U. S. ARMY
TRANSPORTATION RESEARCH COMMAND
FORT EUSTIS, VIRGINIA

TRECOM TECHNICAL REPORT 63-28

AN EXPLORATORY STUDY OF INSTRUMENT APPROACHES WITH STEEP GRADIENT AIRCRAFT

Task 1D121401A14203
(Formerly Task 9R38-11-009-03)
Contract DA 44-177-TC-834

October 1963

prepared by:

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U S ARMY TRANSPORTATION RESEARCH COMMAND
FORT EUSTIS, VIRGINIA

This report has been reviewed by the U. S. Army Transportation Research Command and is considered to be technically sound. The report is published for the dissemination of information and stimulation of ideas.

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TRECOM Technical Report 63-28
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AN EXPLORATORY STUDY OF INSTRUMENT APPROACHES WITH STEEP GRADIENT AIRCRAFT

Princeton University Aeronautical Engineering
Report No. 630

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FOREWORD

The research in this report was conducted by the Department of Aeronautical Engineering, Princeton University, under the sponsorship of the United States Army Transportation Research Command, Fort Eustis, Virginia, under Contract Number DA 44-177-TC-834.

The research was performed under the supervision fo Professor Edward Seckel of the Department of Aeronautical Engineering, Princeton University.

<u>TABLE OF CONTENTS</u>

LIST OF FIGURES

LIST OF SYMBOLS

g acceleration due to gravity
p roll rate (rad/sec)
r yaw rate (rad/sec)
y lateral deviation from localizer center line (feet)
K knots

$K_1 = \frac{\text{\% needle deflection}}{\text{bank angle (radians)}}$

$K_2 = \frac{\text{\% needle deflection}}{\text{localizer radio rate (rad/sec)}}$

$K_3 = \frac{\text{\% needle deflection}}{\text{localizer radio angular position (radians)}}$

P_L period of the second order system localizer return path (seconds)
R slant range from approach transmitter (feet)
$T_{G.S.}$ time constant of glide slope circuit - ratio of radio position signal to radio rate signal (seconds)

$T_L = \frac{K_2}{K_3}$ = time constant of localizer circuit - ratio of radio position signal to radio rate signal (seconds)
V velocity (ft/sec) appropriate subscript for ground speed, airspeed or wind speed
V/S vertical speed (ft/min)
W beam width, plus or minus either side of center line for glide slope or localizer (feet or degrees)
$W_{G.S.}$ glide slope beam width (degrees for standard wedge-shaped ILS type beam patterns or feet for parallel type beam patterns)
W_L localizer beam width (degrees for standard wedge-shaped ILS type beam patterns or feet for parallel type beam patterns)
α_i glide slope inclination angle (degrees) appropriate subscript for ground reference or air mass reference
ζ_L damping ratio of localizer return path as defined in a second order system
$\eta = \frac{y}{R}$
φ bank angle (radians)

φ_L bank angle input to localizer mode (radians)

Ψ flight path direction

ω frequency as defined by second order system

SUMMARY

A series of flight tests of an exploratory nature was conducted to determine the influence of certain parameters and quickened cross-pointer presentations on instrument approaches with steep gradient aircraft. Approximately 50 hooded instrument approaches were flown using a single-rotor helicopter piloted by a highly experienced NASA test pilot. Standard flight instruments were used and the tracking presentation for the pilot consisted of an ILS type cross-pointer indicator. Parallel beam patterns as well as the standard angular, wedge-shaped ILS beam patterns were simulated by a tracking theodolite system coupled to the aircraft cross-pointer by a radio link. Numerous beam widths, glide slope inclination angles, and quickening inputs were investigated.

The maximum glide slope inclination angles studied were in the 8° to 11° range because of operational limitations of the aircraft and task (30 knots minimum airspeed and 500 feet per minute maximum rate of descent). Parallel beam patterns (constant sensitivity) were preferred over the standard angular wedge-shaped beam patterns (sensitivity varying with range from transmitter). No significant improvements were obtained with the quickened presentation in preference to the pure displacement presentation.

INTRODUCTION

In the past, numerous investigations have been conducted in order to determine the possibility of utilizing helicopters under all-weather instrument flight conditions (References 1, 2, and 4). There is a desire to exploit the special flight capabilities of helicopters. For example, it would be possible to reduce the airspace requirements for helicopters at high density terminal areas by special close-in steep approach paths because of the lower maneuvering speeds and the ability to execute descents steeper than conventional airplanes. From the military standpoint, there is a natural desire to develop an all-weather capability in order to be able to accomplish routine instrument approaches to landings at heliports under marginal weather conditions.

In recent years several studies have been made on the problems associated with IFR operational techniques, navigational aids, approach systems, and methods of improving helicopter characteristics for steep instrument approaches (References 3, 5, 6, and 8). The objective of this research was the determination of the influence of changes in beam patterns, beam widths, glide slope angle, and quickened cross-pointer-type indications on pilot opinion and performance of steep instrument approaches in helicopters. A series of flight tests was conducted using a highly qualified NASA test pilot and a tracking theodolite system that provided an ILS type approach pattern. Also, with the use of additional instrumentation, it was possible to test a parallel type beam pattern. The parallel beam pattern provided the pilot with a constant sensitivity (constant beam width) along the approach course that was independent of the distance form the transmitter. Considerable attention was given to quickening of the cross-pointer presentation as well as variations in beam width and glide slope inclination angle.

EXPERIMENTAL PROCEDURE

1. DESCRIPTION OF EQUIPMENT

A single-rotor helicopter was used in this flight test program (Figure 1). The aircraft's angular damping, control sentivities, and other characteristics were not modified from the basic values. The vehicle was equipped with the appropriate instrument display and system for hooded simulated instrument flight. Although the evaluation pilot's display was essentially standard, certain additions or modifications were included in the presentation (Figure 2). For instance, the new instantaneous vertical speed indicator (IVSI) was substituted for the standard, lagging, calibrated-leak vertical speed indicator. A cross pointer of the ILS type was included in the presentation to provide the pilot with an indicator of tracking error along the instrument approach path.

It was possible to provide a variety of different types of presentations on this indicator. By summing appropriate signals obtained from instrumentation on the ground and aboard the aircraft, combined signal or quickened displays of the Zero Reader type were furnished to the pilot by the horizontal and vertical needles of the ILS indicator. This type of combined signal indicator provides the pilot with a presentation that should enable him to maintain a given flight path with less effort. By use of suitable quickening, the pilot is aided in returning to on-course after a flight position error. The instrument effectively computes a best flight path for him to follow to correct a course error. Typical quickening consists of summing rates of departure or closure to the desired flight path and other characteristic flight quantities, such as roll angle and heading, with the radio angular position signal.

In addition to the standard ILS, wedge-shaped beam presentations (sensitivity varies with range from transmitter), provisions were available for parallel beam presentations (constant sensitivity at all ranges from transmitter) on both the vertical needle (azimuth or localizer) and the horizontal needle (glide slope) (Figure 3).

2. QUICKENING INPUTS AND RANGE OF PARAMETERS

Some quickening inputs were used to augment the pilot's standard cross-pointer presentation. The normal ILS indication shows the pilot only his angular position deviation from the localizer and glide slope center line. In this research program additional inputs were provided in order to determine whether the approach task and pilot effort would be altered in a favorable way. When quickening was utilized, the inputs to the vertical needle (azimuth or localizer) of the cross-pointer instruments were: angular position error from the center line (radio position signal), rate of departure or closure to center line (radio rate signal), and aircraft bank angle. The inputs to the horizontal or glide slope needle were: angular position error above or below the glide slope (radio position signal) and vertical rate of departure or closure to glide path on-course (radio rate signal).

Pitch attitude was not used as an input to the horizontal bar because, as airspeed decreases, pitch attitude loses correlation with vertical rate. Glide slope corrections must be made by use of collective pitch and power. Since the pilots attempt to fly instrument approaches at a constant specified airspeed, changes in pitch attitude are made only to maintain the given airspeed and have little to do with attemping to stay on the glide slope center line. This is in keeping with instructions set forth in current manuals on helicopter instrument flight techniques, which suggest that pitch attitude control be used primarily to maintain or change airspeed (Reference 7).

