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EFFECT OF SHEAR ON AIRCRAFT LANDING

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16. ABSTRACT

A simulation study was conducted to determine the effect of wind shear on aircraft landings. The landing of various type of commercial and military aircraft was digitally simulated starting from an initial altitude of 300 feet. Assuming no pilot feedback during descent, the deviation in touchdown point due to vertical profiles of wind shear was determined. The vertical profiles of wind shear are defined in terms of surface roughness, Z_o, and stability, L, parameters. The effects on touchdown due to Z_o and L have been calculated for the different type aircraft. Comparisons were made between the following types of aircraft: C-130E, C-135A, C-141, DC-8, Boeing 747, and an augmentor-wing STOL. In addition, the wind shear effect on touchdown resulting from different locations of the center of gravity and gross weights was also analyzed.

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FOREWORD

The motivation for the research reported in this document was to delineate the adverse effects of wind shear on the landing flight phase of aeronautical systems. Once these effects are known, relative to the total wind environment, it is possible to establish operational wind shear requirements and limits for observing and reporting low level wind shear. To assess the effects of wind shear, or to grade wind shears relative to their effect on aeronautical systems, a criteria must be established in the context of aeronautical system performance parameters. In this study, the degree to which a given shear environment adversely effects the landing flight phase of aeronautical systems was assessed in terms of the departure of the landing touchdown point from the touchdown point that would have occurred in the absence of wind shear. A variety of aircraft types and a broad selection of wind environments were selected for the analysis. The selected wind environments encompass a significant number of low level wind situations that would be encountered during the life of an operational aeronautical system. The effects of the wind environments on the aircraft touchdown point are presented in terms of properties of the selected flow fields. A number of new conclusions resulted from the study relative to how the details in the wind profile can effect the landing flight phase. It is believed that these results can have significant implications relative to the aeronautical safety aspects of the landing problem.

This research was conducted by the University of Dayton Research Institute for the National Aeronautics and Space Administration, George C. Marshall Space Flight Center, Huntsville, Alabama, under the technical direction of Dr. George H. Fichtl and Dr. Stephen W. Winder of the Aero-Astrodynamics Laboratory. The support for this research was provided by Mr. John Enders of the Aeronautical Operating Systems Division, Office of Advanced Research and Technology, NASA Headquarters.

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INTRODUCTION

Wind shear is an important consideration in the landing of aircraft and aerospace vehicles. As an aircraft descends its glide slope, a sudden change in the horizontal wind will instantaneously effect the velocity of the aircraft relative to the air mass.* If the shear is such that the relative velocity of the aircraft increases, the lift force will increase and the aircraft will tend to rise above the glide slope. If the shear causes a sudden decrease in the relative velocity, the aircraft will respond by falling below the glide slope and a potentially hazardous condition could result.

Several reports have been published which link short and long touchdown to a sudden wind shear occurrence during final approach (References 1 and 2). Recent accident reports have found wind shear to be at least a contributing cause to several accidents (Reference 2). In addition, it is believed that wind shear has been responsible for many other accidents though it remained undetected at the time (Reference 3).

The problem of quantitatively defining the effect of shear of given magnitude on an aircraft during descent has not been completely resolved. Noteworthy studies that have investigated wind shear and/or turbulence during landing include References 4, 5, 6, 7, 8, and 9. The study undertaken by the University of Dayton Research Institute (UDRI) was designed to provide answers to three specific questions: a) what shape of wind shear profiles are most critical to aircraft landing, b) which type of aircraft are most responsive to shear, and c) what meteorological parameters relate to those wind shears that provide critical landing problems. The UDRI provided answers to these questions by a digital simulation model for an aircraft landing in various wind profiles. The simulation model is used by first calculating the touchdown point for a conventional-type

* The effect of vertical air motions is not considered in this report.

aircraft trimmed on an initial glide slope of 2.7 degrees (7.0 for a STOL aircraft) in a constant wind field descending from an altitude of 300 feet. The landing simulation is then repeated for a wind shear profile input with initial trim conditions determined at 300 feet for the wind velicity at that altitude. By determining the deviation in touchdown point from the constant wind case, the effect of the shear on aircraft touchdown can be determined. This simulation model assumes a fixed stick model with no pilot or autopilot control.

The wind shear profile is defined in the surface boundary layer according to similarity theory by the surface roughness length, Z_0; the zeroplane displacement, d; the surface friction velocity, u*; and the stability parameter, Z/L. The next two sections describe in further detail the landing simulation model and the wind profiles used in the study.

Throughout this report, English units are used to describe the aircraft-related quantities while metric units are used to describe the meteorological quantities. On all figures, a dual system consisting of both sets of units is used. The use of both unit systems was necessitated to conform to the conventional systems used by the aircraft and meteorological communities.

AIRCRAFT LANDING MODEL

The aircraft trajectory model employed in this study was derived based on the following assumptions.

a) The earth is flat and nonrotating.

b) The acceleration of gravity is constant (32.2 ft/sec^2).

c) Air density is constant (0.002375 $slug/ft^3$).

d) The airframe is a rigid body.

e) The aircraft is constrained to motion in the vertical plane.

f) The aircraft has a symmetry plane (the x-z plane).

g) The mass of the aircraft is constant.

h) Once the aircraft is trimmed, its throttle setting and elevator deflection angle are not changed.

i) The aerodynamic stability derivatives are constant within the altitude and Mach number range experienced in this investigation.

At the beginning of each trajectory (300 feet altitude, H), the aircraft is trimmed by determining the values of angle of attack, throttle setting, and elevator deflection, which will result in unaccelerated flight. The equations of motion are then integrated numerically by a fourth-order Runge-Kutta scheme. For a constant wind and no ground effects, the aircraft flies down the glide slope at a constant velocity until it reachs the ground. Upon introducing a vertically-varying horizontal wind field, the aircraft no longer adheres to the glide slope. The resulting deviation in touchdown point serves as a measure of how severe the particular wind field is to the landing aircraft.

The influence of ground effects on the deviation in touchdown points between constant wind and wind shear conditions was investigated for several of the aircraft considered in this study. It was found that this influence was rather small and therefore was not included in the final analysis since ground effects data was not available for all of the aircraft. This is discussed further in the section describing the analysis of the data.

The aircraft included in this study are the DC-8, C-135A, C-141, C-130E, Boeing-747, and an augmentor-wing STOL aircraft. The first three are representative of the medium-weight turbojet transports. The first two are low-wing design while the third is a high-wing design. The C-130E is a lighter-weight transport powered by propjet engines. The Boeing-747 is, of course, a large turbojet transport. The augmentor-wing STOL aircraft is in the same weight category as the DC-8, C-135, and C-141. The aerodynamic data for this aircraft is similar to that used by NASA Ames Research Laboratory in their computer simulations of an augmentor-wing STOL aircraft.

The equations of motion of the aircraft were derived under the assumptions stated above. Figure 1 shows the forces acting on the aircraft. These include gravity ($m\vec{g}$), thrust of the engines ($\vec{F}_T$), and the aerodynamically-induced lift ($\vec{L}$), and drag ($\vec{D}$) forces. The figure shows the orientation of the forces with respect to the velocity vector relative to the earth ($\vec{V}$), the velocity vector relative to the air mass ($\vec{V}_a$), and the fuselage reference line (FRL) of the aircraft. The X axis in Figure 1 is parallel to the surface of the earth; the Z is perpendicular to the surface of the earth (positive downward).

Two of the equations of motion can be derived by summing the forces parallel and perpendicular to $\vec{V}$ (the velocity vector relative to the earth) and applying Newton's Laws of Motion. The result is

$$\begin{aligned} \dot{V} = &- g \sin\gamma + \frac{F_T}{m} \cos(\delta_T + \alpha) \\ &- \frac{\bar{q}S}{m} C_D \cos\delta \\ &- \frac{\bar{q}S}{m} C_L \sin\delta \ . \end{aligned} \tag{1}$$

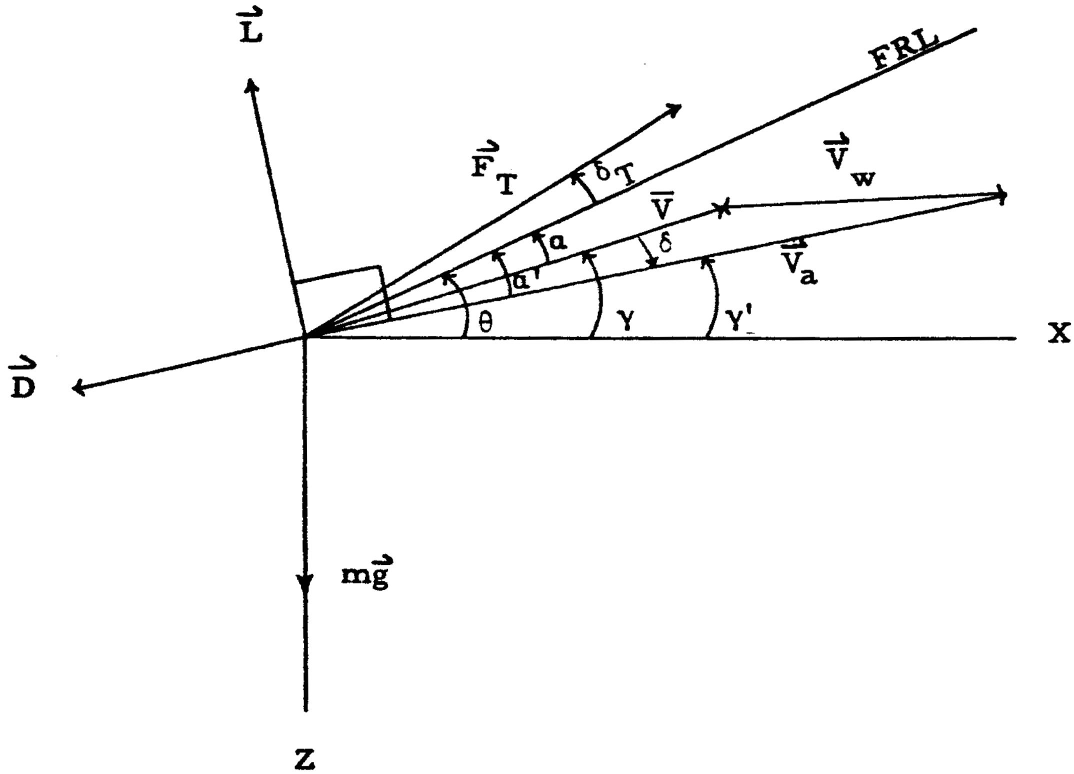

Figure 1. Relationship Between the Various Forces Acting on an Aircraft.

$$\dot{\gamma} = -\frac{g}{V}\cos\gamma + \frac{F_T}{mV}\sin(\delta_T + \alpha) - \frac{\bar{q}S}{mV} C_D \sin\delta + \frac{\bar{q}S}{mV} C_L \cos\delta \quad , \tag{2}$$

where the dot refers to the derivative with respect to time and

- g is the magnitude of the acceleration of gravity,
- V is the magnitude of the velocity relative to the earth,
- γ is the angle between $\vec{V}$ and the X-axis (the flight path angle),
- F_T is the magnitude of the thrust vector,
- m is the aircraft mass,
- δ_T is the angle between the thrust vector and the fuselage reference line (FRL),
- α is the angle between $\vec{V}$ and the FRL,
- $\bar{q}$ is the dynamic pressure which is equal to one half the air density (ρ) times the square of magnitude of the velocity relative to the air mass (V_a), $\bar{q} = 1/2\ \rho V_a^{\ 2}$,
- S is the aircraft wing area,
- δ is the angle between $\vec{V}_a$ and $\vec{V}$,
- C_D is the drag coefficient, and
- C_L is the lift coefficient.

The aerodynamic forces and the thrust from the engines exert a pitching moment on the aircraft. The equation describing the rotational acceleration is

$$\dot{q} = \frac{F_T L_T}{I_{yy}} + \frac{\bar{q}S\bar{c}}{I_{yy}} C_m \quad , \tag{3}$$

where

- $\dot{q}$ is the time derivative of the pitching rate (q),
- L_T is the effective moment arm of the thrust vector,
- $\bar{c}$ is the Mean Aerodynamic Chord,

I_{yy} is the moment of inertia about the symmetry plane of the aircraft, and

C_m is the pitching moment coefficient.

Equations (1), (2), and (3) form the core of the Aircraft Landing Program. These three equations along with

$$\dot{X} = V \cos\gamma$$
$$\dot{Z} = -V \sin\gamma$$
$$\dot{\theta} = q$$

are the six equations of motion of an aircraft constrained to fly in the vertical plane. $\dot{\theta}$ is the time derivative of the angle between the FRL and the X-axis.

In order to evaluate the above equations at each time step, several auxiliary equations are needed. They are

$$V_a = \left[(\dot{X}-W_x)^2 + \dot{Z}^2\right]^{1/2} \quad ,$$
$$\bar{q} = 1/2\ \rho\ V_a^{\ 2} \quad ,$$
$$\delta = \sin^{-1}\left(\frac{W_x \sin\gamma}{V_a}\right) \quad ,$$
$$\alpha' = \theta - \gamma - \delta \quad ,$$
$$\alpha = \theta - \gamma \quad ,$$
$$\dot{\alpha}' = q + \frac{g}{V_a}\cos(\gamma + \delta) - \frac{F_T}{mV_a}\sin(\delta_T + \alpha') - \frac{\bar{q}S}{mV_a} C_L \ ,$$
$$C_L = C_L(\alpha', \delta_E, V_a, q, \dot{\alpha}') \quad ,$$
$$C_D = C_D(\alpha', \delta_E, V_a, q, \dot{\alpha}', C_L) \ , \text{ and}$$
$$C_m = C_m(\alpha', \delta_E, V_a, q, \dot{\alpha}') \ ,$$

where W_x is the horizontal wind speed, α' (the angle of attack) is the angle between V_a and the FRL, and δ_E is the elevator deflection angle. As is indicated above, the aerodynamic coefficients are functions of a number of variables. The expressions for C_L, C_D, and C_m, are not the same for all the aircraft considered. These expressions along with the stability derivative data are presented in Appendix A.

The above set of equations comprise the aircraft model. The initial conditions and aircraft physical data for each of the flights simulated in this study are presented in Table 1. The glide slope for the conventional aircraft flights was 2.7 degrees while its value for the STOL aircraft flights was 7 degrees. As noted in the table, the Boeing-747 was investigated at two landing weights. Flights of this aircraft were simulated with center-of-gravity locations of 15%, 25%, and 33% Mean Aerodynamic Chord. Each aircraft was flown in a wide variety of horizontal wind shear conditions. These are discussed in the following section.

TABLE 1

INITIAL FLIGHT CONDITIONS
AND AIRCRAFT PHYSICAL DATA

Data	DC-8	C-135A	C-141	C-130E	Boeing-747	Boeing-747	STOL
H(ft)	300.0	300.0	300.0	300.0	300.00	300.0	300.0
V_a(ft/sec)	230.0	237.0	200.0	166.5	217.0	184.3	118.1
γ(deg.)	-2.7	-2.7	-2.7	-2.7	-2.7	-2.7	-7.0
W(lb)	200,000	200,000	250,000	80,000	550,000	400,000	203,000
I_{yy} (slug-ft^2)	3.90×10^6	3.21×10^6	4.30×10^6	1.55×10^5	48.13×10^6	24.50×10^6	6.55×10^6
L_T (ft)	4.00	4.49	4.00	0.00*	5.70	5.70	3.58
δ_T (deg)	3.15	0.00*	0.00*	0.00*	2.50	2.50	3.00
S(ft^2)	2758	2433	3228	1746	5500	5500	2620
$\bar{c}$ (ft)	22.16	20.16	22.20	13.71	27.31	27.31	20.20

*This nominal value was chosen since the actual value was not available.

WIND SHEAR MODEL

The wind shear model used in the aircraft landing simulation is completely described in the document, "A Model of Wind Shear and Turbulence in the Surface Boundary Layer" (Reference 10). Only a cursory description of the model is presented here.

The wind shear in the surface boundary layer is considered to be a function of surface conditions, stability conditions, and altitude. According to similarity theory, the mean wind speed for three of the four stability classifications is defined as a function of altitude by

$$\bar{u} = \frac{u*}{k} \left[\mathrm{Ln} \left(\frac{Z}{Z_o} \right) + \psi \left(\frac{Z}{L} \right) \right] \tag{4}$$

where Z_o is the surface roughness length,

$u*$ is the surface friction velocity,

k is the Von Karman's constant ≈ 0.4,

Z is the altitude above the reference level, and

L is the Monin-Obukov stability length.

In the unstable classification, the function ψ is given by

$$\psi \left(\frac{Z}{L} \right) = \int_{Z_o/L}^{Z/L} Z/L \left\{ 1 - (1 - 18\, Z/L)^{-1/4} \right\} d \left(\frac{Z}{L} \right) .$$

The stability parameter, Z/L, is related to the gradient Richardson number for the unstable classification by Businger's Hypothesis:

$$Ri = Z/L \quad \text{for } Ri < 0 .$$

For the neutral classification, $Z/L = 0$ and $\psi(0) = 0$ so that the wind speed, given by Equation (4), is a logarithmic function of altitude.

For the stable condition, that is $0 < Ri \leq 0.2$, the function is described by

$$\phi(Z/L) = 5.2\, Z/L \quad .$$

The relationship between Richardsons number and Z/L is stable air is

$$Z/L = \frac{Ri}{1 - 5.2\,Ri} \quad \text{for } 0 < Ri < 0.2 \quad .$$

Figures 2, 3, and 4 show plots of typical wind profiles for the unstable, neutral,and stable categories.

For the very stable condition, when $Ri \gtrsim 0.2$, the wind speed cannot be represented by Equation (4). In fact, no analytic function has been found to adequately represent the very stable wind profiles. Under strong inversion conditions, turbulence tends to diminish so that the layers of the atmosphere become disconnected. Figures 5 and 6 show two types of profiles that are likely to exist under inversions. Figure 5 shows a calm below the interface level with a constant wind above this level. In Figure 6, a logarithmic wind profile is shown below the interface with a constant wind magnitude above this level. Several values of the interface level and the wing magnitude above the interface were considered in this study.

The wind direction in the surface boundary layer can be considered constant with altitude except in the very stable condition. In very stable air, the wind direction often changes by 45 degrees or more between the surface and 300 feet.

