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PILOTED SIMULATOR DISPLAY SYSTEM EVALUATION - EFFECTIVE RESOLUTION AND PILOT PERFORMANCE IN THE LANDING APPROACH

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SUMMARY

A study was conducted in two parts to investigate the quality of a visual display in a fixed cockpit piloted simulator and ways of measuring pilot-vehicle performance. Part I concerned the effective resolution of a typical simulator display relative to that for the real world; Part II concerned pilots' estimates of range and altitude from the runway threshold and measures of his ability to control the vehicle in the approach and landing. A correlation analysis of the information from part II was used to indicate the degree of association between those performance measures.

The static display characteristics, as measured by the resolution of landolt "C" rings, were found to be degraded by as much as a factor of 12 when compared to the real world. A further loss of resolution by approximately one-third of the static resolution occurred with the moving display and was influenced by the apparent motion of the airplane.

Range estimates to the runway threshold were in error by about 10 percent; altitude estimates above the runway threshold were in error by about 20 percent. Error in range estimates decreased with experience while altitude estimates remained relatively constant.

Performance in the landing approach was very similar to that in actual flight, and even included a "duck under" maneuver by each pilot. The termination of the landing approach was at higher rates of descent, but touchdown distance from the runway threshold was about the same as in actual flight.

A correlation analysis between the various measures of altitude-range estimates, and pilot-vehicle landing performance showed the following: (a) that the touchdown error depends on the pilot's ability to judge altitude in the landing approach, and (b) the touchdown error is highly correlated with the integrated altitude error, and the correlation indicates difficulty in estimating the correct altitude to decrease the rate of descent and to initiate the flare. However, the absence of motion feedback, ground effect dynamic forces, and vestibular and kinesthetic cues may be partially [redacted] responsible for these errors.

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INTRODUCTION

Piloted simulators are being used extensively for research related to advanced aircraft and spacecraft. An important component of some of these simulators is a display of the outside scene for the crew. Because of limitations in state-of-the-art electronics and optics, these visual display systems do not provide a true picture of the real world. Although considerable progress has been made in recent years in developing display systems for research and training (refs. 1, 2), quantitative studies of the visual quality of these systems are needed to relate the display characteristics with man-system performance. This information could provide a more rational basis for defining requirements and specifications for piloted-simulator display systems. Although it was recognized that correlates between basic characteristics of visual display systems (e.g., resolution and pilot-vehicle performance measures) would be difficult to establish because of pilots' adaptive capabilities, it was considered desirable to study an available display system to provide some baseline information in this area.

Accordingly, the present studies had the following primary objectives:

I. To define, experimentally, the effective static resolution of a television display relative to that for the real world, and to measure the loss of resolution that results from motion of the aircraft at landing-approach speeds.

II. To determine pilots' ability to estimate range and altitude with a simulator display system and to land a representative commercial jet transport.

In the first part of this paper, the effective resolution characteristics of the simulator display system are presented for several pilots and compared with those for the real world. In the second part of the report, variations in performance of several pilots for several performance measures, obtained in landing approaches, are provided, and some tentative correlations among these pilot performance measures are briefly noted.

NOTATION

f	number of favorable ways
$\bar{h}$	mean altitude, ft
$\bar{\dot{h}}$	mean rate of descent, ft/sec
N	event of different ways
P	probability
r	correlation, dimensionless

[redacted]

$\bar{S}$ mean touchdown distance from runway threshold, ft

$|\bar{S}_e|$ mean absolute touchdown error from glide-slope runway intersection, ft

$\bar{S}_R$ mean resolvable distance of "C" ring, ft

$\bar{V}$ mean touchdown airspeed, ft/sec

β mean resolvable angle of "C" ring, min

$\bar{\sigma}_e$ mean standard deviation error at discrete altitudes, ft

σ_{eh} standard deviation of altitude estimates, dimensionless

σ_{er} standard deviation of range estimates, dimensionless

σ_h standard deviation of $\bar{h}$, ft

σ_S standard deviation of $\bar{S}_R$, ft

σ_{sd} standard deviation of $\bar{S}$, ft

σ_v standard deviation of $\bar{V}$, ft/sec

$\bar{\int}_{h_e}$ mean [illegible]grated altitude error between command and actual flight path, ft

EQUIPMENT AND METHOD

Description of Apparatus

The components of the visual simulator are a television camera, runway model (scaled at 300 feet = 1 foot), projection system, and cab. The television camera mounted on a five-degrees-of-freedom carriage assembly is shown in figure 1. The belt (runway) transporter with one degree of freedom is also shown. The television camera is a General Electric 525 scan line, 30 frames/sec, 2:1 interlace, 4:3 aspect ratio system. The front projection system is a Schmidt Projector, with correction plates and a retro-reflective screen with a gain of 2.5. Field of view afforded the pilot, located 10 feet from the screen, was 50° horizontal and 37.5° vertical. An Elgeet 13 mm, F2.5 wide angle lens was used to produce a unity magnification ratio.

Experimental Procedures

Three pilots participated, one Ames test pilot, and two engineers with military flight experience. Simulator resolution was investigated by measuring the pilots' performance as they viewed stationary or moving objects. The performance index used was essentially the pilot's visual acuity for a test object observed under a static or dynamic condition.

Resolution characteristics (static).- A special light box and matrix plate (fig. 2) was constructed for the pilots to observe the orie tation of landolt "C" rings, i.e., left, down, right, or up. This method, which has no form discrimination, was designed to determine the relative acuity of the observers as a function of the television resolution. The average light reading of the matrix box that minimized blooming at the projector was determined to be 66.4 foot-lamberts with a contrast ratio of 99.2 percent. The complete matrix box was rotated 45° (figs. 1, 2) because of an unequal horizontal and vertical scan of the television camera. All "C" rings within the matrix thus have the same number of picture elements transmitted by the vidicon. Each individual "C" ring was scaled at 6 feet in diameter from which the mean resolvable angle can be determined.

Resolution characteristics (dynamic).- In order to assess pilot performance, on the basis of information used for visual contact with the runway threshold during aircraft landings, it was necessary to produce relative measurements comparable to observations by human subjects with normal viewing conditions. This was accomplished by using a single landolt "C" ring rotated from run to run, and located at a comparable real world wheel height above the runway threshold. The pilot's task was to acquire the runway threshold visually during a normal landing approach and, when the orientation of the ring became discernible, to activate a switch that would record altitude, range to threshold, speed, and other pertinent variables.

Range and altitude estimates.- The pilot's ability to estimate altitude and range, at discrete points along a normal 3° glide slope to the runway threshold, was measured by normalized error responses. Altitude varied from a minimum of 30 feet to a maximum of 270 feet, while the range varied from a minimum of 500 feet to a maximum of 2500 feet.

The experimental design required a pilot-run matrix of 25 altitude-range combinations that were displayed with equal probabilities in seven variations according to a Latin square experimental design.

Landing-approach performance.- Pilot performance was measured in actual landing approaches and in a fixed cockpit landing-approach simulator (fig. 3) with the Boeing 707 dynamics. The principal dynamics used were those for the aircraft longitudinal response including both the phugoid and short period. The pilot's approach task was to establish a stable, well-controlled rate of descent to the runway threshold with visual references and to make a termination maneuver including a successful flare and touchdown. Initially, the pilot's altitude was 300 feet, flight path, 3°; ground distance to runway threshold, 5731 feet; and the approach airspeed, 135 k. Each pilot made a total of 45 approaches and landings.

RESULTS AND DISCUSSION

Display Resolution

(Static): 100 percent correct detection of "C" ring opening.- The results of 25 observations per pilot of the static landolt "C" ring matrix

through the television system are summarized in table I. Of primary interest are the mean resolvable distance ($\bar{S}_R$), standard deviation (σ_S), mean resolvable angle (β), and Snellen acuity for each pilot.