On the vertical needle, the localizer angular position signal was "backed off" with radio rate signal rather than direction information (compass heading). When compass heading is used for a canceling signal on the combined signal indicator, care must be taken by the pilot to make allowances for "hang off" or position error due to cross winds. Unless a combination of techniques is used, the aircraft will not fly down the correct center-line course even though the Zero Reader needle is centered. This situation is avoided by the use of radio rate signal for quickening. Moreover, in coordinated flight the aircraft will not be lined up with the runway heading when making an appraoch in a cross wind. The "hang off" position error and misalignment of the aircraft axis with runway heading become more pronounced as cross wind velocity increases and flight speed decreases.

In realation to the quickening for the localizer mode, the flight path control equation satisfies the standard second-order differential equation of the form

$$\frac{d^2y}{dx^2} + 2\zeta\omega\frac{dy}{dx} + \omega^2 y = 0, \qquad (1)$$

when the pilot flies the cross pointer as a simple tracker and always keeps the needles centered.

Although this equation applies to the parallel beam pattern case where the sensitivities are constant and independent of range, it provides only a quasi-steady approximation or one-point solution for the standard angular beam patterns where sensitivity varies with range. (Since the damping ratio and period are functions of the changing sensitivity with range for the standard ILS type patterns, the flight path control would actually be described by a nonlinear equation).

Using the bank angle, radio rate signal, and radio angualr position signal, the localizer needle on the indicator follows the equation

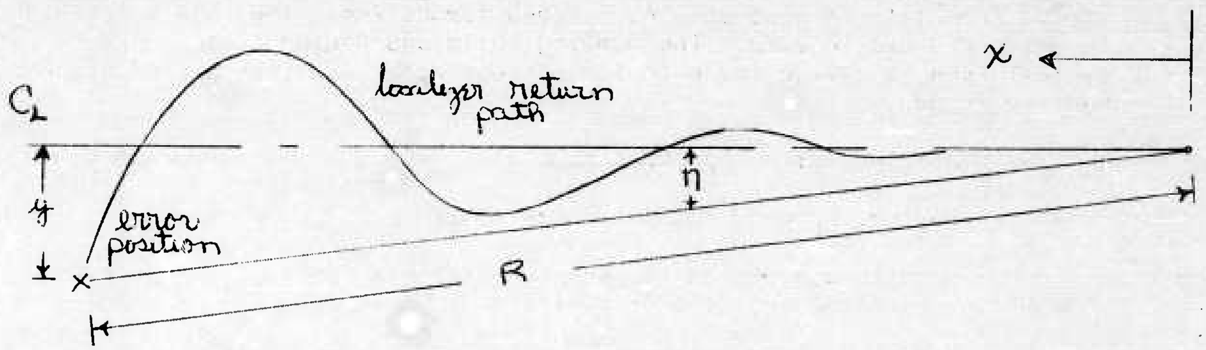
$$K_1 \varphi_L + K_2 \frac{d\eta}{dt} + K_3 \eta = 0 \qquad (2)$$

where

$$\eta = y/R \qquad (3)$$

$$\frac{d\eta}{dt} = \frac{d}{dt}(y/R) \qquad (4)$$

φ_L — aircraft bank angle



and K_1, K_2, and K_3 are the quantities representing the ratios between localizer needle deflection to bank angle, radio rate signal, and radio angular position signal:

$$K_1 = \frac{\text{(\%) needle deflection}}{\text{bank angle (radians)}}$$

$$K_2 = \frac{\text{(\%) needle deflection}}{\text{localizer radio rate (radians/sec.)}}$$

$$K_3 = \frac{\text{(\%) needle deflection}}{\text{localizer radio angular position (radians)}}$$

The damping ratio and period for the second order system may be determined and expressed as

$$\zeta_L = \frac{T_L}{2}\sqrt{\frac{g}{R} \times \frac{\varphi_L}{W_L}}$$

$$P_{L(\text{sec.})} = 2\pi\sqrt{\frac{R}{g} \times \frac{W_L}{\varphi_L}}$$

where T_L is the constant in the localizer circuit, $\frac{K_2}{K_3}$.

Numerous combinations of the quickening inputs were tested on the parallel and wedge-shaped ILS patterns.

a. Parallel Beam Pattern

The bank angle input φ_L required for full-scale deflection of the localizer needle was varied from 8^o to 18^o. The time constant of the localizer T_L (ratio between radio position signal and radio rate signal) varied from 1 to 13 seconds. As T_L goes toward zero, the rate quickening is being reduced to zero. The damping ratio and period (second-order system) used to define the path for correcting a localizer course error had the ranges

Damping ratio, φ_L (0.1 to 1.2)

Period, P_L (20 to 33 seconds).

The damping ratio and period for the parallel beam pattern are constants independent of range from the transmitter.

The path for correcting a glide slope course error is defined by the first-order system time constant $T_{G.S.}$ (ratio between radio position signal and radio rate signal), and was varied from 5 to 10 seconds.

b. Standard ILS Type Beam Pattern

The bank angle input φ_L required for full-scale deflection of the localizer needle was varied from 8^o to 18^o. Since the sensitivity of the wedge-shaped angular patterns varies with range from the transmitter, the damping ratio and the period of the second-order system return path approximation vary with the range. In this report, the damping ratio and period for the angular beam patterns are always calculated using the slant range to 300 feet altitude. Also, as bank angle input is changed, the rate of return input is altered in such a way that the damping ratio is kept a specified constant value at 300 feet altitude. The damping ratio could be specified at any slant range, but it was defined at the range associated with 300 feet altitude because that is near the critical weather breakout altitude. The damping ratio at this range was held constant at 1.2. The localizer time constant varied from 9 to 12 seconds, and the period of the second-order return path changed from 25 to 37 seconds.

The path for correcting a glide slope course error is defined by a first-order system time constant and was varied from 5 to 10 seconds.

3. FLIGHT PROBLEM

The evaluation pilot's flight task consisted of maintaining level flight at a 1200-foot initial approach altitude at an azimuth angle of entry of 30^o to 60^o to the simulated ILS course. A theodolite with a radio link to the helicopter was used to track the incoming aircraft and, through the radio link, activated the appropriate needles of the cross-pointer instrument in the cockpit in a fashion similar to standard ILS approach presentations. The azimuth indication was full-scale until the pilot intercepted the fringes of the beam that defined the approach pattern boundaries or preset beam widths. The elevation indication was full-scale "fly up" because at this phase of the approach the helicopter was still below the glide slope and maintaining the desired initial approach altitude to the "letdown corner" where the required rate of descent would be initiated.

Approaches were carried down to a simulated breakout altitude of 300 feet, although numerous approaches were flown almost to simulated touchdown. This was made possible by special instrumentation that permitted the apex or origin of the standard ILS beam patterns to be elevated above the true ground with no alteration or change in the true sensitivities or characteristics of the standard solid angle type approach beams. This special instrumentation technique was not used in the case of the parallel beam patterns since sentivities were constant and all portions of the beam patterns on both axes were independent of altitude, permitting the pilot to use any segment of the beam, at any altitude, for tracking purposes. Simply by mismatching his altimeter to read a high simulated ground level, the evaluation pilot was allowed to make very low altitude, slow-speed, steep-descent approaches with no compromise in safety and still have the authentic and precise beam patterns.

4. METHOD OF OBTAINING DATA

Approximately two hundred shakedown and preliminary exploratory steep instrument approaches were made prior to the actual evaluation flight tests. These were flown in order to check the entire approach system setup and to determine the area of interest, suitable combinations of parameters, and reasonable test configurations from the large number of combinations available for all the variables. The majority of these two hundred preliminary instrument approaches were flown by Princeton University's helicopter pilots. A total of about 50 additional instrument approaches were flown by one of the highly experienced and expertly qualified NASA helicopter pilots. These additional approaches were used as the formal evaluation test flights for pilot opinion data purposes. Tape recordings of in-flight commentary and post-flight discussions were made and analyzed to determine the acceptability of each approach and the particular test condition.

