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WIND SHEAR AND TURBULENCE SIMULATION

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The work conducted at NASA Langley in relation to simulation of wind shear is actually based on a broader effort. This effort is funded by the Simulation Technology Program at NASA Headquarters under the cognizance of the Human Factors Research and Technology Office. The Simulation Technology Program is a companion effort to the Langley Flight Management Program. There is no question that we, as an aviation community, are increasing our reliance on flight simulators. This is true both in pilot training and in research and development. In moving research concepts through the development pipeline, there is a sequence of events which take place (Figure 1): analysis, ground-based simulation, inflight simulation, and flight testing. Increasing fidelity as we progress toward the flight testing arena is accompanied by increasing cost. The question that seems to be posed here in relation to the meteorological aspects of flight simulation is, "How much fidelity is enough in this business, and can we quantify it?" As a part of the Langley Simulation Technology Program, we have three principal areas of focus, one being improved simulation of weather hazards. A close liaison with the JAWS project was established because of the Langley Simulation Technology interests regarding reliable simulation of severe convective weather phenomena and their impact on aviation systems.

Let me summarize what I believe is the current situation. There is no question that we have well-founded data collection programs under way. These are expensive programs and they are logistically difficult to conduct. They include Langley's severe storms effort, the JAWS effort, the Gust Gradient Program, and others. Under the term "others" is the work that is going on in heavy rain effects at Langley and the Icing Program at Lewis. The R&D systems development and pilot training community require the best available meteorological data. There is (as indicated by Figure 2) a gap between the data collection programs and implementation of these data into R&D and training simulators. There are a number of issues as shown in Figure 3 that are based on how we have conducted business in the past which have precluded optimum utilization of the atmospheric measurements derived from these large-field programs.

An approach to bridge the gap is straightforward (Figure 4). We need to identify the relevant data sources and develop models reflecting the best available data, interface those disturbance models with aerodynamics and flight management systems that are of interest to simulation activities, and conduct and publish well-established verification and evaluation results of the simulation process and research findings.

Simulation offers the only feasible approach for examining the utility of new technology and new procedures for coping with severe convective weather phenomena such as wind shear. Wind shear models currently employed in simulation studies, however, are very simple analytical forms, validation for which, with respect to either strength or structure, does not exist. Based on the premise that our confidence in safety-related studies, which necessarily

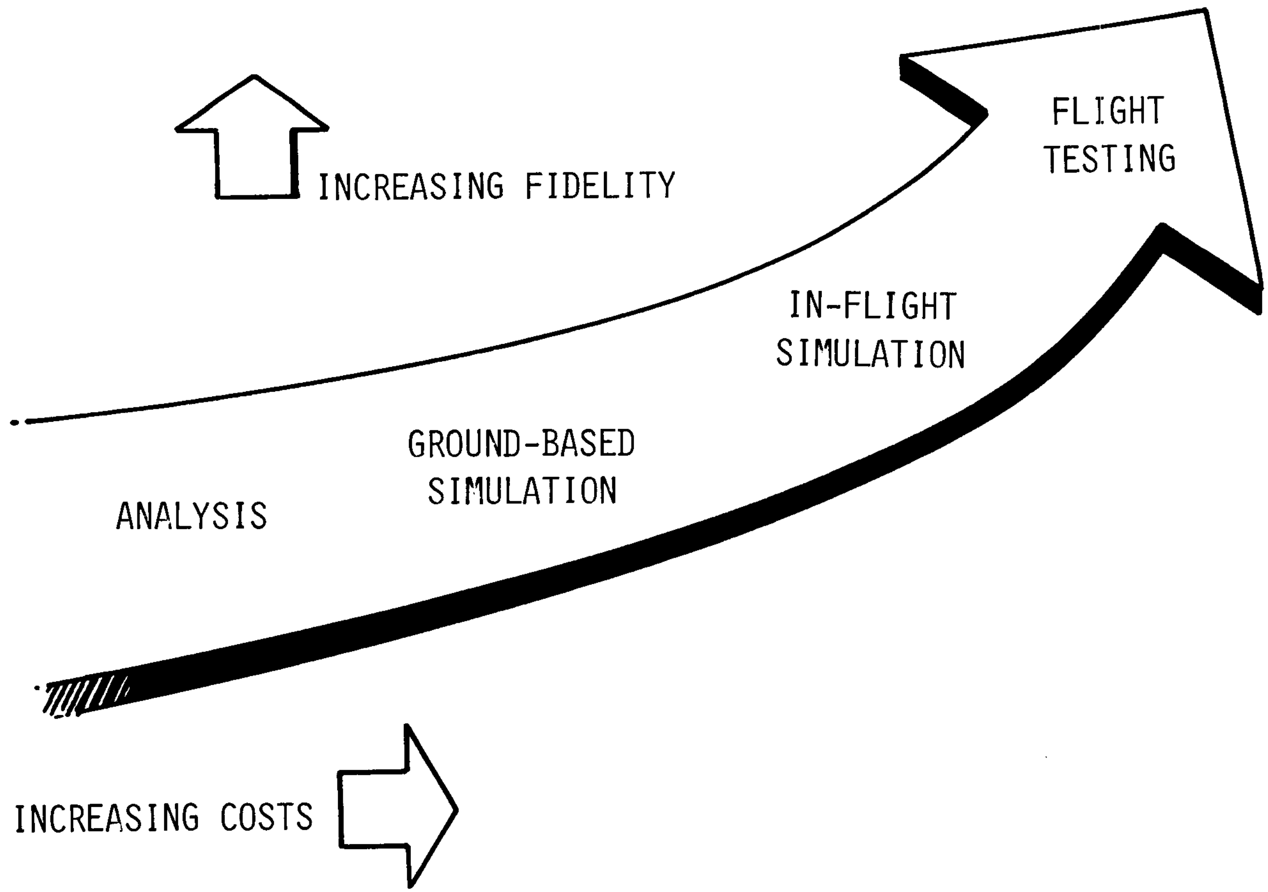

Figure 1. Hierarchy of design validation methods.

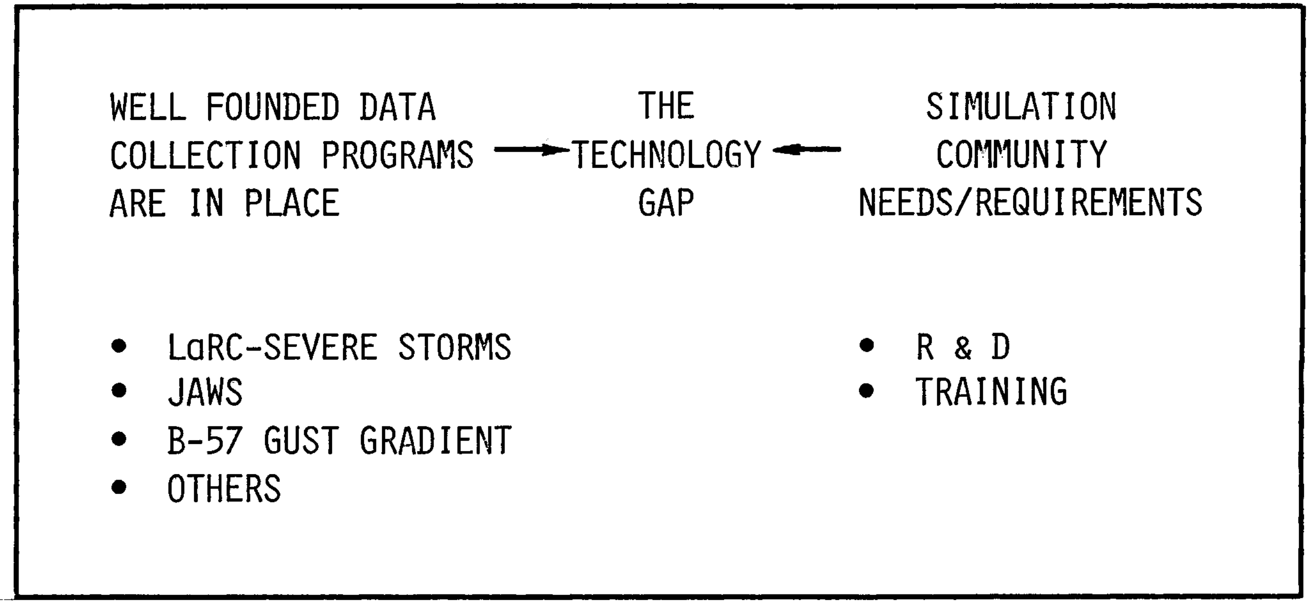

Figure 2. Weather hazard simulation current situation.

- INADEQUATE COMMUNICATIONS AND REQUIREMENTS DEFINITION
  - SIMULATION COMMUNITY
  - DATA COLLECTORS
- WIND SHEAR/TURBULENCE DATA BASE AND MODELS HAVE BEEN SPECIALIZED AND LIMITED
  - NON-UNIFORM WIND HAZARDS DATA BASE
  - AD HOC MODELS
  - LIMITED RESOLUTION
- SIMULATION DESIGN CRITERIA AND IMPLEMENTATION GUIDELINES ARE POORLY DEFINED
  - STANDARDS DO NOT EXIST
  - SELECTION CRITERIA FOR CANDIDATE DATA BASE AND DISTURBANCE MODELS NEED DEFINITION
  - INCONSISTENT TREATMENT OF WIND SHEAR/TURBULENCE EFFECTS ON AERODYNAMICS AND INTERFACE WITH EQUATIONS OF MOTION
  - MOTION/VISUAL FACTORS
- VAGUE SIMULATOR UTILIZATION STRATEGIES INVOLVING WEATHER HAZARDS
  - PERFORMANCE VERIFICATION AND VALIDATION
  - DOMAIN OF SIMULATION APPLICABILITY

Figure 3. The simulation gap.