TABLE I.- STATIC LANDOLT "C" RING SUMMARIES

Parameter	Pilot A	Pilot B	Pilot C
$\bar{S}_R$	846.48 ft	869.86 ft	862.82 ft
σ_S	13.67 ft	3.05 ft	5.29 ft
β	4.87 min	4.74 min	4.78 min
Snellen acuity	20/13	20/13	20/20

The mean resolvable angle (β), subtended at the eye by the "C" ring opening, is a measure of the minimum separable acuity which, in this case, is 4.79 minutes of arc or 287.4 seconds of arc. The nominal value resolved by human subjects under normal viewing conditions is 24 seconds of arc (ref. 3). Thus, this is a reduction in resolution equivalent to a reduction in acuity of 12 to 1. This ratio may be slightly reduced if the visual threshold distance of the landolt "C" ring can be determined from the probability of a correct answer. It will be recalled that the probability, P, of a correct answer may be defined as:

$$P = f/N$$

where

f = number of correct ways
N = number of different ways

Let

A = a correct answer
B = subject detecting ring position
C = correct answer by guessing only

Then

$P(C) = 1/4$ (Since there are four possible positions of the "C" ring)
$P(\bar{C}) = 3/4$
$P(B) = 1/2$ at threshold (50 percent detected correctly)
$P(\bar{B}) = 1/2$ at threshold (50 percent not detected correctly)

Therefore,

$$P(A) = P(B) + P(\bar{B})P(C) = 1/2 + 1/2 \cdot 1/4 = 5/8$$

The probability of a wrong answer:

$$P(\bar{A}) = P(\bar{B})P(\bar{C}) = 1/2 \cdot 3/4 = 3/8$$

Therefore, in 25 tries, the expected number of correct responses at the subject's sensitivity threshold is:

$$(25)P(A) = 25(5/8) = 15\text{-}5/8$$

Thus, the just resolvable threshold distance can be determined if each pilot can correctly identify 16 landolt "C" ring positions consistently out of the 25. The results show that approximately 100 feet can be added to each pilot's mean resolvable distance ($\bar{S}_R$) for each respective threshold distance. Consequently the televisual resolution ratio indicates a reduction in acuity of about 11:1.

(Dynamic).- The dynamic flight landing approach to the runway threshold required the pilots to observe the orientation of the landolt "C" ring as it was rotated randomly, but with the same order for each pilot, from landing approach to landing approach. Table II summarizes the parameters of mean range ($\bar{S}_R$), mean altitude ($\bar{h}$), their respective standard deviations (σ_S, σ_h), and mean resolvable angle (β) for which acuity is maximum.

TABLE II.- LANDING-APPROACH "C" RING SUMMARIES

Parameter	Pilot A	Pilot B	Pilot C
$\bar{S}_R$	601.47 ft	565.04 ft	575.86 ft
σ_S	47.68 ft	54.22 ft	65.95 ft
$\bar{h}$	93.08 ft	76.70 ft	89.08 ft
σ_h	6.02 ft	6.40 ft	6.28 ft
β	6.86 min	7.30 min	7.16 min

The dynamic mean resolvable angle (β) for all pilots if 7.10 minutes of arc or converted to minimum separable acuity is 426 seconds of arc. The ratio between static and dynamic minimum separable acuity is:

$$\frac{(\beta)_{static}}{(\beta)_{dynamic}} = \frac{287.4}{426} = 0.6746$$

This figure is analogous to the pilot's ability to discriminate visual detail of a moving object and is sometimes called dynamic visual acuity (refs. 4, 5). The change in acuity of approximately 1/3 under simulated pilot approach dynamic conditions, which could be expected in the real world comparison, shows that the loss in resolving power is strongly influenced by the apparent motion of the airplane. It is quite possible that this ratio could be further impaired for aircraft with higher approach speeds.

It is interesting to note from figure 4 that pilot A, whose static acuity was the worst, had a better dynamic acuity than pilots B and C. Likewise, pilot B, whose static acuity was the best among the pilots, had the worst dynamic acuity. Pilot C falls between pilots A and B for both static and dynamic acuity. The significance is that the pilot's dynamic and static acuity are not the same. This difference may be influenced by each pilot's

training and his particular method of controlling the aircraft in the landing approach.

Pilot Performance Measures

Range and altitude estimation.- The pilot performance in estimating range and altitude are represented in figure 5. The standard deviation (σ_{eh}) and (σ_{er}) of errors is shown as a relative error since the pilot's response to actual altitude and range has been normalized with respect to the actual altitude. Each pilot shows an asymptotic level in estimating range after at least five sessions. This indicates some learning has taken place. Little learning is indicated for altitude estimates except for pilot C. Generally, all pilots estimated range twice as well as they estimated altitude, which may indicate more horizontal visual cues than vertical cues. Although the pilots attempted to judge altitude by the intersection of the runway with the horizon, their relative altitude estimate errors still exceeded their range estimate errors.

The mean standard deviation ($\bar{\sigma}_e$) in feet at discrete altitudes is shown in figure 6 for all pilots. The figure indicates errors in altitude estimates are around 15 percent and not 20 percent as indicated from the pilot performance curves of figure 5, which were the overall responses.

Landing performance.- The results of 45 landings per pilot are shown in table III. These are mean rate of descent at touchdown ($\bar{\dot{h}}$), mean touchdown distance from runway threshold ($\bar{S}$), mean touchdown velocity ($\bar{V}$), and each respective standard deviation. These data were used to show interpilot performance variations with actual flight data.

TABLE III.- LANDING PERFORMANCE SUMMARIES

Parameter	Pilot A	Pilot B	Pilot C
$\bar{\dot{h}}$	4.51 ft/sec	3.72 ft/sec	2.77 ft/sec
$\sigma_{\bar{\dot{h}}}$	1.75 ft/sec	1.50 ft/sec	1.56 ft/sec
$\bar{S}$	1703.78 ft	1368.49 ft	1841.53 ft
σ_{sd}	236.66 ft	451.30 ft	361.51 ft
$\bar{V}$	109.65 k	109.32 k	124.03 k
σ_V	4.32 k	5.41 k	3.17 k

Among measurement criteria for performance is the absolute distance error between command glide-slope intersection of the runway and the point at which the pilot lands the aircraft. It can be seen from figure 7 that the absolute distance errors (S_e) over the span of the trials for pilots A and C have a mean error less than 400 feet, which compares favorably with real flight landings (ref. 6), however, pilot B has a greater mean error of about 700 feet.

The lines of regression for figure 7 show trends over wide variations. Appreciable negative or positive regression line slopes (± correlation) indicate either an increment or decrement in learning. However, since the slopes for all three pilots are small, learning does not appear to be a factor in this particular performance measure.

The integral absolute altitude error is a measure of how well the pilot adheres to the command flight path until touchdown. Figure 8 indicates a mean integrated altitude error of about 200 feet for pilot A, about 300 feet for pilot B, and only about 160 feet for pilot C. The larger errors of pilots A and B are related to a "duck-under" maneuver (ref. 6) executed upon visually acquiring the runway threshold.

Table III shows that the simulator mean rate of descent is higher (2.77 ft/sec - 4.51 ft/sec) than that recorded in real flight VFR conditions of about 2 ft/sec (ref. 6). The problem associated with higher rates of descent for the simulated landings indicates that the pilots had some difficulty in estimating altitude prior to starting the flare. Although the "ground effect" equations were not included in the simulation, there may be other effects which degrade performance such as missing motion feedback, vestibular and kinesthetic cues, or limited image resolution (ref. 7).

Mean distance traversed from the runway threshold during VFR conditions is about 1500 feet for real flight (ref. 6), which is comparable with the piloted simulator range (subject means) of 1370-1840 ft. Wheel height above threshold recommended by the ICAO (International Civil Aviation Organization) standard is 40 feet; flight data from 108 landings at Kennedy International show a predominate wheel height of 20 feet (ref. 6); the simulator data show a wheel height of about 35 ft.

Performance correlates.- Correlation is simply the similarity, in direction and degree, of variations in corresponding pairs of observations of two variables. The principal problem of simple correlation is that of determining the degree of association between these pairs of observations. The aggregate of plotted points was consolidated into averages (means) and standard deviations in order to investigate more easily the pilots' scatter diagram that might show a trend. The pilot scatter diagram can be expressed by an equation of the trend line called "the line of regression," which is a minimum-squared-error linear curve fitted to the scatter diagram. The slope of this line depends upon the coefficient of correlation (r), $-1 \leq r \leq 1$. It appears that the closer the points lie to a line of regression, the more nearly a simple linear equation expresses the association between the variables. Thus, a few measured parameters were thought to contribute to problems associated with the landing approach and were tested for a correlation coefficient close to ±1 (indicating a definite linear relationship between the variables). Those with a correlation coefficient close to zero (indicating practically no linear relationship) were not included in this report.

Figure 9 shows the relationship of the standard deviation of velocity (σ_V) versus the mean integral altitude error ($\bar{\int} h_e$) which are shown to be highly correlated ($r = 0.983$).