5. PATTERNS AND RANGE OF PARAMETERS INVESTIGATED

The primary objective was the determination of the influence on pilot's opinion of steep instrument approaches in helicopters caused by changes in approach beam patterns, related parameters, and pilot's display presentation. The beam patterns and range of parameters utilized were:

a. Standard ILS Type Beam Patterns

A tracking theodolite with a radio link to the helicopter provided a localizer and glide slope beam pattern similar to the wedge-shaped or standard ILS beams currently being used by airplanes. The standard unquickened angular positional type ILS indicator used in many airplanes is utilized for this system. With this wedge-shaped pattern, the width of the course or beam width in feet is greater as the distance from the transmitter increases. For any deviation from the on-course, the rate of movement of either the horizontal or the vertical needle is inversely proportional to the distance from the station. When the pilot knows the approximate distance to the station, the rate of movement and amount of deflection of the needle dictates the amount and type of corrective action the pilot needs to supply to counteract the deviation. This establishes a technique that the pilot must continually alter as his distance from the station changes.

b. Parallel Beam Patterns

Additional instruments and a second tracking theodolite situated at right angles to the localizer course and with an electrical link to the primary theodolite provide the means of setting up a system of parallel type beams on both axes. The standard ILS type indicator was used for the parallel beam system, but the width (in feet) of the course remained constant and independent of the distance from the transmitter. For any deviation from the on-course, the rate of movement of either the horizontal or the vertical needle remains constant and independent of range. The pilot is presented with a display that shows errors from an on-course directly in feet instead of the angular error presented with standard ILS beam patterns. Since the sensitivity is constant and error information is directly available in the more desirable form, the pilot does not need to vary his error correcting techniques with distance from the transmitter. Opinions have been expressed that this type of beam arrangement may permit more accurate approaches for a given pilot effort.

c. Beam Widths

The approximate beam widths or cross sections of the two approach patterns are defined by the full-scale deflections of the cross-pointer instrument (Figure 3). The standard ILS wedge-shaped approach beam widths are given in degrees plus or minus either side of center line. For example, a localizer beam width of $\pm 6^{\circ}$ represents a 12° wide beam for full-scale deflection on the right side of the center line to full-scale deflection on the left side of the center line. Given a specific range from the transmitter and a beam width in degrees, one may easily calculate the rectangular cross-sectional dimensions of the pattern in feet at that range for full-scale deflections of the needles (Table 1). The instrumentation utilized in this research provided localizer full-scale beam widths up to $\pm 15^{\circ}$ and glide slope full-scale beam widths up to $\pm 10^{\circ}$ maximum for the wedge-shaped beam patterns.

Because of the constant sensitivity of the parallel beam system, the cross-sectional dimensions of the rectangular parallelepiped defined by full-scale deflections of the needles may be given directly in feet and remain constant all along the approach path. The instrumentation used in this research provided full-scale parallel beam widths up to ± 500 feet maximum on both axes.

d. Glide Slope Inclination Angles

Because of the particular design and versatility of the instrumentation, there was essentially no limit to the inclination angle that could be set with the tracking theodolite. The actual inclination angles studied are listed in the Discussion.

DISCUSSION AND RESULTS

1. EFFECT OF STEADY WIND ON TEST CONDITIONS AND RESULTS

Figure 5 shows the relationship of vertical rate of descent, glide slope inclination angle, and ground speed. In this report it is assumed that 500 feet per minute is the desirable vertical rate of descent for instrument approaches. This has been discussed by many instrument pilots and at this time seems to be at least a very practical or perhaps mandatory specification for instrument approaches in relatively poor ceilings and visibilities. If the vertical rate of descent is specified as 500 feet per minute (Figure 6), then the glide slope inclination angle relative to the ground is a direct function of the ground speed (or airspeed for zero wind conditions). Therefore, steady winds will alter the aircraft's ground speed and have an important influence on the glide slope inclination angle that the pilot will find acceptable. The influence of winds becomes more significant when the wind speeds are of the same order as the approach airspeeds. Another limitation on the steepness of the glide slope inclination angle occurs because of the reluctance of many pilots to reduce their airspeed below the 25-to 35-knot range. Many of the reasons for this are well known and have been discussed at some length in previous studies and amply demonstrated in a variety of helicopters (References 1 through 6). One of the usual complaints repeatedly stated by the pilots used in this program was the lack of a completely reliable low-speed indicator (either airspeed or ground speed). The absence of reliable speed indications at these slow flight speeds deprived the pilots of a vital feedback quantity needed to stabilize the aircraft on the on-course. In any event, the preliminary flights with the H-23D seem to confirm the 25- to 35-knot speed range as the minimum acceptable airspeed for the steep instrument approaches in this aircraft also. During steep descents at approximately 20 knots, the test aircraft was very sensitive directionally and the airspeed indicator was completely unreliable. The pilot felt that the approach was unacceptable and found it difficult to control the aircraft during the descent even under visual flight conditions. He stated that the aircraft was getting into the edge of an unsteady flow condition where the control forces and reactions are quite variable. Therefore, from the present operational viewpoint, two rather mandatory limitations (airspeed approximately equal to 30 knots and vertical rate of descent approximately equal to 500 feet per minute) were imposed on this steep descent problem. As seen in Figure 6, for a no-wind condition these impositions limit the maximum glide slope inclination angle to about 9.5°.

During the preliminary instrument flight tests, it became evident that only the airspeed and vertical speed were of primary concern to the pilot when flying the aircraft on the approach. The ground-referenced glide slope inclination angle was of lesser concern provided that the pilot could stay on the on-course without violating the desired minimum airspeed and maximum vertical rate. Although some runs were made at slower airspeeds and greater vertical rates of descent, the majority of evaluation approaches were conducted at 30 knots airspeed and 500 feet per minute rate of descent. It is important to note that the imposition of these two conditions in these flight tests fixes the glide slope inclination at a constant angle of 9.5° measured with respect to the air mass. The inclination angle measured with respect to the earth or tracking site was of no immediate concern to the pilot and could have been any angle depending on the prevailing wind and the direct effect on the ground speed at the time of the approach.

The indifference on the part of the pilot to the ground-referenced descent angle was clearly displayed during numerous preliminary approaches in strong steady winds. For one set of preliminary test runs with steady winds on the order of 20 knots, the safety pilot and ground tracking personnel set up direct downwind and upwind instrument approaches. The evaluation pilot was instructed that, in order to stay on the preset glide slope, he would have to maintain 30 knots airspeed and 500 feet per minute rate of descent. In this case, the air mass inclination angles were always constant at 9.5° but the approach angles with respect to the ground were greatly different (30° for the 10-knot ground speed case and 5° for the 50-knot ground speed case, Figure 6). When questioned about the two approach angles, the pilot understandably had no means to detect the difference in the two actual ground-referenced approach angles and felt that they were the same inclination angles.

In order to present the material obtained in this program in a realistic and more meaningful form, the effects of steady winds are eliminated and all flight results are presented in terms of the air mass parameters. Therefore, the localizer and glide slope beam widths as well as ground-referenced inclination angles were altered in order to compensate for the effects of the wind. This was accomplished by estimating the prevailing wind and setting up a descent angle with respect to the ground which would permit the pilot to remain on course while maintaining 500 feet per minute rate of descent and 30 knots airspeed. The relationship between the glide slope inclination angles, α_i, is shown by the following expression:

$$\alpha_{i\,\text{ground reference}} = \alpha_{i\,\text{air mass reference}} \times \frac{V_{\text{airspeed}}}{V_{\text{ground speed}}}$$

where

$$V_{\text{ground speed}} = V_{\text{airspeed}} + V_{\text{wind}}$$

and

$$V_{airspeed} = 30 \text{ knots}$$

V_{wind} — estimated at the time of each approach

$$\alpha_{i \text{ air mass reference}} = 9.5^{\circ} \text{ for 30 knot airspeed and V/S equal to 500 feet per minute}$$

For example, with a 10-knot headwind (V_{wind} = -10K and 500 feet per minute vertical rate), the tracking theodolite incination angle was at approximately 14° (ground reference $\alpha_i = 9.5^{\circ} \times \frac{30}{20} \approx 14^{\circ}$), although the angle for data purposes was interpreted as 9.5°. This system was self-checking between the pilots and ground tracking personnel since an error in wind speed estimation would require airspeeds or vertical rates other than the average values of 30 knots and 500 feet per minute in order to maintain the on-course. No difficulty was encountered in estimating the winds for the accuracy required in this technique, and the pilots felt that it provided a realistic basis for the approach system setup.

