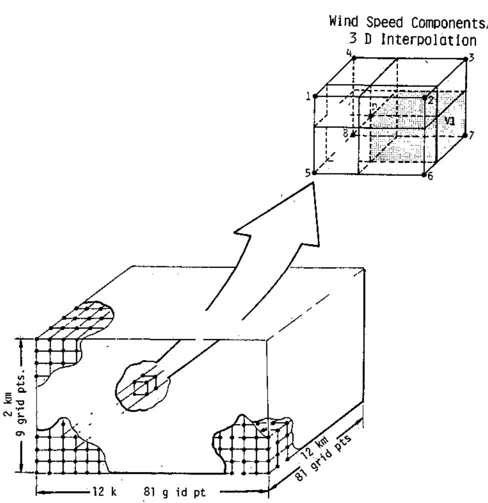

Fig 2 Handling the variable wind

investigated; however, those shown in Fig 4 are selected for presentation and discussion.

To investigate the influence of microburst position relative to the runway, the runway location is shifted with respect to the storm along the path Figure 5 illustrates the nomenclature used in defining the orientation of the runway to the wind field for the approach case A 3 deg glide slope is positioned over each path The runway is positioned relative to the center of the microburst such that an aircraft following the glide slope passes through the center of the microburst at a given height designated as z_o The x_o, y_o coordinates designate the position in the horizontal plane at which z_o is measured. Values of x_o and y_o are measured relative to an origin located at (−7 05, −18 05 km) measured from CP-2 as shown in the figure

Approach Paths

To test the severity of each path through the microburst, the flight of a 727 type aircraft is computed when attempting an approach along the glide slope The aircraft is trimmed at the 2000-ft level A simple control law algorithm[5] is used to maintain the 3 deg glide slope If the airplane remains exactly on the instrument landing system (ILS) beam, it passes through the center of the microburst located at the position x_o and y_o at a height z_o The approach criteria call for an aircraft to attempt a go-around if it is outside a 0 7 deg localizer/glide slope cone centered on the ILS beam This go around criterion is somewhat less severe than that used in practice In practice, a pilot is generally required to initiate go around if he is one "dot" (approximately 0 2 deg) outside the localizer/glide slope

If at any time the aircraft is outside a 0 7 deg localizer/glide slope, a go-around, consisting of full thrust and a 15 deg pitch angle command, is initiated If the aircraft cannot achieve go-around with a 15 deg pitch angle command, the case is rerun with a 20 deg pitch angle command If a go around fails in both cases, the wind shear is considered moderate Finally, the wind shear along a given path is considered weak if the aircraft does not pass outside the localizer/glide slope during an approach

Each selected path is named according to the conventional shown by Fig 6 Figure 7 shows the computed approach of the aircraft along path $AB+30AP$ In this case, the runway is located such that if the aircraft remains on the glide slope it passes through the center of the microburst at roughly 300 ft above the ground The airplane tracks the glide slope reasonably well to a level of 300 ft (i.e , at the center of the microburst) but then loses airspeed and sinks rapidly On losing the ILS, the aircraft is commanded to full thrust and to a pitch angle of 20 deg; however, because of the severe sinking speed and loss of airspeed (increasing tailwind) so near the ground, it is unable to recover Figure 8 shows a similar situation for an approach along flight path $CD+00AP$ For this case, the runway is located such that the center of the microburst is directly over the end of the runway The aircraft drops below the localizer beam at roughly 400 ft altitude prior to encountering the center of the microburst. The aircraft negotiates a go-around and climbs to approximately 1600 ft. At this point, it passes through the center of the microburst The downdraft velocity at the center of the microburst is much higher aloft than near the surface because the vertical wind must be zero at ground level Thus, as the aircraft climbs to 1600 ft on its go around, it encounters a very strong downdraft and sinks with the air mass However, the aircraft has sufficient performance to negotiate the downdraft and completes a successful go-around Many studies, such as those depicted by Figs 7 and 8, were carried out to classify various profiles through the wind as severe, moderate/severe, moderate, and weak Four paths recommended for general training scenarios are listed in Fig. 5