Figure 10 shows the mean absolute touchdown error ($|\bar{S}_e|$) versus the mean integral altitude error with a high correlation ($r = 0.94$).

Figure 11 shows the mean integral altitude error ($\bar{\int} h_e$) versus the mean touchdown distance from the runway threshold ($\bar{S}$) to be highly correlated ($r = 0.995$). This high correlation indicates difficulty in estimating the correct altitude to level off the rate of descent prior to and at the start of the flare.

The relationship between the pilots' static standard deviation of altitude estimates (σ_{eh}) and the simulated flight mean touchdown errors ($\bar{S}$) are shown in figure 12 to be highly correlated ($r = 0.914$). This may be significant in that the mean distance from runway threshold may be due chiefly to the pilots' inability to judge altitude correctly in the landing approach.

Similarly, figure 13 shows the standard deviation of touchdown error (σ_{sd}) versus the standard deviation of static altitude estimates (σ_{eh}) to be highly correlated ($r = 0.983$). This shows that the touchdown error is closely related to the pilots' inability to judge altitude in the landing approach.

CONCLUSIONS

The resolution characteristics of the display system, determined from measurements of static acuity, show a considerably degraded resolution equivalent to a reduction in acuity of 12 to 1. An additional loss of resolution (dynamic visual acuity) by approximately one-third occurred in the landing approach.

Static and dynamic visual acuity apparently have a negative correlation. Pilots have different static acuity but dynamic acuity may be further influenced by pilot training and methods of controlling the aircraft in the landing approach. This may account for a negative correlation; furthermore, it shows that the relative motion of the airplane can cause a loss of resolution during a landing approach.

A television-projected simulator display appears to lack the sharpness and clarity of actual flight conditions for the landing approach VFR (visual flight rules) maneuver.

The pilot uses visual cues in both the horizontal and vertical planes to estimate range and altitude. The pilots of the simulator visually estimated altitude with an error of about 20 percent. There was a correlation between altitude estimates and touchdown errors. Range estimate errors were about 10 percent, but there was little correlation between range estimates and touchdown errors.

Real flight touchdown distance (from the threshold) and rate of descent during VFR conditions are somewhat less than those recorded from the piloted

simulator. However, these errors, which degrade performance in the simulator, may be due to the absence of kinematic feedback, vestibular cues, kinesthetic cues and image degradation.

The correlation analysis of the landing-approach performance has shown the following: (1) the touchdown error is closely associated with the pilots' inability to judge altitude in the landing approach, (2) the touchdown error is also closely related to the integrated altitude error which indicates the pilot's difficulty in estimating the correct altitude for leveling off the rate of descent prior to and while initiating the flare.

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FIGURE TITLES

Figure 1.- Landing-approach model assembly.

Figure 2.- Light source and landolt "C" ring matrix.

Figure 3.- Pilot station and projected runway image.

Figure 4.- Pilots' static and dynamic resolving angle.

Figure 5.- Pilot performance curves for estimates of range and altitude.

Figure 6.- Pilots' average altitude error at discrete altitudes.

Figure 7.- Pilots' touchdown error versus landing trials.

Figure 8.- Pilots' integrated altitude error versus landing trials.

Figure 9.- Pilot correlation between velocity and integrated altitude error.

Figure 10.- Pilot correlation between integrated altitude error and touchdown error.

Figure 11.- Pilot correlation between touchdown distance and integrated altitude error.

Figure 12.- Pilot correlation between touchdown distance and static altitude error estimates.

Figure 13.- Pilot correlation between standard deviations of static altitude error estimates and touchdown error.

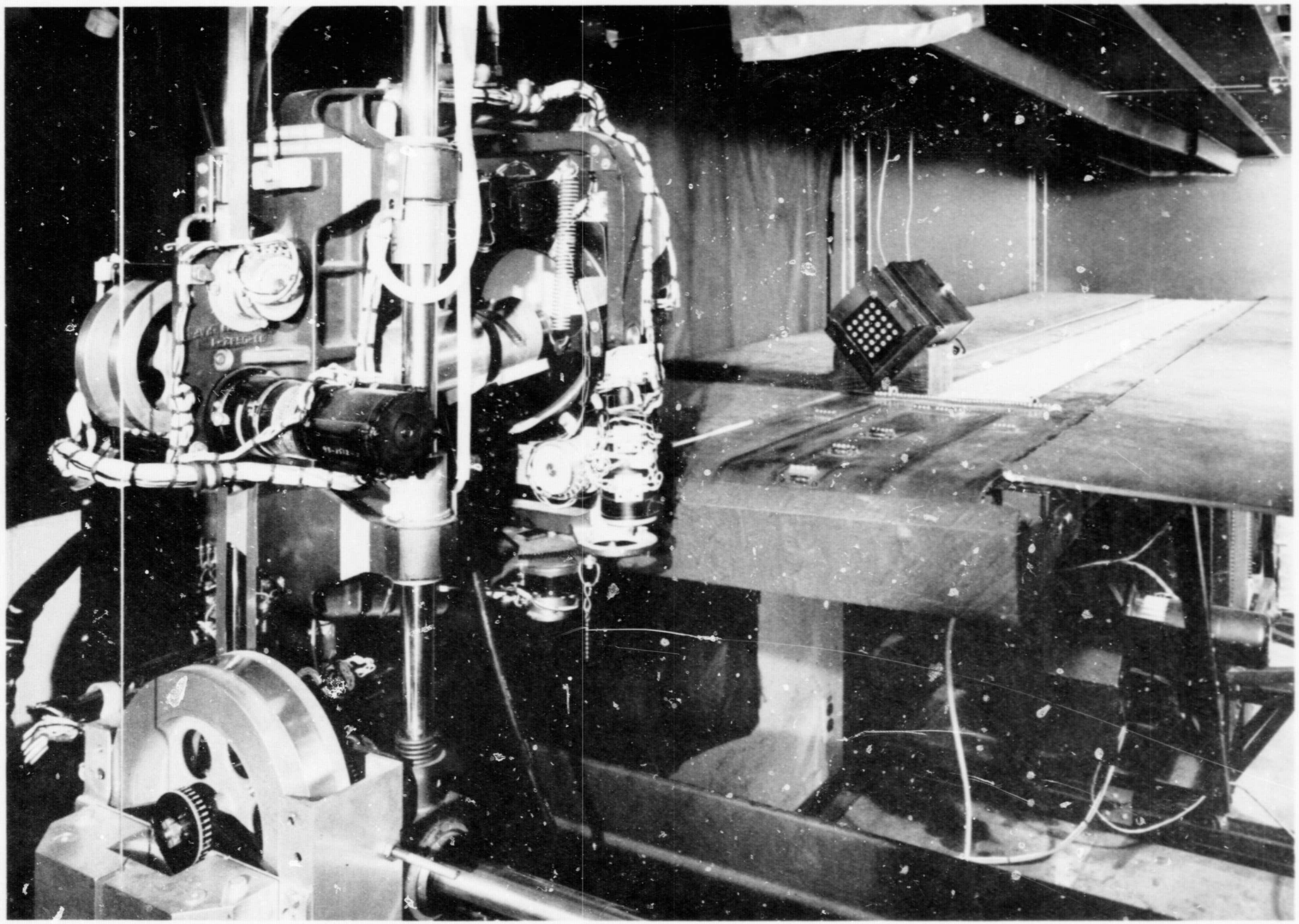

Figure 1.- Landing-approach model assembly.