The beam widths for the wedge-shaped standard ILS patterns had to be altered by an expression of the same form:

$$W_{\substack{\text{ground}\\ \text{reference}}} = W_{\substack{\text{air mass}\\ \text{reference}}} \times \frac{V_{airspeed}}{V_{ground\ speed}}$$

For example, with a 10-knot headwind (V_{wind} = -10K), the full-scale sensitivities for a ± 6° localizer beam width and ± 4° glide slope beam width are calibrated on the theodolite at ± 9° and ± 6° respectively. The ground-referenced beam width values are obtained by using the above expression.

$$W_{L_{\substack{\text{ground}\\ \text{reference}}}} = 6^{\circ} \times \frac{30}{20} = 9^{\circ}$$

$$W_{G.S._{\substack{\text{ground}\\ \text{reference}}}} = 4^{\circ} \times \frac{30}{20} = 6^{\circ}$$

In this way the effects on apparent beam widths caused by steady winds are eliminated. The flight data are interpreted on the basis of the air mass values ± 6° and ± 4°. Because of the constant sensitivity of the parallel beams and the method of calibration utilized, the parallel beam <u>widths</u> did not need to be corrected for the effect of the wind. The parallel beams had to be altered in <u>inclination angle only</u> in order to compensate for the wind effect.

Although certain previous work in this field draws conclusions on various ground-referenced steep inclination angles obtained by flying in headwinds, the logic for interpreting and presenting flight data in terms of zero wind conditions should be obvious. Pilots executing steep instrument approaches in winds cannot discuss the characteristics of the pilot-vehicle-display combination in terms of particular ground-referenced inclination angles. The ground-referenced angles may be of any value dependent on external conditions (prevailing winds) and are not readily apparent to the pilot. To draw conclusions for steep approaches under these circumstances is deceptive since the actual descent angle studied, as far as the pilot and the data are concerned, is determined from the relationship of airspeed and vertical speed, not from the approach angle he happens to make with respect to the earth due to the help provided by a favorable wind field.

Approaches steeper than approximately 8^{o} to 11^{o} cannot be truly investigated in the presence of winds unless the 25- to 35-knot minimum airspeed and the 500 feet per minute maximum vertical rate limitations are considerably relaxed. For example, in order to conduct investigations using a 30^{o} descent angle (V/S equal to 500 feet per minute), the aircraft must be slowed to less than 10 knots airspeed (Figure 6).

The convenient use of sufficient headwind as an artifice in achieving the required ground speed (without regard to the airspeed and vertical rate) to obtain a steep ground-referenced approach does not provide the true situation for the pilot to evaluate. With the proper wind fields, it would be possible to let down at any angle and airspeed with the hooded pilot being unable to readliy perceive the steepness of the ground-referenced approach. At the very steep angles, say above 45^{o}, pilots may be able to begin to detect the steepness of the beam by noting that it is easier to bracket the glide slope by changing horizontal speed rather than vertical speed.

While it must be recognized that winds are usually present and that, in the final application, the value of the ground-referenced approach angle is of prime importance, allowances for the effects of winds on the approach angle may be made after it is determined which <u>air mass referenced</u> descent angles are acceptable.

2. GLIDE SLOPE ACQUISITION AND BRACKETING TIME

If the initial approach altitude is constant and the pilot attempts to hold a specified vertical rate of descent, the length of time available for beam "bracketing" is constant and independent of the inclination angle. By maintaining an average vertical rate of descent of 500 feet per minute from the initial approach altitude of 1200 feet, the pilot will always have a little over 2 minutes of bracketing time available regardless of the glide slope inclination angle. Also, the ability to anticipate the glide slope interception in order to establish the specified vertical rate will depend more on the initial approach ground speed and beam widths rather than the inclination angle of the glide slope. Good instrument flight technique suggests that the pilot will have made his final adjustment to the approach speed prior to intercepting the glide slope at the "letdown corner." In this way his only primary problem at that point is to establish (at constant horizontal speed) a 500-feet per minute vertical rate of descent from level flight. Although the problem of setting up a 500-feet per minute vertical rate of descent from level flight remains the same, the warning or time available for establishing the vertical speed depends on the effective beam width and ground speed more than on glide slope inclination. A wide beam and/or slow ground speed provides the pilot with a better lead or longer indication of glide slope interception and allows him more time to establish the desired vertical rate. The glide slope inclination angle had little effect on the anticipation required, since it is assumed that the pilot has fixed his speed at the proper value for the approach and therefore he needs only to establish a 500-feet per minute rate of descent in order to stay on the glide slope.

3. RESULTS OF FLIGHT TESTS

a. Beam Patterns

The simplest and most clearly defined result of these flight experiments was the preference by the pilots for the parallel beam pattern over the wedge-shaped ILS beam pattern. With the parallel beam patterns, the width of the on-course is constant (sensitivity is independent of the range from the transmitter) and does not vary during the approach. The error information is presented directly to the pilot in the more desirable form of distance in feet from the localizer or glide slope center line. Also, since the sensitivity is constant, the pilot does not need to change his error-correcting techniques with distance from the transmitter. The pilots indicated without reservation that they were able to make repeated accurate instrument approaches and favored the parallel beam patterns over the wedge-shaped ILS pattern.

b. Beam Widths

(1) Parallel Patterns

Four different combinations of localizer and glide slope parallel beam widths were tested. The full-scale distances on either side of center line were:

Combination Number	Localizer Width W_L	Glide Slope Width $W_{G.S.}$
1	± 400 feet	± 300 feet
2	± 200 feet	± 150 feet
3	± 115 feet	± 85 feet
4	± 100 feet	± 65 feet

During the formal evaluation flight tests, the NASA pilot felt that combination number 1 ($\pm$ 400/$\pm$ 300) was good and easy to fly; however, he felt that the accuracy of the approach could be improved by reducing the beam widths. Combination number 2 ($\pm$ 200/$\pm$ 150) was also good and relatively easy to fly. Combination number 3 ($\pm$ 115/$\pm$ 85) was "quite good and usable but very, very slightly too tight." Combination number 4 ($\pm$ 100/$\pm$ 65) was a little too tight on both axes. The harmony between the localizer beam width and the glide slope beam width was always suitable on all four combinations.

Considering the pilot's comments and expert ability and proficiency, it would seem that beam widths between combination numbers 2 and 3, say $\pm$ 150/$\pm$ 100, would be the most favorable for the range of test conditions studied.