The wind input to the aircraft landing simulation program consists of defining the wind profile from 300 feet altitude to the surface. The wind magnitude has been defined for the unstable, neutral, and stable conditions by Equation (4). The parameters $u*$, Z_o, and L were varied

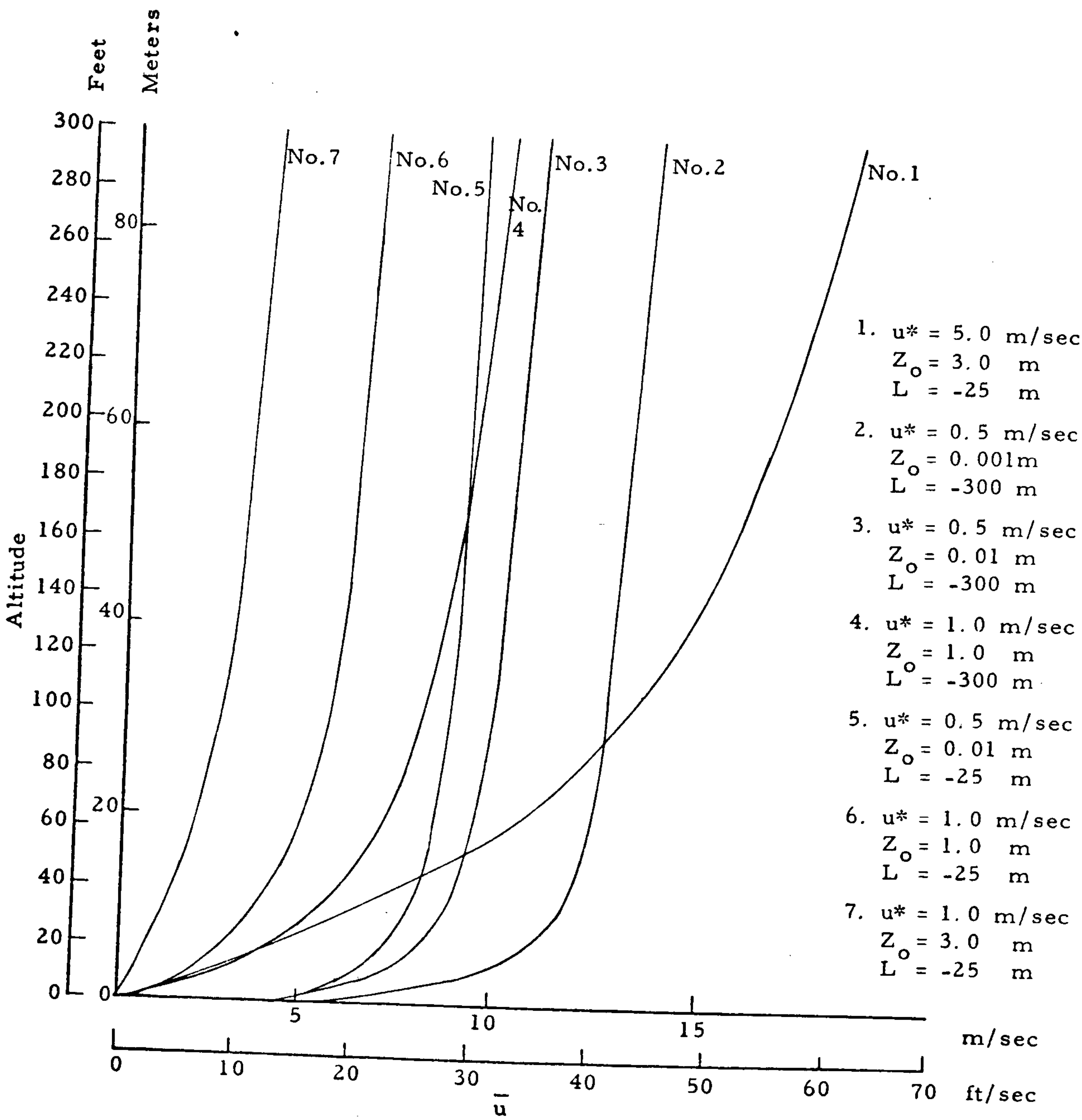

Figure 2. Unstable Wind Profiles.

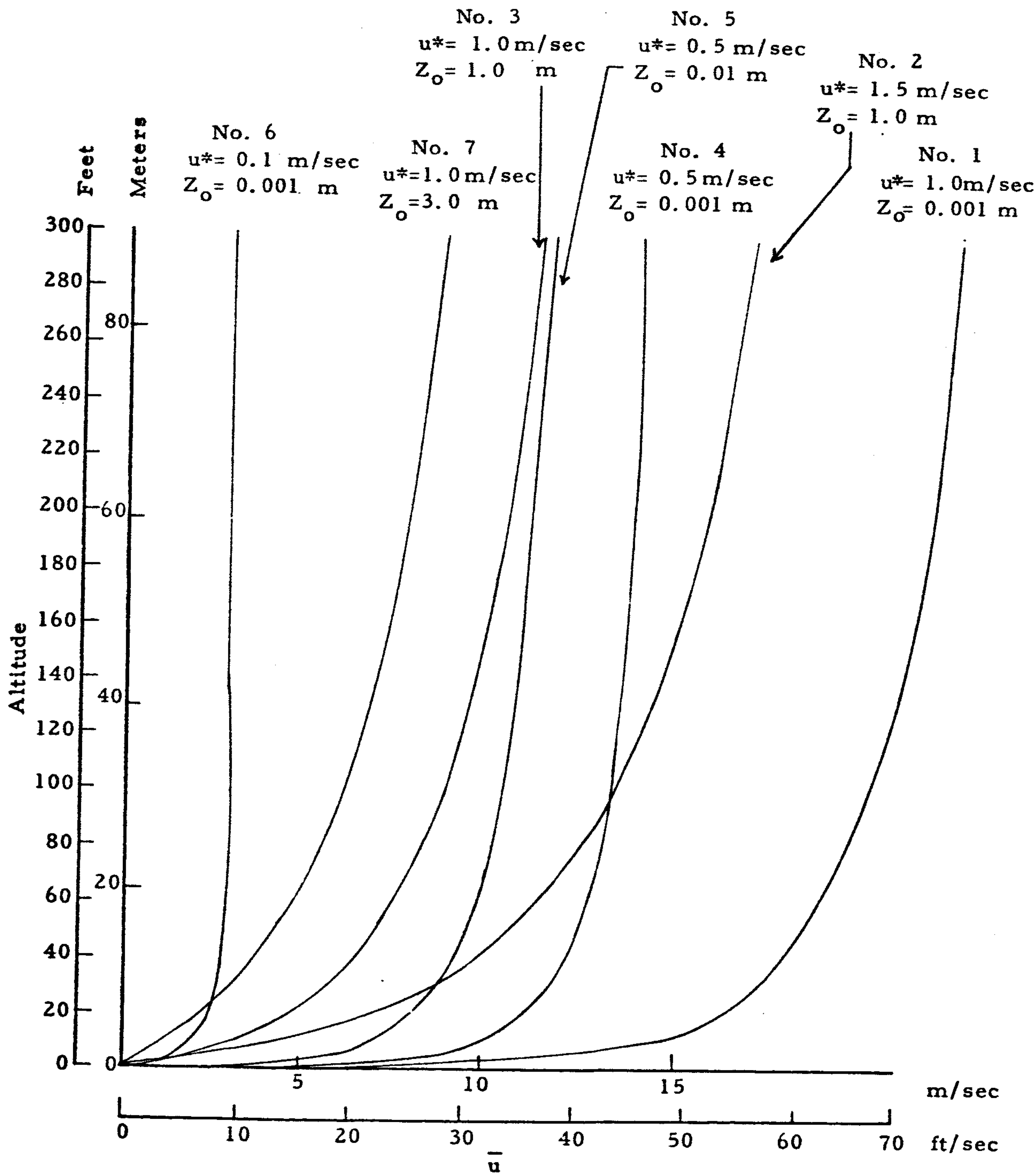

Figure 3. Neutral Wind Profiles.

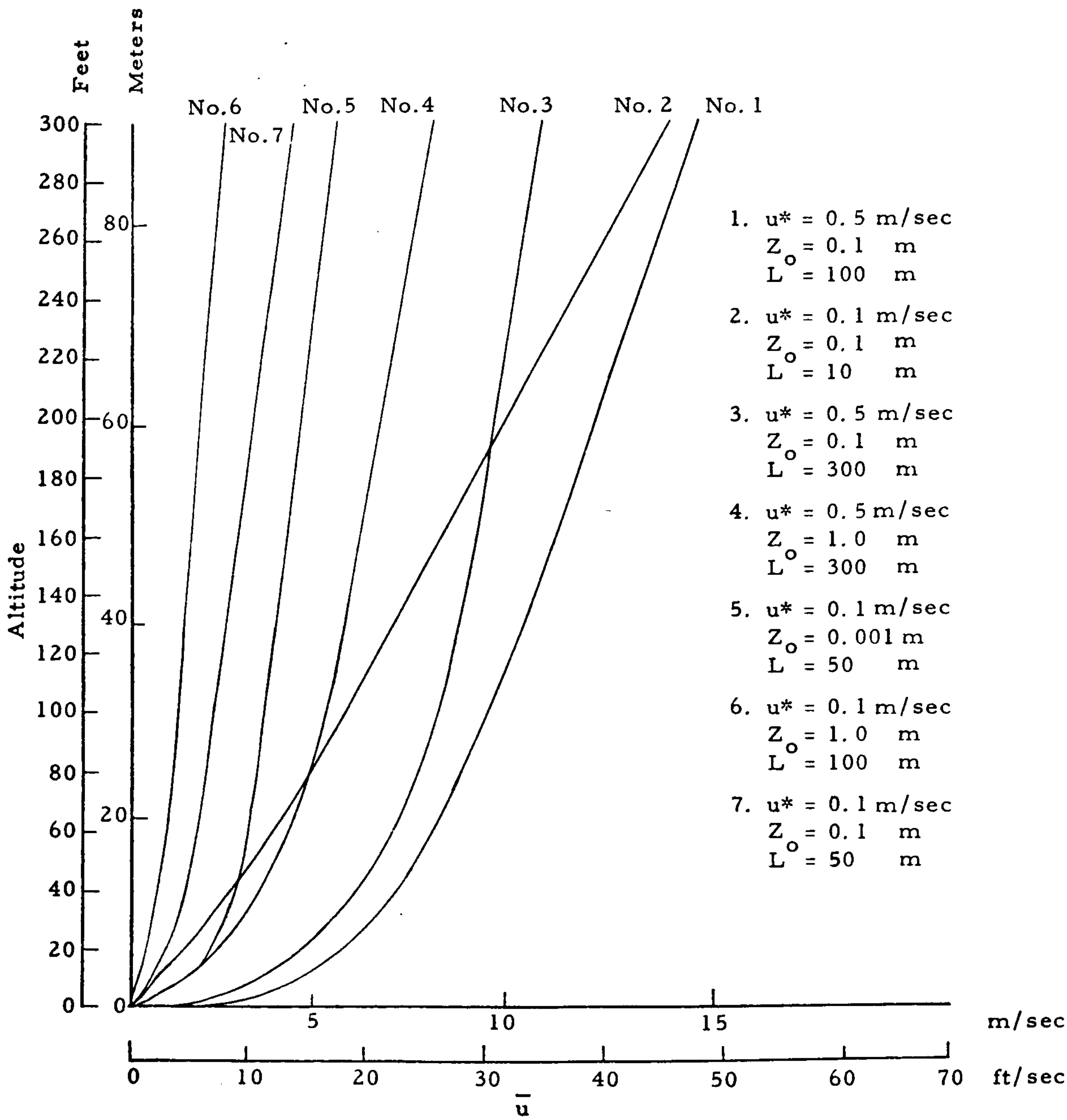

Figure 4. Stable Wind Profiles.

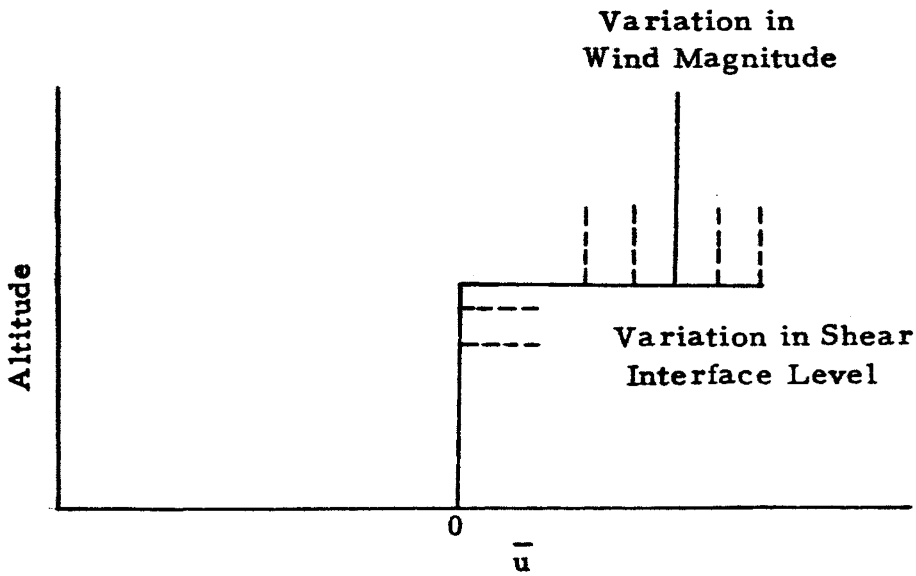

Figure 5. Very Stable Wind Profiles.

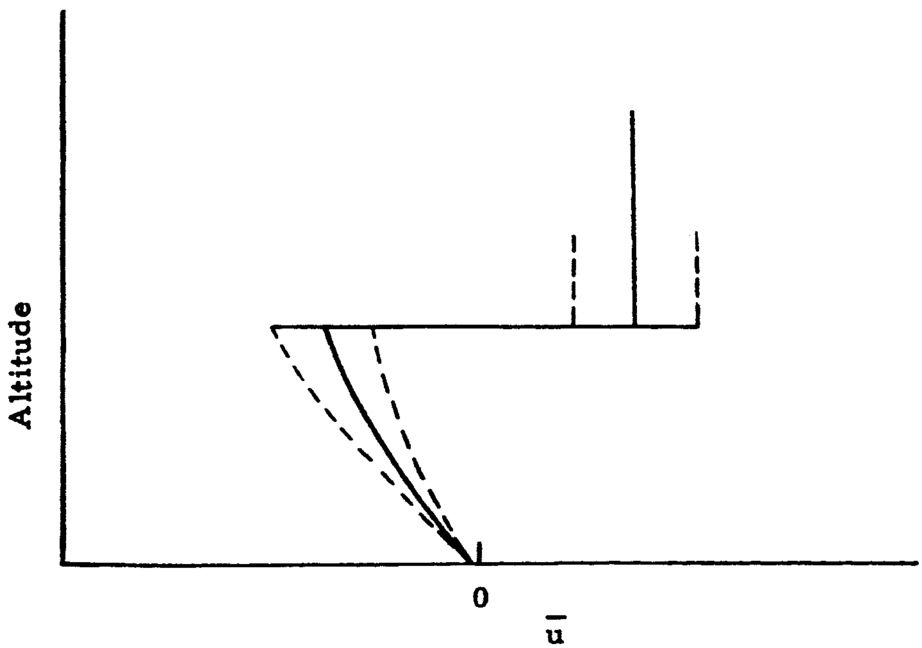

Figure 6. Very Stable Wind Profiles.

so as to include all reasonable wind profiles. For the very stable condition, wind profiles of the type shown in Figures 5 and 6 have been used. The wind direction is considered constant with altitude for all stability conditions. In the landing simulation program, only headwinds and tailwinds have been considered with the emphasis being on the more conventional headwind landing case.

ANALYSIS OF CONVENTIONAL AIRCRAFT LANDINGS

The initialization conditions for the simulated landings of conventional aircraft were a 2.7-degree glide slope with the descent beginning at an altitude of 300 feet. (An augmented-wing STOL aircraft is discussed in a later section.) This corresponds to a touchdown point 6361 feet downrange from where the descent begins. The aircraft is trimmed at 300 feet to maintain the 2.7-degree glide slope for the wind speed existing at that point. Any variation in wind speed will cause the aircraft to deviate from the glide slope. The deviation in touchdown point is defined as the distance between the actual touchdown point and the 2.7-degree glide slope touchdown point. That is, if the aircraft lands at a distance X downrange from its initial descent point (300 feet altitude), then the deviation in touchdown point, ΔT, is

$$\Delta T = X - 6361.$$

Note that a positive ΔT indicates a long landing while a negative ΔT indicates a short landing.

Figures 7, 8, and 9 show the descent of the DC-8 through the unstable, neutral, and stable wind profiles of Figures 2, 3, and 4. The numbering of the aircraft descent trajectories corresponds to the numbers on the wind profiles. The trajectories numbered 1 through 7 correspond to headwind profiles. The No. 8 trajectory corresponds to a zero wind (or constant wind) profile. The No. 9 and 10 trajectories correspond to tailwind profiles. In particular, the No. 9 profile has the same shape as the No. 6 profile but differs in direction by 180 degrees. Similarly, the No. 10 profile is the same as the No. 3 profile except for direction. The above is true for the unstable, stable, and neutral wind profiles. Figure 10 shows the DC-8 landing through the very stable wind profiles of Figure 11. The No. 1 through 8 profiles are headwinds, No. 9 is a zero wind, and Profile No. 10 is the same as No. 5 but is a tailwind.

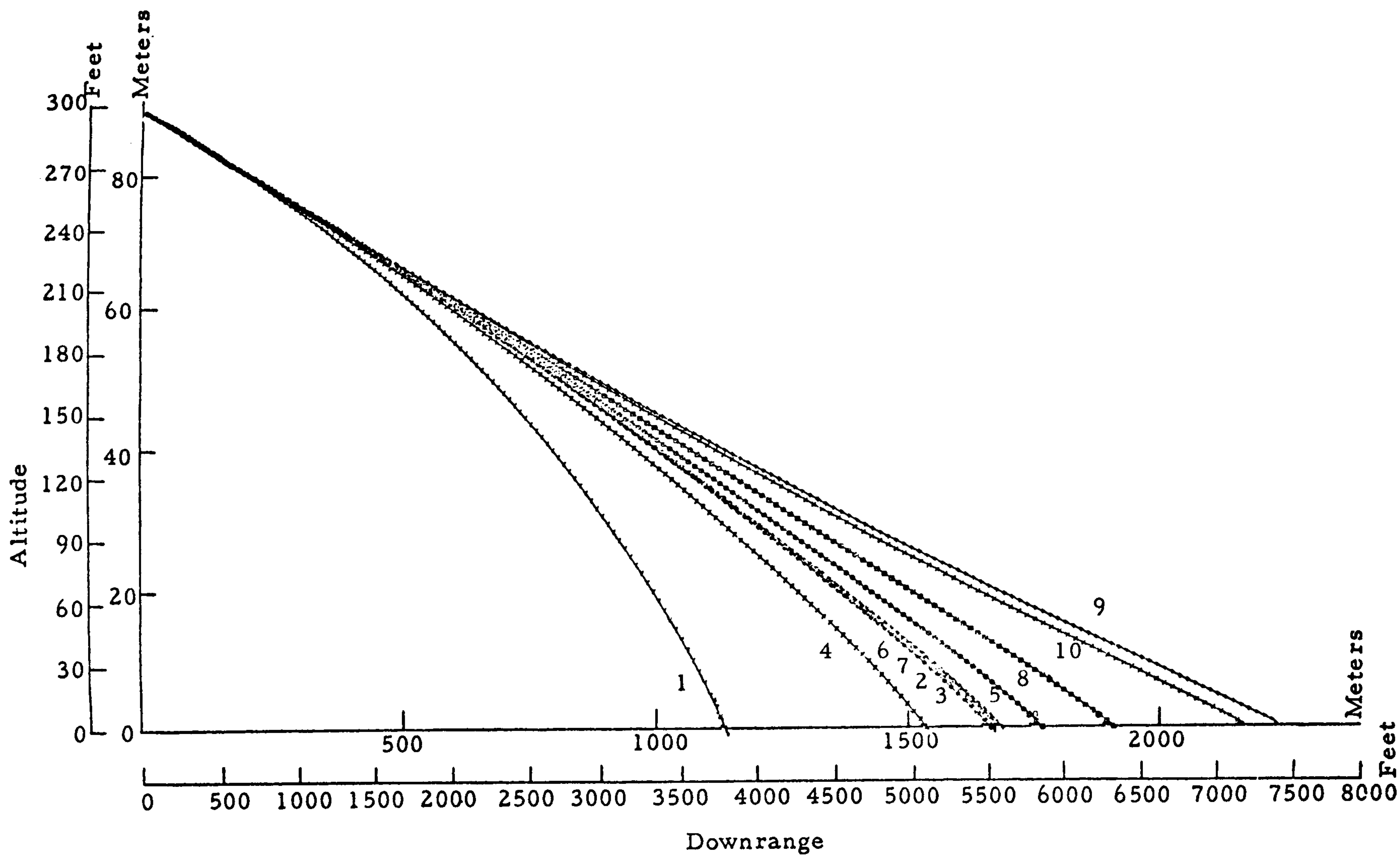

Figure 7. Aircraft Descent Trajectories Through Unstable Wind Profiles.

