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SUMMARY

An evaluation of a landing-approach instrument display incorporating a cross-pointer presentation has been conducted in landing-approach tests with a helicopter. The display consisted of a vertical-situation—flight-director indicator, a horizontal-situation indicator, and small vertical-scale instruments for the presentation of airspeed, ground speed, vertical speed, range, and height. The tests of the display were conducted under simulated IFR (Instrument Flight Rules) conditions along a 6° glide slope at approach speeds of 30 and 60 knots.

The results of tests of four configurations of the attitude-guidance elements of the display showed that course guidance information in the form of control-command (flight-director) signals provided more precise control of course than that provided by course-deviation and ground-track angle information. With the best of the four configurations of slope guidance information, satisfactory guidance along a 6° glide slope could be maintained at airspeeds below that for minimum power.

Using the best display of course and slope guidance, one pilot flew twenty (out of twenty-two) 30-knot approaches (in head, cross, and tail winds) to a successful 50-foot (15.24 meters) breakout and visual slowdown to hover. The success of these approach tests, however, can be considered as only a partial indication of the operational suitability of the test display.

INTRODUCTION

The instrument display requirements for low-visibility landings of helicopters and other V/STOL aircraft are dependent, in many respects, on the approach task (defined by the approach slope, the approach airspeed, and the breakout ceiling) and on the controllability of the aircraft at the approach speed.

In order to avoid excessive rates of descent, the airspeed must be decreased as the approach path is steepened; for a given glide slope, the airspeed must also be decreased as the breakout ceiling is lowered. This decrease in airspeed is usually accompanied by a deterioration in controllability because of the increased adverse effects of winds and the generally poor stability and control characteristics of V/STOL aircraft at low airspeeds. Since the information requirements for guidance and control increase as the control of the aircraft becomes more difficult, the instrument display problem becomes increasingly complex for steep approaches to low breakout ceilings.

At the present time, helicopters in civil operations are certified for instrument approaches along the nominal $2\frac{1}{2}^{\circ}$ slope of ILS (Instrument Landing System) installations to a breakout ceiling of 200 feet (60.96 meters). For normal operations, the helicopters are required to incorporate some form of artificial stabilization and to fly at high approach speeds (generally above 60 knots). The guidance instruments approved for these operations are conventional ILS cross-pointer indicators that display path deviations from slope and course.

Exploratory investigations of cross-pointer instruments for the guidance of helicopters along steep approaches are reported in references 1 to 3. For the low approach speeds (about 30 knots) and steep approach paths $\left(9\frac{1}{2}^{\circ} \text{ to } 12^{\circ}\right)$ of these studies, the guidance information was presented in quickened form as control-command (or flight-director) signals. In addition, since slope guidance of a helicopter at low speeds is accomplished by control of both power (to control lift) and pitch attitude (to control airspeed), separate command indications were presented for the control of these two quantities. In contrast, a single indication is sufficient for slope guidance at high speeds, since, in this case, slope control is maintained primarily by changes in pitch attitude.

As a part of an investigation of the instrument display requirements for the landing of V/STOL aircraft, the National Aeronautics and Space Administration has conducted tests, with a helicopter as the test vehicle, of a landing-approach display incorporating a cross-pointer presentation. The display consisted of a vertical-situation—flight-director indicator, a horizontal-situation indicator, and small vertical-scale instruments for the indication of airspeed, ground speed, vertical speed, range, and height. The tests were conducted under simulated IFR (Instrument Flight Rules) conditions along a 6° glide slope at approach speeds of 30 and 60 knots. This report presents the results of evaluation tests of four configurations of the attitude-guidance elements of the display and of operational capability tests of one of these configurations.

SYMBOLS

c_c control-command (flight-director) signal for course guidance

d_c proportionate course deviation, y/w_c

d_s proportionate slope deviation, $\Delta z/w_s$

e airspeed error (from command airspeed), knots

r slant range, distance between radar antenna and aircraft, feet (meters)

w_c course width from course center line, displacement from course for full-scale deflection of ILS course-deviation indicator, feet (meters) (see fig. 1)

w_s slope width from slope center line, displacement from slope for full-scale deflection of ILS slope-deviation indicator, feet (meters) (see fig. 1)

x range, distance of aircraft from slope origin as measured in ground plane along or parallel to course, feet (meters) (see fig. 1)

y course deviation, lateral displacement of aircraft from selected course, feet (meters) (see fig. 1)

z height of aircraft above ground plane, feet (meters) (see fig. 1)

Δz slope deviation, vertical displacement of aircraft from glide slope, feet (meters) (see fig. 1)

$\dot{x}$ longitudinal velocity of aircraft, knots

$\dot{y}$ lateral velocity of aircraft, knots

$\dot{z}$ vertical velocity of aircraft, feet per minute (meters per second)

γ glide-slope angle, degrees (see fig. 1)

β elevation angle of radar antenna, degrees

ψ azimuth angle of radar antenna, degrees

θ pitch angle of aircraft, degrees

INSTRUMENT DISPLAY

The instrument display evaluated in the present investigation is shown in figure 2. The display consisted of a vertical-situation—flight-director indicator, a horizontal-situation indicator, five vertical-scale instruments (for indications of airspeed, ground speed, vertical speed, range, and height), and a dial-type torquemeter. Calibration of these instruments with the exclusion of the dial-type torquemeter is discussed in appendix A.

Attitude-Guidance Instruments

Vertical-situation—flight-director indicator.- The vertical-situation—flight-director indicator (VSFDI) was a standard flight instrument representative of present-day integrated displays that combine attitude and guidance information. The instrument was designed to provide control-command (flight-director) signals for both slope and course control (from deflections of the vertical and horizontal needles across the center of the instrument); the instrument also provides indications of glide-slope deviations (by the vertically moving tab on the left of the instrument) and indications of roll and pitch attitude (from the gyro-stabilized sphere). Slip, skid, and rate-of-turn indications are provided by the small turn-and-bank indicator at the bottom of the instrument.

The control-command signals are generated in a flight-director computer that combines position, attitude, and rate information. The control-command signal for course guidance is produced by combining course deviation, course-deviation rate, roll angle, roll-angle rate, and heading deviation. The command signal for slope guidance is produced by combining slope deviation, pitch attitude, and pitch-attitude rate; as will be noted, the slope-command signal was not used in the present investigation.

The flight-director computer had been designed for use in a conventional, fixed-wing airplane. During initial trials of the computer in the test helicopter, the control-command signal for course guidance was found to produce oscillatory movements of the vertical needle near its null position. Since these oscillations appeared to be associated with the roll inputs, the roll-rate input was disconnected and the roll-angle input was made less sensitive. As finally adjusted for the present tests, the roll-angle input was 9° for half-scale deflection of the vertical needle. The settings of the remaining information inputs were left at their original values – namely, a course-deviation input of two-thirds the course beam width, a course-deviation rate of approximately 0.07 deg/sec, and a heading deviation of 10°, all for half-scale deflection of the needle.

The slope-control command provided by the computer was not used in the present investigation because most of the approach tests were to be made at a low speed for which separate indications for the control of power and pitch attitude would be required. Instead, the horizontal needle of the flight director was used in conjunction with the slope tab or the gyro horizon to provide separate indications of slope deviation and pitch attitude. To make provision for the testing of various combinations of guidance and attitude information, the slope-command circuit was modified to permit the display of pitch attitude, airspeed error, or slope deviation on the horizontal needle. (It was recognized that it would have been of interest to have also presented combined signals such as pitch with pitch rate, pitch with airspeed error, and slope deviation with slope-deviation rate, but this could not be accomplished without extensive revision of the computer network.) The sensitivities of the pitch, airspeed-error, and slope-deviation inputs for half-scale deflection of the horizontal needle were 7^{o} pitch, 15 knots airspeed error (from a reference speed of 30 knots), and about one-third the slope beam width. In terms of indicator deflections, the sensitivity of the needle movement to pitch attitude was about the same as that of the gyro horizon; the sensitivity of the needle to slope deviation was about two-thirds that of the slope-deviation tab.

Horizontal-situation indicator.- The horizontal-situation indicator (HSI) provides indications of (1) course deviation (from lateral movement of the double-line course bar), (2) heading (from the rotating compass ring, referenced to the lubber line at the top), and (3) ground-track angle with respect to selected course (from the rotating pointer). The course bar, together with the inverted V at the top of the bar, can be set to a selected course by rotating the disk inside the compass ring. Since the disk thereafter rotates with the compass ring, the angular position of the inverted V with respect to the lubber line provides an indication of relative heading from the selected course. The double-square symbol on the compass ring is a heading index which, when set to a desired heading, rotates with the compass ring. It may be noted here that, in conventional operations, the path deviation information presented by the slope tab of the VSFDI and the course bar of the HSI is used as backup information for the control commands on the cross pointers.

Vertical-Scale Instruments

The vertical-scale instruments were especially designed (with regard to size, scale sensitivity, and display format) for the test display. All instruments were of fixed-scale type, with moving pointers (small triangles on moving tapes) for the airspeed, ground speed, and vertical speed indicators and moving tapes (thermometer-type indications) for the range and height indicators. The scale length of the indicators was 4.5 in. (11.43 cm) and the scale ranges were as follows:

Airspeed	0 to 100 knots
Ground speed	-10 to 50 knots
Vertical speed	-800 to 200 ft/min (-4.06 to 1.02 m/sec)
Range	0 to 2750 ft (838.2 m)
Height	0 to 275 ft (83.82 m)

The range information provided by the range indicator was supplemented by signals from three lights (located above the HSI) which were actuated at ranges of 5000, 4000, and 3000 ft (1524, 1219, and 914.4 m).

The airspeed transducer did not actuate the airspeed indicator at speeds below about 10 knots; in addition, the indications were unreliable at speeds below about 20 knots. The useable range of the indicator, as indicated by the cross-hatched area at the lower part of the scale (fig. 2), was therefore from about 20 to 100 knots.

The scales of the range and height indicators were changed during the test program. Initially, the height scale was 100 ft (30.48 m) and the range scale 1000 ft (304.8 m). With these scales, the tapes were found to move too rapidly to be of use. When scales were changed to 500 and 5000 ft (152.4 and 1524 m), the tapes moved slowly enough but did not provide the precision required for low breakout ceilings. As a compromise, the scales were changed to their final settings of 275 and 2750 ft (83.82 and 838.2 m). Although the height scale was satisfactory for low breakout operations, the pilots felt the need for an additional height indicator having a greater range (to assist, for example, in slope acquisition during the initial part of the approach).

The arrangement of the vertical-scale indicators shown in figure 2 was arrived at mainly from a consideration of the pilot's scanning problem. The airspeed indicator, for example, was placed beside the VSFDI, because these two instruments are of primary interest during the approach to breakout. The vertical-speed indicator, being of secondary importance, was located below the airspeed indicator. The height indicator was placed above the range indicator so that the tapes of the two instruments would move toward each other as the breakout height was approached. The ground-speed indicator was located beside the height and range indicators because of the importance of ground speed at breakout.

Display Configurations

Since the signals to the flight-director needles could be switched off and the needles deflected from view, guidance information could be displayed on the two attitude-guidance indicators in the form of slope and course deviations. With the presentation of pitch attitude, airspeed error, or slope deviation on the horizontal needle, three additional displays of slope guidance could be presented in combination with control-command information on the vertical needle. Thus, four configurations of the guidance display elements could be displayed for the present investigation; diagrams of these display configurations, showing the attitude-guidance elements of primary interest, are shown in figure 3.

In display A, the information for course guidance is presented by the course-deviation bar and the ground-track angle indicator. Slope deviation information is presented by the slope-deviation tab and pitch-attitude indications by the gyro horizon.

In displays B, C, and D, course guidance information is presented as control commands on the vertical needle. With reference to the slope guidance information, display B differs from display A in presenting a reference pitch attitude on the horizontal needle, display C differs from display B in presenting airspeed error instead of pitch attitude on the horizontal needle, and display D differs from the other three displays in presenting slope deviation on the horizontal needle instead of on the slope-deviation tab.

GUIDANCE SYSTEM

The guidance system consisted of (1) a ground-based radar together with computers and telemeters for generating and transmitting aircraft position and velocity information and (2) airborne receiving and computing equipment for processing the information for presentation on the instrument display. A brief description of the radar and a discussion of the guidance system used in the present investigation are given in appendix B; the accuracy of the radar system is discussed in appendix A.

RECORDING INSTRUMENTS

Recording instruments were installed both in the ground station and in the aircraft.

In the ground station, two automatic plotters (fig. 4) recorded the vertical and horizontal tracks of the aircraft on 10-in. by 15-in. charts (25.40 cm by 38.10 cm). The scales of these charts were adjusted to 500 ft/in. (60.00 m/cm) for range and 100 ft/in. (12.00 m/cm) for displacement from slope and course. Calibration tests of these plotters are discussed in appendix A.

A radar-data recorder in the ground station (fig. 4(b)) recorded time histories of the quantities x, $\dot{x}$, y, Δz, $\dot{z}$, d_S, and d_C. The timing signals recorded on this instrument were also transmitted by radio link to the recording instruments in the aircraft. A second radio link system in the ground station was used to mark the records of both the radar-data recorder and the airborne recorders at selected times (such as breakout and hover).

Two NASA flight recorders, an airspeed-altitude recorder and an oscillograph, were installed in the aircraft. The quantities recorded on the oscillograph included (1) the movements of the four aircraft controls and throttle, (2) aircraft attitude (roll, pitch, and heading) and (3) the deflections of the slope tab, the course bar, and the flight-director needles.

TEST AIRCRAFT

The test aircraft used for the evaluation of the instrument display was a 10-place, turbine-powered, single-rotor helicopter (fig. 5) having dual (side by side) controls. This helicopter was not equipped with artificial stabilization equipment.

The test instrument display was installed on a special panel on the left side of the cockpit. The display was located directly in front of the pilot at a height more nearly at eye level than the aircraft instrument panel. Because of the depth of the instruments, it was necessary to enclose them in a housing that protruded through the windshield.

In order to simulate blind-landing conditions, the normal viewing area from the left seat was shielded with amber plastic; by wearing a visor of blue plastic, the pilot was unable to see outside the cockpit.

Other modifications to the helicopter included the installation of a corner reflector on the front of the cabin, the removal of the passenger seats to provide space for the test equipment, and the installation of an observer's seat behind the pilots' seats.