(2) Standard ILS Type Beam Patterns

Two combinations of localizer and glide slope angular beam widths were tested. The full-scale angular deviations on either side of center line were:

Combination Number	Localizer Width W_L	Glide Slope Width $W_{G.S.}$
5	$\pm 8^{\circ}$	$\pm 6^{\circ}$
6	$\pm 4^{\circ}$	$\pm 3^{\circ}$

The opinion obtained from the NASA pilot indicated that combination number 5 ($\pm 8^{\circ}/\pm 6^{\circ}$) was not too sensitive and that the beam widths could be reduced. Repeated flights with combination number 6 ($\pm 4^{\circ}/\pm 3^{\circ}$) revealed that these widths were quite good and usable but on occasion were a little too sensitive. Again the harmony between the localizer width and glide slope width was suitable for both combinations. The test pilot felt that a combination with a localizer width of $\pm 6^{\circ}$ and a glide slope width of $\pm 4^{\circ}$ probably would be the most ideal for the range of parameters and conditions tested.

c. Quickening

(1) Parallel Beam Pattern

For the limited number of flight tests made using the parallel beam width combination number 3 (W_L = $\pm$ 115 feet and $W_{G.S.}$ = $\pm$ 85 feet), the most favorable values obtained for the quickening parameters were:

Bank angle input for full-scale deflection, φ_L, equal to 8°
Localizer time constant, T_L, equal to 8 seconds
Period of localizer return path, P_L, equal to 31 seconds
Damping ratio of localizer return path, ζ_L, equal to 0.8
Glide slope time constant, $T_{G.S.}$, equal to 5 seconds

(2) Standard ILS Type Beam Patterns

For the limited number of flight tests made using the wedge-shaped angular beam pattern combination number 6 ($W_L = \pm 4^\circ$ and $W_{G.S.} = \pm 3^\circ$), the most favorable values obtained for the quickening parameters were:

Bank angle input for full-scale deflection, φ_L, equal to 8°
Localizer time constant, T_L, equal to 12 seconds
Period of localizer return path, P_L, equal to 37 seconds
Damping ratio of localizer return path (at 300 feet altitude and slant range, R, equal to 1800 feet), ζ_L, equal to 1.2
Glide slope time constant, $T_{G.S.}$, equal to 5 seconds

(3) General Remarks on Quickening

Within the large range of values of the quickening parameters tested, it was not possible to determine any quickening combination for either the parallel or standard beam patterns that resulted in a significant improvement over the pure displacement presentation. Even the most favorable values of quickening, listed under (1) and (2) above, furnished, at best, only a little assistance and a minor or negligible improvement over the pure displacement presentation.

The execution of precision steep instrument approaches in a helicopter is a very demanding task that requires a high degree of proficiency and experience on the part of the pilot. The degree of difficulty is especially noticeable in the directional mode or localizer tracking. Lateral control inputs cause rapid responses, and desired heading changes at high turn rates may be obtained with relatively small bank angles at the slow approach speeds utilized. Conversely, large undesired heading changes may occur because of power changes or small inadvertent lateral attitude errors. When attempting to correct a localizer position error, the pilot has to control the aircraft in a double or triple integrator type control loop depending on whether he has a rate or acceleration type roll controller. Lateral position is altered by lateral rate which is proportional to flight path direction, ψ, in coordinated flight. The flight path direction is proportional to the double integral of roll rate:

$$\psi \sim \int r\, dt \sim \int \varphi\, dt \sim \iint p\, dt^2.$$

Therefore, the pilot has to operate or predict the control input to compensate for a phase lag of between -180° to -270° in the output in order to control lateral position properly. Operating in a control loop with this much phase lag indicates the degree of difficulty that the pilot experiences in precisely controlling the localizer position mode. Under these circumstances it would seem that some localizer quickening should be a significant benefit to the pilot.

Glide path control is less difficult and responsive. Corrections to the glide path are made with collective pitch (power) changes which decrease or increase the thrust and alter the vertical rate of descent after some time lag. When attempting to correct a vertical position error on the glide slope, the pilot is faced with a simpler task as compared to the localizer. Vertical position on the glide slope is controlled by vertical rate which, in turn, is directly proportional to collective pitch position with a phase lag of 0° to 90° between the input and the output. Control of vertical position does not seem to be as difficult a problem as control of the lateral position.

Nevertheless, using the complete range and combinations of quickening values available, it was impossible to provide either a localizer or a glide slope presentation to the pilot that was significantly better than the unquickened presentation. This inability to find any significant improvement with quickening (especially in the localizer mode presentation) for the helicopter steep instrument approach task is somewhat puzzling. Rechecks and recalibrations of all instrumentation and quickening values were made and confirmed the accuracy of all settings and parameter values. The NASA test pilot stated that this was the first task or flight condition where quickening did not provide him with a significant improvement on the tracking problem and pilot effort.

It should be stated that the NASA test pilot used in the formal evaluation flights of this program is probably one of the most experienced and highly proficient pilots in the world for helicopter steep descent instrument approaches. During the preliminary flights with other, less-experienced pilots, it was determined that quickening was of some definite aid especially in the initial acquisition of the localizer on-course. The NASA pilot did not find this to be the case and stated that he had no difficulty making the initial localizer acquisition on either the parallel or the standard beam patterns with just a pure displacement presentation. Depending on the beam width and wind conditions, he would determine a beam intercept angle to the known localizer course heading and turn to the on-course with good precision.

Some special flight tests were conducted after the formal evaluation flight series to investigate the influence of the individual quickening inputs. For this purpose, four different localizer presentations were tested using parallel beam width combination number 3 (parallel type localizer beam pattern with a beam width, W_L, equal to $\pm$ 115 feet). The four different localizer presentations are listed as follows:

- Case 1. No Quickening. Radio position signal only
- Case 2. Second-order quickening. Radio rate signal plus bank angle signal plus radio position signal
- Case 3. Bank angle signal plus radio position signal
- Case 4. First-order quickening. Radio rate signal plus radio position signal

The results of the flight test runs using these four localizer presentations are listed below.

In order to evaluate the results obtained from these presentations, it is necessary to discuss some methods of interpreting quickened indicators since it is possible that evaluation of certain types of quickening may be altered by pilot techniques. While the particular methods used by pilots for interpreting different quickened cross-pointer indications are not exactly known, some discussion is possible as a result of the different cases tested.

With a properly quickened presentation, the pilot may fly the approach by simply moving the controls so as to keep the needles always positioned in the center and with little attention to the information provided by the other instruments. He obtains practically no physical picture of what is occurring (heading, attitude, etc.) except that he knows he is always on course or making a proper correction toward it. In a second technique he may desire to obtain steering information and aid from his other instruments while manipulating the controls in proportion to the <u>rate</u> of movement of the quickened cross-pointer. In this way he picks up some physical picture of what is occurring during the tracking. In a third technique, the pilot may mix the two former methods, using the first when course displacement errors are small and the second when course displacement errors are large. Although the special runs were not controlled closely enough to obtain precise information on how each presentation was interpreted, the following remarks, partly factual and partly conjectural, are offered.

Case 1. No localizer quickening. Radio position signal only

Using this localizer presentation, intense concentration and a high degree of proficiency and experience are demanded of the pilot. He must use an extremely high scanning rate and combine properly each bit of information gained from other instruments in order to be able to execute smooth and precise approaches. It would be impossible for the pilot to make an acceptable approach with this presentation without combining the information from scanning other instruments.

Using the wider wedge-shaped beams (wider compared to present airplane type ILS installations) and especially with the parallel beams, the evaluation pilot felt that this presentation was satisfactory. After a few attempts, the pilot developed a good cross-check and was able to combine the information well enough to control the aircraft precisely. The presentation was relatively easy to fly and resulted in acceptable and accurate instrument approaches.

Case 2. Second-order localizer quickening. Radio rate signal plus bank angle signal plus radio position signal

With the proper quickening, this presentation normally makes it possible for the pilot to control the aircraft precisely during the approach without the need for attention to other information such as heading, rate of turn, or attitude. Certain signals are combined in this indicator to provide the pilot with one "simple tracker" type presentation. Systems of this type normally give excellent results for instrument flight and ILS approaches in airplanes. Since the instrument will compute a best return path or control input to stay on the center line, the pilot need only to keep the needles centered. He has practically no physical picture of what is occurring and need not provide any "predictive" steering of his own. Ideally, with this type of system, the pilot should be able to match the precision obtained with "coupled approaches."

Using the most favorable combinations of second-order quickening (as listed under (1) and (2) of this section), the pilot was able to keep the needles approximately centered and paid primary attention to the quickened presentation with much less reference to the other instruments. Unfortunately, it was not possible to provide the pilot with a quickened presentation that was a significant improvement over the unquickened presentation. For the large range of parameters tested, the pilot felt that the most favorable values of quickening made only a minor improvement to the task effort.

Normally a second cross-pointer instrument such as a standard ILS indicator is provided for the pilot to show his instantaneous position on the beam. This was not included in the panel display during these tests and undoubtedly made it difficult for him to determine his exact position or instantaneous displacement from the center line. By referring to his other instruments, he could level his aircraft and attept to reduce his lateral rate to zero, and then read position on the vertical needle. However, the pilot did not often try this and felt that the difficulty of it was not a major reason for the inability to obtain a significant improvement in the presentation due to quickening.