- DATA SOURCES
- DISTURBANCE MODELS REFLECTING "BEST AVAILABLE" DATA
- INTERFACE DISTURBANCE MODELS WITH AERODYNAMICS AND FLIGHT MANAGEMENT SYSTEMS
- VERIFICATION AND EVALUATION

Figure 4. Key elements/approach.

rely on these models, can be no better than our confidence in the validity of the models themselves, the criticality of this validation deficiency is clear. Fortunately, as a result of wind shear measurements recently provided from the JAWS Program (Joint Airport Weather Studies), the basic information required to correct this deficiency exists, but special techniques were required to implement the JAWS wind field measurements in simulation. For example, the JAWS data is taken with respect to a grid system that is very coarse when compared with aircraft dimensions. Also, because they are actual measurements, the data contains noise. In the present study (Figure 5), a technique using fluid-flow theory was developed to smooth and interpolate the JAWS measurements, providing a validated analysis model from which a wind shear data base can be generated and interfaced with real-time simulators.

Relative to modeling wind shear flow fields, I want to discuss some results of a computer generated microburst. This effort capitalizes on the fantastic developments that are occurring in computational fluid dynamics and related meteorological mathematical modeling. Langley is very fortunate to have a staff of seven computational meteorologists on site, and over the years they have put together a fairly sophisticated capability that deals with the synoptic scale coverage of U. S. continental weather. This model utilizes input from National Weather Service rawinsonde, surface, and satellite observations. The particular effort that we are currently pioneering is increased wind field resolution for a terminal area simulation. This is a computational-based numerical weather model (cloud scale) which can produce data bases that are not unlike the JAWS observations. Also, these data bases can be interfaced with simulators in the same manner as the JAWS data bases. For example, the cloud scale downburst model is initiated from observed temperature and humidity of Denver, 2300 GMT, June 30, 1982. Figure 6 depicts the time history of the downburst and the gust front evolution. The roll vortex forms immediately after the precipitation drops through the top boundary. It then propagates vertically downward, lagging the leading edge of the falling precipitation. Upon reaching the surface, the roll vortex propagates outward with the leading edge of the gust front. The most intense outflow speeds occur as the roll vortex reaches its lowest point and begins to propagate outwards (cf. Figure 6, Table 1). (The maximum radial outflow of 23.2 m/s occurs just before seven minutes). The gust front shape and slope vary as the outflow evolves. The "nose" (defined by the protruding edge of outflow which extends towards the warm air) becomes well defined after t = 8 min. The nose appears to be formed and maintained by the counter-clockwise circulation of the roll vortex. The forward edge of the outflow, defined as the "head", is produced as fast-moving outflow piles up behind the slower propagating gust front. The head contains the deepest region of cool outflow outside of the incipient precipitation area. Cool surface-layer flow toward the precipitation area, defined as "backflow", appears after t = 6 min. beneath the head. Backflow, as well as the head and nose structures of outflow, has been detected from actual measurements near gust fronts. The simulated outflow from the precipitation shaft does not remain undiluted. From the stream function field (Figure 6), entrainment of subsiding environmental air is apparent. Ambient air is first lifted several hundred meters as the cool outflow undercuts the warm environmental air. Then it sinks and some is entrained into the outflow layer. However, due to the dryness of ambient air in this experiment, the modest lifting is not enough to initiate condensation and the formation of a roll cloud above the head.

ADVANCED NUMERICAL WEATHER MODELS BASED ON FLUID-FLOW THEORETIC TECHNIQUES

PROBLEM:

LACK OF HIGH-FIDELITY WIND SHEAR MODEL FOR SAFETY-RELATED STUDIES OF A/C PERFORMANCE/CREW PROCEDURES/AVIONICS SYSTEM BENEFITS

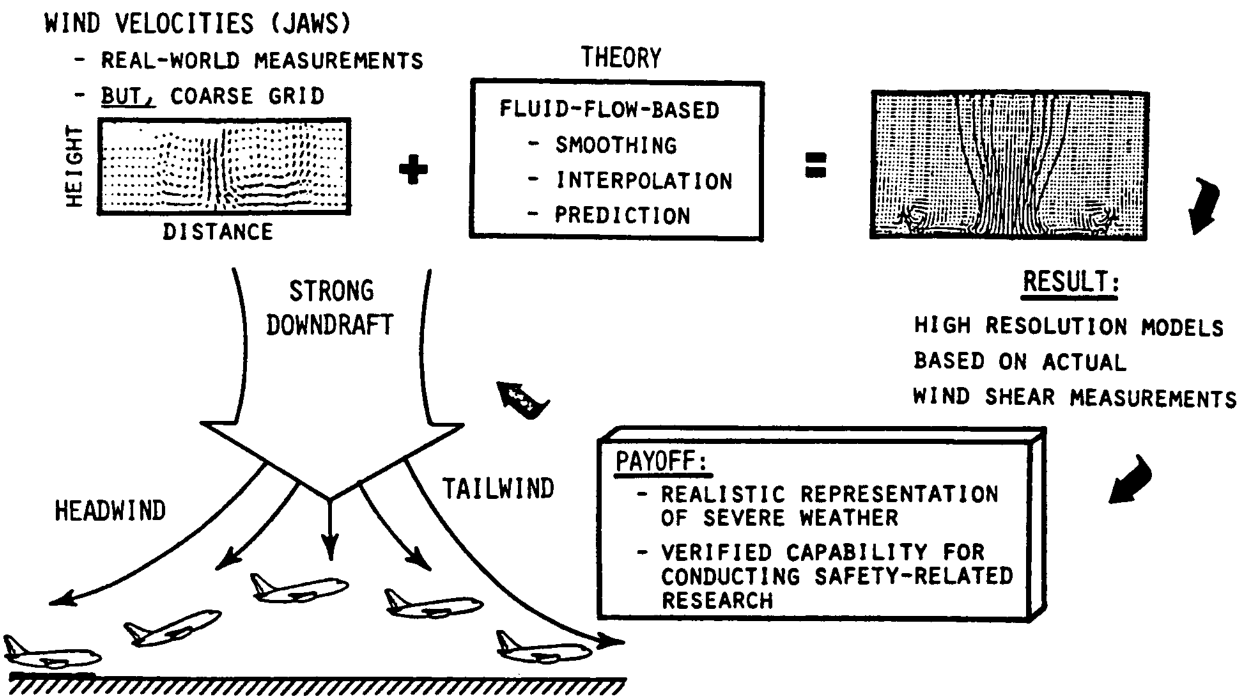

Figure 5.- Methodology for wind shear modeling.

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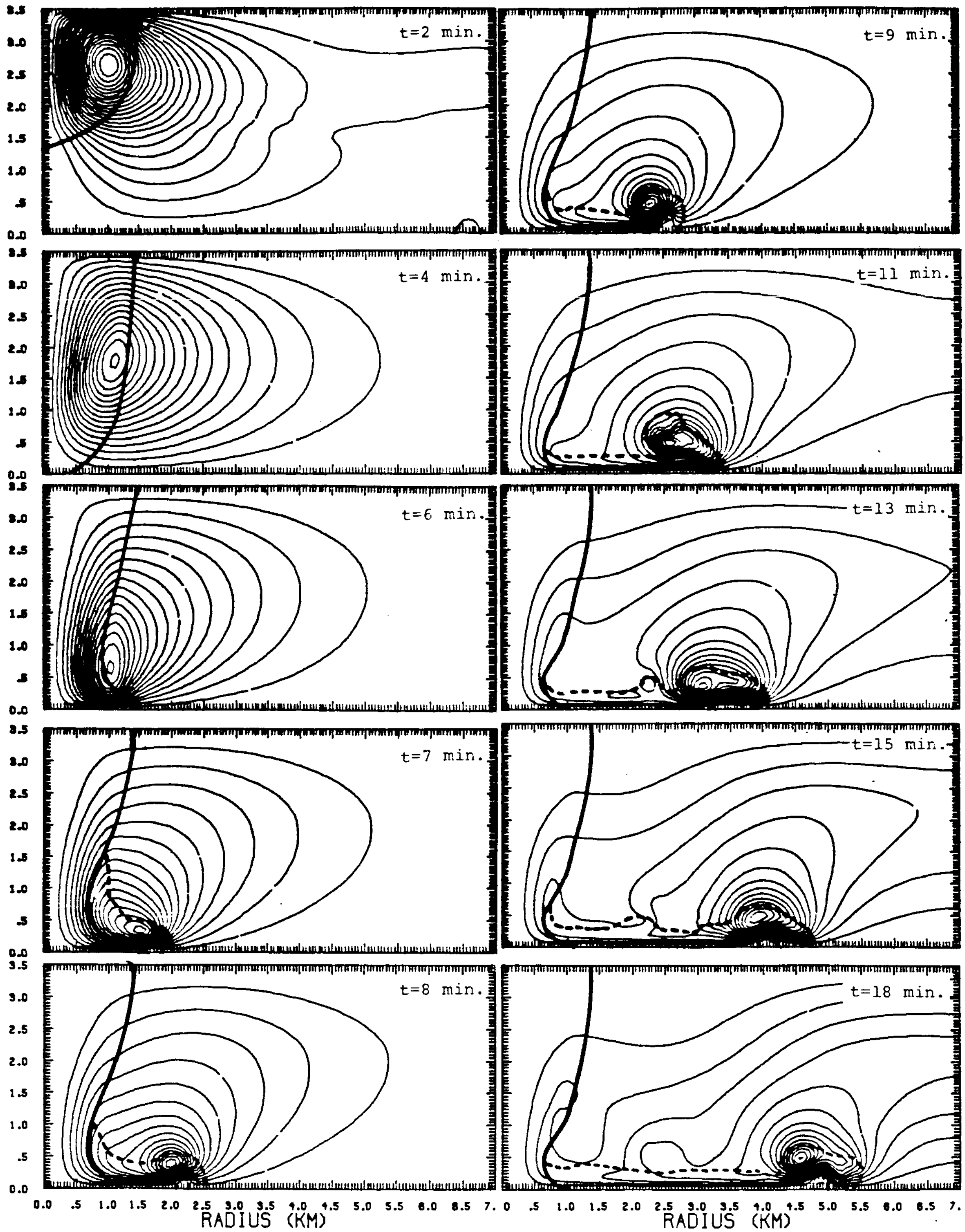


Figure 6. Time history of a simulated downburst.