FLIGHT-TEST PROGRAM

The flight-test program was divided into three phases: In the first phase, the project pilot evaluated the individual display elements with regard to their input signals and scale sensitivities. In the second phase, the project pilot performed a comparative evaluation of the four display configurations (fig. 3) and selected the one that he felt represented the best configuration of the attitude-guidance elements. In the third phase, the project pilot performed a series of approaches with the selected display configuration to obtain an indication of its operational capability under a variety of wind conditions. Additional tests with the selected display were also performed by two other pilots. All three pilots were NASA research test pilots.

Approach Task

The approach task consisted of a constant-speed IFR approach along a 6° slope to either a specified range for starting a speed reduction or to a specified breakout ceiling. The 6° slope was selected because previous work by the NASA (ref. 4) had indicated that this was the maximum angle to which helicopters could operate on a routine basis.

Each approach was started at a range of about 2 miles (3220 m), an altitude of about 800 ft (243.8 m) and to one side of the course. For the initial part of the task, therefore, the pilot was required to intercept the course, acquire the glide slope, and establish the approach speed.

In the comparative evaluation tests of the display configurations, the pilot initiated a speed reduction at a range of about 1500 ft (457.2 m) and attempted to bring the helicopter to a hover. Although he was partially successful in these attempts to slow down, the task was generally too difficult, primarily because of the unreliability of the airspeed indications at speeds below 20 knots and the great difficulty of controlling the aircraft at very low speeds.

For the operational capability tests, therefore, the task was changed to an IFR approach to a specified breakout ceiling followed by a visual slowdown to hover. In this task the pilot lifted his visor when the height indicator showed that the breakout ceiling had been reached; he then brought the aircraft to a hover along the course center line in as short a distance as possible. If, near the range for the breakout height, the pilot saw that the aircraft was too high above the slope or displaced too far from the course, he executed a missed approach, still using the instrument display for guidance. It may be noted here that, for the visual slowdown operations, the pilot's visibility was somewhat restricted by the instrument display installation (fig. 5).

Approach Airspeeds

The approach airspeed for the evaluation tests of the four display configurations was about 30 knots. For the operational capability tests, the primary task was a 30-knot approach to a breakout height of 50 ft (15.24 m). At the completion of these tests, limited tests were made at approach speeds of 60 knots to a breakout height of 100 ft (30.48 m).

Since the speed for minimum power for the test helicopter is about 55 knots, the aircraft was flown on the back side of the power-required curve for the 30-knot approaches and just on the front side for the 60-knot approaches. The basic control technique for the two approach speeds was, therefore, quite different. For the 30-knot approaches, displacements from slope were corrected principally by the control of power and variations in airspeed by the control of pitch attitude. For the 60-knot approaches, slope displacements were corrected by pitch-attitude control.

The 30-knot airspeed had been selected for the lower approach speed because this was near the minimum indicated airspeed for controllable operation of the test helicopter. To avoid excessive time periods for completing approaches in head winds, however, the airspeed was increased to values required to maintain a ground speed of 30 knots. Thus, the pilot was required to determine, from a comparison of the readings of the airspeed and the ground-speed indicators, the proper airspeed for each approach.

Approach Path Patterns

The boundaries of the slope and course patterns about the 6° slope are shown in figure 6. The slope and course patterns were both of constant width (±50 ft (±15.24 m) for slope, ±75 ft (±22.86 m) for course) to a range of 1500 ft (457.2 m) and angular (±2° for slope, ±3° for course) beyond that point. The constant-width terminal paths were combined with the angular approach patterns in the present investigation because previous helicopter approach tests by the NASA had indicated the desirability of providing constant sensitivity path-deviation indications during the final portion of the approach.

At the beginning of the test program, the course boundaries were set at ±10° with a terminal path ±250 ft (±76.20 m) in width. During preliminary trials, the project pilot felt that his tracking performance could be improved if the pattern were made narrower (thereby increasing the sensitivity of the course-deviation indicator). The course boundaries were therefore narrowed first to ±5° with a ±125-ft (±38.10 m) terminal path and then to a final setting of ±3° with the ±75-ft (±22.86 m) terminal path.

The angular patterns for course and slope used in the present tests were appreciably narrower than those used in previous investigations. In reference 1, for example, the patterns for a 10° glide slope were ±12° for course and ±4° for slope. For the 12° glide slope used in reference 2, the preferred patterns were ±7° for course and ±3° for slope. In reference 3, it was concluded that the best patterns for a 9.5° glide slope were ±6° for course and ±4° for slope. These wider patterns were probably necessitated, at least in part, by the steeper approach paths. However, the need for the wider paths may also have been because constant-width terminal paths were not incorporated as in the present investigation.

Flight Tests

During the first two phases of the test program, the project pilot flew about 70 approaches during six 2-day operations over a period of about 8 months. The comparative evaluation of the display configurations was performed for the most part during the final two test periods.

For the operational capability tests of one of the display configurations, the project pilot flew twenty-two 30-knot approaches to a 50-ft (15.24 m) breakout in head, cross, and tail winds; these approaches were conducted during a 2-day period about 3 weeks after the evaluation tests. In a subsequent 1-day operation, the project pilot flew seven 60-knot approaches to a 100-ft (30.48 m) breakout under cross-wind conditions.

During the operational capability tests by the project pilot, a second pilot, who had flown as safety pilot during the latter part of the test program, performed fifteen 30-knot approaches using the display selected by the project pilot. This pilot had previously flown about 25 approaches during the display evaluation tests.

In a final test of the selected display, a third pilot flew six 30-knot approaches and four 60-knot approaches.

RESULTS AND DISCUSSION

Evaluation of Display Configurations

In using an instrument display for the control of the attitude, speed, and flight path of an aircraft, the pilot must interpret the indications of the various display elements, integrate the information to assess the existing situation, and then decide what control action he should take. In his evaluation of the four display configurations of the present investigation, therefore, the pilot was influenced by such factors as what information was displayed, how the information elements were presented (for ready interpretation), and how these elements were arranged (for ease in scanning and assessment of the overall situation).

Display A.- In his evaluation of the course guidance information of display A, the project pilot found that the ground-track angle indication was a helpful supplement to the course deviation information. If the aircraft began to deviate from course, for example, the ground-track pointer indicated this situation immediately, whereas the course bar, being relatively insensitive to lateral displacement, would not show a detectable deviation until sometime later. Similarly, if the aircraft was off course, the ground-track pointer would indicate when the aircraft had begun to return to course and, in addition, the angle at which the course was being approached. In a cross wind, the indicator was of assistance in determining the crab angle required to maintain course. With the presentation of heading on a rotating disk, however, the interpretation of the three indications to determine heading with respect to ground track and course proved somewhat difficult, particularly under rapidly changing conditions.

In using the artificial horizon and the slope deviation tab for speed and slope control, the pilot found that he was able to control the helicopter along a 6° slope at speeds (about 30 knots) on the back side of the power-required curve. However, because of the many combinations of pitch attitude and slope deviation encountered at low airspeeds, the dual information presentation was found to require intense concentration to assess the situation and determine the proper control action (pitch change, power change or some combination of the two) to correct the situation.

Because of the separate presentations of the vertical and horizontal situations and the number of individual attitude-guidance elements that must be monitored, the problem of scanning and integrating the information of this display was felt to be quite difficult.

In his final evaluation of display A, the project pilot flew eight consecutive approaches at an approach speed of 30 knots. The course and slope tracks for these approaches through a range of from 7000 ft to 1500 ft (2134 m to 457.2 m) are presented in figure 7. Since the approaches were started at a range beyond 7000 ft (2134 m), the track patterns for course acquisition do not appear on the course track plot. The tracks were terminated at a range of 1500 ft (457.2 m) because, as noted previously, it was at this point that the pilot attempted a speed reduction. Since the tracking in both course and slope generally became erratic following the speed reduction, the tracking performance for the evaluation tests of the four display configurations will be compared for only the initial constant-speed portion of the approach.

The winds for all of these approaches were fairly high and very gusty. The magnitudes and directions of the winds near the ground are shown for each approach by the wind speed-direction diagram in figure 7.

The course plots in figure 7 show that, although the aircraft wandered widely during the approach, the tracks were, for the most part, within the boundaries of the $\pm 3^{\circ}$ course pattern. Similarly, the slope tracks were within the boundaries of the $\pm 2^{\circ}$ slope pattern. The plots for both course and slope tracks, incidentally, present a distorted picture of the actual tracks, because of the five to one difference in the chart scales for range and displacements from slope and course.

Display B.- In his evaluation of the course control information on display B, the project pilot found that he could maintain course more closely and with less difficulty than with the course deviation and ground-track angle information of display A. This improvement was because the guidance information was presented as a single indication and the indication was in the form of a control command (that relieved the pilot of a part of the information-integration and situation-assessment task). The improved control was also due to the fact that the course control information was presented on the same indicator as the slope control information so that the scanning pattern was reduced considerably.

With pitch attitude displayed on the horizontal needle, the pilot thought that he was able to control the attitude (and, thus, the airspeed) more precisely than with the gyro horizon presentation of display A. This improved control was because, with the artificial horizon, the magnitude of a pitch attitude change was more difficult to gage when the artificial horizon indicated angles of roll. The difficulty of interpreting the dual information presentation for slope control, however, was essentially the same as with display A.

The course and slope tracks of five approaches with display B are presented in figure 8. These approaches were made during the same test period and under the same gusty wind conditions as the eight approaches with display A. The course tracks in figure 8 show that with the control command signals, the course tracking was markedly better than with the course deviation and ground-track angle information of display A (fig. 7). A comparison of the slope tracks in figure 8 with those in figure 7 shows that the slope tracking with display B was also better than that with display A. Some part of this improvement in slope tracking was probably due to the less difficult course control and to the reduced scanning, both of which allowed the pilot to give more attention to the slope control task. (Note that the approach with display B that began well above the 2° slope boundary was the first approach of this series.)

Display C.- With the display C configuration, in which airspeed error was presented on the horizontal needle and pitch attitude on the gyro horizon, the pilot was required to interpret two superimposed and closely related information symbols for speed control. Because of the parallel arrangement of the two symbols and the fact that their movements were not always in the same direction (due to the airspeed lag with pitch attitude change), the pilot found the dual information presentation confusing and difficult to use effectively.

The tracks for course and slope for three consecutive approaches with display C are shown in figure 9. The wind conditions for these approaches were about the same as those for the approaches with displays A and B.

Figure 9 shows that the slope tracking with display C was definitely poorer than that with display B (fig. 8); thus, the pilot's evaluation of the slope guidance information of the two displays was confirmed. The fact that the course tracking with display C was also poorer than that with display B may have been due to increased difficulty with the slope control using display C.

Display D.- With display D, the three primary guidance indications (course control command, slope deviation, and pitch attitude) were superimposed; the pilot's scanning pattern was therefore reduced somewhat. The beneficial effects of reduced scanning, however, were offset by the difficulty of using the artificial horizon for pitch attitude indications (as in the case of display A). The problem of distinguishing between the indications of the artificial horizon and the horizontal needle, however, was less difficult than with display C, because with display D the information presented by the two symbols was not directly related.

The tracks for four consecutive approaches with display D are presented in figure 10. These approaches were made under wind conditions that were somewhat lower and much less gusty than those for the approaches with displays A, B, and C. The better wind conditions probably account for the fact that the course tracking with display D was more precise than that with display B using the same control-command signals. The improved wind conditions are also believed to have accounted for the better slope tracking than with display B, even though the pilot preferred the slope guidance presentation of display B (particularly as regards the display of pitch attitude on the horizontal needle instead of the artificial horizon).

Pilot evaluation of displays.- On the basis of the tests of the four display configurations, the project pilot considered display B the best for operations at speeds below that for minimum power. The course guidance information of this display, based both on the pilot's opinion and on his tracking performance, was much superior to that provided by the course deviation and ground-track angle indications of display A. The slope guidance information on display B was considered the best of the four configurations because better speed control was achieved with pitch attitude displayed on the horizontal needle instead of the artificial horizon. The display of slope displacement on the slope-deviation tab on this display required somewhat greater scanning than the horizontal needle presentation of display D, but this was not considered a serious problem.

For approach speeds above that for minimum power, where an indication of slope displacement is the primary requirement for slope control and the need for a precise indication of pitch attitude is of secondary importance, display D would probably have been considered better than display B because the presentation of slope displacement on the horizontal needle would have been preferable and the display of pitch attitude on the artificial horizon would have been satisfactory.

Operational Capability Tests

Tests by project pilot.- For the operational capability tests of display B, the project pilot flew seven approaches into head winds, eight in cross winds, and seven in tail winds. The approach task for these approaches was a 30-knot approach to a breakout height of 50 ft (15.24 m) and a visual slowdown to hover.

The course and slope tracks for these approaches from the 7000-ft (2134 m) range to the hover point are shown in figures 11, 12, and 13. For two of the approaches in tail winds (fig. 13), the pilot aborted the approach while still on instruments. Thus, 20 of the 22 approaches were flown to a successful breakout and visual slowdown to hover.

From a comparison of the tracks for the three sets of approaches, it is apparent that the tracking performance in both course and slope was considerably better for the head- and cross-wind conditions than for the tail winds. From a comparison of the tracks in the head and cross winds, it is evident that tracking along the slope (using two indications for slope guidance) was less precise than tracking in course using the single control-command signal. The tracking in figures 11 and 12 was noticeably better than the tracking of the evaluation tests with display B (fig. 8); this difference was primarily because of the gusty conditions during the evaluation tests, but it may also have been because, in the evaluation tests, the pilot tended to concentrate occasionally on particular elements of the display, whereas in the operational capability tests, he scanned and made use of the entire display in a more consistent manner.

The tracks in figures 11, 12, and 13 were examined to determine the deviations at breakout and the distances from breakout to hover. Figure 14 shows the lateral deviations from course and the longitudinal deviations from the prescribed range for the

50-ft (15.24 m) breakout. The longitudinal deviations are shown to be considerably greater than the lateral deviation; this difference can be accounted for by the fact that, for equal deviations from slope and course, the slope deviation from a 6° slope would result in a longitudinal deviation ten times as great. Thus, longitudinal deviations due to slope deviation at breakout are an important factor that should be considered in the layout of V/STOL approach and landing areas.

The stopping distances from breakout to hover are given in table I in terms of the average, the maximum, and the minimum values for each of the three wind conditions. The stopping times from breakout to hover varied from 10 to 15 seconds, depending on the ground speeds at breakout. Although these data are not relevant to the instrument display problem, they are included as incidental information of interest from an operational standpoint.

