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LOW-LIFT-TO-DRAG-RATIO APPROACH AND LANDING STUDIES USING A CV-990 AIRPLANE

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16. Abstract

This paper presents the results of a flight-test program utilizing a CV-990 airplane, flown in low-lift-to-drag-ratio (L/D) configurations, to simulate terminal area operation, approach, and landing of large unpowered vehicles. The results indicate that unpowered approaches and landings are practical with vehicles of the size and performance characteristics of the proposed shuttle vehicle. Low L/D landings provided touchdown dispersion patterns acceptable for operation on runways of reasonable length. The dispersion pattern was reduced when guidance was used during the final approach. High levels of pilot proficiency were not required for acceptable performance.

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INTRODUCTION

The National Aeronautics and Space Administration has proposed that completely reusable booster and orbiter vehicles be developed to reduce the cost of transporting large payloads to and from orbit. Such vehicles probably will return to earth for horizontal landings at designated sites and be refurbished for further use. This system is referred to as a space shuttle.

A space shuttle vehicle may be required to make an unpowered approach and landing, because of payload penalties that may make air-breathing engines impractical or because of fuel limitations if engines are included. The feasibility of unpowered landing has been assessed and successfully demonstrated in previous studies (refs. 1 to 6), but the studies were performed primarily with relatively small airplanes (F-104, F-102, X-15, for example). Because the shuttle vehicles will be comparatively large, the feasibility of an unpowered landing for large vehicles needed verification.

The use of turbojet aircraft to simulate the approach and landing of unpowered vehicles is well established. The F-104 airplane was used extensively prior to the X-15 program to establish landing patterns and techniques and was used, in a similar manner, to support the M-2, HL-10, and X-24A lifting body programs.

To provide some background for unpowered landings of large vehicles, a program was initiated using a CV-990 airplane operated in a low-lift-to-drag-ratio (L/D) configuration to simulate shuttle vehicle performance characteristics. The objectives of the CV-990 program were to demonstrate (1) the feasibility of making low L/D (unpowered) landings with large vehicles, (2) that low L/D visual approaches can be made with a consistently small touchdown dispersion pattern, (3) that low L/D approaches require neither exceptional pilot skill nor additional training, and (4) the feasibility of low L/D instrument approaches.

This paper presents the results of the unpowered approach studies with the CV-990 airplane, including touchdown dispersion, pilot comments, and comparisons with predicted landing characteristics.

SYMBOLS

Physical quantities in this report are given in the International System of Units (SI) and parenthetically in U. S. Customary Units. The measurements were taken in U. S. Customary Units. Factors relating the two systems are presented in reference 7.

AF	acceleration factor
a	speed of sound, m/sec (ft/sec)
C_L	lift coefficient
h	altitude, m (ft)
L/D	lift-to-drag ratio
M	Mach number
q	dynamic pressure, N/m^2 (lb/ft^2)
S	wing area, m^2 (ft^2)
T	ambient temperature, °C (°K)
t	time, sec
V_e	equivalent airspeed, knots
V_i	indicated calibrated airspeed, knots
V_t	true airspeed, m/sec (ft/sec)
W	weight, kg (lb)
x, y, z	vehicle position
Δ	increment
δ_f	flap deflection, deg
δ_{sb}	speed brake deflection, percent total travel
σ	standard deviation
γ	flight path angle, deg

AIRPLANE DESCRIPTION

The CV-990 airplane is a four-engine jet transport with a swept wing and tail (figs. 1 and 2) designed for cruise at approximately Mach 0.85 at altitudes up to 12,180 meters (40,000 feet). Maximum takeoff weight of the airline airplane was approximately 114,800 kilograms (253,000 pounds). Overall dimensions of the airplane are presented in table 1.

Aerodynamic Controls

The aerodynamic controls consisted of the following movable surfaces: ailerons, spoilers, wing flaps, leading-edge flaps, elevators, horizontal stabilizer, and rudder. The primary pilot controls were ailerons, spoilers, rudder, and elevator.

The ailerons and spoilers provided lateral control, which was accomplished by rotating the pilot's control wheel. The ailerons were actuated by aerodynamic boost from pilot controlled aileron flight control tabs. The flight tabs deflected ±20° and commanded ±15° of aileron deflection. Two spoilers were mounted on the top surface of each wing forward of the inboard and outboard flaps. They were hydraulically actuated and provided about 80 percent of the total lateral control. Full travel limits of the outboard and inboard spoilers were 60° and 75°, respectively. The spoilers could be used for speed brakes and, in an emergency, for longitudinal trim. The spoiler deflection angles were limited by the hinge moment capabilities of the actuators operating with full hydraulic pressure.

For directional control a 30-percent-chord rudder was provided that was controlled hydraulically or manually through conventional rudder pedals. For manual control a 1:1 tab-to-rudder deflection control and a trim tab were provided. Maximum rudder deflection was limited by the structure to ±25° and kept within allowable limits by the hinge moment capability of the dual hydraulic system. Complete dual hydraulic system failure resulted in automatic reversion to conventional aerodynamic control. In the manual mode, rudder pedal force was a function of aerodynamic hinge moment, deflection of the centering spring, and differential cable motion. In the powered mode, rudder pedal force was a function of the artificial feel system and of spring and cable motion.

Longitudinal control was accomplished by moving the pilot's or co-pilot's control column forward or aft. The motion was transmitted to the flight tabs, which deflected opposite to the desired elevator movement. Elevator auxiliary tabs provided antifloat compensation to keep the elevators faired to the stabilizers. Elevator travel limits were 25° up and 12° down from the streamlined position. Flight tab limits were 12° up and 25° down from streamline. Elevator auxiliary tab travel was about 4° to 25° trailing-edge down.

The horizontal tail was used for longitudinal trim by varying its angle of incidence. The tail could be actuated hydraulically, electrically, or mechanically.

Two slotted Fowler flaps were installed on either side of the aileron on the trailing edge of the wing. The flap design provided high lift and low drag when partially extended and high lift and high drag when fully extended. The flaps had five detents (up, or 0°; 10°; 27°; 36°; and 50°). Eight leading-edge (Krueger) flaps were hinge-mounted to the underside of each wing at about the 2-percent-chord position. These flaps were either fully closed or fully extended and were used for takeoff and landing.

Operating Limitations

Because of its inherent design, the test aircraft was operated within the following limitations:

Landing gear down	320 knots or Mach 0.83
Flap limit speeds for a flap deflection of -	
0°	Normal airplane limits
10°	245 knots or Mach 0.6
27°	240 knots or Mach 0.58
36°	220 knots or Mach 0.51
50°	195 knots or Mach 0.40
Spoiler blowback	Initiated at V_i = 200 knots

BACKGROUND FOR UNPOWERED APPROACH AND LANDING TECHNIQUE

An unpowered approach is primarily distinguished from a powered approach by two features: an unpowered approach is always flown with energy in excess of that required to reach the touchdown point, and the final approach glide slope does not intersect the ground at (or near) the touchdown point.

An airplane without an engine has only the energy associated with its altitude and velocity. This energy must be sufficient to allow the aircraft to flare and touch down at the desired location and velocity; therefore, in an unpowered approach, an excess of energy relative to the intended touchdown location must be maintained. The excess energy is retained until the latest possible time, and the touchdown may even be at a higher speed than that normally specified. However, the excess energy is usually dissipated in a controlled manner during the approach phase of a landing, so that the required conditions are established on final approach.

Two basic methods are used to modulate energy in an unpowered approach: L/D modulation and path length variation. In the L/D modulation technique, the approaches are flown on the front side of the L/D versus C_L curve (airspeeds above maximum L/D) (fig. 3). This results in a stable flight path angle/airspeed relationship. That is, if the airplane is on a given flight path, the airspeed will tend to stabilize at the value required to maintain that angle, and the L/D can be varied directly by changing the pitch attitude (increased by pulling up, decreased by pushing over). From a piloting standpoint this technique makes energy modulation a natural task. If the desired ground reference is being overshot, the excess energy can be dived off, and if the reference point is being undershot, the vehicle can be "pulled up" to the reference point. In addition to the L/D variation with C_L it is almost essential that an unpowered airplane be equipped with speed brakes for further L/D modulation. Speed brakes can be used to adjust the rate of energy dissipation just as engines are used to vary the energy input.

The combination of front side operation on the L/D versus C_L curve and speed brake capability makes it possible to use two different flying techniques. The front side operation leads directly to the technique in which the desired glide angle is achieved by varying pitch attitude (therefore airspeed) only. The other technique is to maintain the desired airspeed by using pitch control and to achieve the desired glide slope by varying speed brake position.

Varying the path length (ground track) over which the vehicle flies can also be used to modulate energy. This method is illustrated in figure 4. If the vehicle's energy is low, the distance to be flown is reduced, by turning inside the planned track. Conversely, if the vehicle's energy is high, the vehicle is flown outside the planned track, increasing the distance to be flown. Generally, path length variation is used for gross energy adjustments and not for relatively small or precise adjustments.

These techniques are used in various combinations to arrive on final approach at the desired location and airspeed. Experience has shown that a wide range of excess energy at high key can be accommodated if the vehicle has been designed with a large L/D modulation capability (effective speed brakes and an overspeed capability).

One way to arrive at a desirable approach speed (which defines the approach angle) and aim point (the point at which the final approach glide slope intersects the ground) is to work backward from the desired touchdown velocity, post-flare float time, and flare. The aim point and preflare airspeed are defined from the energy required by the flare, the postflare deceleration, and the desired touchdown airspeed. Therefore, by specifying the touchdown speed and by assuming a 10- to 15-second postflare deceleration and a 1.2g to 1.5g flare, the geometry and velocities are defined throughout the maneuver. This technique yields a relatively high approach speed, which in turn provides a great deal of excess g capability to make the flare, and a long enough deceleration for the pilot to achieve the desired touchdown condition. A profile of an unpowered flare and landing is presented in figure 5.

An unpowered approach requires that the pilot maneuver the airplane to the specified aim point at the required airspeed. Prior to the flare the pilot concentrates on achieving these conditions, almost ignoring the touchdown point, because the touchdown point is defined within a very small tolerance from the preflare conditions.

TEST PROCEDURE

The objective of this flight investigation with the CV-990 airplane was to perform low L/D (simulated unpowered) approaches with a vehicle that had the probable size and performance characteristics of a shuttle orbiter. Touchdown dispersion data were collected from both visual and instrument approaches. Most of the data were obtained from flights by experienced, proficient, engineering test pilots; however, two airline pilots and two former test pilots also participated in the program (table 2).

Performance Characteristics

To determine the performance characteristics of the airplane and to select a configuration representative of current proposed shuttle vehicles, it was necessary to measure the L/D characteristics of the CV-990 airplane. The L/D was measured by a constant-airspeed, timed-descent technique. Basically, this technique measures rate of sink and true airspeed to give a flight path angle which can then be converted to L/D ($\cot \gamma \approx L/D$) and lift coefficient. No instrumentation is required beyond that normally installed in an airplane.

The timed-descent technique is sensitive to position error on the pitot-static system, atmospheric conditions (thermals and winds), and pilot ability, in that constant indicated airspeed must be maintained during the descent. These factors contribute to the scatter in the L/D data presented. The data reduction format is presented in appendix A. A more complete description of the technique is included in references 8 and 9.

The CV-990 airplane was flown in several idle-power, gear-down, low L/D configurations. Data were obtained with 100-percent spoiler (speed-brake) deflection at flap settings of 0°, 10°, and 27°. This large spoiler deflection caused airframe buffet that was not acceptable for extended operation. At a flap setting of 36° and a spoiler deflection of approximately 25 percent, the buffet was acceptable and the L/D characteristics were representative of shuttle vehicles. The L/D characteristics of these configurations are presented in figures 6(a) and 6(b).

The spoilers, when used as speed brakes, had a blowback feature to limit the loads imposed on the structure; blowback started at 200 knots indicated airspeed (KIAS). This blowback caused the shape of the L/D curves to change at the lower lift coefficients and contributed to the scatter in the data because L/D is related to airplane weight (airspeed) as well as to the lift coefficient.

Low L/D Approaches

Two types of low L/D approaches were flown: 360° overhead visual approaches and straight-in instrument approaches (fig. 7). For the 360° overhead approaches the high key altitudes varied between 4572 meters (15,000 feet) and 7620 meters (25,000 feet) mean sea level (field elevation, 701 m (2300 ft)); the pilots attempted to touch down at the 914-meter (3000-foot) marker at 150 KIAS on Edwards Air Force Base runway 22, which is 4572 meters (15,000 feet) long and 91.4 meters (300 feet) wide. The runway had extension lines prominently marked for several miles on the surface of a dry lakebed and other distinguishing features along the extended centerline which permitted the pilot to see his aiming point shortly after turning from the high key position. Calculations were made to establish the aim point short of the desired touchdown point to provide the desired speed bleed off. For the planned preflare airspeed of 220 knots, this aim point was computed to be 2286 meters (7500 feet) from the intended touchdown location.

The straight-in instrument approaches were initiated at an altitude of about 6096 meters (20,000 feet) and flown with a glide slope of -11° or -12°, depending upon winds. These approaches were flown both VFR and simulated IFR. The aim point (intersection of the glide slope with the ground) was 2286 meters (7500 feet) from the intended touchdown point (the same point as used in the visual circling approaches). The instrument landing system used had a crosspointer display for position information. This guidance system is described more completely in appendix B.

The preflare airspeed for all approaches was planned at 220 KIAS.

