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# A PILOTED-SIMULATION EVALUATION OF TWO ELECTRONIC DISPLAY FORMATS FOR APPROACH AND LANDING

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16. Abstract

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The results of this experiment show that the addition of a perspective runway image and relative track information to a basic situation-information EADI format resulted in improved tracking performance both laterally and vertically during an approach-to-landing task and that the mental workload required to assess the approach situation was thus reduced as a result of integration of information.

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# A PILOTED-SIMULATION EVALUATION OF TWO ELECTRONIC
# DISPLAY FORMATS FOR APPROACH AND LANDING

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## SUMMARY

This report presents the results of a piloted-simulation evaluation of the benefits of adding runway symbology and track information to a baseline electronic-attitude-director-indicator (EADI) format for the approach-to-landing task. The evaluation was conducted both for the baseline format and for the same format with the added symbology during $3^O$ straight-in approaches with calm, cross-wind, and turbulence conditions. Flight-path performance data and pilot subjective comments were examined with regard to the pilot's tracking performance and mental workload for both display formats.

The results of this experiment show that the addition of a perspective runway image and relative track information to a basic situation-information EADI format resulted in improved tracking performance both laterally and vertically during an approach-to-landing task and that the mental workload required to assess the approach situation was thus reduced as a result of integration of information.

## INTRODUCTION

With the advent of electronic displays, the potential exists for displaying considerable information to aid the pilot in his decision-making process. Many reports have been written describing electronic display hardware now available with various display formats for both military and commercial application. (For example, see refs. 1 and 2.) The problem, however, becomes one of determining the information essential to the pilot's performance of the task and presenting this information to the pilot in a simple, easily understandable, integrated form.

This report presents the results of a piloted-simulation evaluation of the benefits of adding runway symbology and track information to a baseline electronic-attitude-director-indicator (EADI) format for the approach-to-landing task. The runway symbology and track information were added to the EADI format to aid the pilot in maintaining a current mental picture of the vertical and horizontal situation. The revised format was

designed to improve the pilot's interpretation of the situation of the aircraft with respect to the runway during an instrument approach. The evaluation was conducted for the baseline format and for the same format with the added symbology during $3^o$ straight-in approaches with calm, cross-wind, and turbulence conditions. Flight-path performance data and pilot subjective comments were examined with regard to the pilot's tracking performance and mental workload for both display formats. Four National Aeronautics and Space Administration (NASA) pilots were used as test subjects, and the approach task was terminated at a flare altitude of approximately 12.2 m (40 ft).

## SYMBOLS

Values are given in both SI and U.S. Customary Units. The measurements were made in U.S. Customary Units.

$A_{ij}$      matrix representing runway to inertial transformation

a,b,c      positional values measured in the eye coordinate, meters

$C_{ij}$      matrix representing inertial to body transformation

$\bar{c}$      mean aerodynamic chord

D1      display format number 1

D2      display format number 2

df      degrees of freedom, dimensionless

F(calculated)      calculated test statistic, dimensionless

F(tabulated)      value for confidence level with (n, np) degrees of freedom, dimensionless

H,N,E      orthonormal axes representing inertial reference frame

O      origin of eye coordinate system

Q,Q'      points located along the $Z_e$-axis in the eye coordinate system

R      range

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| | |
|---|---|
| R' | range in eye coordinate system, measured on screen |
| s | standard deviation, dimensionless |
| W1 | evaluation window number 1, dimensionless |
| W2 | evaluation window number 2, dimensionless |
| W3 | evaluation window number 3, dimensionless |
| W4 | evaluation window number 4, dimensionless |
| W5 | evaluation window number 5, dimensionless |
| X,Y,Z | orthonormal axes |
| x,y,z,h | positional states measured in inertial coordinate system, meters |
| $\bar{x}$ | statistical mean value, dimensionless |

Subscripts:

| | |
|---|---|
| B | body coordinate system |
| e | eye coordinate system |
| R | runway coordinate system |
| s | screen coordinate system |
| T | threshold |

Acronyms:

| | |
|---|---|
| ADEDS | advanced electronic display system |
| ADI | attitude director indicator |
| CRT | cathode ray tube |

EADI      electronic attitude director indicator

HSI      horizontal situation indicator

ILS      instrument landing system

IVSI      instantaneous vertical speed indicator

## BACKGROUND

The Langley Research Center has implemented a long-range effort known as the terminal configured vehicle (TCV) program. The program consists of work in analysis, piloted simulation, and flight testing to research and develop the advanced flight-control capability for time-controlled navigation with transition to the new microwave landing system (MLS). This program, by using the MLS, is also investigating precision curved, steep, decelerating, time sequenced final approaches as well as low-visibility landings through turnoff.

To accomplish these goals in a realistic fashion, the NASA acquired a B-737 aircraft equipped with advanced avionics which include digital implementation of the navigation and guidance functions, cathode ray tube displays of the vertical and horizontal situation, and a triplex digital control system. The aircraft is also equipped with a fly-by-wire research cockpit (located in the cabin area behind the normal aircraft cockpit). This research cockpit allows the optimization of the aircraft handling qualities and the study of modernization of the flight-deck station and control system (refs. 3 and 4).

The TCV program is using the advanced electronic display system (ADEDS) as a starting point on the aircraft for its initial display research and development effort. The ADEDS is an integrated navigation, guidance, and display system based on the design and development effort for the supersonic transport (SST) prototype program. A description of the ADEDS system can be found in reference 4.

One of the research elements in support of the TCV program is a sophisticated simulation system. The simulator provides a testing ground for research and advanced concepts proposed for flight evaluation aboard the aircraft. The simulation has been developed to duplicate the operation of the aft flight deck in the B-737 aircraft. Nonlinear effects such as engine lag, varying stability functions, and control surface servo models enable the simulation to represent the aircraft with a high degree of realism. The comparison study was conducted on this facility.