The airspeeds and ground speeds at breakout were determined from the records of the airspeed recorder and the radar-data recorder. The average, maximum, and minimum values of the speeds for the three wind conditions are given in table II. The tabulated airspeeds were corrected for the position error of the pitot-static system. The radar recordings of ground speed were not corrected to the component along the track; however, from an examination of the ground-track angles at breakout, it was determined that the $\dot{x}$ recordings were within 0.3 knot of the speeds along the track. The airspeeds for the cross-wind condition are not given because of a failure to record six of the eight approaches.

In a final test period, the project pilot flew seven 60-knot approaches to a breakout height of 100 ft (30.48 m). These runs were made in cross winds and within a period of about 4 hr. The course and slope tracks for the seven approaches are shown in figure 15. On the first run, the pilot overshot the zero-range point by 125 ft (38.10 m). For all remaining approaches, the aircraft was stopped short of this point.

The lateral and longitudinal deviations from the prescribed 100-ft (30.48 m) breakout point are presented in figure 16. A comparison of these data with those in figure 14 for the cross-wind condition shows about the same deviations for the 50-ft (15.24 m) and the 100-ft (30.48 m) breakout operations.

The stopping distances from breakout to hover for the 100-ft (30.48 m) breakout approaches are given in table I. The airspeeds and ground speeds at breakout for these runs are given in table II.

For both the 30-knot and the 60-knot approaches, maintaining constant speed proved to be one of the most difficult control tasks. Examples of the variations in airspeed from the nominal approach speed are presented in figure 17(a) for the 30-knot approaches of figure 11 and in figure 17(b) for the 60-knot approaches of figure 15. The airspeed variations shown in figure 17 are plotted as a function of time for a range of about 7000 ft

(2134 m) to the breakout position. Since the 30-knot approaches were made into headwinds, the pilot tried to hold a higher airspeed in order to maintain a ground speed of 30 knots. For the 60-knot approaches, he tried to stabilize at 60 knots. (The approach in figure 17(b) in which the airspeed was reduced to about 30 knots near breakout was the first approach made by the pilot.) In both the 30- and 60-knot approaches, the airspeed varied about 5 knots from the speed the pilot was attempting to maintain.

Pilot work load.- The work load experienced by a pilot in using an instrument display can be increased considerably by the difficulty in controlling the aircraft. The influence of the stability and control characteristics and the effects of winds on the problem of controlling single-rotor helicopters in steep approaches are discussed in reference 4.

With the test helicopter, heading control and speed control were considered to be the most demanding tasks. At very low speeds, speed control became more critical because of the possibility of complete loss of glide-path control.

For the low-speed approaches in gusty air, the speed and attitude were constantly changing, so that the display-interpretation and control-response process became a continuous one requiring intense concentration and mental effort. Under some conditions, the situation changed so rapidly that the pilot was unable to scan and react quickly enough to perform the entire task. In these situations he was forced to concentrate on the speed and attitude control, to the detriment of the guidance task. Thus the work load could probably have been reduced and the guidance improved if the helicopter had been equipped with some form of artificial stabilization.

For the 30-knot approaches in head and cross winds, the pilot considered the work load to be quite high. With tail winds, the work load increased to the point that the pilot very nearly reached the limit of his ability to cope with the task.

For the 60-knot approaches in cross winds, the work load was considered to be only slightly lower than that for the 30-knot approaches in comparable wind conditions.

Tests by other pilots.- The fifteen 30-knot approaches that were flown by the second pilot with display B were made in head, cross, and tail winds. About 50 percent of the approaches were flown to a successful 50-ft (15.24 m) breakout and hover. This pilot had been assigned to the project late in the program; his experience with the test display was therefore considerably less than that of the project pilot. In addition, his experience in instrument flight and in the operation of the test helicopter was also much less.

For the 10 approaches with display B by the third pilot, 50 percent were flown to a successful breakout and hover. Although this pilot had a broad background of experience both in instrument flight operations and in the testing of helicopters and V/STOL aircraft, he had no experience with the test display prior to these tests and, in addition, had flown the test helicopter on only a few occasions during the preceding year.

In view of the limited success achieved by these two pilots, it is evident that the successful operations by the project pilot must be considered as only a partial indication of the operational suitability of the display. For 6^{o} approaches to a 50-ft (15.24 m) breakout, therefore, it was concluded that the operational use of the display would require that the pilot be highly competent in the operation of the machine, fully qualified in instrument flight operations, and trained for a considerable time in the use of the display.

SUMMARY OF RESULTS

An evaluation of a landing-approach instrument display incorporating a cross-pointer presentation has been conducted in landing approach tests with a helicopter. The approaches were made under simulated IFR (Instrument Flight Rules) conditions along a 6^{o} glide slope at approach speeds of 30 and 60 knots. The tests of four configurations of the guidance-attitude elements of the display showed the following results:

1. Course guidance information in the form of control command (flight director) signals provided more precise control of course than that provided by course-deviation and ground-track angle information. With the flight director commands, guidance along the course was kept well within the boundaries of a $\pm 3^{o}$ course pattern having a 1500 ft (457.2 m) terminal path ± 75 ft (± 22.86 m) wide.

2. With the best of the four configurations of slope guidance information (slope deviation and pitch attitude), satisfactory guidance along a 6^{o} slope could be maintained at airspeeds below that for minimum power. With this configuration, 30-knot approaches were flown within the boundaries of a $\pm 2^{o}$ slope pattern with a 1500 ft (457.2 m) terminal path ± 50 ft (± 15.24 m) in width. The tracking along the slope, however, was less precise than the tracking in course using the control command signal.

3. With the best display of course and slope guidance, one pilot flew twenty (out of twenty-two) 30-knot approaches (in head, cross, and tail winds) to a successful 50-ft (15.24 m) breakout and visual slowdown to hover. With the same display, he also flew seven 60-knot approaches to a breakout height of 100 ft (30.48 m).

4. For the 30-knot approaches, the pilot work load was considered to be quite high; for the 60-knot approaches, the work load was only slightly lower. For both approach speeds, the work load would probably have been reduced if the helicopter had been equipped with some form of artificial stabilization.

5. For 6^{o} approaches to a 50-ft (15.24 m) breakout, the operational use of the test display would require that the pilot be highly competent in the operation of the machine,

fully qualified in instrument flight operations, and trained for a considerable time in the use of the display.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., June 14, 1966.

APPENDIX A

INSTRUMENT CALIBRATION TESTS

Instrument Display

The accuracies of the displayed quantities in the aircraft were determined by a variety of means. The range and course deviation indicators were calibrated by placing the helicopter at surveyed distances from the slope origin and the course center line. The height and slope deviation indicators were calibrated with a tape line at heights up to 100 ft (30.48 m) at a range where the slope was 50 ft (15.24 m) above the ground. The airspeed and the ground-speed indicators were calibrated in pacing approaches with an automobile having a calibrated speedometer. Calibrations of the ground-track angle indicator were made by flying the helicopter along course lines at known angles to the course center line. No calibrations were made of the vertical-speed indicator because of the difficulty of making accurate height-time measurements.

As a means of checking the stability of the calibrated accuracies of the range, height, ground-speed, vertical speed, and ground-track angle indicators, fixed-value signals for x, z, $\dot{x}$, $\dot{z}$, and $\dot{y}/\dot{x}$ were telemetered from the ground station, at the beginning of each series of flights, to check the zero settings and the sensitivities of the instruments at one point on their scales. At the same time, ILS calibrate signals were transmitted to check the sensitivities of the slope and course deviation indications on the VSFDI and the HSI.

The results of the instrument calibration tests revealed no bias or sensitivity errors in any of the instruments except the airspeed indicator, which was found to read low by about 3 knots throughout the range of approach speeds of the present tests; this error was caused by the position error of the pitot-static installation.

From the results of both the calibration tests and the stability checks, it was determined that, in general, the accuracies of the displayed indications were within the reading accuracies of the instruments.

Radar and Automatic Plotters

In order to realize the utmost accuracy from the radar, the x, y, and z coordinate measurements were adjusted at the beginning of each day's operation by transmitting signals to a number of corner reflectors located at known distances from the antenna. The measurements from these reflectors were also used to adjust the range sensitivity of the automatic plotters. The sensitivities of slope and course on these plotters were adjusted to path-width charts which had been established as standards for the test program.

APPENDIX A

Prior to each approach, the helicopter was placed on the ground at the slope origin to check the zero settings of the x-y and x-z plotters. The helicopter was thereafter placed over surveyed positions in the course path to check the longitudinal sensitivity of the two plotters and the lateral sensitivity of the x-y plotter.

The accuracy (one sigma value) of the radar as specified by the manufacturer is 0.3 mil (0.02°) for the azimuth and elevation angles of the antenna and 10 ft (3.048 m) or 1 percent (whichever is greater) for slant range. For the angular scanning ranges of the present tests, the accuracies (one sigma value) of the rectangular coordinates (as derived from the specified accuracies for slant range and antenna angles) should have been as follows:

x coordinate	10 ft (3.048 m) or 1 percent (whichever is greater)
y coordinate	3 ft (0.9144 m) at zero range 8 ft (2.438 m) at 7000-ft (2134 m) range
z coordinate	1 ft (0.3048 m) at zero range 11 ft (3.353 m) at 7000-ft (2134 m) range

On the basis of the x-y plotter checks with the helicopter over the surveyed points in the course path, however, the accuracy of the x coordinate was found to be appreciably better than the specified accuracy of the radar; the accuracy of the y coordinate was found to be within the specified accuracy. From the tape-line calibration of the height indicator, the accuracy of the z coordinate appeared to be about the same as the specified accuracy.

APPENDIX B

RADAR AND GUIDANCE SYSTEM

Radar

The radar was a precision tracking radar (fig. 18) having an antenna beamwidth of approximately $1/2^{\circ}$. The angular tracking ranges were -10° to 30° in elevation and $\pm 45^{\circ}$ in azimuth. The system had the capability of determining aircraft position both in rectangular (x, y, and z) 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 deflections of ILS path deviation indicators. The boundaries of these beam patterns could 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, and the intersection of the slope with ground could be set some distance ahead of the radar; these features provided considerable flexibility in positioning the landing site for the aircraft. For the present tests, the radar was located 250 ft (76.20 m) to one side of the course and the slope intercept at the ground was located 650 ft (198.2 m) ahead of the radar.

Guidance System

A functional diagram of the guidance system is presented in figure 19. The position of the aircraft (as referenced to a corner reflector on the nose of the helicopter) is first determined from the slant range r and the elevation and azimuth angles β and ψ of the radar 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. Five of these quantities x, z, $\dot{x}$, $\dot{y}$, and $\dot{z}$ are transmitted directly to the aircraft. Three of the quantities x, y, and z are processed through the slope-deviation computer that compares x and z coordinates with the desired flight path and determines the linear displacement Δz of the aircraft from the selected slope. In the proportionate path-deviation computer, the linear displacements from slope and course Δz and y 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 $d_c = y/w_c$). 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 to the aircraft by two radio transmitters.

APPENDIX B

In the aircraft, the telemetered signal is filtered and processed in discriminators and analog computers (fig. 20) into x, z, $\dot{x}$, and $\dot{z}$ signals for display on the range, height, ground-speed, and vertical-speed indicators. The velocities $\dot{x}$ and $\dot{y}$ are transformed into the quantity $\dot{y}/\dot{x}$ for the indication of ground-track angle, which is referenced to heading in a differential servo before display on the HSI. The display of $\dot{x}$ as ground speed and $\dot{y}/\dot{x}$ as ground-track angle are, of course, only approximations of the actual values; for ground-track angles up to 15°, however, the displayed quantities are correct to within 3 percent of the actual values. The airspeed indicator is driven by an electrical pressure transducer which is actuated by the pitot-static system of the aircraft.

From the ILS receivers, the proportionate path-deviation signals (d_s and d_c) are transferred to the VSFDI, the HSI, and the flight-director computer. The steering command signal c_s and the signals for pitch attitude, airspeed error, and slope deviation θ, e, and d_s are transferred from the flight director computer to the vertical and horizontal needles of the VSFDI.

Three gyros (vertical, compass, and turn-rate) provide inputs of roll, pitch, heading, and heading rate to the VSFDI and the HSI.

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2. Seckel, E.; Traybar, J. J.; and Miller, G. E.: A Note on the Effect of Helicopter Dynamics on Steep Instrument Approaches. Rept. No. 600 (Contract DA 44-177-TC-524), Dept. Aeron. Eng., Princeton Univ., Feb. 1962.

3. Seckel, E.; Traybar, J. J.; and Miller, G. E.: An Exploratory Study of Instrument Approaches With Steep Gradient Aircraft. Rept. No. 630 (TRECOM Tech. Rept. 63-28), Dept.Aeron. Eng., Princeton Univ., Oct. 1962.

4. Reeder, John P.; and Whitten, James B.: Notes on Steep Instrument Approaches in a Helicopter. Proc. Twelfth Ann. Natl. Forum, Am. Helicopter Soc., Inc., May 1956, pp. 80-86.

TABLE I.- STOPPING DISTANCES FROM BREAKOUT TO HOVER

Wind	Stopping distance					
	Average		Maximum		Minimum	
	ft	m	ft	m	ft	m
30-knot approaches to a breakout height of 50 ft (15.24 m)						
Head	286	87.17	375	114.3	200	60.96
Cross	300	91.44	425	129.5	165	50.29
Tail	386	117.6	465	141.7	325	99.06
60-knot approaches to a breakout height of 100 ft (30.48 m)						
Cross	915	278.9	985	300.2	835	254.5

TABLE II.- AIRSPEEDS AND GROUND SPEEDS AT BREAKOUT

Wind	Airspeed, knots (a)			Ground speed, knots		
	Average	Maximum	Minimum	Average	Maximum	Minimum
30-knot approaches to a breakout height of 50 ft (15.24 m)						
Head	33.1	39	28	24.4	30	20
Cross	----	--	--	28.1	36	13
Tail	28.2	33	23	38.5	44	29
60-knot approaches to a breakout height of 100 ft (30.48 m)						
Cross	56.2	64	30	45.5	57	17

[a]Corrected for position error of pitot-static system.