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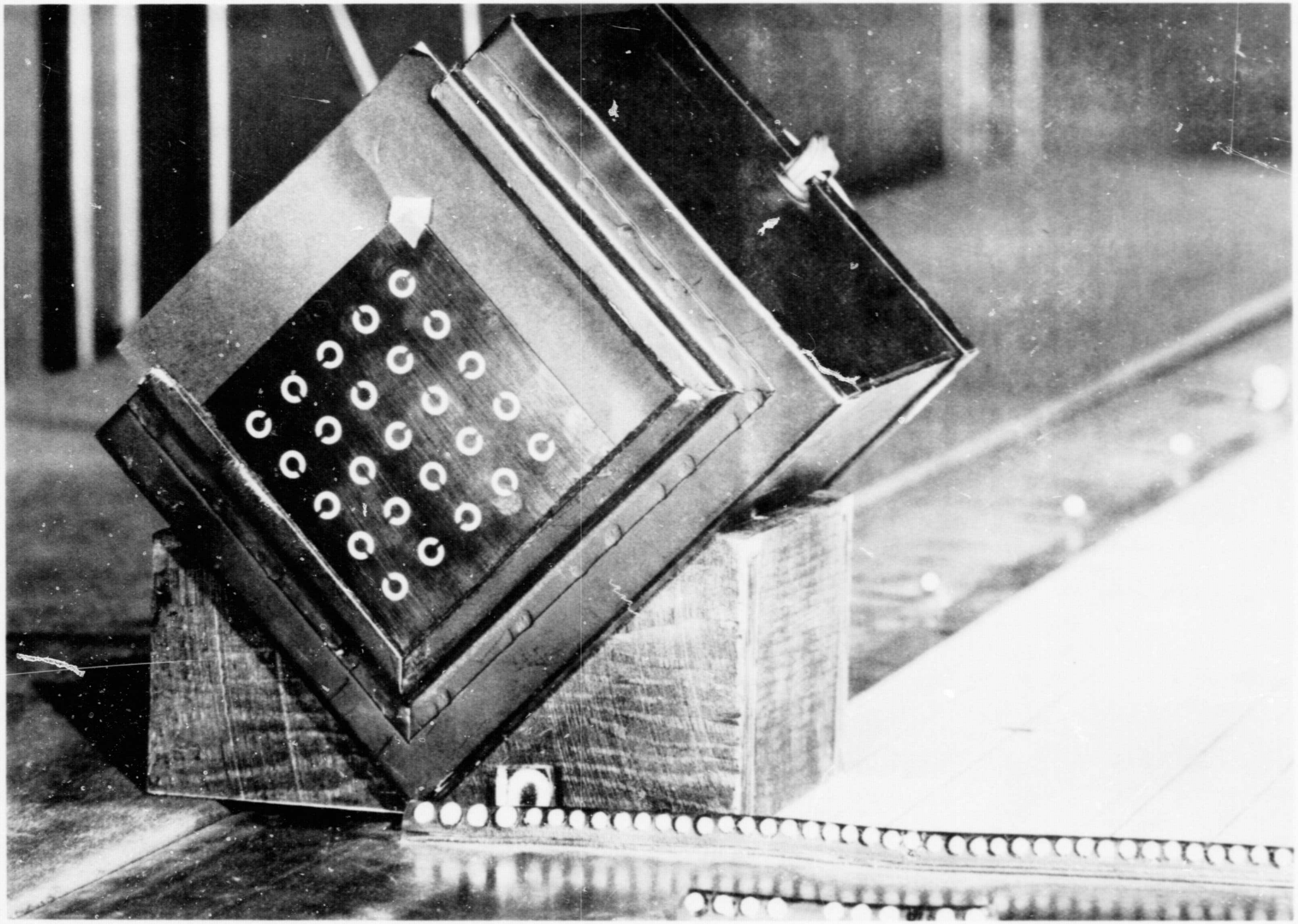

Figure 2.- Light source and landolt "C" ring matrix.

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Figure 3.- Pilot station and projected runway image.