Case 3. Bank angle signal plus radio position signal

The bank angle input used in this presentation was selected as the value listed under (1) and (2) of this section (bank angle signal of 8^{o} for full-scale localizer deflection). This presentation can be flown as a Zero Reader type indicator simply by attempting to keep the needles centered. This was easily accomplished by the pilot because of the rapid response of the aircraft to roll commands. The cross-pointer indication proved to be too sensitive and resulted in an unsatisfactory presentation and pilot technique because of the undamped nature of the oscillatory return path. When attempting to correct a localizer position error with no radio rate input, the return path is described by a continuous oscillation across the on-course (as predicted by Equation 2, page 4) unless the pilot mixes his technique and uses additional information from other instruments to aid in damping the path. This presentation is of no great benefit to the pilot and was adjudged unsatisfactory.

Case 4. First-order quickening. Radio rate signal plus radio position signal

This localizer presentation with first-order quickening (where the time constant T_L is the ratio of the radio position signal to the radio rate signal) represents a type of compromise between a no-quickening and a second-order quickening presentation. The evaluation pilot quickly determined that the localizer time constant had to be on the order of 1 or 2 seconds; otherwise the localizer needle moved much too rapidily. Time constants that are this small provide very little quickening and are essentially equivalent to an unquickened presentation. The pilot cannot fly this cross-pointer indicator by simple tracking, since it is practically impossible for him to lead the error display enough to provide stable corrective action without heavy reliance on the other primary flight instruments. This defeats the purpose of the combined signal indicator, and the small time constants indicate that the pilot prefers a pure displacement signal and standard cross-check technique.

Although the first-order quickening seems to be totally unsatisfactory for the localizer mode, it is satisfactory for the glide path mode. Because of the lower order and smaller phase lag in the vertical response to collective pitch, the pilot can fly the glide slope (with first-order quickening) by simple tracking. This arrangement was reasonably acceptable, and favorable time constants for the glide slope were easily determined.

CONCLUSIONS

The following general conclusions are made for the range of parameters and conditions studied in this report:

1. Parallel beam type patterns (constant sensitivity with range) were preferred over the standard wedge-shaped ILS beam patterns (changing sensitivity with range). The pilots found that they could keep their error-correcting techniques constant regardless of the range from the transmitter and preferred the parallel type presentation (needle displacement always represents error distance in feet) over the angular type.

2. The maximum glide slope inclination angles studied were in the 8° to 11° range because of operational limitations of the aircraft and task (30 knots minimum airspeed and 500 feet per minute maximum rate of descent).

3. For a 9.5° glide slope inclination angle and the standard wedge-shaped ILS beam pattern, the localizer and glide path beam width values had to be approximately two and six times greater, respectively, than those used on present-day airplane ILS systems.

4. For a 9.5° glide slope inclination angle and the parallel beam type patterns, the most favorable beam widths for the localizer and glide path were approximately $\pm$ 150 feet and $\pm$ 100 feet respectively. These beam widths are roughly equivalent to the most favorable cross-section beam widths of the wedge-shaped patterns at the assumed breakout altitude of 300 feet.

5. Within the large range of values of the quickening parameters tested, it was not possible to determine any quickening combination for either the parallel or the standard beam patterns, that resulted in a significant improvement over the pure displacement presentation. The most favorable values of quickening determined by this research furnished, at best, only a little assistance and a minor or negligible improvement over the pure displacement presentation.

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TABLE I
STANDARD ILS TYPE BEAM CROSS SECTION DIMENSIONS (in feet)
VERSUS SLANT RANGE AND ALTITUDE

Altitude (ft)	100	200	300	400	500	595	693	792	891	990	1200
Slant Range (ft)	600	1200	1800	2400	3000	3600	4200	4800	5400	6000	7280
Beam Width ± 3°	± 31	± 62	± 94	± 125	± 157	± 188	± 219	± 251	± 282	± 314	± 382
Beam Width ± 4°	± 41	± 84	± 125	± 167	± 209	± 251	± 293	± 335	± 376	± 418	± 508
Beam Width ± 6°	± 63	± 125	± 188	± 251	± 314	± 376	± 439	± 502	± 565	± 628	± 777
Beam Width ± 8°	± 83	± 167	± 251	± 334	± 418	± 502	± 585	± 669	± 753	± 837	±1050