Approximately 90 low L/D landings were made in the CV-990 airplane in various configurations at gross weights as high as 86,213 kilograms (190,000 pounds). The approach lift-to-drag ratios were as low as 3.25; however, most were flown in the 36° flap, 25-percent-spoiler configuration that gave an approach L/D of about 4.7 and a maximum L/D of 7. On 77 of these landings, touchdown miss distance and airspeed were recorded.

To determine the piloting skill requirements, two airline pilots were invited to participate in the program. Neither pilot had flown the CV-990 airplane nor had been exposed to approach maneuvers of the types being flown. After a preflight briefing, a demonstration, and an aircraft familiarization period, the pilots flew both visual overhead and instrument approaches. To evaluate current proficiency requirements, two former test pilots, both familiar with low L/D approaches, were asked to perform visual approaches. Neither pilot could be considered to be current in the CV-990 airplane or in low L/D approaches. Touchdown dispersion data were collected on all the low L/D landings for these evaluations. Because the study was oriented toward a space shuttle vehicle, several astronauts were invited to participate in the tests. Five astronauts made visual overhead and ground command guidance (GCG) approaches and landed successfully on the runway; however, no dispersion data were recorded during these landings.

RESULTS AND DISCUSSION

Engineering Evaluation

Touchdown dispersion. – The touchdown miss distance and airspeed data recorded during 77 CV-990 landings are presented in table 3, and the miss distances are summarized in figure 8. The 1σ value of the miss distances is 254 meters (835 feet). These data include visual overhead approaches and simulated ILS approaches that provided glide slope and localizer information for the final approach in a display similar to that for an instrument landing system. The visual approach touchdown dispersion pattern for maneuvers performed at $\delta_f = 36°$ is shown in figure 9. This technique provided a 1σ miss distance of 269 meters (883 feet). The ground command guidance (GCG) approaches provided the touchdown dispersion pattern shown in figure 10 and a 1σ miss distance of 120 meters (394 feet). It would appear that the touchdown dispersion pattern was adequate for routine operation on runways of reasonable length; however, guidance significantly reduced the dispersion.

Instrument operation aspects. – To evaluate the weather aspects of the approach and landing the pilots flew under a hood (to eliminate outside visibility) down to an altitude of 183 meters (600 feet) above ground level (AGL) on 15 of the landings. The GCG type of instrument landing system presentation was used for guidance. After the hood was removed at 183 meters (600 feet) AGL, the pilot was required to flare visually (starting at approximately 122 meters (400 feet) AGL) and maneuver the airplane to the desired touchdown point. The pilots commented that this presented no problem; however, the visibility after hood removal was, for practical purposes, unlimited. The occurrence of a 183-meter (600-foot) ceiling with unlimited visibility beneath is questionable. Thus the question of weather minimums for this type of approach, which is also complicated by factors such as displays, system redundancy, and guidance parameters, is not completely resolved.

Pilot experience and proficiency requirements.—Before the program was started, neither of the two airline pilots (table 2) had been exposed to approaches of the types being flown. Each pilot was given a preflight briefing on the approaches, was allowed to observe one 360° visual overhead approach and one steep instrument approach, and was permitted to fly one conventional 3° glide-slope instrument approach for aircraft familiarization (neither pilot had flown a CV-990 airplane). Each pilot then flew one steep ($\gamma = -11°$) GCG approach without a hood, one steep GCG approach hooded to 183 meters (600 feet) AGL, and two 360° overhead approaches. The maximum touchdown miss distance was 243 meters (800 feet). (See table 3 for complete tabulation.) Both pilots commented that with enough guidance to allow the vehicle to enter the acceptable energy window anywhere in the pattern, any good pilot would find the task of maneuvering the airplane to the touchdown point a reasonable one.

Two former lifting body vehicle test pilots (table 2) flew the CV-990 airplane in a low L/D configuration from a high key altitude of 6096 meters (20,000 feet) to touchdown. One pilot had not flown a low L/D approach maneuver for approximately 4 years and had not flown any airplane for 4 months. The other pilot had not flown a low L/D approach for approximately 10 months but had relatively recent experience with helicopters and had flown a CV-990 airplane previously. Each pilot received a preflight briefing on the aircraft characteristics and on the geometry of the pattern. The pilot who had previously flown the CV-990 airplane was given a 30-minute period to refamiliarize himself with the vehicle, during which he made two normal approaches. He then flew the airplane to a high key altitude of 6096 meters (20,000 feet) and made a low L/D 360° visual overhead approach to landing. The touchdown was 853 meters (2800 feet) short of the intended touchdown point. The pilot commented that previous training interfered with his judgment: his previous low L/D training had been for the M2-F2 lifting body vehicle, which had an approach angle of approximately -30°, contrasted to approximately -11° for the CV-990 airplane. The initial part of the pattern was too high in energy, and he overcorrected for it when he adjusted the energy state downward (by turns and L/D modulation). On the succeeding two approaches the miss distance was -30 meters (-100 feet).

The other pilot was not given any aircraft familiarization prior to the first low L/D 360° visual overhead approach. He controlled the aircraft to a touchdown with a miss distance of -152 meters (-500 feet). His second landing was 61 meters (200 feet) beyond the intended touchdown point.

Both pilots commented that aircraft handling qualities (discussed later) degraded their ability to concentrate on the energy management task.

After observing other pilots perform these maneuvers, the five astronauts experienced no particular difficulty in performing the approaches.

None of the approaches had to be abandoned because of energy management difficulties.

Wind effects. —During the GCG approaches, with the geometry of the approach fixed, the effects of wind had to be accounted for. An average headwind or tailwind could be compensated for during the approach by changing the approach angle (ref. 8). However, wind shear effects could not be compensated for, and the airplane was subject to significant shear effects during the approaches. At times there were almost instantaneous indicated airspeed changes of up to 15 knots. The effect of this is obvious, because the pilots depended entirely upon indicated airspeed for an energy indicator. The best procedure to reduce or correct for these effects has not yet been defined.

Pilot Observations

Flying a large jet transport through power-off landing patterns developed for experimental aircraft such as the X-15 and HL-10 vehicles showed both the similarities and the differences in the piloting task imposed by the high inertia airplane. The primary purpose of the tests was to determine the feasibility of adapting power-off landing techniques to space shuttle vehicle missions rather than to the recovery of experimental aircraft, so emphasis was placed on the pilot's observations of relevant large aircraft handling qualities, instrument requirements, and piloting factors. Throughout the tests, the pilots considered the unguided circling approach to be a backup procedure, that is, a necessary maneuver for the space shuttle vehicle were the pilot to find that the guidance systems were degraded. The steep, hooded, instrument approaches were probably more representative of normal space shuttle vehicle operation than the normal ILS approaches. They provided an opportunity to evaluate the limitations of conventional aircraft instruments and controls during high-speed descents and to suggest changes which would increase the system capability under conditions of reduced visibility.

Although unpowered approaches and landings in a large aircraft are unusual, the procedure has been well established by glider operations. However, higher wing loadings and much greater speeds expand the approach geometry, making it more difficult for the pilot to judge rates, angles, and distances as he maneuvers the airplane to a landing. Modifications to maneuvering techniques have to be made to allow for the handling qualities and control characteristics of large airplanes (especially their more sluggish response) as well as to allow for the wide range of winds which is normally encountered during a descent. The pilots completed most of the circling approaches by using only judgment and visual reference to the ground, to illustrate the performance possible without guidance signals. The series of landings that was made with flight path displacement error guidance in the form of an instrument landing system display showed that unpowered instrument approaches (hooded) could be flown using relatively simple guidance laws.

Aircraft handling qualities. —The stability and control characteristics of the CV-990 airplane are representative of this general class of airplane, with the exception of the lateral control forces, which are high. The tests were flown at a midcenter of gravity, and none of the subject pilots had any difficulty adapting to the longitudinal control characteristics. Lateral stability and control, particularly the Dutch roll mode coupled with the high lateral forces, created a problem for the pilots who had not encountered the condition previously. The pilots who were experienced to any degree with large aircraft commented adversely only on the high lateral forces. The circling approach required bank angles (45° to 60°) and roll rates higher than are normally used in transport operation; however, the existing control system and control power were satisfactory for the task. Fighter pilots with minimum experience with wheel controls had no problem making the transition from a center stick to the wheel control. The comparatively slow response of the large airplane produced some adverse comment from the same group, but their performance was not affected. It would appear that handling qualities similar to those of the CV-990 airplane would be adequate for the shuttle vehicle. No unusual stability and control requirements were encountered during these tests, and the approach technique itself, in which high speeds were used, allowed better airplane response than is possible at the constant, lower speeds of a conventional approach.

Overhead 360° visual approaches.—A 360° overhead approach is illustrated in figure 11. For these tests the airplane was flown visually to the high key position; however, any method of guidance to that point could be used. The consideration of primary importance was that the airplane have the altitude necessary to provide enough energy to satisfactorily complete the pattern. During the program the high key altitude was varied from 7010 meters (23,000 feet) AGL to 3962 meters (13,000 feet) AGL. Successful patterns could be flown from high key altitudes anywhere within that range, but the most comfortable altitude at the high key position was approximately 5486 meters (18,000 feet) AGL. The turn from this high key position was planned with a 35° bank when the pattern speed was 210 to 220 KIAS. The bank angle required varied with altitude and airspeed. At the high key position it was important to roll immediately into the bank to avoid dissipating too much energy (altitude) before reaching the low key position. As would be expected, the lower the high key position, the more important this became. The 180° turn from the high key was essentially a mechanical turn, because judgment was not critical at that part of the pattern and visibility was limited. It was desirable to be able to see the landing area at all times in the pattern, but this visibility was not essential until the airplane was on the downwind leg. Once the airplane was established on the downwind leg parallel to the landing area, approximately 3.0 to 4.0 nautical miles from the runway, it was almost essential to be able to see the runway continuously until touchdown.

The ideal range of low key altitude was 2743 meters to 3048 meters (9000 feet to 10,000 feet) AGL but, if the downwind leg were kept close to the runway, the altitude could have been as low as 2134 meters (7000 feet) AGL. At the low key position, pilot judgment became important in maneuvering the airplane toward the aim point. From this point until flare initiation, the pilot would have completely disregarded the desired touchdown point and concentrated on maneuvering toward the aim point.

The option of diving off excess energy was not available in the CV-990 airplane, because the pattern speed was near or at the flap limit speed of 220 KIAS. Varying the pattern and S-turning the airplane to adjust energy was effective but not particularly precise and could have led to greater touchdown dispersions. The airbrake setting was increased or decreased occasionally for L/D adjustment, but the CV-990 airbrake did not significantly affect L/D. A more effective airbrake would have been desirable as well as a greater speed margin above the minimum preflare speed.

The aim point was approximately 2286 meters (7500 feet) short of the touchdown point for the configuration and airspeed used. The aim point was not as easy to judge on these approaches as it was on the steeper approaches flown in lifting body vehicles, because the ground intercept point was much easier to visualize on the steeper approaches. The airplane was maneuvered toward the aim point until the flare was initiated. Flare altitude was normally approximately 122 meters (400 feet) AGL but was not critical. The flare could be started as high as 244 meters (800 feet) AGL and as low as 61 meters (200 feet) AGL without greatly affecting the touchdown point. The radar altimeter was used to assist the pilot in determining flare altitude; however, the pressure altimeter would have been satisfactory because the flare was not critical and the touchdown point was insensitive to variations in flare altitude. If the aim point was properly located and the pilot maneuvered toward that point at the planned speed, touchdown invariably occurred within a few hundred feet of the planned point unless the pilot deliberately touched down at a higher or lower speed than planned.

Instrument approaches.—Simulated power-off instrument approaches using an ILS deviation display on a -11° or a -12° glide slope were performed with the pilot hooded down to about 183 meters (600 feet) AGL. The glide slope and localizer intercept technique was much the same as that used for a conventional ILS approach. In this instance, the airplane was maneuvered in its best glide configuration until the approximate center of the glide slope was intercepted. Then the low L/D landing configuration was selected which, with power at idle, provided an L/D to match the selected glide slope at the planned speed. Tailwinds up to 60 knots were encountered at the glide slope intercept height; however, glide slope tracking alone showed the pilot the need to change the L/D ratio to compensate. Spoiler blowdown at high speeds reduced the effectiveness of L/D modulation, and the drag change with speed was less than optimum, limiting the total L/D modulation available. The drag compensation available was adequate, however, and the pilots used drag modulation in the same way thrust is used to manage a power-on approach.

No adverse pilot comments were made about the constant levels of sensitivity provided by the guidance system; in fact, several advantages of the system were noted. First, the descent path intercept range and altitude were not constant, and with the parallel edge guidance system beam, the intercept angles and aircraft turn rates used to prevent overshooting were simplified. With an angular beam ILS, the path displacement indicator sensitivity changes as a function of range in terms of linear displacement error, thereby changing the intercept procedure. Secondly, the pilot could adapt to the display gains early in the approach and, in effect, practice using the system before he reached the critical low altitudes. Of course, these considerations could all be eliminated by using a flight director computer or automatic control. However, this program showed that only normal pilot compensation is required to complete a simulated space shuttle vehicle instrument approach using raw displacement data presented in a parallel beam edge format.

CONCLUSIONS

A flight investigation was performed with the CV-990 airplane, flown in low-lift-to-drag-ratio (L/D) configurations, to simulate terminal area operation, approach, and landing of large unpowered vehicles, such as space shuttle vehicles. Both visual and instrument types of maneuvers were performed by pilots of various experience and proficiency. The investigation led to the following conclusions:

1. Unpowered approaches and landings are practical with vehicles of the size and performance characteristics of the proposed shuttle vehicle.