A difference between aircraft and simulator can be noted in the generation of electronic displays. The ADEDS aboard the aircraft uses both raster and stroke drawing techniques. For the simulator, however, a different graphics system, with more flexibil-

ity in programing but no raster capability, was chosen in order to permit research in display formats to be realistically interwoven into the support schedule. The ADEDS formats were reprogramed for the simulation using only stroke techniques but retaining basic symbology and information software. The lack of a raster capability in the simulation display system prevented an earth-sky shading in display formats; this problem, however, was circumvented by overemphasizing (double-stroke drawn and continuous) the horizon line in the pitch grid presentation.

## INITIAL DISPLAY INFORMATION DEVELOPMENT

During the initial development of the computer-generated runway mathematical model, photographs of actual runways were taken from numerous points along the final approach course to a landing. These photographs were used to assist in confirming that the computer-generated runway geometry was drawn correctly as a function of relative position, altitude, and heading between the aircraft and the runway. The photographs were also examined to determine what real-world cues might be enhanced on the display to assist the pilot in determining the position of his aircraft with respect to the runway more readily.

The photographs were taken from a helicopter with the camera positioned in the area of the pilot's head. A horizontal line with reference marks in the center and $15^O$ left and right of the center of the pilot's field of view was taped on the canopy of the helicopter for a relative heading reference. Photographs were taken from the helicopter while it hovered at various altitudes and positions along the center line of the runway. When the helicopter was displaced laterally from the runway center line, two photographs from the same position were taken: one with the runway centered in the picture, the second with the camera alined with the longitudinal axis of the helicopter. Several sequence series of photographs were also made while the helicopter executed $3^O$ and $6^O$ approaches. Photographs were taken every 10 seconds over a range beginning 5556 m (3 n. mi.) from the runway with an approach speed of 50 knots.

Subjective comparisons were made between the computer-generated runway geometry and the actual runway with the aircraft (pilot's eye view) at approximately the same position and direction relative to the runway. Runway size and growth as a function of range was examined with a series of photographs taken during several "on-localizer and on-glide-slope" instrument approaches. Runway size changes as a function of altitude were examined with a series of photographs taken 926 m (0.5 n. mi.) from the threshold, on the runway center line from various altitudes between 30.48 m (100 ft) and 213.36 m (700 ft) above ground level. Runway shape and symmetry as a function of lateral displacement were examined from photographs taken with the helicopter displaced a full localizer width ($2.5^O$) left and right of the runway center line. Lateral movement (within the field of view

of the camera) of the computer-generated runway as a function of relative heading between the aircraft and the runway was also examined.

Several combinations of large lateral displacements and aircraft bank angles (such combinations would result in a missed approach during instrument conditions) were examined to determine if they would cause the computer-generated runway to be drawn incorrectly. Figures 1 and 2 show a comparison of the actual runway as it would be seen by the pilot if the aircraft had a relatively large lateral displacement, a relatively steep bank angle, and a very short range to the threshold and similar conditions when simulated on a computer-generated runway. It can be seen in both pictures that the runway is almost horizontal to the bottom of the picture. The computer-generated runway appeared to be drawn correctly with all combinations of bank angles and displacements examined.

In summary, the computer-generated runway was drawn as the actual runway would be seen by the pilot from all positions, altitudes, and aircraft attitudes photographed. The sequence series of photographs indicated that runway growth rate as a function of altitude and range was the same as that for the actual runway.

The photographs of the actual runway were also used to determine whether other cues, with the exception of rate cues (that is, lateral displacement rate, etc.), were available for the pilot to use as aids in the approach to landing. Identification and enhancement of these cues would have an important influence on the techniques and visual scan that the pilot would use when conducting an approach with the computer-generated display. In addition, cues from which the pilot derived inconsistent or erroneous conclusions about his position with respect to the runway were identified.

One of the strongest cues available to the pilot from the runway geometry is the symmetry (slant) of the runway with lateral displacement. The pilot may determine from the runway symmetry, regardless of his altitude or relative heading (assuming the runway is still in the pilot's field of view), whether his aircraft is on or is displaced to the left or right of the runway center line. Figure 3 shows that the far end of the runway slants toward the side of the runway on which the aircraft is displaced (that is, the far end of the runway slants toward the right if the aircraft is displaced laterally to the right of the runway center line). Photographs of both small and large runways indicate that within 3704 m (2 n. mi.) (or where the runway appeared sufficiently long), lateral position from the runway center line could be distinguished within a quarter width of the runway (assuming the pilot was within the lateral borders of the runway). Lateral deviations outside the width of the runway borders were easily determined although precise determination of the magnitude of displacement was not possible.

Aircraft altitude, aircraft range to the runway threshold, and deviations from the ILS glide slope were difficult to assess solely from runway geometry cues. While growth rate and runway size did give the pilot a feel for closure rate at ranges less than 3704 m

(2 n. mi.), estimates of range and altitude were not consistent, particularly when the pilot was looking at runways of various lengths and widths. The pilot seemed to use other objects such as trees, houses, or roads along his approach path to judge range and altitude.

Another important cue necessary to enhance the computer-generated display is relative heading between the longitudinal axis of the aircraft and the center line of the runway. The pilot must know the relative heading since very small differences cause the aircraft to fly away from the localizer course. During actual approaches, the pilot uses the directional gyro if he is flying on instruments and the top of the instrument panel or nose cowling if he is flying by outside references. Lateral rate cues are also used by the pilot, particularly when he is flying by references outside of the cockpit.

