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OPERATIONAL LIMITATIONS IN FLYING NOISE-ABATEMENT APPROACHES

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16. Abstract

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OPERATIONAL LIMITATIONS IN FLYING NOISE-ABATEMENT APPROACHES

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SUMMARY

An investigation of the capability of jet transport airplanes to be operated on steep noise-abatement profiles under simulated 200-foot-ceiling (60.96-meter) instrument flight conditions was conducted. Six airplanes ranging in type from a twin-engine turbojet executive transport to a four-engine turbofan intercontinental commercial transport were used. Both single-segment glide-slope (up to 7°) and two-segment glide-slope (up to 9°) profiles were investigated.

The investigation showed that for the airplanes flown, the pilots considered 6° to be the maximum glide slope on which speed and flight path could be consistently controlled. A rate of change of flight-path angle of 1° every 7 seconds was considered to be optimum for both the landing flare from a 6° glide slope and the slope transition (6° to 3°) on a two-segment glide slope. From an operational viewpoint, the two-segment glide slope was preferred over the single-segment glide slope as a noise-abatement profile because of the lower vertical velocities near the ground. Difficulty in stabilizing lateral flight on the 6° single-segment glide-slope approaches resulted in course deviations after breakout which were often wide of the runway at the threshold. Glide-slope tracking difficulties in the noise-abatement approaches, leading to below-glide-slope deviations, were experienced in the landing-flare and slope-transition maneuvers. Difficulty was also experienced in acquiring the steepened glide slope at intercept without overshooting. Throttle activity was high during these maneuvers. Autothrottle speed control was found to reduce substantially the pilot workload connected with the thrust changes required in the transition and flare maneuvers. For routine operations, new and/or improved flight instrumentation appeared to be required to improve tracking performance and to reduce pilot workload. In the operations on the steep glide slopes, throttle positions were found to be near the flight idle position. For these positions, engine-thrust-response characteristics on some of the airplanes were considered to be poor with regard to the "go-around," particularly in view of the high descent rates near the ground. Adequate thrust response was indicated by the pilots as a prerequisite for safe operations on noise-abatement profiles.

INTRODUCTION

On a standard 2.5° to 3.0° glide-slope approach, current turbojet and turbofan transports can produce noise of an objectionable level when the flight path is over populated areas. A possible method of reducing the ground noise level would be to fly steeper than normal approach profiles; this procedure would increase the distance between the observer and the noise source and would reduce the thrust required to maintain the desired approach airspeed.

In order to determine the capability of modern jet transport airplanes to be flown on such noise-abatement profiles under simulated 200-foot-ceiling (60.96-meter) instrument flight conditions and to determine problem areas created by flight on these profiles, an investigation was initiated by the NASA Langley Research Center. Exploratory flight tests to study operational techniques on several noise-abatement profiles were made by using a twin-engine propeller-driven transport, a single-engine turbojet military trainer, and a medium-sized turbojet cargo transport. Results of these exploratory tests were reported in references 1 to 3. Since that time, more extensive tests have been made with six airplanes: three four-engine jet transports, a four-engine intercontinental jet transport, a three-engine jet transport, and a twin-engine executive jet transport. A progress report covering the tests with the three four-engine jet transports was published in reference 4. The present report covers the final results obtained on these airplanes. The approach and landing tests of these airplanes covered both single-segment and two-segment ILS profiles, glide slopes up to a maximum of 9°, and various airplane control modes. Measurements were made of pilot control motions, airplane response, and airplane displacement from the desired flight path.

SYMBOLS

d_c	proportionate course deviation, $\Delta y/w_c$
d_s	proportionate glide-slope deviation, $\Delta z/w_s$
n	number of approaches
r	slant range, distance between radar antenna and airplane, ft (m)
V_h	vertical velocity, ft/sec
V_c	calibrated airspeed, knots

w_c course boundary width, course deviation for full-scale deflection of ILS course deviation indicator from center, ft (m)

w_s glide-slope boundary width, glide-slope deviation for full-scale deflection of ILS slope-deviation indicator from center, ft (m)

x distance from target touchdown point measured in ground plane along or parallel to course, ft (m)

y lateral distance from localizer center line, ft (m)

z height above ground plane through target touchdown point, ft (m)

Δy course deviation, lateral displacement of airplane from localizer center line, ft (m)

Δz glide-slope deviation, vertical displacement of airplane from glide-slope center line, ft (m)

δ_c control column displacement, deg

δ_f flap deflection, deg

δ_ω control wheel displacement, deg

δ_t throttle displacement, deg

Γ glide-slope angle, deg

β elevation angle of radar antenna, deg

ψ azimuth angle of radar antenna, deg

$\Delta\gamma$ change in flight-path angle, deg

Abbreviations:

Flt dir flight director

GS glide slope

ILS	instrument landing system
LOC	localizer
IFR	instrument flight rules conditions
VFR	visual flight rules

Dots over symbols denote derivatives with respect to time.

EQUIPMENT AND INSTRUMENTATION

Airplanes

General characteristics of the airplanes used in the tests are noted in table I. Airplane types ranged from a two-engine executive jet transport to the four-engine intercontinental commercial transport. The column in table I labeled as cockpit guidance display lists the type of cockpit instrument presentation available to the pilot to fly ILS approaches. All the airplanes had available glide-slope (GS) and localizer (LOC) deviation instruments. The airplanes all had flight director (Flt dir) systems, but only airplanes C, D, and F had computed pitch commands for vertical flight-path control together with computed bank commands for lateral flight-path control. Airplanes A, B, and E had flight director systems which presented only bank commands. Airplanes A, B, and C had autopilots with capability of being coupled to the approach guidance system. Airplane D was the only airplane with an automatic throttle control system.

In order to simulate instrument flight conditions, the test pilot's view outside of the airplane was obscured by one of two methods – a pilot hood or a windscreen shield. At an altitude of 200 feet (60.96 meters), the shield or hood was removed in order that the pilot could then use visual cues to control the airplane in the final approach and landing or "go-around."

Guidance

Vertical flight-path guidance (including flare path) and directional guidance for all approach profiles flown in these tests was provided by a precision radar through an ILS data link. The AN/GSN-5ST radar system is unique in that curved flight paths can be generated by the equipment and displayed to the pilot by means of conventional cockpit instruments. Details regarding the guidance system are given in the appendix.

Airplane and Ground Instrumentation

Instrumentation was provided in both the ground station (radar trailer) and in the airplane to record pertinent flight information. In the ground station, two automatic plotters recorded elevation profiles x,z and the ground tracks x,y produced by the airplane during flight on the conventional and noise-abatement profiles. In addition, a multichannel oscillograph recorded time histories of the radar-derived quantities x, Δy, Δz, d_s, and d_c.

Flight-test instrumentation was installed in the airplane to record time histories of airspeed, altitude, engine speed, pitch rate, roll rate, yaw rate, control column position, control wheel position, throttle positions, normal acceleration, longitudinal acceleration, lateral acceleration, and pitch angle. In addition to these parameters, recorders on airplane D documented vertical velocity, heading variation, stabilizer trim input, stabilizer position, glide-slope signal, localizer signal, radio altimeter, turbine exit pressures, fan exit pressures, indicated airplane total temperature, and exhaust gas temperature. A corner reflector was installed either on the nose gear or in the radome to allow positive acquisition of the airplane by the GSN-5 radar. A time telemetry system was used to correlate airplane and ground station data.

TESTS

Pilots

The approaches were flown by NASA research pilots and pilots from the Federal Aviation Administration, airlines, and industry. The NASA project pilot flew most of the approaches made with each airplane, and the data from these approaches were used as the consistent basis for the evaluation of tracking performance on noise-abatement profiles. Operation viewpoints on the procedures were obtained from the other pilots. The copilot served as a safety pilot.

Test Procedure

The approaches were made during daylight hours in clear weather to the 8000-foot (2438-meter) east-west runway at the NASA Wallops Station Airfield. Clear weather was taken to exist when the visibility was at least 3 miles (4.8 km) and cloud bottoms were above 3000 feet (914.4 meters). The approach pattern was a counterclockwise pattern with a final approach leg of approximately 10 miles (16.09 km).

Flight tests of each of the six airplanes were initiated with a number of approaches on a 3° conventional glide slope. Single-segment glide-slope approaches at increasing angles up to 7° were then flown to determine the maximum operational glide slope – the maximum glide slope on which the speed and flight path of the airplane could be consistently controlled in the landing configuration at the target airspeed. A number of approaches were then made at the maximum operational glide slope to evaluate tracking performance and operational problems. For all these single-segment approaches, the profile guidance included a landing flare. Landing-flare paths based on two rates of change of flight-path angle were used.

Two-segment glide-slope approaches were also made which consisted of a steepened initial glide slope followed by a transition to a conventional glide slope. Tests were made of various initial glide slopes (up to 9^{o}) and transition patterns to determine the maximum operational glide slope for two-segment glide-slope approaches. A number of tracking performance evaluation approaches were then made, the initial segment having the maximum operational glide slope.

Characteristics of the various approach profiles flown are presented in table II for both the single- and two-segment approaches. Presented for the single-segment profiles are: glide slope, flare rate, and flare initiation range x and altitude z. For the two-segment profiles, the characteristics shown include: initial glide slope, final glide slope, transition rate, transition initiation range and altitude, and transition completion range and altitude. The actual profiles flown with the various airplanes are indicated in table III along with the number of approaches on each profile. Also shown in table III for the various approaches flown are the airplane operating modes to be discussed in the following sections. Table IV presents the airplane operating weight, variations in approach and stalling speeds, and flap deflections.

Operating Modes

Longitudinal and lateral control.- Longitudinal and lateral control were provided either by the pilot (manual mode) or by the autopilot (coupled mode).

Throttle control.- During several approaches, the throttles were operated by either an autothrottle system or by the safety pilot; thus, the pilot was relieved of the speed control task and could concentrate on directional and longitudinal control. Airplane D was the only aircraft with an autothrottle system installed.

Constant speed.- Those approaches made at one value of speed from glide-slope intercept to the runway threshold are referred to as constant-speed approaches. The reference approach speed had a value 30 percent to 35 percent greater than stall speed. Speed increments were added to this value to compensate for gusty conditions and the resulting speed is referred to as "target speed."

Constant-throttle setting.- Constant-throttle-setting approaches were those approaches made with a fixed throttle setting from glide-slope intercept to runway threshold. The objective of constant-throttle-setting approaches was to relieve the pilot of the task of throttle changes for maintaining constant speed on the two-segment glide-slope approaches.

RESULTS AND DISCUSSION

The results of this investigation cannot be completely conclusive because the pilots did not have an adequate training period on the noise-abatement profiles. A training period was not feasible because the test vehicles could only be leased or borrowed for a brief period. The pilots, however, were all above average in education, ability, and experience; it is believed that these qualities somewhat compensated for the lack of training.

Maximum Operational Glide Slope

The maximum operational glide slope has been defined herein as the maximum glide slope on which the pilot felt he could consistently control the speed and flight path of the airplane in the normal landing configuration at the target airspeed. On this slope the trimmed thrust level had to be sufficiently above the idle thrust level to allow for a thrust reduction in order to effect a downward displacement to the glide slope when the aircraft was displaced above it, for example, by a gust. The maximum operational glide slope also had to be such that it did not result in any significant increase in pilot work-load above that for the normal glide slope of 2.5° to 3.0°.

For each of the airplanes, the pilots considered 6° to be the maximum operational glide slope for both single-segment and two-segment glide-slope approaches. This glide slope was 1° to 3° lower than the maximum glide slope that could be flown with the throttle at flight idle position at a constant airspeed.

Approach Profiles

Although a variety of approach profiles were flown in the development of suitable noise-abatement profiles (as may be seen in tables II and III), the evaluation of glide-slope tracking performance was primarily made on three profiles. Profile 1, a 3° single-segment profile, representing the slope of a conventional ILS, was used as a basis for comparison with the noise-abatement profiles. The guidance for this profile included a landing flare; however, the flare guidance was not used because the altitude for initiation of flare guidance was below the breakout altitude of 200 feet (60.96 meters).

Profile 8 was used in the evaluation of tracking performance on a single-segment noise-abatement profile. This profile consisted of a 6° glide slope with landing-flare guidance starting at an altitude of 520 feet (158.5 meters). The flare path was based on a rate of change of flight-path angle of 1° every 7 seconds at an airspeed of about 140 knots.

Profile 18 was used in the evaluation of tracking performance on a two-segment noise-abatement profile. This profile consisted of a 6° slope transitioning to a 3° slope. The transition flare began at an altitude of about 1150 feet (350.52 meters) at a range of 20 500 feet (6 248.4 meters) and ended at an altitude of 760 feet (231.65 meters) at a range of 15 500 feet (4 724.4 meters). The transition flare path was based on a rate of change of flight-path angle of 1° every 7 seconds at an airspeed of about 140 knots. For this profile, when transition to the 3° slope was completed at shorter ranges than given, there was insufficient time to stabilize the airplane on the flight path before breakout (at an altitude of 200 feet (60.96 meters)). At greater ranges for completion of transition, although more time was available to stabilize the airplane on the 3° glide slope, the benefits of the noise-abatement profiles were eliminated or reduced.

Paths for the landing flare on profile 8 and the transition on profile 18, based on a rate of change of flight-path angle of 1° every 7 seconds at an airspeed of about 140 knots, were considered to be optimum by the pilots of the three rates used in the tests.