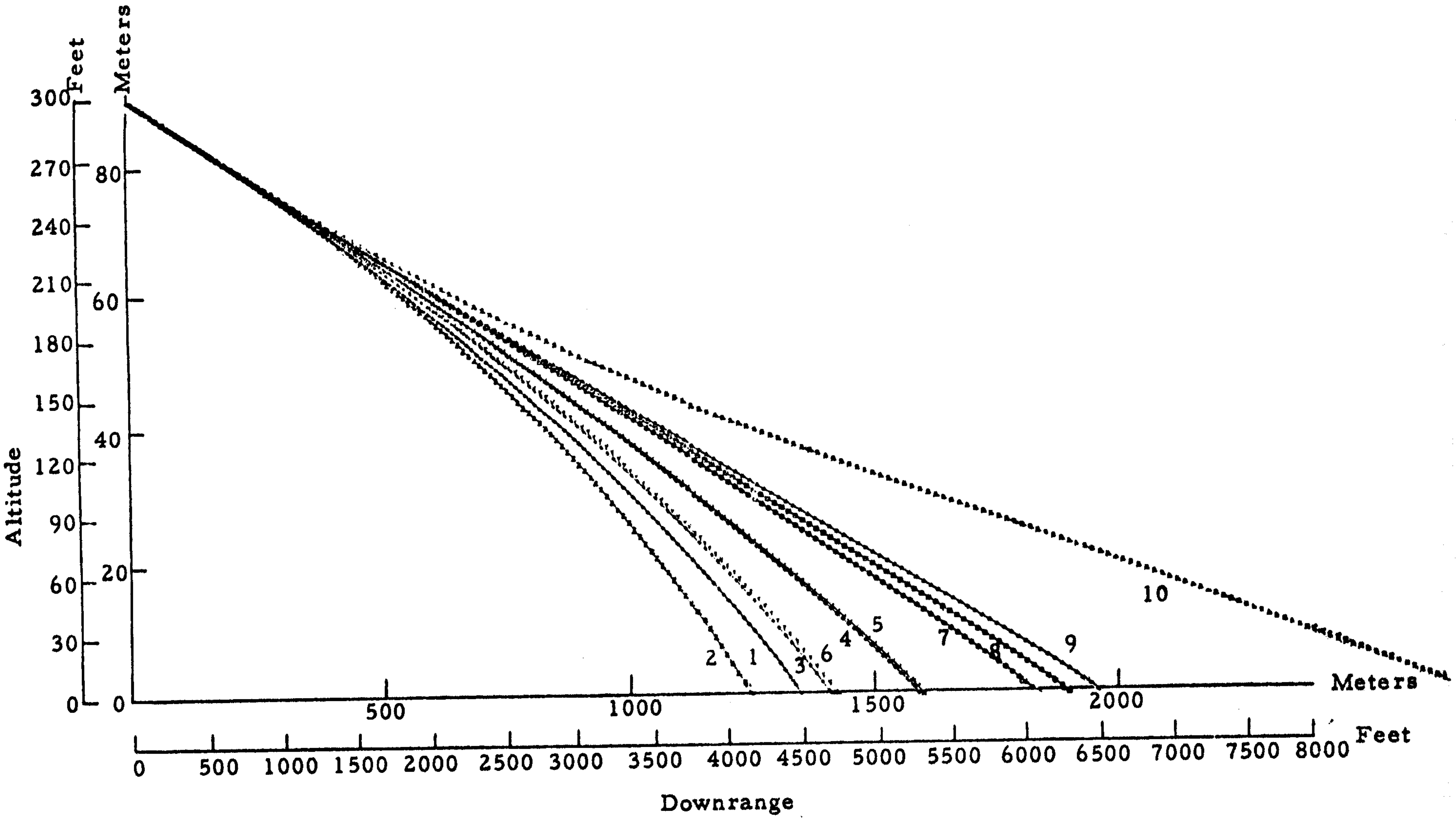

Figure 8. Aircraft Descent Trajectories Through Neutral Wind Profiles.

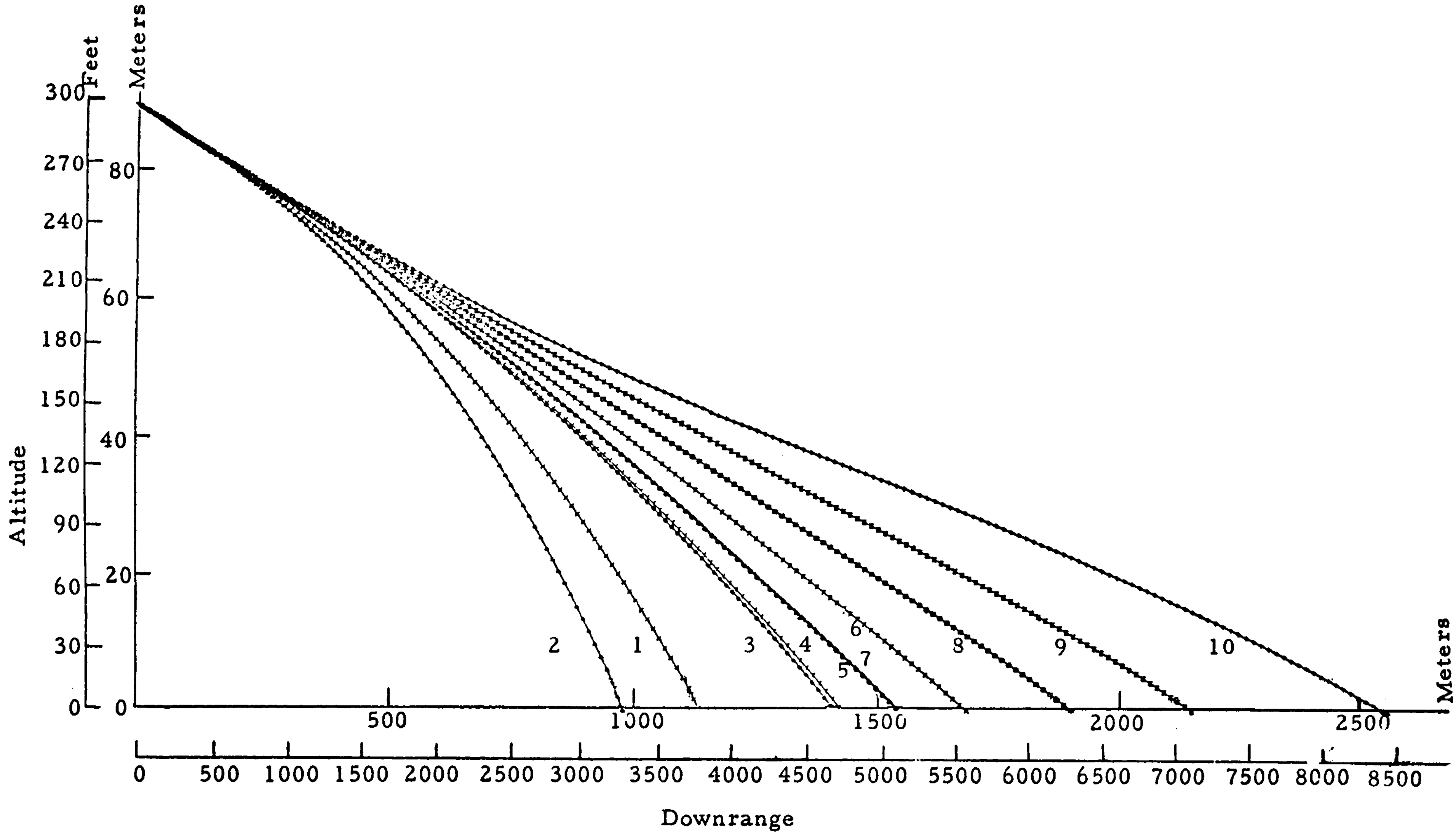

Figure 9. Aircraft Descent Trajectories Through Stable Wind Profiles.

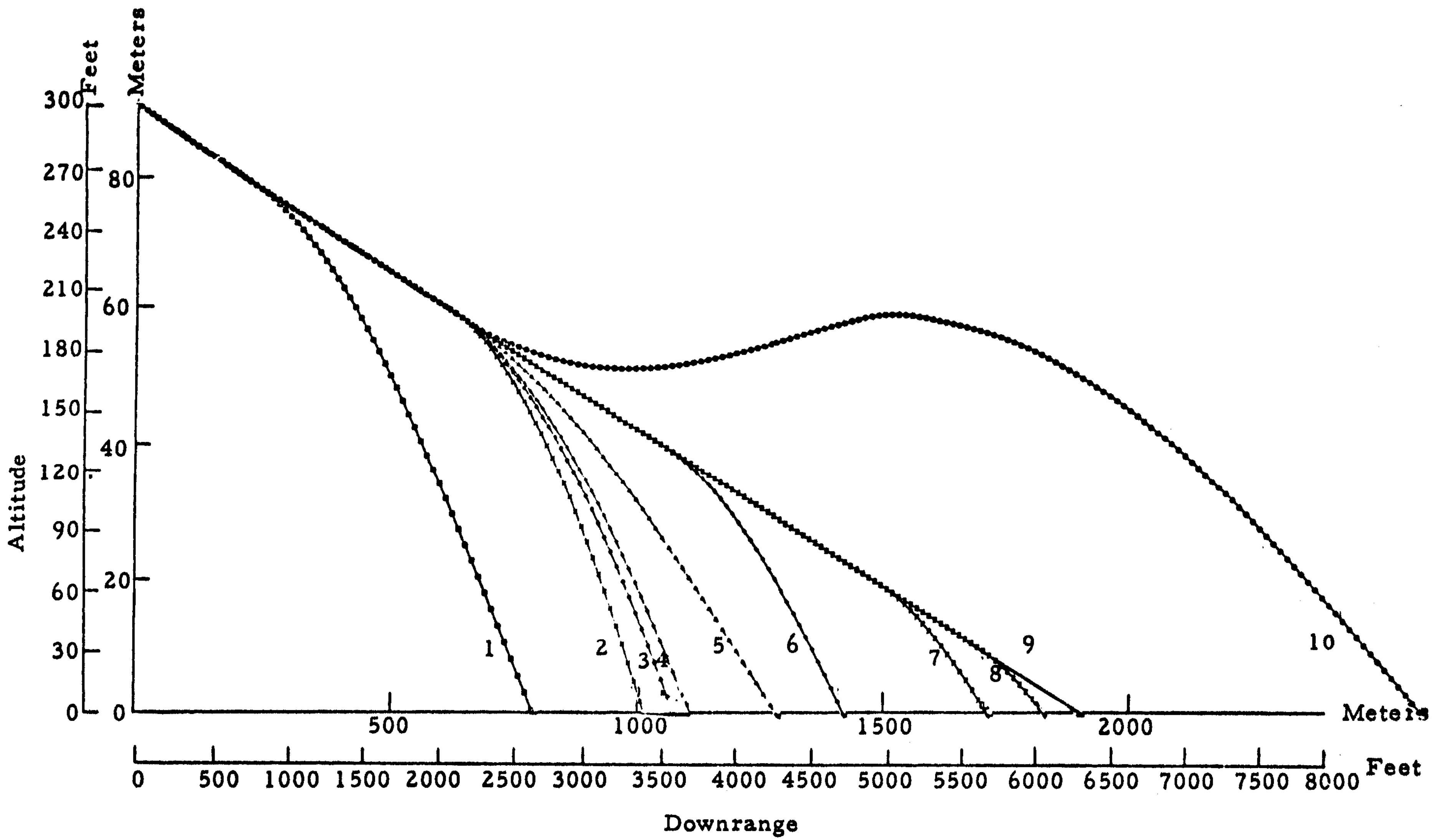

Figure 10. Aircraft Descent Trajectories Through Very Stable Wind Profiles.

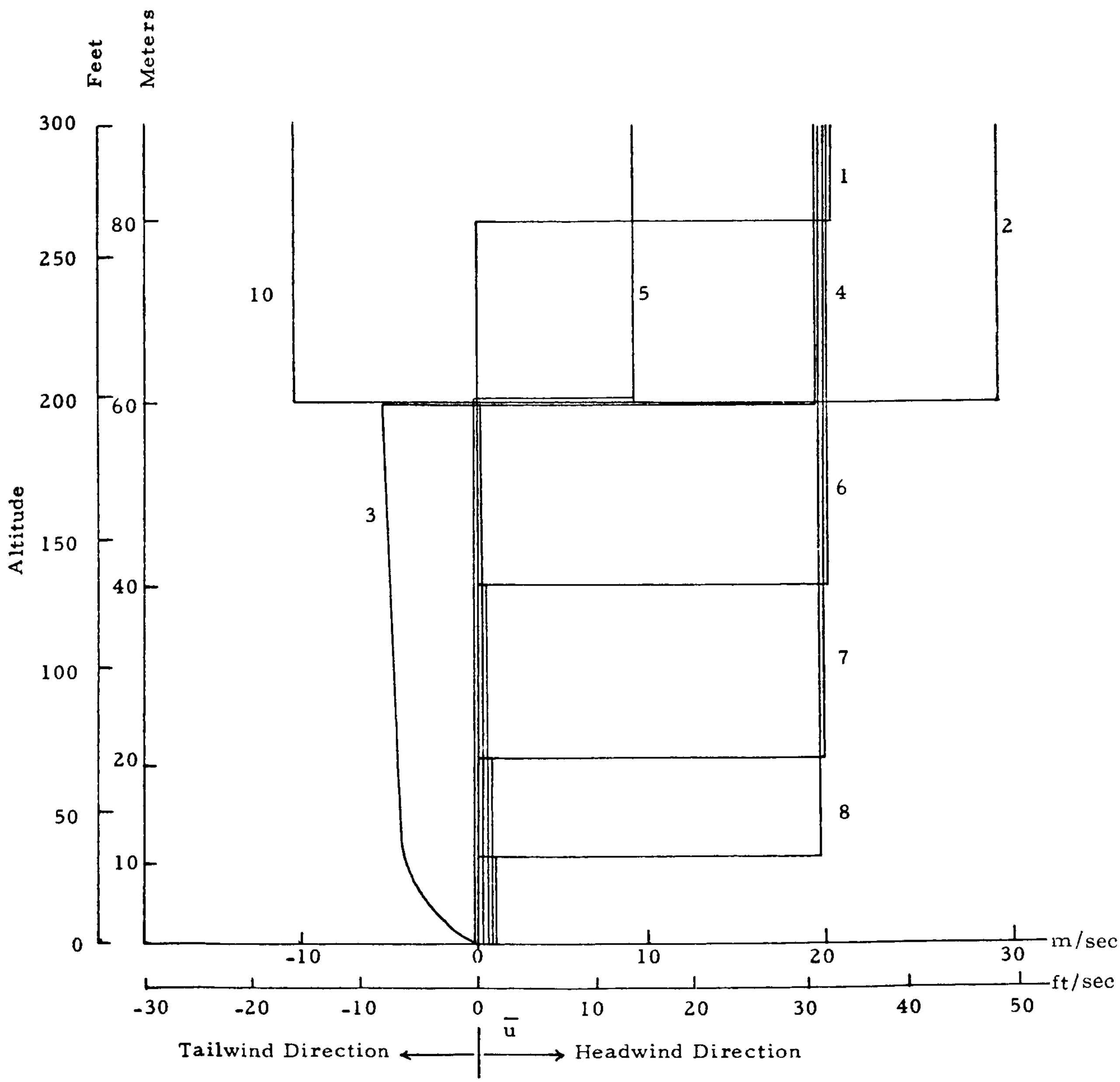

Figure 11. Very Stable Wind Profiles

Headwind Landings

For headwind landings, the unstable wind profiles show the least scatter in touchdown point. As the stability increases, the aircraft becomes more effected by the wind profile causing larger deviations in touchdown point. The very stable profiles produce very large deviations from the desired touchdown point, in one case over 3600 feet. In addition, the actual trajectory of the aircraft follows a steeper slope as the stability increases. The magnitude of the deviations in touchdown point for the stable and very stable conditions are significant and could lead to hazardous landing conditions. This is especially true since the simulation began at an altitude of only 300 feet. In the very stable case, if the shear layer occurred above 300 feet, the effect on touchdown would certainly be greater than that shown in Figure 10. The same is not true for the other stability conditions. For the unstable, neutral, and stable profiles, the shear is close to the ground and little additional effect on touchdown point would result from beginning the simulation above 300 feet. Consequently, the very stable condition has the greatest potential for adversely affecting the landing of aircraft.

Tailwind Landings

For a tailwind, a somewhat larger deviation in touchdown occurs over the case of the same wind profile being encountered in the headwind direction. However, a landing accident involving a tailwind condition is probably not as likely to occur as one involving a headwind condition for two reasons. First of all, landings are made in the runway direction that has a headwind component whenever possible. As a result, tailwind landings, especially with high wind magnitudes, are seldom required. Secondly, since a tailwind implies overshoot, the pilot has a slower descent rate and can more easily abort the landing. In addition, a light tailwind shear can provide the somewhat desirable effect of a natural flare maneuver.

At this point, it is well to recall that the simulation model assumes no further control of the aircraft after trimming at the initial altitude of 300 feet for a constant wind field; that is, no pilot feedback or automatic landing system is introduced. The deviation in touchdown point can therefore be considered as a worst-case analysis in that any pilot or autopilot feedback during descent would, hopefully, result in smaller deviations in touchdown point. From this point of view, the Landing Simulation Program is intended to serve as a standard which will indicate the areas in which further research is required.