Figures 3 and 4 show the runway with the aircraft in the same position and altitude; the relative heading only has been changed. Although the shape and size of the runway are the same in both pictures, the lateral position of the runway within the field of view of the camera has changed. If a horizontal grid fixed relative to the aircraft is used, the pilot can judge the relative heading between the runway and the aircraft precisely by extending the runway center line to the horizon and then down, perpendicular to the horizontal grid line.

The track-angle pointer and track scale were added to the display as a result of these photographs. Instead of heading, the track angle of the aircraft was implemented since the track angle is the desired information for the landing-approach task.

## EXPERIMENT DESIGN

The objective of the experiment was to evaluate the effect of adding situation information, a perspective runway image combined with a relative track-angle indicator, to a previously established EADI display format.

The perspective runway image, drawn on a $30^\circ$ by $40^\circ$ field of view, includes the basic outline of the runway, a center line being drawn from 1828.8 m (6000 ft) before the runway threshold to the horizon (fig. 2). The runway image represents a runway 3048 m (10 000 ft) in length and 45.72 m (150 ft) in width. Four equally spaced lines were drawn perpendicular to the center line of the runway at 304.8-m (1000-ft) intervals. Two lines parallel to the center line of the runway were drawn on the runway dividing it into equal quarters. The mathematics of drawing the runway image are outlined in the appendix.

A relative track-angle indicator gave the pilot the inertially referenced track angle of the aircraft relative to the runway heading. Relative track-angle information was indicated by a tab that moved along the horizon line of the EADI. An angular scale

referenced to the runway heading was drawn on the horizon line of the EADI so that the pilot could readily determine the magnitude of the relative track angle of the aircraft.

The evaluation process was both qualitative and quantitative. The opinions of the pilots with regard to their acceptance of and confidence in the display format were sought as well as the quality of their performance during the tests. Aircraft position and tracking parameters were recorded and analyzed.

The aircraft simulation model was a B-737. The simulation model included non-linear functions and ground effects. Handling qualities and performance measures of the simulation were matched to various standards supplied by the aircraft manufacturer. The subjective opinions of several pilots from the aircraft manufacturer and NASA test pilots were used to validate the handling qualities and performance of the all-digital, fixed-base simulator.

## Displays

The cockpit panel layout is shown in figure 5. Only the upper CRT was used in this study. The cockpit display was a 20.32-cm (8-in.) CRT mounted horizontally. Video information was generated on an Adage graphics systems computer and transmitted to the cockpit display through a video link.

The two display formats which were compared contained only situation information. The formats differed by the addition of a perspective runway with relative track information. Both display formats contained basic ADI information such as aircraft attitude and glide-slope and localizer deviations. Altitude in digital readout form, flight-path angle wedges, and a potential flight-path angle indicator were also provided in both configurations.

Display format 1 (figs. 6 and 7) was the baseline display format. Display format 2 (figs. 8 and 9) contained the addition of the perspective runway and relative track-angle information. Since display format 1 did not display aircraft heading information, the pilot was required to use a standard HSI located below and to the left of the CRT display. (See fig. 5.)

## Experimental Task

The experimental task required the pilot to intercept and track an ILS beam to the runway threshold at a constant airspeed of 120 knots. The pilot was to complete the landing by reference to the computer-generated display.

The ILS beam tracked during the data runs was modeled without errors such as noise, multipaths, or beam bends. The glide-slope angle was $3^O$ and terminated on the

runway 304.8 m (1000 ft) past the runway threshold. The localizer course was ±2.5$^O$ wide and started 3352.8 m (11 000 ft) beyond the runway threshold.

The B-737 airplane simulated during the experiment weighed 40 815 kg (90 000 lb) and had a 0.3$\bar{c}$ center-of-gravity position. The control system of the airplane was unaugmented with the exception of a beta feedback loop for turn coordination.

Each data run was started with the airplane 625.45 m (2052 ft) left of the localizer, at a range of 13 898.88 m (45 600 ft) from the runway threshold, and at an altitude of 457.20 m (1500 ft). The initial airplane heading gave the pilot a 20$^O$ intercept angle to the localizer. The airplane was trimmed in level flight in its approach configuration: 120-knot airspeed, 40$^O$ flaps, and gear down.

## Test Subjects

Four NASA test pilots were used to evaluate each display. Two of the pilots were rated for the B-737, and the other two pilots had some flight experience in the B-737. All of the pilots had some previous experience in the simulator. One of the pilots actively participated in the design of the display and was quite familiar with the display functions.

## Test Procedure

Each subject pilot was given a briefing on the features of each display format before his practice runs in the simulator. Then each subject pilot performed a satisfactory number of practice runs with each display format to prevent the test evaluation from being substantially influenced by his learning curve. To insure further that learning-curve effects would be minimized during the test runs, half of the subject pilots evaluated the display formats in reverse order. No significant differences in performance were noted.

During the data runs, each subject pilot flew six approaches with each display format. In order, these six approaches consisted of: two approaches with no wind and no turbulence; two approaches with a steady left, 10-knot cross wind; and two approaches with a steady left, 10-knot crosswind and a 0.3048-m/sec (1-ft/sec) mean level of random turbulence introduced in the translational axis.

Airplane attitude and airplane path kinematics were recorded in digital printout form once per second. (At a 120-knot approach speed, these data were recorded approximately every 60.96 m (200 ft) of airplane travel.) Selected data parameters were plotted in real time at a rate of 32 data points per second on analog strip-chart recorders.

Pilot comments were recorded during each test run, after each test run, and during a debriefing after each session in the simulator. The subject pilots' opinions are summarized in the section "Results and Discussion."