Performance evaluation positions on profiles.- For the evaluation of glide-slope tracking performance on profiles 1, 8, and 18, the positions shown in figure 1 were selected. Position (a) is the point where breakout to visual reference would occur for all profiles. Position (b) corresponds to the initiation of flare on profile 8. Positions (c) and (d) correspond to the completion and initiation, respectively, of the transition from 6° to 3° glide slope for profile 18. Position (e) is the point where stabilized flight on the glide slope would normally be expected to have occurred for all profiles. The x and z coordinates for these positions are given in table V. Also shown in table V for each position along the profiles are the deviations from the ILS glide slope w_s and from the ILS course w_c corresponding to full-scale deflections from the center position on the pilot's ILS indicator.

Tracking performance on course.- Representative course x,y plots of 10 approaches in the manual mode for airplane D (which are also typical for other airplanes flown) on each of the three profiles 1, 8, and 18 are presented in figure 2. The tracking performance evaluation positions are indicated for each profile. The results show that course tracking performance on the three profiles from position (e) (stabilized flight on the glide slope) to position (a) (breakout) was similar; however, stabilized lateral flight on the noise-abatement profiles was apparently more difficult to achieve than on the 3° profile as evidenced by the greater tendency to oscillate about the localizer center line. After breakout, a much different degree of tracking performance is shown. On profile 1, deviations decreased until touchdown where the smallest dispersions were noted. On profile 8, deviations increased after the pilot began using visual reference. Four of the

10 approaches illustrated were wide of the runway at the runway threshold. The approaches on profile 18 show a slight divergence from the localizer center line after breakout, but all approaches illustrated were within the width of the runway at runway threshold. The poorer performance on the noise-abatement profiles after breakout appears to be related to the difficulty of achieving stabilized control of the lateral flight path before breakout. The observed winds for the approaches illustrated were similar; that is, they were all crosswinds, 80° to 90° from runway center line with velocities of 6 to 14 mph (22.4 km/hr). The pilots indicated that they believed their performance on these approaches was not affected by the local winds or other atmospheric disturbances.

The results of the evaluation of course tracking performance in the manual mode are summarized in figure 3 as frequency distributions of course deviations at each of the profile evaluation positions. The distributions are plotted as histograms showing the frequency in percent of approaches for each 0.20 interval of proportional course deviation d_c. A study of figure 3 indicates that for the three profiles, the deviations tended to become smaller as the airplane approached the runway. In general, the course tracking performance was about the same on the two noise-abatement profiles as on the 3° glide slope. One interesting fact shown in figure 3 is the small changes in course deviation in the landing flare of profile 8 and through the slope transition of profile 18.

Three representative approaches of the 10 approaches illustrated in each part of figure 2 were selected to show pilot movements of the control wheel for lateral-directional control. In figure 4, moderate control wheel movements are evident on profile 1, on the initial portion of profile 8, and on profile 18. The magnitude and frequency of control wheel movements, however, increased greatly just prior to and during the landing flare on profile 8. This increased activity is associated with the attempt by the pilot to reduce the course deviation to as small a value as possible at breakout. (See fig. 2(b).) On the other hand, the results also show that the pilots did not particularly increase lateral control in the transition from one slope to the other on profile 18. Several of the pilots indicated that during the transition, attention was basically devoted to slope and speed control and that deviations from the localizer went uncorrected until the transition was completed and the required power adjustment to keep the speed constant was accomplished.

Tracking performance on glide slope.- Glide slope x,z plots of the same approaches on profiles 1, 8, and 18 shown in figure 2 are presented in figure 5. The tracking-performance-evaluation positions are indicated for each profile. The results show that the glide-slope tracking performance between position (e) (stabilized flight on the glide slope) and position (a) (breakout) was, in general, about the same on profile 18 as on the conventional 3° glide slope. The tracking performance on profile 8 (single-segment 6° glide slope), however, appears to be somewhat poorer than on the other two profiles. Tracking of the glide slope on the steepened slopes of profiles 8 and 18 was reported by the pilots to be a more difficult task than on the 3° glide slope. Lack of experience with this task was probably the main reason for this difficulty.

The results in figure 5 also show that difficulty in tracking was experienced in the flare of profile 8 and the transition of profile 18. These tracking difficulties were, in part, associated with the changes in attitude and thrust required in making the changes in flight-path angle – tasks not involved in conventional 3° glide-slope approaches. Further, neither the glide-slope deviation nor flight director instrumentation provided the guidance needed for anticipation of the flight-path angle change with the result that, in general, deviations below the glide slope resulted during these maneuvers. On profile 8, in some cases, the deviations during the flare were great enough to result in full-scale deflection of the flight director indicator. Because of the added difficulties in flight-path control associated with flaring just prior to breakout, the pilots had an unfavorable reaction to this noise-abatement profile. On profile 18, deviations below the glide slope during transition of as much as 80 feet (24.38 meters) at an altitude of about 600 feet (182.88 meters) were noted. The pilots expressed considerable concern about such deviations, but indicated that sufficient time and altitude were available on the remainder of the profile to correct the deviations prior to breakout.

Another tracking difficulty during the noise-abatement approaches was noted in the task of intercepting and stabilizing on the 6° glide slope. During this maneuver, there was a greater tendency to overshoot the glide slope than on the 3° glide-slope approach. Contributing to this difficulty was the fact that the flight director was programed to provide guidance to the conventional 3° glide slope and did not provide sufficient lead on the "fly-down" command to effect the twofold increase in flight-path-angle change without the overshoot. The narrower boundary width of the 6° glide slope compared with the 3° glide slope at the intercept altitude also gave the pilot less time to anticipate the flight-path change. However, the pilots were able to improve their performance in stabilizing on the 6° glide slope with less overshoot by using glide-slope-deviation information instead of flight-director-command information to initiate the maneuver. The overshoot of the 6° glide slope was a more serious problem than for the 3° glide slope because the descent angle required from above the slope in some cases exceeded the maximum glide-slope-angle capability of the airplane at the target speed. Consequently, a speed increase was necessary in order to obtain the increased rate of descent required to descend to the glide slope.

The results of the evaluation of glide-slope tracking performance in the manual mode are summarized in figure 6 as frequency distributions of the glide-slope deviations at each of the profile evaluation positions. The distributions are plotted as histograms showing the frequency in percent of approaches for each 0.20 interval of proportional glide-slope deviation d_s. The results in figure 6 show that at position (a) (breakout), the deviations from glide slope on the two noise-abatement profiles tended to be below the glide slope, apparently because of the difficulties in controlling the flare on profile 8 and the transition on profile 18 discussed previously. The below-glide-slope deviations during transition on profile 18 are very evident in the results shown at position (c). Also very evident in the results are the deviations above the glide slope at position (e) on the two noise-abatement profiles resulting from the tendency to overshoot in intercepting and acquiring the glide slope.

Representative examples of pilot-induced movements of the control column during approaches on the three profiles are illustrated in figure 7. Although the movements were almost continuous, they did not exceed 4°. Very little difference is evident in the amount of control motion activity between the results from flights on profiles 1, 8, and 18. The periods corresponding to the flare of profile 8 and the transition of profile 18 are noted on the figure. No unusual control-motion activity is evident in these periods compared with the other phases of the approaches.

Time histories of deviations in airspeed from target speed on three representative flights on each of profiles 1, 8, and 18 are shown in figure 8. Basically, the speed control was precise and errors about the target speed were less than about ±10 knots. On the 6° glide slopes (profile 8 and the initial segment of profile 18) and during transition from the 6° to 3° slope, however, the speed deviations, in general, were above the target speed. On these profiles, the speeds were reduced to about target speed prior to the flare. The pilots favored the positive speed deviation as a safety margin to expedite "go-around." Unfortunately, such increased airspeed requires increased thrust which, in turn, can substantially decrease the noise reductions possible from the steepened glide path. A discussion of the effect of thrust on ground track noise is presented in reference 5.

Throttle-movement time histories on the same approaches used in the preparation of figure 8 are presented in figure 9. As noted previously, speed control on all profiles was satisfactory. The satisfactory speed control on profiles 8 and 18, however, was at the expense of pilot workload as shown in figure 9. Throttle movement is minimal on flights on profile 1 with the throttle position generally almost constant during the entire approach. If a deviation in speed or from glide slope developed, the throttles were moved to correct the deviation and then were returned to the original position. Throttle movement on profile 8, however, was more frequent and of greater magnitude. These extra and larger adjustments added appreciably to the pilot's workload. Further, during the flare from the single-segment 6° glide slope, the throttles had to be continuously moved forward to provide the increased thrust required. The movement, illustrated in figure 9, was substantial. On profile 18, the results showed throttle movements to be small (increments of approximately 5°) but frequent. Also in the approaches on profile 18, the throttles had to be moved forward during the transition to provide the increased thrust required. After transition, further adjustments of the thrust level were often required because of the below-glide-slope deviation which generally occurred. These changes in thrust level were additional factors adding to the pilot's workload.

Although not shown, pitch trim activity was greater on profiles 8 and 18 than on profile 1 because of the increased thrust change activity noted previously for these profiles.

Approaches With Automatic Control

Coupled approaches.- Approaches with the autopilot coupled to the ILS guidance signals were made during tests with airplanes A, B, C, and D on 3° single-segment and 6° to 3° two-segment profiles. (See table III.) With airplane A, 4 coupled approaches were made on the 3° profile and 21 coupled approaches on the 6° to 3° profile. Because coupled approaches were found to be not practicable on the two-segment profile in the tests with airplane A, coupled approaches on the two-segment profile with the other airplanes were limited to one each.

The coupled approaches on the two-segment profiles were found to be not practicable because the autopilots as installed in the airplanes could not provide sufficient signal inputs to the pitch control system to perform the transition from the 6° glide slope to the 3° glide slope. This lack of command authority arose because the strength of the input signal to the autopilots was programed in the standard approach coupler to be gradually reduced during the phase from intercept to touchdown (1500-foot (457.2-meter) altitude to touchdown for the nominal 3° glide-slope approach); consequently, for the two-segment approach in which intercept was made at an altitude of 3000 feet (914.4 meters), the signal-strength reduction was completed at an altitude of about 1500 feet (457.2 meters), and thus only minimal autopilot command authority remained during the transition. The result of coupled approaches on the two-segment profile was a large below-glide-slope error after the transition from which recovery could not be made with autopilot control. The type of autopilots used can be reset to increase the sensitivity and command authority; however, attempting to use this procedure only distracted the pilot in the critical portion of the approach.

Autothrottle.- Approaches were made on profiles 1, 8, and 18 with all the airplanes except airplane E by using autothrottle or simulated autothrottle speed control. Simulated autothrottle control was effected by the safety pilot actuating the throttles in response to airspeed error. On the steep noise-abatement profiles, autothrottle speed control was found to reduce substantially the high pilot workload connected with the thrust changes for the transition and flare maneuvers as discussed earlier. Reduction of this workload allowed more concentration on the longitudinal task.

For the one autothrottle system investigated, the thrust reduction capability was limited; throttle travel was stopped by a friction gate approximately 10° before the flight idle detent to prevent retardation of the engine speed to a condition of poor thrust response. The lowest thrust level available with the automatic system was not sufficiently low in most cases during flight on the steep glide slopes; therefore, an approach speed greater than the target speed value had to be accepted.

Constant Throttle Setting Approaches

Methods of reducing the number of throttle changes required on noise-abatement profiles were attempted during flight tests on airplanes A and B. A method tried with airplane A on the two-segment noise-abatement profile was to use a constant throttle setting from glide-slope intercept to touchdown and allow the airspeed to vary. Based on previous experience, the throttles were set at the intercept altitude prior to glide-slope capture for the thrust required in the conventional landing configuration on the 3° glide slope at a target speed of 1.35 times the computed stall speed. Upon glide-slope intercept, the airplane was controlled normally in pitch and heading with no throttle change. The airplane thus accelerated during the initial steep segment of the two-segment profile and decelerated during the flare and final segment of the approach. The objective of the constant throttle setting was to arrive at the runway threshold on glide slope at the target speed. Of eight approaches, only one was successful. The technique reduced the throttle changes required, but the effect of wind shears and atmospheric conditions resulted in unacceptably high variations in airspeed from the target speed when stabilized on the 3° glide slope.

Variable Configuration Approaches

Configuration changes were investigated as another method to allow the throttle setting to remain constant throughout the two-segment approach. During flight tests of airplane B, several approaches were made on the two-segment profile with the flaps at 50° deflection on the initial segment and at 36° deflection on the final segment. The objective of this procedure was to balance the thrust increase necessary at the reduced descent angle on the second segment by a decreased drag at the lower flap deflection. A satisfactory thrust and drag balance however did not result. Further, because of variable atmospheric conditions (varying with altitude), the higher stall speed at the lower flap deflection and the characteristic below-glide-slope errors of the two-segment approach, a change of thrust was required immediately after the transition. The upward flap configuration change, however, caused a nose-up pitch change. This pitch change was found to be advantageous in flight-path control in the transition and resulted in reducing the trim change required compared with constant configuration approach.

A few approaches were flown with airplane B by using the spoilers for assistance in flight-path control. The spoilers were extended from the flush position to correct for above-glide-slope deviation very successfully. The added drag and reduced lift allowed steepened angles without increase in speed. Only very small pitch changes were noted with spoiler actuation.

Operational Considerations

From an operational viewpoint, the pilots indicated that they preferred the two-segment glide slope over the steep single-segment glide slope as a noise-abatement profile because of the lower vertical velocities near the ground.