Time (min)	Maximun outflow speed (m/s)	Maximum downdraft speed (m/s)
2	0.3	2.2
4	1.7	10.3
6	21.6	16.1
7	21.9	14.9
8	19.9	13.9
9	16.5	14.1
11	16.6	15.0
13	17.7	16.0
15	17.9	16.5
18	17.2	16.5

Table 1 Maximum outflow and downdraft speeds as a function of time for the 2300 GMT 30 June 1982, Denver simulation.

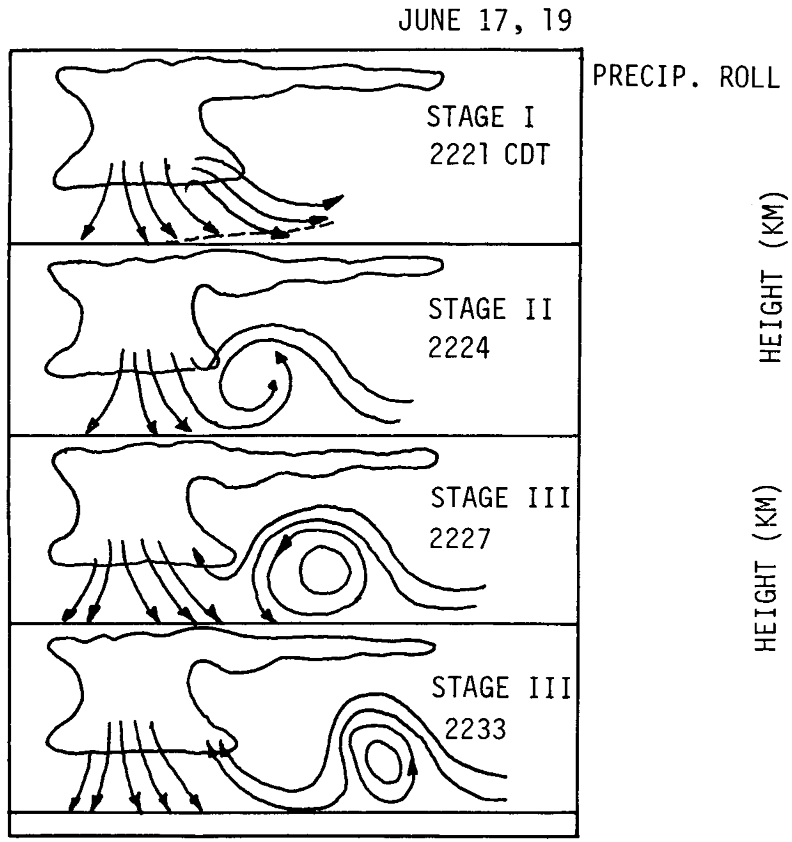
For the particular case study represented in Figure 6, the maximum outflow and downdraft speeds as a function of time are listed in Table 1. The computations were achieved with a 2-D axisymmetric Navier-Stokes model with the Z axis as the axis of symmetry. The maximum observed outflow speed was 21.9 m/s which translates to approximately 42 knots differential across the core of the microburst. Differentials of this magnitude and attendant downdraft speeds were observed during the JAWS program.

Figure 7 illustrates a comparison of classical (Ref. 1) gust front formation with computed results. Using Doppler radar, Wakimoto has observed a reflectivity pattern of precipitation, defined as a precipitation roll, which revolves in a horizontal roll near the gust front (Figure 7a). This feature is simulated by using the 2315 GMT 4 June 1973 Norman, Oklahoma, sounding as initial data for temperature and humidity. The computed stream function and radar reflectivity are shown at t = 8 min and t = 9 min (Figure 7b). The precipitation roll forms as the roll vortex moves radially outward from the precipitation shaft. Strong low-level outflow (> 20 m/s) sweeps rain out of the precipitation shaft and around the center of the roll vortex. Rain trapped in the roll vortex circulation eventually evaporates or falls to the ground. The lifetime of the simulated precipitation roll was only a few minutes, and its structure was very similar to the larger and more persistent precipitation roll observed by Wakimoto (cf. Figure 6a).

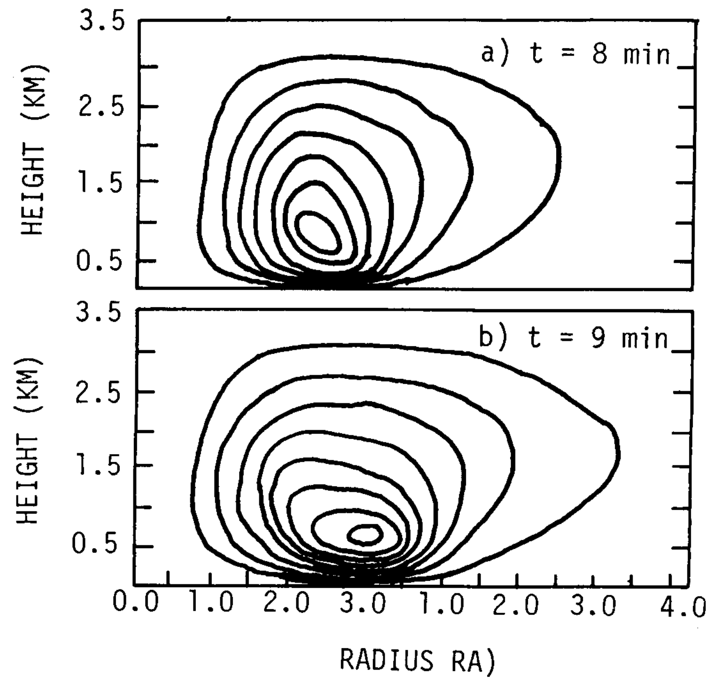
Figure 8 represents a vertical cross-section of the velocity field for the computer microburst initialized from June 30, 1982, soundings. As can be seen, the vortex rolls are well formed at t = 9 min. The vortex rolls represent complex and intense flows and may have significant impact on large airplanes operating close to ground beyond that of the classical microburst phenomena involving downdraft and divergent outflow.

The computer output shown in Figure 8 provides a wind shear data base on a uniform grid mesh of 30 m. resolution. This data base plus an interpolation technique is easily interfaced with real-time piloted simulators and provides what I would consider as a simple wind shear model. I do not suggest that we calculate, in real time, the complex fluid flow equations which give rise to microburst phenomena. To the contrary, we can generate high resolution wind shear data bases off-line and easily interface them with piloted simulators.

Figure 9 outlines three principal elements one must consider when developing wind shear models for application in the aviation context. First is the characterization of environment itself; technical issues remain to be addressed with regard to both wind shear severity and structure. The ad hoc committee, in my view, has not done a good job in responding to what the community has been trying to tell us regarding these issues. For example, consider the wind shear threat selection critieria. Frost (Ref. 2) has explained a rationale for selecting interesting wind shear profiles from the JAWS August 5 microburst event; I more or less filtered and studied the same cases. However, one JAWS data base provides an infinity of wind shear profiles and we have examined very few to date. Inherent classification of the wind shear environment, whether it is stochastic or deterministic, requires some thought. Is differential outflow ΔV characterization enough, or do we need probability of exceedance? Relative significance of vertical and horizontal scales of atmospheric motion is another area which requires careful consideration as well as pressure and temperature variations.



a) Wakimoto's conceptual model of the evolution of a gust front and precipitation roll.



b) Field distributions of stream function (dashed lines) and radar reflectivity (solid lines) of a simulated downburst and precipitation roll at (a) t = 8 min., and (b) t = 9 min.

Figure 7. Comparison of classical gust front formation with computed results .