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PILOTS' STATIC AND DYNAMIC
RESOLVING ANGLE

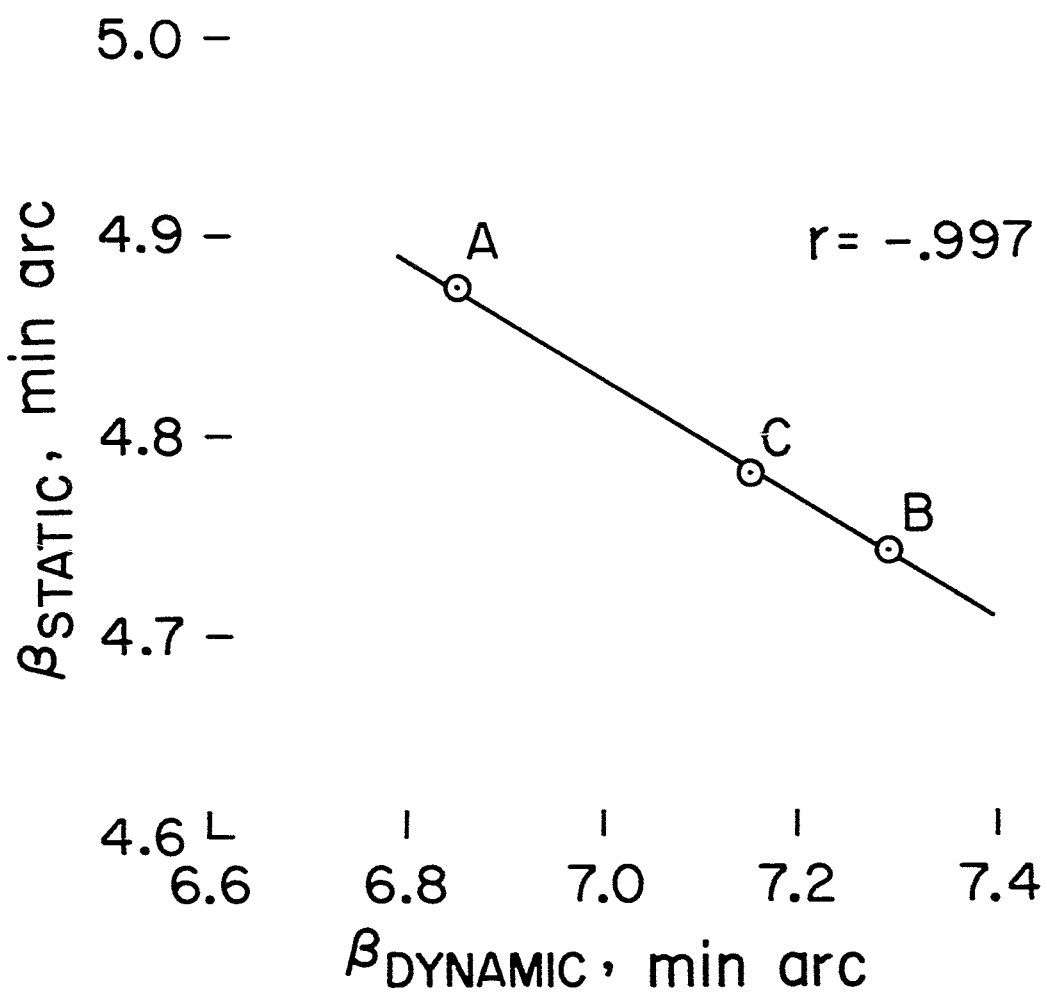

Figure 4

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PILOT PERFORMANCE CURVES FOR ESTIMATES OF RANGE AND ALTITUDE

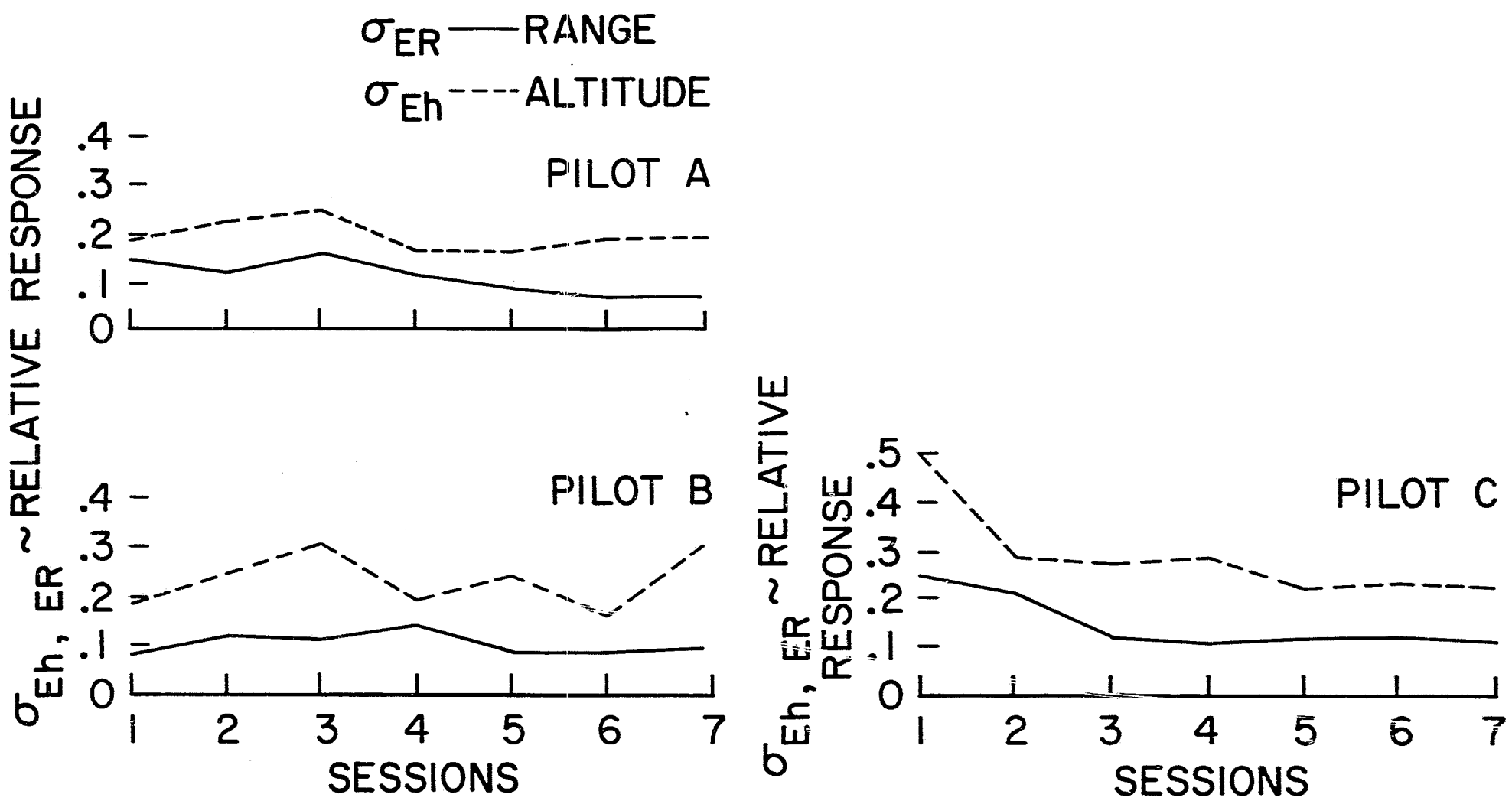

Figure 5

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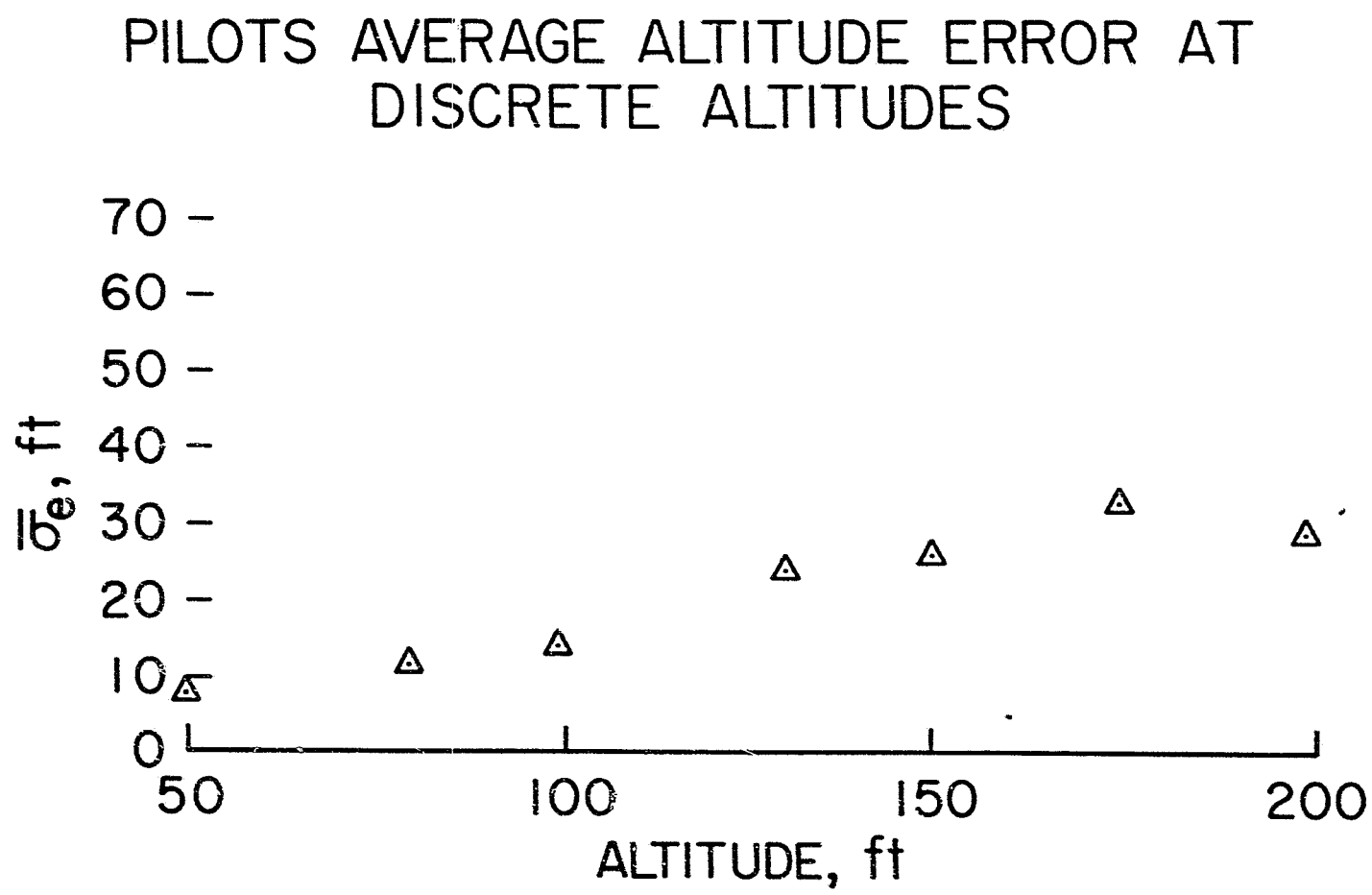