2. Low L/D (unpowered) landings provided touchdown dispersion patterns acceptable for operation on runways of reasonable length.

3. Guidance during final approach reduced the dispersion pattern.

4. High levels of pilot proficiency were not required for acceptable performance.

Flight Research Center
National Aeronautics and Space Administration
Edwards, Calif., October 29, 1971.

APPENDIX A

L/D DATA REDUCTION FORMAT FOR TIMED-DESCENT TECHNIQUE

The sample calculation below illustrates the timed-descent data reduction format for one configuration used in the flight measurement of performance characteristics.

Configuration: Idle power, $\delta_{sb} = 25$ percent, $\delta_f = 36°$, gear down

Weight = 77,900 kg (171,800 lb)

Data:

h, m	h, ft	t, sec	T, °C	V_i, knots
3962	13,000	0	--	220
3657	12,000	12	14	220
3352	11,000	23	16	220
3048	10,000	35	18	220
2743	9,000	46	20	220

Reduction: (1) Determine dh/dt:
dh/dt = -25.8 m/sec (84 ft/sec).

(2) Determine V_e at selected altitude of 3048 m (10,000 ft):
using figure 12 (from ref. 10), $V_e = 218$ knots.

(3) Determine Mach number at selected altitude:
using figure 13, $V_e/M = 546$; therefore $M = 0.398$.

(4) Compute speed of sound at selected altitude:
$a\ (\text{m/sec}) = 20.048\ (T + 273)$
$a = 342$ m/sec (1122 ft/sec).

(5) Compute V_t ($V_t = Ma$):
$V_t = 136$ m/sec (448 ft/sec).

(6) Compute $\sin\gamma$ $\left(\sin\gamma = \dfrac{dh/dt}{V_t}\right)$:
$\sin\gamma = 0.189$; therefore $\gamma = -11°$.

(7) Determine acceleration factor from figure 14: AF = 1.1.

(8) Determine L/D from figure 15:
$L/D = 4.8$.

(9) Compute q from V_e:
$q = 3.38\ N/m^2$ (162 lb/ft^2).

(10) Compute C_L ($C_L = W \cos \gamma / qS$):
$C_L = 0.427$.

APPENDIX B

DESCRIPTION OF ILS GUIDANCE SYSTEM

To evaluate energy management techniques and to provide an IFR capability for unpowered vehicles, the Flight Research Center has developed an instrument landing system which utilizes a tracking radar, a digital computer, and a radio-frequency link to the airplane to present the pilot with error signals. This system, the ground command guidance (GCG) system, is shown schematically in figure 16. Basically, a radar measures the vehicle position (x, y, z), and this information is transmitted to a computer. The computer compares the actual position with the desired position (left or right of centerline, above or below glide slope) and computes error signals. These errors are transmitted to the airplane and presented to the pilot on a crosspointer indicator.

The pilot is presented with the raw position error and some position error rate. The error signals presented to the pilot and the scaling are illustrated in figure 17. With this technique, the vehicle is directed to fly down a tube, rather than a cone as with a conventional instrument landing system. As shown in the figure, the tube is uniform until it reaches a distance of 12.87 kilometers (8 miles) from the aim point. It then tapers until it becomes one-tenth its original diameter at 1.29 kilometers (0.8 mile) from the aim point. This diameter is maintained until the glide slope intersects the ground. This system is more flexible in terms of sensitivity and accuracy than a conventional instrument landing system, because at large distances the presentation is still sensitive enough to be useful, and close in it does not become too sensitive to fly.

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TABLE 1.—PHYSICAL CHARACTERISTICS OF THE CV-990 AIRPLANE

Fuselage -	
Maximum width, m (ft)	3.51 (11.50)
Maximum height, m (ft)	3.78 (12.42)
Length, m (ft)	42.60 (139.75)
Wing -	
Incidence (root), deg	4
Aerodynamic span, m (ft)	35.97 (117.99)
Area, m^2 (ft^2)	209 (2250)
Root chord, m (ft)	8.28 (27.15)
Tip chord, m (ft)	2.69 (8.83)
Mean aerodynamic chord, m (ft)	6.34 (20.81)
Dihedral, deg	7
Aspect ratio	6.2
Leading-edge sweep, deg	39
Horizontal tail -	
Area, m^2 (ft^2)	39.6 (426.55)
Dihedral, deg	7.5
Leading-edge sweep, deg	41
Span, m (ft)	11.80 (38.74)
Aspect ratio	3.52
Vertical tail -	
Area, m^2 (ft^2)	27.4 (295)
Sweep at 30-percent chord, deg	35
Span, m (ft)	6.45 (21.17)
Aspect ratio	1.52
Aileron -	
Area, m^2 (ft^2)	2.78 (29.97)
Span, m (ft)	2.93 (9.62)
Maximum travel, deg	±15
Inboard spoiler -	
Area, m^2 (ft^2)	1.65 (17.8)
Mean aerodynamic chord, m (ft)	0.85 (2.8)
Maximum travel, deg	75
Outboard spoiler -	
Area, m^2 (ft^2)	3.86 (41.51)
Mean aerodynamic chord, m (ft)	0.95 (3.11)
Maximum travel, deg	60

TABLE 2.—PILOTS PARTICIPATING IN THE TEST/EVALUATION PROGRAM

Pilot	Experience
A	Engineering test pilot
B	Engineering test pilot
C	Engineering test pilot
D	Engineering test pilot
E	Airline pilot
F	Airline pilot
G	Test pilot
H	Former test pilot
I	Former test pilot

TABLE 3.—SUMMARY OF LOW L/D LANDING APPROACH MANEUVERS PERFORMED WITH THE TEST AIRPLANE AND TOUCHDOWN DISPERSION

Flight number 1
Purpose: Touchdown dispersion data
Airplane configuration: Idle power, gear down, 36° flap, no spoiler
Tasks: Touch down at 3218-meter (2-mile) marker (lakebed runway) at 135 KIAS

Number	Type of approach	Pilot	Gross weight,		High key altitude,		Touchdown airspeed,	Touchdown miss distance,	
			kg	lb	m	ft	knots	m	ft
1	Overhead[1]	B	76.7×10^3	169.2×10^3	Not recorded	Not recorded	146	1036	3400
2	Overhead	B	75.9	167.3	Not recorded	Not recorded	138	396	1300
3	Overhead	B	74.9	165.2	Not recorded	Not recorded	133	-30	-100
4	Overhead	B	73.7	162.5	Not recorded	Not recorded	130	-91	-300
5	Overhead	B	72.7	160.2	Not recorded	Not recorded	134	-396	-1300
6	Overhead	A	71.3	157.2	Not recorded	Not recorded	133	-762	-2500
7	Overhead	A	69.9	154.0	Not recorded	Not recorded	134	0	0
8	Overhead	A	68.5	151.0	Not recorded	Not recorded	138	-213	-700
9	Overhead	A	67.2	148.2	Not recorded	Not recorded	134	-15	-50
10	Overhead	A	66.0	145.4	Not recorded	Not recorded	133	-762	-2500

[1] Refers to a visual 360° overhead pattern or some portion thereof.

TABLE 3.—SUMMARY OF LOW L/D LANDING APPROACH MANEUVERS PERFORMED WITH THE TEST AIRPLANE AND TOUCHDOWN DISPERSION - Continued

Flight number 2
Purpose: Practice
Airplane configuration: Idle power, gear down, 36° flap, 25-percent spoilers
Tasks: Touch down at 914-meter (3000-foot) marker at 150 KIAS

Number	Type of approach	Pilot	Gross weight,		High key altitude,		Touchdown airspeed, knots	Touchdown miss distance,	
			kg	lb	m	ft		m	ft
1	Overhead	C	85.1×10^3	187.7×10^3	5.5×10^3	18×10^3	(a)	---	----
2	Overhead	C	83.5	184.0	5.5	18	160	671	2200
3	Overhead	C	82.0	180.7	5.5	18	158	61	200
4	Overhead	B	80.0	176.3	5.5	18	158	183	600
5	Overhead	B	78.1	172.2	5.5	18	(b)	---	----
6	Overhead	B	76.8	169.3	5.5	18	136	-610	-2000
7	Overhead	B	75.1	165.5	5.5	18	140	213	700
8	Overhead	A	73.4	161.8	5.5	18	150	61	200
9	Overhead	A	71.7	158.1	5.5	18	149	0	0
10	Overhead	A	70.0	154.3	5.5	18	150	152	500

[a] Missed approach, excess energy.
[b] Go-around, traffic.

TABLE 3.—*SUMMARY OF LOW L/D LANDING APPROACH MANEUVERS PERFORMED WITH THE TEST* AIRPLANE AND TOUCHDOWN DISPERSION - Continued

Flight number 3
Purpose: Touchdown dispersion data
Airplane configuration: Idle power, gear down, 36° flap, 25-percent spoilers
Tasks: Touch down at 914-meter (3000-foot) marker at 150 KIAS

Number	Type of approach	Pilot	Gross weight,		High key altitude,		Touchdown airspeed, knots	Touchdown miss distance,	
			kg	lb	m	ft		m	ft
1	Overhead	B	77.6×10^3	171.0×10^3	5.5×10^3	18×10^3	157	152	500
2	Overhead	B	76.4	168.5	6.7	22	140	-91	-300
3	Overhead	B	74.9	165.1	7.6	25	143	366	1200
4	Overhead	B	73.5	162.0	4.6	15	159	213	700
5	Overhead	B	72.0	158.7	5.5	18	156	122	400
6	Overhead	A	70.1	154.5	5.5	18	158	91	300
7	Overhead	A	68.1	150.2	6.7	22	157	244	800
8	Overhead	A	66.3	146.2	7.6	25	152	122	400
9	Overhead	A	65.6	144.7	4.6	15	156	305	1000
10	Overhead	A	64.9	143.0	5.5	18	146	0	0
11	Overhead	A	64.2	141.5	4.6	15	149	0	0

TABLE 3.—SUMMARY OF LOW L/D LANDING APPROACH MANEUVERS PERFORMED WITH THE TEST AIRPLANE AND TOUCHDOWN DISPERSION - Continued

Flight number 4
Purpose: Touchdown dispersion data
Airplane configuration: Idle power, gear down, 36° flap, 25-percent spoilers
Tasks: Touch down at 914-meter (3000-foot) marker at 150 KIAS

Number	Type of approach	Pilot	Gross weight,		High key altitude,		Touchdown airspeed, knots	Touchdown miss distance,	
			kg	lb	m	ft		m	ft
1	Overhead	B	86.2×10^3	190.0×10^3	5.5×10^3	18×10^3	143	-366	-1200
2	Overhead	B	85.1	187.5	4.6	15	150	335	1100
3	Overhead	B	83.1	183.2	6.7	22	144	122	400
4	Overhead	B	81.1	178.9	7.6	25	160	30	100
5	Overhead	B	79.4	175.0	5.5	18	148	0	0
6	Overhead	A	77.9	171.8	5.5	18	139	-244	-800
7	Overhead	A	76.5	168.7	4.6	15	153	0	0
8	Overhead	A	74.6	164.5	6.7	22	141	0	0
9	Overhead	A	72.3	159.5	7.6	25	146	0	0
10	Overhead	A	71.0	156.5	5.5	18	159	122	400

TABLE 3.–SUMMARY OF LOW L/D LANDING APPROACH MANEUVERS PERFORMED WITH THE TEST AIRPLANE AND TOUCHDOWN DISPERSION - Continued

Flight number 5
Purpose: Checkout of GCG system
Airplane configuration: Idle power, gear down, 36° flap, 25-percent spoilers
Tasks: Touch down at 914-meter (3000-foot) marker at 150 KIAS

Number	Type of approach	Pilot	Gross weight,		High key altitude,		Touchdown airspeed, knots	Touchdown miss distance,	
			kg	lb	m	ft		m	ft
1	GCG	B	--------	--------	6.1×10^3	20×10^3	---	-91	-300
2	GCG	B	73.5×10^3	162×10^3	6.1	20	150	0	0
3	GCG	A	--------	--------	6.1	20	145	-152	-500
4	GCG	A	--------	--------	6.1	20	156	-30	-100

TABLE 3.–SUMMARY OF LOW L/D LANDING APPROACH MANEUVERS PERFORMED WITH THE TEST AIRPLANE AND TOUCHDOWN DISPERSION - Continued

Flight number 6
Purpose: Touchdown dispersion data (approaches 1 to 8)
Demonstration (approaches 9 and 10)
Airplane configuration: Idle power, gear down, 36° flap, 25-percent spoilers
Tasks: Touch down at 914-meter (3000-foot) marker

Number	Type of approach	Pilot	Gross weight,		High key altitude,		Touchdown airspeed, knots	Touchdown miss distance,	
			kg	lb	m	ft		m	ft
1	GCG	A	85.0×10^3	187.5×10^3	6.1×10^3	20×10^3	142	61	200
2	GCG	A	82.9	182.8	6.1	20	147	-213	-700
3	GCG	A	81.0	178.6	6.1	20	142	-91	-300
4	GCG	A	79.5	175.3	6.1	20	136	-122	-400
5	GCG	B	77.8	171.6	6.1	20	135	91	300
6	GCG	B	76.1	167.9	6.1	20	139	-30	-100
7	GCG	B	74.1	163.4	6.1	20	138	61	200
8	GCG	B	72.2	159.3	6.1	20	138	305	1000
9	GCG	G	70.7	155.8	6.1	20	137	[a]91	300
10	Overhead	G	68.9	151.8	6.1	20	---	-671	-2200

[a]First flight in CV-990 airplane.