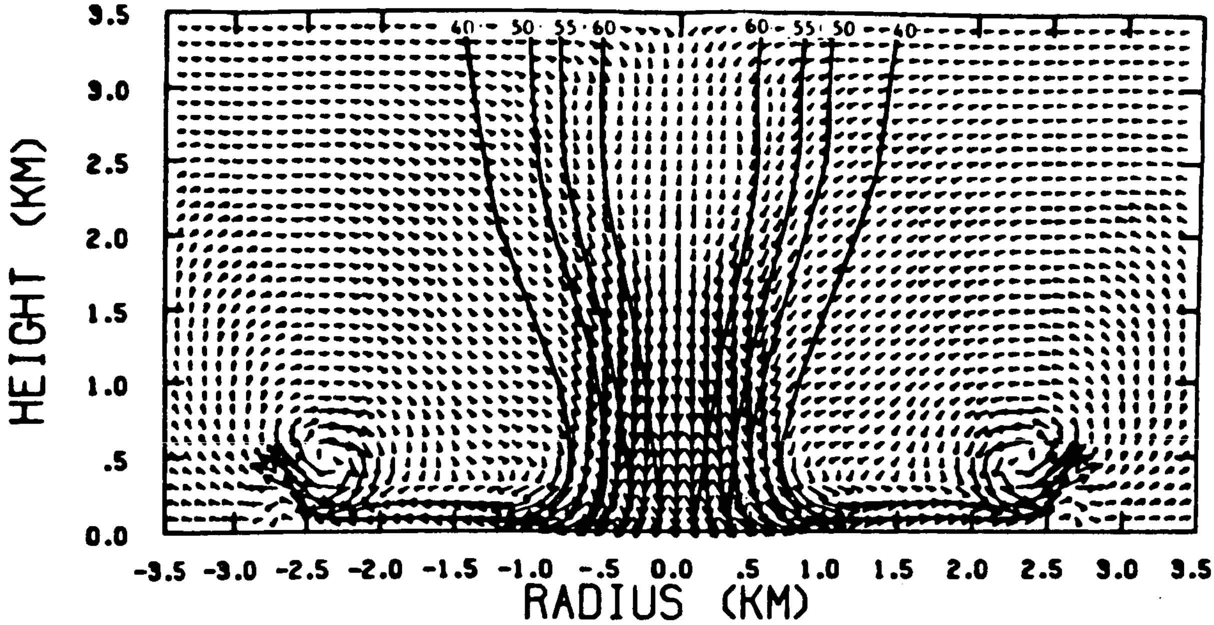


Figure 8.- Vector field of wind velocity at
t = 9 min.

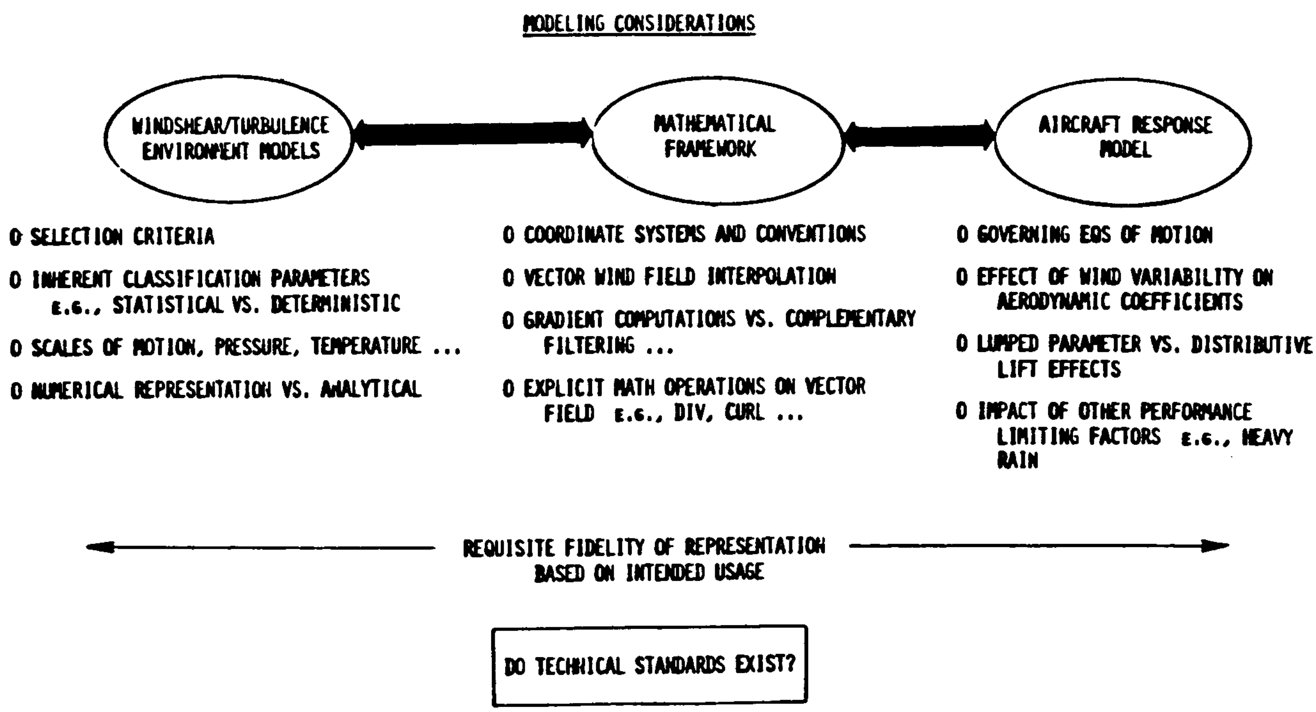


Figure 9.- Modeling considerations.

Secondly, a consistent mathematical framework and vector wind field interpolation technique are required for implementing the JAWS data into simulators. There is no question that in terms of simulator utilization, simple wind shear models are attractive. Given the x, y, z position of the aircraft an algebraic evaluation of f_1, f_2, f_3 to give three wind components is a desired property as long as the model represents the wind shear phenomena being studied. I would also point out that a numerical data base combined with an appropriate mathematical structure can also constitute a "simple" wind shear model. The third area considered in Figure 9 is the aircraft response model. The proper integration of the wind shear environment with the simulated vehicle aerodynamics is an important part of the problem. If we can specify technical standards regarding meteorological aspects of wind shear models, the aircraft response and performance impact has to reflect that environment with reasonable levels of fidelity.

Figures 10 and 11 summarize the current situation regarding wind shear and turbulence simulation capability resident at the Langley Research Center. At the present time, we have implemented all three of the volumetric data sets produced by the JAWS project, i.e., June 29, July 14, and August 5, in addition to the simplified two- and three-plane corridor data. We found that a trivial amount of computer resource is required to implement the corridor data sets; in fact, they can be implemented at less cost than the current FAA specified SRI wind shear models.

Operational flexibility for application of the JAWS data is an issue which can be easily handled. For example, we locate the data centroid of the volumetric wind field relative to any crucial point on the runway, either GPIP or threshold, so that the data base can be moved at will relative to the runway. We also establish an arbitrary rotation of the data base about the centroid thus providing different wind shear profiles for given approach or take off flight path.

In addition to the JAWS data base, we also provide the 21 SRI/FAA profiles and a variety of turbulence models which probably are not adequate for their intended purpose. The overall operational philosophy, as illustrated in Figure 11, allows us to interface any number of flight simulators in our real-time simulation complex with any specific wind shear environment. For example, some aircraft performance results that I will shortly present were obtained using the TSRV simulator which is based on 737-100 model. However, a number of other simulators reflecting different levels of flight management systems sophistication could have been used. The bottom line is that we can make a landing approach through the August 5 JAWS data followed by an approach through the SRI Kennedy data within the time it takes to push the buttons and read data from disks.

The question of interfacing an arbitrary vector wind field with airplane flight and aerodynamic characteristics is important to the validity of the overall simulation process. Typically, the simulator development community is required to interface new wind shear environments with an existing simulator, the development of which required large investments of both manpower and dollars. Simulators which reflect complex flight management systems are evolutionary developments occurring over many years and we do not wish to let wind shear be the "tail that wags the dog." Generally a new wind shear environment, such as JAWS, must be retrofit into an already available

CURRENT WINDSHEAR/TURBULENCE SIMULATION CAPABILITY

WINDSHEAR DATA BASE

- JAWS VOLUMETRIC WIND FIELDS
  - JUNE 29
  - JULY 14
  - AUGUST 5
- SIMPLIFIED TWO AND THREE PLANE REPRESENTATIONS OF AUGUST 5 CASE
- APPLICATION FLEXIBILITY
  - USER SELECTED SUBDOMAIN
  - ARBITRARY LOCATION OF DATA CENTROID RELATIVE TO GPIP
  - ARBITRARY ORIENTATION OF DATA VOLUME RELATIVE TO RUNWAY
  - WIND FIELD SCALING PRESERVES MASS FLOW CONTINUITY
- 21 SRI/FAA PROFILES
  - ACCIDENT RECONSTRUCTIONS
  - TOWER DATA
  - THEORETICAL MODELS

TURBULENCE MODELS/DATA BASE

- STANDARD MIL. SPEC. (MIL-F-87851B)
- SRI/FAA CHARACTERIZATION
- NASA DEVELOPED NON-GAUSSIAN

Figure 10.- Current wind shear simulation capability.