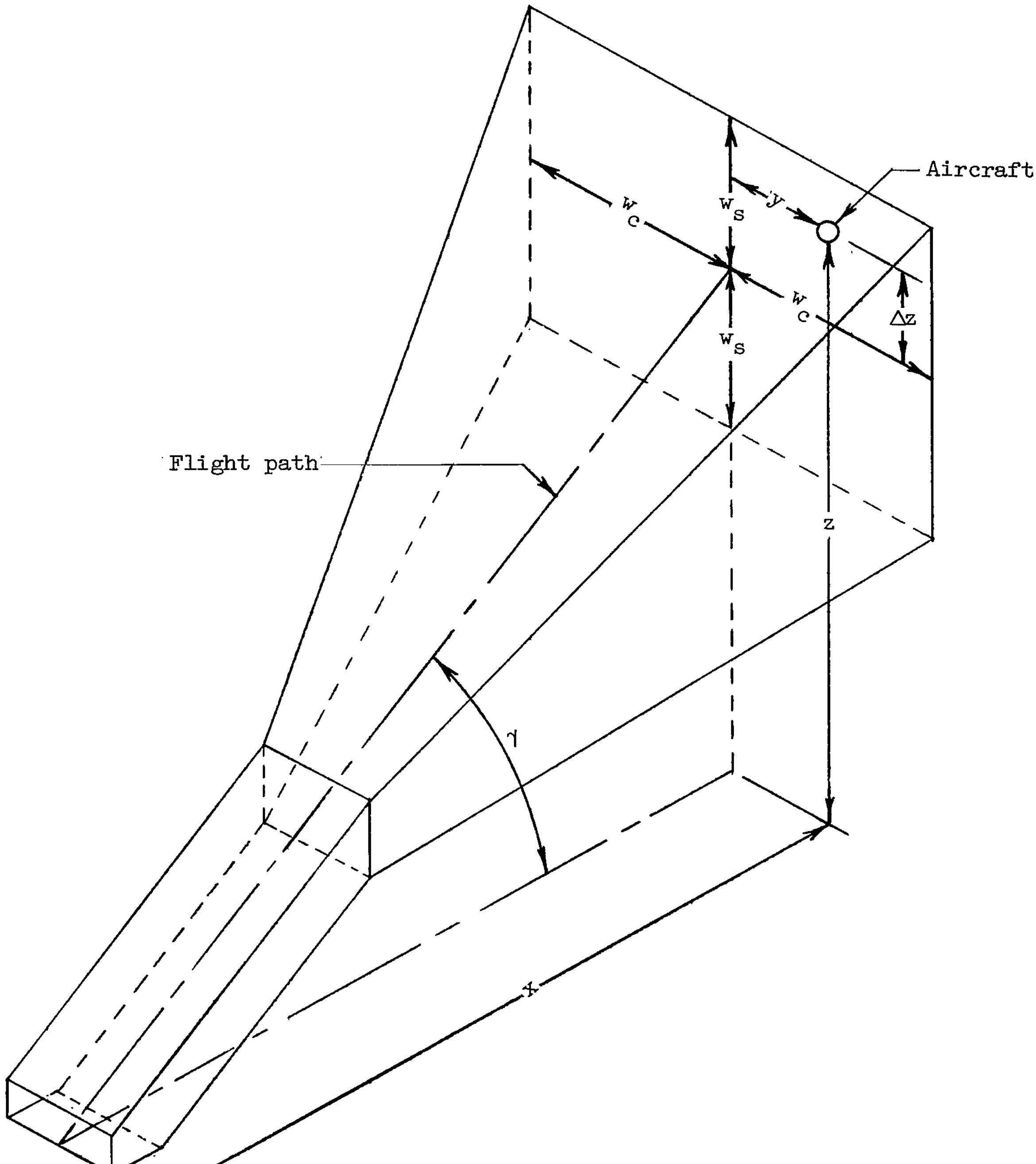


Figure 1.- Diagram showing rectangular coordinates and slope and course boundaries.

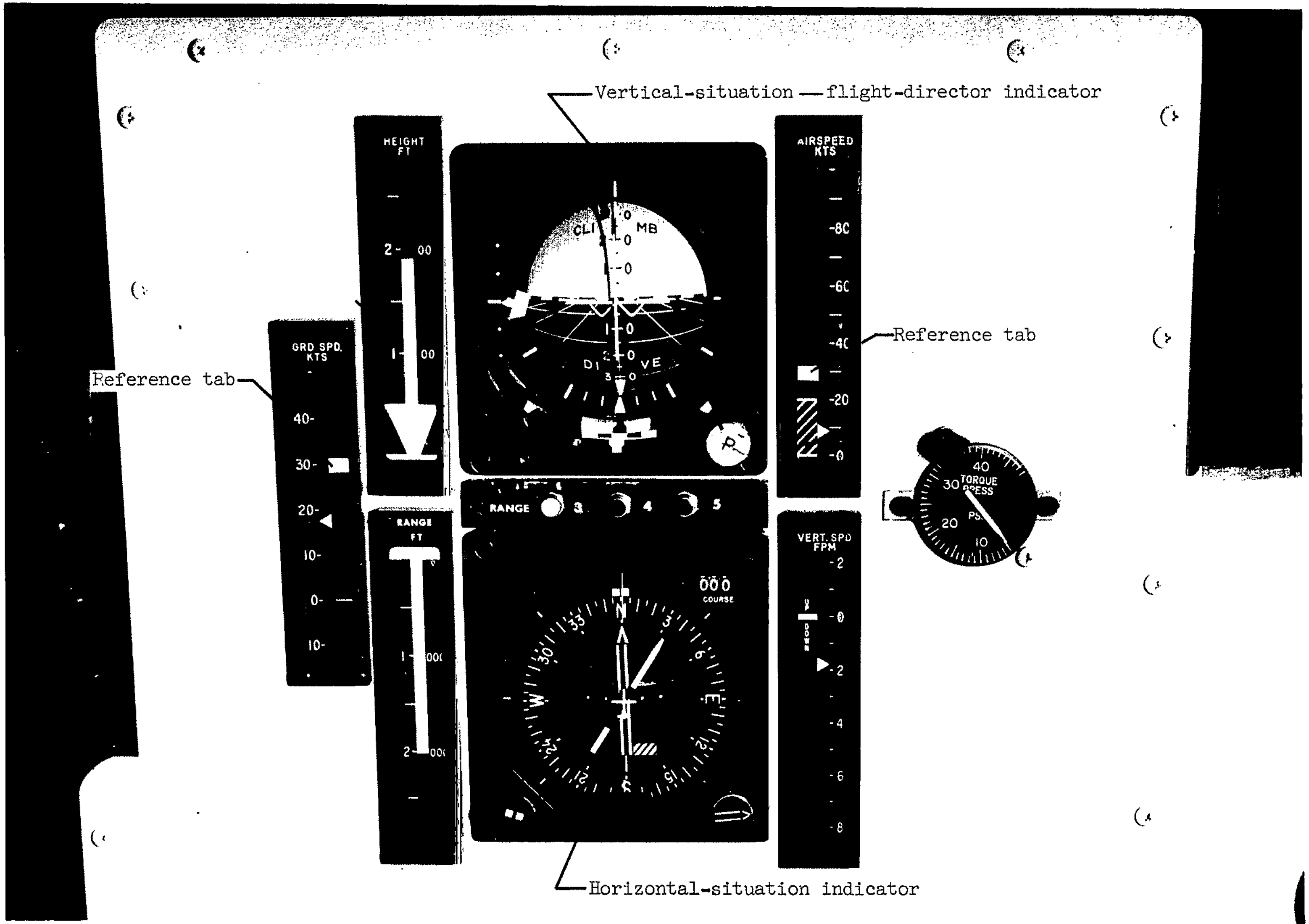


Figure 2.- Test instrument display.

L-66-93.1

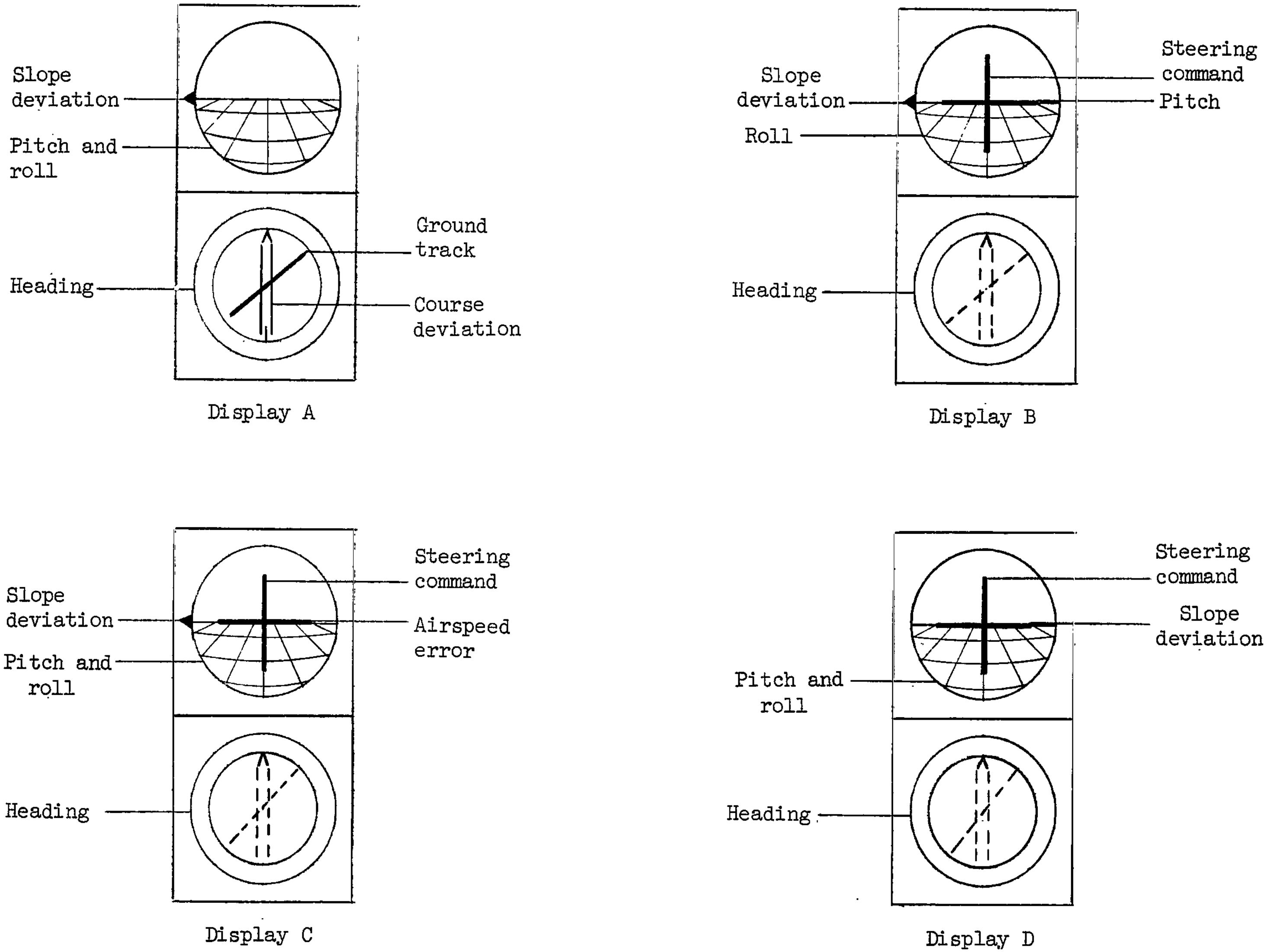
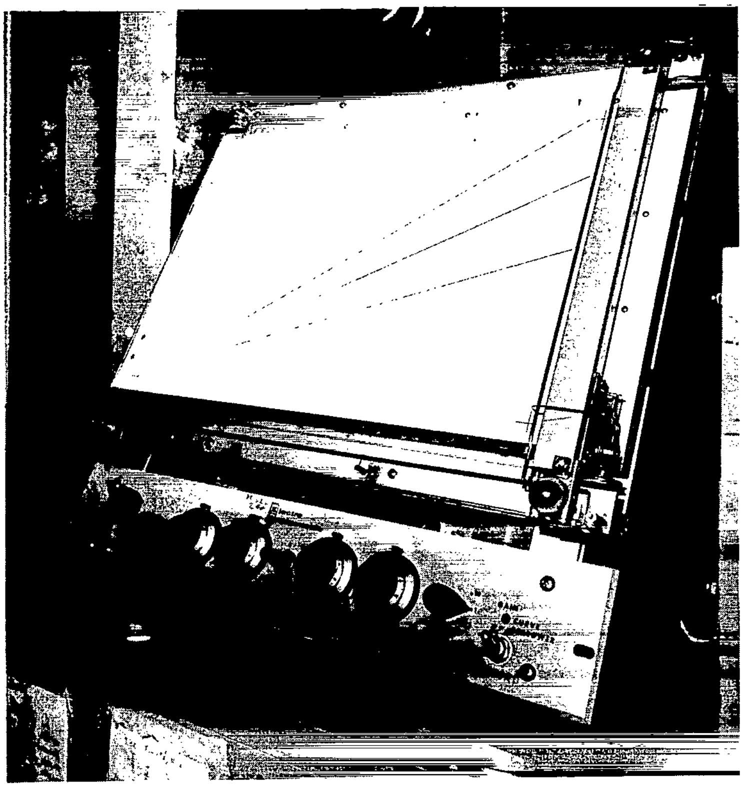
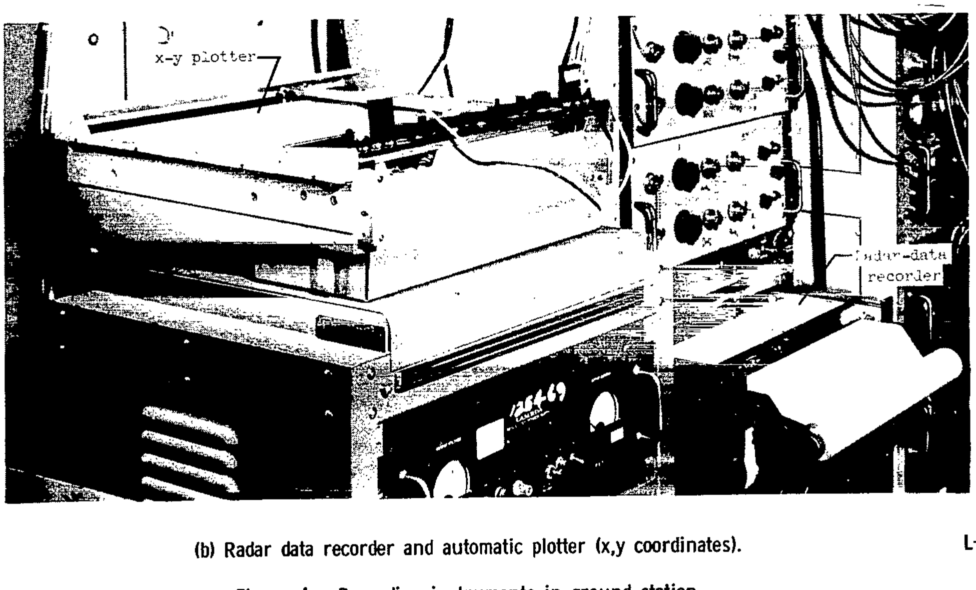


Figure 3.- Diagrams of display configurations showing attitude-guidance elements of primary interest.