TABLE 3.–SUMMARY OF LOW L/D LANDING APPROACH MANEUVERS PERFORMED WITH THE TEST AIRPLANE AND TOUCHDOWN DISPERSION - Continued

Flight number 7
Purpose: Demonstration (approaches 1 to 5)
Touchdown dispersion (approaches 6 to 9)
Airplane configuration: Idle power, gear down, 36° flap, 25-percent spoilers
Tasks: Touch down at 914-meter (3000-foot) marker

Number	Type of approach	Pilot	Gross weight,		High key altitude,		Touchdown airspeed, knots	Touchdown miss distance,	
			kg	lb	m	ft		m	ft
1	Overhead	B	84.8×10^3	187.0×10^3	6.1×10^3	20×10^3	162	-30	-100
2	Overhead	D	82.5	181.8	6.1	20	≈155	914	3000
3	GCG	B	79.5	175.2	5.5	18	158	152	500
4	GCG	C	77.2	170.3	3.4	11	151	-213	-700
5	GCG	D	75.6	166.8	3.4	11	144	-30	-100
6	GCG	A	74.1	163.3	3.4	11	145 to 150	[a]152	500
7	GCG	A	72.8	160.5	3.4	11	140	[b]91	300
8	GCG	A	70.9	156.4	3.4	11	142	0	0
9	GCG	A	69.1	152.4	3.4	11	137	0	0

[a]Hood off at 185 meters (600 feet).

[b]Hood off at 125 meters (400 feet).

TABLE 3.–SUMMARY OF LOW L/D LANDING APPROACH MANEUVERS PERFORMED WITH THE TEST AIRPLANE AND TOUCHDOWN DISPERSION - Continued

Flight number 8
Purpose: Airline pilot evaluation
Airplane configuration: Idle power, gear down, 36° flap, 25-percent spoilers
Tasks: Touch down at 914-meter (3000-foot) marker

Number	Type of approach	Pilot	Gross weight,		High key altitude,		Touchdown airspeed, knots	Touchdown miss distance,	
			kg	lb	m	ft		m	ft
1	GCG[1]	B	86.2×10^3	190.0×10^3	5.5×10^3	18×10^3	148	-61	-200
2	Overhead[1]	B	84.3	185.9	6.1	20	146	61	200
3	ILS[2]	E	82.9	182.8	Not applicable	Not applicable	---	(1)	---
4	GCG	E	80.7	178.0	5.5	18	146	-152	-500
5	GCG	E	79.4	175.0	5.5	18	139	152	500
6	Overhead	E	78.0	171.9	6.1	20	142	-152	-500
7	Overhead	E	76.0	167.7	6.1	20	≈140	-91	-300
8	ILS[2]	F	74.3	163.9	Not applicable	Not applicable	(3)	---	---
9	GCG	F	72.6	160.1	5.5	18	132	244	800
10	GCG	F	71.2	157.0	5.5	18	(3)	---	---
11	GCG	F	69.6	153.5	5.5	18	130	244	800
12	Overhead	F	67.8	149.5	6.1	20	128	-91	-300
13	Overhead	F	66.2	146.0	6.1	20	132	30	100

[1]Demonstration.

[2]Conventional.

[3]Go-around, traffic.

TABLE 3.–SUMMARY OF LOW L/D LANDING APPROACH MANEUVERS PERFORMED WITH THE TEST AIRPLANE AND TOUCHDOWN DISPERSION - Concluded

Flight number 9
Purpose: Proficiency requirements
Airplane configuration: Idle power, gear down, 36° flap, 25-percent spoilers
Tasks: Touch down at 914-meter (3000-foot) marker

Number	Type of approach	Pilot	Gross weight,		High key altitude,		Touchdown airspeed, knots	Touchdown miss distance,	
			kg	lb	m	ft		m	ft
1	Visual[1]	I	85.9×10^3	189.3×10^3	Not applicable	Not applicable	≈145	-61	-200
2	Visual	I	85.3	188.0	Not applicable	Not applicable	145	0	0
3	Overhead	I	83.4	183.8	6.1×10^3	20×10^3	139	-853	-2800
4	Overhead	I	81.4	179.5	6.1	20	139	-30	-100
5	Overhead	I	80.1	176.5	6.1	20	150	-30	-100
6	Overhead	H	78.5	173.0	6.1	20	140	-152	-500
7	Overhead	H	76.8	169.3	5.2	17	152	61	200

[1] Conventional.

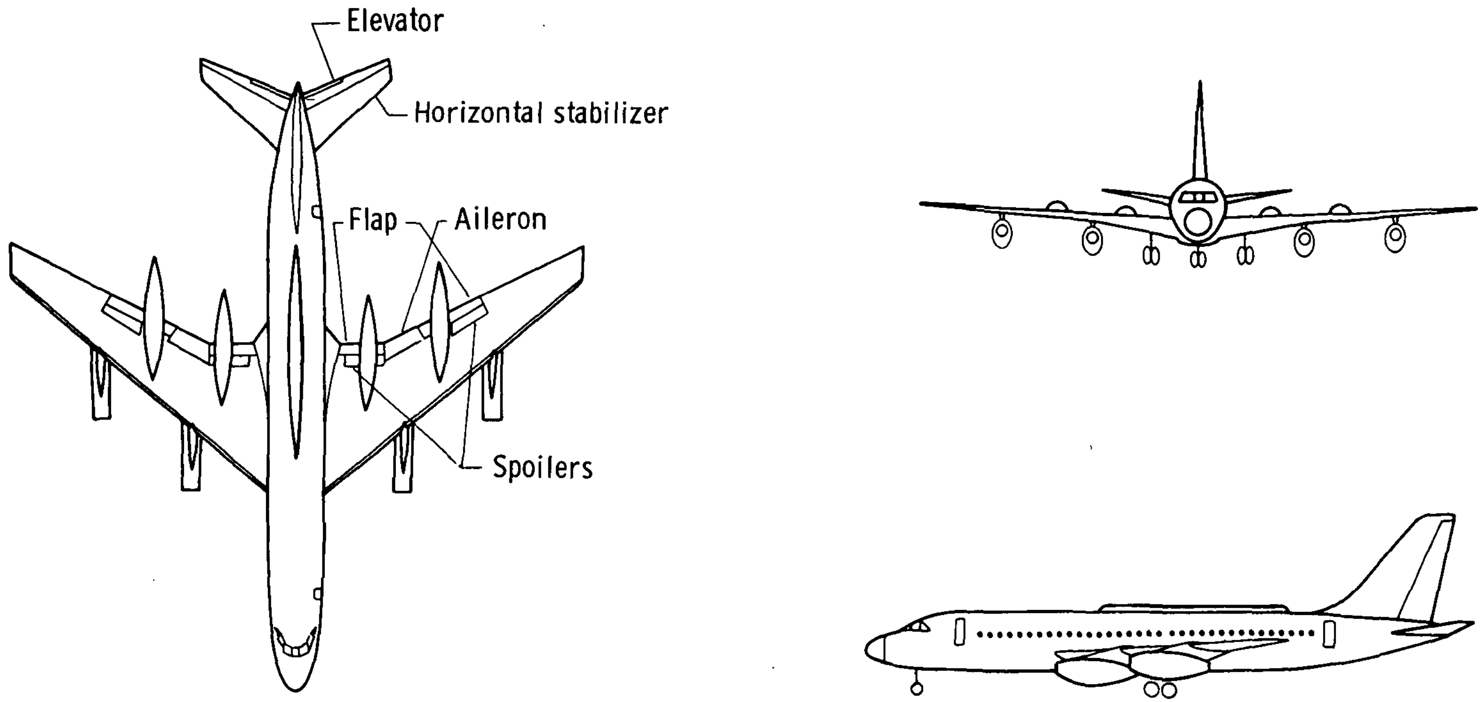


Figure 1. Three-view drawing of CV-990 airplane.

Figure 2. CV-990 airplane in a low-lift-to-drag-ratio configuration. E-21754

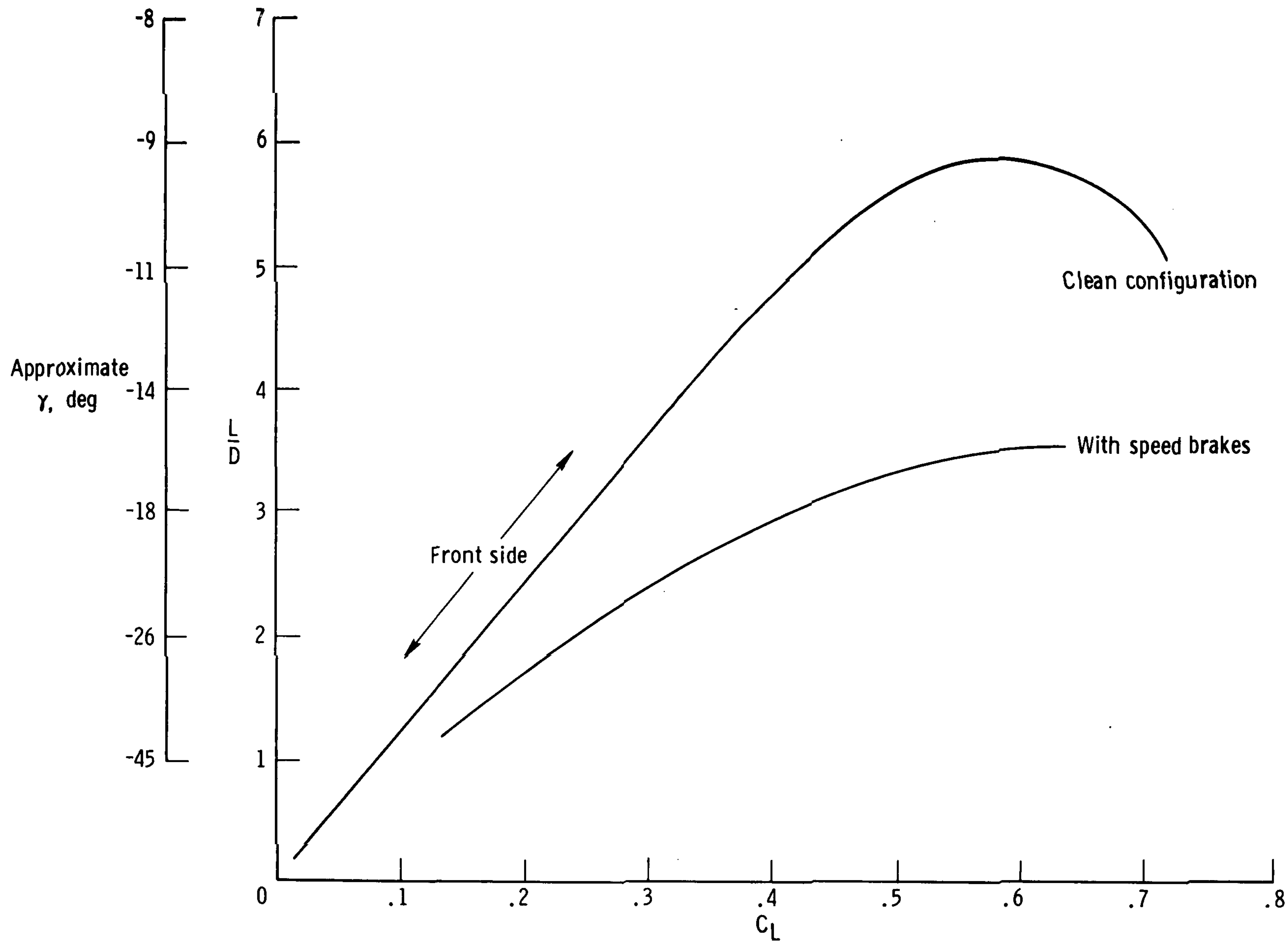


Figure 3. Lift-to-drag ratio (and therefore flight path angle) versus lift coefficient for a typical airplane illustrating front side operation on the L/D versus C_L curve and speed brake effect.

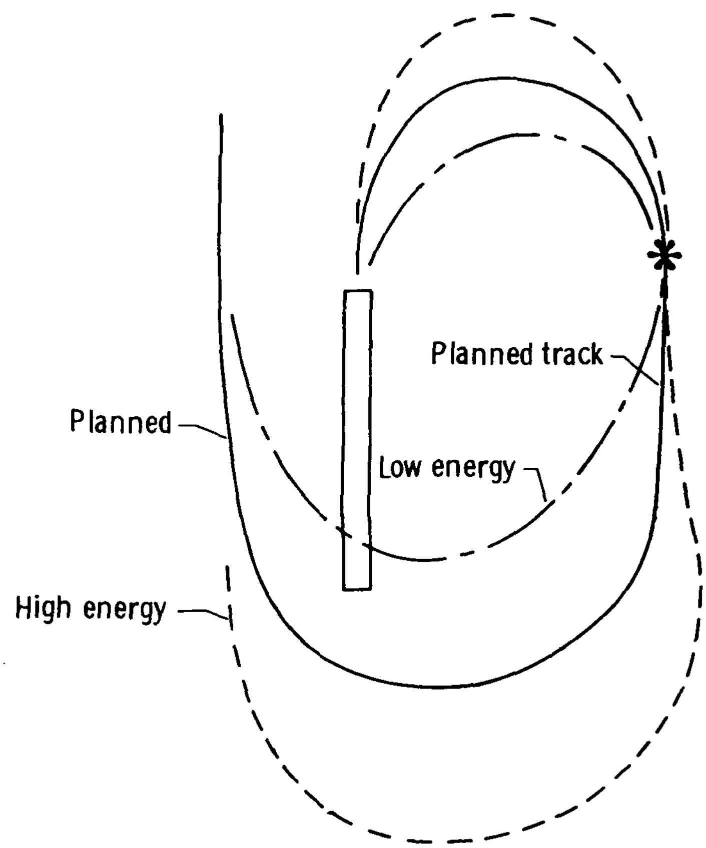


Figure 4. Illustration of path length variation to accommodate various energy levels in terminal approach pattern.