Ground Effects

In addition to wind shear causing an aircraft to depart from its desired 2.7-degree glide slope, the ground effects on the aircraft aerodynamics near the surface will cause a small departure from the glide slope. To estimate the deviation in touchdown due to ground effects, simulations of the DC-8 and Boeing-747 landings were made with and without the inclusion of the ground effects terms for the wind profiles of Figures 2, 3, 4, and 11. Table 2 shows the results for the extreme stability conditions, unstable and very stable. For headwinds, the deviation in touchdown point is nearly identical with and without the ground effects included. For the zero wind case, the change in touchdown point is the largest but still less than 100 feet. For the tailwind cases in unstable air, larger changes in touchdown point occur; however, this is somewhat misleading. In Case 6 of the Boeing-747, for example, the ground effects caused the aircraft to touch down at $\Delta T = 891$ feet; whereas, without ground effects, the aircraft descended to an altitude of three feet at $\Delta T = 1320$ feet downrange, then began to rise, finally touching down at $\Delta T = 3779$ feet. With the pilot control, the actual difference between touchdown points would be considerably less. Consequently, since ground effects cause rather small deviations in touchdown and since accurate ground effect terms were not available for all the aircraft used in this study, it was decided not to use the ground effects term in any further analyses of conventional aircraft.

TABLE 2

DEVIATION FROM TOUCHDOWN POINT
WITH AND WITHOUT GROUND EFFECTS

Wind Profiles		B-747 With Ground Effects	B-747 Without Ground Effects	DC-8 With Ground Effects	DC-8 Without Ground Effects
Zero Wind		- 90	0	- 91	0
Unstable	No. 1	- 566	- 502	- 553	- 492
	No. 2	- 852	- 800	- 834	- 786
	No. 3	- 821	- 783	- 809	- 767
	No. 4	+ 738	+1049	+ 770	+1033
	No. 5	- 890	- 881	- 888	- 858
	No. 6	+ 891	+3779	+ 996	+3715
	No. 7	-1314	-1317	-1297	-1281
	No. 8	- 859	- 858	- 862	- 835
	No. 9	-2651	-2652	-2580	-2579
Very Stable	No. 1	-3671	-3677	-3668	-3669
	No. 2	+1854	+1833	+2161	+2167
	No. 3	-2048	-2065	-2057	-2056
	No. 4	-2685	-2650	-2625	-2625
	No. 5	-2992	-2965	-2932	-2933
	No. 6	-2758	-2762	-2734	-2735
	No. 7	-1641	-1644	-1619	-1619
	No. 8	- 715	- 709	- 675	- 668
	No. 9	- 333	- 299	- 305	- 265

Wind Shear Effects on Touchdown

The equation used to define the wind profile for unstable, neutral, and stable atmospheric conditions is defined in terms of the parameters $u*$, Z_o, and L. The very stable profiles use as parameters the wind magnitude above the shear level and the altitude at which the shear occurs. Landing simulations of the DC-8 have been made to determine the influence of each of these parameters on touchdown point for headwind landings. Figure 12 shows the results for the unstable case. For ease of interpretation, the X-axis does not use the frictional velocity, $u*$, but rather the wind speed at the initial height of 300 feet. From Figure 12, it is observed that the stability length, L, has little effect on touchdown point. The larger negative values of L, which imply increased stability, produce somewhat larger deviations in touchdown point. The surface roughness length, Z_o, however, causes a larger variation in touchdown point. Over a very smooth surface such as mown grass ($Z_o \approx 0.001$m) deviation in touchdown point, ΔT, greater than 1000 feet cannot occur even under a very strong wind field. If, however, the runway is surrounded by large buildings, with associated roughness length of one to three meters, ΔT increases by a factor of 2 to 3.

The neutral wind profiles, Figure 13, for headwind landings can be considered as the limiting case of the unstable profiles as $L \to -\infty$. Thus, for a given Z_o, ΔT will be larger for the neutral than for the unstable cases. The effect of Z_o on ΔT is, however, somewhat less in neutral stability. That is, for a given wind speed, the difference between ΔT for say Z_o=3m and ΔT for Z_o=1m is smaller for neutral than for the unstable condition. As stability further increases to the positive side, Z_o becomes less important while L exerts greater influence on ΔT (Figure 14). Under highly stable conditions, with say L = 10, very large values of ΔT are produced. The terrain roughness has almost no influence on these values of ΔT. It is under these highly stable conditions that hazardous landing situations are most likely to occur.

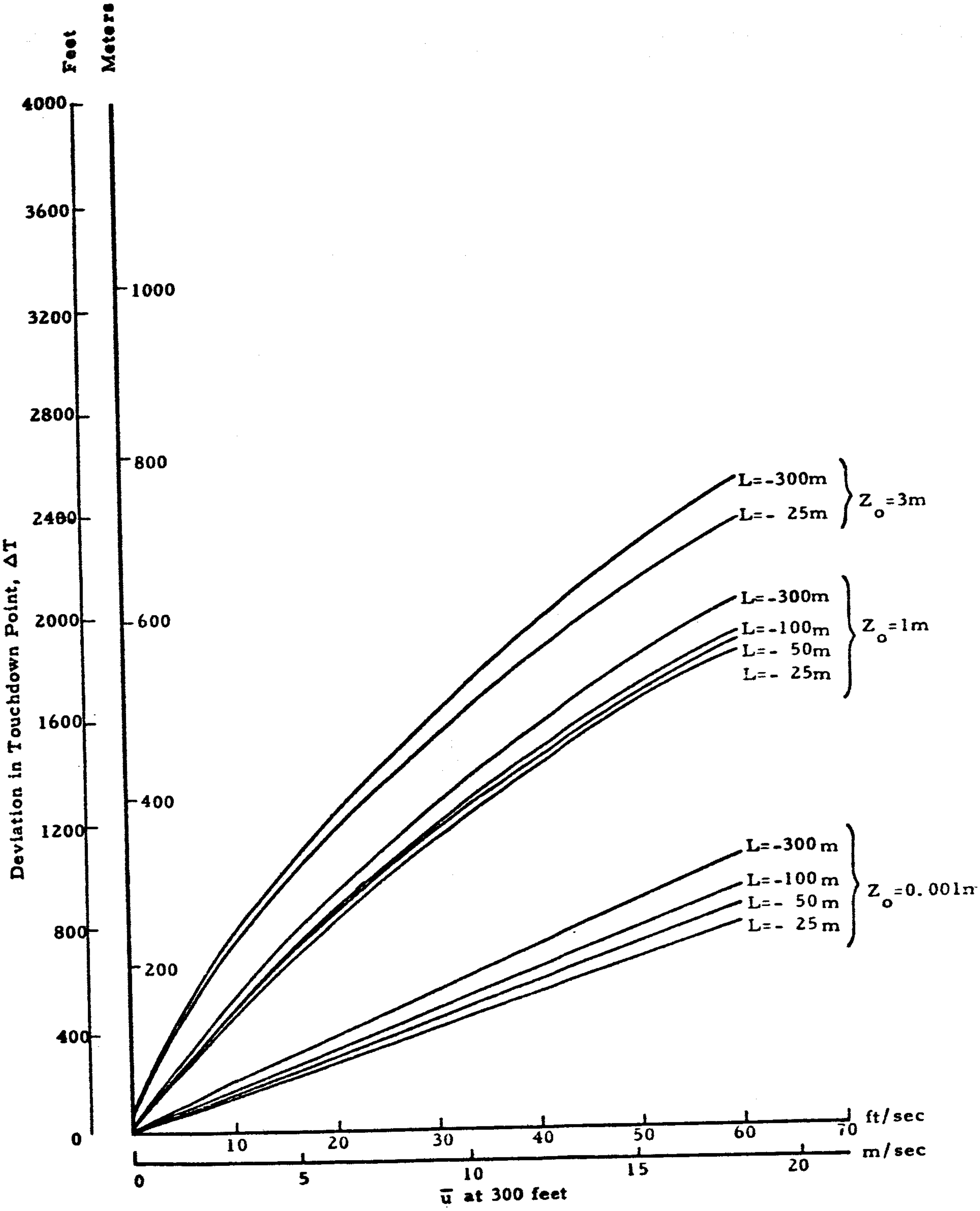

Figure 12. Deviation in Touchdown for DC-8 in Unstable Wind Profiles: Headwind.

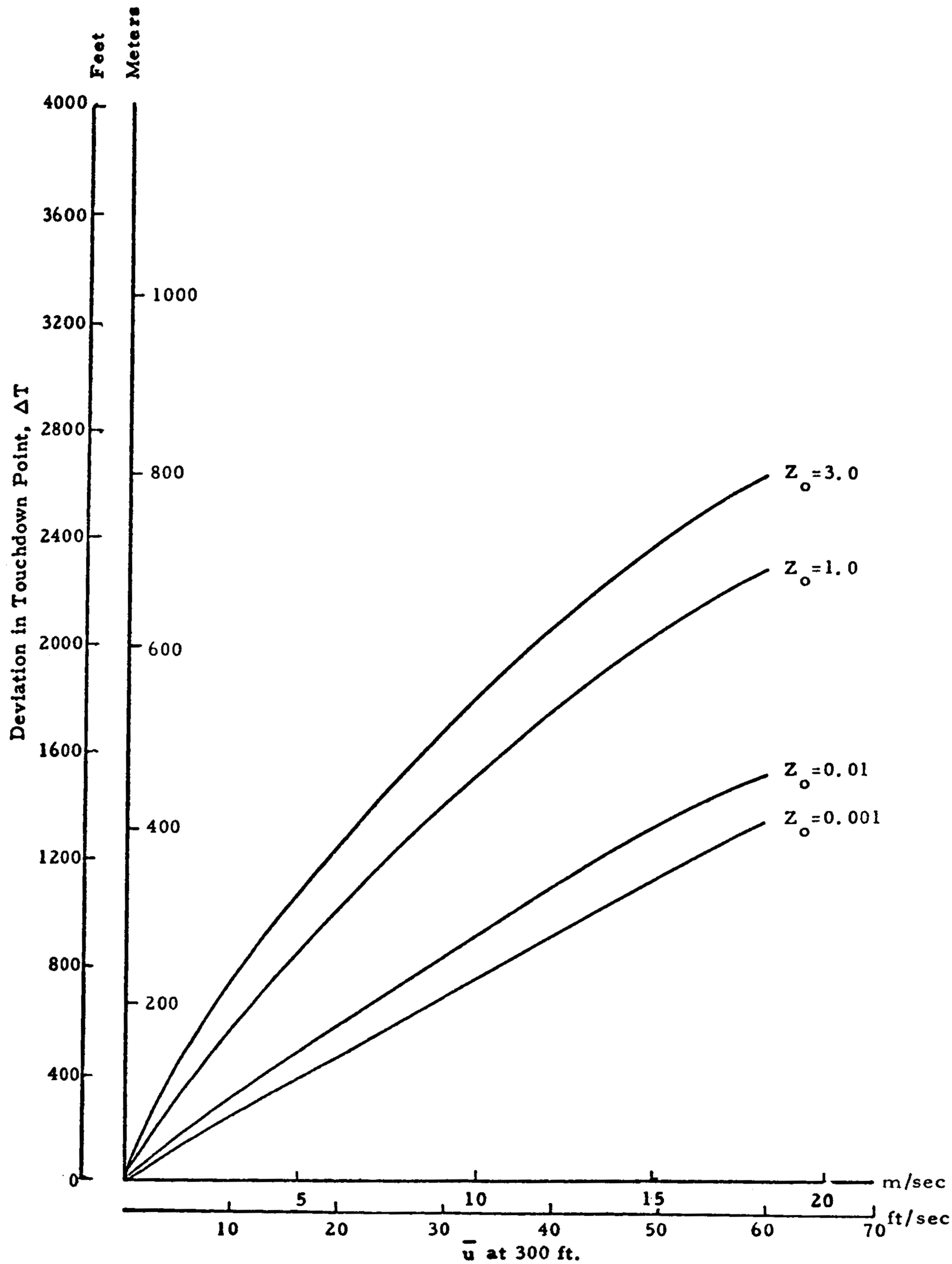

Figure 13. Deviation in Touchdown for DC-8 in Neutral Wind Profiles: Headwind.

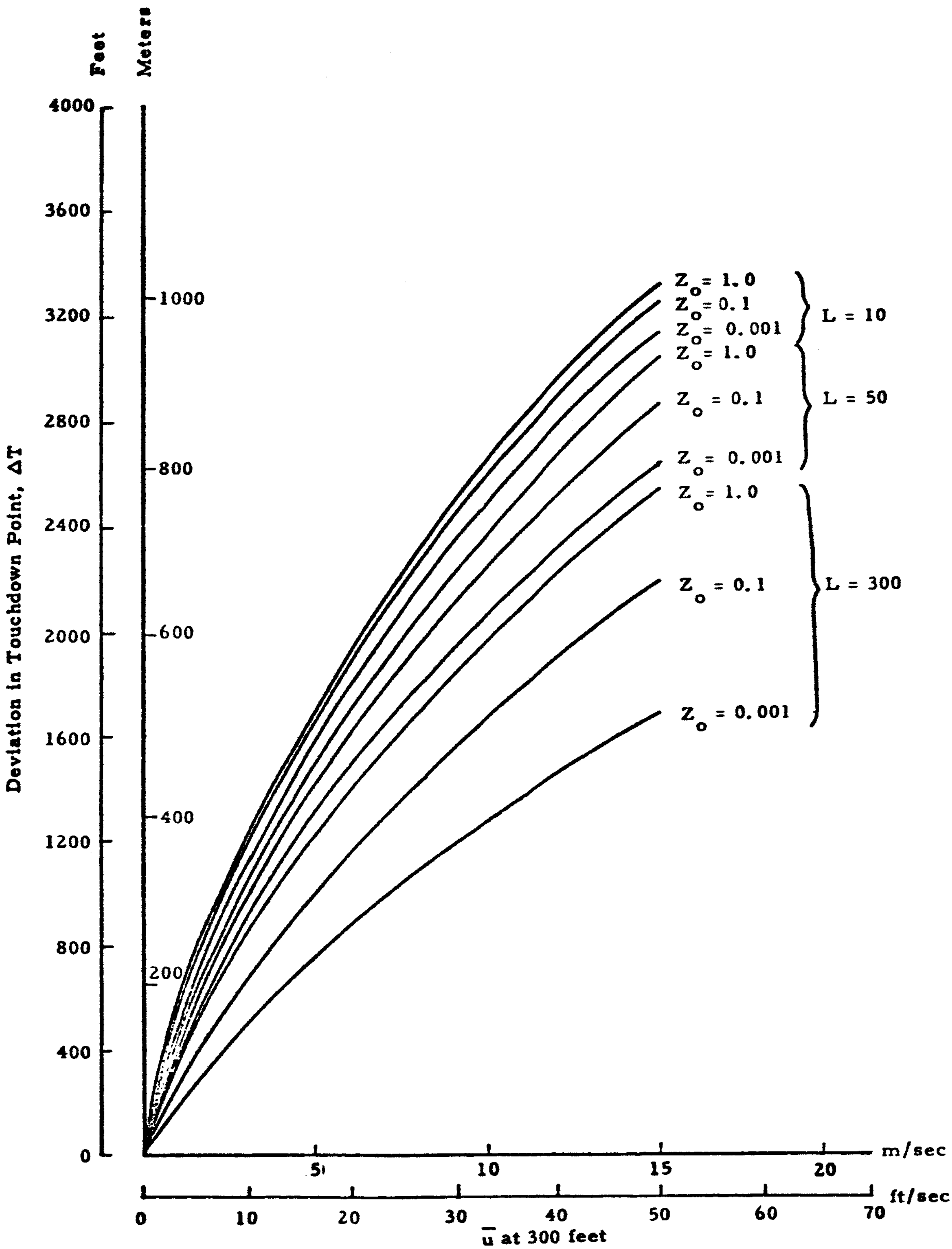

Figure 14. Deviation in Touchdown for DC-8 in Stable Wind Profiles: Headwind.

The values of ΔT for very stable profiles are shown in Figure 15 for headwind landings as a function of the altitude at which the shear, or interface layer occurs. The very stable profiles cause a larger deviation in touchdown point than the other wind profiles, especially when the shear for the very stable profile occurs at a high altitude. It is also the very stable profiles that cannot be predicted by an analytical expression involving meteorological parameters. Thus, during very stable atmospheric conditions with Richardson number greater than 0.2, careful attention should be payed to the natural environment.

Comparison of Different Types of Conventional Aircraft

Figures 16 through 19 compare the results from the DC-8 with that of other aircraft. The aircraft considered span a large range of size, weight, and landing speeds. Table 1 can be consulted for the exact aircraft weight and landing speeds used in the simulation. In general, the variation in touchdown point, ΔT, is not largely dependent on the type aircraft. Even the C-130 which is slower and lighter performs very similarly to the other aircraft. It is interesting to observe that the relative sensitivity of different aircraft to a given wind field depends upon the wind field. For example, a stable profile with $Z_o = 0.1$ and $L = 10$ (Figure 18) shows the C-130 to produce the largest values of ΔT and the C-135A the smallest. However, by changing the value of L to $L = 300$, the result is that the C-130 produces the smallest values of ΔT with the C-135A falling in the middle range.

The variation in ΔT resulting from the simulated landing of different type aircraft is smaller than the variation in ΔT due to surface roughness and to stability. For practical considerations, the type of wind profile that is hazardous to one type of aircraft is hazardous to all types - at least within the range of aircraft discussed in this report.