Engine thrust response.- As is shown in figure 9, the throttles were positioned near the flight idle position most of the time during two of the noise-abatement approaches on profile 8. To study the implications of low thrust close to the ground, the thrust response attained upon advancing the throttles as rapidly as possible to full forward position was determined during tests of airplane D. Tests were made from three initial thrust levels including flight idle. These initial thrust levels corresponded to descent speeds of 1500, 1700, and over 2000 feet per minute (457.2, 518.16, and 609.6 meters per minute) in the landing configuration. The results of these tests (fig. 10) show that throttle movement was completed in all cases in less than 2 seconds. For the flight-idle condition, more than 10 seconds elapsed after the throttle movement was started before maximum thrust level was reached. Figure 10 also shows for this condition that 6 seconds passed before the 20-percent thrust level was realized. These engine response times related to descent rates that are often greater than 25 fps (7.62 m/s) (see fig. 11) are meaningful in terms of possible altitude losses which might occur in a go-around from a steep glide slope. The pilots referred to the thrust response from the flight-idle condition as less than desirable to poor on several of the airplanes. The pilots all felt that adequate thrust response is a prerequisite for safe operations on noise-abatement approach profiles.

Airplane anti-icing.- The engine, wing, and tail anti-icing systems installed on the airplanes use engine bleed air for operation and require a minimum engine speed above idle for efficient system functioning. The engine speed levels recorded during flight on the steepened glide slopes were found to be below the minimum levels specified by the manufacturers. Anti-icing systems would thus require redesign for satisfactory operation during the reduced power conditions associated with noise-abatement profiles.

Passenger consideration.- The normal, lateral, and longitudinal accelerations associated with the flight path and maneuvers on the noise-abatement approaches were found to be extremely small and were not distinguishable from those on conventional approaches by observers in the airplanes. Mild turbulence experienced during tests imposed greater accelerations than the flight-path maneuvers. Reactions of observers in the passenger compartments – not having been exposed to steepened glide slope angles previously – were favorable. The airplane attitudes experienced did not cause the observers any undue apprehension.

Procedure implementation.- In the conventional approach under IFR conditions, the airplane configuration generally remains unchanged from glide-slope capture to breakout to VFR; vertical velocity and airspeed are held as constant as possible; and attitude and thrust are adjusted only as necessary to make flight-path and airspeed correction. In contrast, on the noise-abatement profiles examined in these tests, the flight-path angle changes in the landing flare and in slope transition in two-segment approaches required both changes in pitch attitude and thrust level. It follows that to implement noise-abatement procedures involving steeper than normal profiles, considerable pilot training will be involved. Further, new guidance systems must be provided to generate the profiles; and new and/or improved flight instruments must be developed to provide guidance in the flare and transition maneuvers.

CONCLUDING REMARKS

The results of an investigation of the capability of jet transport airplanes to be operated on steep-approach ILS noise-abatement profiles under simulated 200-foot-ceiling (60.96-meter) instrument flight conditions have been presented. Six airplanes ranging in type from a twin-engine turbojet executive transport to a four-engine turbofan intercontinental commercial transport were used. Research, airline, industry, and Federal Aviation Administration pilots participated in the tests. Both single-segment glide-slope (up to 7°) and two-segment glide-slope (up to 9°) profiles were investigated. Flight-path guidance for manual control was supplied by flight-director-system display commands except for three airplanes for which vertical flight-path guidance was supplied by conventional glide-slope-deviation indicators. Some autopilot-coupled approaches were attempted. Autothrottle speed control was used or simulated in some approaches. The principal results are:

1. For the airplanes flown, the pilots considered 6° to be the maximum glide slope on which speed and flight path could consistently be controlled. A rate of change of flight-path angle of 1° every 7 seconds was considered to be optimum for both the landing flare from a 6° glide slope and the slope transition (6° to 3°) on a two-segment glide slope. From an operational viewpoint, the two-segment glide slope was preferred over the single-segment glide slope as a noise-abatement profile because of the lower vertical velocities near the ground.

2. In the noise-abatement approaches, the course (localizer) tracking performance prior to breakout was generally similar to that on the conventional 3° glide-slope approaches; however, stabilized lateral flight was apparently more difficult to achieve on the steepened glide slopes. For the single-segment 6° approaches, the difficulty of stabilizing lateral flight resulted in course deviations after breakout which were often wide of the runway at the threshold.

3. In the noise-abatement approaches, glide-slope tracking performance was, in general, about the same on the two-segment (6° to 3°) glide-slope profile as on the conventional 3° glide slope. The tracking performance on the 6° single-segment glide-slope profile was somewhat poorer than that on the other profiles. Tracking difficulties, leading to below-glide-slope deviations, were experienced during the landing flare and slope transition maneuvers. Difficulty was also experienced in acquiring the steepened glide slope without overshooting. Throttle activity was high during these maneuvers. Autothrottle speed control was found to reduce substantially the pilot workload connected with the thrust changes required in the transition and flare maneuvers. For routine operations, new and/or improved flight instrumentation appeared to be required to improve tracking performance and to reduce pilot workload.

4. On the steepened glide slopes and through the slope transition maneuver, the pilots tended to fly at airspeeds above the target airspeed as a safety margin to expedite "go-around." Thus, only part of the noise reduction possible from the steepened glide-path operations was apparently attained because these higher airspeeds required higher thrust levels.

5. Coupled approaches on the two-segment profile were not practicable because autopilot command authority as programed by the standard approach coupler was insufficient to perform the transition from the 6° to the 3° glide slope without substantial deviations below the glide slope.

6. Throttle positions for operations on the steep glide slopes were near the flight-idle position. For these positions, engine-thrust-response characteristics on some of the airplanes were considered to be poor with regard to the "go-around," particularly in view of the high descent rates near the ground. Adequate thrust response was indicated by the pilots as a prerequisite for safe operations on noise-abatement profiles.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., September 2, 1969.

APPENDIX

RADAR AND GUIDANCE SYSTEM

Radar

The AN/GSN-5ST radar was a precision tracking radar having an antenna beam width of approximately 1/2°. The angular tracking capability was -10° to 30° in elevation and ±45° in azimuth. The system had the capability of determining aircraft positions both in rectangular coordinates and with respect to a selected glide slope. The desired glide slope could be preset at any angle up to 15°.

In the computing equipment, ILS beam patterns could be simulated – the boundaries of the patterns being defined by the displacements from slope or course for full-scale deflection of ILS path deviation indicators. The boundaries of these beam patterns can be made constant width, angular, or a combination of the two; in addition, the slope and course widths could be adjusted independently.

The selected course could be displaced to one side of the radar; the ground plane can be elevated to various altitudes; and the intersection of the slope with the ground can be set some distance ahead of the physical location of the radar antenna. The latter feature allowed flight tests to be conducted that utilized approaches from either end of the active runway with a minimum of repositioning of the radar antenna and associated equipment.

Guidance System

A functional diagram of the guidance system is presented in figure 12. The position of the aircraft as referenced to a corner reflector installed on the test vehicle is first determined from the slant range r and the elevation and azimuth angles β and ψ of the antenna. This polar coordinate information is then transformed into rectangular coordinates x, y, and z and velocities $\dot{x}$, $\dot{y}$, and $\dot{z}$ in the coordinate computer. The three quantities x, y, and z are processed through the slope-deviation computer that compares the x and z coordinates with the desired flight path and determines the linear displacement Δz of the aircraft from the selected slope. The selected slope was approximated (composed of straight-line segments) by installation of a 20-segment diode function generator (DFG). Single-segment guidance utilized one DFG to provide flare paths for 3°, 4°, 5°, 6°, and 7° profiles, and another DFG was used to provide the transition between the 6° and 3° portions of the two-segment profiles. In the proportionate path deviation computer, the linear displacements from slope and course Δz and Δy are compared with the path widths w_s and w_c at the distance x and converted to proportionate path deviations d_s and d_c (where $d_s = \Delta z/w_s$ and $d_c = \Delta y/w_c$). The proportionate path deviations are transformed into ILS tone signals for corresponding proportionate displacements in an ILS beam pattern, and these signals are then transmitted on normally used ILS frequencies to the aircraft.

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4. Zalovcik, John A.; and Schaefer, William T., Jr.: NASA Research on Noise-Abatement Approach Profiles for Multiengine Jet Transport Aircraft. NASA TN D-4044, 1967.

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TABLE I.- GENERAL CHARACTERISTICS OF TEST AIRPLANES

Airplane	Engine type	Number of engines	Thrust per engine, lb (N)	Maximum take-off weight, lb (N)	Maximum landing weight, lb (N)	Wing span, ft (m)	Wing area, ft^2 (m^2)	Cockpit guidance display	
								ILS	Flt dir
A	Turbojet	4	11 650 (51 842)	193 000 (858 850)	155 000 (689 750)	120.0 (36.6)	2000 (185.8)	GS/LOC	LOC
B	Turbofan	4	16 050 (71 422)	253 000 (1 125 850)	202 000 (898 900)	120.0 (36.6)	2250 (209)	GS/LOC	LOC
C	Turbojet	4	12 000 (53 400)	229 000 (1 019 050)	175 000 (778 750)	130.8 (39.9)	2433 (226)	GS/LOC	GS/LOC
D	Turbofan	4	18 000 (80 100)	327 000 (1 455 150)	247 000 (1 099 150)	145.8 (44.4)	3010 (279.6)	GS/LOC	GS/LOC
E	Turbojet	2	2 850 (12 682)	12 500 (55 625)	11 800 (52 510)	35.6 (10.8)	231.1 (21.5)	GS/LOC	LOC
F	Turbofan	3	14 000 (62 300)	169 000 (752 050)	142 500 (634 125)	108 (32.9)	1650 (153.3)	GS/LOC	GS/LOC

TABLE II.- CHARACTERISTICS OF APPROACH PROFILES FLOWN

Profile	Profile type	Initial glide-slope angle, deg	Final glide-slope angle, deg	Time for $\Delta\gamma = 1^{\circ}$ in flare, sec (*)	Time for $\Delta\gamma = 1^{\circ}$ in transition, sec (*)	Flare initiation, ft (m)		Transition initiation, ft (m)		Transition completion, ft (m)	
						x	z	x	z	x	z
1	Single segment	3	---	3.5	---	2.2 $\times 10^3$ (0.67)	63 (19.2)	---------	----------	---------	----------
2	Single segment	3	---	7.0	---	4.4 (1.34)	125 (38.1)	---------	----------	---------	----------
3	Single segment	4	---	3.5	---	3.0 (0.91)	112 (34.1)	---------	----------	---------	----------
4	Single segment	4	---	7.0	---	6.0 (1.83)	226 (68.8)	---------	----------	---------	----------
5	Single segment	5	---	3.5	---	3.8 (1.16)	176 (53.6)	---------	----------	---------	----------
6	Single segment	5	---	7.0	---	7.7 (2.35)	356 (108.5)	---------	----------	---------	----------
7	Single segment	6	---	3.5	---	4.6 (1.40)	252 (76.8)	---------	----------	---------	----------
8	Single segment	6	---	7.0	---	9.3 (2.83)	520 (158.5)	---------	----------	---------	----------
9	Single segment	7	---	3.5	---	5.4 (1.65)	344 (104.8)	---------	----------	---------	----------
10	Single segment	7	---	7.0	---	10.9 (3.32)	700 (213.2)	---------	----------	---------	----------
11	Two segment	5	2.5	---	7.0	----------	------	17.0 $\times 10^3$ (5.2)	7.90 $\times 10^2$ (2.41)	14.0 $\times 10^3$ (4.3)	6.05 $\times 10^2$ (1.84)
12	Two segment	5	3	---	7.0	----------	------	14.4 (4.4)	7.60 (2.32)	11.0 (3.4)	5.25 (1.60)
13	Two segment	6	3	---	3.5	----------	------	13.7 (4.2)	7.35 (2.24)	11.0 (3.4)	5.25 (1.60)
14	Two segment	6	3	---	3.5	----------	------	18.2 (5.6)	9.70 (2.96)	15.5 (4.7)	7.60 (2.32)
15	Two segment	6	3	---	3.5	----------	------	22.7 (6.9)	12.05 (3.67)	20.0 (6.1)	9.95 (3.03)
16	Two segment	6	3	---	5.5	----------	------	19.4 (5.9)	10.65 (3.25)	15.5 (4.7)	7.60 (2.32)
17	Two segment	6	3	---	7.0	----------	------	15.2 (4.6)	8.30 (2.53)	11.0 (3.4)	5.25 (1.60)
18	Two segment	6	3	---	7.0	----------	------	20.5 (6.4)	11.53 (3.51)	15.5 (4.7)	7.60 (2.32)
19	Two segment	7	3	---	7.0	----------	------	16.4 (5.0)	9.60 (2.93)	11.0 (3.4)	5.25 (1.60)
20	Two segment	8	3	---	7.0	----------	------	19.1 (5.8)	12.80 (3.90)	11.0 (3.4)	5.25 (1.60)
21	Two segment	9	3	---	7.0	----------	------	20.6 (6.3)	15.00 (4.58)	11.0 (3.4)	5.25 (1.60)

*For a nominal speed of about 140 knots.