(a) Automatic plotter (x,z coordinates). L-65-8503



(b) Radar data recorder and automatic plotter (x,y coordinates). L-65-8501.1

Figure 4.- Recording instruments in ground station.

Figure 5.- Test helicopter.

L-65-8688.1

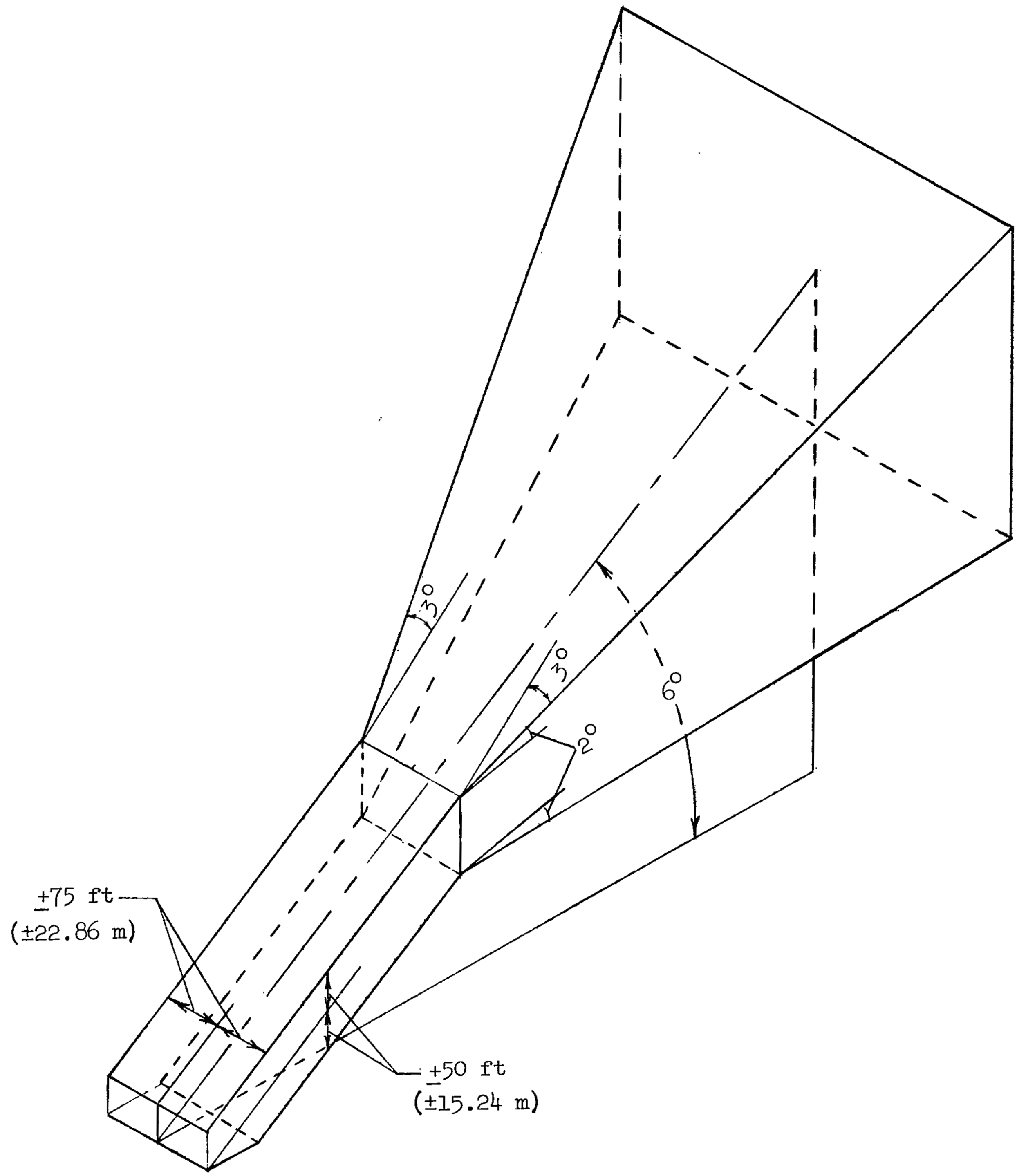


Figure 6.- Boundaries of simulated ILS beam patterns for present investigation.

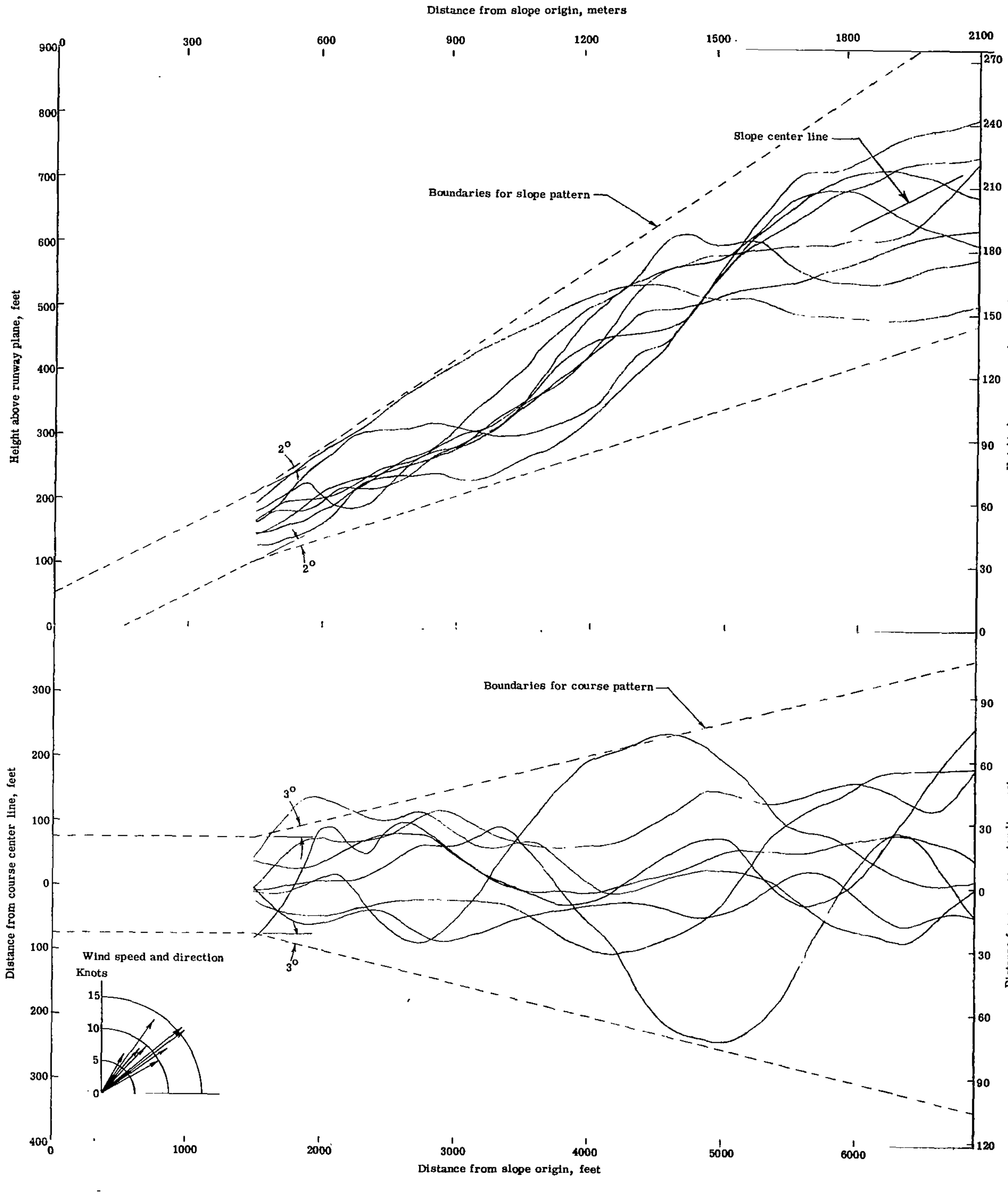


Figure 7.- Course and slope tracks for eight 30-knot approaches with display A.

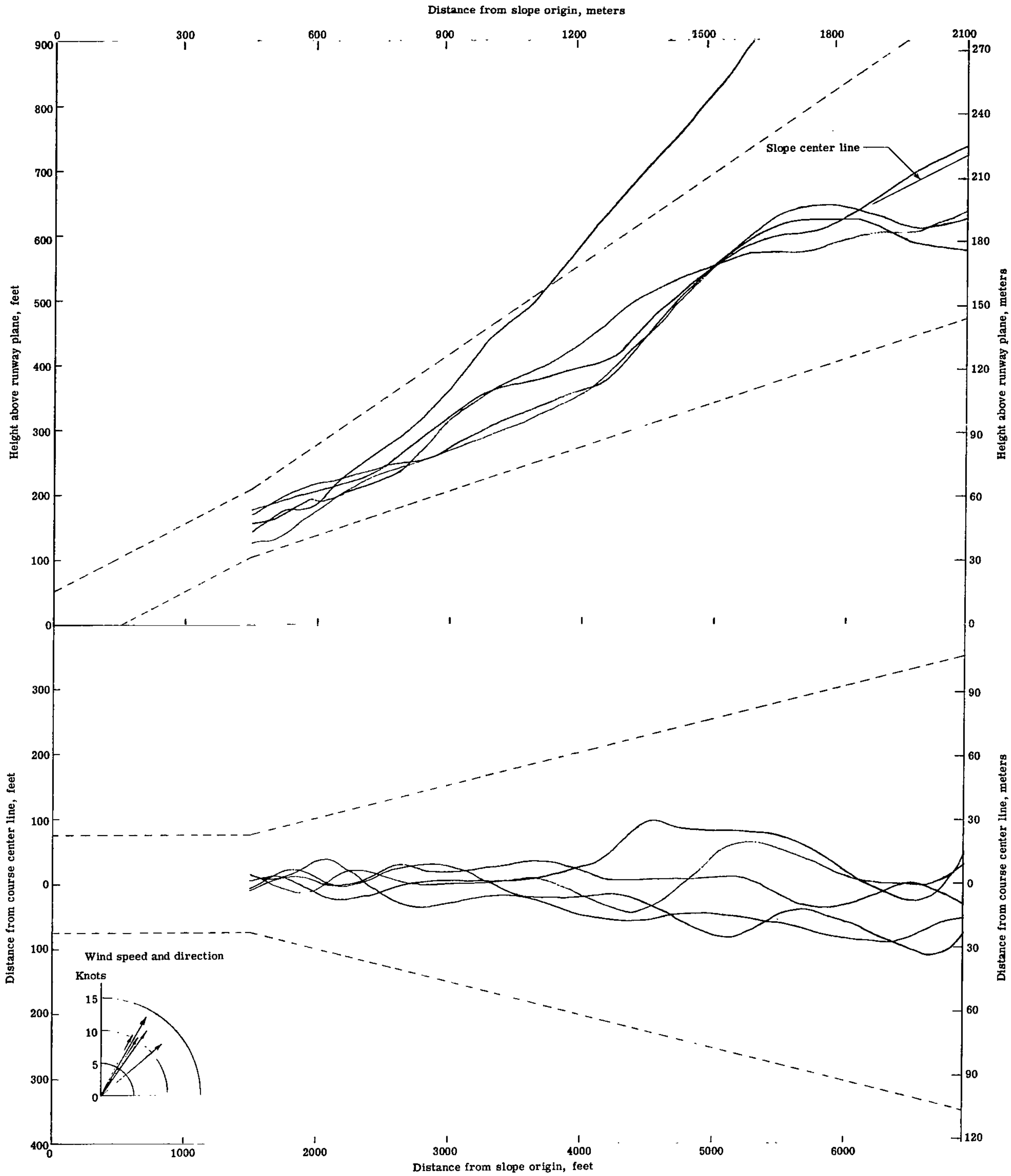


Figure 8.- Course and slope tracks for five 30-knot approaches with display B.

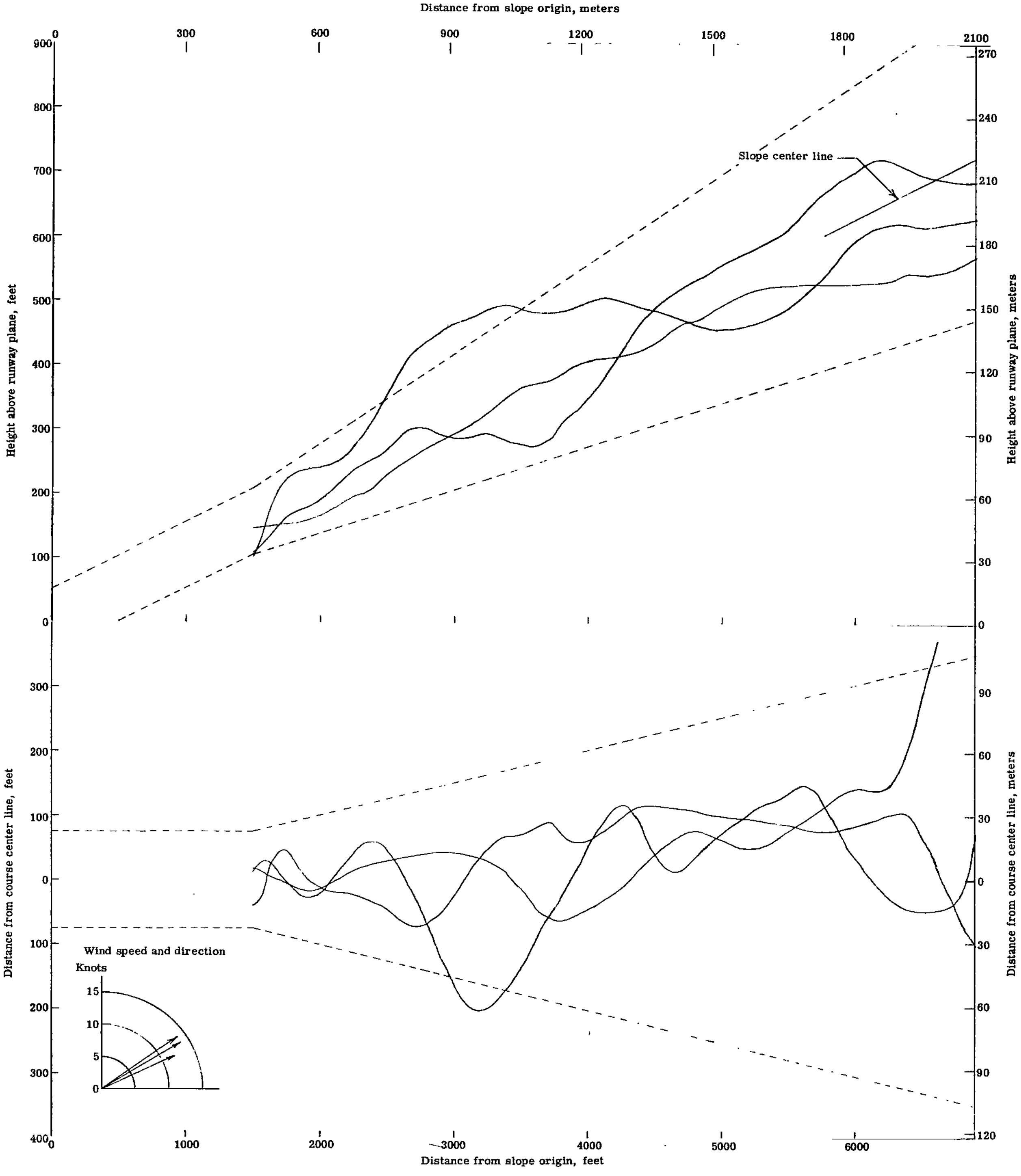


Figure 9.- Course and slope tracks for three 30-knot approaches with display C.