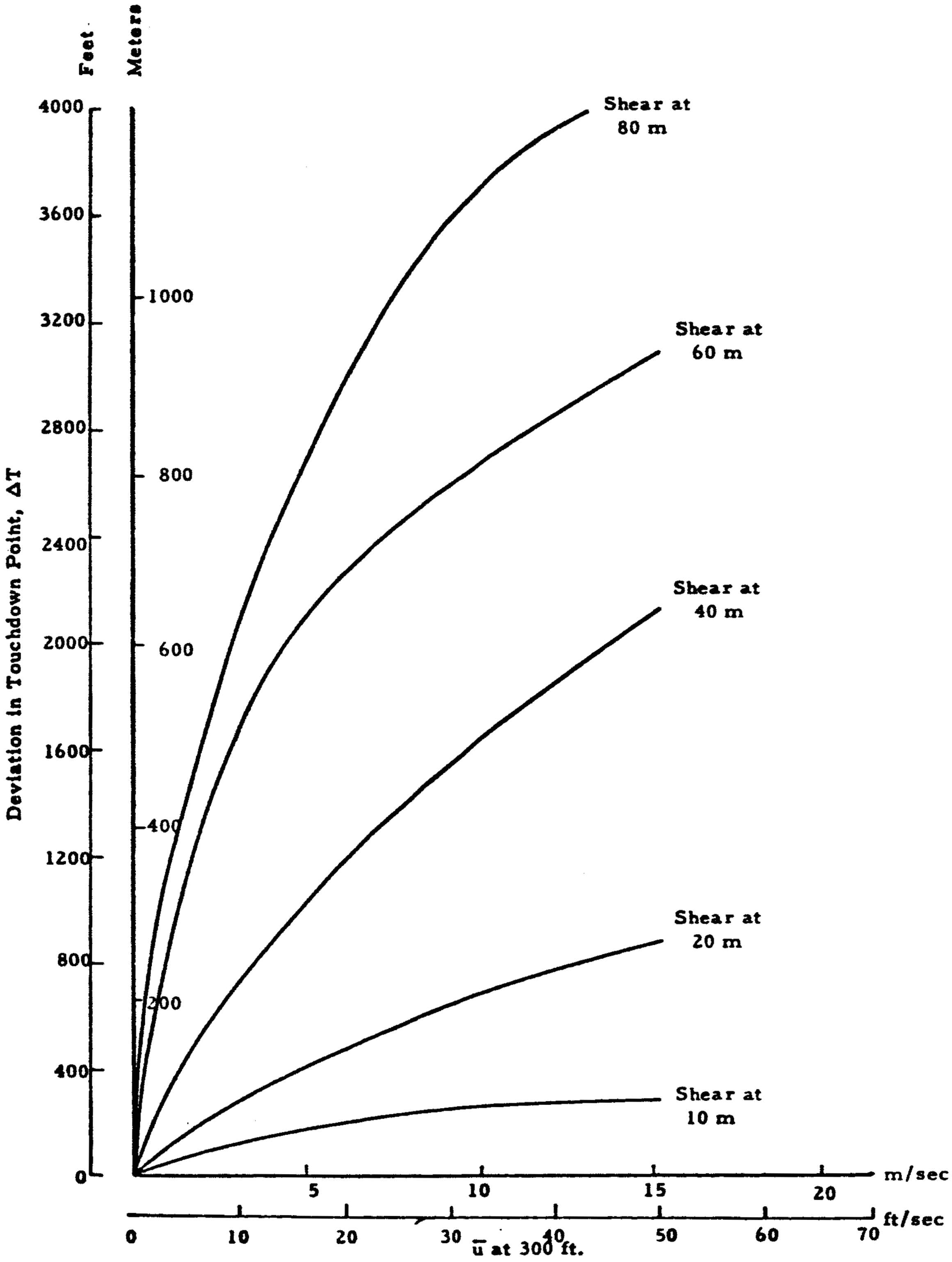

Figure 15. Deviation in Touchdown for DC-8 in Very Stable Wind Profiles: Headwind.

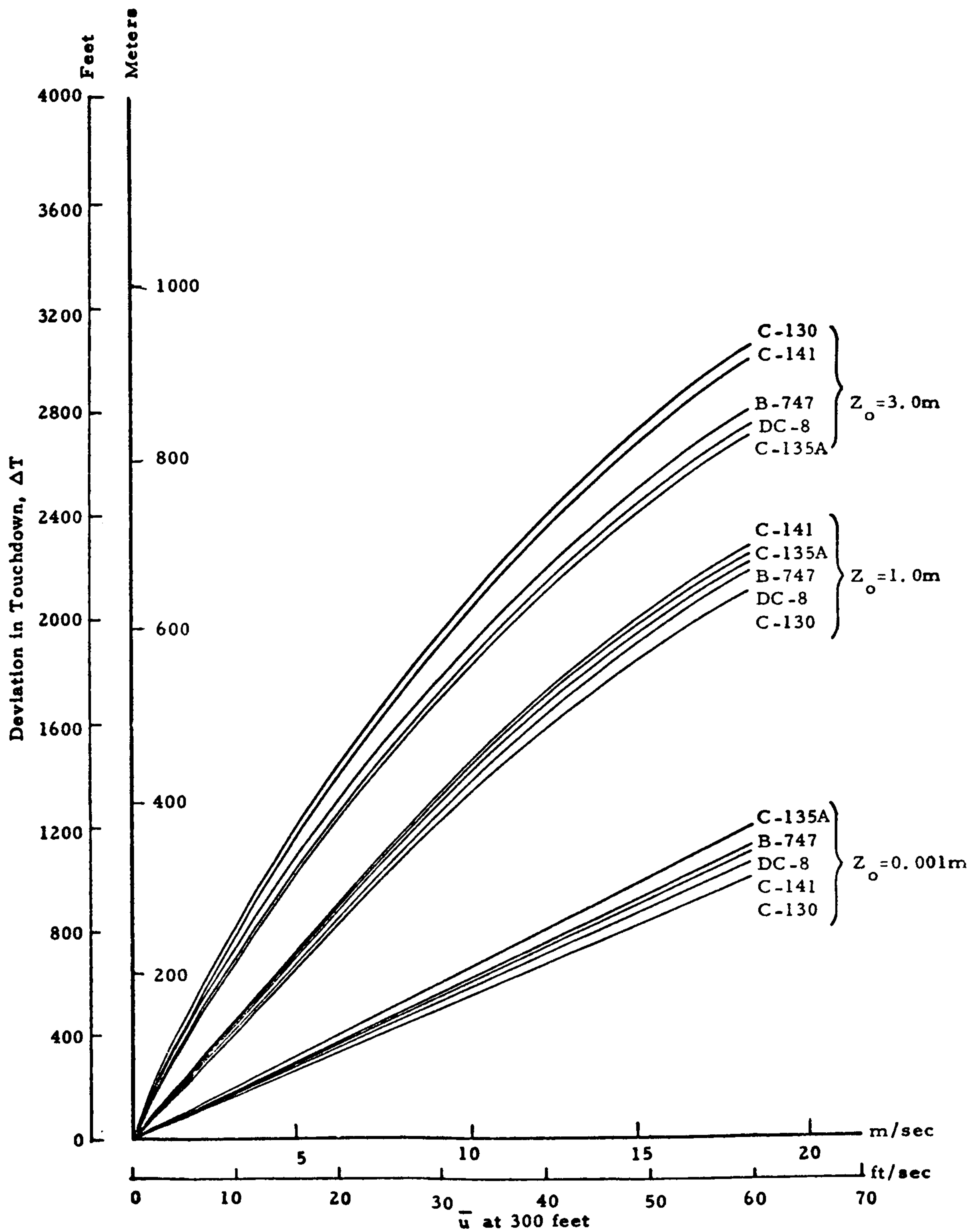

Figure 16. Deviation in Touchdown for Different Type Aircraft in Unstable Wind Profiles: L = -300 m.

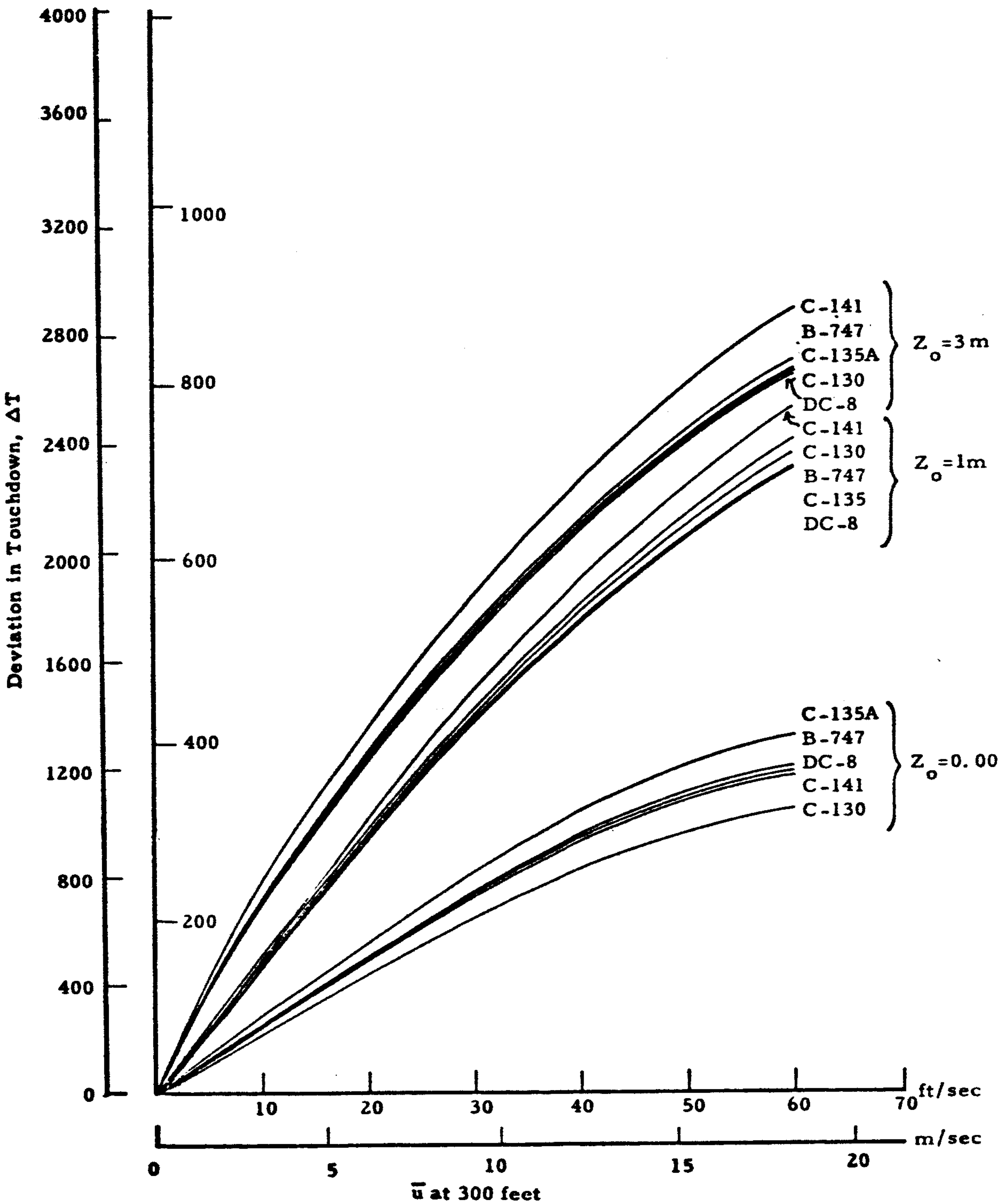

Figure 17. Deviation in Touchdown for Different Type Aircraft in Neutral Wind Profiles.

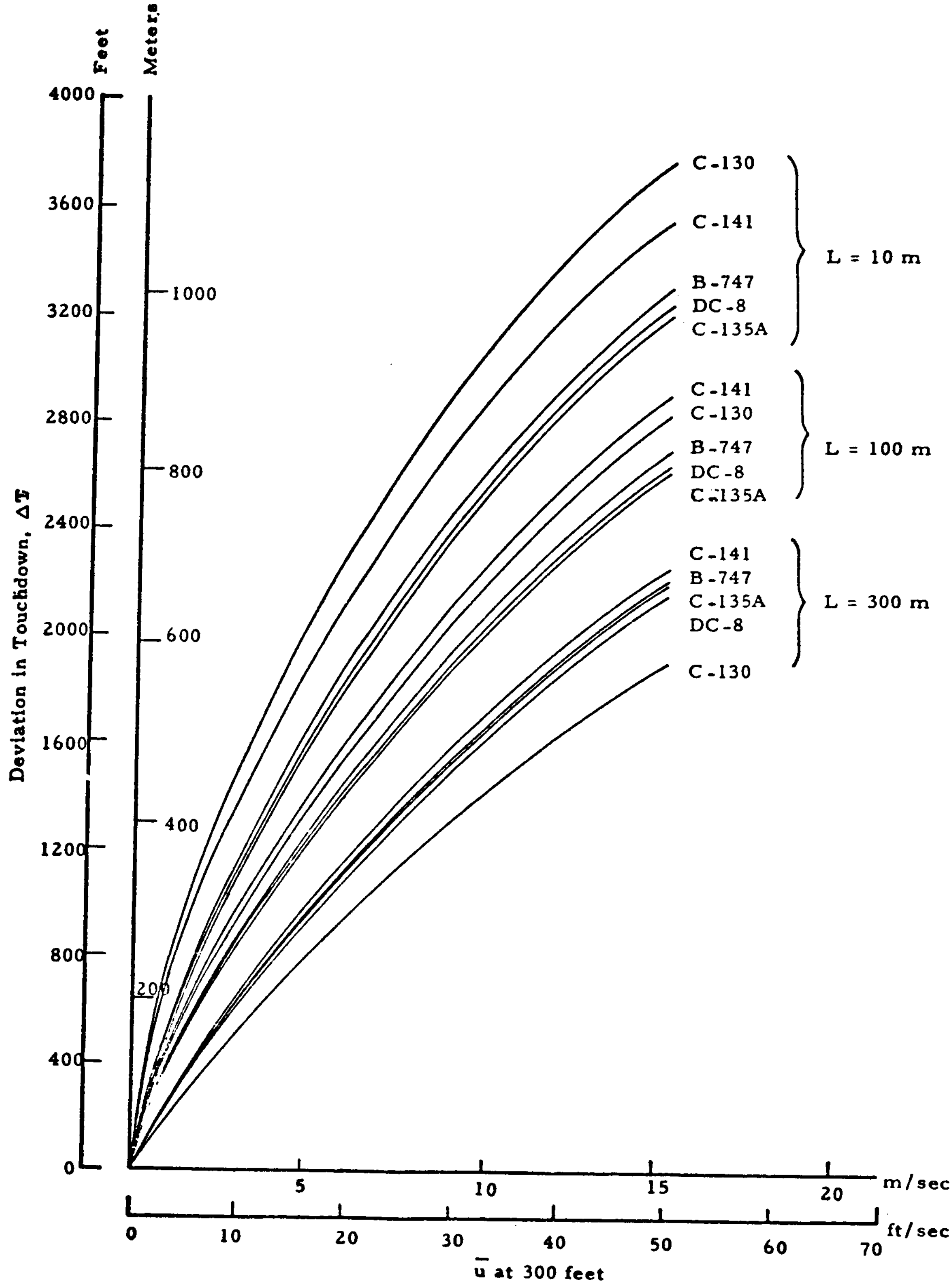

Figure 18. Deviation in Touchdown for Different Type Aircraft in Stable Wind Profiles: $Z_o = 0.1$ m

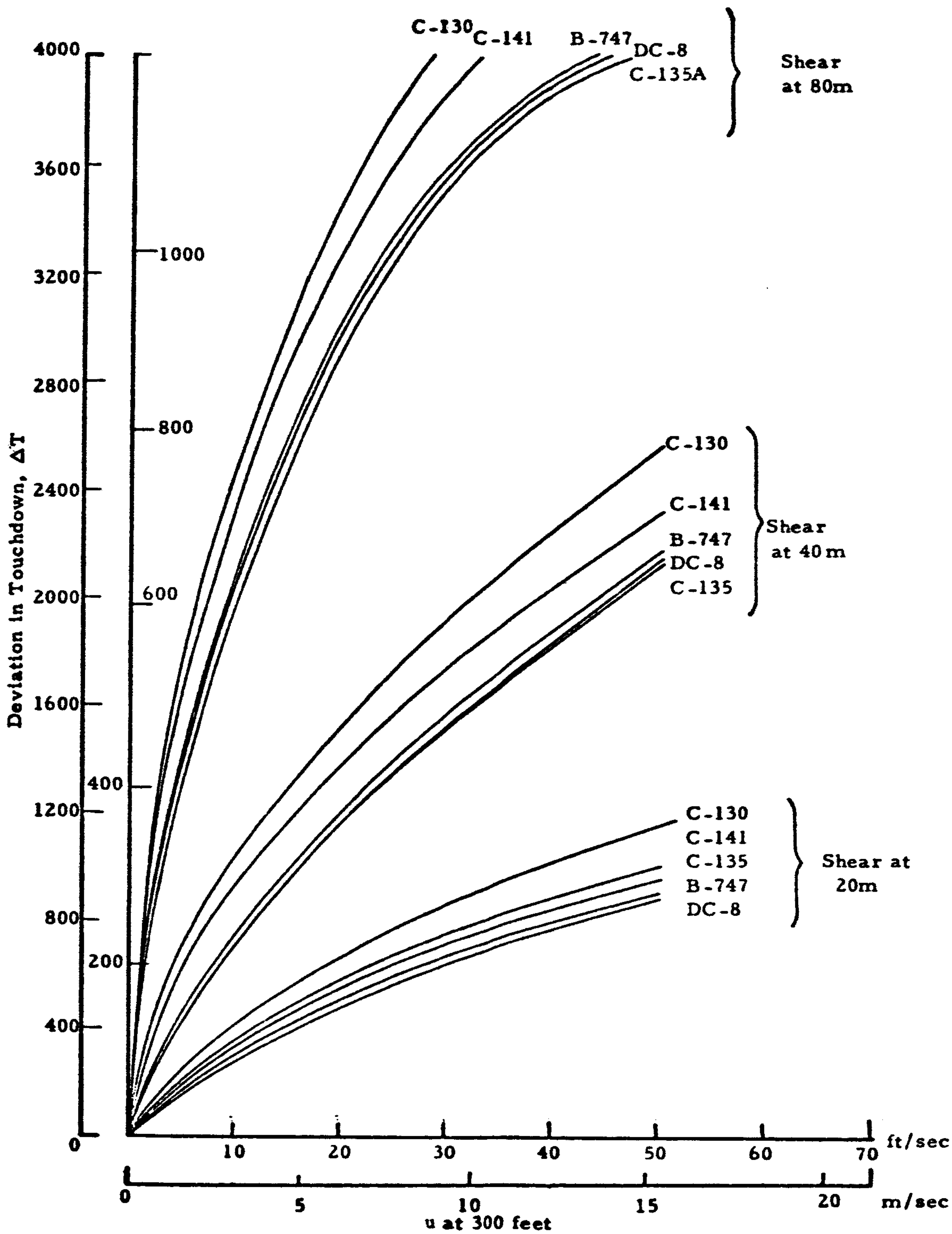

Figure 19. Deviation in Touchdown for Different Type Aircraft in Very Stable Wind Profiles.

Variation in ΔT due to Aircraft Weight

In simulating the landing of an aircraft, the gross weight of the aircraft was chosen approximately midrange between its tolerance extremes. To determine the influence of the gross weight of an aircraft on ΔT, landings were simulated for the Boeing-747 with gross weights of 400,000 pounds and 550,000 pounds. These values correspond approximately to minimum and maximum landing weight limitations for this aircraft. Figure 20 compares the values of ΔT for the very stable profiles. The difference between ΔT for the two gross weights is small; generally less than 200 feet. For the other stability cases, the difference between the ΔT's are even smaller and hence not presented in this report. To summarize, the gross weight of an aircraft appears to have little effect on touchdown point, especially when compared to the effects produced by surface roughness and stability.

Variation in ΔT due to Cg Locations

The location of the center of gravity, Cg, of an aircraft depends upon the gross weight and weight distribution of the aircraft. In most of the previous simulations, the Cg location was chosen approximately midway between the tolerance extremes. To observe the influence of the Cg location on touchdown point, simulated landings of the Boeing-747 were made with three different Cg locations: 15% Mean Aerodynamic Chord; 25% Mean Aerodynamic Chord; and 33% Mean Aerodynamic Chord. The 15% and 33% Mean Aerodynamic Chord are the extreme allowable tolerances. Table 3 shows the results for the unstable and very stable profiles. The difference between ΔT values for the three Cg locations is negligible in all cases. The differences in ΔT for neutral and stable profiles were found to be intermediate between the unstable and very stable extremes. Thus, the Cg location seems to have little influence on the deviation in touchdown point due to wind shears.