TABLE III.- SUMMARY OF TESTS

Profile	Glide-slope angle, deg	VFR	Simulated IFR	Control mode		Throttle control			Number of approaches
				Manual	Coupled	Manual constant speed	Autothrottle constant speed	Manual constant-throttle setting	
Airplane A									
1	3	X		X		X			2
1	3		X	X		X			14
1	3		X		X	X			4
3	4		X	X		X			4
5	5	X		X		X			1
5	5		X	X		X			7
7	6	X		X		X			2
7	6		X	X		X			8
9	7	X		X		X			1
9	7		X	X		X			2
13	6 to 3		X	X		X			11
13	6 to 3		X	X				X	5
13	6 to 3		X	X			X		8
13	6 to 3		X		X	X			8
13	6 to 3		X		X			X	3
14	6 to 3		X	X		X			9
14	6 to 3		X	X			X		11
15	6 to 3		X	X		X			10
15	6 to 3		X	X			X		14
15	6 to 3		X		X	X			10
Total									134
Airplane B									
1	3		X	X		X			12
1	3		X	X			X		1
3	4	X		X		X			1
3	4		X	X		X			3
5	5		X	X		X			4
7	6	X		X		X			2
7	6		X	X		X			11
12	5 to 3	X		X		X			3
12	5 to 3		X	X		X			35
12	5 to 3		X	X			X		2
17	6 to 3	X		X		X			2
17	6 to 3		X	X		X			29
17	6 to 3		X	X			X		9
16	6 to 3		X	X		X			4
19	7 to 3	X		X		X			1
20	8 to 3	X		X		X			2
18	6 to 3	X		X		X			5
18	6 to 3		X	X		X			30
18	6 to 3		X	X			X		11
18	6 to 3		X		X	X			1
Total									137

TABLE III.- SUMMARY OF TESTS – Continued

Profile	Glide-slope angle, deg	VFR	Simulated IFR	Control mode		Throttle control			Number of approaches
				Manual	Coupled	Manual constant speed	Autothrottle constant speed	Manual constant-throttle setting	
Airplane C									
1	3	X		X		X			12
1	3		X	X		X			12
12	5 to 3	X		X		X			2
12	5 to 3		X	X		X			8
12	5 to 3		X	X			X		4
19	7 to 3	X		X		X			3
20	8 to 3	X		X		X			3
21	9 to 3	X		X		X			1
11	5 to 2.5	X		X		X			2
11	5 to 2.5		X	X		X			9
11	5 to 2.5		X	X			X		6
18	6 to 3	X		X		X			4
18	6 to 3		X	X		X			12
18	6 to 3		X	X			X		8
16	6 to 3		X	X		X			6
14	6 to 3		X	X		X			6
18	6 to 3		X		X	X			1
Total									99
Airplane D									
2	3	X		X		X			8
2	3		X	X		X			17
2	3		X	X			Autothrottle		14
2	3	X			X		Autothrottle		1
8	6	X		X		X			12
8	6		X	X		X			28
8	6		X	X			Autothrottle		2
18	6 to 3	X		X		X			11
18	6 to 3		X	X		X			18
18	6 to 3		X	X			Autothrottle		12
19	7 to 3	X		X		X			1
19	7 to 3		X	X		X			2
20	8 to 3		X	X		X			3
Total									129

TABLE III.- SUMMARY OF TESTS – Concluded

Profile	Glide-slope angle, deg	VFR	Simulated IFR	Control mode		Throttle control			Number of approaches
				Manual	Coupled	Manual constant speed	Autothrottle constant speed	Manual constant-throttle setting	
Airplane E									
2	3	X		X		X			1
2	3		X	X		X			34
4	4	X		X		X			1
4	4		X	X		X			3
6	5		X	X		X			4
8	6	X		X		X			2
8	6		X	X		X			26
10	7	X		X		X			6
18	6 to 3	X		X		X			2
18	6 to 3		X	X		X			19
Total									98
Airplane F									
2	3	X		X		X			2
2	3		X	X		X			8
4	4		X	X		X			4
4	4		X	X		X			4
6	5		X	X		X			4
6	5		X	X		X			4
8	6	X		X		X			2
8	6		X	X		X			8
10	7	X		X		X			1
18	6 to 3	X		X		X			2
18	6 to 3		X	X		X			9
18	6 to 3		X	X			X		9
Total									57

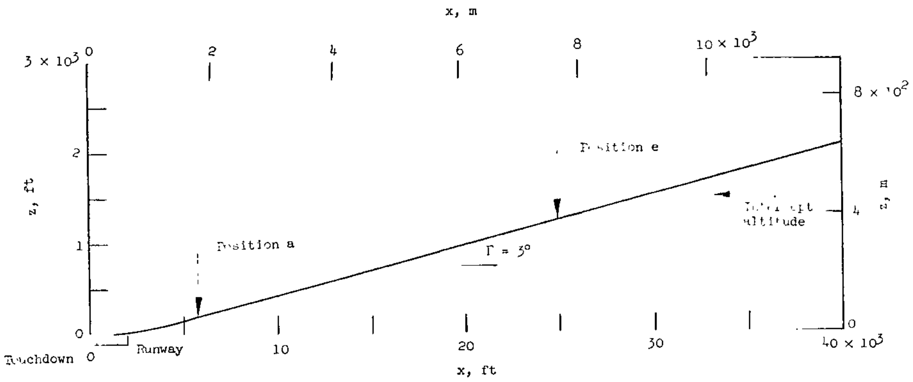
TABLE IV.- OPERATING CONDITIONS IN APPROACHES

Airplane	δ_f, deg	Weight range, lb (N)	Stalling speed variation, knots	Overall airspeed variation, knots
A	44	112 000 to 155 000 (498 400 to 689 750)	100 to 118	130 to 153
B	50,36,27	149 000 to 195 000 (663 050 to 867 750)	101 to 117	133 to 154
C	50	121 500 to 175 000 (540 675 to 778 750)	82 to 99	109 to 132
D	50	192 000 to 247 000 (354 400 to 1 099 150)	96 to 109	125 to 155
E	40	8 200 to 12 400 (36 490 to 55 180)	80 to 106	115 to 130
F	40,30	110 000 to 139 700 (489 500 to 621 665)	84 to 96	109 to 123

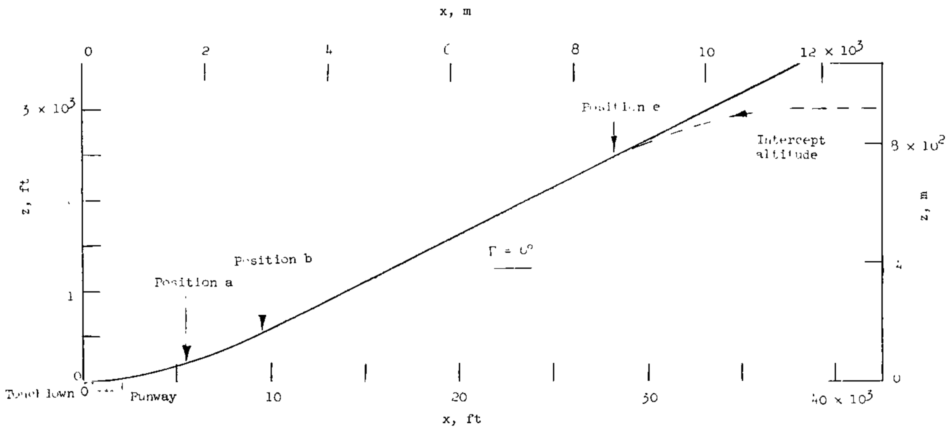
TABLE V.- PERFORMANCE EVALUATION POSITIONS ON SELECTED APPROACH GUIDANCE PROFILES

Function	Position[1]									
	a		b		c		d		e	
	ft	m	ft	m	ft	m	ft	m	ft	m
Profile 1										
z	200	61.0	----	------	------	------	------	------	1 250	381
x	5400	1645	----	------	------	------	------	------	26 000	7 925
w_s	±75	±22.8	----	------	------	------	------	------	±350	±106.6
w_c	±500	±152.5	----	------	------	------	------	------	±1 500	±458
Profile 8										
z	200	61.0	520	158.5	------	------	------	------	2 500	762
x	5700	1737	9310	2838	------	------	------	------	28 300	8 625
w_s	±75	±22.8	±125	±28.1	------	------	------	------	±375	±114.3
w_c	±500	±152.5	±665	±202.8	------	------	------	------	±1 650	±503
Profile 18										
z	200	61.0	----	------	760	231.7	1 150	350.8	2 500	762
x	4700	1433	----	------	15 500	4722	20 400	6220	33 500	10 200
w_s	±55	±16.18	----	------	±200	±61.0	±250	±76.2	±420	±128
w_c	±465	±141.6	----	------	±950	±289.5	±1 200	±366	±1 835	±560

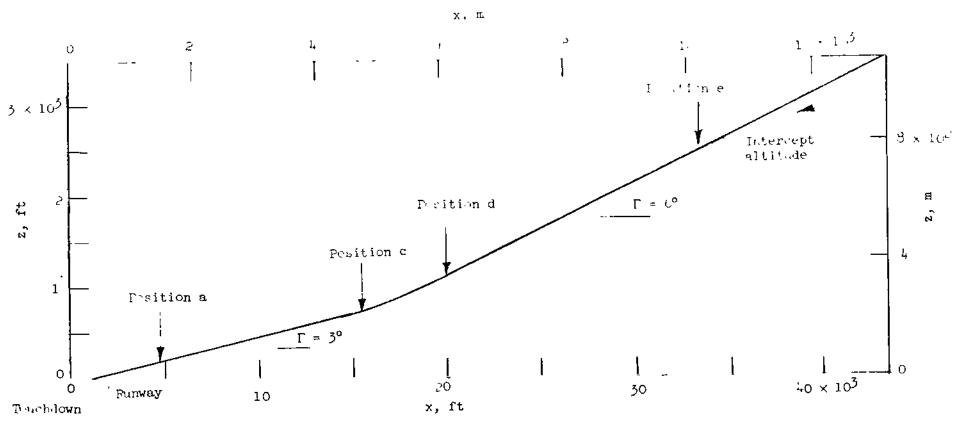
[1]Position a is at intended breakout to visual reference.
Position b is at initiation of flare guidance for landing.
Position c is at completion of transition guidance from 6^{o} to 3^{o} glide slope.
Position d is at initiation of transition guidance from 6^{o} to 3^{o} glide slope.
Position e is at point where stabilized flight on glide slope should normally be expected.



(a) Profile 1.

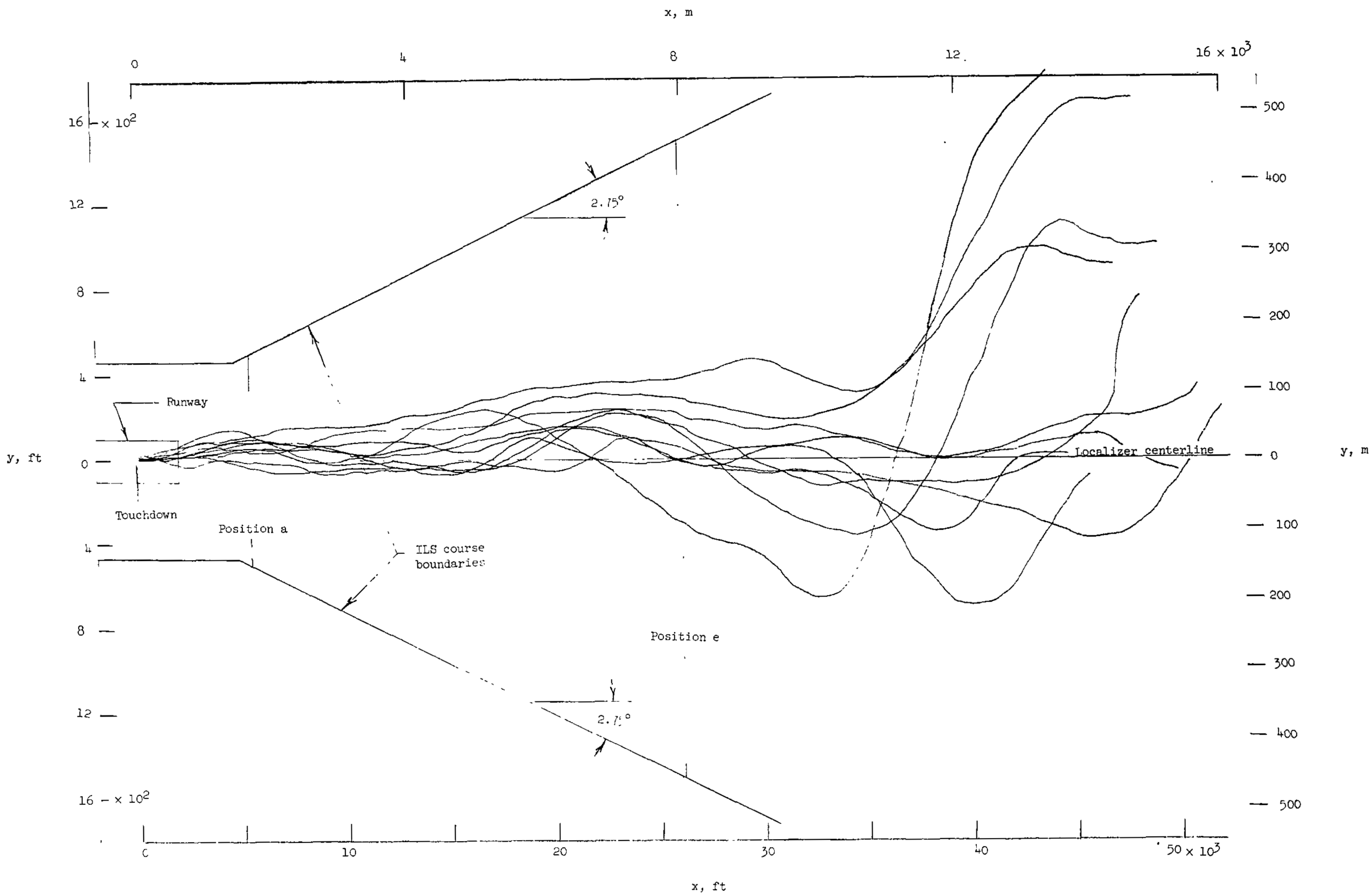


(b) Profile 8.