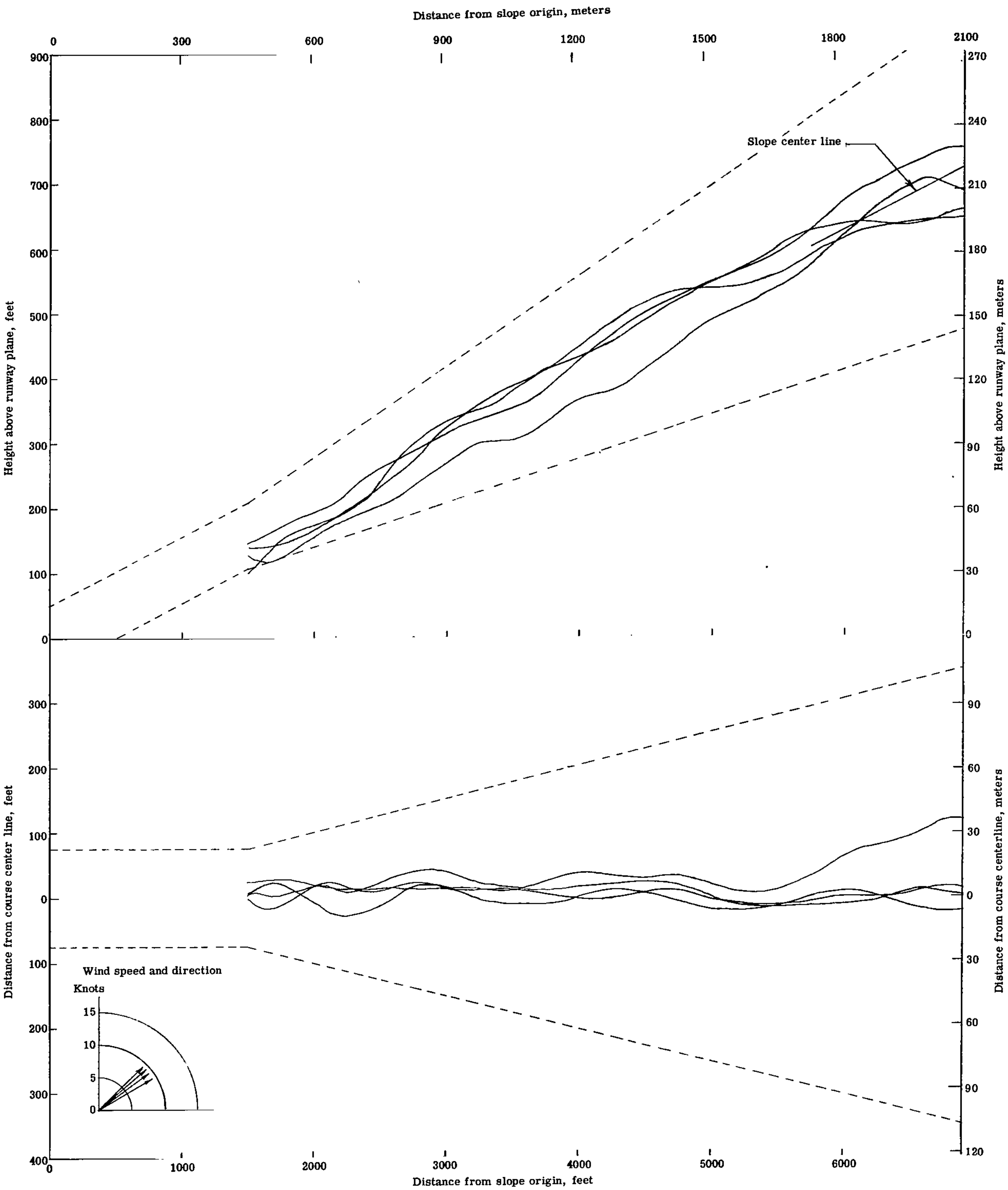


Figure 10.- Course and slope tracks for four 30-knot approaches with display D.

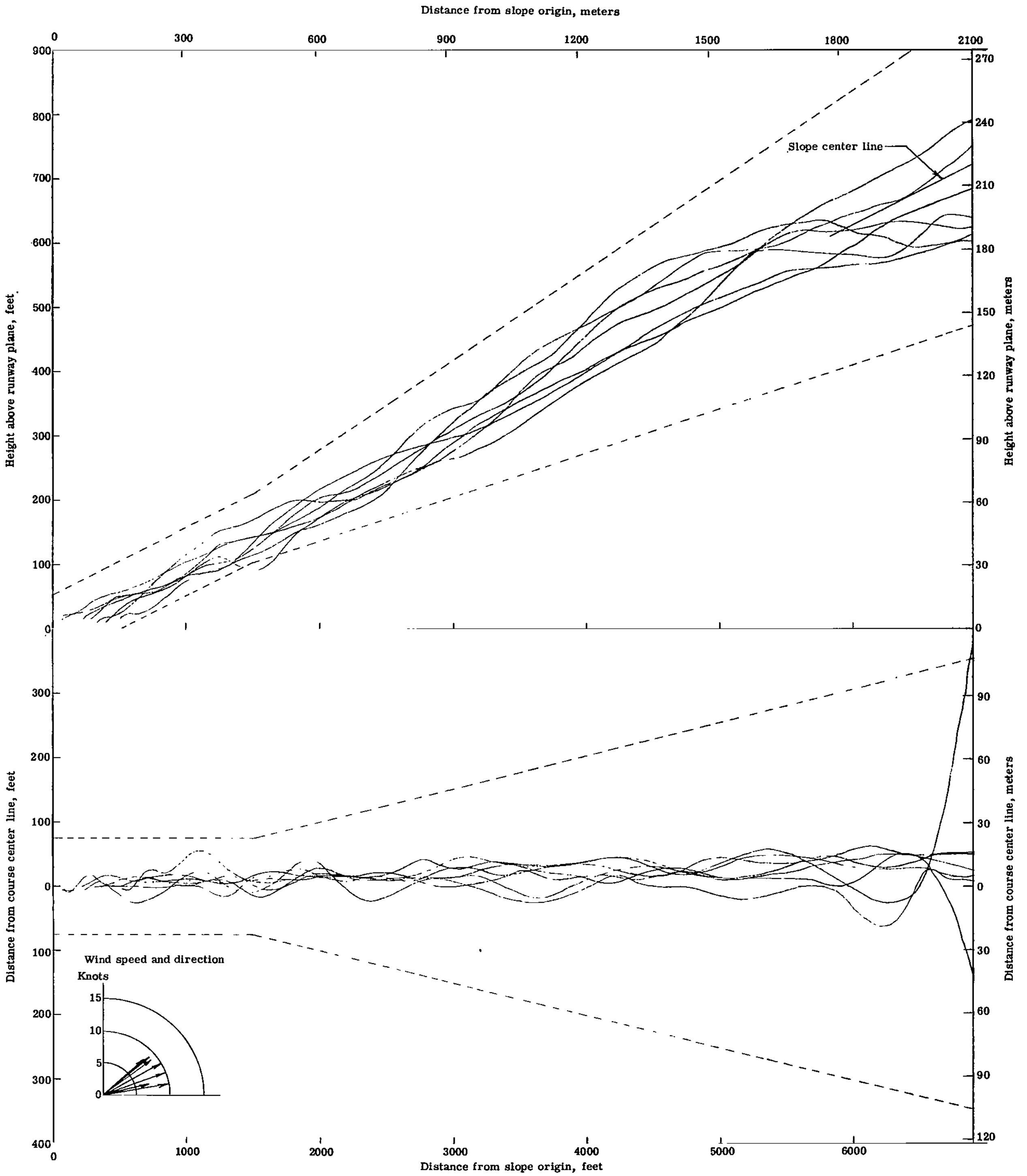


Figure 11.- Course and slope tracks of seven approaches into headwinds. Nominal 30-knot airspeed to breakout height of 50 ft (15.24 m); display B.

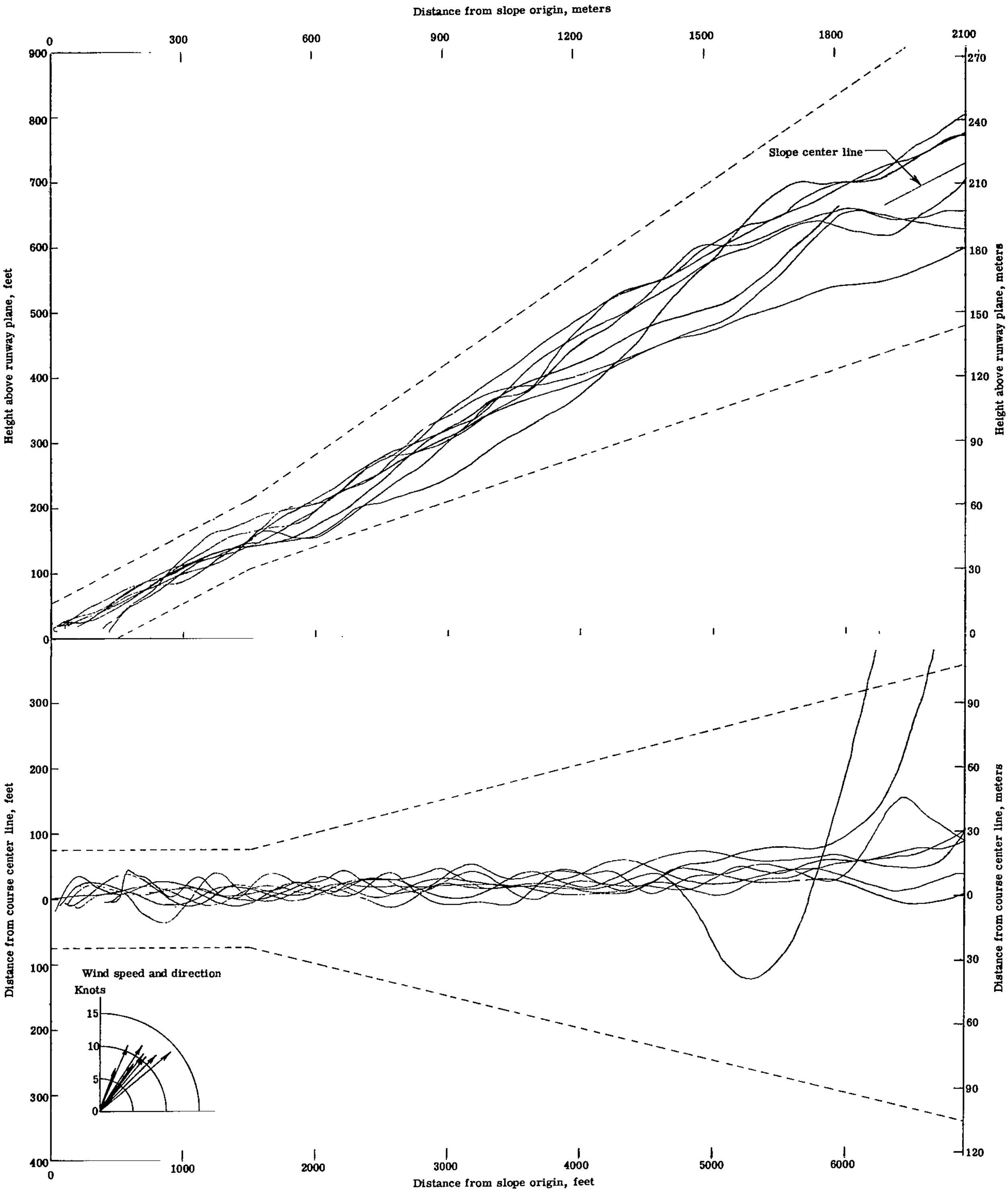


Figure 12.- Course and slope tracks of eight approaches in crosswinds. Nominal 30-knot airspeed to breakout height of 50 ft (15.24 m); display B.