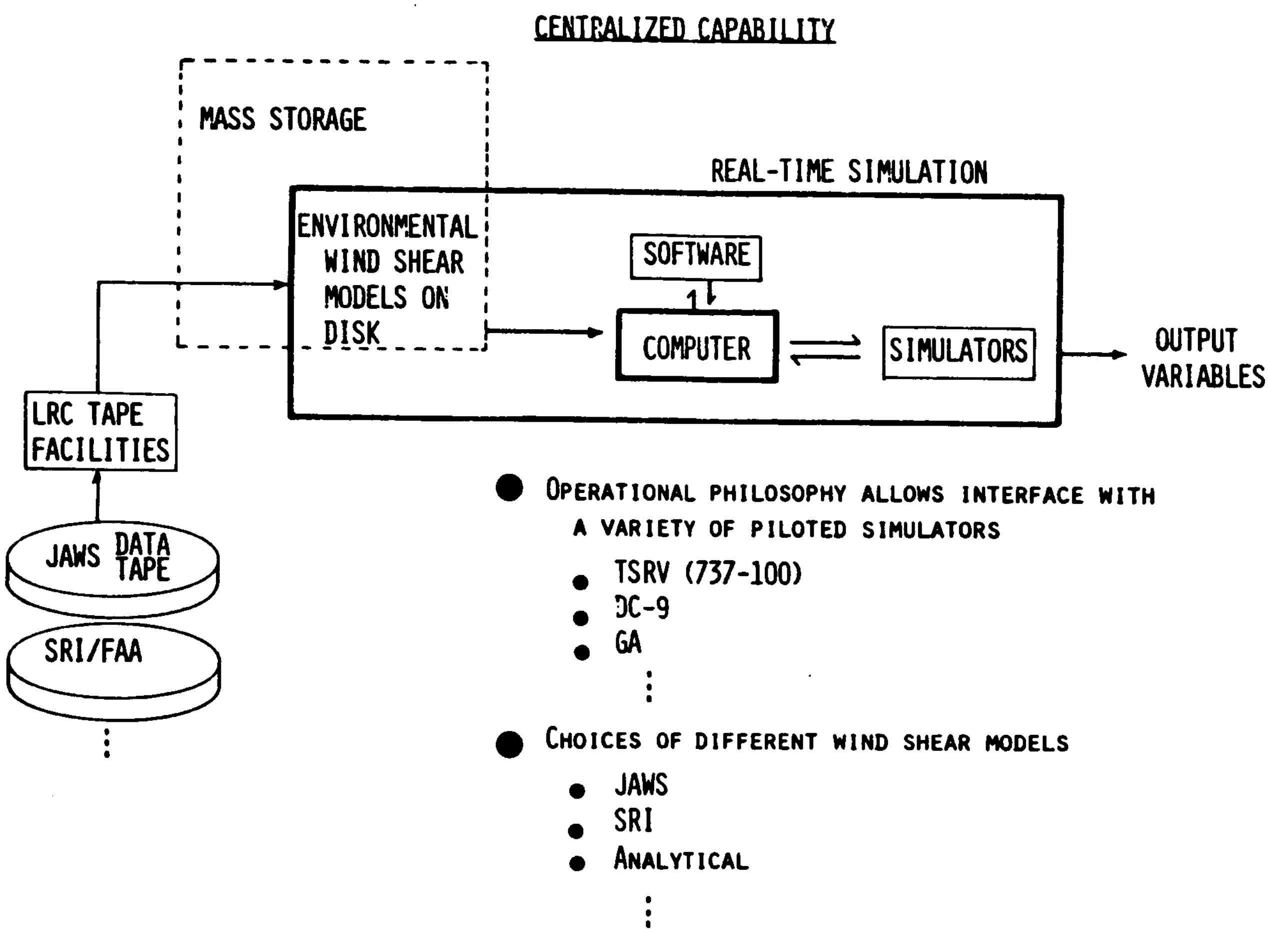


Figure 11.- Current wind shear philosophy.

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simulator and aerodynamic model which presumably have proven flight characteristics in still air. The salient features of this retrofit process, as applied to the Langley Research Center simulator, are outlined in Figure 12. As seen in Figure 12, the key baseline assumptions are that the aircraft is rigid with a plane of symmmetry as well as a "point approximation" for the aerodynamic model. Engine characteristics are also assumed known. The lump parameter aerodynamic model assumes uniform wind over the aircraft and the usual treatment of quasi-steady aerodynamics. Since aerodynamic forces acting on aeroplanes do not respond instantaneously to changes in angle of attack and sideslip these effects are approximated based on conventional wisdom which is thought to be adequate for rigid airplanes in still air. In implementing the JAWS wind shear, we assumed a 3-D frozen field. The vector wind field is interpolated using a tri-linear technique which provides the three-axis mean winds within a cube whose vertex points are defined by the eight closest data mesh points. The nine partial derivatives (spatial wind gradients) of the wind field are determined as a no-cost byproduct of the interpolation technique.

It is interesting that the FAA AC-120-41 advisory circular (Ref. 3) now calls for output data that provide the partial derivatives as part of the evaluation plan. As a matter of fact, for the first time ever, JAWS has given us the ability to compute all nine spatial wind gradients. This was not possible before with the SRI wind shear models.

For the direct aerodynamic interface, we relax the uniform wind assumption over the airplane. The assumption is made that the scales of atmospheric motion in the JAWS data base are large enough relative to span and cord lengths that the flow can be treated as linearly distributed. The three-axis velocity components and their x, y, z spatial gradients are evaluated at mass center in real time. This calculation is done at whatever iteration rate required to satisfy the dynamics of the process. They are, however, evaluated along the trajectory of the mass center. Thus, we compute them only where they are needed to interface with the aerodynamics. Quasi-steady aerodynamics are directly computed in terms of these spatial wind gradients and the rotational effects discussed by Frost and Bowles (Ref. 4) are incorporated in the force and moment calculations.

In general, knowledge of both wind field and its gradient matrix is required to support aerodynamic calculations if the linear field approximation is used (see Figure 12). The above discussion implies that wind shear effects enter directly in the feedback loops of vehicle force and moment equations. We currently model the velocity and accelerations of the aircraft relative to the air mass with components taken in body axes. With the state vector chosen in this manner the integrals of the force and moment equations directly support the necessary aerodynamic calculations. The nine spatial derivatives are used to compute quasi-steady aerodynamics and the rotational effects produced by span and streamwise wind shear variations.

I will now describe a simulator experiment and present results based on simulated flight in the JAWS August 5 volumetric data base. Actually, Langley implemented the June 29 microburst data a year ago and demonstrated it to the National Research Council Wind Shear Study Committee. Several of the Aircraft Performance Committee members had the opportunity to fly in a microburst environment for the first time. The individuals who were exposed to the

VECTOR WIND FIELD INTERFACE WITH FLIGHT DYNAMICS

BASE LINE ASSUMPTIONS

- AIRCRAFT IS RIGID WITH PLANE OF SYMMETRY
- "POINT APPROXIMATION" FOR AERODYNAMICS
  - UNIFORM WIND OVER A/C
  - QUASI-STEADY AERO

SIMULATOR IMPLEMENTATION TECHNIQUES

- 3D-FROZEN FIELD
- TRI-LINEAR INTERPOLATION OF VECTOR WIND FIELD
  - LAGRANGE POLYNOMIAL BASIS FUNCTIONS
  - NINE PARTIAL DERIVATIVES PROVIDED AS A NO COST BY-PRODUCT
  - METHOD EASILY GENERALIZED TO 4-D INTERPOLATION
- LINEAR FIELD APPROXIMATION
  - SCALES OF ATMOSPHERIC MOTION SUCH THAT WIND IS, AT MOST, LINEARLY DISTRIBUTED OVER A/C
  - X,Y,Z GRADIENTS OF 3-COMPONENT VELOCITIES AND THEIR VALUES AT MASS CENTER
  - QUASI-STEADY AERO EFFECTS DEPEND ON SPATIAL WIND GRADIENTS
  - ROTATIONAL EFFECTS PRODUCED BY SPAN AND STREAMWISE SPATIAL GRADIENTS INCLUDED IN FORCE AND MOMENT CALCULATIONS (GENERATED BY WIND FIELD VORTICITY)
- GENERAL CASE IMPLEMENTATION OF WIND SHEAR DEPENDS ON

$$\begin{bmatrix} u_x & u_y & u_z \\ v_x & v_y & v_z \\ w_x & w_y & w_z \end{bmatrix} \quad \text{AND} \quad \bar{V}_w (x,y,z) = (u,v,w)^T$$

Figure 12.- Wind shear interface with simulated flight and aerodynamic characteristics.

simulator experience provided strong comment on their perception of the wind shear hazard and its potential impact on aviation safety.

The specific simulator test conditions for the August 5 wind shear penetration experiment are given in Figure 13. This particular simulator replicates the advanced flight management systems and crew interfaces incorporated in the Transport Systems Research Vehicle (TSRV) operated by the Langley Research Center. The flight and propulsion characteristics are those of a B737-100. This simulator has attributes which provides a nice environment in which to evaluate wind shear characteristics; i.e., electronic displays, panel mounted controllers, and sophisticated flight control augmentation. The autoland is inertially smoothed and the velocity vector control wheel steering mode provides good flying qualities for precision flight path management. The advanced primary flight display provides both airspeed and groundspeed information as well as inertial flight path angle and potential flight angle.

Twelve approach paths were preselected because of their interesting windshear properties and both autoland and manual approaches were flown. The simulator experiment evaluation criteria are shown in Figure 14. The evaluation criteria were based on FAA advisory circulars AC-120-29 (Ref. 5) and AC-20-57A (Ref. 6). Based on these selected sources, quantitative results were obtained for 100 ft. decision height CAT II approach criteria, acceptable touchdown performance and dispersion. Qualitative information was collected on whether the pilots would have aborted the approach and why, and pilot commentary regarding windshear severity rating was also obtained. For the twelve selected paths, the autoland was not disengaged so that 100 ft. decision height and touchdown data could be obtained and compared with certification criteria. Figures 15 and 16 illustrate graphically the longitudinal and lateral touchdown criteria, on a two sigma basis, for application to CAT II flight director and autoland certification.

Figures 17 and 18 illustrate the autoland 100 ft. decision height performance for the twelve selected paths in the JAWS August 5 windshear environment. Figure 17 also shows the decision height performance for a manual approach for path AB 2 using velocity vector control wheel steering, and Figure 18 shows that the manual approach for path PQ 12 was aborted at an altitude of 180 ft. Although the touchdown was successful for the manual approach for path AB 2, the airspeed dropped to 98 kts. and the pilot experienced an angle of attack warning and stick shaker. The current decision height window shown on Figures 17 and 18 is bounded by a ±12 ft. linear glide slope deviation at 100 ft. altitude, which is about one dot on a flight director, and ±5 kts. from V-reference. The decision height window is designed in such a way as to assure a successful landing under wind shear conditions up to 8 kt./100 ft. from 100 ft. altitude to the ground.