GLIDE SLOPE INCLINATION ANGLE EQUAL TO 9.5°

Figure 1. Flight Test Aircraft

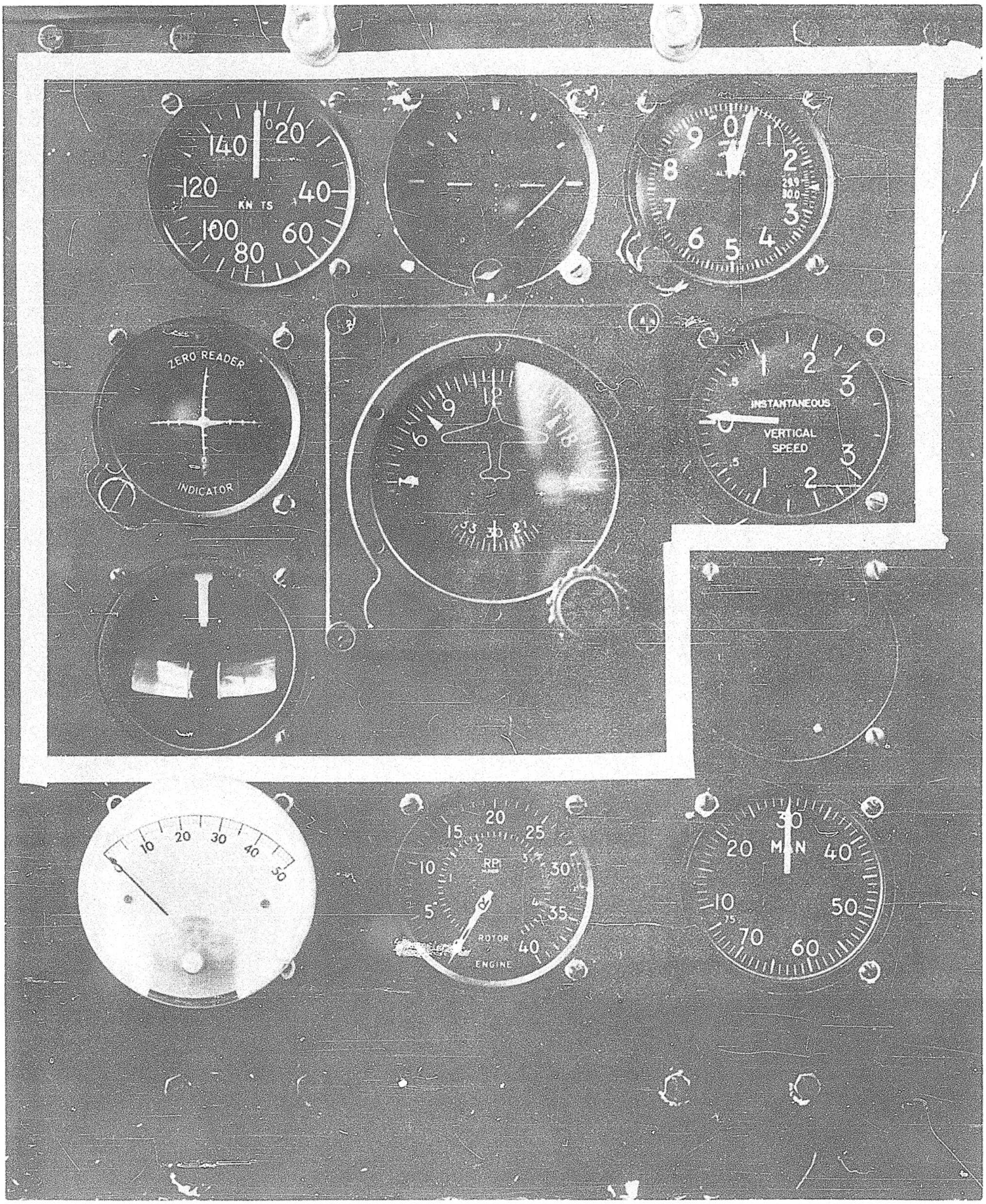

Figure 2. Instrument Panel Display

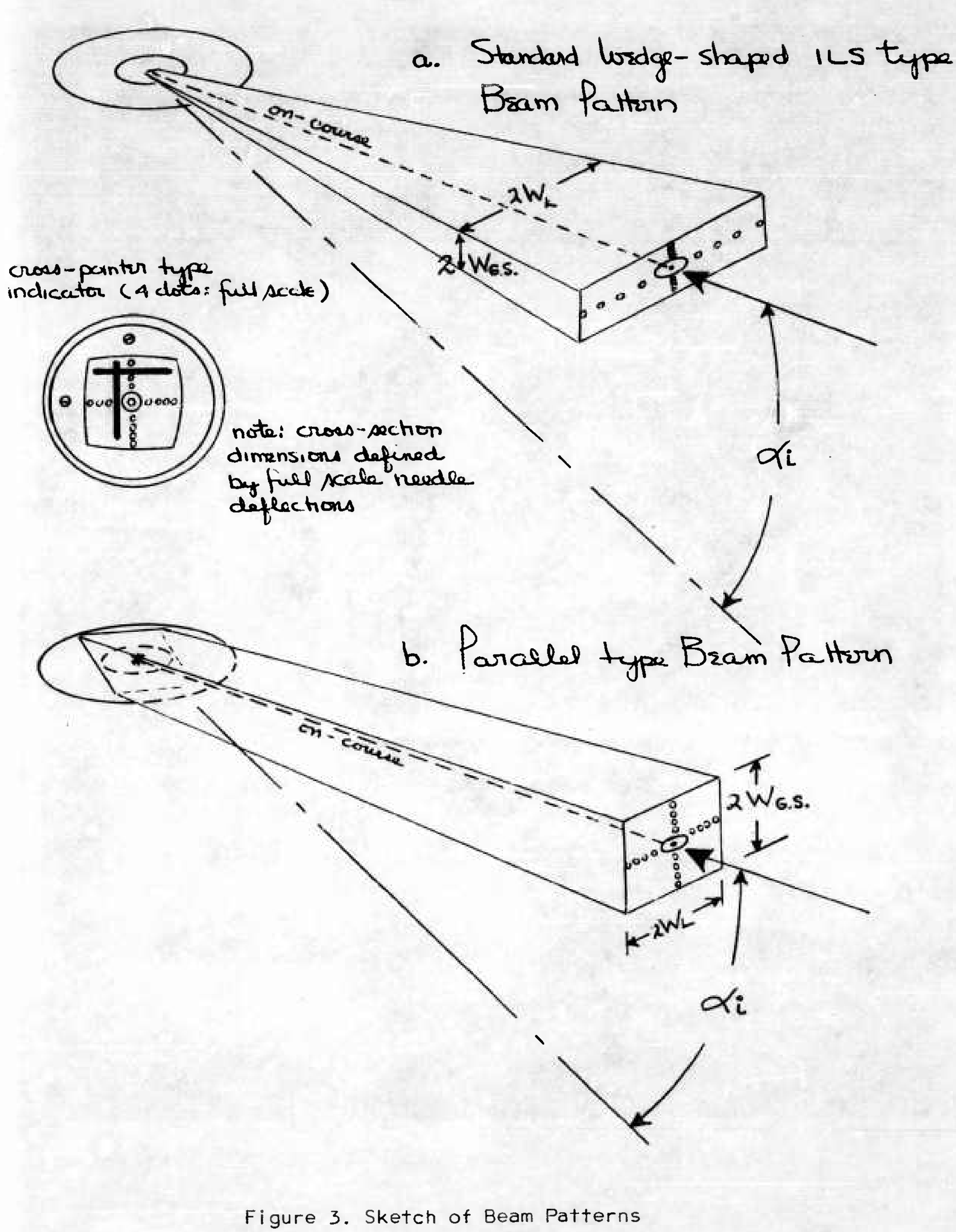

Figure 3. Sketch of Beam Patterns

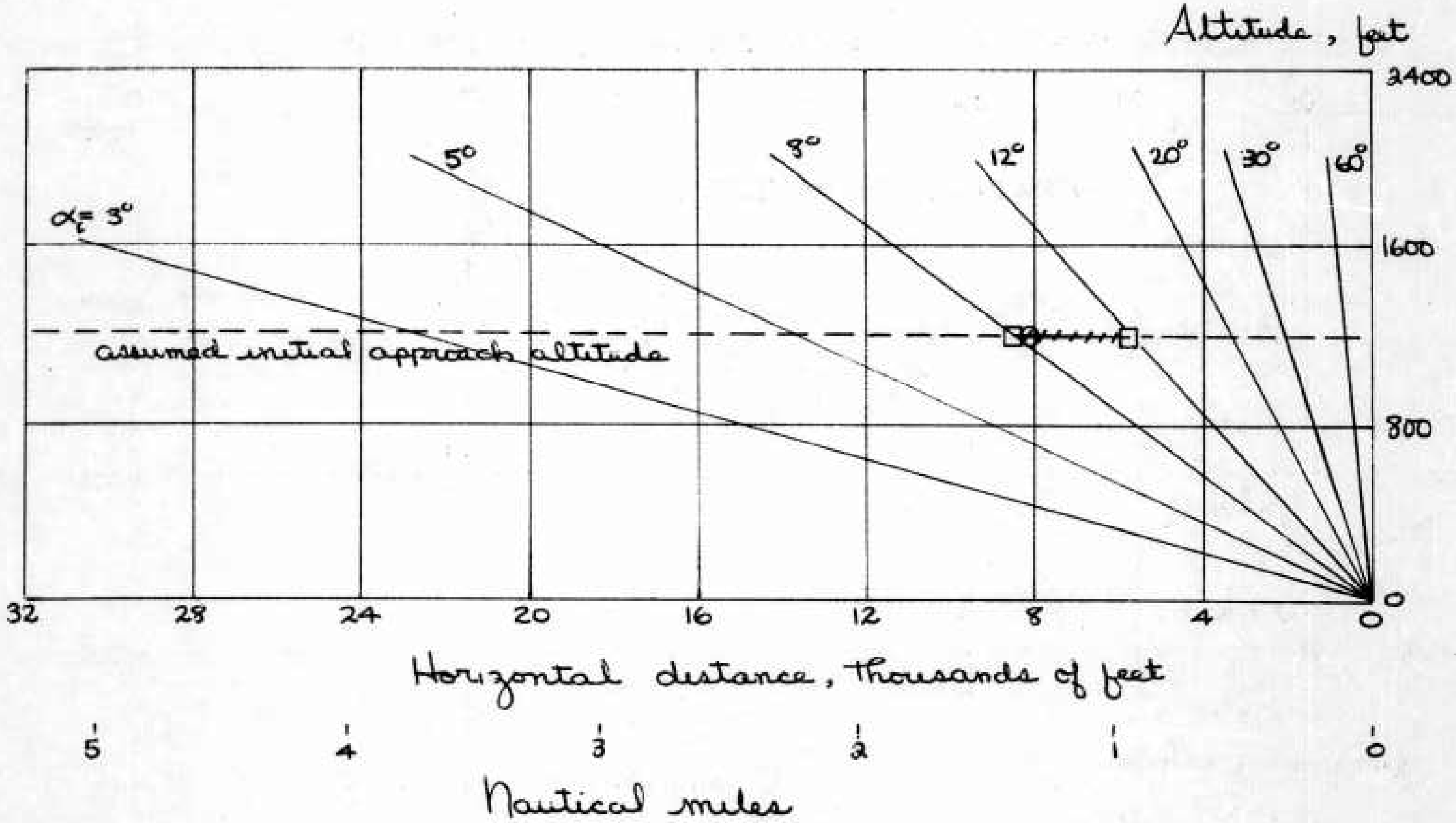

Figure 4. Glide Slope Angle Versus Horizontal Distance From Touchdown