Data sampled from five windows along the task profile were statistically treated and analyzed. The first window W1 was chosen to examine performance in intercepting and transitioning to the localizer beam. A settling period was allowed between the localizer intercept point and the window position. The second window W2 was chosen to examine performance in intercepting and transitioning to the glide-slope beam. Again a settling period was allowed. The remaining three windows W3, W4, and W5 were selected at the positions of the middle marker, the 30.48-m (100-ft) decision height, and the threshold, respectively. These windows are shown graphically in figure 10.

## RESULTS AND DISCUSSION

### Localizer Tracking

From localizer tracking data, the mean $\bar{x}$ and the standard deviation $s$ for each window, display format, and test subject were calculated and $s$ was examined in an analysis of variance process. (See ref. 5.) This process was conducted with regard to treatments of pilots, windows, display formats, and the window display-formats interaction. The significance of the analysis of variance was determined by the use of an F-test table.

Table I presents the results of this statistical process for all five window locations. The results indicated no significant differences (F tests) in the data for pilot treatments and the window display-format interactions. The window treatments and display-format treatments, however, were both significant at the 99-percent level. It was felt that the two outer windows, W1 and W2, were the cause of the significant difference in the window treatments.

To verify this assumption, the statistical process was repeated with the data contained in the remaining three windows: W3, W4, and W5. The results are presented in table II. The treatment of windows here indicates no significant difference in the data but still retains the high significant difference in data between the display formats. Examination of the plots (figs. 11 to 14) of mean and standard deviation values of localizer tracking data of W3, W4, and W5 for each test subject generally illustrates that the significant difference between display formats arises from better consistence with display format 2.

A general pilot comment was that the addition of the runway symbology and extended center line together with track reference information (display format 2) enhanced localizer capture and allowed precise lateral tracking with a low mental workload. Horizontal situation, except for raw localizer error data, was missing in display format 1 (typical ADI format), and the pilot had to scan the HSI for localizer capture and relative track information. With display format 1, the pilot had to assimilate vertical situation information quickly from the ADI, make the appropriate pitch-axis control inputs, and then refer to

the HSI so that proper lateral-directional control inputs could be made based on the horizontal situation information observed. As there is no integration of horizontal and vertical information in display format 1, the pilot usually acted as a single axis controller.

Pilot comments on display format 2 indicated that the runway symbology and track reference information helped considerably in the integration and interpretation of the horizontal and vertical situations so that coordinated control inputs could be made. Displaying track and attitude information in the same display enabled the pilot to increase both lateral and vertical tracking accuracy.

## Glide-Slope Tracking

The glide-slope tracking data were analyzed in a manner identical to the localizer tracking data, and the results of an analysis of variance performed on the standard deviation s for all five windows are presented in table III. Like the localizer tracking-data analysis, a significant level of difference appears in the treatment of windows and formats.

The results of an analysis of variance (table IV) performed on the last three windows (W3, W4, and W5) show that significant differences remain in the treatment of windows and display formats and that an additional significant difference appears in the pilot treatment. However, an examination of pilot-display-format interaction revealed no significant difference.

Figure 15 shows that the major difference between windows occurs at W4. Logical reasons for the tighter grouping at W4 are not apparent. However, the major difference in the pilot treatment can be seen by comparing the combined performance of pilots A and B plotted against pilots C and D. This situation is true for both display formats. Plots of mean and standard deviation of glide-slope tracking data for each test subject and display format are presented in figures 16 to 19. The difference which is indicated in display-format treatment can also be clearly seen in the plots. This difference shows that the performance under display format 2 is superior.

Flight-path angle and potential flight-path information together with glide-slope error provided the test subjects with vertical situation information for glide-slope capture, tracking, and the landing flare. Test subjects felt that glide-slope capture and tracking were good. They also felt that low pilot workload for both display formats resulted because of this information. The potential flight-path information provided an indication of flight-path acceleration and was used for precise speed control.

With display format 1, when the pilots detected a deviation from the glide slope, they had to scan to the vertical speed indicator for lead information to determine whether their current flight path would take them back to the desired glide slope. After obtaining this information, the pilots were then able to make the required pitch-attitude change.

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With display format 2, once the deviation from the glide slope was detected, flight-path angle information relative to the runway symbology (aim point) was used to assess quickly the pitch change necessary to recapture the glide slope. In this manner pilot workload for the glide-slope tracking task was reduced. Glidepath tracking in the final stages of the approach tended to be a matter of positioning the flight-path symbol on the aim point. Little attention needed to be given to the raw glide-slope error information. This technique was accepted by the pilots because they felt they had adequate control of the vertical situation.

Figures 20 to 22 are plots of the glide-slope and localizer deviations at the last three windows for each test subject. Each data run made with both display formats is plotted for comparison purposes. Tracking performance with both display formats was good, but comments from the pilots confirmed that display format 2 provided the situation information necessary for pilots to accomplish straight-in ILS approaches consistently with a higher degree of confidence. These subjective opinions correlate with the objective results.

## CONCLUDING REMARKS

The results of this experiment show that the addition of a perspective runway image and relative track information to a basic situation information electronic-attitude-director-indicator format resulted in improved tracking performance both laterally and vertically during an approach-to-landing task. In addition, the mental workload required to assess the approach situation was reduced because of integration of information.

The improvement in the lateral tracking performance arose from the pilot's ability to assess and correct track errors quickly and thus to maintain an accurate track profile. Glide-path tracking was improved because of the aim-point capability with the combination of runway image (target) and flight-path angle information (aiming device).

Overall, the integrated information, perspective runway, flight-path angle, and relative track information allowed a quicker assessment of the current situation and any corrections necessary. Thus, the mental workload on the pilot was notably reduced, creating an improved performance during the approach-to-landing task.