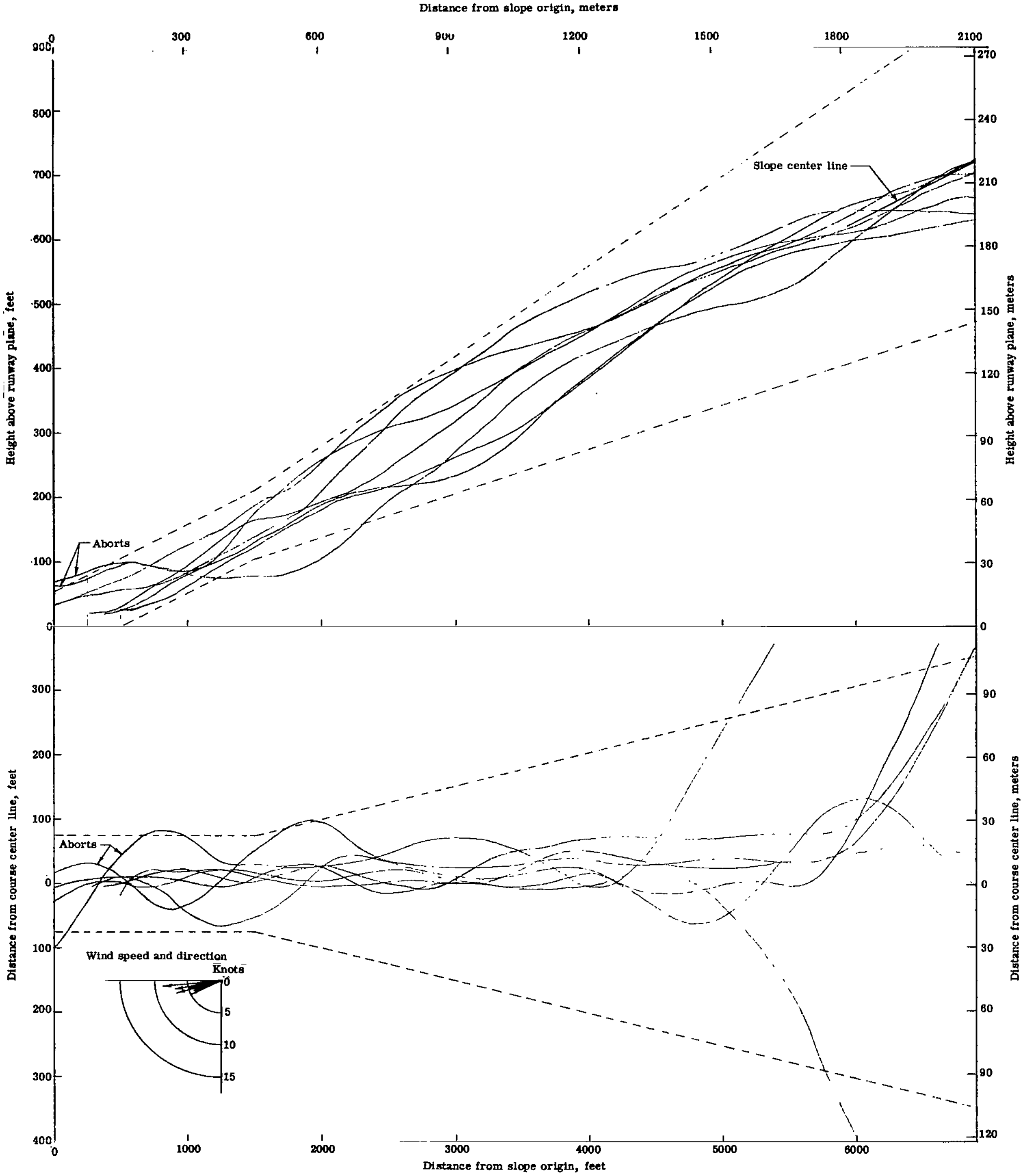


Figure 13.- Course and slope tracks of seven approaches with tailwinds. Nominal 30-knot ground speed to breakout height of 50 ft (15.24); display B.

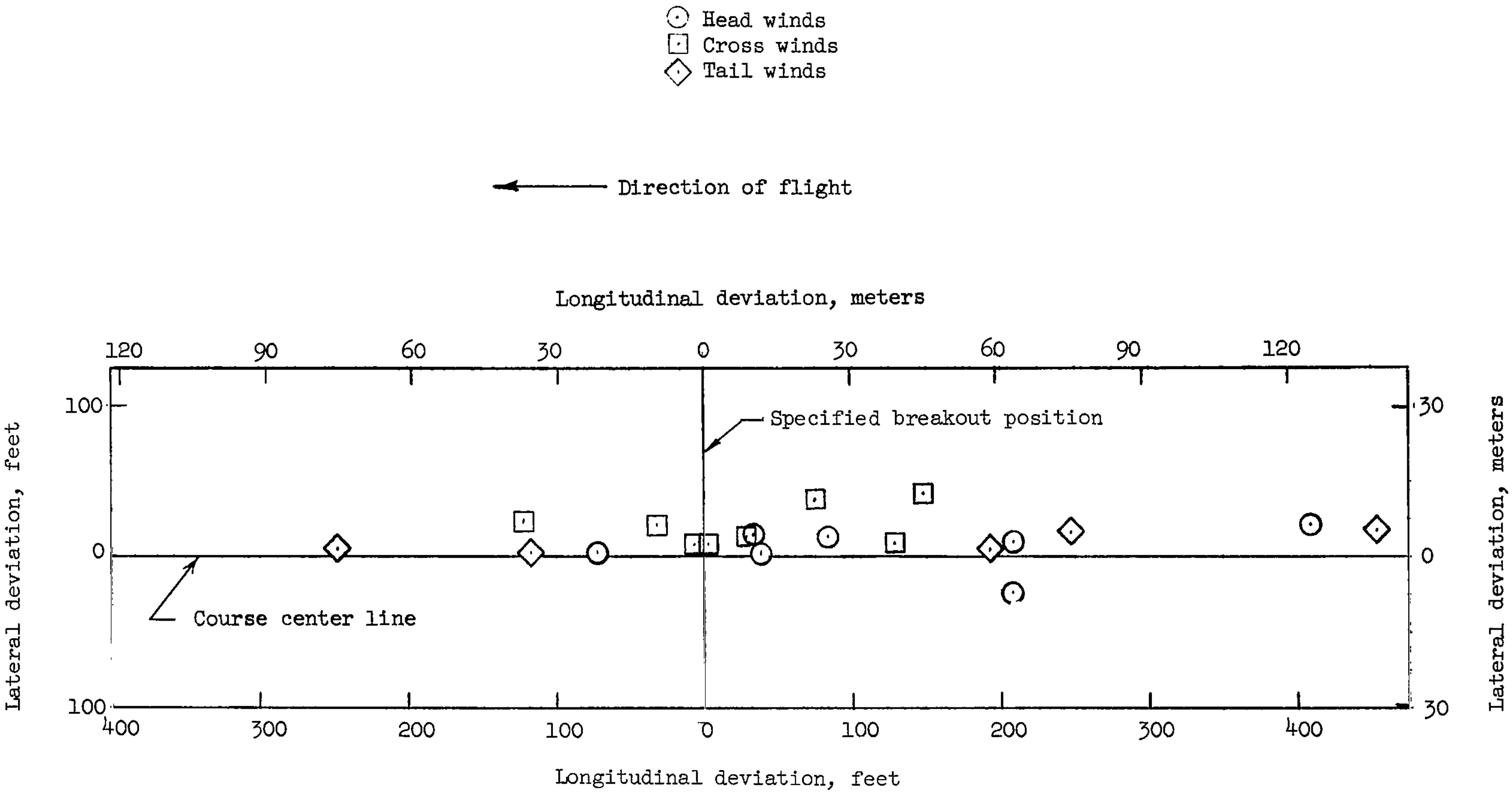


Figure 14.- Longitudinal and lateral deviation of aircraft at 50-ft (15.24 m) breakout. Data from figures 11, 12, and 13.

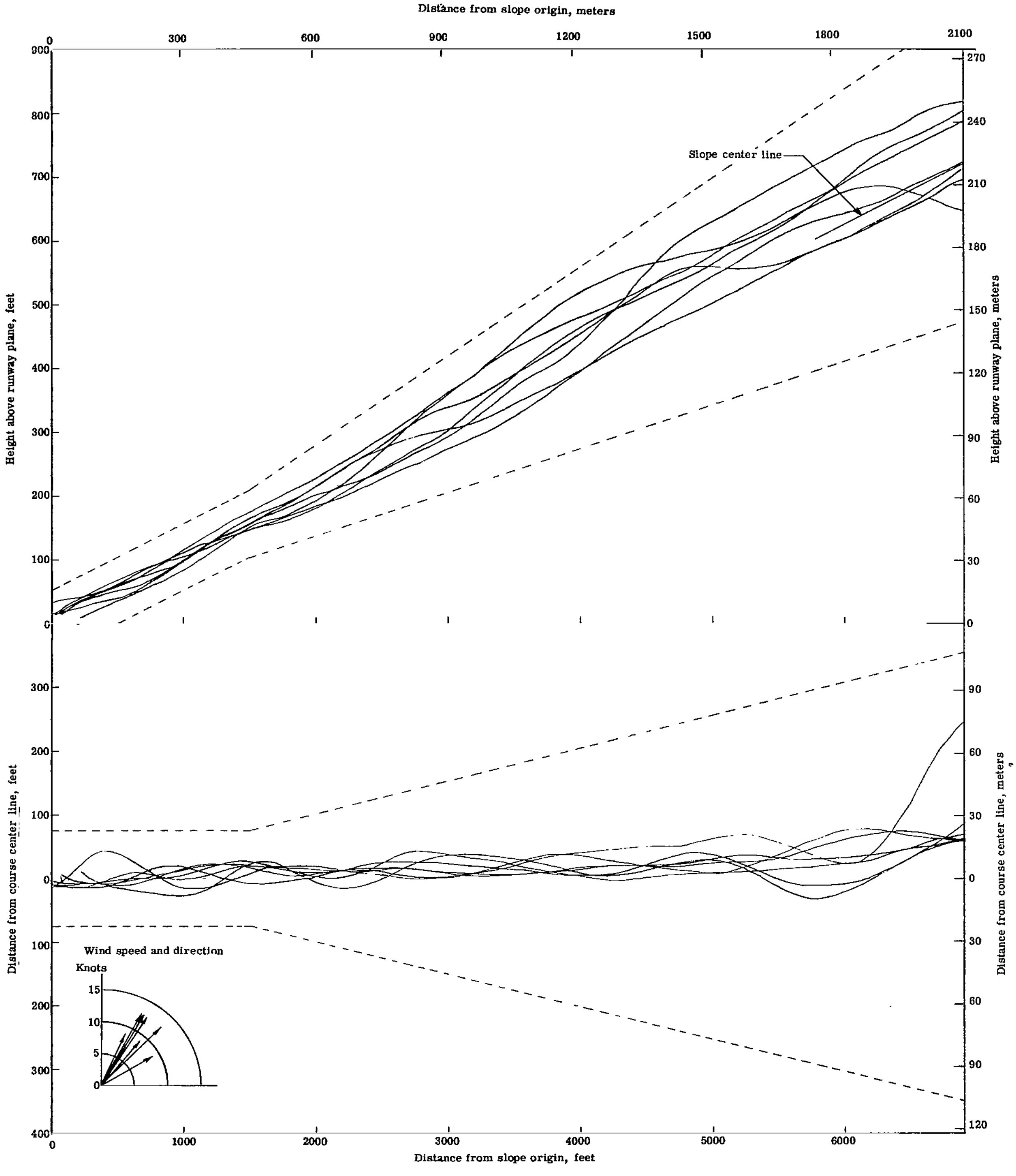


Figure 15.- Course and slope tracks of seven approaches in crosswinds. Nominal 60-knot airspeed to breakout height of 100 ft (30.48 m); display B.