Takeoff Paths

A number of studies to classify takeoff wind fields were also carried out In the takeoff algorithm, the aircraft thrust is increased through the thrust control law until the aircraft accelerates to 60 knots of airspeed The thrust is then held constant as the aircraft reaches takeoff speed. At takeoff speed a 10 deg pitch angle is commanded. The rate of pitch angle increase is controlled at 3 deg/s until 10 deg is

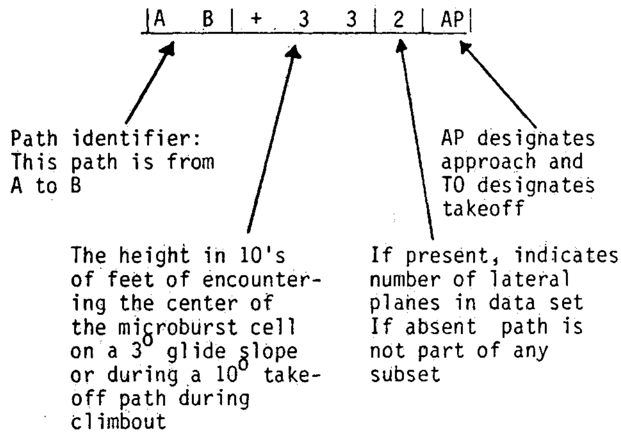

Fig 6 Wind field designation conventions

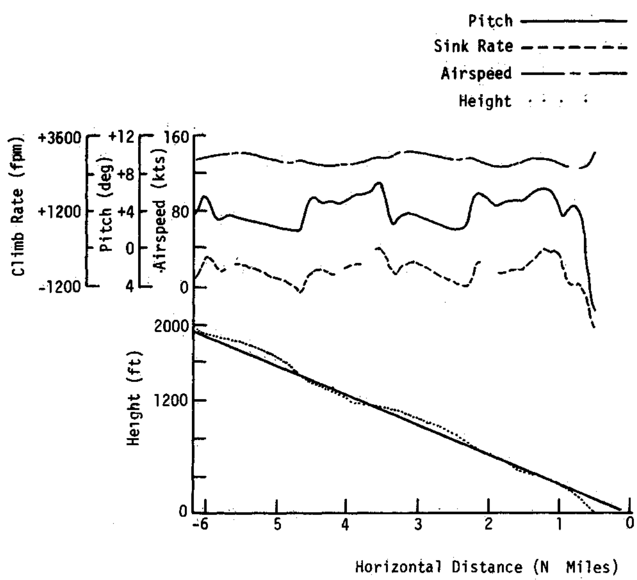

Fig. 7 Approach in wind field (AB + 30AP)

Flight Path	x_o ft x 10^3 [m]	y_o ft x 10^3 [m]	o ft [m]	(deg)	Classification	Designator
AB	17.2 [5250]	19.2 [5850]	+328 [+100]	52 7	S e e	AB 30 AP
YZ	17.2 [5250]	19.2 [5850]	+492 [+150]	37 0	Se e	YZ 49 AP
CD	16.2 [4950]	20.4 [6230]	0 [0]	19 9	M de t	CD 00 AP
GH	13.3 [4050]	25.1 [7650]	0 [0]	52 7	We k	GH 00 AP

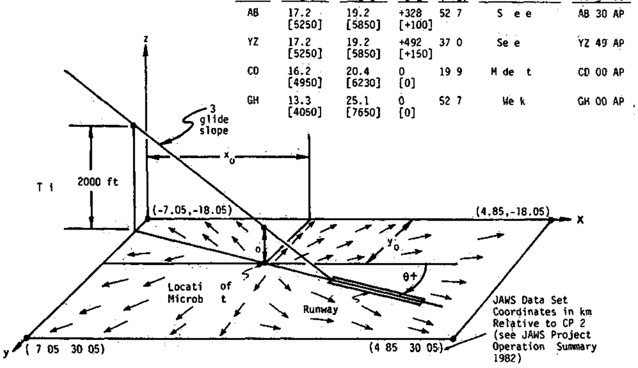

Fig 5 Description of coordinate system and approach path orientation.