A literal interpretation of Ref. 5 suggests a lateral decision height window, at 100 ft. altitude, of the type shown in Figure 19. The window requirement of Figure 19 stems from the fact that at 100 ft. of altitude the airplane should be positioned so that the cockpit is within the lateral confines of the runway and the airplane is tracking so as to remain within the lateral confines of the runway. For the airplane to be within the lateral confines of the runway means a +75 ft. maximum localizer deviation for a standard 150 ft. wide runway. Tracking to remain within the lateral confines

- **FLIGHT PARAMETERS**
  - **APPROACH CONFIGURATION**
  - **85,000 LBS G.W. AND .2 CG**
  - **125 KT V REF**
  - **-3° GLIDESLOPE**
- **ENVIRONMENTAL FACTORS**
  - **10,000 FT RUNWAY**
  - **750 FT BREAKOUT, 10,000 FT RVR**
  - **6 KT HEADWIND REPORT, NO TURBULENCE**
  - **PILOTS WARNED OF WIND SHEAR IN THE SECTOR**
- **CONTROL MODES**
  - **INERTIALLY SMOOTHED AUTOLAND**
  - **ADVANCED VV-CWS**
- **ADVANCED PRIMARY FLIGHT DISPLAY**
  - **INERTIAL FLIGHT PATH ANGLE**
  - **GROUND SPEED**

Figure 13.- Simulator test conditions for JAWS August 5 wind shear penetration experiment.

- **SELECTED SOURCES**
  - **AC 120-29**
  - **AC 20-57A**

- **QUANTITATIVE**
  - **100 FT DECISION HEIGHT CAT II APPROACH CRITERIA**
  - **ACCEPTABLE TOUCHDOWN PERFORMANCE**

- **QUALITATIVE**
  - **PILOT COMMENTARY AND WIND SHEAR SEVERITY RATING**
  - **OTHER OBSERVATIONS**

Figure 14.- Evaluation criteria for JAWS August 5 wind shear penetration experiment.

APPLICABILITY: CAT II FLIGHT DIRECTOR
AUTOLAND

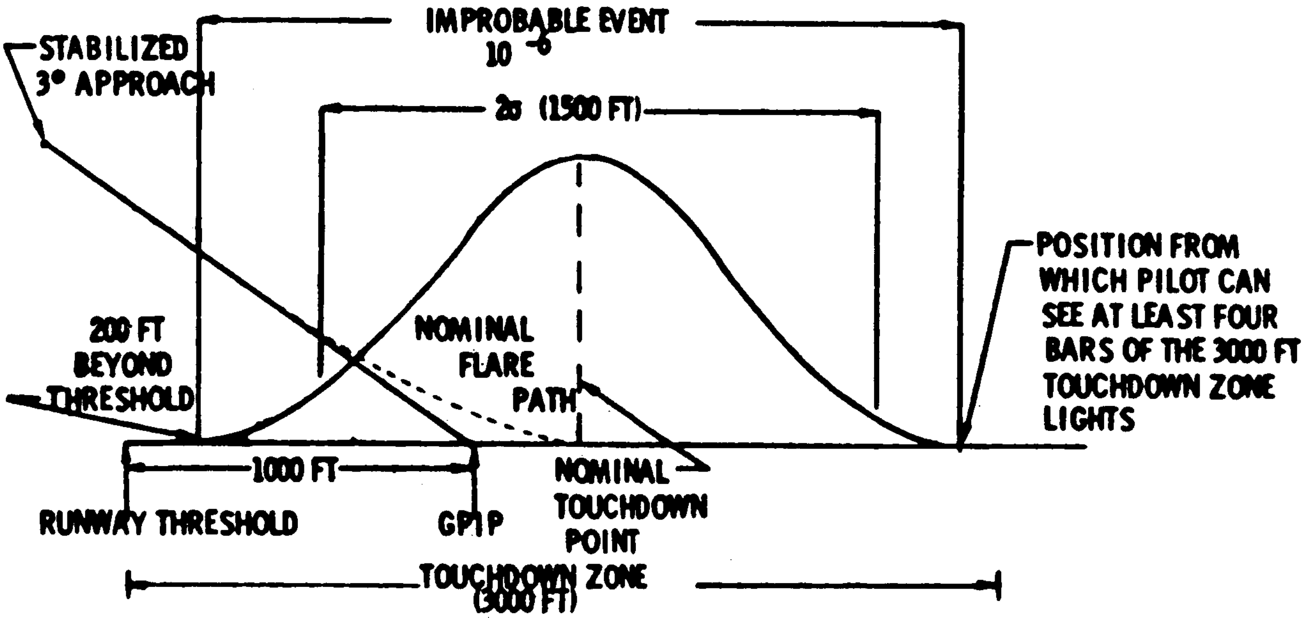

Figure 15.- Longitudinal dispersion certification requirement.

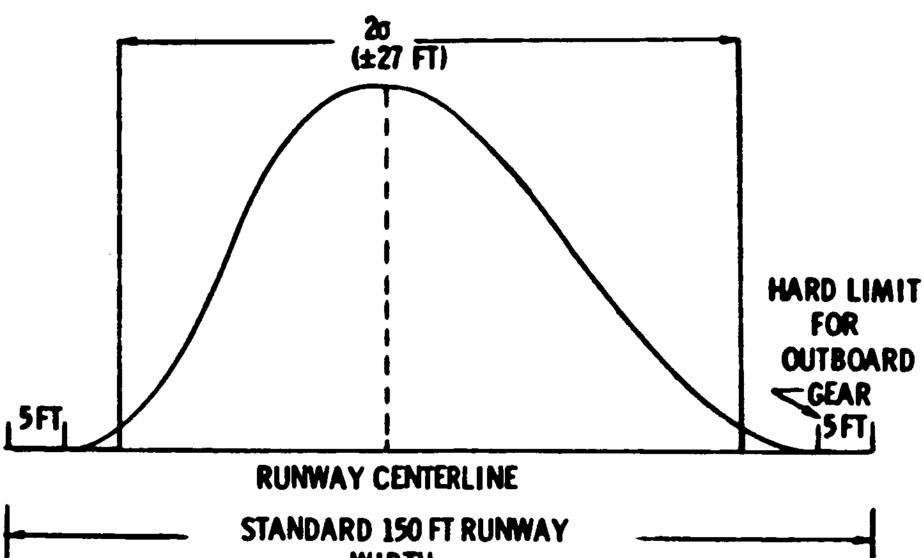

Figure 16.- Lateral dispersion certification requirement.

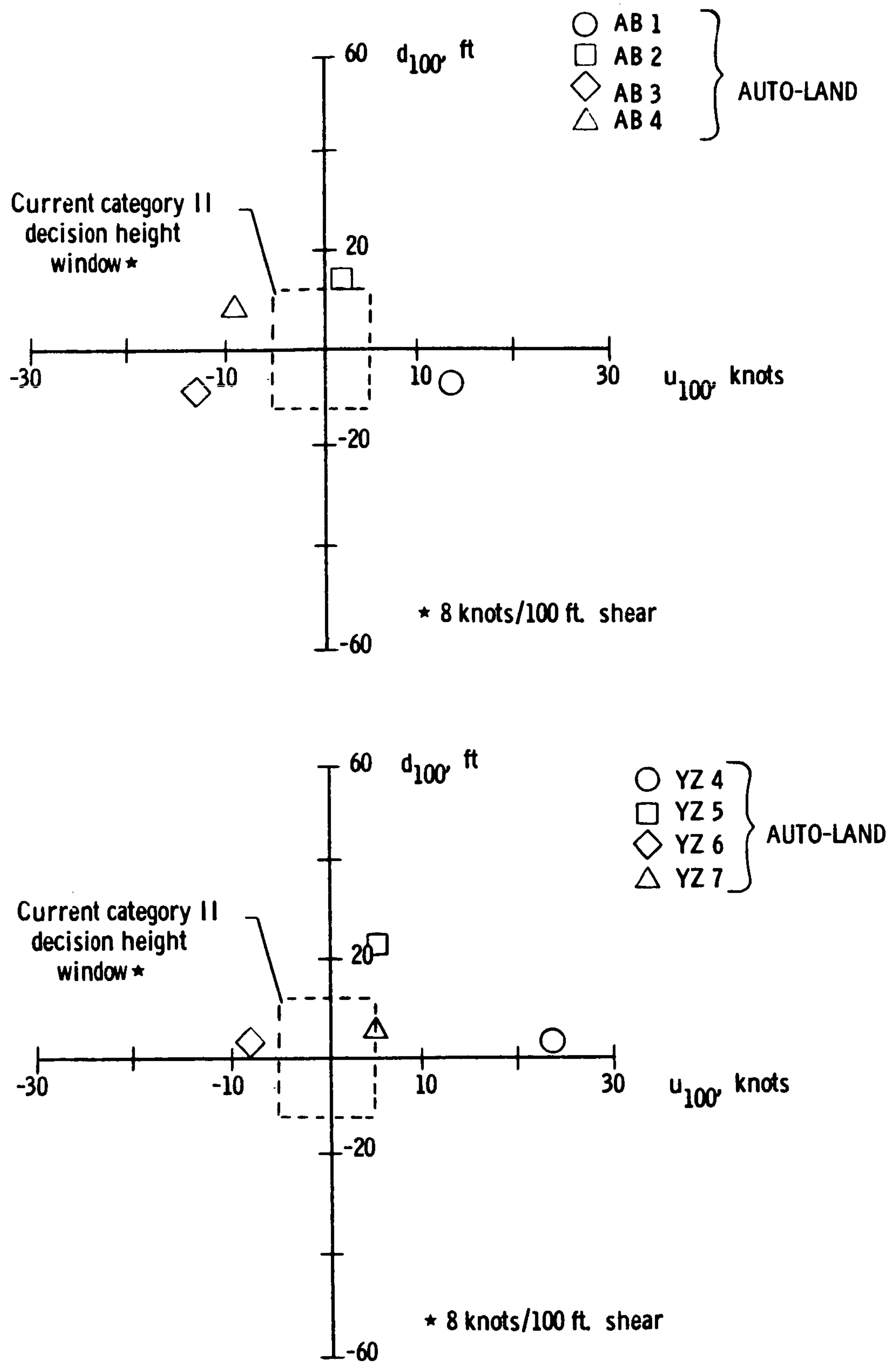

Figure 17.- Preliminary results for AB and YZ paths: Longitudinal decision height window-- Category II approach criteria.