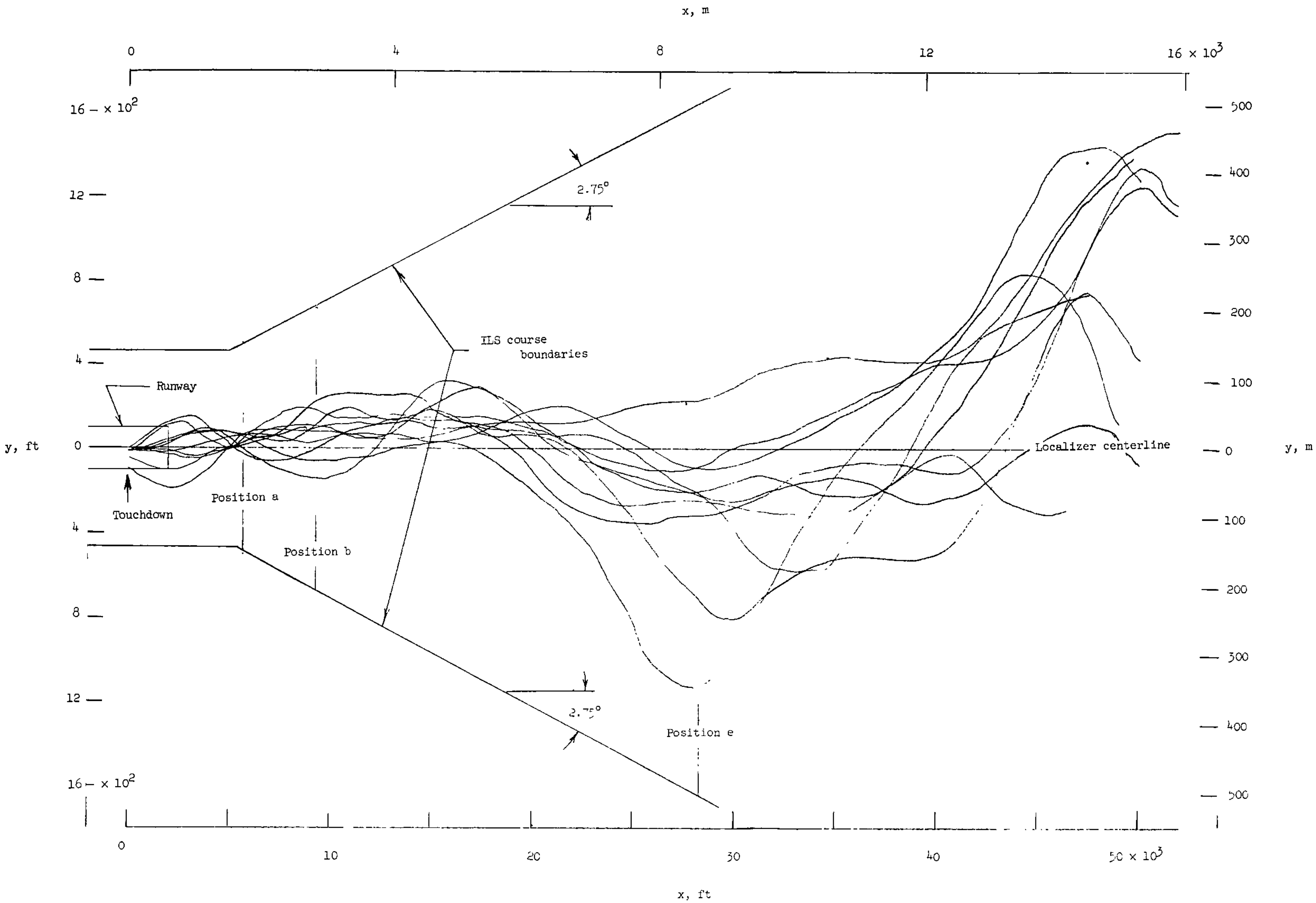
(c) Profile 18.

Figure 1.- Tracking performance evaluation positions on profiles 1, 8, and 18.



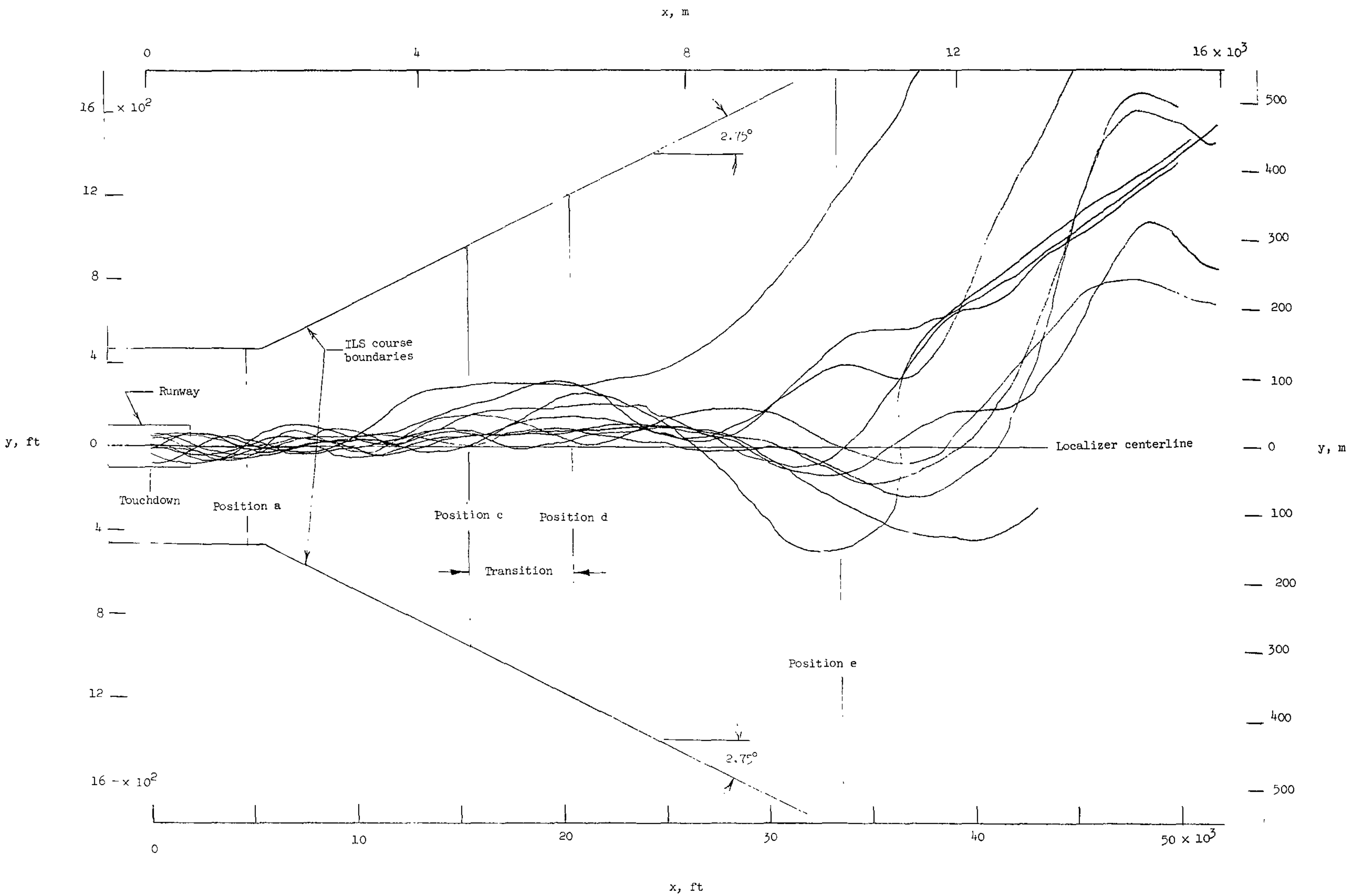
(a) Profile 1, n = 10.

Figure 2.- Course tracks of approaches made on profiles 1, 8, and 18.



(b) Profile 8, n = 10.

Figure 2.- Continued.



(c) Profile 18, n = 10.

Figure 2.- Concluded.

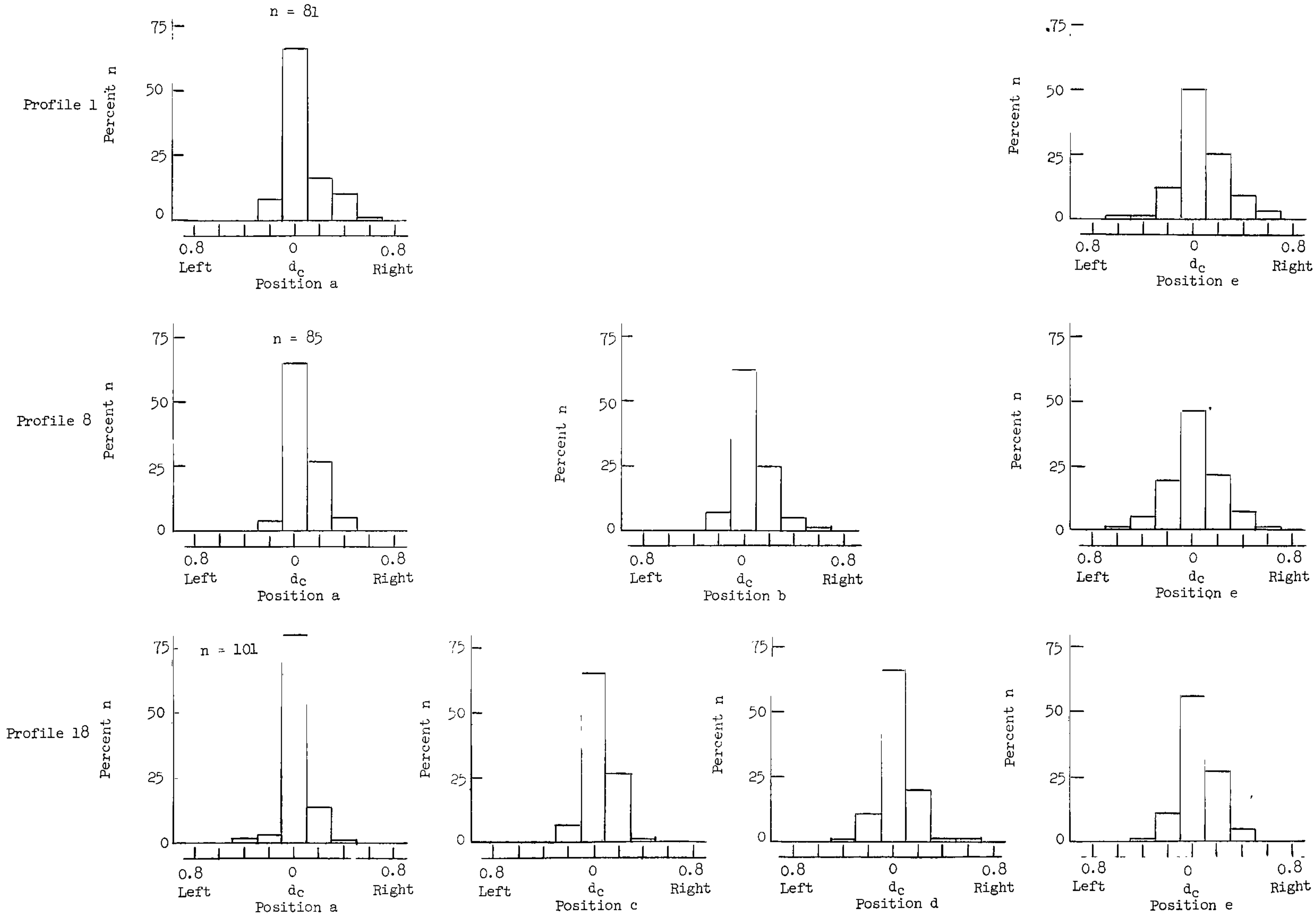


Figure 3.- Frequency distribution of course deviation at various positions on profiles 1, 8, and 18.