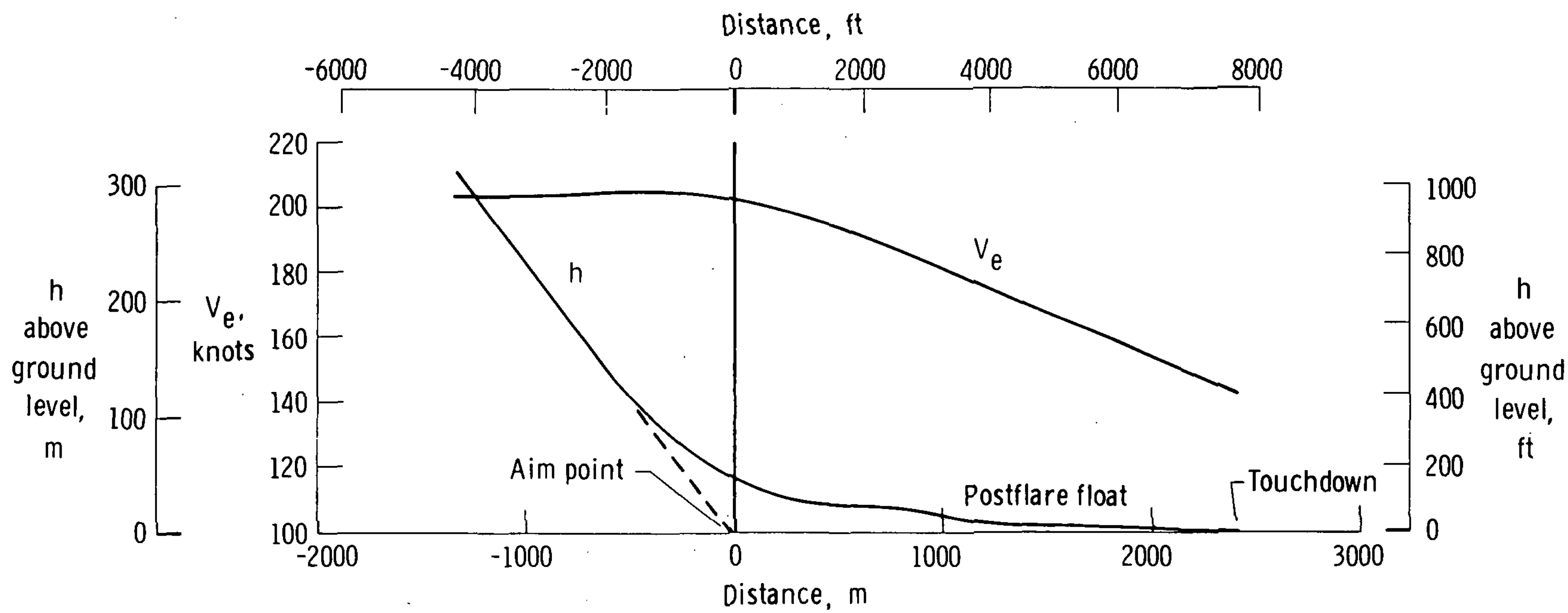
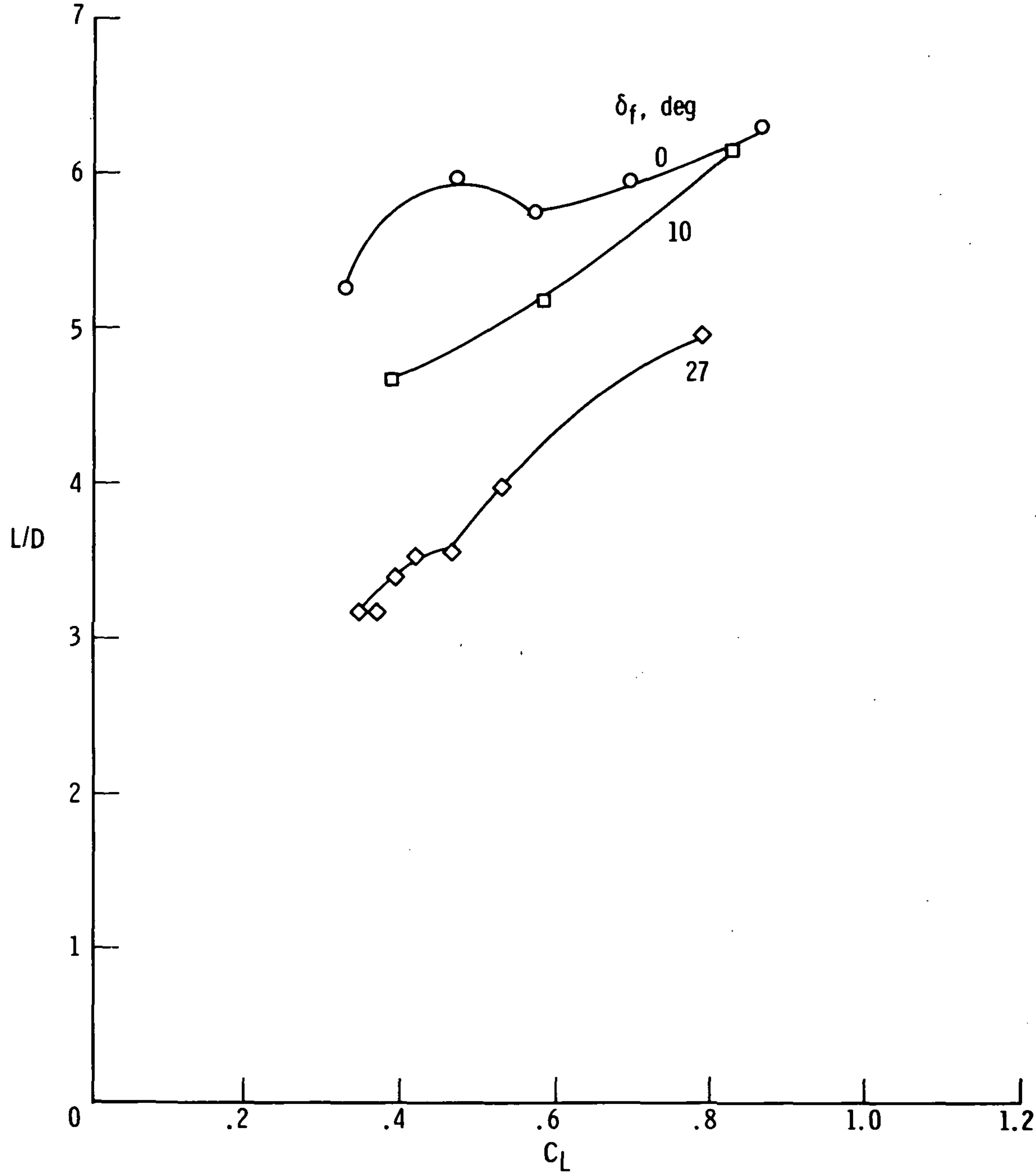
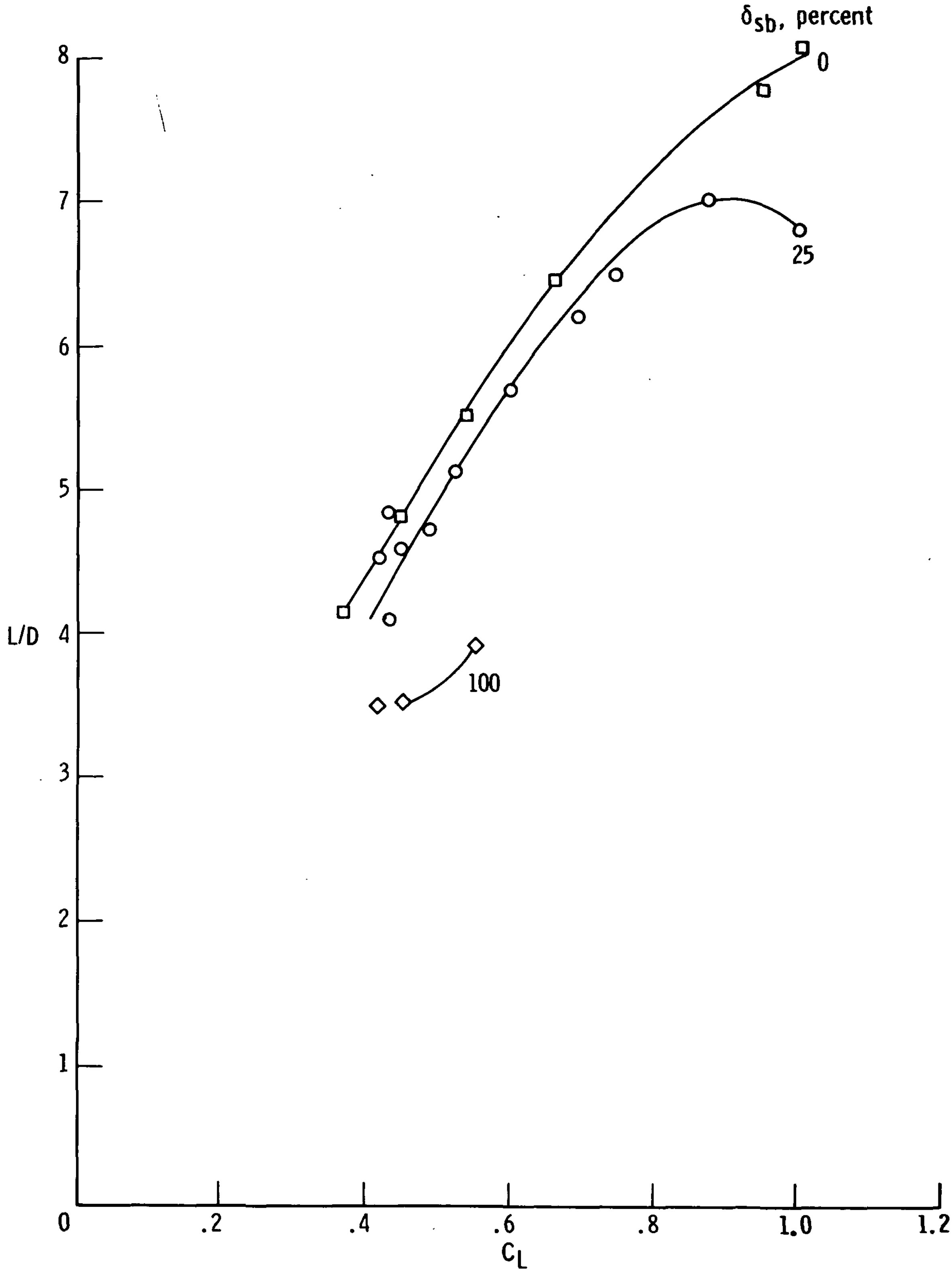


Figure 5. Typical CV-990 low L/D approach, flare, and landing. $\delta_f = 36°$; $\delta_{sb} = 25$ percent; gear down; idle power.



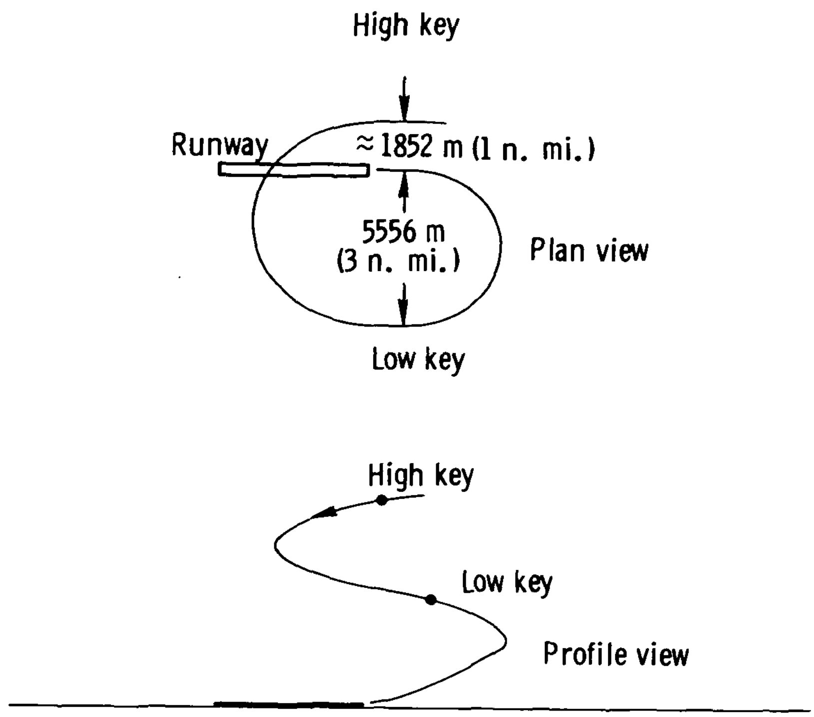
(a) Effect of flap deflection; 100-percent speed brake.

Figure 6. CV-990 L/D characteristics. Gear down; idle power.