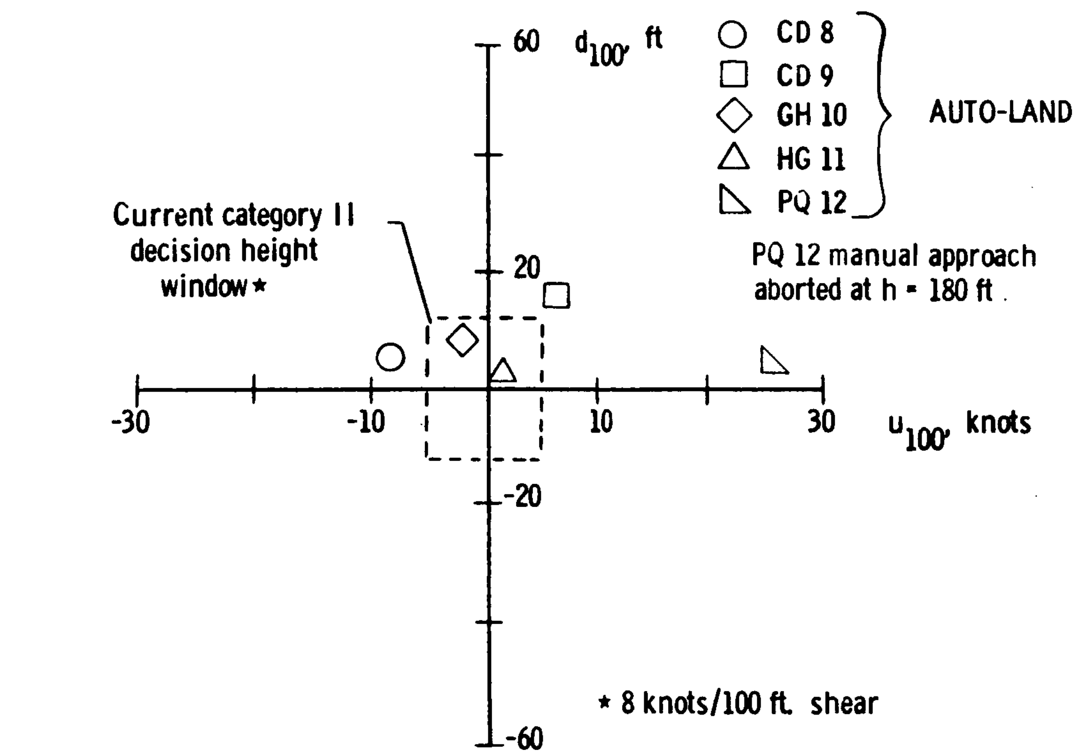

Figure 18.- Preliminary results for other selected paths: Longitudinal decision height window--Category II approach criteria.

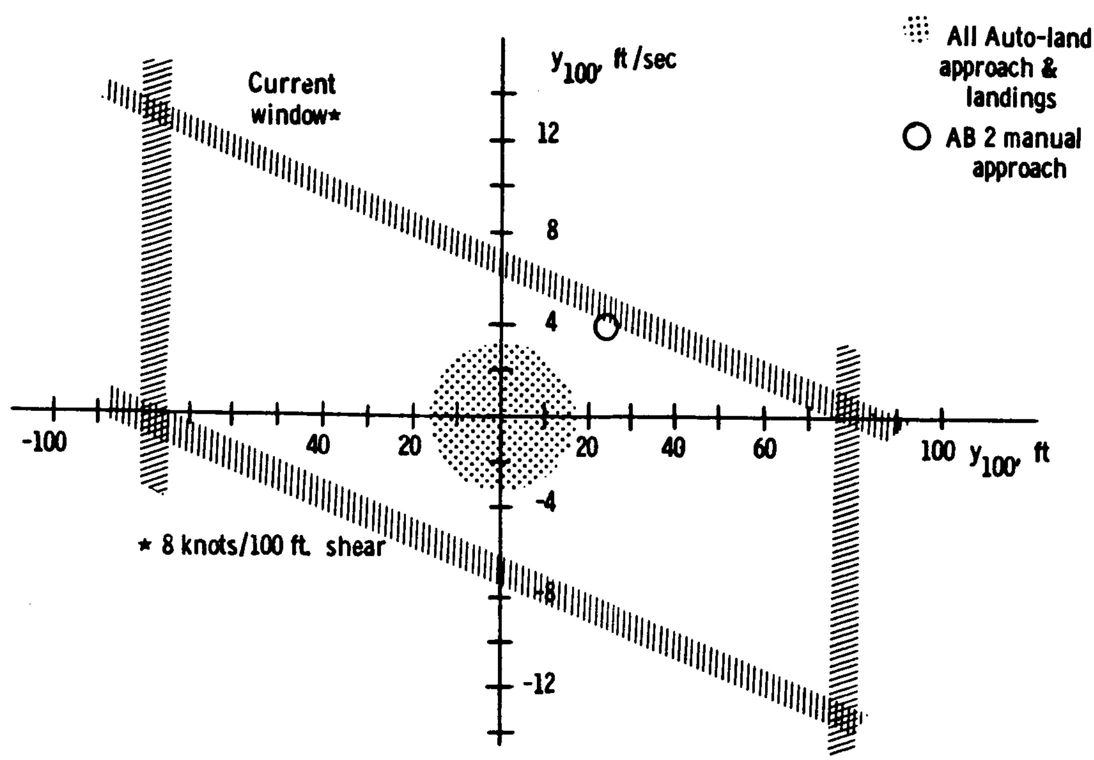

Figure 19.- Preliminary results for lateral decision height window--Category II approach criteria.

of the runway means that the combination of current lateral deviation and lateral deviation rate (cross track velocity) at the decision height results in a projected touchdown point that is still on the runway. As seen in Figure 19, all autoland approaches for the twelve selected approach paths fell within the lateral decision height window. The manually flown approach for path AB 2 produced a combination of lateral position offset and cross track velocity error very close to the stipulated decision height window.

Figure 20 illustrates the touchdown dispersion for the twelve autoland approaches as referenced to an acceptable landing region for a standard runway. The acceptable landing region is computed based on the two sigma criteria shown in Figures 15 and 16. Note that the manual approach for path AB 2 resulted in touchdown position which was slightly outside the acceptable landing region. A number of the selected paths resulted in automatic landings that were outside the acceptable landing region. These particular landings were generally longer and hotter due to the positioning of the microburst relative to runway threshold. For these cases, the airplane typically experienced a decreasing head wind shear or a head wind shearing to tail wind in such a way as to dramatically increase groundspeed prior to touchdown. Figure 21 shows a touchdown dispersion comparison between JAWS wind shear penetrations and the same simulator system flown against the 21 SRT wind shear profiles. No crashes occurred as a result of flying in the JAWS wind shear environment; however, the flight system was unable to negotiate three of the SRI profiles and crashed short of the runway. Figures 22 and 23 provide additional summary data collected during the JAWS wind shear simulation study, including touchdown criteria for state variables other than those mentioned previously, pilot comments, and wind shear severity ratings for the twelve selected paths.

The JAWS wind fields appear to be data rich and provides a multiplicity of wind shear profiles exhibiting subtle inflections and large dynamic range. Inherent properties of the wind fields provide abundant quantitative and qualitative wind shear clues including cross wind shear. Pilot perception of wind shear severity and attendant missed-approach decision depends strongly on shear phasing relative to runway and magnitudes of wind gradients encountered. A preliminary simulator experiment indicated performance violations, based on 100 ft. decision height criteria and acceptable touchdown dispersion for the candidate flight system studied.