established The aircraft then climbs out along an ap proximately 10 deg takeoff path With zero wind conditions, a run of approximately 5000 ft is required before liftoff occurs

The location of the center of the microburst is selected relative to this liftoff point, in a manner similar to that for the approach The value of z_o for takeoff is defined as the height at which the aircraft would pass through the center of the microburst when accelerating along the runway for 5000 ft and then climbing out along a 10 deg path Note that a negative z_o indicates the aircraft is passing through the center of the microburst while still on the runway

For every flight path investigated, the aircraft was able to take off without impacting the ground However, there were many situations where liftoff was barely achieved and would not have succeeded if obstacles similar to those typically found around an airport were accounted for in the computer simulation Figure 9 is a typical example of takeoff in wind field AB + 07TO, In this case, the center of the microburst is located where the aircraft passes over a point 70 ft above the ground (on a 10 deg departure path) or approximately 400 ft horizontally from the departure end of the runway Figure 9 shows that the aircraft lifts off and climbs to roughly 50 ft, where it begins to encounter a rapidly increasing tailwind The aircraft has an insufficient performance margin to maintain altitude and actually sinks to roughly 30 ft above the runway Although the aircraft is accelerating relative to the ground, it is losing airspeed because the headwind is decreasing at a greater rate Eventually the resultant tailwind ceases and the airplane encounters an increasing headwind which allows it to recover A constant climb rate does not occur, however, until roughly a full nautical mile from the point of initial liftoff This wind shear is classified as severe

Figure 10 shows takeoff performance in a less severe wind field In this particular situation, the microburst occurs at a negative value of $z_o = -160$ ft This corresponds to a horizontal position roughly 600 ft from the beginning of the runway As indicated in the figure, the airplane requires a longer period of time to lift off The reason is that the aircraft is attempting to gain flying speed in an increasing tailwind after passing through the center of the microburst while still on the runway After liftoff, the aircraft climbs relatively slowly due to the fact that the tailwind is still increasing Finally, the aircraft encounters an increasing headwind and resumes a normal climb out

The location of the microburst relative to the runway is obviously critical to the aircraft performance Figure 11 clearly illustrates the effect of the microburst locaton during takeoff Three curves are plotted for path *CD* where the microburst is encountered at 330 ft above the ground along a 10 deg climb out path, 164 ft and -33 ft, respectively Also plotted on the figure is the longitudinal wind speed en countered by the aircraft In all cases, the aircraft initially takes off with a headwind of slightly more than 20 knots, depending on the relative position of the storm to the runway and because of this headwind, the aircraft lifts off relatively quickly In these three paths, a headwind loss of ap proximately 0 8 knots/100ft is encountered

When the aircraft encounters the wind shear early in its takeoff roll ($z_o = -33$ ft, the dashed line), an extremely long distance is required before flying speed is attained The aircraft does lift off, however, and climbs out at a slow but steady rate until it exits the microburst In the opposite case where the aircraft encounters the center of the microburst at approximately 330 ft above the ground after liftoff, it climbs out normally up to approximately 200 ft altitude and then cannot climb regardless of the fact that takeoff thrust is maintained The aircraft then begins to sink slightly until it exits the microburst as shown by the upper curves After exiting the microburst, the aircraft experiences an increasing headwind and resumes a normal climb out

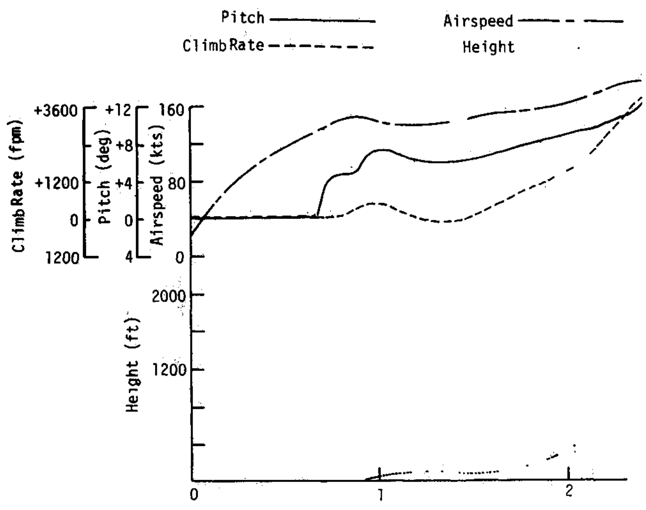

Fig. 9 Takeoff in wind field (AB + 07TO)