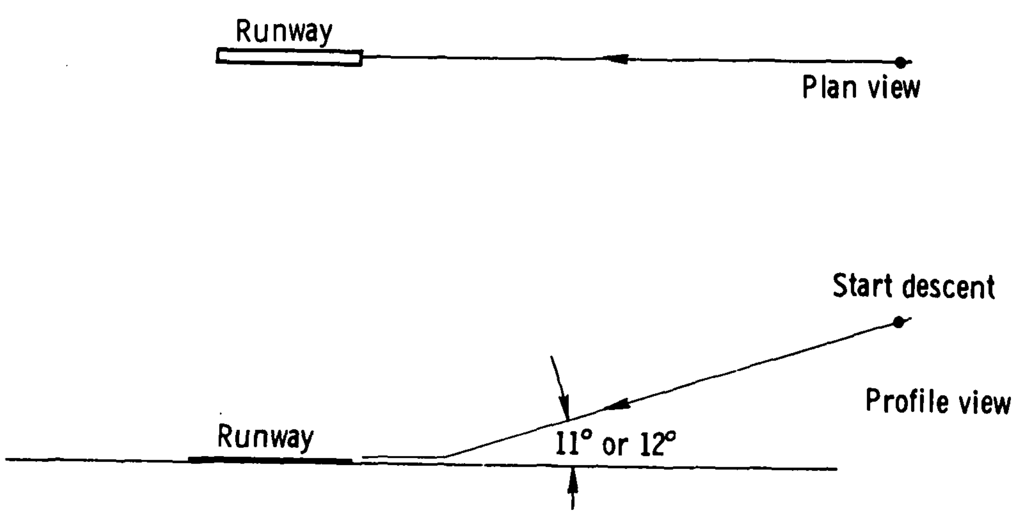


(b) Effect of speed brake setting; $\delta_f = 36°$.

Figure 6. Concluded.



(a) Typical 360° overhead approach.



(b) Straight-in approach.

Figure 7. Types of approaches used during CV-990 low L/D test program.

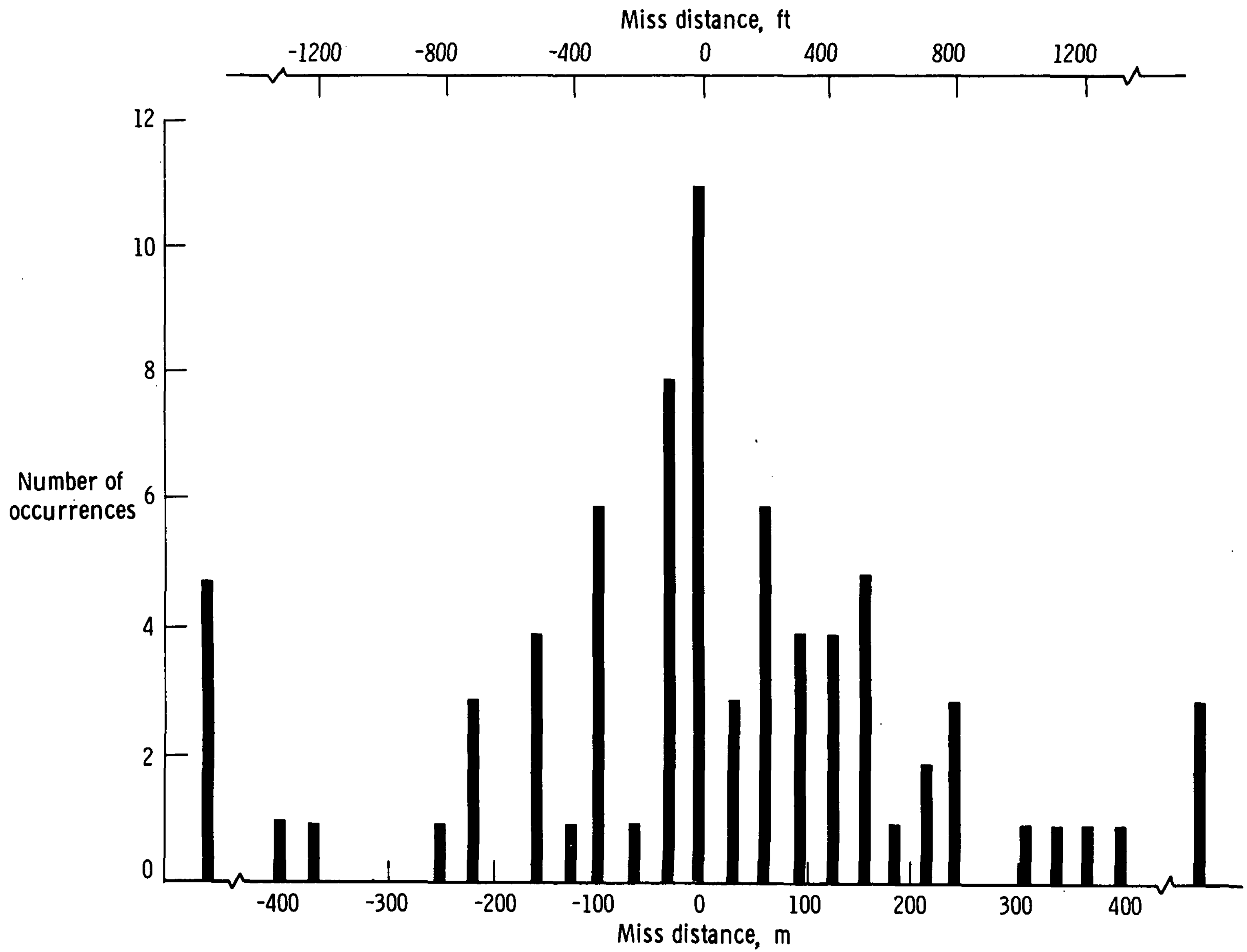


Figure 8. Touchdown dispersion pattern for 77 CV-990 low L/D landings.

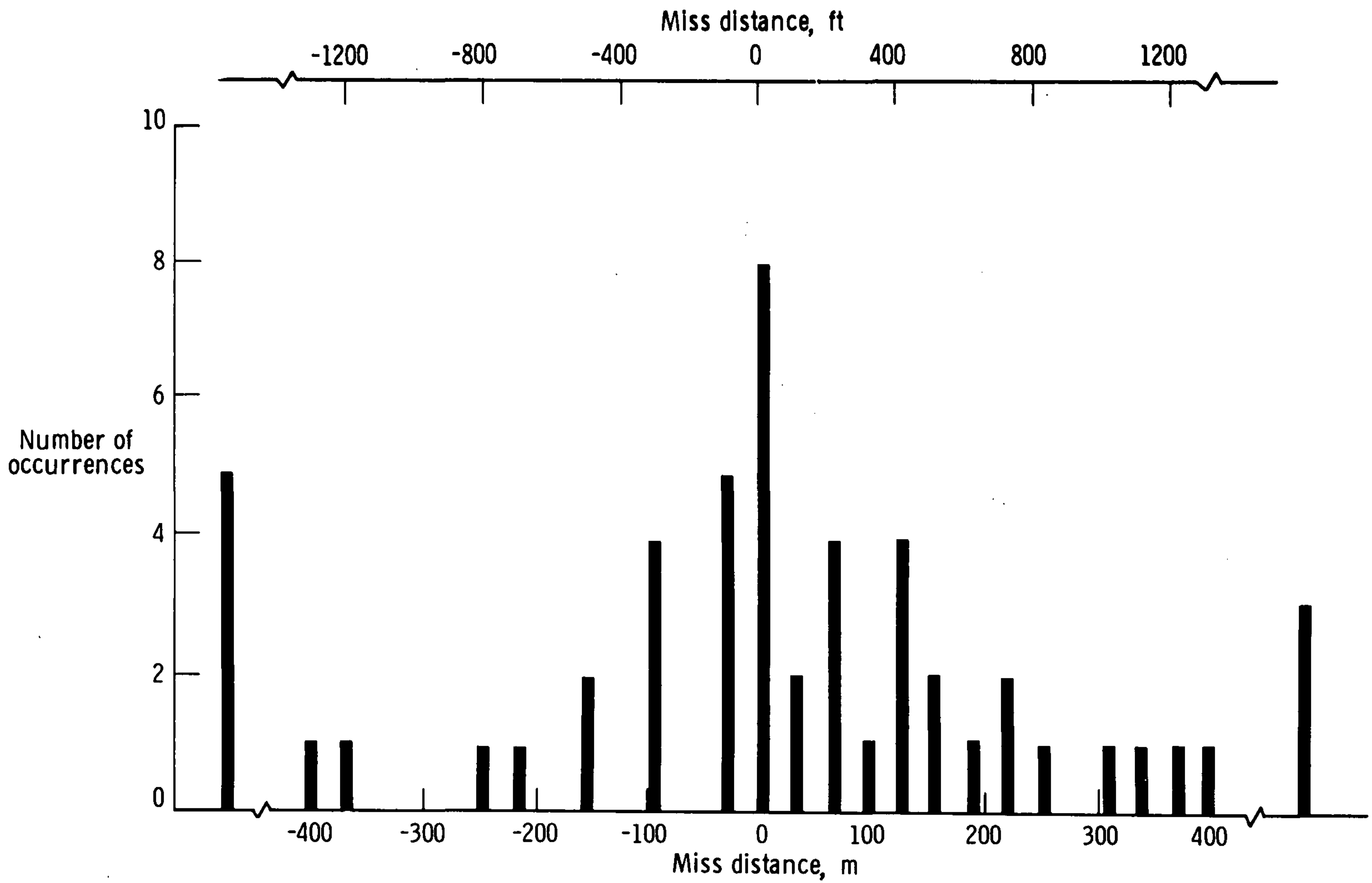


Figure 9. Touchdown dispersion data for CV-990 low L/D visual approaches. $\delta_f = 36°$.

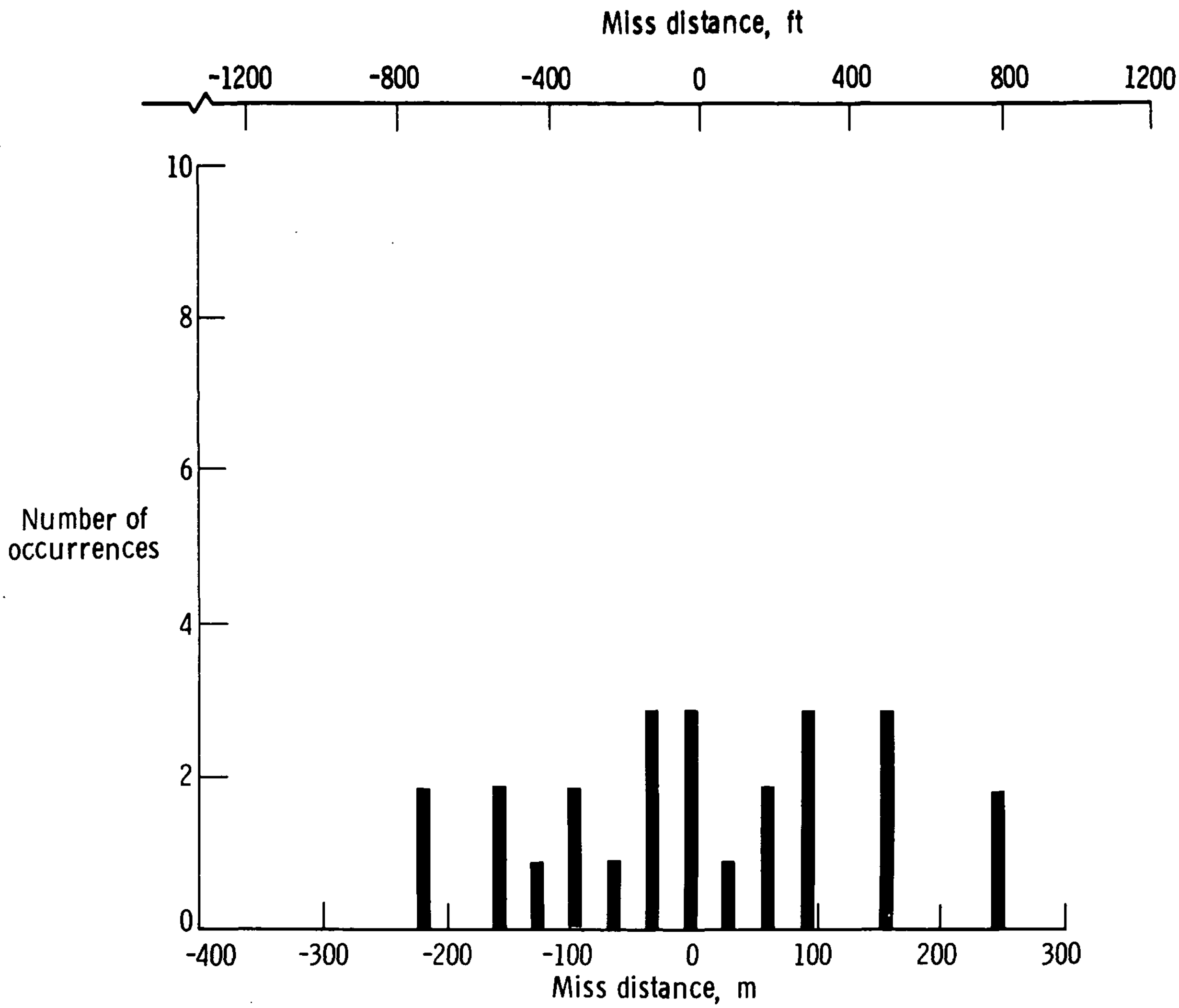


Figure 10. Touchdown dispersion data for CV-990 ground command guidance approaches.