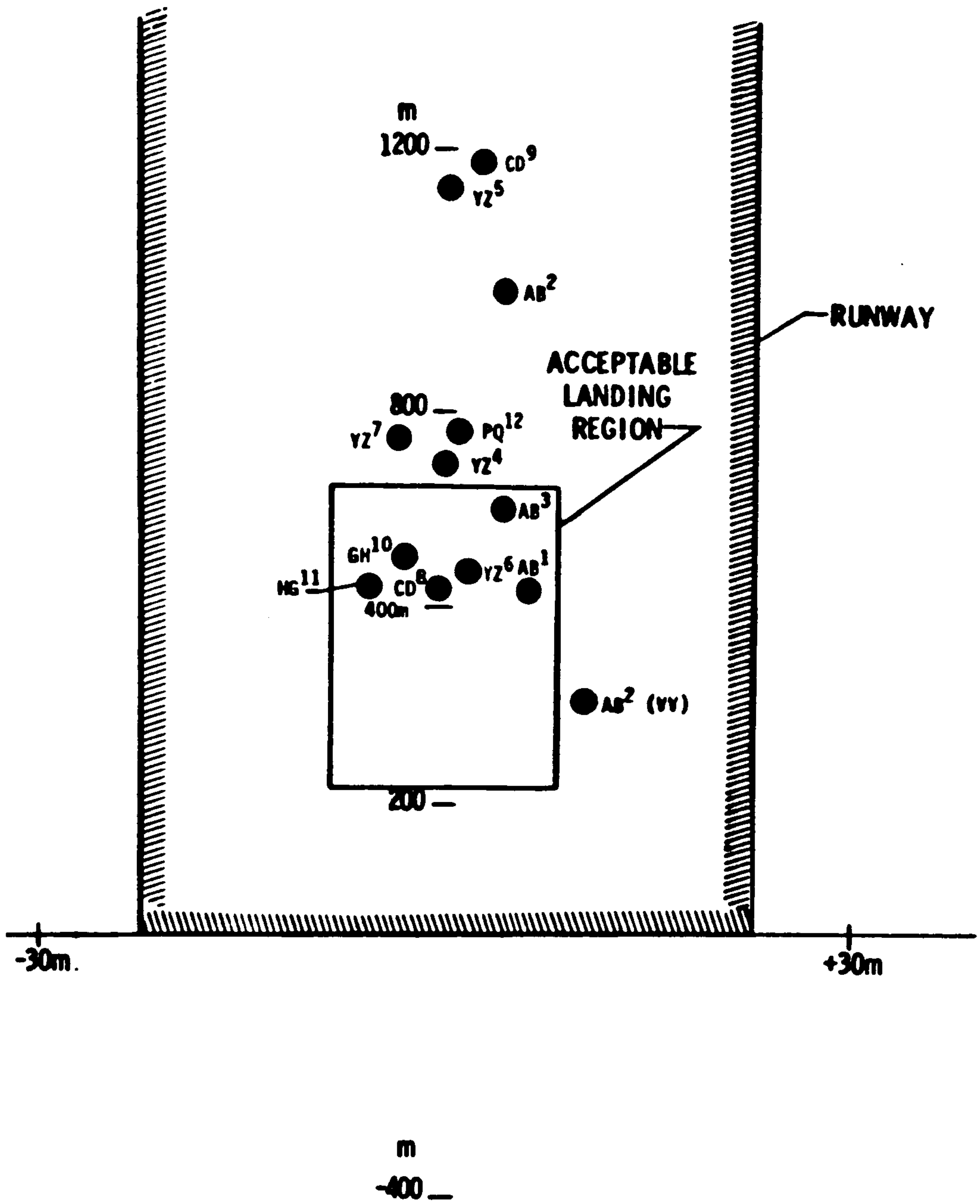

Figure 20.- Touchdown dispersion.

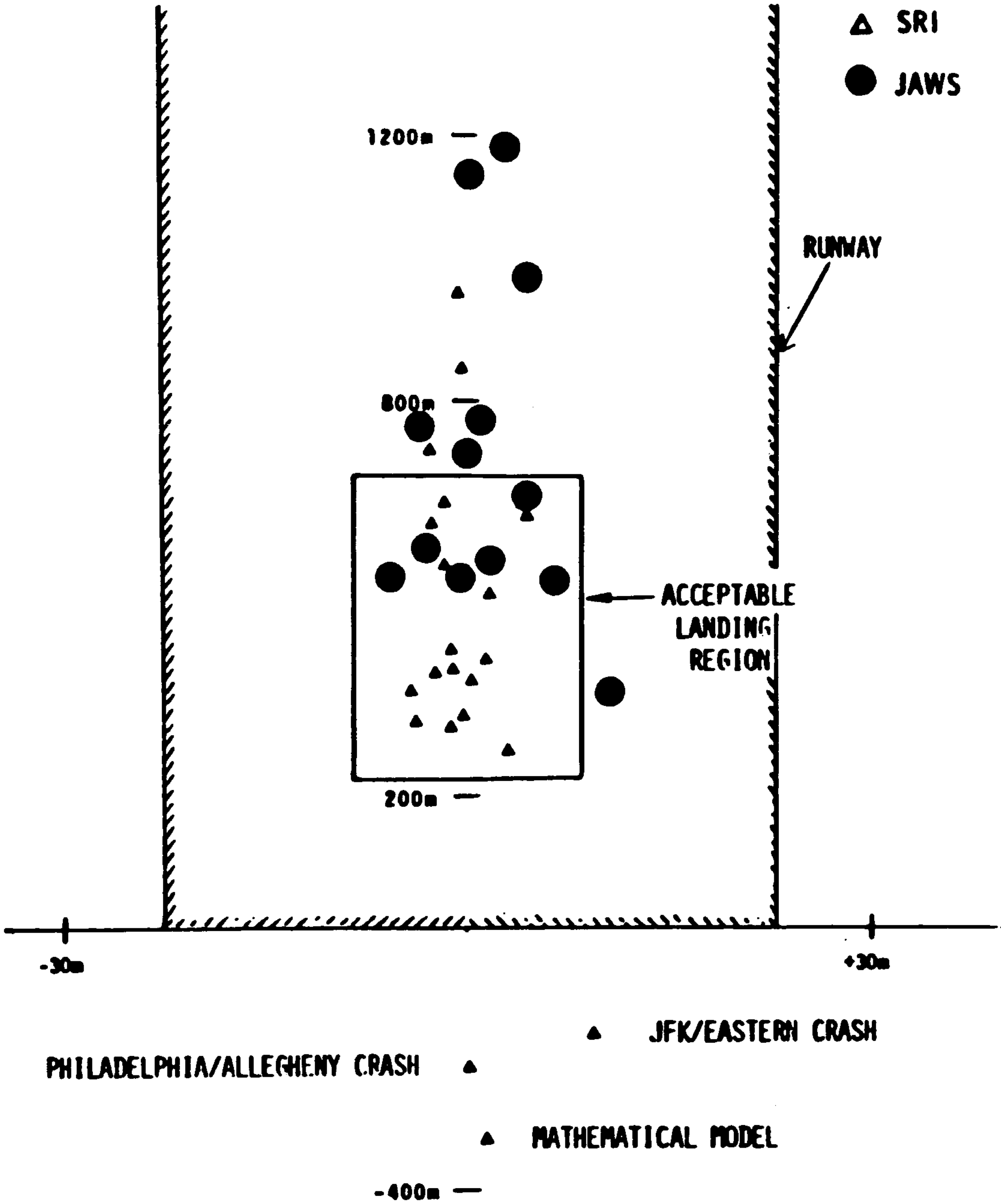

Figure 21.- Touchdown dispersion comparisons for SRI and selected JAWS wind shears.

FLIGHT PATH LABEL	TOUCHDOWN CRITERIA X_{TD}	$\dot{h}_{TD}$	θ_{TD}	U_{TD}	C_L	Y_{TD}	$\dot{Y}_{TD}$	β_{TD}	Φ_{TD}	COMMENTS
AB 1										All touchdown parameters in tolerance
AB 2	X		X	X						$U_{TD} > 1.3\ U_{stall}$, nosewheel landing, approach not stabilized
AB 3										All touchdown parameters in tolerance
AB 2 (manual)						X				CAS = 98 knots at h = 220 feet, stick shaker, AOA warning
YZ 4	X		X	X						$U_{TD} > 1.3\ U_{stall}$, nosewheel landing, approach not stabilized
YZ 5	X		X	X						$U_{TD} >> 1.3\ U_{stall}$, nosewheel landing, autothrottle limit cycle
YZ 6										All touchdown parameters in tolerance
YZ 7	X		X	X						$U_{TD} > 1.3\ U_{stall}$, nosewheel landing, insidious flight path de-stabilization
CD 8										All touchdown parameters in tolerance
CD 9	X		X	X						$U_{TD} >> 1.3\ U_{stall}$, nosewheel landing, approach not stabilized
GH 10										All touchdown parameters in tolerance
HG 11										All touchdown parameters in tolerance
PQ 12	X		X	X						$U_{TD} >> 1.3\ U_{stall}$, nosewheel landing, autothrottle limit cycle
PQ 12 (manual)										Abort landing at h = 180 feet, executed go-around

X - Denotes unacceptable performance

Figure 22.- Touchdown criteria.

FLIGHT PATH LABEL	PILOT RATING			COMMENTS
	+ SEVERE -	+ MODERATE -	WEAK	
AB 1		← X		Engine spool down cause for concern, go around at 520 feet Based on airspeed change
AB 2		← X		Go around based on airspeed change, horizontal shear noted
AB 3		X		Pilot went head-up, co-pilot would go around nose down attitude unacceptable, pilot decision to proceed marginal
YZ 4		X		Go around at 400 feet, based on airspeed change
YZ 5		← X		Go around at 100 feet, based on glide-slope error
YZ 6			X	Pilots monitored wind changes well
YZ 7		X →		Go around, high and fast
CD 8			X	Pilot apprehensive engine spool down, noted slight airspeed loss
CD 9		X		Go around at 100 feet, high and fast
GH 10			X	Apprehensive about spool down, "see this everyday"
HG 11			X	Noted down draft at 750 feet
PQ 12		X		Go around at 440 feet, airspeed loss, high pitch attitude

Figure 23.- Pilot rating.

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