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# APPENDIX

## PROCEDURE AND EQUATIONS FOR GENERATING PERSPECTIVE
## RUNWAY IMAGE AND RELATIVE TRACK INFORMATION

The objective in the generation of a perspective runway is to cast on two dimensions (the viewing screen or image space) the outline of an object (the runway) located in a three-dimensional space (ref. 6). The procedure is to locate the object in a three-dimensional axis system in which the viewing screen bears a fixed relationship to the origin. The rays or vectors from the origin to the various points on the object are then formed and the vector intersections in the viewing plane are determined. The presentable edges of the object, as seen in the viewing plane, are drawn by properly connecting the intersection points.

The boundaries of the viewing plane are determined by the desired field of view. These boundaries can be expressed either by angular measures or by the ratio of the screen dimensions, width $b$ and height $a$, to the offset distance $c$ between the screen and the origin. (See fig. 23(a).) Thus,

$$\tan \frac{\theta_w}{2} = \frac{b}{c}$$

and

$$\tan \frac{\theta_h}{2} = \frac{a}{c}$$

where $\theta_w$ is the full screen width and $\theta_h$ the full screen height in angular measure. Once the boundaries are established, clipping routines (ref. 6) can be used to eliminate those portions of the object outside the prescribed field of view while the necessary intersections to describe visible edges are retained.

A point $R_T$ is in the three-dimensional axis system previously mentioned and the axis system is labeled the eye coordinate system. The viewing screen is fixed in the eye system by the parameters $a$, $b$, and $c$ and remains perpendicular to the $Z_e$ axis. The point $R_T$ $(x_e,y_e,z_e)$ and the origin of the eye system form a vector which penetrates the display screen at some point $R_T'$ $(x_s,y_s,c)$. With plane views as shown in figure 23, the similar triangles $OQ'R_T'$ and $OQR$ are apparent. The following equations result:

$$\frac{y_s}{c} = \frac{y_e}{z_e}$$

and

$$\frac{x_s}{c} = \frac{x_e}{z_e}$$

Once the equations are solved for the screen coordinate and are divided by the desired screen size either  a   or   b, the following equations are obtained:

$$y_s = \frac{c}{b} \frac{y_e}{z_e}$$

and

$$x_s = \frac{c}{a} \frac{x_e}{z_e}$$

These equations can be used as normalized quantities and the appropriate scale factors and centering locations can be applied to program them in a display computer. The development of these equations and suggestive scaling procedures can be found in reference 6.

Once the points needed to outline an object are processed in this manner, the connecting vectors on the display screen can be drawn to form the image. Since the depth $z_e$ of each point is used in the calculations, a true perspective image is obtained.

The perspective runway used in display format 2 is formed by locating the four corners of the runway on the display screen. Then the appropriate vectors are drawn between them. Additional features such as extended center line and crosshatching are calculated in a similar manner.

The relative tracking markings are plotted on the horizon line. The horizon line is obtained from the aircraft pitch information and by fixing the center of the display screen to the body axis of the aircraft. Since the screen width   2b   represents a fixed angular width, degree increments such as the $10^{\circ}$ markers used bear a fixed distance relationship on the screen. These $10^{\circ}$ marks are plotted relative to the junction of the extended center line and the horizon line and are clipped appropriately. A track indicator, driven by drift angle $\psi_D$ $\left(\psi_D = \text{Aircraft track - Aircraft heading}\right)$ is used to determine (by the pilot) the path bearing of the aircraft relative to the runway alinement. All of these symbols are rotated with aircraft orientation.

As stated in the preceding paragraph, the screen center is on the aircraft body axis and the eye system is thus chosen to be coincident with the aircraft body-axis system. No pilot position offsets are taken into account.

The positional states   x,  y, and  h   of the aircraft are measured relative to an inertial coordinate system located at the center of the runway threshold (fig. 24). These measurements can be used to create a vector from the aircraft to the runway but are still in an inertial coordinate system. The next step is to transform these vectors into the eye system. Thus, the standard inertial to body transformation matrix $C_{ij}$ (ref. 7) is available. Usually this matrix is oriented to an inertial system which is alined along

north and east bearings. If the runway alinement is other than north (or $360^O$), an additional rotation must be added. This rotation can be expressed in element form as

$$A_{11} = \cos \psi_r \qquad A_{12} = -\sin \psi_r \qquad A_{13} = 0$$

$$A_{21} = \sin \psi_r \qquad A_{22} = \cos \psi_r \qquad A_{23} = 0$$

$$A_{31} = 0 \qquad A_{32} = 0 \qquad A_{33} = -1$$

where $\psi_r$ is the runway bearing. The $C_{ij}$ elements are

$$C_{11} = \cos \theta \cos \psi \qquad\qquad C_{12} = \cos \theta \sin \psi \qquad\qquad C_{13} = \sin \theta$$

$$C_{21} = \sin \phi \sin \theta \cos \psi - \cos \phi \sin \psi \qquad C_{22} = \sin \phi \sin \theta \sin \psi + \cos \phi \cos \psi \qquad C_{23} = \sin \phi \cos \theta$$

$$C_{31} = \cos \phi \sin \theta \cos \psi + \sin \phi \sin \psi \qquad C_{32} = \cos \phi \sin \theta \sin \psi - \sin \phi \cos \psi \qquad C_{33} = \cos \phi \cos \theta$$

The two rotations can be combined in this way since $\vec{X}_I = A_{ij}\vec{X}_R$ and $\vec{X}_B = C_{ij}\vec{X}_I$. Then $\vec{X}_B = C_{ij}A_{ij}\vec{X}_R$ where $\vec{X}_R$ is a three-dimensional vector in the runway coordinate system, $\vec{X}_I$ is a three-dimensional vector in the inertial system, and $\vec{X}_B$ is a three-dimensional vector in the aircraft body system.