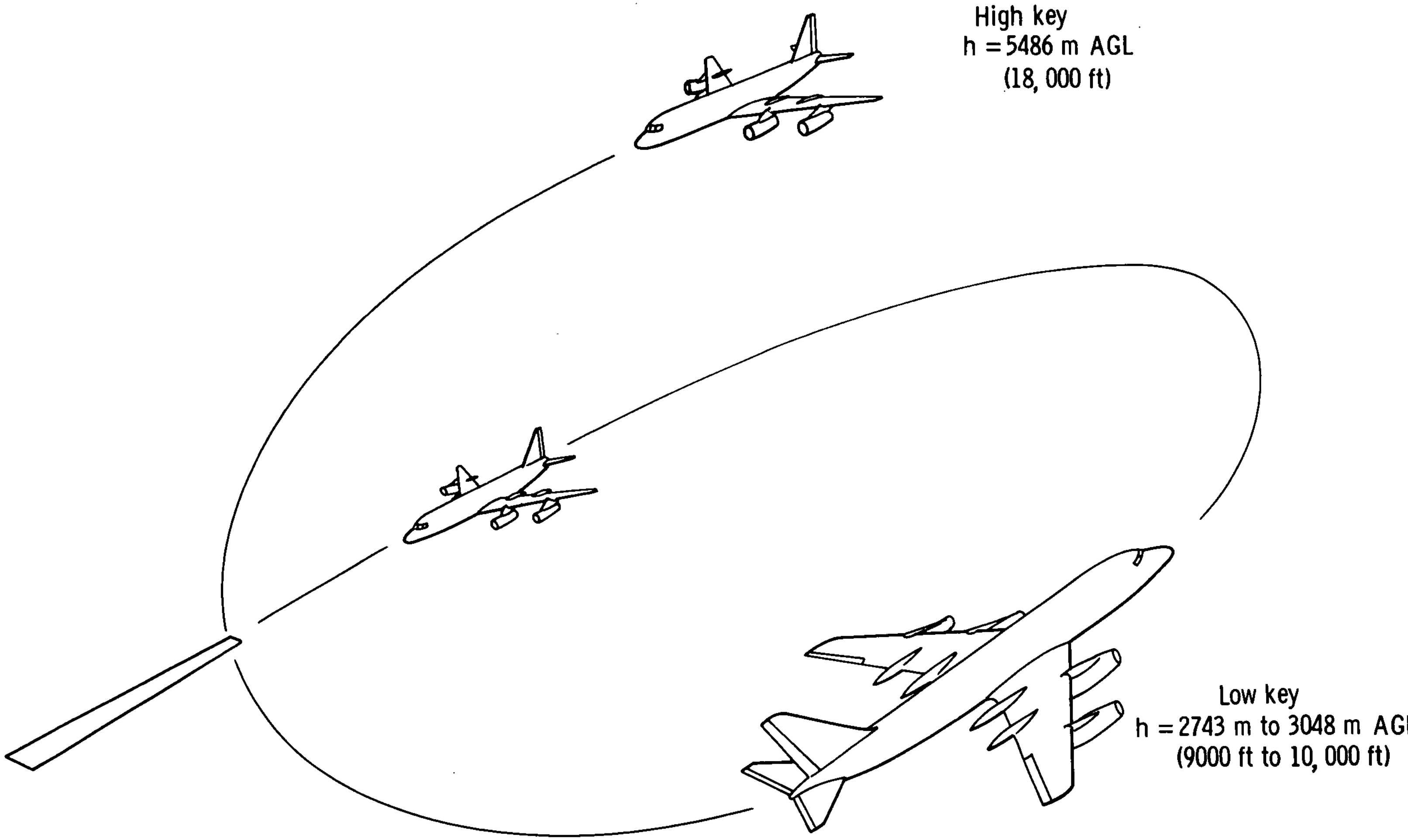


Figure 11. Illustration of a 360° overhead approach.

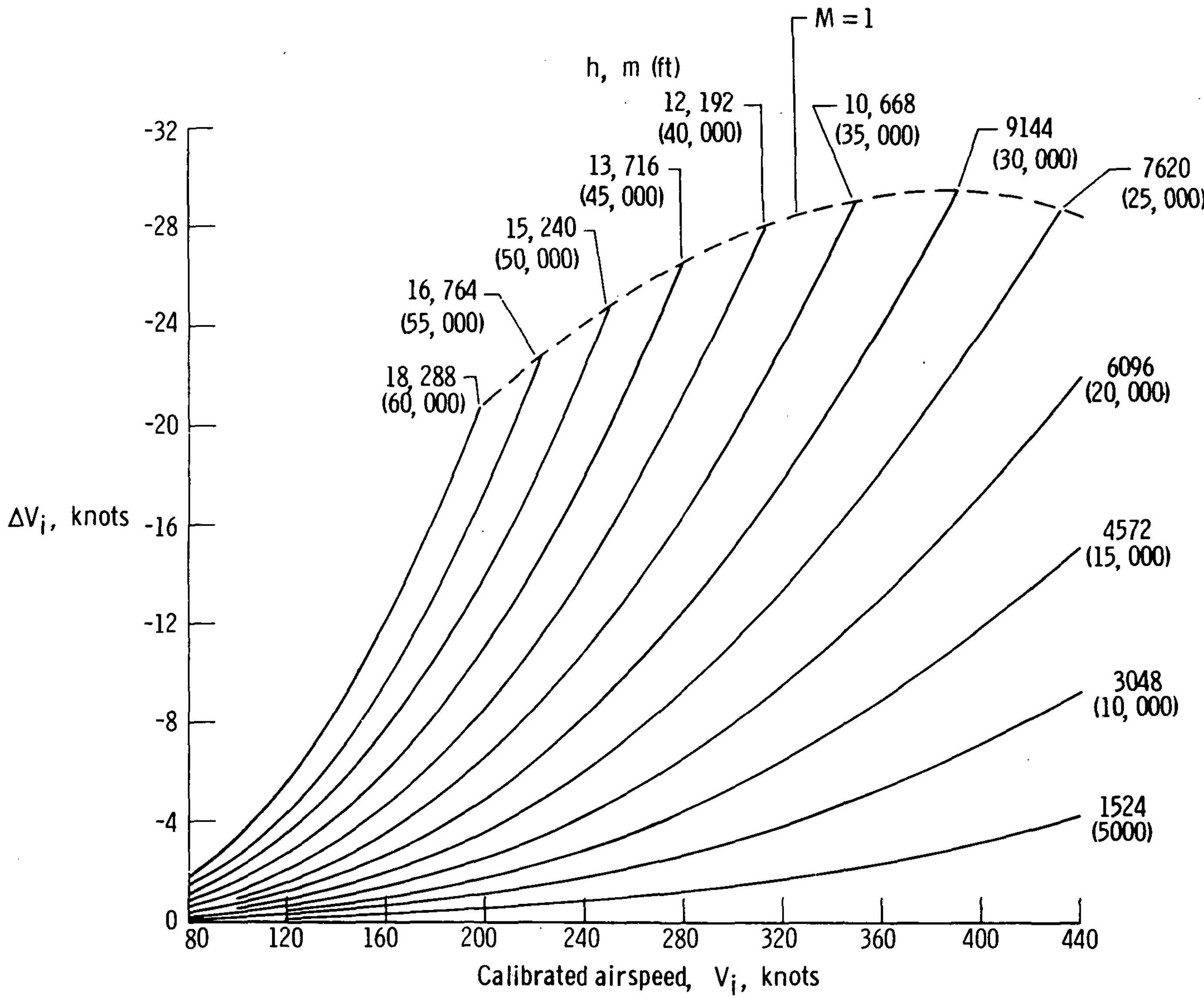


Figure 12. Compressibility correction to calibrated (indicated) airspeed to obtain equivalent airspeed. $V_e = V_i + \Delta V_i$ (from ref. 10).

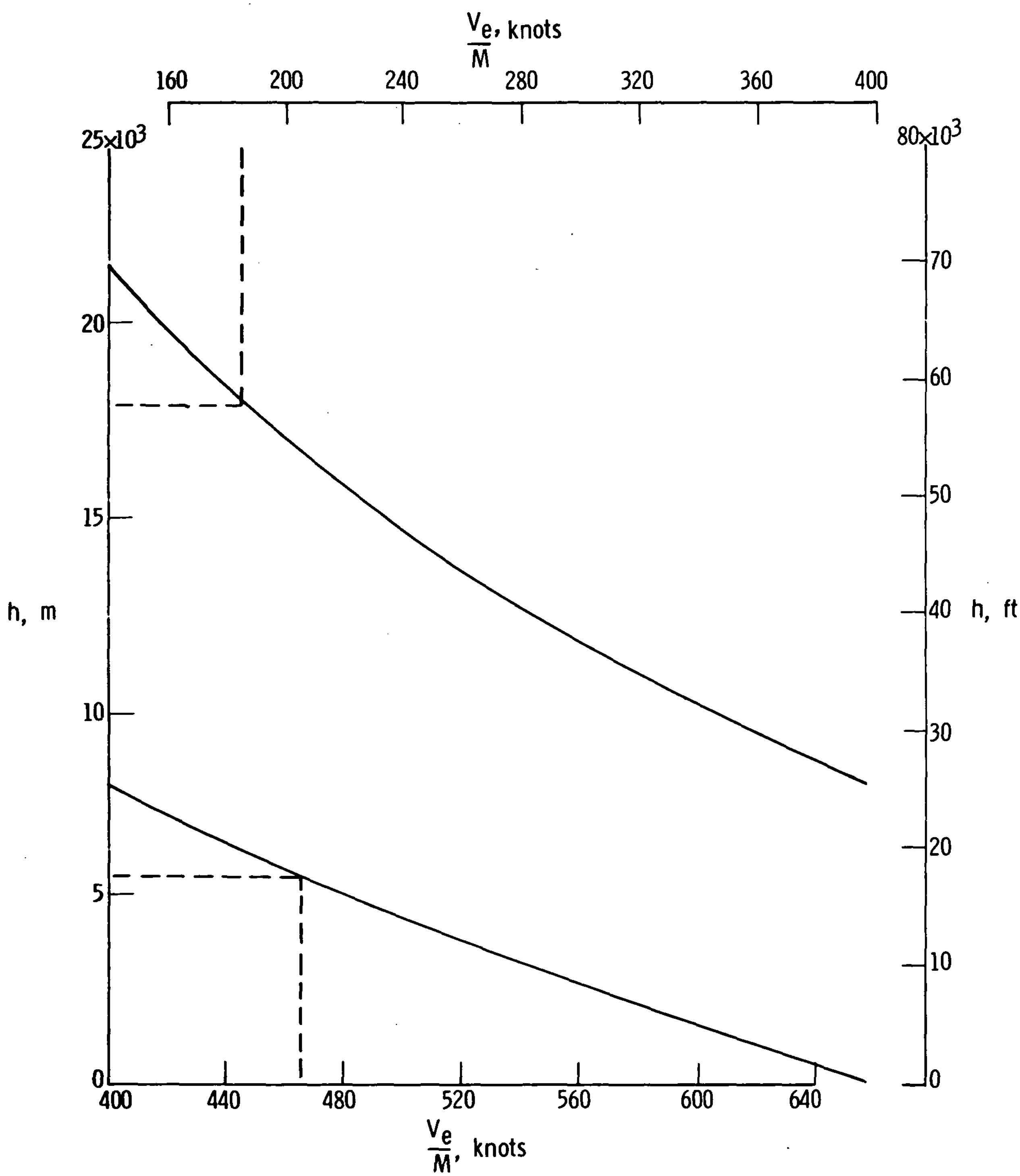


Figure 13. Equivalent airspeed to Mach number ratio as a function of altitude (from ref. 10).

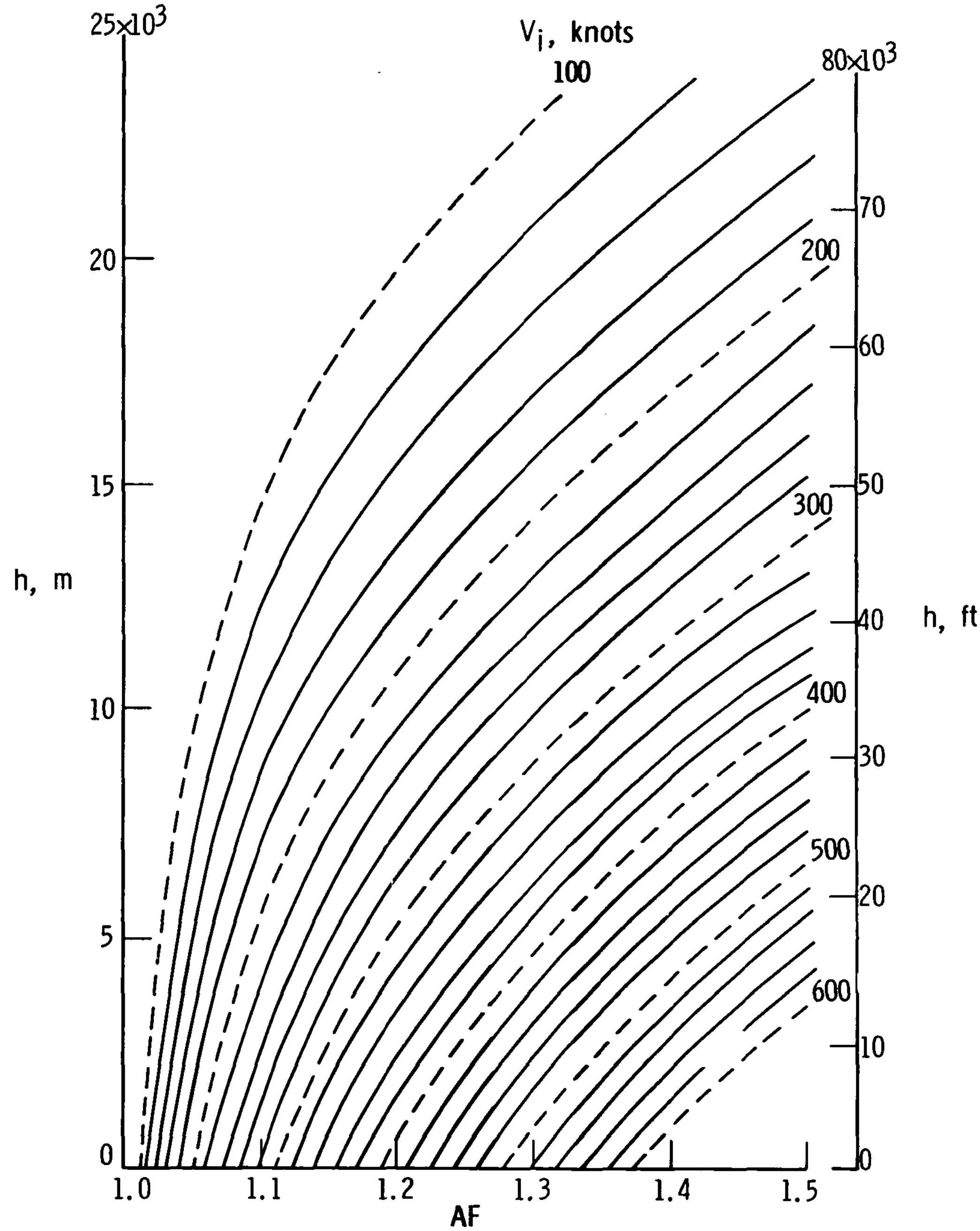


Figure 14. Acceleration factor as a function of altitude and calibrated airspeed (from ref. 8).