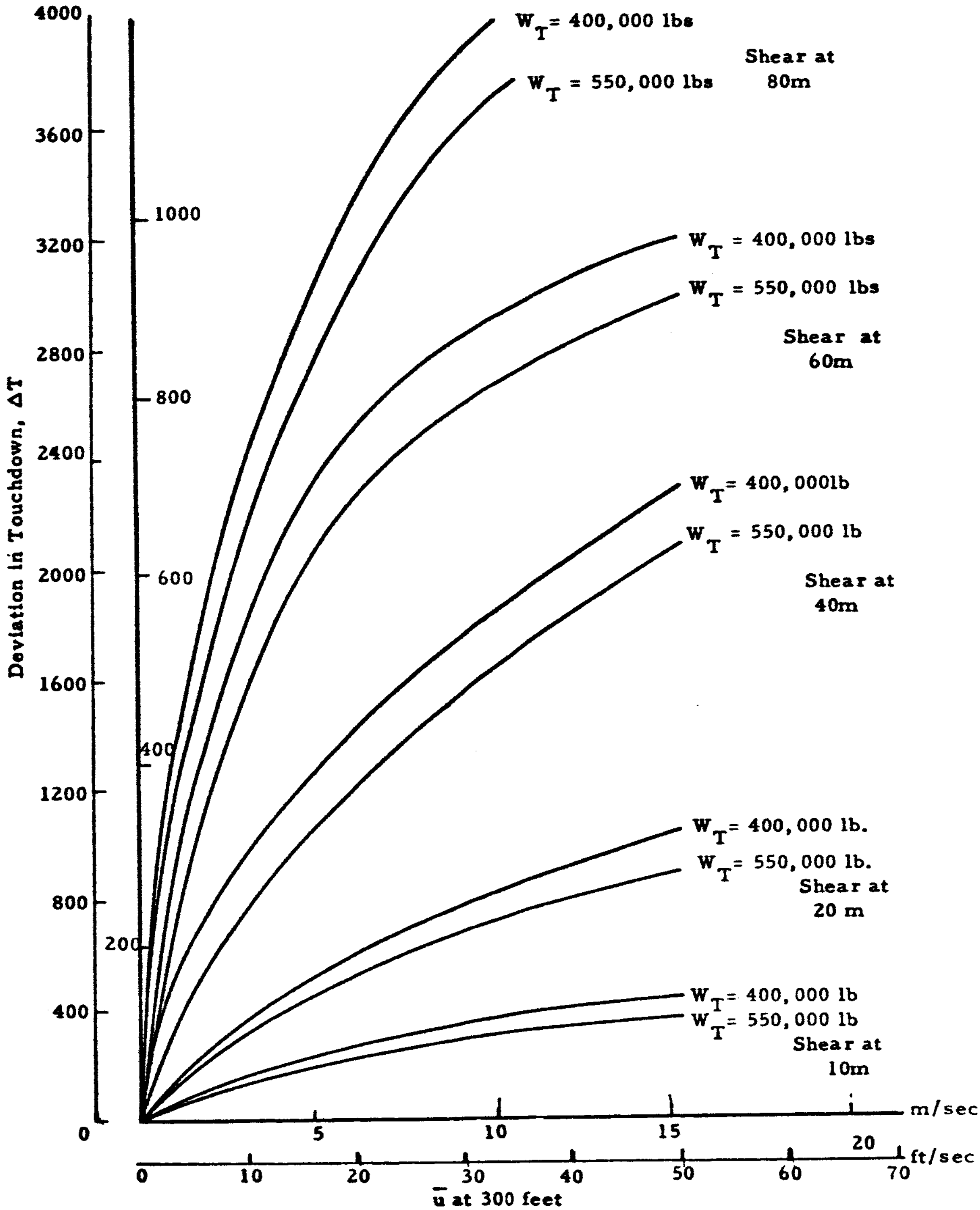

Figure 20. Deviation in Touchdown for B-747 in Very Stable Wind Profiles with Different Landing Weights

TABLE 3

DEVIATION FROM TOUCHDOWN POINT FOR VARIOUS LOCATIONS OF THE CENTER OF GRAVITY: B-747, Weight=400,000 pounds

	Wind Profiles	Cg=15% Mean Aerodynamic Chord	Cg=25% Mean Aerodynamic Chord	Cg=33% Mean Aerodynamic Chord
Unstable	No. 1	- 463	- 462	- 463
	No. 2	- 737	- 736	- 737
	No. 3	- 731	- 731	- 731
	No. 4	+ 951	+ 942	+ 942
	No. 5	- 856	- 855	- 849
	No. 6	+2877	+2985	+3633
	No. 7	-1323	-1317	-1299
	No. 8	- 849	- 847	- 837
	No. 9	-2887	-2845	-2781
Very Stable	No. 1	-4028	-3953	-3854
	No. 2	+1164	+1126	+1260
	No. 3	-2370	-2299	-2204
	No. 4	-2936	-2884	-2821
	No. 5	-3212	-3177	-3138
	No. 6	-3031	-2985	-2932
	No. 7	-1854	-1827	-1797
	No. 8	- 824	- 818	- 813
	No. 9	- 352	- 352	- 351

ANALYSIS OF AUGMENTOR-WING STOL AIRCRAFT

The landing of the augmentor-wing STOL aircraft described in the Aircraft Landing Model Section was simulated for the same unstable, neutral, stable, and very stable wind profiles identified in the Analysis of Conventional Aircraft Section. The trim conditions were defined for a 7-degree glide slope with descent again beginning at 300 feet. Under these conditions, the resulting touchdown point for a constant (or zero) wind field would be (ignoring for a moment the ground effects on the aircraft) 2443 feet downrange. Figures 21 through 24 show the landing of the STOL aircraft in the unstable, neutral, stable, and very stable profiles previously presented as Figures 2, 3, 4, and 11, respectively. For several of the tailwind profiles, in particular those for which the wind velocity exceeded 17 ft/sec, it was impossible to trim the aircraft to follow a 7-degree glide slope by controlling only the thrust magnitude and elevator. The solution of the initialization subroutine showed a negative thrust would be required for the STOL aircraft to descend the 7-degree glide slope at a constant velocity relative to the air of 118 ft/sec. Thus, the results from those runs where negative thrust was assumed have been discarded. For several wind fields, the shear causes the aircraft to depart from the glide slope but the natural response of the aircraft eventually brings it back toward the glide slope. Trajectories No. 1 and 10 of Figure 23 and Trajectory No. 10 of Figure 24 are good examples of this phenomenon. These oscillations arise from the Phugoid mode of the aircraft. In several of the STOL trajectories, the aircraft was further from the glide slope at some point prior to touchdown than it was at touchdown. This was not true of the conventional aircraft flights. In the latter case, the period of the Phugoid oscillation was much larger so that touchdown occurred before the first quarter-cycle of the flightpath oscillation.

For most of the STOL trajectories in which the above phenomenon was present, ΔT was not greatly less than the maximum deviation from the glide slope during the flight. Nonetheless, the ΔT's observed for the STOL

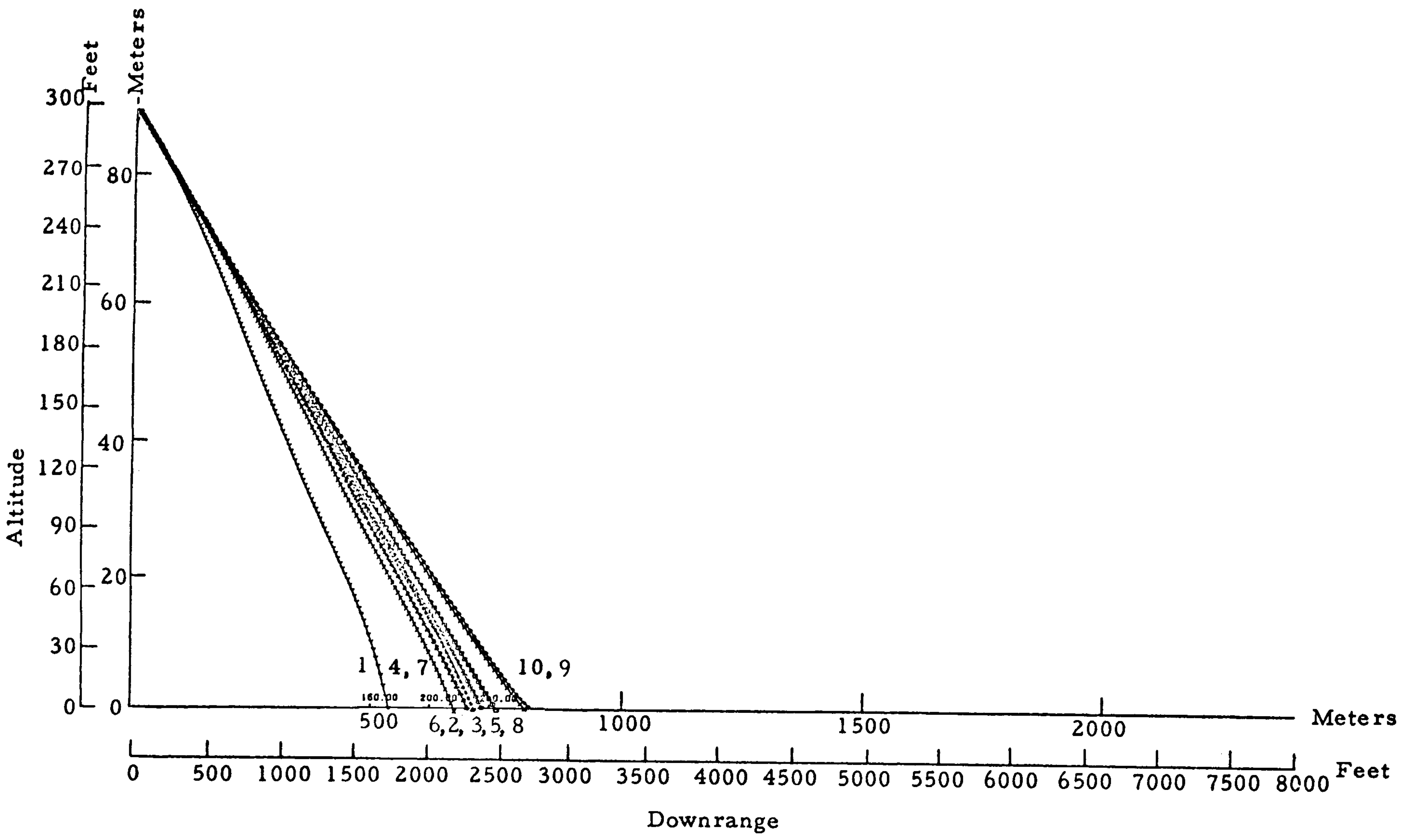

Figure 21. STOL Descent Trajectories Through Unstable Wind Profiles.

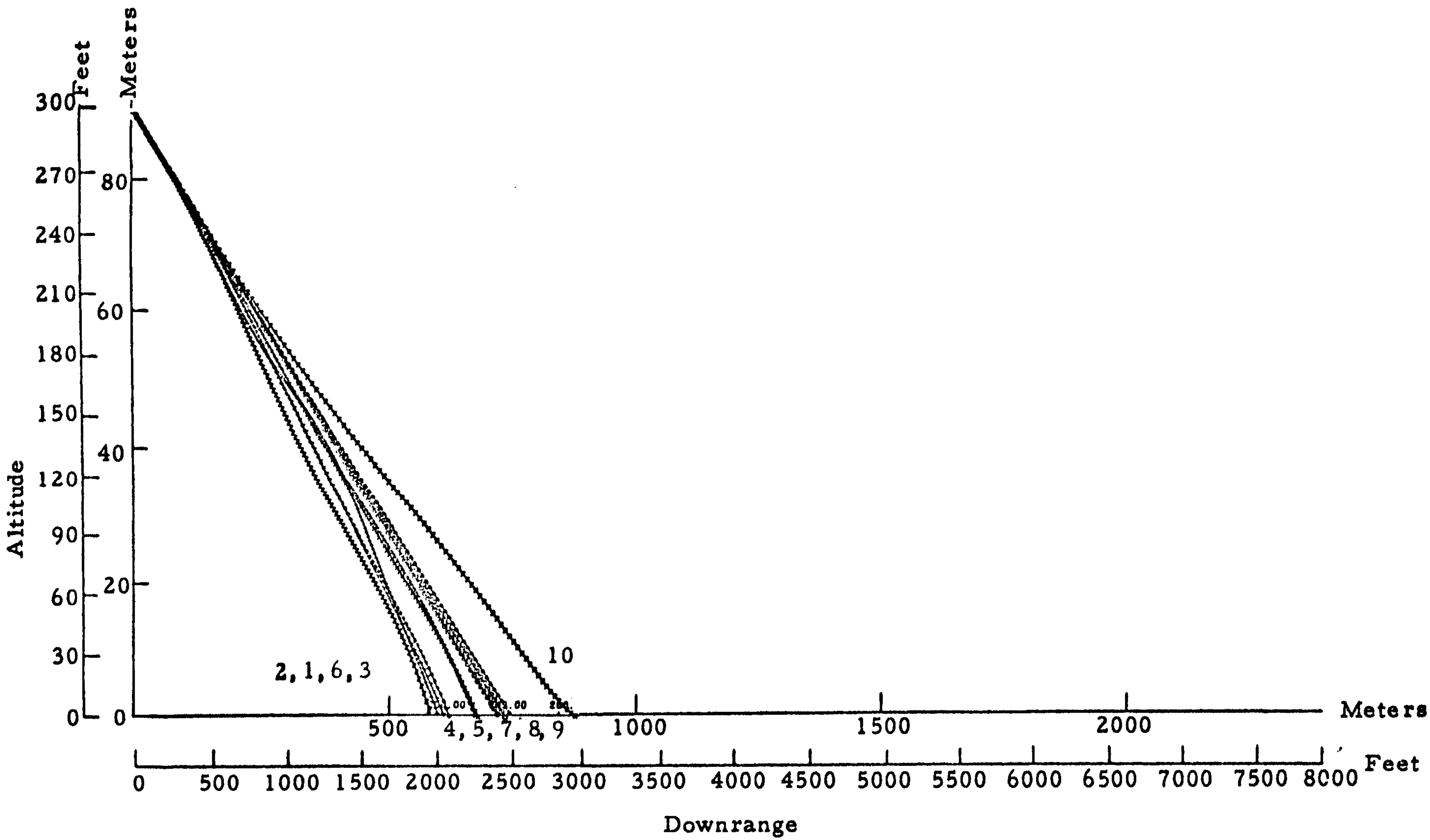

Figure 22. STOL Descent Trajectories Through Neutral Wind Profiles.

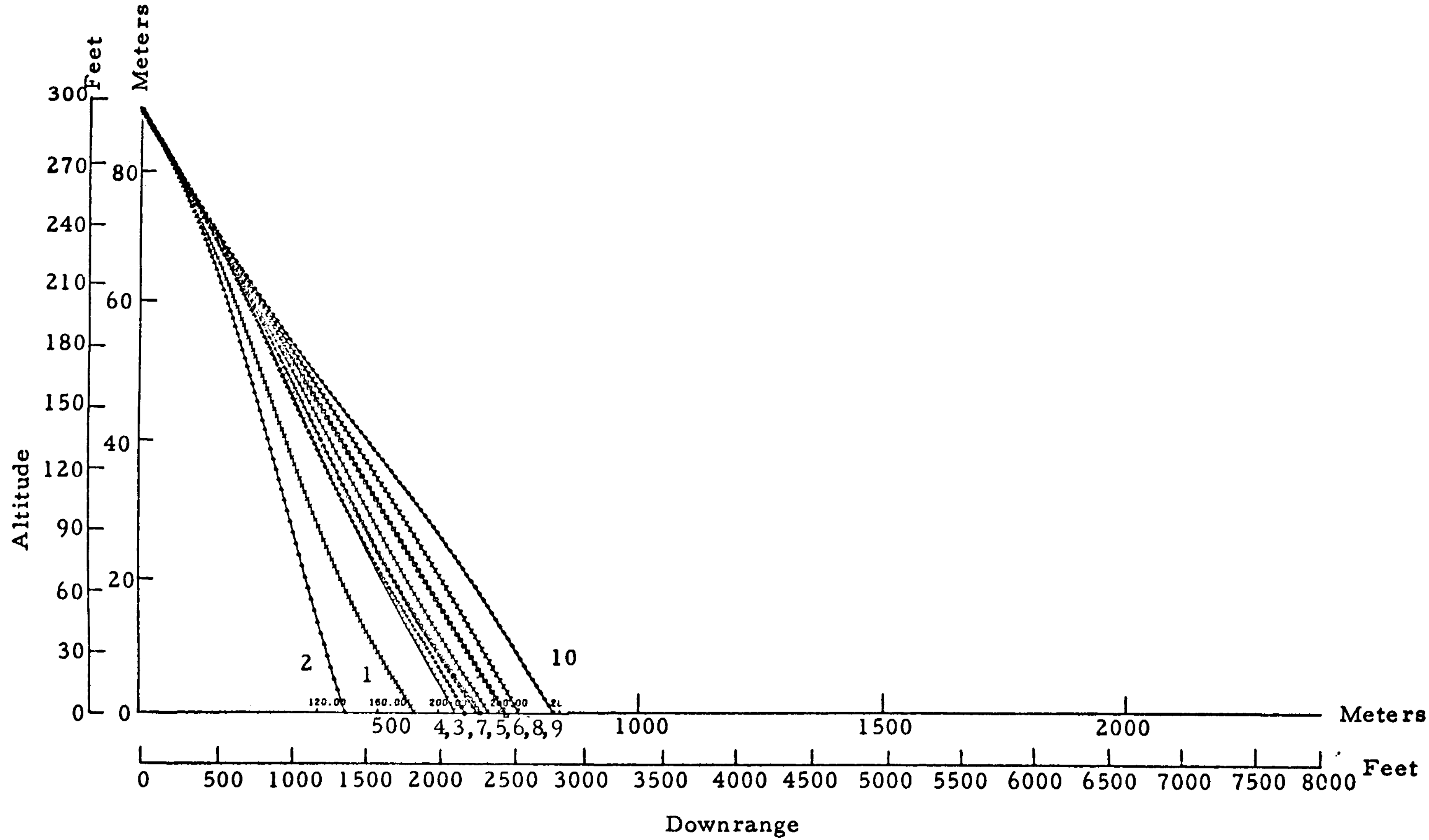

Figure 23. STOL Descent Trajectories Through Stable Wind Profiles.