Figure 6

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PILOTS' TOUCHDOWN ERROR VERSUS LANDING TRIALS

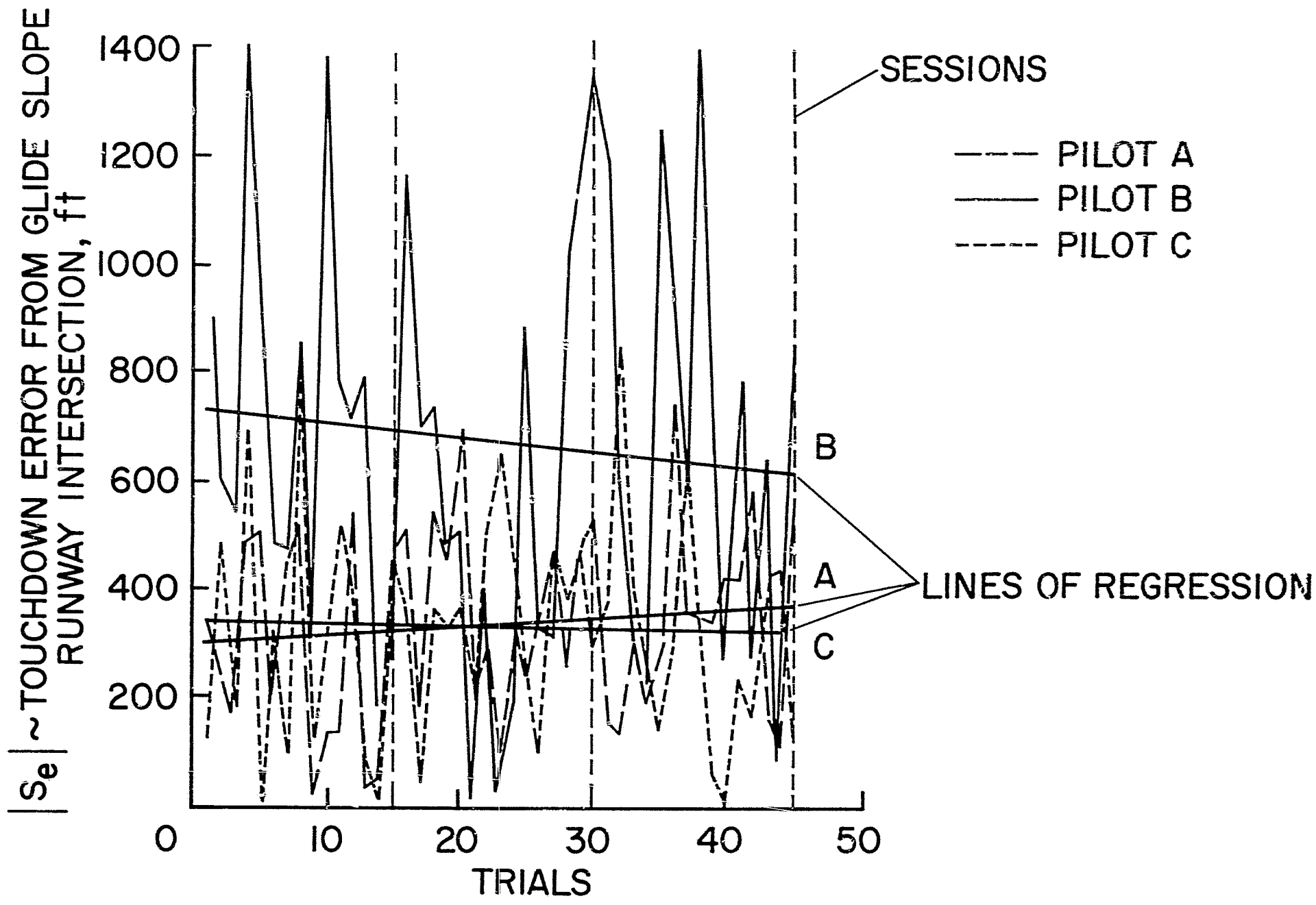

Figure 7

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PILOTS' INTEGRATED ALTITUDE ERROR
VERSUS LANDING TRIALS

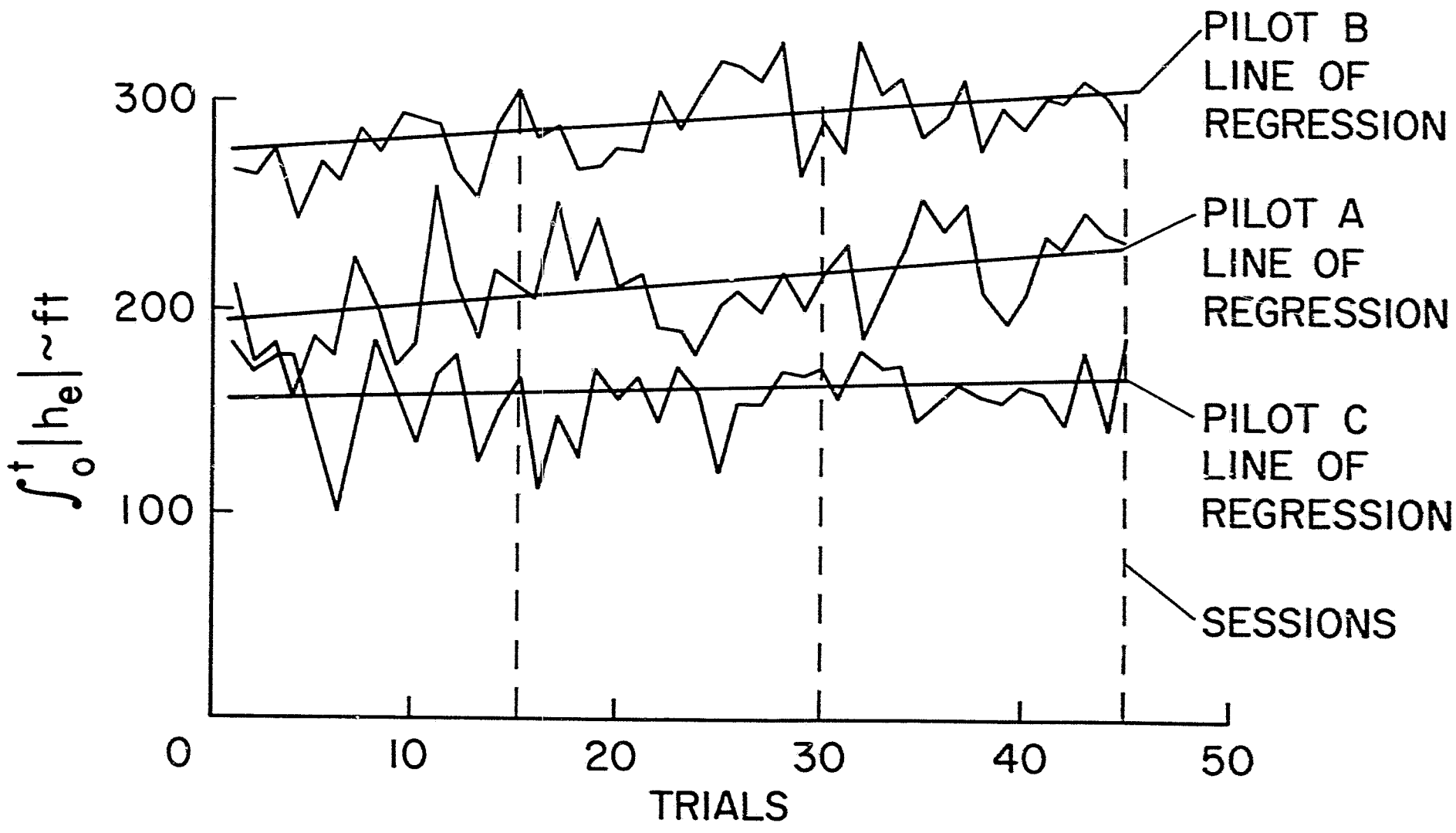

Figure 8

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PILOT CORRELATION BETWEEN VELOCITY AND INTEGRATED ALTITUDE ERROR

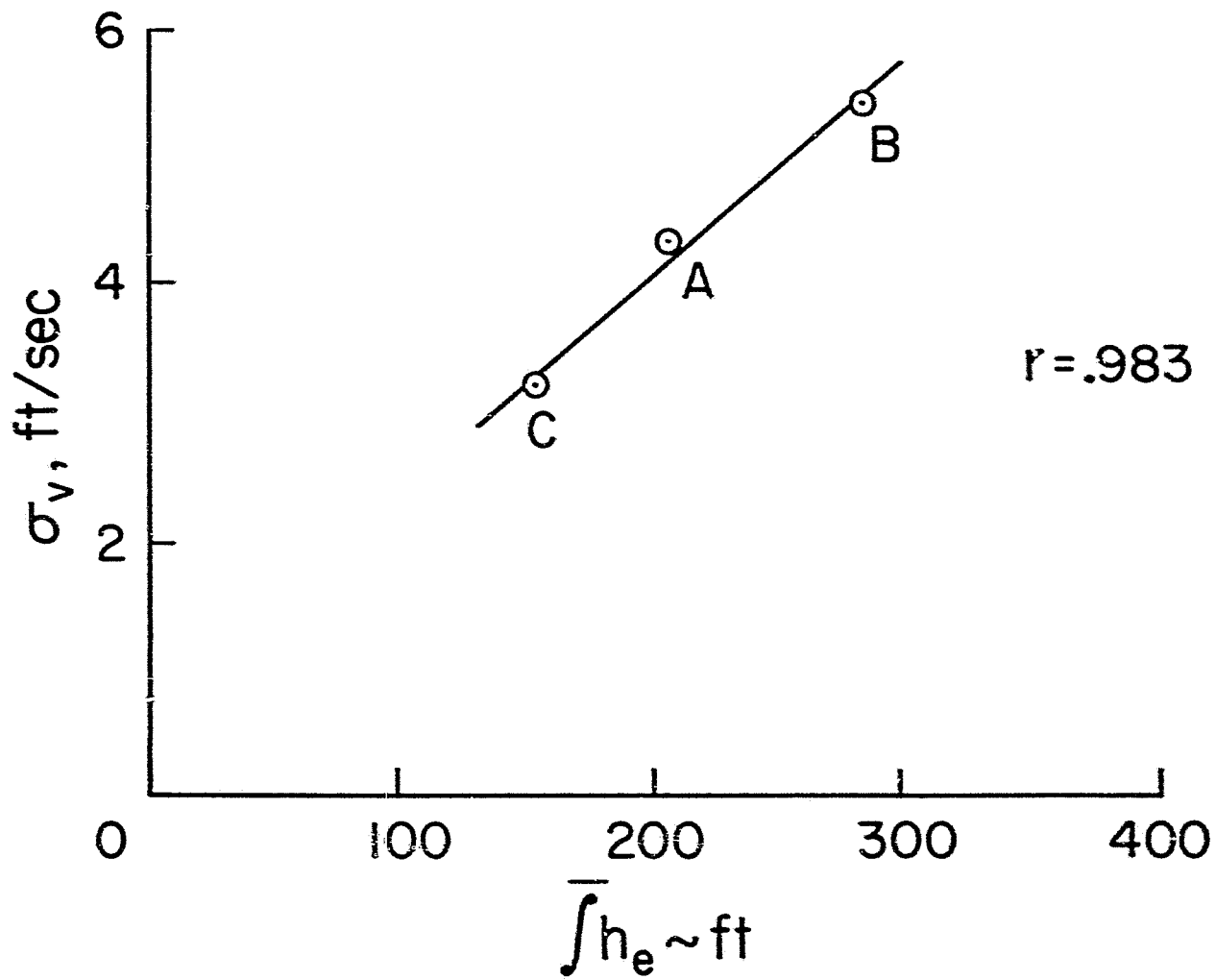

Figure 9

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PILOT CORRELATION BETWEEN INTEGRATED ALTITUDE ERROR AND TOUCHDOWN ERROR