Once the vector is defined in the body axis, it is a simple matter to define the vector in the eye system and thus to create the display screen coordinates. This entire procedure can be followed for all vectors between the aircraft and any defined point in the runway system.

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6. Newman, William M.; and Sproull, Robert F.: Principles of Interactive Computer Graphics. McGraw-Hill Book Co., Inc., c.1973.

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TABLE I.- ANALYSIS OF VARIANCE OF LOCALIZER TRACKING DATA

FOR ALL FIVE WINDOWS

| Sources | df | F(calculated) | F(tabulated) |
|---|---|---|---|
| Pilot treatment | 3 | 1.70 | 2.96 (95%) |
| Window treatment | 4 | [a]19.18 | 4.11 (99%) |
| Display-format treatment | 1 | [a]10.68 | 7.68 (99%) |
| Window and display-format treatment | 4 | .28 | 2.73 (95%) |
| Error | 27 | | |
| Total | 39 | | |

[a]An indication that the F(calculated) value is significant at the 99-percent level.

TABLE II.- ANALYSIS OF VARIANCE OF LOCALIZER TRACKING DATA

FOR LAST THREE WINDOWS (W3, W4, AND W5)

| Sources | df | F(calculated) | F(tabulated) |
|---|---|---|---|
| Pilot treatment | 3 | 2.85 | 3.29 (95%) |
| Window treatment | 2 | .17 | 3.68 (95%) |
| Display-format treatment | 1 | [a]14.48 | 8.68 (99%) |
| Window and display-format treatment | 2 | $10^{-2}$ | 3.68 (95%) |
| Error | 15 | | |
| Total | 23 | | |

[a]An indication that the F(calculated) value is significant at the 99-percent level.

TABLE III.- ANALYSIS OF VARIANCE OF GLIDE-SLOPE TRACKING DATA

FOR ALL FIVE WINDOWS

| Sources | df | F(calculated) | F(tabulated) |
|---|---|---|---|
| Pilot treatment | 3 | 0.22 | 2.96 (95%) |
| Window treatment | 4 | [a]20.85 | 4.11 (99%) |
| Display-format treatment | 1 | [b]4.81 | 4.21 (95%) |
| Window and display-format treatment | 4 | .30 | 2.73 (95%) |
| Error | 27 | | |
| Total | 39 | | |

[a]An indication that the F(calculated) value is significant at the 99-percent level.

[b]An indication that the F(calculated) value is significant at the 95-percent level.

TABLE IV.- ANALYSIS OF VARIANCE OF GLIDE-SLOPE TRACKING DATA

FOR LAST THREE WINDOWS (W3, W4, AND W5)

| Sources | df | F(calculated) | F(tabulated) |
|---|---|---|---|
| Pilot treatment | 3 | [a]5.07 | 3.49 (95%) |
| Window treatment | 2 | [b]11.47 | 6.93 (99%) |
| Display-format treatment | 1 | [b]17.49 | 9.33 (99%) |
| Window and display-format treatment | 2 | 2.23 | 3.89 (95%) |
| Pilot and display-format treatment | 3 | 3.11 | 3.49 (95%) |
| Error | 12 | | |
| Total | 23 | | |

[a]An indication that the F(calculated) value is significant at the 95-percent level.

[b]An indication that the F(calculated) value is significant at the 99-percent level.

Figure 1.- Real-world runway with aircraft in a steep bank, laterally offset and close to runway threshold.
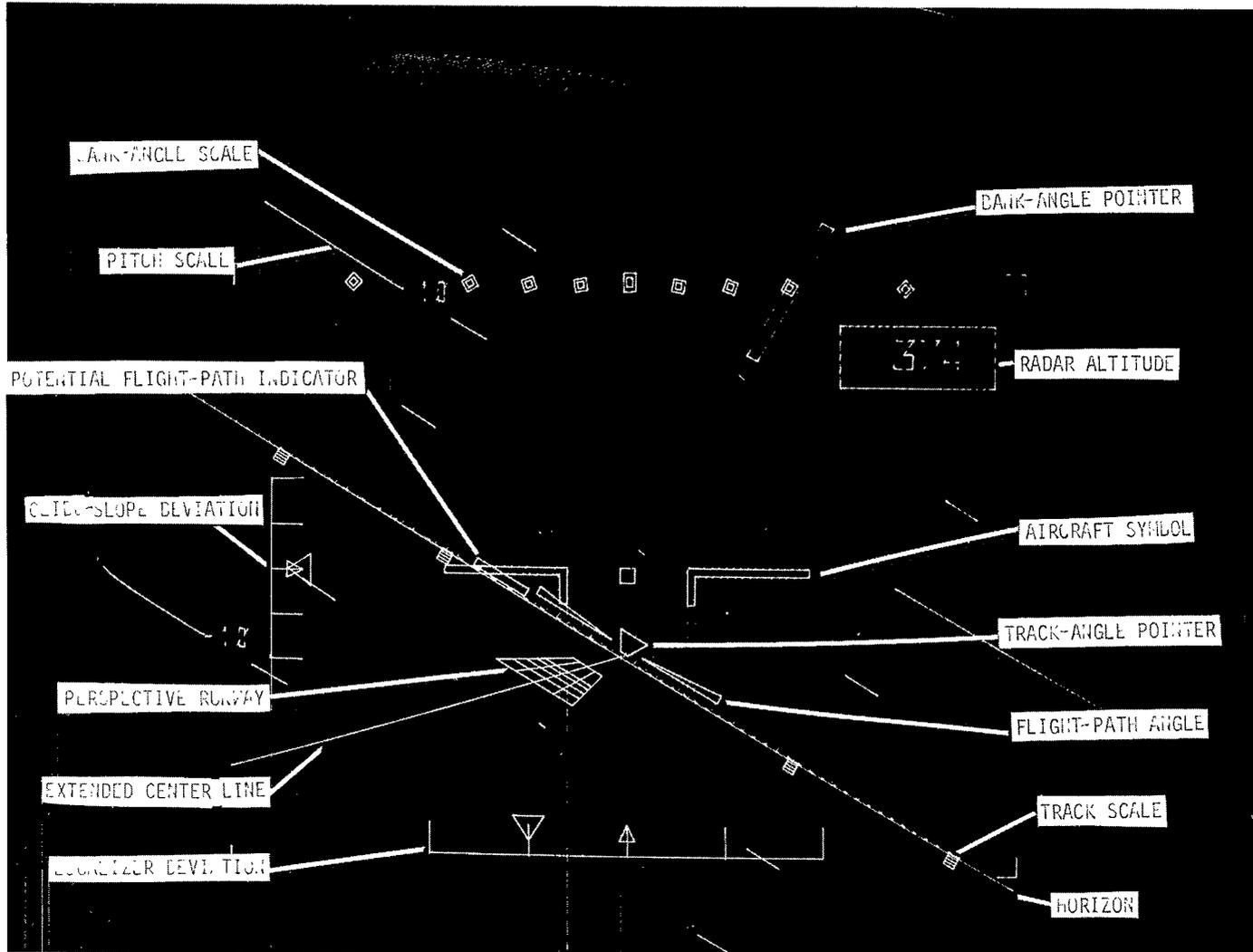
L-76-134