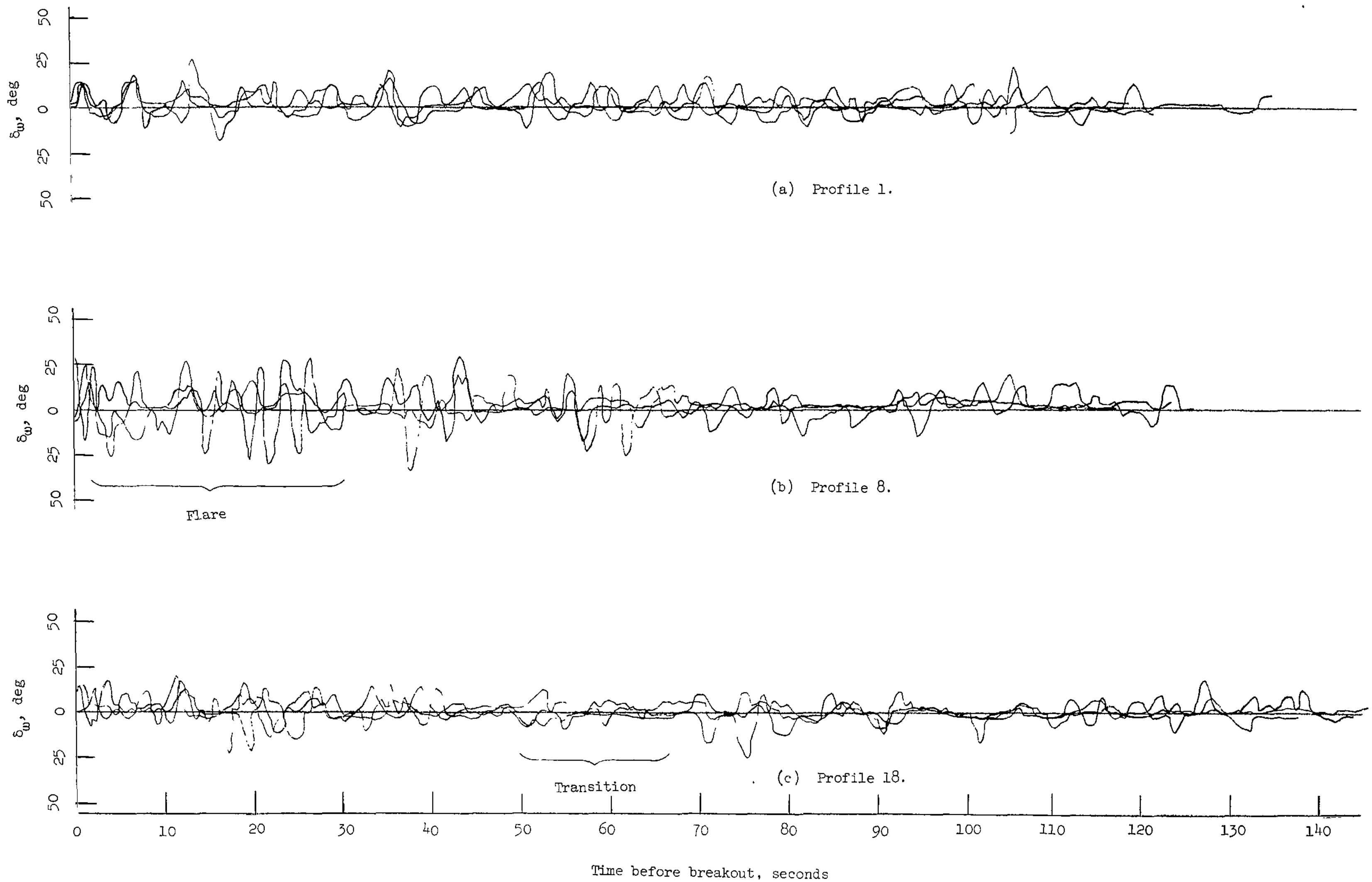
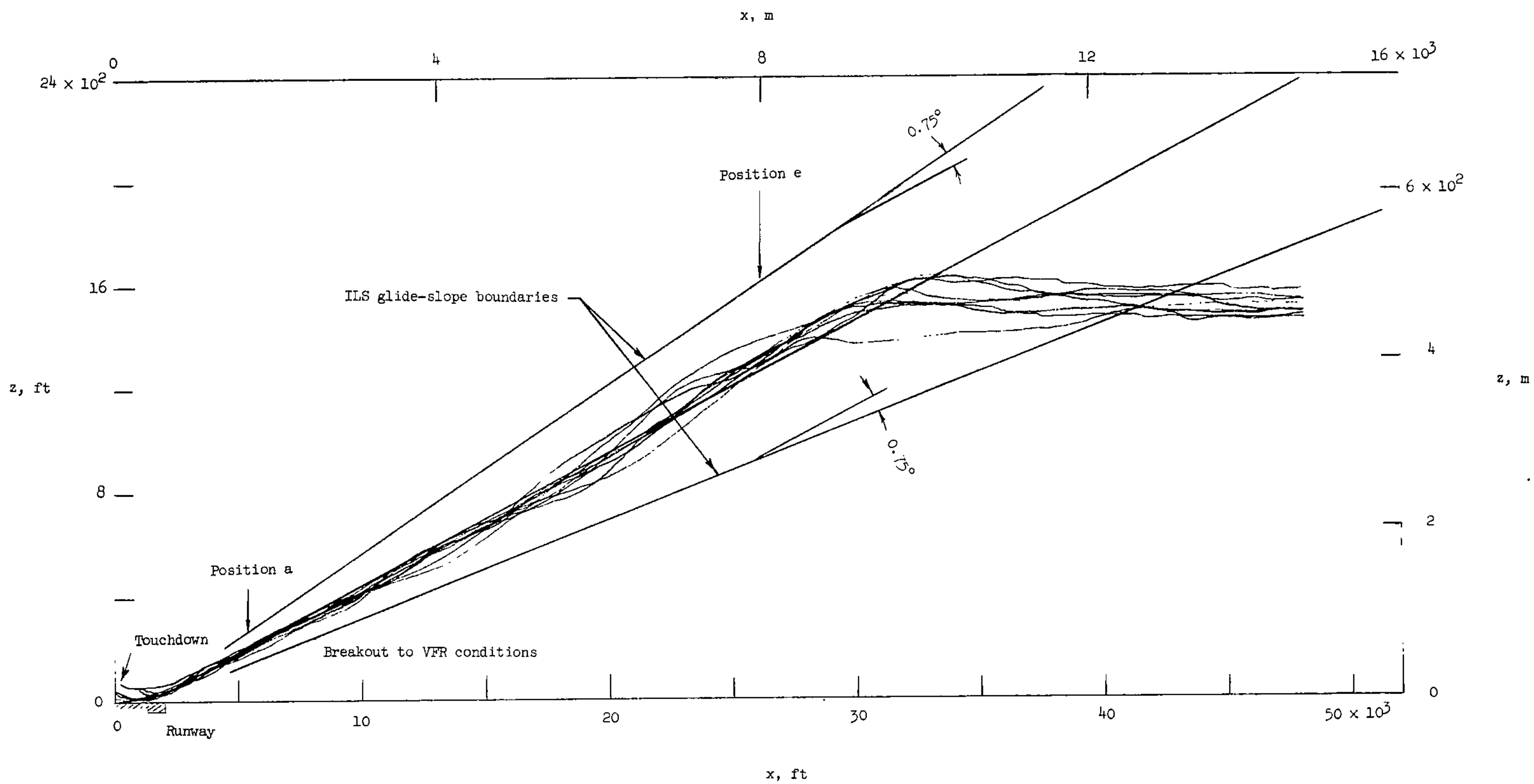
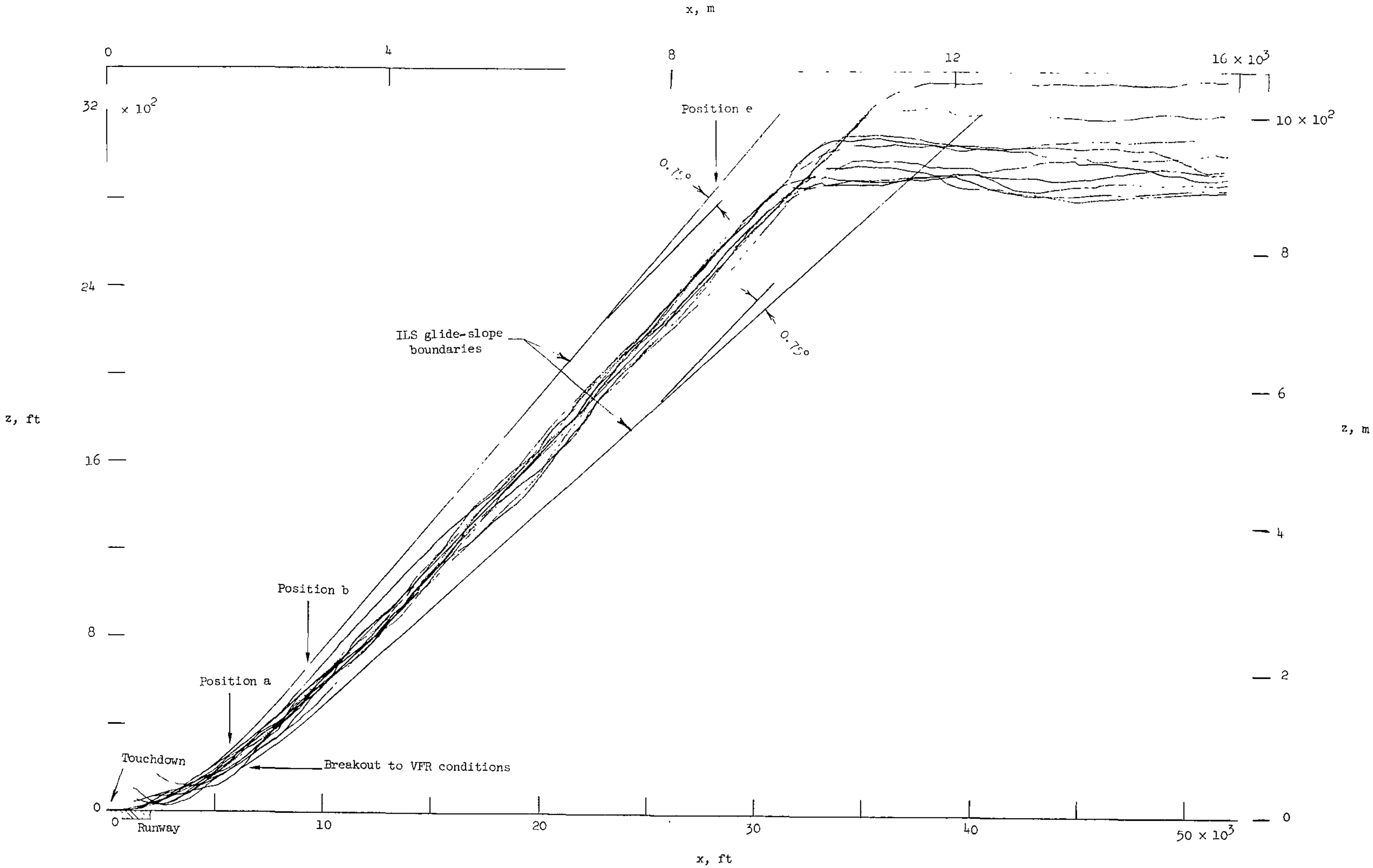


Figure 4.- Typical time histories of pilot control wheel movements on profiles 1, 8, and 18.



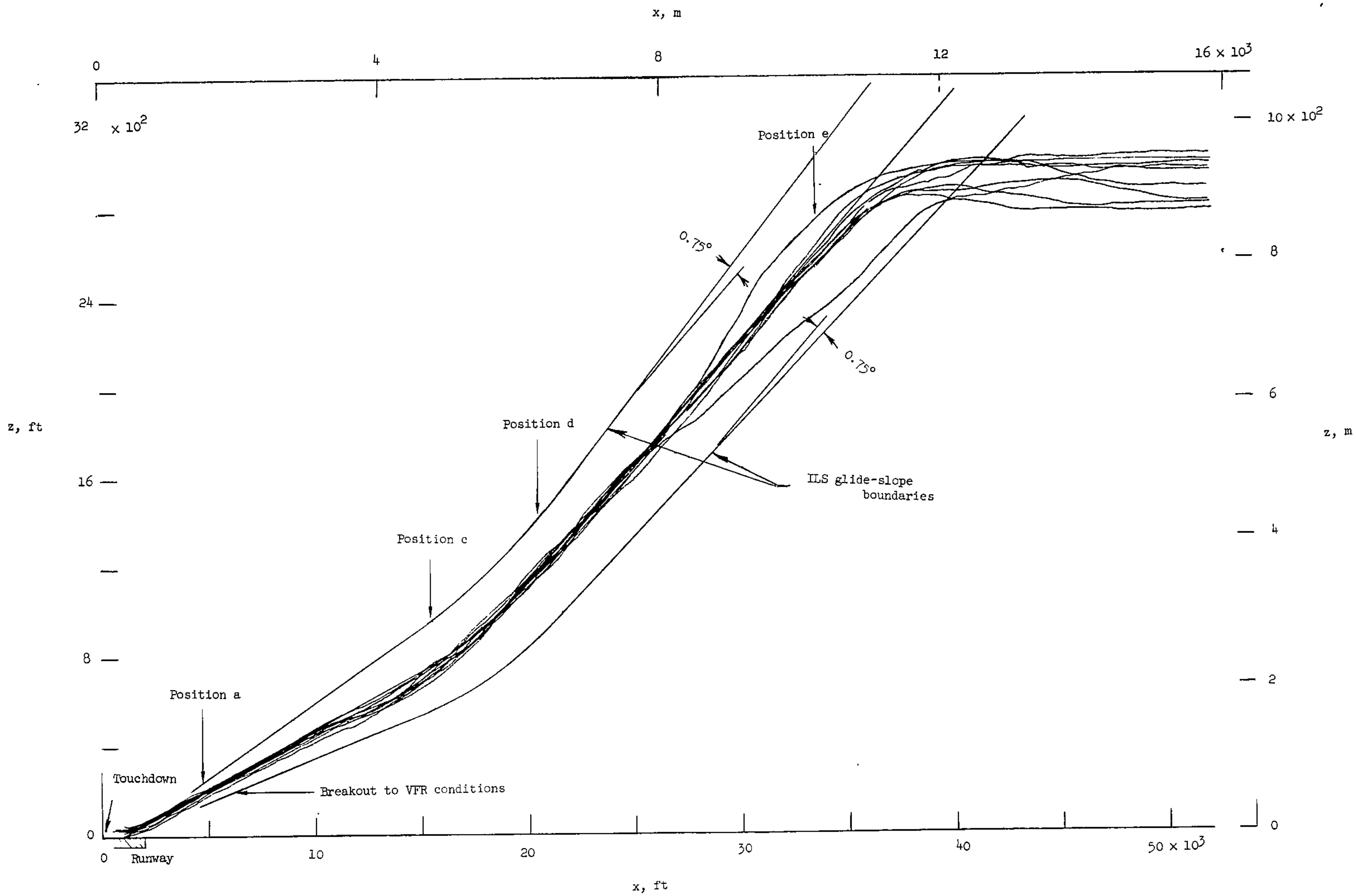
(a) Profile 1, n = 9.

Figure 5.- Typical slope tracks of approaches made on profiles 1, 8, and 18.