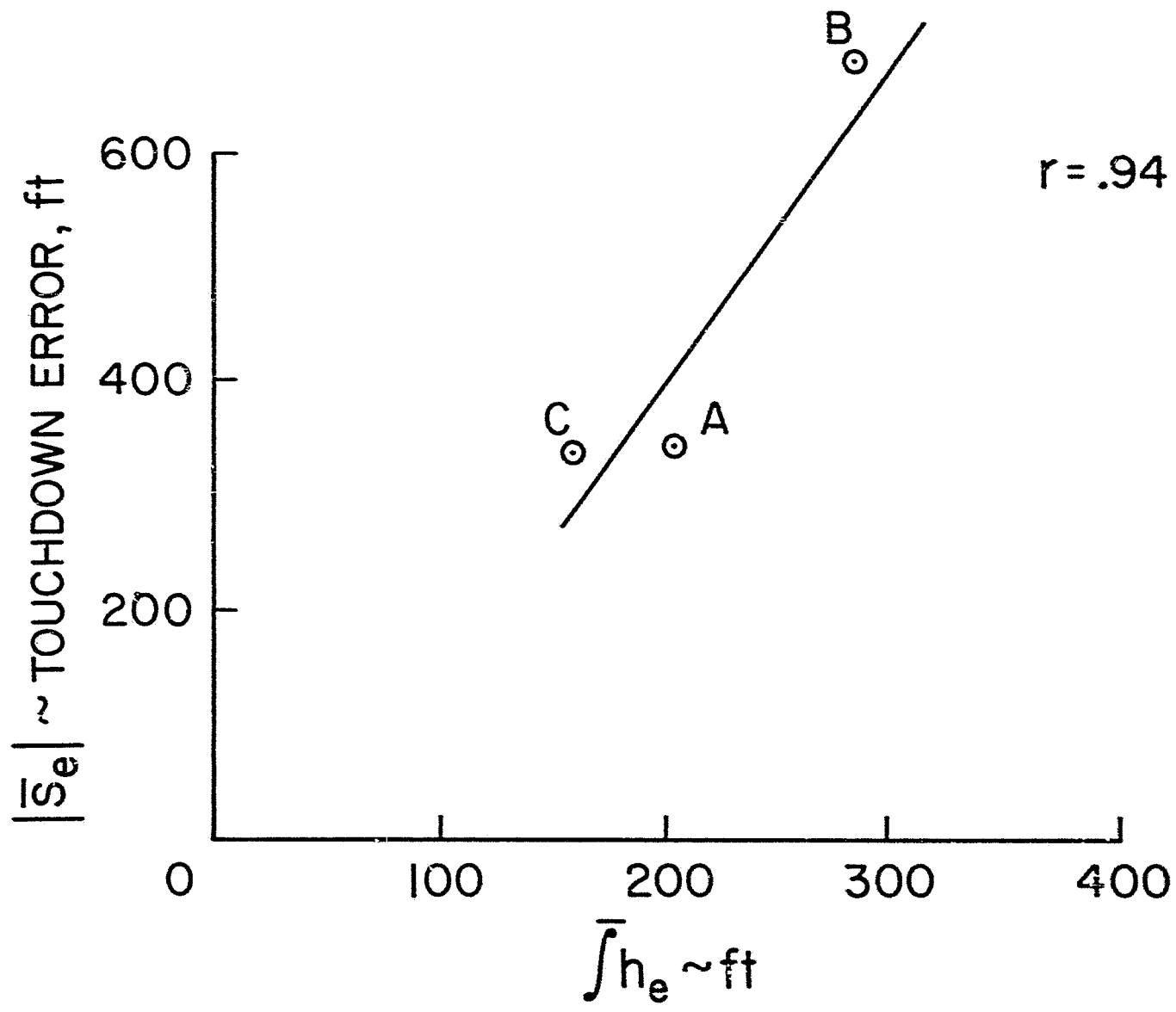

Figure 10

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PILOT CORRELATION BETWEEN TOUCHDOWN DISTANCE AND INTEGRATED ALTITUDE ERROR

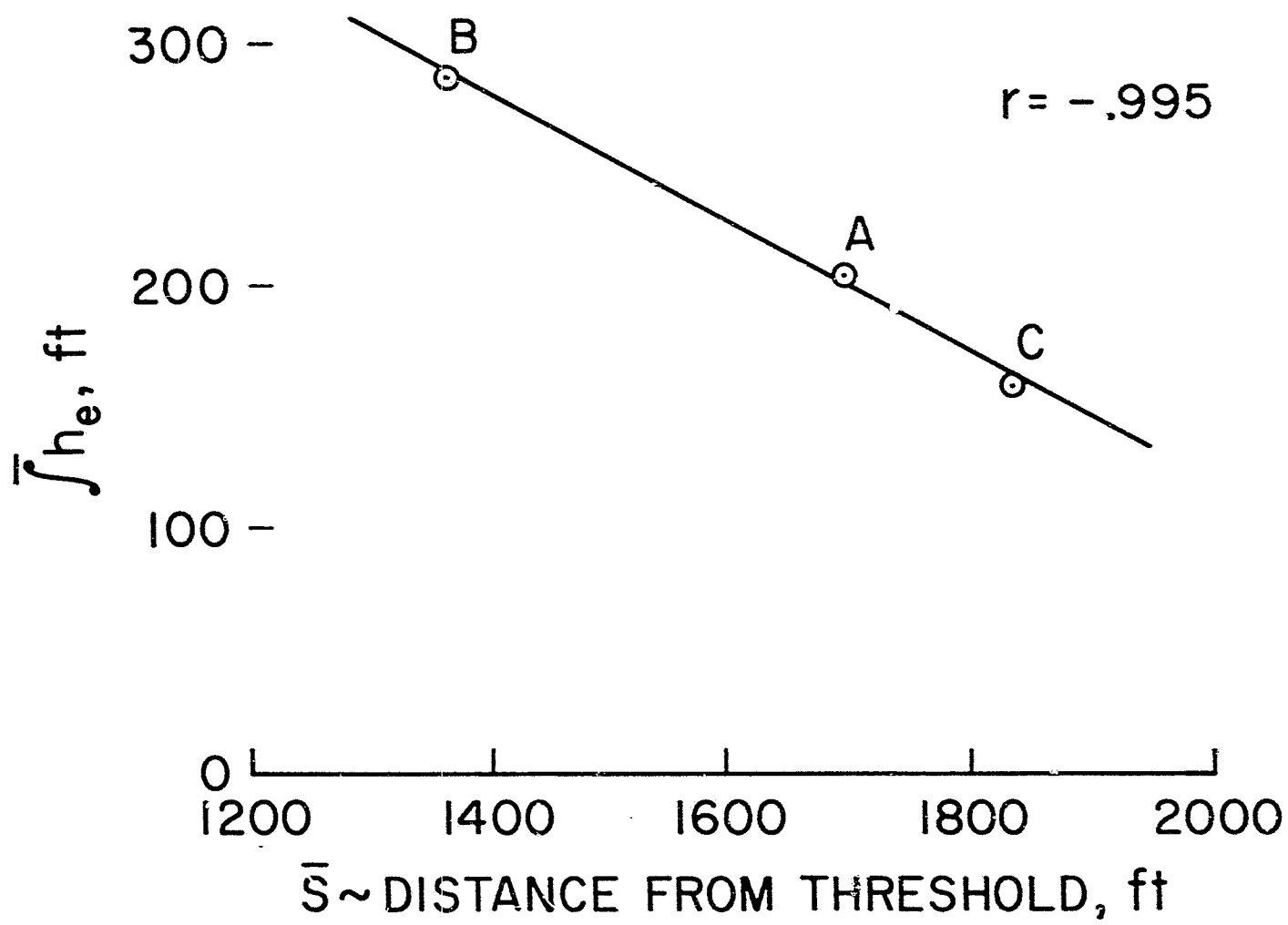

Figure 11

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PILOT CORRELATION BETWEEN TOUCHDOWN DISTANCE AND STATIC ALTITUDE ERROR ESTIMATES