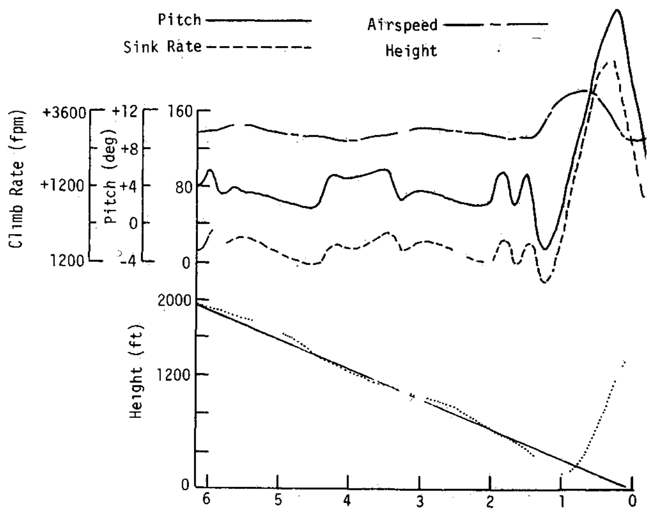

Fig 8 Approach in wind field (CD + 00AP)

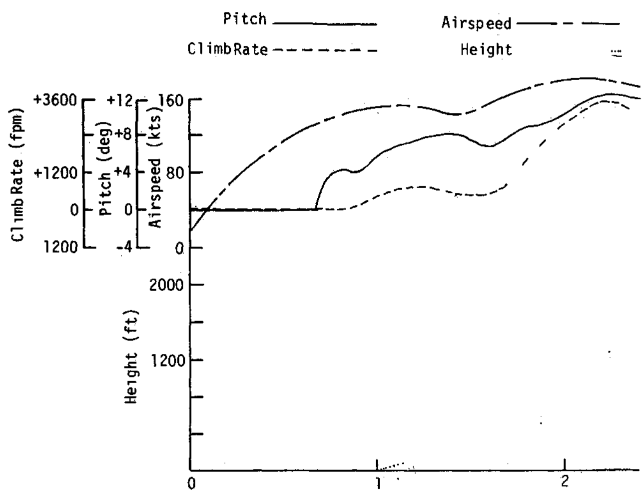

Fig 10 Takeoff in wind field (IJ – 16TO)