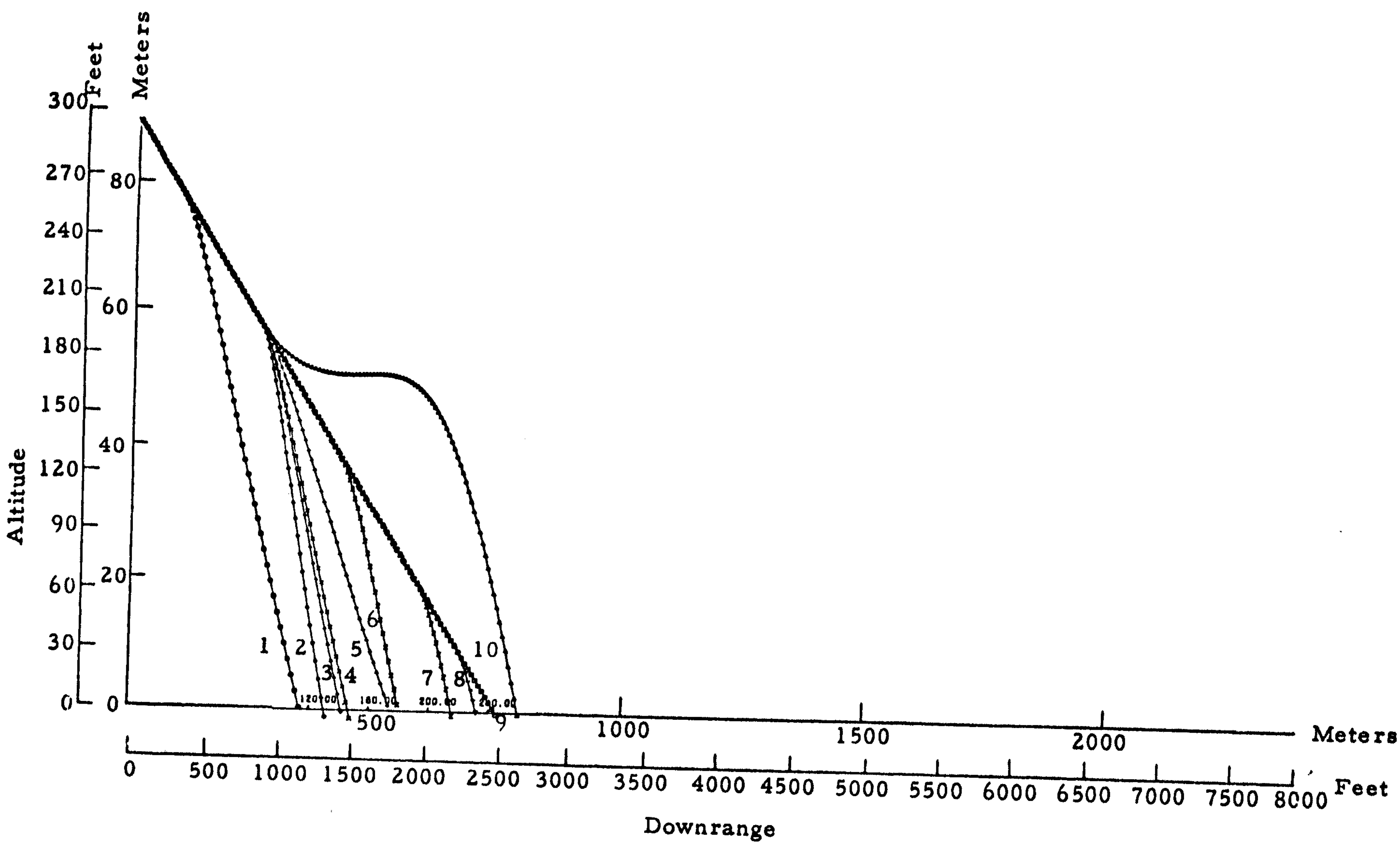

Figure 24. STOL Descent Trajectories Through Very Stable Wind Profiles.

aircraft cannot be interpreted in quite the same manner as they were for the conventional aircraft. The STOL ΔT's only approximate the maximum deviation from the glide slope for a given wind shear.

Ground Effects of STOL Aircraft

The landing of the augmentor-wing STOL aircraft was simulated both with and without ground effects terms to determine the degree to which the aircraft ground effects influenced touchdown point. Table 4 shows the deviation in touchdown for the very stable and unstable wind profiles for the simulations with and without ground effects. For the zero wind field, the ground effects causes a touchdown 180 feet beyond the 7-degree glide slope touchdown point. This contrasts with the 90-feet-short touchdown point for the Boeing-747 and DC-8 aircraft. For the unstable profiles, the ground effects causes a deviation in touchdown point on the order of 150 to 200 feet. For the very stable profiles, the deviations in touchdown are much smaller. In general, the ground effects provide the largest influence when the wind shear is light and the aircraft's descent follows a path near its desired glide slope. Since, even under these conditions, the influence of ground effects on touchdown is generally less than 200 feet, ground effects are not an important consideration in our study.

Wind Shear Effects on Touchdown

Figure 25 shows deviation in touchdown, ΔT, for selected stable and unstable wind profiles when the landing approach is in the headwind direction. For the stable wind profiles, ΔT shows the most variation with the parameter L. For a fixed value of L, the variation of ΔT with Z_o is small (not shown in Figure 25). For the unstable profiles, the variation in ΔT is greater with respect to Z_o than with respect to L. This is consistent with the previously observed variations in ΔT with Z_o and L for

TABLE 4

DEVIATION FROM TOUCHDOWN POINT WITH AND WITHOUT GROUND EFFECTS FOR STOL AIRCRAFT

Wind Profiles	Augmentor-Wing STOL		
	ΔT With Ground Effects	ΔT Without Ground Effects	Difference
Zero Wind	+180	0	180
Unstable No. 1	+125	- 91	216
Unstable No. 2	+ 32	-161	193
Unstable No. 3	+ 57	-145	202
Unstable No. 4	+349	+190	159
Unstable No. 5	- 8	-179	171
Unstable No. 6	Negative Thrust Needed to Trim		
Unstable No. 7	-113	-280	167
Unstable No. 8	- 49	-189	140
Unstable No. 9	-599	-713	114
Very Stable No. 1	-1299	-1303	4
Very Stable No. 2	+ 157	+ 137	20
Very Stable No. 3	- 683	- 701	18
Very Stable No. 4	- 975	- 978	3
Very Stable No. 5	-1141	-1141	0
Very Stable No. 6	-1024	-1025	1
Very Stable No. 7	- 623	- 639	16
Very Stable No. 8	- 189	- 290	101
Very Stable No. 9	+ 54	- 123	177

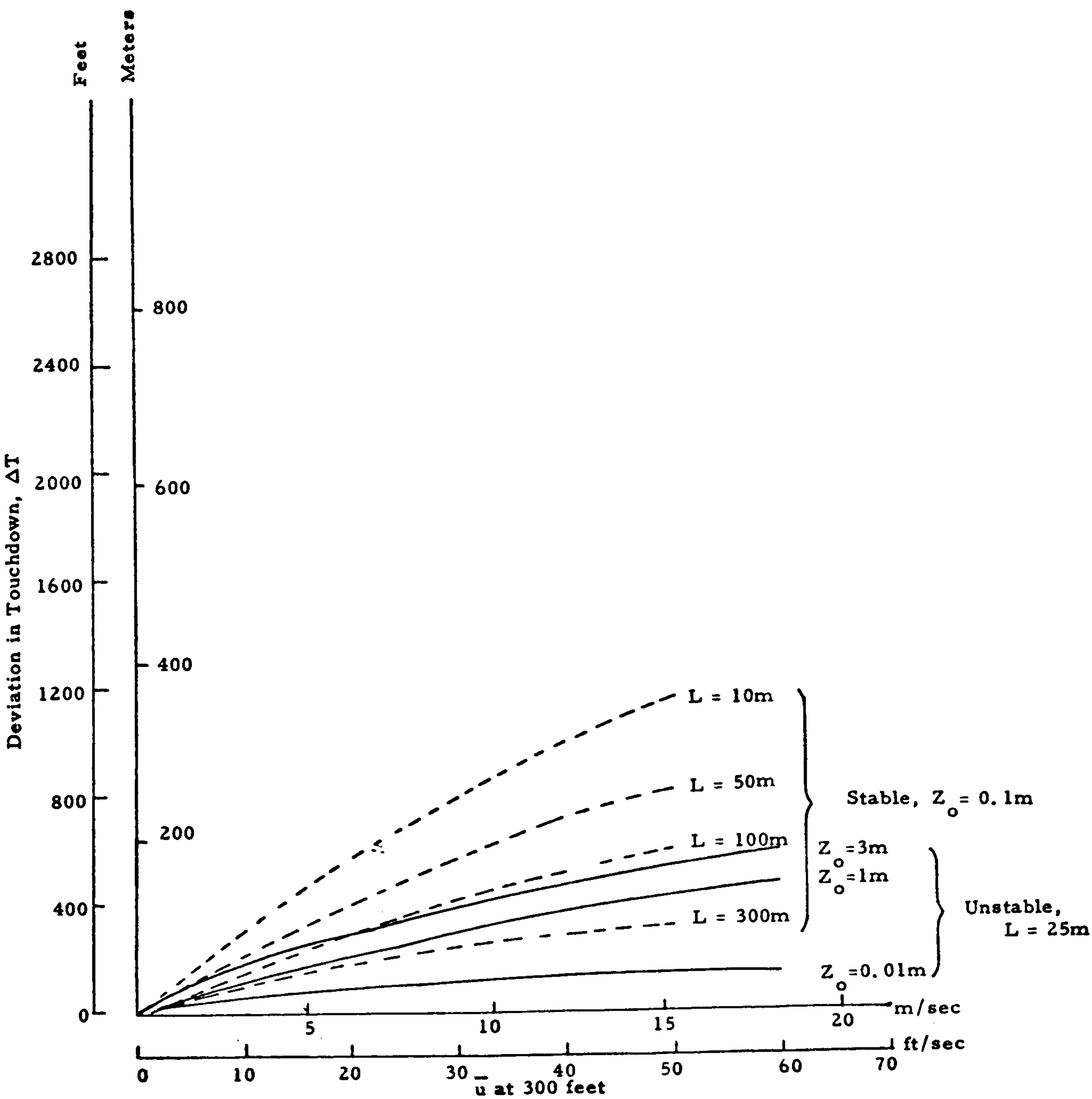

Figure 25. Deviation in Touchdown for STOL in Unstable and Stable Wind Profiles: Headwind.

conventional-type aircraft. The variation of ΔT in neutral wind profiles, though not shown in Figure 25, lies intermediate between the results for the stable and unstable wind profiles. Figure 26 shows the variations in ΔT for the very stable wind profiles. The values of ΔT are approximately three times smaller for the STOL aircraft than for the conventional aircraft. In comparing the STOL results to that of the conventional aircraft, it must be remembered that the simulated landings for the STOL aircraft were down a desired glide slope of 7 degrees as compared to a 2.7-degree glide slope for the conventional aircraft. The difference in glide slope angle allowed the STOL aircraft to descend the glide slope in a shorter length of time which apparently accounted for the much smaller deviations in touchdown observed with the STOL. On the other hand, since a 2.7-degree slide slope is typical for a conventional aircraft, and 7 degrees typical for a STOL, the comparison between the two is valid when considering the effect of wind shear on typical landing conditions at a given airfield.

Landing of the augmentor-wing STOL aircraft in a tailwind presents a problem if the tailwind is greater than 17 ft/sec. With a 17 ft/sec tailwind, zero thrust is required to maintain the 7-degree glide slope with a relative air velocity of 118 ft/sec. For a tailwind in excess of 17 ft/sec the seven-degree glide slope cannot be maintained without increasing the speed of the aircraft as it descends. If it becomes necessary to land this STOL aircraft in a large tailwind, the pilot should probably decrease his glide slope angle to two or three degrees if possible.

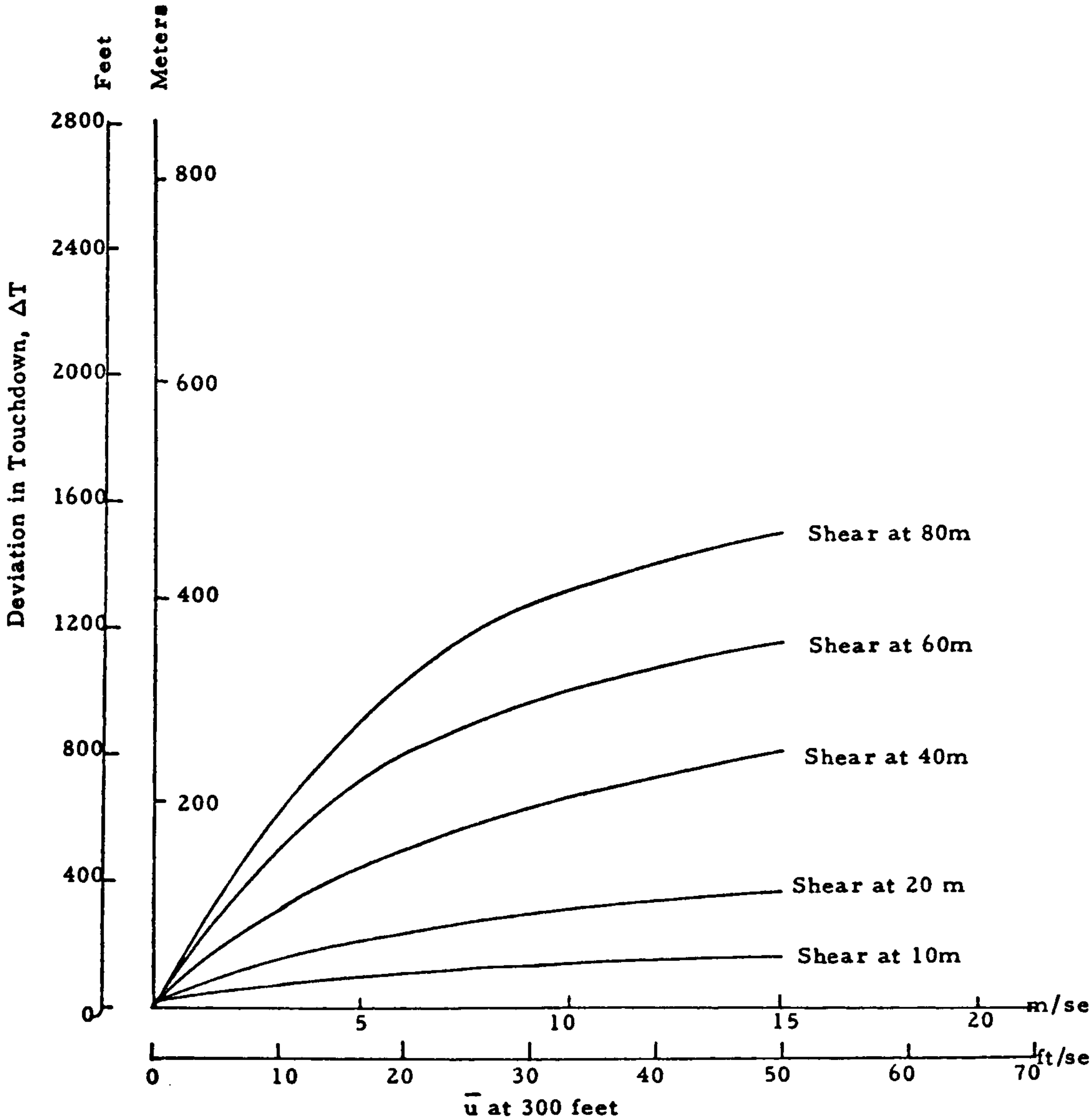

Figure 26. Deviation in Touchdown for STOL in Very Stable Wind Profiles: Headwind.

SUMMARY AND CONCLUSIONS

The three-degrees-of-freedom aircraft landing simulation study has determined the types of wind shear profiles that can produce potentially hazardous landing conditions. No pilot or auto-pilot feedback was introduced into the simulation. Deviations in touchdown point in excess of 3000 feet resulting from variation of the horizontal wind during the final 300 feet of descent have been observed under wind shear conditions that are not unrealistic. The influence of ground effects, center of gravity location, and gross weight of the aircraft on the deviation in touchdown point due to wind shears has also been investiaged. The specific conclusions resulting from this study are:

a) Stable $(0 < Ri < 0.2)$ and very stable $(Ri > 0.2)$ conditions are most likely to produce hazardous landing conditions. Deviations in touchdown of 2000 to 4000 feet have been observed for conventional aircraft. Neutral and unstable wind profiles seldom cause deviations in touchdown point in excess of 2000 feet for conventional aircraft and 600 feet for the augmentor-wind STOL.

b) The deviation in touchdown point, ΔT, is more dependent upon the terrain roughness, Z_o, than upon the stability length, L, under unstable and neutral wind conditions. Under stable wind conditions, the reverse is true.

c) For very stable conditions, ΔT is most dependent upon the altitude at which the shear layer occurs. Very stable wind profiles are highly unpredictable and are not dependent upon the surface parameters (Z_o, u^*, L) that characterize the other stability conditions.

d) For the aircraft considered here, the variation in touchdown due to the ground effects on the aircraft is small in comparison to the variation which can result from the wind shears investigated.

e) For a given wind profile, a tailwind direction produces a slightly larger deviation in touchdown than does a headwind direction.

f) For the conventional aircraft, the size, type, and the landing speed of the aircraft has some influence on ΔT but this influence is considerably less than that due to surface roughness and stability length. The types of conventional aircraft studied were the C-130E, C-135A, C-141, DC-8, and B-747.

g) The landing of the augmentor-wing STOL in a given wind field produced a much smaller value of ΔT than the landing of conventional aircraft in the same wind field. In particular, ΔT values for a STOL landing were 3 to 6 times smaller than the corresponding ΔT values for a conventional landing. The large glide slope angle for the STOL (7 degrees) allowed it to land in less time and was a major reason why ΔT was smaller for the STOL. Under all but the most extreme shear conditions, values of ΔT for the STOL aircraft did not exceed 1000 feet.

h) The difference in touchdown points between the landing of a fully loaded aircraft and an empty aircraft was found to be small. The aircraft analyzed was the Boeing 747.

i) The difference in touchdown point resulting from a shift in the Cg, within operational tolerance, was found to be negligible. The aircraft analyzed was the Boeing 747. In particular, this indicates that the Boeing 747 was well designed with respect to its response to wind shear.

Aeronautical Safety Considerations

This research program has provided results that have direct application to aeronautical safety at airports. It has been shown that the most critical landing conditions are likely to occur under the stable and very stable atmospheric conditions. Unfortunately, the wind profile under very stable conditions cannot be determined from a single wind measurement knowing the surface roughness and stability parameters. Very stable conditions often occur during the night under strong temperature inversions. Under these conditions, height and magnitude of the shear can only be determined by empirical measurements. Thus, an important consideration in improving airport safety is to provide the capability of measuring a vertical profile of shear. A first-order shear approximation could be derived by a simple two-point shear, calculated from an airport surface wind measurement and an onboard aircraft wind speed measurement. A more refined profile could perhaps be derived by some of the remote sensing techniques presently under development.

A second safety consideration relevant to air traffic control is the observation that a severe shear condition effects all aircraft (at least those within the range of size and type considered in this report) to approximately the same degree. Thus, if one aircraft reports landing difficulties due to wind shear, it should be assumed that all-size aircraft will experience similar landing problems.

A third consideration related to airport safety concerns the homogeneous terrain that immediately surrounds different airports. Since the surface roughness parameter, Z_o, shows little influence on touchdown points under stable and very stable conditions, the roughness of the terrain surrounding the airport is not an important consideration for determining which airports experience the critical shear profiles. This statement needs some qualification, however, since the wind profiles defined in this study assumed the terrain to be homogeneous of a given roughness length. At many airports, as the aircraft descends the glide slope, the roughness of the terrain that regulates the profile changes so that more shear could possibly be introduced into the wind profile. A study should be directed toward the change in terrain problem before a firm conclusion delineating the terrain effects of airport surroundings can be made.