Figure 2. - Computer-generated image.

L-76-135

Figure 3.- Real-world runway with aircraft displaced laterally to right and heading $10^O$
to left of runway center line.
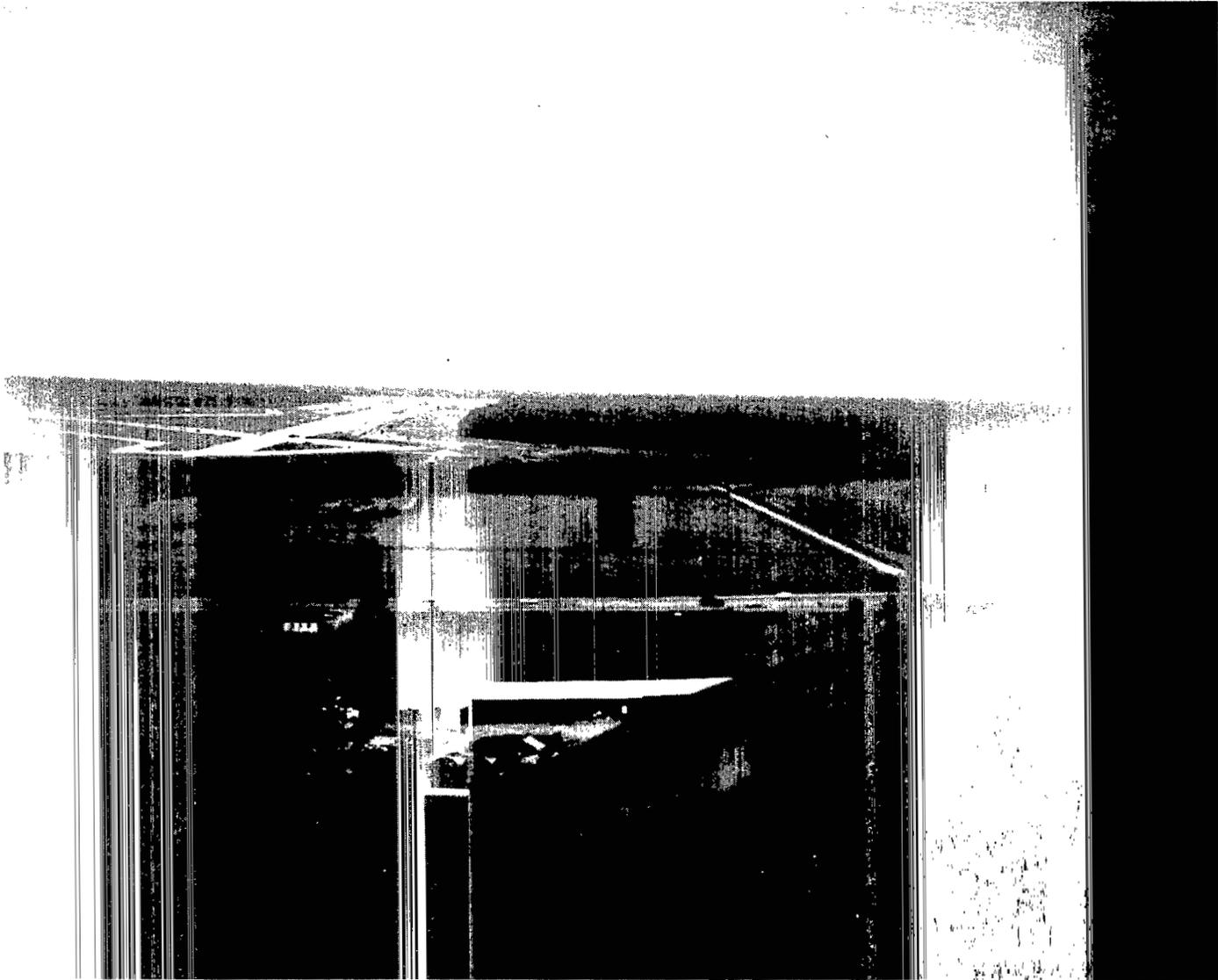
L-76-136

Figure 4.- Real-world runway with aircraft displaced laterally to right and leading parallel
to runway center line.