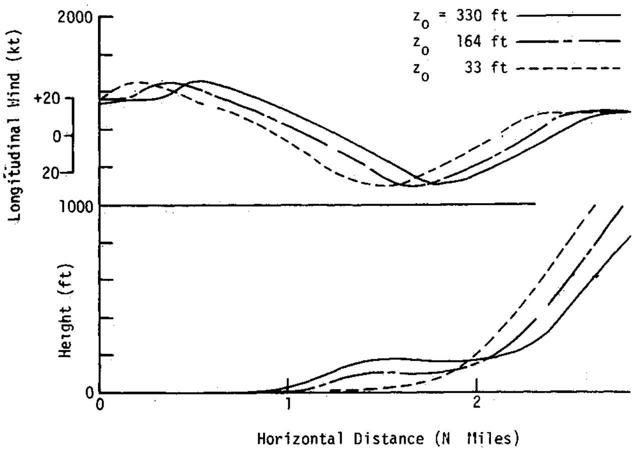

Fig 11 Takeoff flight path *CD*

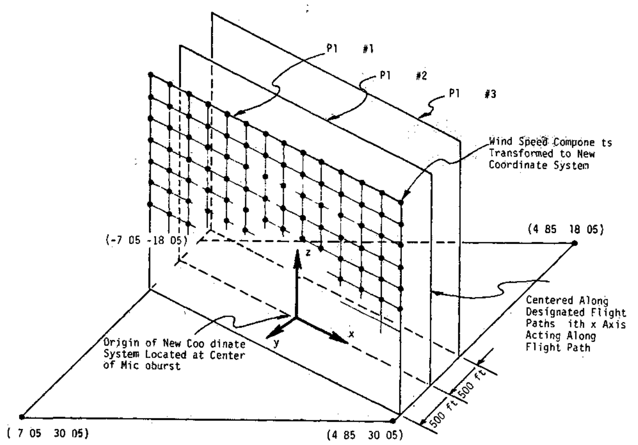

Fig 12 Description of coordinate system and data planes

Wind Fields for Simulator Application

The JAWS wind shear data set provides a unique set of wind fields for simulator application and training and for operational procedure and control system design Prior to this date, no three dimensional wind fields were available Foy[6] reports three dimensional wind shear models for use in simulators; however, these are, at best, three component, two dimensional spatial wind fields Foy's models are colloquially referred to as the SRI (Standard Research In stitute) models They represent winds in a given plane through the flowfield Any departure in the lateral direction from this plane does not encounter changes in the wind In the JAWS data set, three dimensional variations in the wind are truly represented

Total Data Set

Wind shear models based on the JAWS data sets, as noted earlier, consist of variables numbering in the hundreds of thousands and thus require extensive computer storage At the JAWS Wind Shear Simulator Workshop,[¶] representatives of the training community suggested that this large amount of storage would be a handicap to many of the older simulator models Also, the computation time required to locate the specific position of the aircraft in the grid system and to interpolate the wind speed and nine wind gradients would overextend the capabilities of most computers used in present day simulators For these reasons, as described in a later section, subelements of the flowfield have been selected relative to the severe, moderate, and weak wind field cases described earlier

Momentarily putting aside the problems of storage and interpolation time, simulator facilities and researchers who wish to utilize the total volume of wind shear from the JAWS data can obtain digitized wind speed values on magnetic tape from Mr Kim Elmore (c/o JAWS Project, NCAR, P O Box 3000, Boulder, Colo 80307) Total data sets consisting of 175,000 or more variables have already been installed in the NASA Langley Research Center simulator [7] Flight simulation along some of the selected paths described earlier has been carried out

With the wind field modeled throughout a 12x12x2 km spatial region, an infinite number of flight paths through the wind shear can be flown in a simulator Once a flight path is initiated, any control input by the pilot will result in the aircraft penetrating a unique wind field—it would be the greatest coincidence for two pilots to fly exactly the same wind fields even if they started from identical positions

The general characteristics of the wind field, however, are what is important and these have been selected as described in the earlier sections of this paper Thus, the user of the data knows approximately the location of severe mod erate/severe, moderate, and weak wind shear embedded in the total wind field In using the JAWS wind shear model, the path classification will thus assist training personnel in identifying regions of wind shear severity to satisfy their training objectives

Subelements of the Total Data Set

Subelements of the JAWS wind fields have been developed for users with limited simulator storage (also available by request from JAWS at NCAR) These subelements are available on magnetic tape or in hard copy Figure 12 describes the coordinate system and the method for presenting the subelements of the data The data are presented in terms of three plane, two plane, and one plane data sets The three plane sets consist of three planes of data oriented along a selected path The central plane passes through the designated path; i e , *AB CD*, etc Two planes on each side of the central plane, separated by a distance of 500 ft, complete the data set The data are expressed in terms of a new coordinate system The origin of the coordinates is located at the center of the microburst (i e at x_o, y_o), and the x axis is oriented along the designated path. For the three plane set, the storage requirements are reduced to essentially 6500 variables

Two plane sets with the designated path centrally located between the two planes are also available The coordinate system, as in the three plane set, is located at the center of the microburst, and the x axis is measured along the selected path

One plane sets have been prepared and are available In view of the fact that they add nothing new to the existing data sets presented in the Federal Aviation Administration Ad visory Circular No 120,[8] issued in November 1983, they are not considered significantly different The JAWS data sets, however, are believed to be more representative of real winds The wind shear models in AC 120 are based on data that have either been extrapolated from a single flight data recorder trace or interpolated from tower measurements using Taylor's hypothesis The JAWS data are measured spatially with scanning radar and thus do not rely upon extrapolation or the assumption of Taylor's hypothesis.