(b) Profile 8, n = 10.

Figure 5.- Continued.



(c) Profile 18, n = 9.

Figure 5.- Concluded.

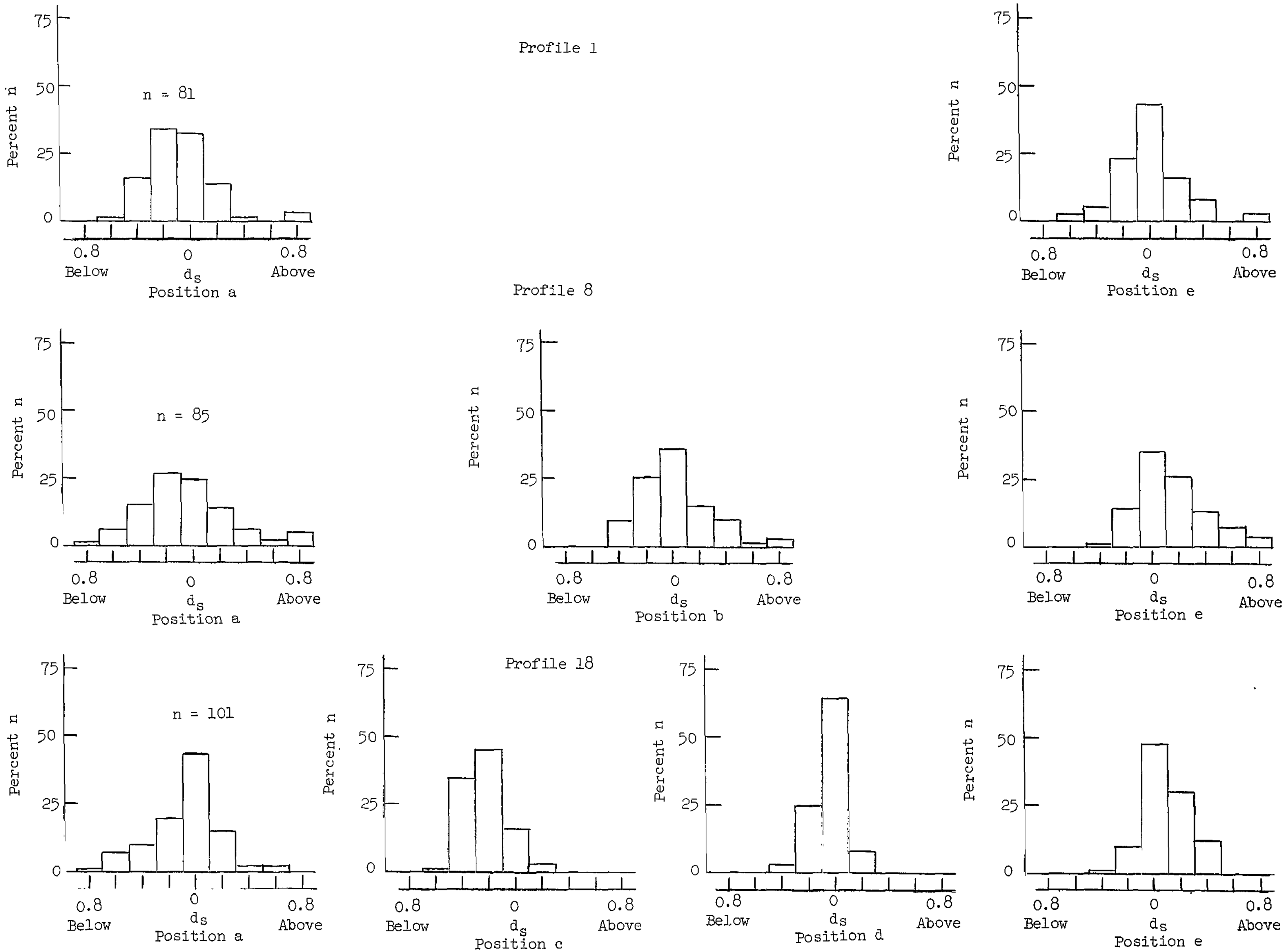


Figure 6.- Frequency distribution of glide-slope deviation at various positions on profiles 1, 8, and 18.

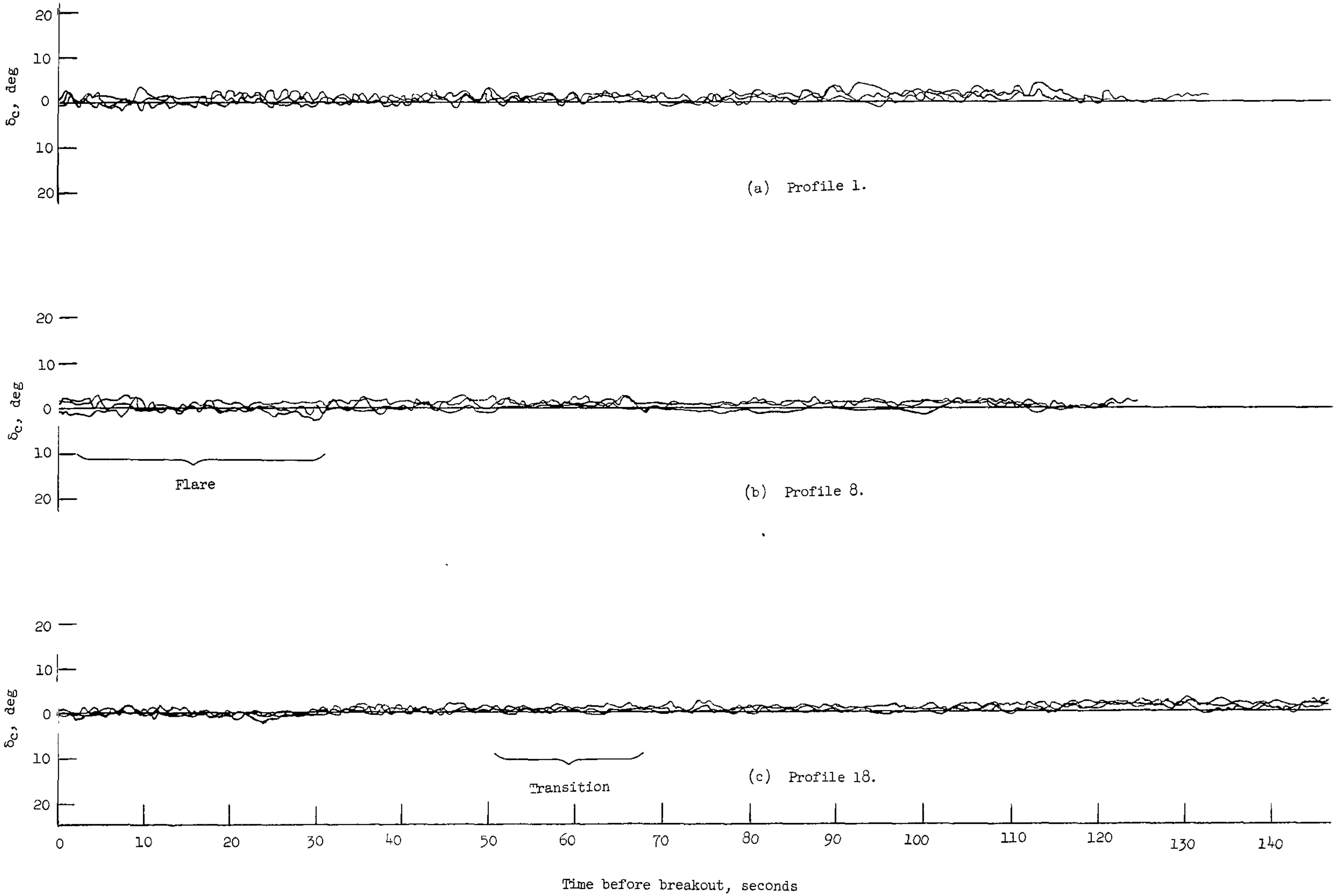


Figure 7.- Typical time histories of manual control column deflections δ_c on profiles 1, 8, and 18.

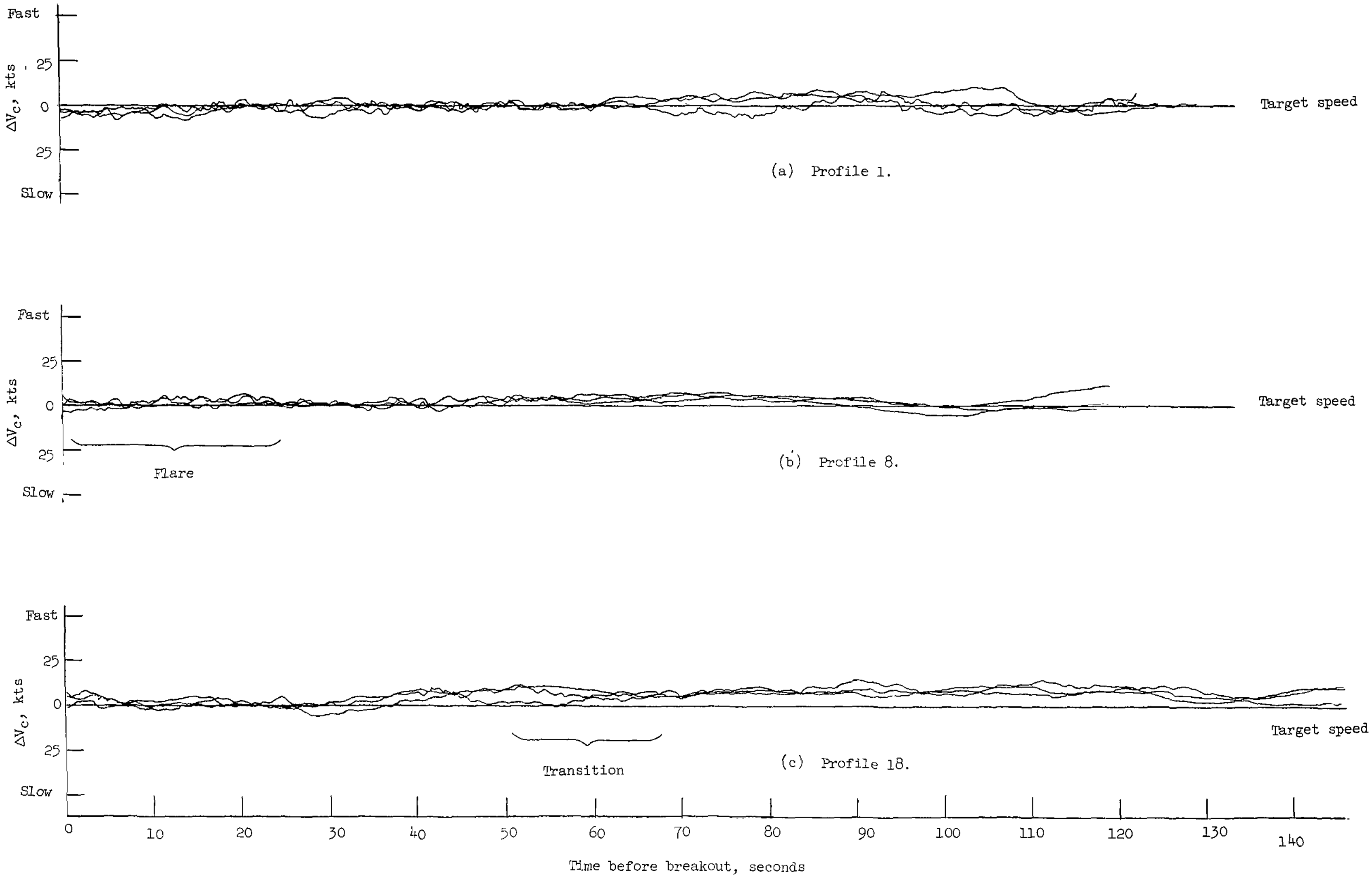


Figure 8.- Typical time histories of deviations in airspeed from target speed on profiles 1, 8, and 18.