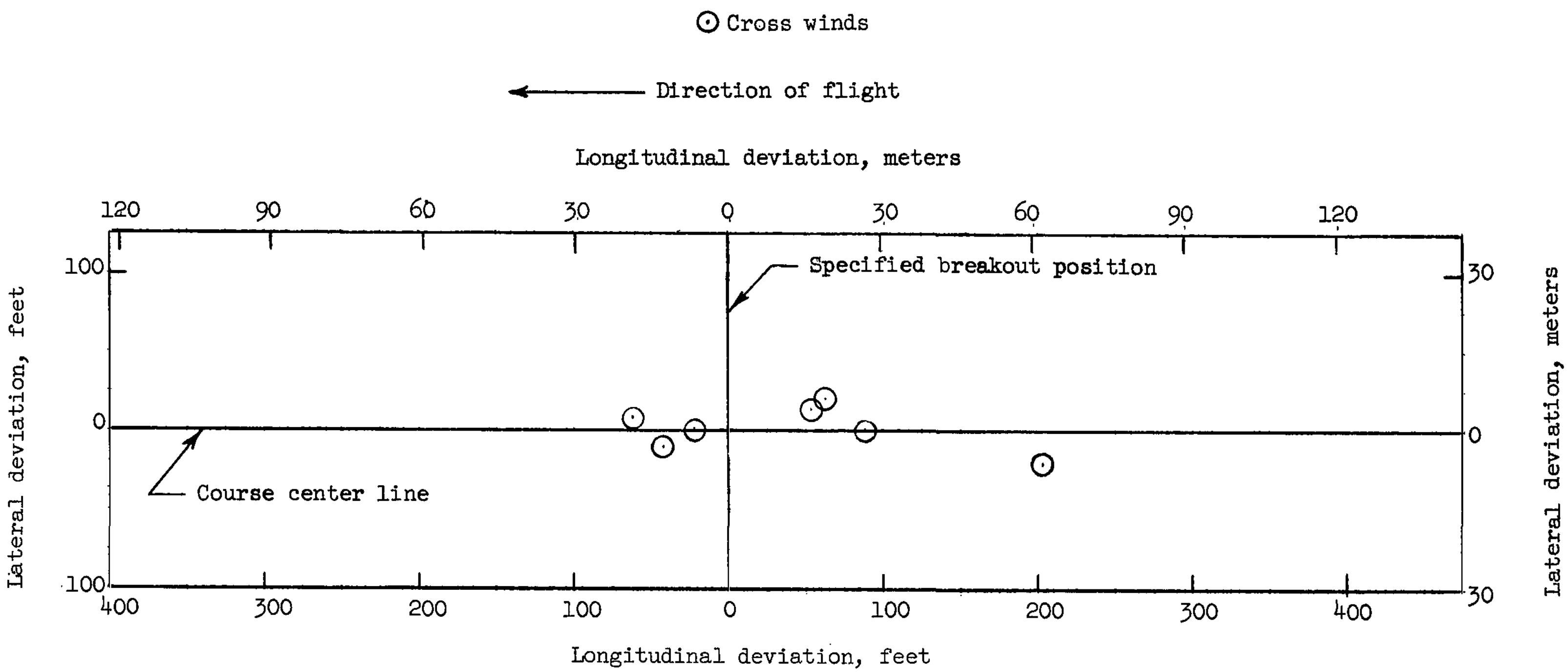
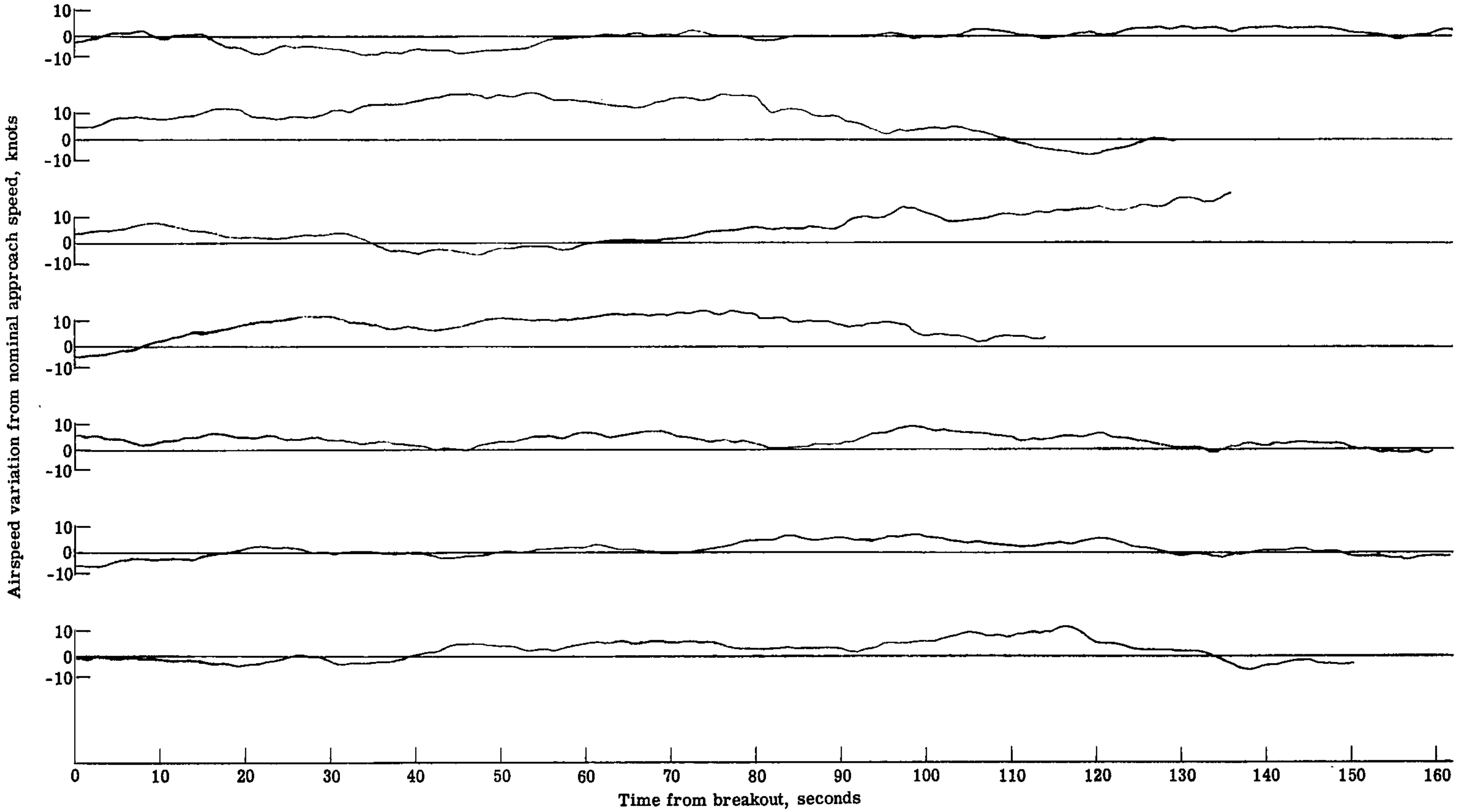
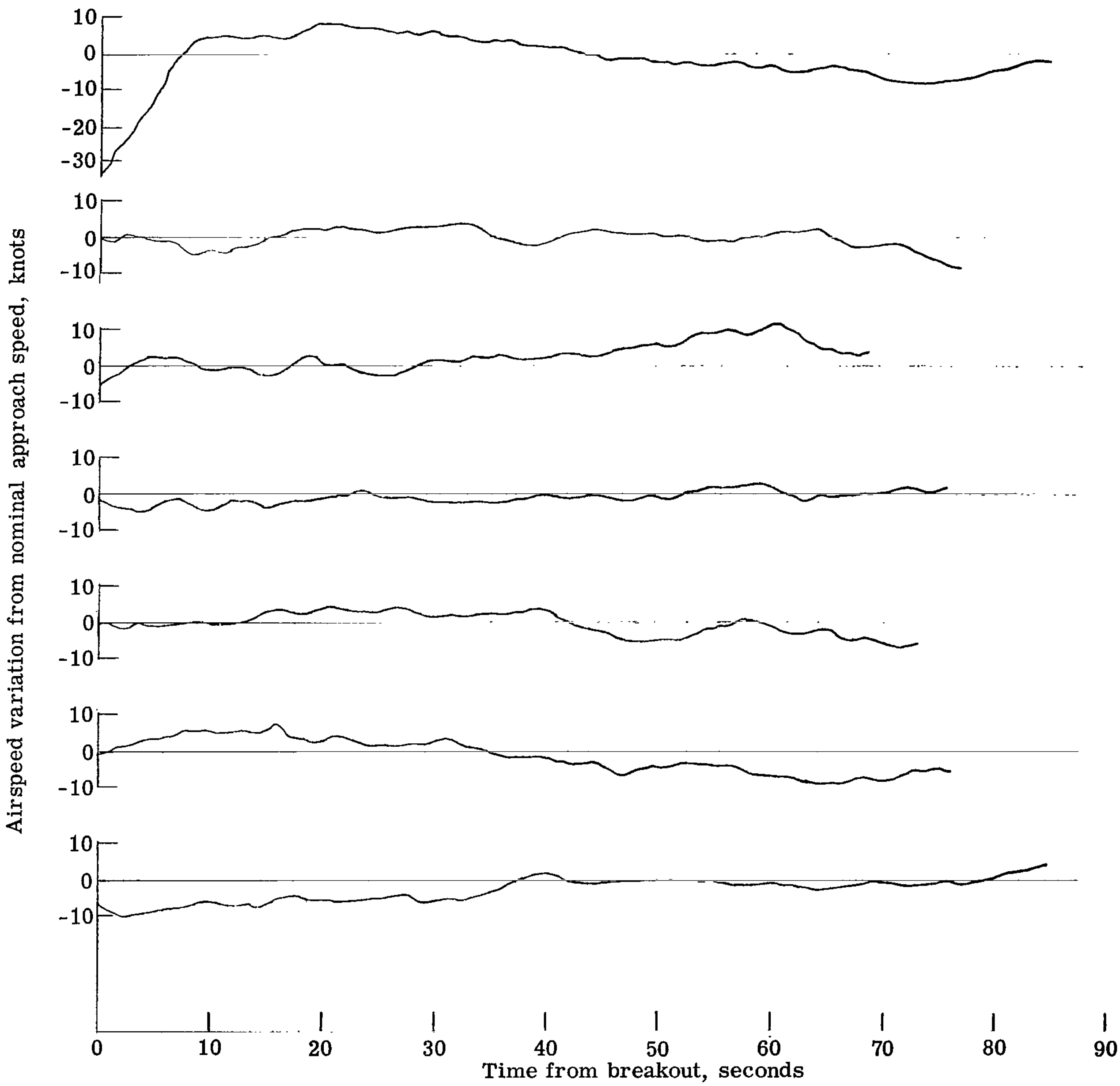


Figure 16.- Longitudinal and lateral deviation of aircraft at 100-ft (30.48 m) breakout. Data from figure 15.



(a) 30-knot approaches into head winds.

Figure 17.- Time-histories of airspeed variations from nominal approach speeds of 30 and 60 knots. All approaches start at range of about 7000 ft (2134 m).



(b) 60-knot approaches in cross winds.

Figure 17.- Concluded.

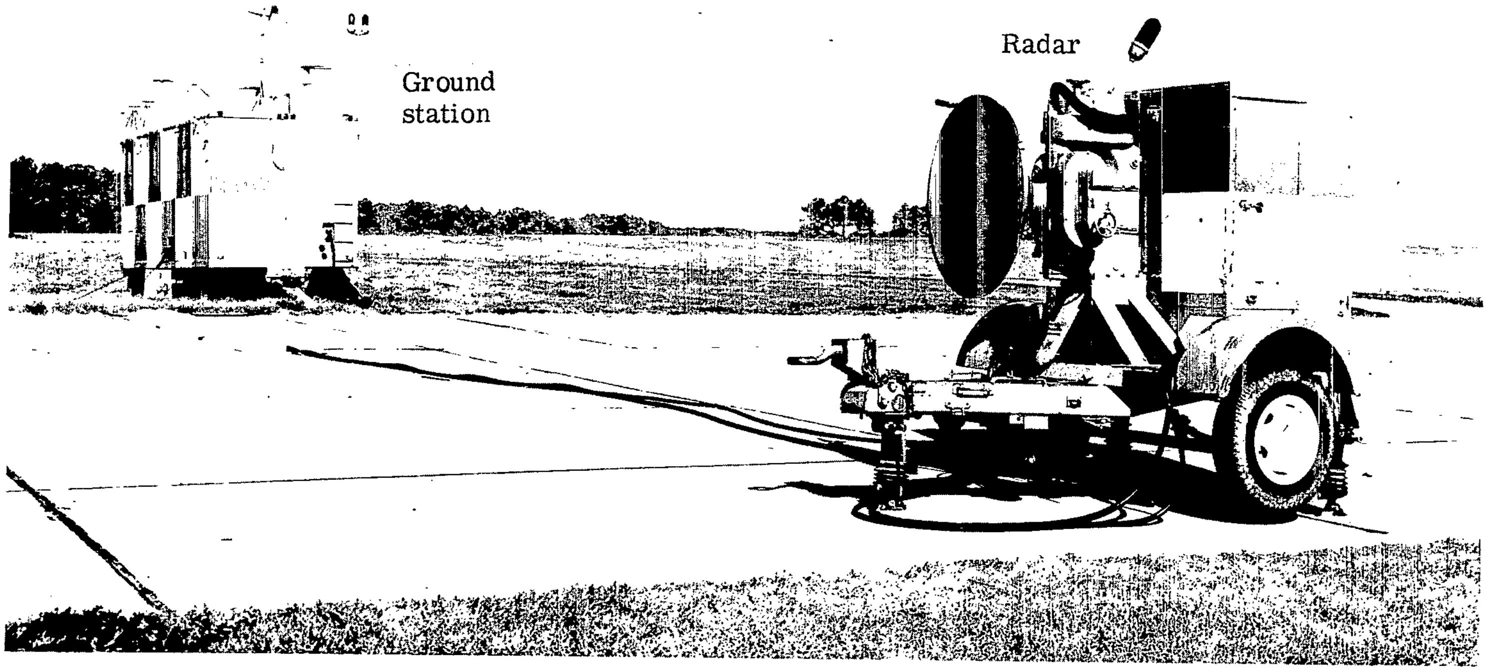


Figure 18.- Ground-based guidance equipment. L-65-8502.1

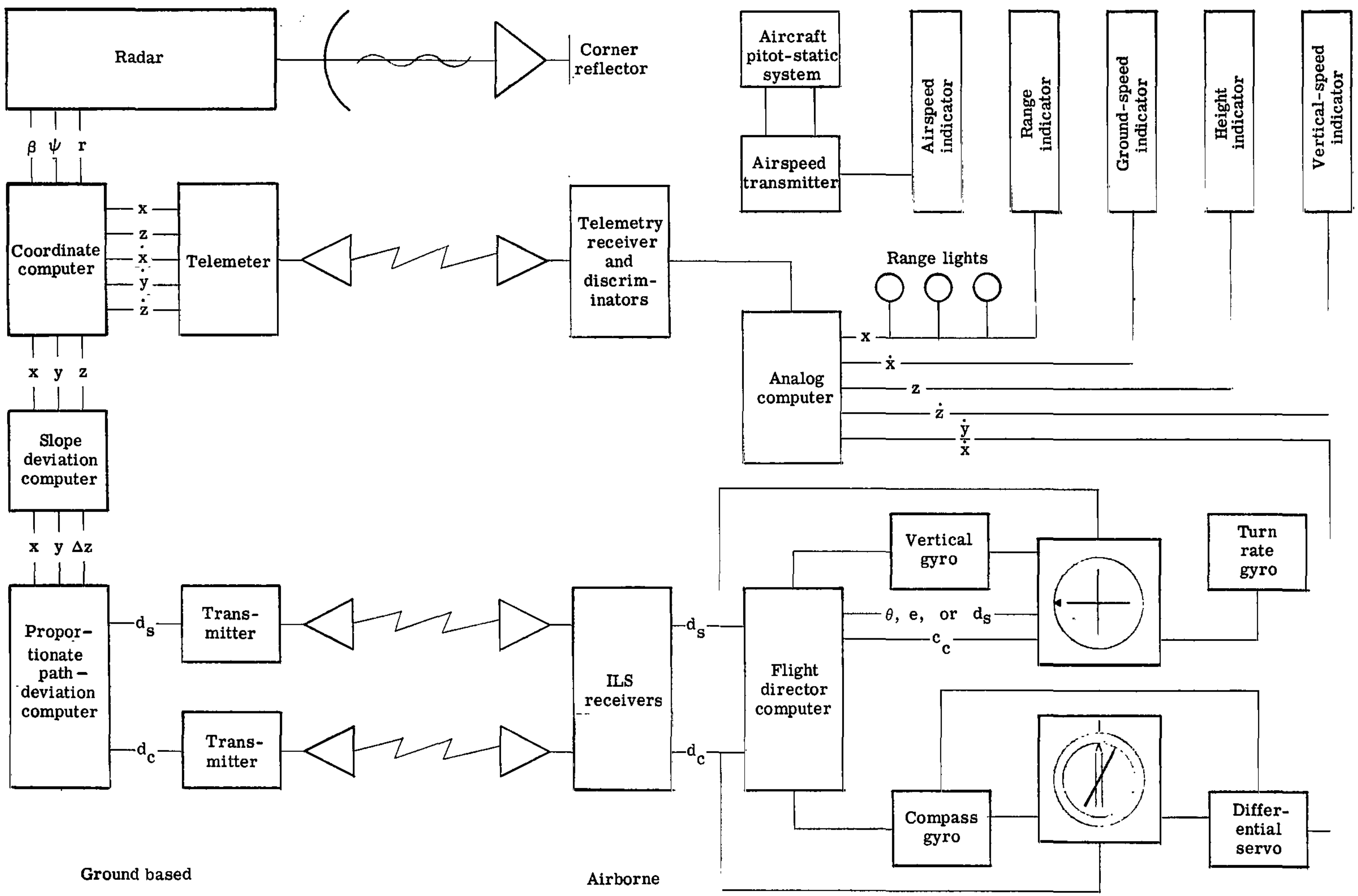


Figure 19.- Functional diagram of guidance system.

Figure 20.- Airborne guidance equipment.

L-65-8687.1

NASA-Langley, 1966 L-4989

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