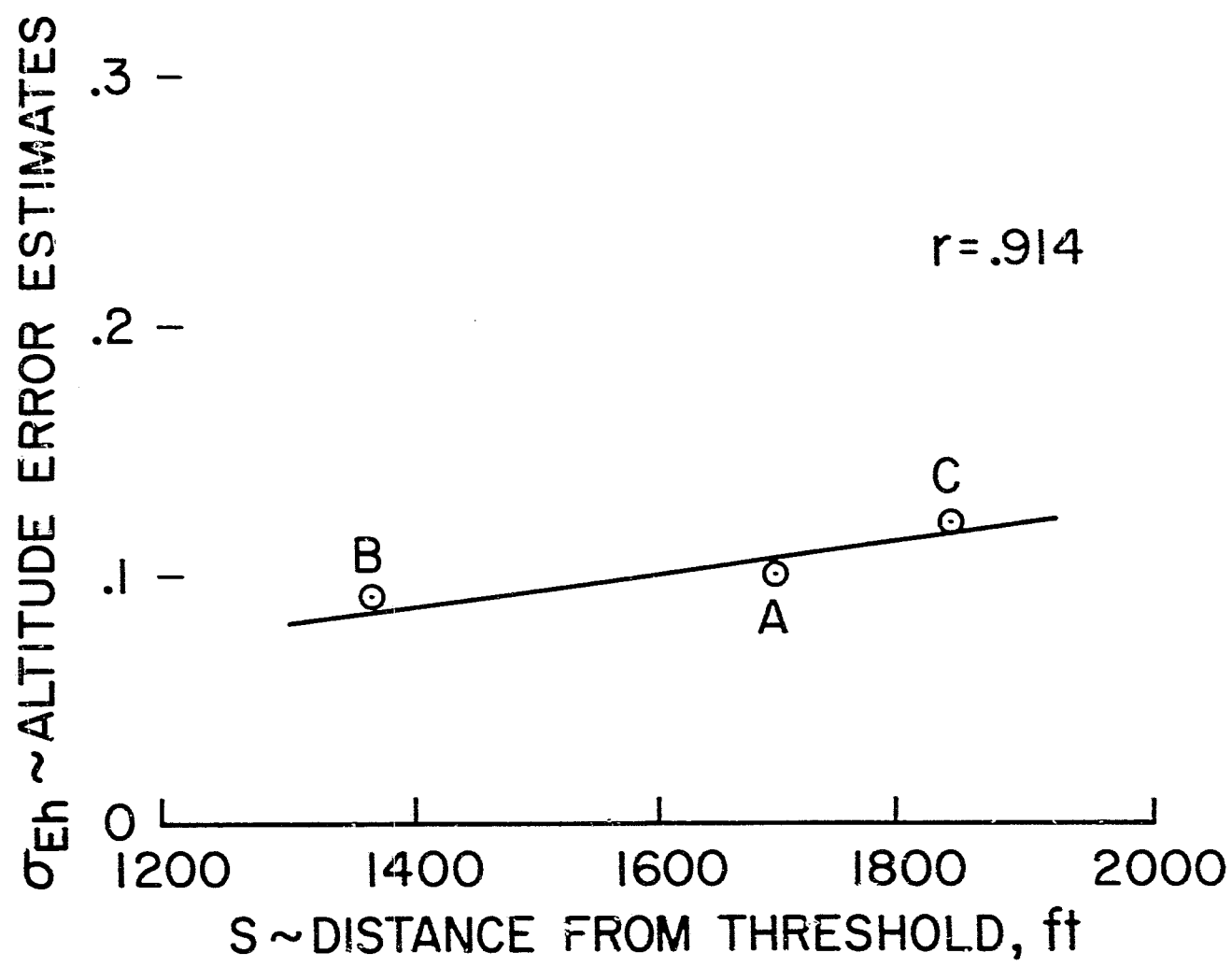

Figure 12

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PILOT CORRELATION BETWEEN STANDARD DEVIATIONS OF STATIC ALTITUDE ERROR ESTIMATES AND TOUCHDOWN ERROR

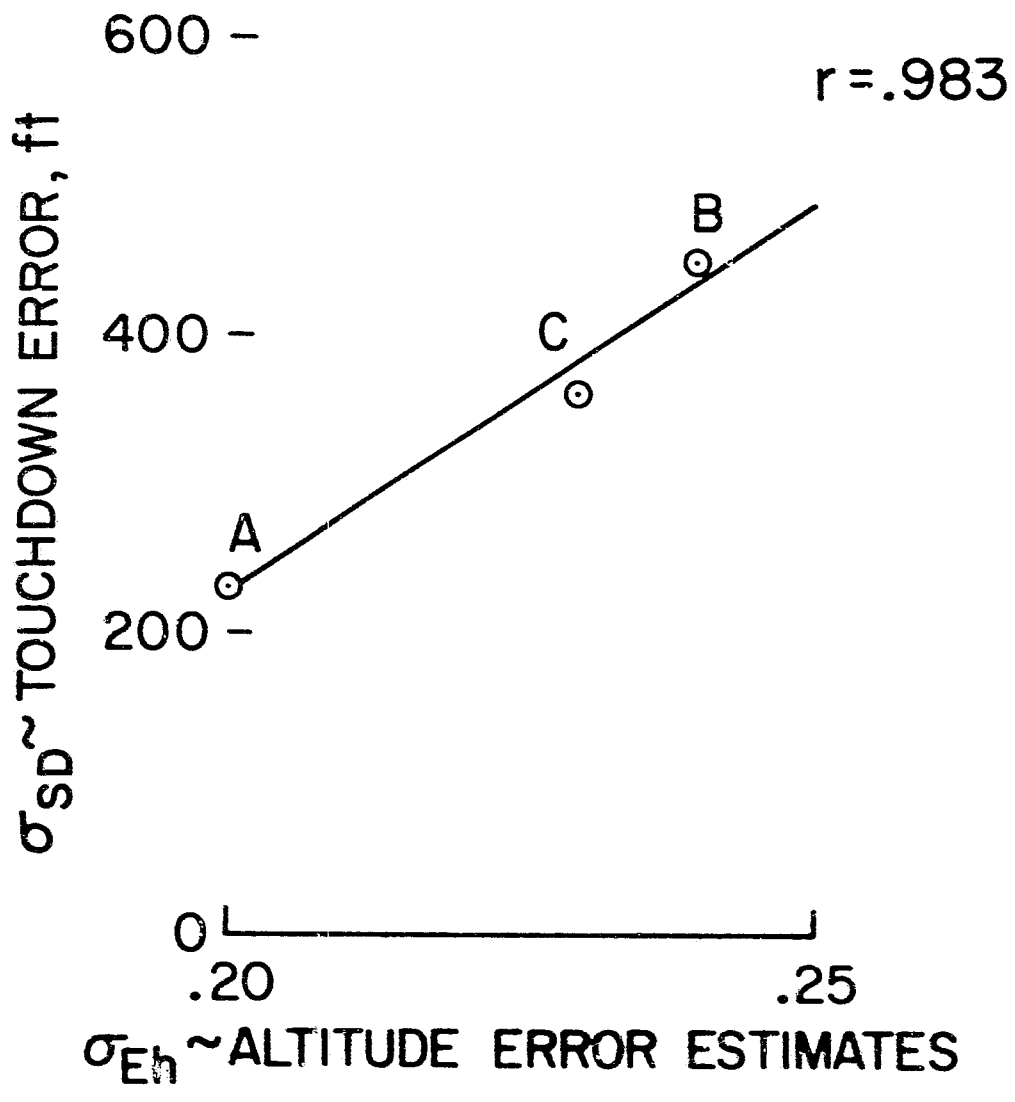

Figure 13

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