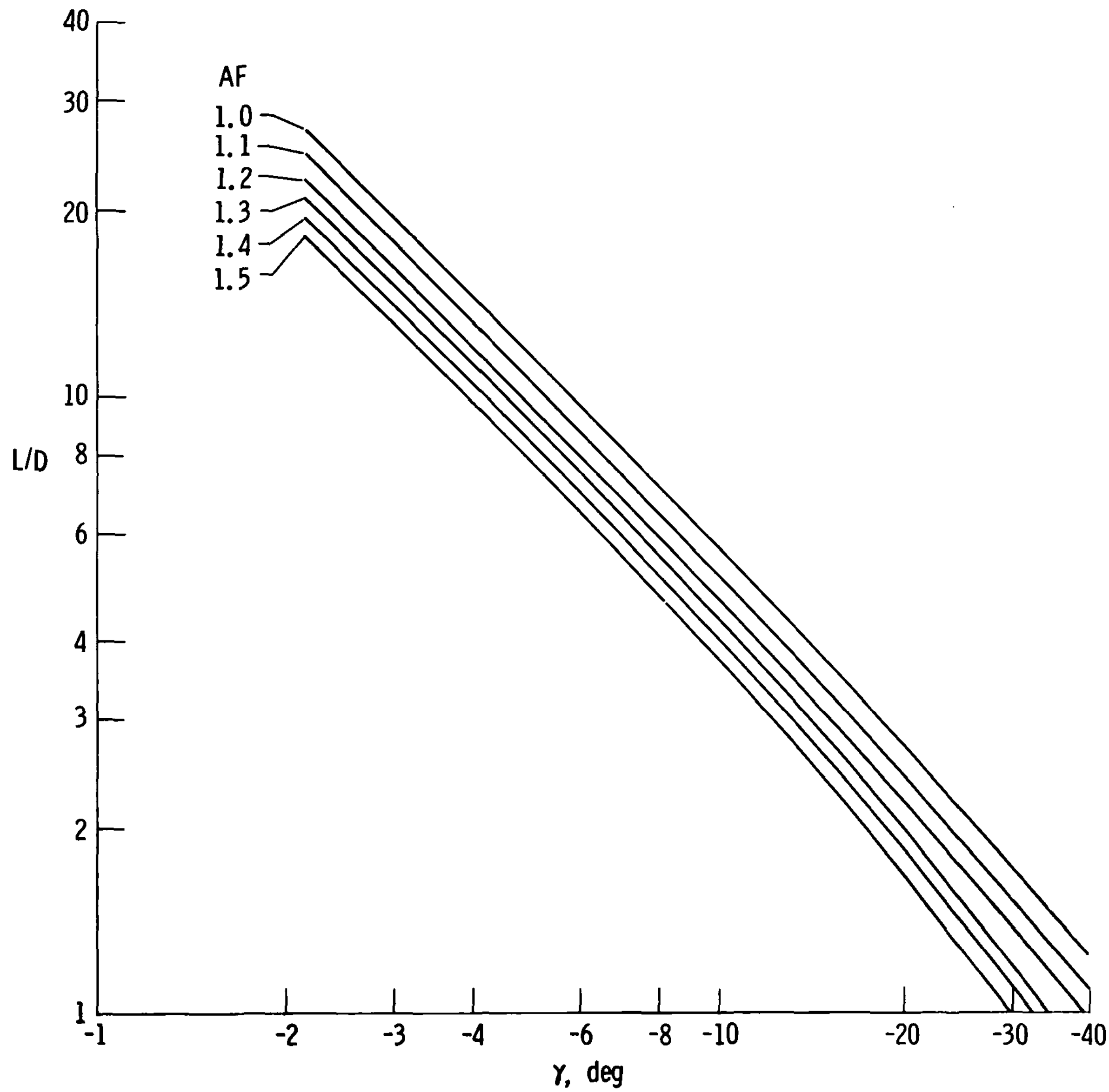


Figure 15. L/D as a function of acceleration factor and flight path angle (ref. 8).

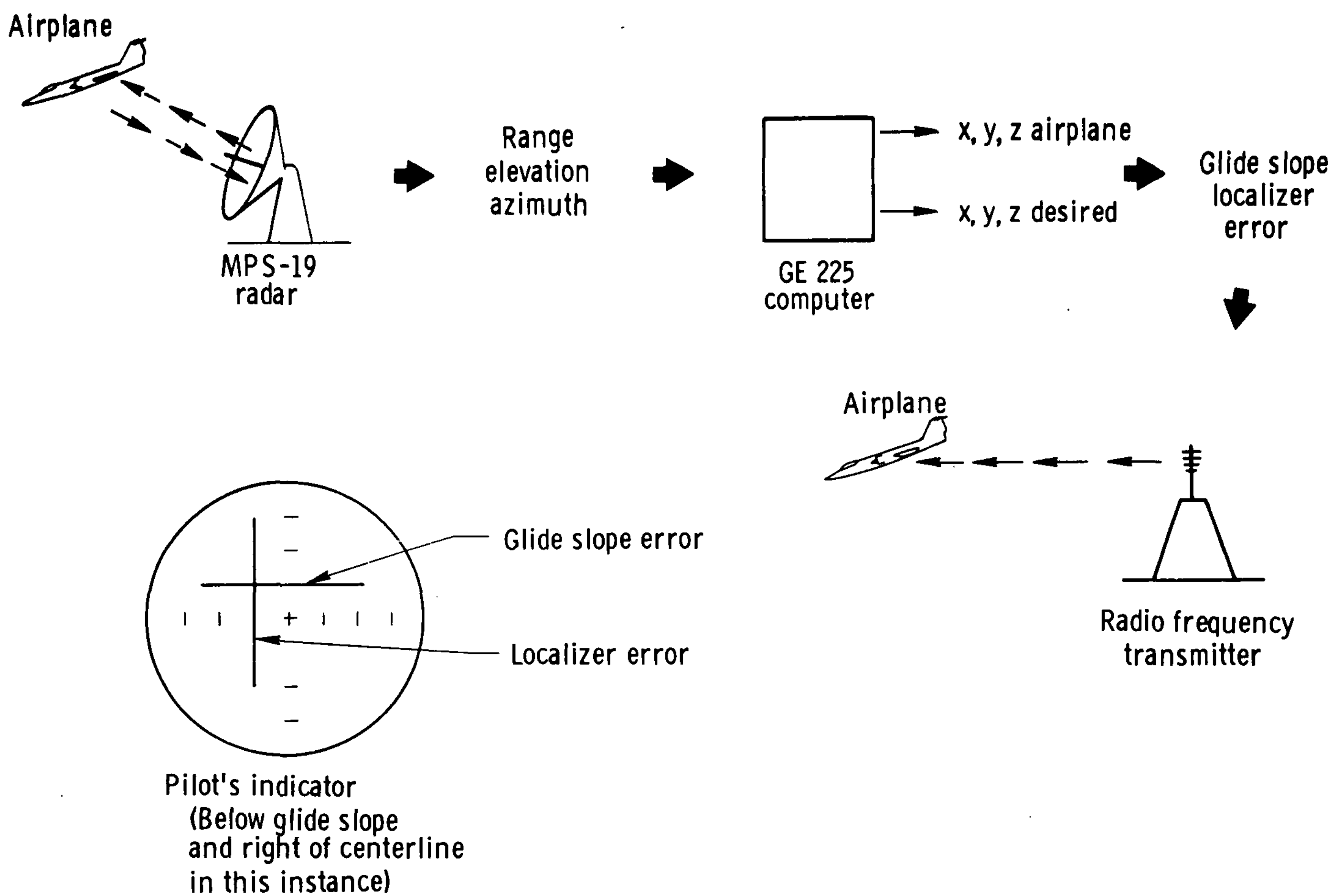


Figure 16. Schematic of ground command guidance system utilized for CV-990 ILS approaches.

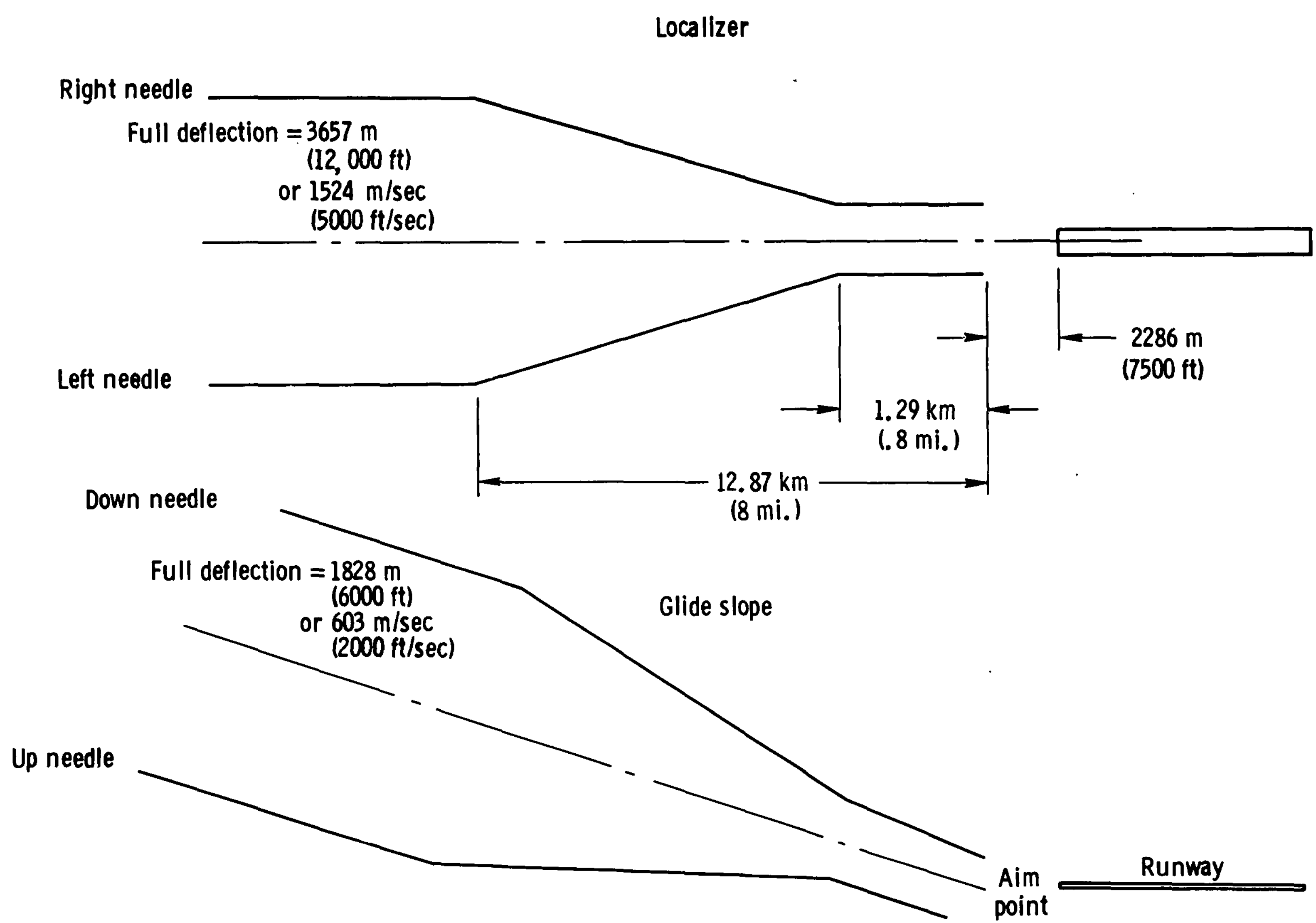


Figure 17. Schematic of glide slope and localizer geometry used in CV-990 GCG approaches.

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

— NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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