Four-Dimensional Wind Shear Models

The JAWS data sets also provide the possibility of four-dimensional wind shear models, the fourth dimension being time Data sets separated in time by 2 min periods are available for most of the microbursts measured during JAWS Use of the four dimensional data requires an in

¶The workshop was sponsored by NASA and FAA and held at NCAR Boulder Colo. Sept. 7 8 1983 terpolation scheme between time fields The importance of time variation in the wind fields has not been fully assessed, but this question is being addressed under a continuing NCAR contract effort

Conclusions

The JAWS wind shear data sets provide the first truly four dimensional wind field of a microburst available for ap plication to flight training and engineering research simulators In addition, the three-dimensionality of the Doppler-derived wind measurements represents a quantum step ahead in fundamental resolution compared to the SRI data used by Foy[6] Based on computer analysis and preliminary flight simulator studies it is believed that the three and four-dimensionality of the data provide more realism to flight simulators

Analysis of aircraft performance in the three-dimensional wind fields clearly illustrates the hazards associated with particular regions of the wind field Thus, these regions have been classified as severe, moderate/severe, moderate, and weak The classifications can be used by airline training flight simulator users as well as research and development sim ulator engineers to readily select wind shears of the severity necessary for their particular project

It is recommended that the entire data set be used in ad vanced flight simulators when carrying out wind shear studies For older simulators having less core capabilities and other smaller, less sophisticated simulators that are unable to accomodate the large amounts of data, subvolumes have been selected and specifically formatted for their needs

In carrying out simulations, at least a two-plane subvolume of the wind shear data should be utilized This will permit lateral motions relative to the flight path of as much as ± 250 ft This value is normally not exceeded during a typical approach, and thus the full three dimensional effects due to lateral departure from the flight path can be simulated with a maximum of two planes

Further research using the JAWS data sets will investigate the performance of other generic types of aircraft in wind shear and will identify scales of motion most hazardous to each aircraft (only a Boeing 727-type aircraft was considered in this study) Also, plans to investigate adding turbulent fluctuations representative of length scales less than the grid spacing of the current data set are being made. In this regard, it is anticipated that the second moment Doppler data will provide a measure of the spatial distribution in turbulence intensity Finally, additional interaction with research and engineering simulator personnel and facilities will be carried out This interaction will result in further refinement and application of the JAWS data for simulating fully four dimensional wind shears In the meantime, JAWS data will be flown by the simulator flight training community as a prerequisite to publishing improved wind shear profiles

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References

[1]McCarthy J , ' The Joint Airport Weather Studies Project Current Analysis Highlights in the Aviation Safety Context, ' AIAA Paper Jan 1984

[2]McCarthy J Wilson J and Fujita, T. T The Joint Airport Weather Studies Project *Bulletin of American Meteorological Society* Vol 63 1982 pp 15 22

[3]Frost W and Bowles R L Incorporation of Wind Shear Terms into the Governing Equations of Aircraft Motion ' AIAA Paper 84 0275 Jan 1984

[4]Frost, W Chang H P , McCarthy, J , and Elmore K Air craft Performance in a JAWS Microburst,' *Preprints: 21st Con ference on Radar Meteorology*, Sept 19 23 1983, Edmunton Alberta Canada American Meteorological Society Boston Mass pp. 630 637.

[5]Turkel B S., Kessel P A and Frost W Feasibility Study of a Procedure to Detect and Warn of Low Level Wind Shear ' NASA CR 3480 Nov 1981

[6]Foy, W H Airborne Aids for Coping with Low Level Wind Shear " Rept No FAA RD 79 117 U S. Dept. of Transportation FAA, Washington, D C 1979

[7]Bowles R L personal communications Sept 1983

[8] Criteria for Approval of Airborne Wind Shear Detection Systems, Federal Aviation Administration Advisory Circular No 120 U S Dept of Transportation FAA Washington, D C , Nov 1980