A fourth safety consideration is related to pilot training and automatic landing systems. A wide variety of wind profiles representing the various terrain roughness and stability conditions should be used as input to flight simulators where pilot response or pilot training is required. The same variety of wind profiles should be used for the evaluation of an automatic landing system.

A final safety consideration has application to those involved in STOL airport design. The deviations in touchdown observed for the STOL aircraft should provide preliminary guidelines for the runway length safety factor needed to allow for touchdown dispersions due to wind shear.

Suggestions for Additional Research

This study has provided some basic results concerning the amount of dispersion in touchdown that is likely to occur for an aircraft landing under a specific set of assumptions. These assumptions limit the reality of the simulation model to some extent since the actual situation is different when a pilot-controlled aircraft descends the glide slope. Many factors which were not in cluded in this study may be important and could be considered in a more defined six-degree-of-freedom aircraft simulation model. A six-degree-of-freedom model could extend the analysis to consider cross wind landings and landings in wind fields where the direction of the wind changes significantly over the final 300 feet of descent. The effect of turbulence could also be studied by introducing three-dimensional turbulence structure into the mean wind profile. Further work is also needed in defining the wind profile along the glide slope when a change in terrain roughness occurs. The effect of the roughness change from sea to land terrain should also be studied. A final recommendation is to improve the reality of the simulation by introducing pilot feedback or an automatic landing system into the simulation model. Only by introducing control can a completely realistic simulation be anticipated. Such a research program as defined above would produce more definitive results under a much broader range of conditions.

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APPENDIX A

The equations for the lift, drag, and moment coefficients (C_L, C_D, C_m) and the aerodynamic coefficient data for each aircraft considered in this study are presented below. The ground effects terms for four of the aircraft (DC-8, C-135A, Boeing 747, and the STOL) are discussed. Ground effects data were not available for the C-130E and the C-141 aircraft. The aerodynamic data presented corresponds to a given flap setting and, where applicable, a given horizontal tail setting. The data includes the effects of the landing gear.

DC-8

The expressions for the aerodynamic coefficients of the DC-8 aircraft are:

$$C_L = C_{L_o} + C_{L_\alpha} \alpha' + C_{L_{\delta_E}} \delta_E + \frac{\bar{c} q}{2V_a} C_{L_q} + \frac{\bar{c} \dot{\alpha}'}{2V_a} C_{L_{\dot{\alpha}}} + \Delta C_{L_{GE}}$$

$$C_D = C_{D_o} + C_{D_\alpha} \alpha' + C_{D_\alpha^2} \alpha'^2 + \Delta C_{D_{GE}}$$

$$C_m = C_{m_o} + C_{m_\alpha} \alpha' + C_{m_{\delta_E}} \delta_E + \frac{\bar{c} q}{2V_a} C_{m_q} + \frac{\bar{c} \dot{\alpha}'}{2V_a} C_{m_{\dot{\alpha}}} + \Delta C_{m_{GE}}$$

where the usual notation is used for the various stability derivatives. The last term in each of the above equations is the ground effects term. The values of the stability derivatives are given in Table A.1 for a flap setting of 50 degrees. The ground effects terms for the DC-8 are:

$$\Delta C_{L_{GE}} = 0.063 \, (C_{L_\infty}) \, \epsilon_{GE}$$

$$\Delta C_{D_{GE}} = (-0.02 - 0.332\alpha') \, \epsilon_{GE}$$

$$\Delta C_{m_{GE}} = -0.066 \, (C_{L_\infty}) \, \epsilon_{GE}$$

TABLE A.1

DC-8 AERODYNAMIC DATA

C_{L_o}	0.90
C_{L_α}	5.30/rad
$C_{L_{\delta_E}}$	0.0053/deg
C_{L_q}	7.68/rad
$C_{L_{\dot{\alpha}}}$	0.0
C_{D_o}	0.140
C_{D_α}	0.501/rad
$C_{D_{\alpha^2}}$	1.818/rad^2
C_{m_o}	-0.01
C_{m_α}	-1.062/rad
$C_{m_{\delta_E}}$	-0.0161/deg
C_{m_q}	-12,30/rad
$C_{m_{\dot{\alpha}}}$	-4.01/rad

where

$$\epsilon_{GE} = 0.972\, e^{-h/17}$$

h is the wheel height, and C_{L_∞} is the free stream value of C_L.

C-135A

The expressions for C_L and C_m for the C-135A are the same as those for the DC-8. The expression for the drag coefficient is

$$C_D = C_{D_o} + C_{DC_L^2}\, C_L^2 + \Delta\, C_{D_{GE}}$$

Table A.2 shows the aerodynamic data for a flap setting of 30 degrees and a horizontal tail deflection of -4 degrees. The ground effects terms are:

$$\Delta C_{L_{GE}} = (0.039 + 0.2292\alpha')\, \epsilon_{GE}$$

$$\Delta C_{D_{GE}} = (0.119 - 0.357\, C_{L_\infty} + 0.186\, C_{L_\infty}^2)\quad \epsilon_{GE}$$

$$\Delta C_{m_{GE}} = (0.0228 - 0.1408\, C_{L_\infty} + 0.054\, C_{L_\infty}^2)\, \epsilon_{GE}$$

where

$$\epsilon = e^{-h/29}$$

C-141

The expressions for the lift, drag, and pitching moment coefficients for the C-141 are the same as those for the C-135A. Table A.3 presents the aerodynamic data for a flap setting of 45 degrees and a horizontal tail setting of -6 degrees. No data were available for C-141 ground effects terms.

TABLE A.2

C-135A AERODYNAMIC DATA

C_{L_o}	0.612
C_{L_α}	4.01 /rad
$C_{L_{\delta_E}}$	0.00376/deg
$C_{L_{\dot{\alpha}}}$	0.0
C_{L_q}	0.0
C_{D_o}	0.0685
$C_{D_{C_L^2}}$	0.0473
C_{m_o}	0.0922
C_{m_α}	-0.765/rad
$C_{m_{\delta_E}}$	-0.0108/deg
C_{m_q}	-14.182/rad
$C_{m_{\dot{\alpha}}}$	-5.787/rad

TABLE A.3

C-141 AERODYNAMIC DATA

C_{L_o}	1.309
C_{L_α}	5.44/rad
$C_{L_{\delta_E}}$	0.00443/deg
C_{L_q}	0.0
$C_{L_{\dot{\alpha}}}$	0.0
C_{D_o}	0.0835
$C_{D_{C_L^2}}$	0.0388
C_{m_o}	0.391
C_{m_α}	-1.351/rad
$C_{m_{\delta_E}}$	-0.0149/deg
C_{m_q}	-15.75/rad
$C_{m_{\dot{\alpha}}}$	-5.17/rad

C-130E

The C-130E aircraft is powered by four propjet engines. For this type of aircraft several of the stability derivatives depend upon the thrust coefficient T_C defined as

$$T_C = F_{T_E} / 2\bar{q} d^2$$

where F_{T_E} is the thrust per engine, $\bar{q}$ is the dynamic pressure, and d is the propeller diameter. For the C-130E, d is equal to 13.5 feet. The expressions for C_L, C_D, and C_m for the C-130E are the same as for the C-135A except that C_{L_o}, C_{L_α}, C_{m_o}, and C_{L_α} depend upon T_C. This dependence is shown in Table A.4. The data in Table A.4 is for a flap setting of 18 degrees. No ground effects data were available for this aircraft.

Boeing 747

The expressions for C_L, C_D, and C_m used in this study for the Boeing 747 are the same as those of the DC-8 with the exception that an additional term has been added to C_m to account for different center of gravity locations. This term is:

$$C_L \; (Cg \; - 0.25)$$

where Cg is the location of the center of gravity in terms of the mean aerodynamic chord, $\bar{c}$. For a center of gravity location of 25% $\bar{c}$, the above term is zero. The aerodynamic data presented in Table A.5 is for a flap setting of 30 degrees and a horizontal tail setting of -4 degrees. It was assumed that the inboard and outboard elevator deflections are the same. The expressions for the ground effects terms are:

TABLE A.4

C-130E AERODYNAMIC DATA

C_{L_o}	$0.379\ T_C + 0.702$
C_{L_α}	$(3.62\ T_C + 6.70)$/rad
$C_{L\delta_E}$	0.0092/deg
C_{L_q}	6.59/rad
$C_{L_{\dot{\alpha}}}$	2.52/rad
C_{D_o}	0.0638
$C_{DC_L^2}$	0.0305
C_{m_o}	$-0.224\ T_C + 0.338$
C_{m_α}	$(2.75\ T_C - 1.785)$/rad
$C_{m\delta_E}$	-0.0285/deg
C_{m_q}	-20.06/rad
$C_{m_{\dot{\alpha}}}$	-7.91/rad

TABLE A.5

BOEING 747 AERODYNAMIC DATA

C_{L_o}	0.960	
C_{L_α}	5.735/rad	
$C_{L\delta_E}$	0.0062/deg	
C_{L_q}	5.68/rad	for c.g. = 25% $\bar{c}$
	6.76/rad	for c.g. = 15% $\bar{c}$
	4.88/rad	for c.g. = 33% $\bar{c}$
$C_{L_{\dot{\alpha}}}$	-6.70/rad	
C_{D_o}	0.1381	
C_{D_α}	0.5498/rad	
$C_{D_{\alpha^2}}$	2.190/rad^2	
C_{m_o}	0.094	
C_{m_α}	-1.536/rad	
$C_{m_{\delta_E}}$	-0.0246/deg	
C_{m_q}	-21.50/rad	
$C_{m_{\dot{\alpha}}}$	-3.40/rad	for c.g. = 25% $\bar{c}$
	-3.81/rad	for c.g. = 15% $\bar{c}$
	-3.09/rad	for c.g. = 33% $\bar{c}$

$$\Delta C_{L_{GE}} = K^B_{GE}(0.240)\cos[8.036(\alpha' - 0.00526)]$$

$$\Delta C_{D_{GE}} = K^A_{GE}(2.308\alpha'^3 - 0.9796\alpha'^2 - 0.1769\alpha' - 0.0384)$$

$$\Delta C_{m_{GE}} = K^B_{GE}(2.736\alpha'^2 - 0.621\alpha' - 0.115)$$

where

$$K^A_{GE} = 1.7034 \times 10^{-6} h^3 - 1.0736 \times 10^{-4} h^2 - 1.4813 \times 10^{-2} h + 1.0$$

$$K^B_{GE} = 3.7906 \times 10^{-6} h^3 - 4.937 \times 10^{-4} h^2 + 2.807 \times 10^{-3} h + 1.0$$

The ground effects terms are included only during the last 82.5 feet of flight.

STOL

The equations for the aerodynamic coefficients for the augmentor wing STOL aircraft are somewhat different than for the previously discussed aircraft. Several of the stability derivatives are functions of the thrust coefficient C_j. In the present study, a value for C_j of 0.75 was chosen. The aerodynamic coefficients are expressed as:

$$C_L = C_{L_{WB}} + C_{L_{H_o}} + C_{L_{H_\alpha}}\alpha' + C_{L_{\delta_E}}\delta_E + \frac{\bar{c}q}{2V_a}C_{L_q} + \frac{\bar{c}\dot{\alpha}'}{2V_a}C_{L_{\dot{\alpha}}}$$

$$C_D = C_{D_o} + C_{D_\alpha}\alpha' + \Delta C_{DGE}$$

$$C_m = C_{m_o} + C_{m_\alpha}\alpha' + C_{L_{WB}}\left(\frac{\ell_W}{\bar{c}}\cos\alpha' + \frac{Z_W}{\bar{c}}\sin\alpha'\right)$$

$$+ C_D\left(\frac{\ell_W}{\bar{c}}\sin\alpha' - \frac{Z_W}{\bar{c}}\cos\alpha'\right) + (C_{L_{H_o}} + C_{L_{H_\alpha}}\alpha' + C_{L_{\delta_E}}\delta_E)$$

$$\left(\frac{Z_H}{\bar{c}}\sin\alpha' - \frac{\ell_H}{\bar{c}}\cos\alpha'\right) + \frac{\bar{c}q}{2V_a}C_{m_q} + \frac{\bar{c}\dot{\alpha}'}{2V_a}C_{m_{\dot{\alpha}}} + \Delta C_{mGE}$$

The subscripts H and WB refer to the contributions from the horizontal tail and wing-body, respectively. $C_{L_{WB}}$ is the basic lift coefficient for the wing-body. The parameters ℓ_W, Z_W, ℓ_H, and Z_H are distances which relate the aircraft center of gravity to the wing-body C_m reference point and the 25% mean aerodynamic chord of the horizontal tail. (See Figure A.1). The values of these parameters are:

$$\ell_W = 3.95 \text{ ft.}$$
$$Z_W = 0.083 \text{ ft.}$$
$$\ell_H = 75.39 \text{ ft.}$$
$$Z_H = -24.75 \text{ ft.}$$

The values for the various stability derivatives are shown in Table A.6. The flap setting is 70 degrees and the auxiliary flap is set at 6 degrees.

The description of the ground effects for the STOL aircraft is much more complex than for the conventional aircraft investigated. The ground effects come into play at approximately 200 feet altitude. Prior to this point, $C_{L_{WB}}$ is given by

$$C_{L_{WB_\infty}} = C_{L_{WB_o}} + C_{L_{WB_\alpha}} \alpha'$$

The subscript ∞ denotes the free stream value. The value of $C_{L_{WB_\infty}}$ is modified by ground effects according to the equation

$$C_{L_{WB_{GE}}} = [\, C_{L_{C_j}} C_j (1 - q/q_\infty) + C_{L_{WB_\infty}} q/q_\infty \,][\, 1/\left(1 - (\frac{\Delta\alpha}{C_L})\, C_{L_{WB_\alpha}}\right)]$$

where

$$q/q_\infty = \left\{ \frac{1}{1 + \frac{C_{L_{WB_\infty}}}{8\pi\, h/\bar{c}} \left(\frac{1}{[\,1 + 16(\frac{h}{\bar{c}\cdot A_R})^2\,]^{1/2}} \right)} \right\}^2$$

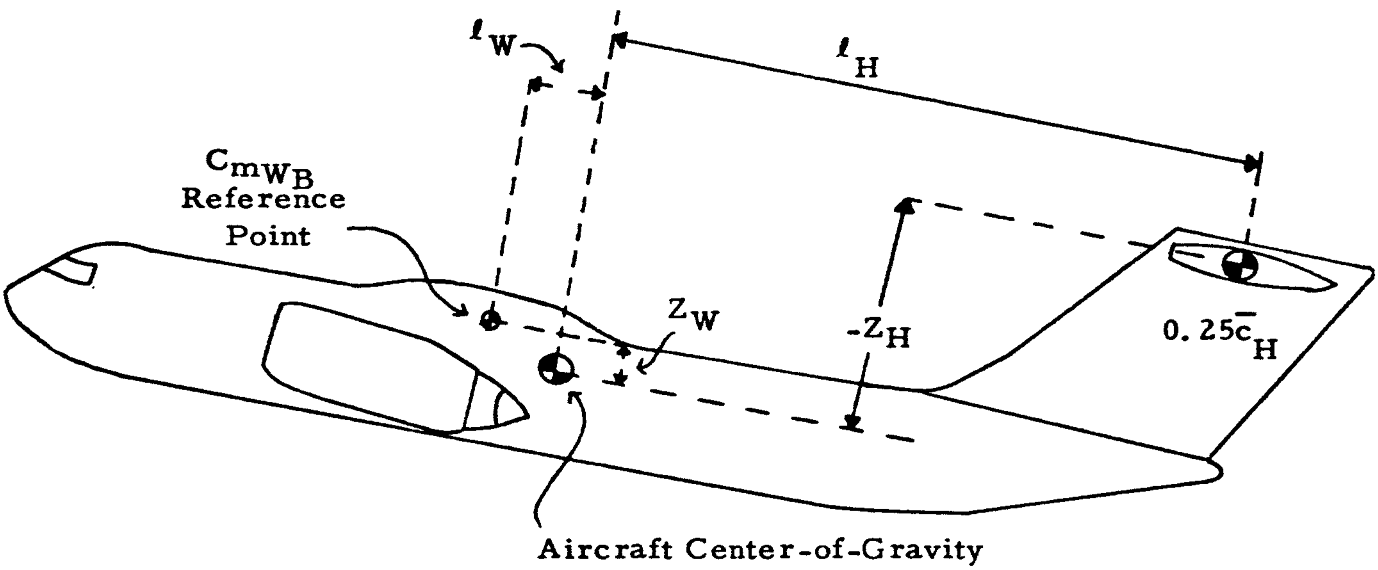

Figure A. 1 Some Geometric Parameters for the Augmentor-Wing STOL Aircraft.

TABLE A.6

AUGMENTOR-WING STOL AERODYNAMIC DATA

$C_{L_{WB_o}}$	4.274
$C_{L_{WB_\alpha}}$	4.498/rad
$C_{L_{H_o}}$	-0.124
$C_{L_{H_\alpha}}$	0.743/rad
$C_{L_{\delta_E}}$	0.00936/deg
C_{L_q}	0.0
$C_{L_{\dot{\alpha}}}$	0.0
C_{D_o}	0.449
C_{D_α}	2.12/rad
C_{m_o}	-1.245
C_{m_α}	0.372/rad
C_{m_q}	-0.0265/rad
$C_{m_{\dot{\alpha}}}$	0.0
$C_{L_{C_j}}$	2.20
$C_{D_{C_j}}$	$0.1709\alpha' - 0.031$
$C_{m_{C_j}}$	-0.780
C'_{m_α}	0.384/rad

$$\frac{\Delta\alpha}{C_L} = \frac{1}{2\pi A_R \left[1 + 16 \left(\frac{h}{\bar{c} \cdot A_R}\right)^2\right]}$$

and A_R is the wing aspect ratio which has a value here of 6.5. The above equation does not apply if $C_{L_{WB_{\infty}}}$ exceeds its maximum allowable value which for the present case is 6.74. The drag and pitching moment ground effects terms are:

$$\Delta C_{D_{GE}} = (C_{D_o} + C_{D_\alpha} \alpha')(q/q_{\infty} - 1) - \left[C^2_{L_{WB_{\infty}}} \left(\frac{\Delta\alpha}{C_L}\right)\right] (q/q_{\infty})$$

$$+ (1 - q/q_{\infty})\, C_{D_{C_j}}\, C_j$$

$$\Delta C_{m_{GE}} = (C_{m_o} + C_{m_\alpha} \alpha')\,(q/q_{\infty} - 1) + C'_{m_\alpha} \left(\frac{\Delta\alpha}{C_L}\right) C_{L_{WB_{GE}}}$$

$$+ C_{m_{C_j}} C_j \,(1 - q/q_{\infty})$$

Values for $C_{L_{C_j}}$, $C_{D_{C_j}}$. $C_{m_{C_j}}$, and C'_{m_α} are presented in Table A.6 for a C_j value of 0.75.