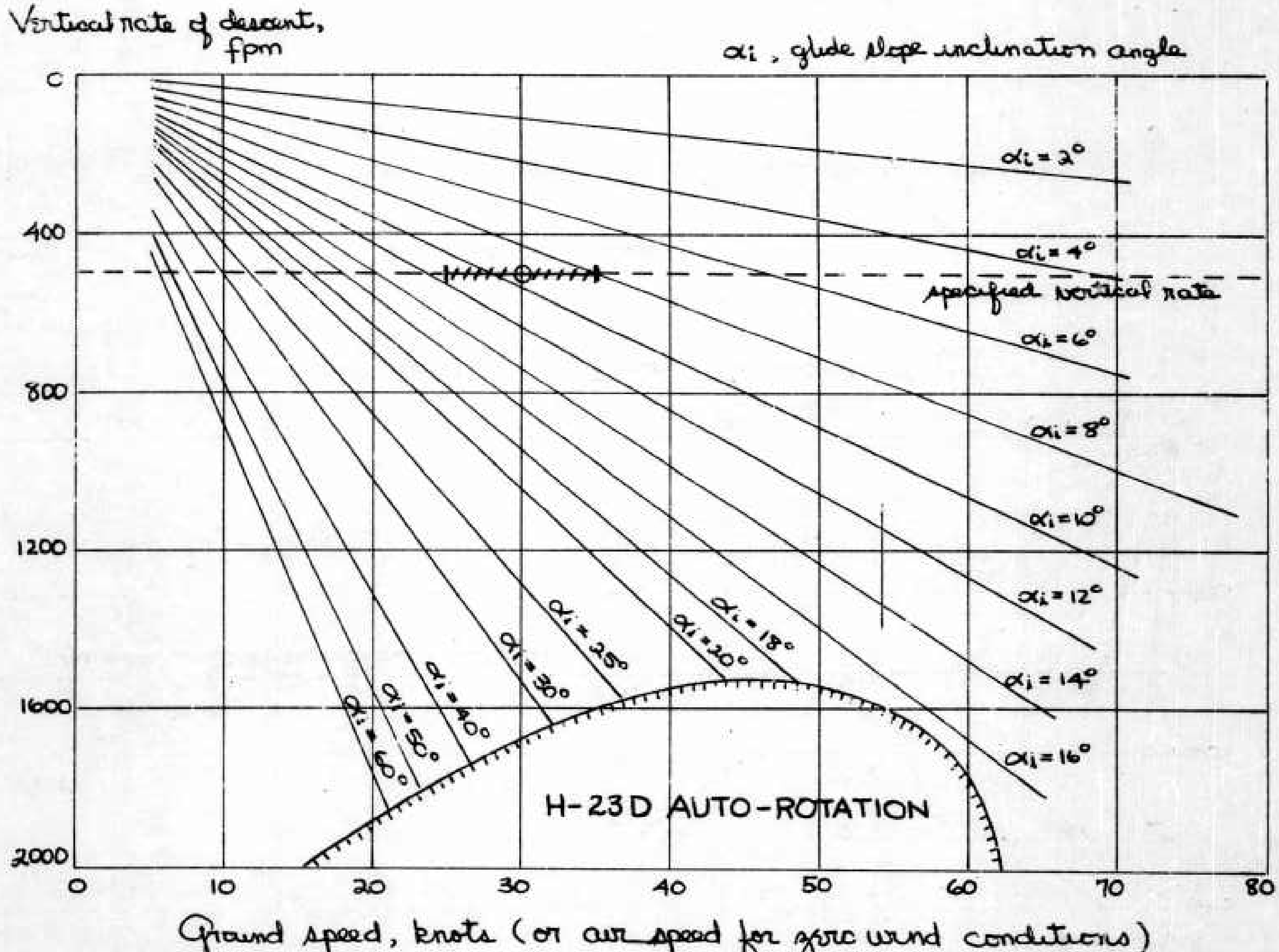

Figure 5. Relationship Among Rate of Descent, Glide Slope Angle, and Ground Speed

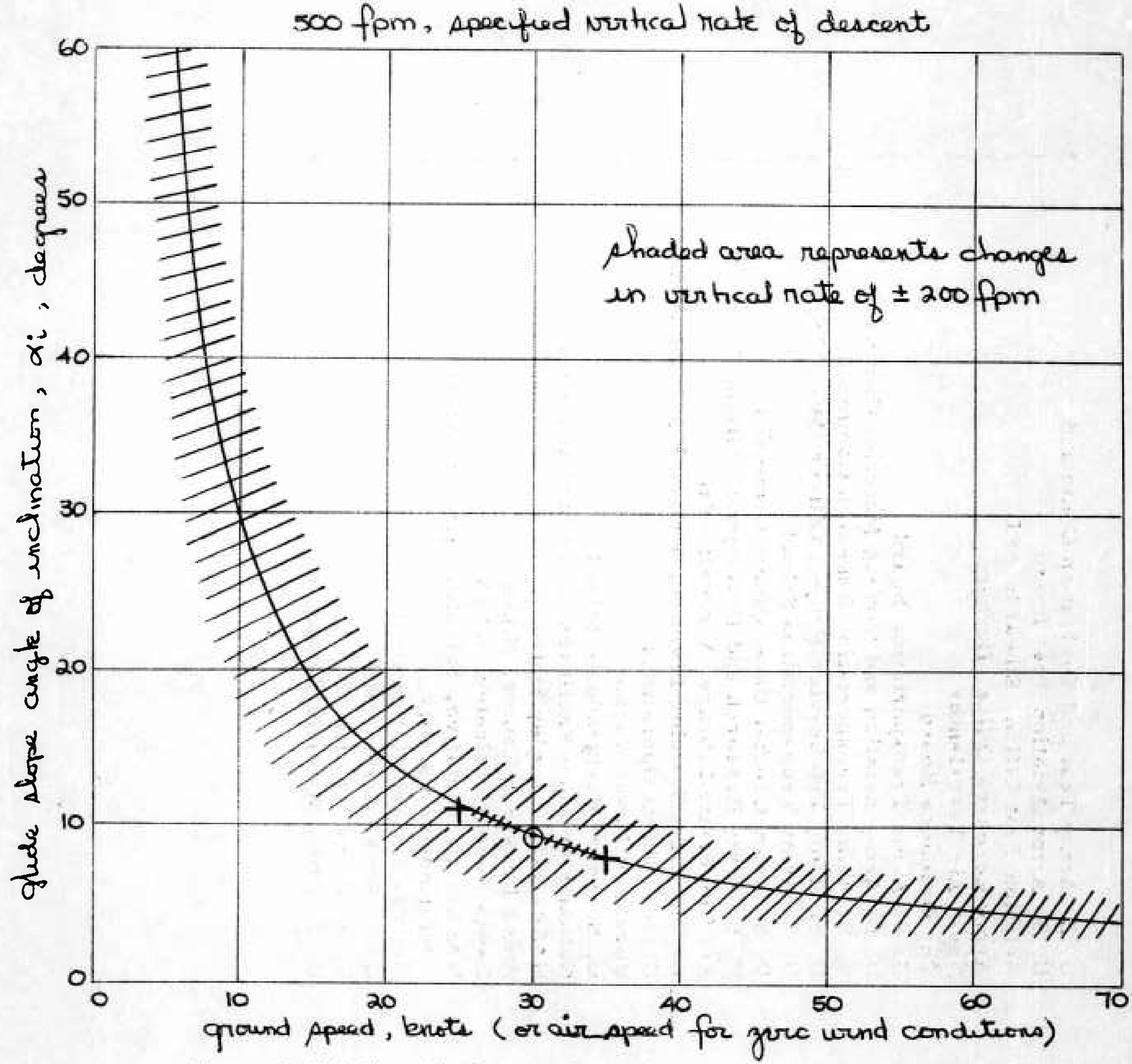

Figure 6. Relationship Between Glide Slope Angle and Ground Speed

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