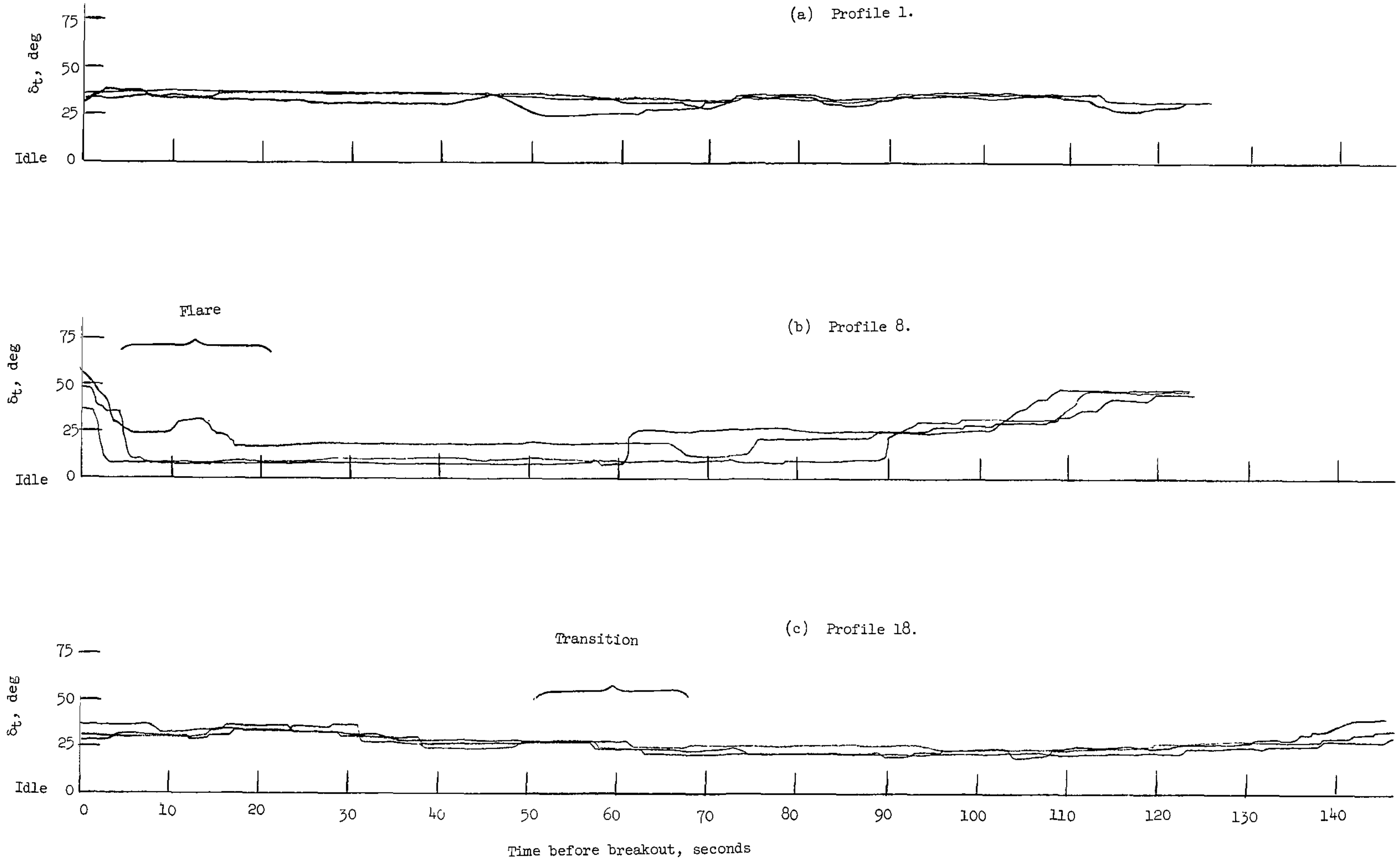


Figure 9.- Typical time histories of manual throttle movements on profiles 1, 8, and 18.

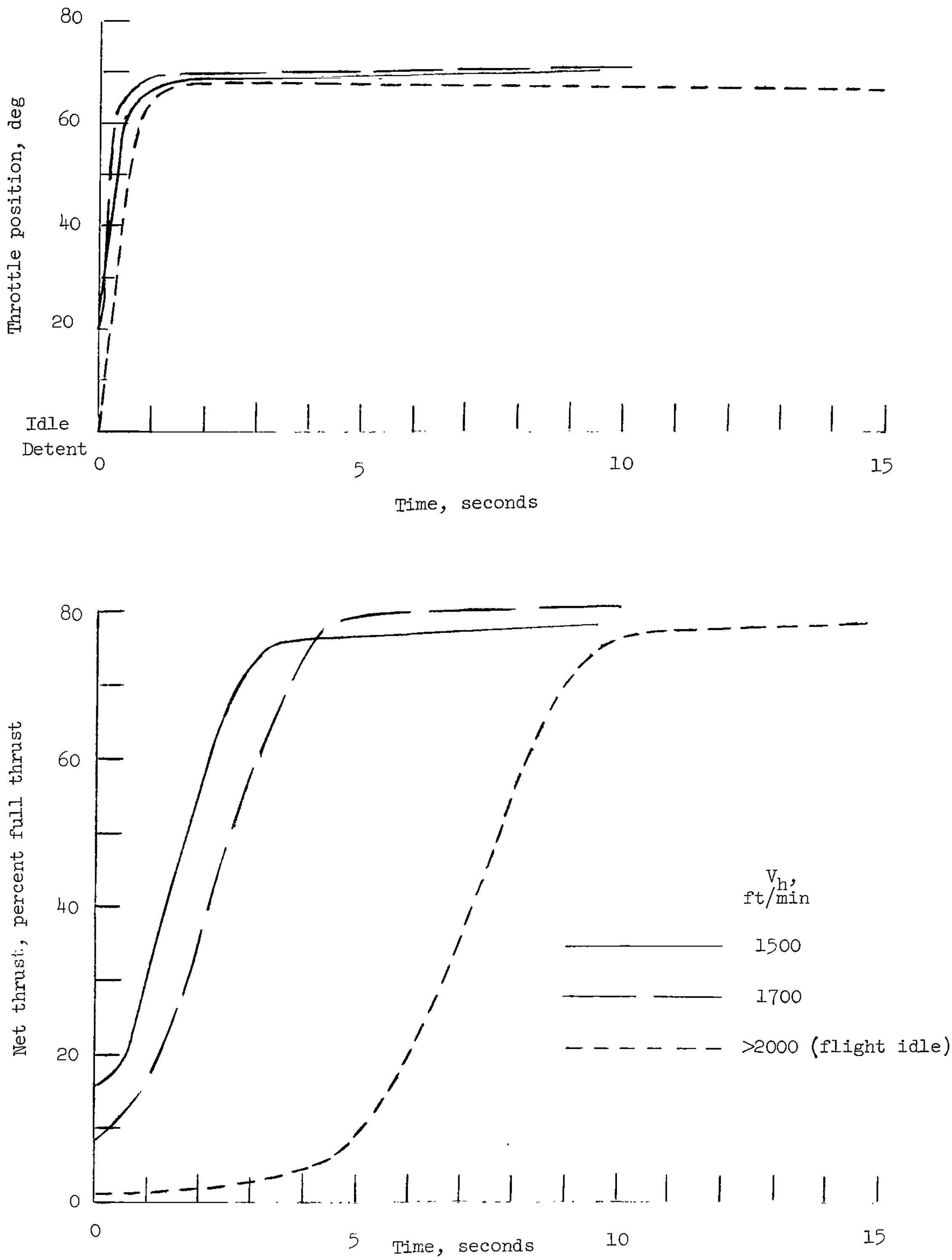
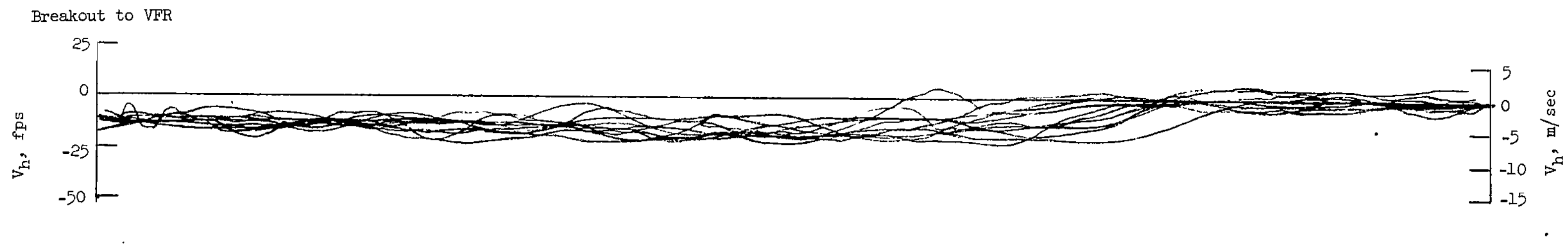
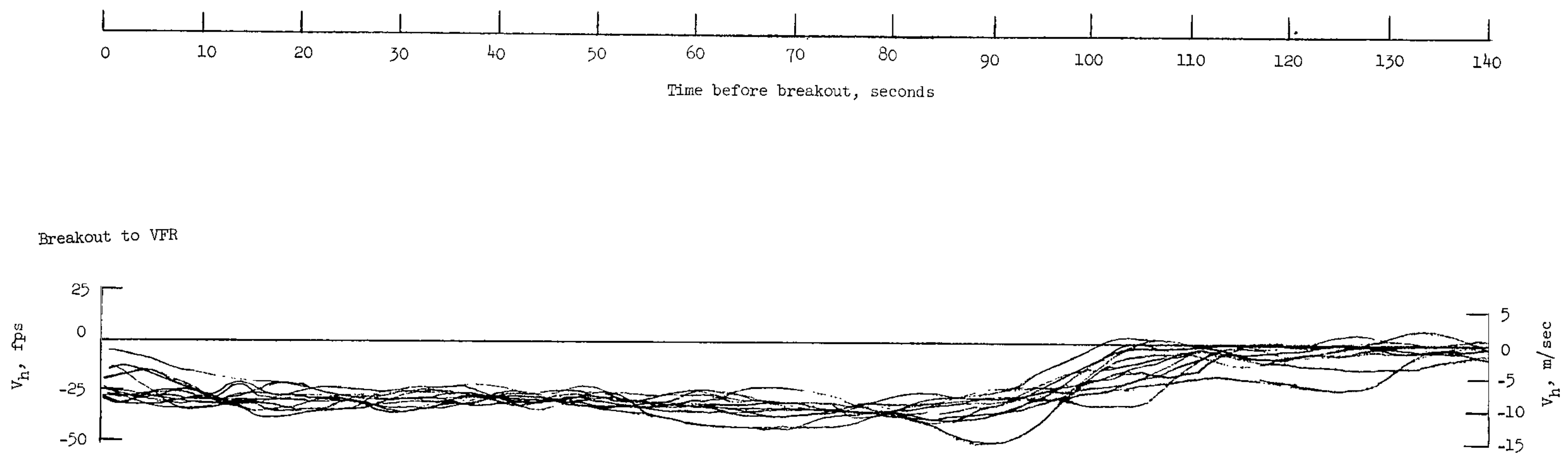


Figure 10.- Three examples of thrust response (airplane D) to pilot control throttle input. Flaps at 50^0, gear extended.



(a) Profile 1.



(b) Profile 8.

Figure 11.- Representative time histories of descent velocity V_h on profiles 1 and 8.

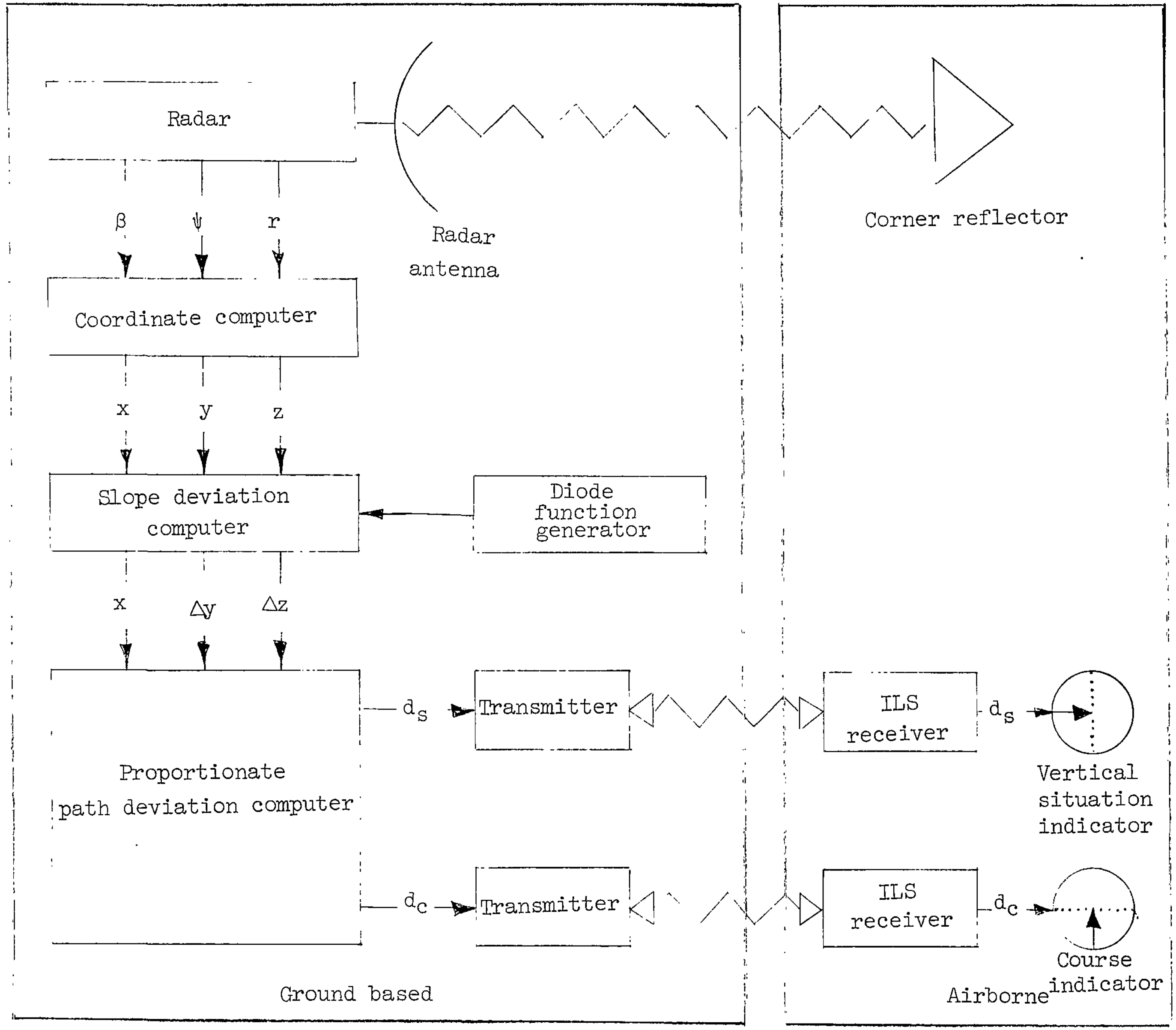


Figure 12.- Functional diagram of AN/GSN-5ST guidance system.

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