CRT
(EADI)

Airspeed

Altitude

CRT
(not used)

HSI

IVSI
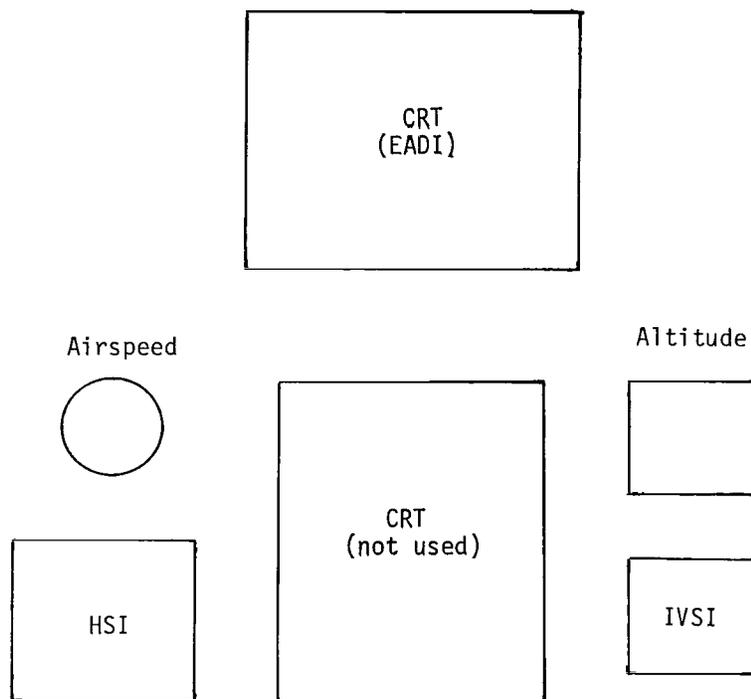
Figure 5. - Cockpit panel layout.
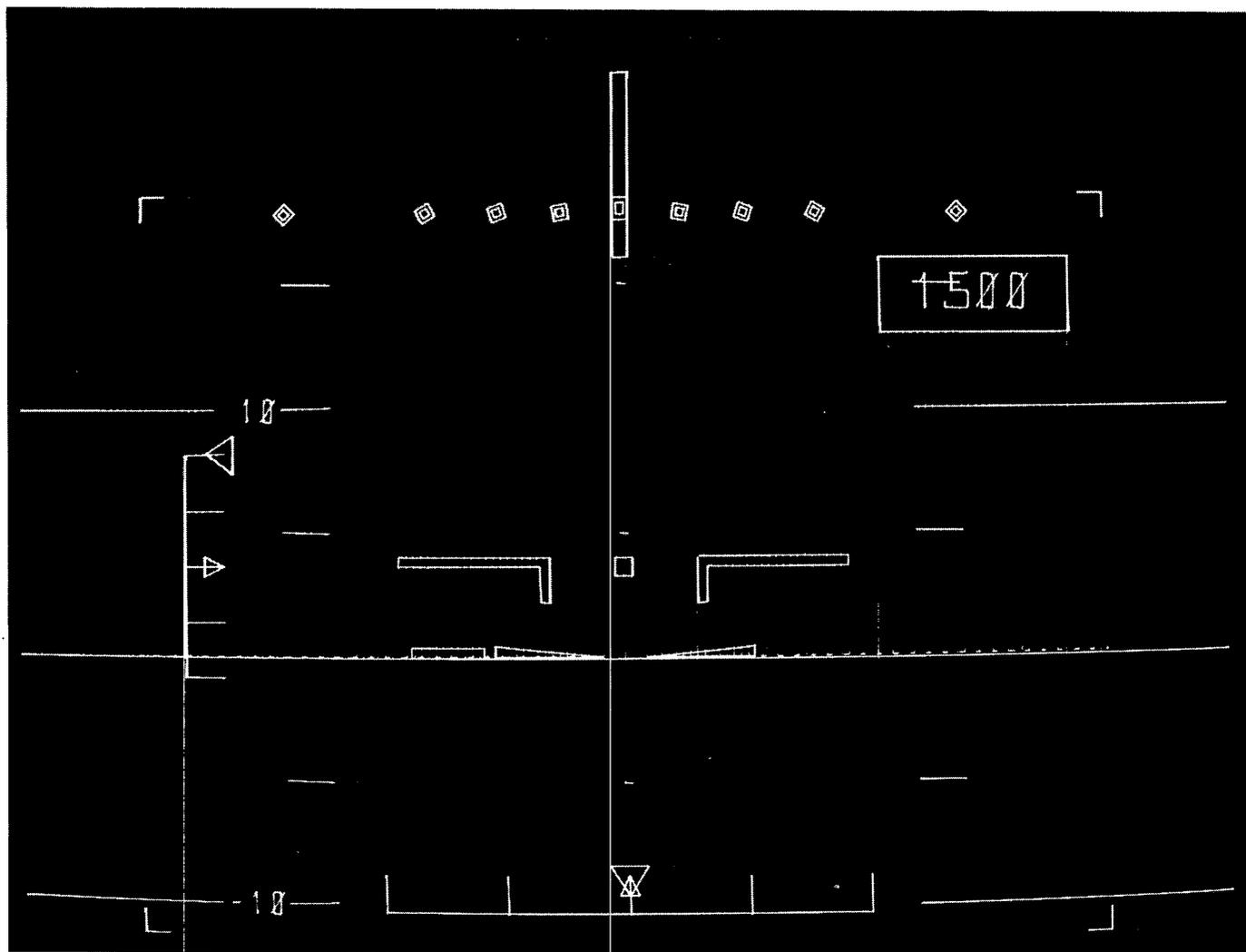
L-76-137

Figure 6.- Display format 1 for level flight on localizer center and below glide slope.
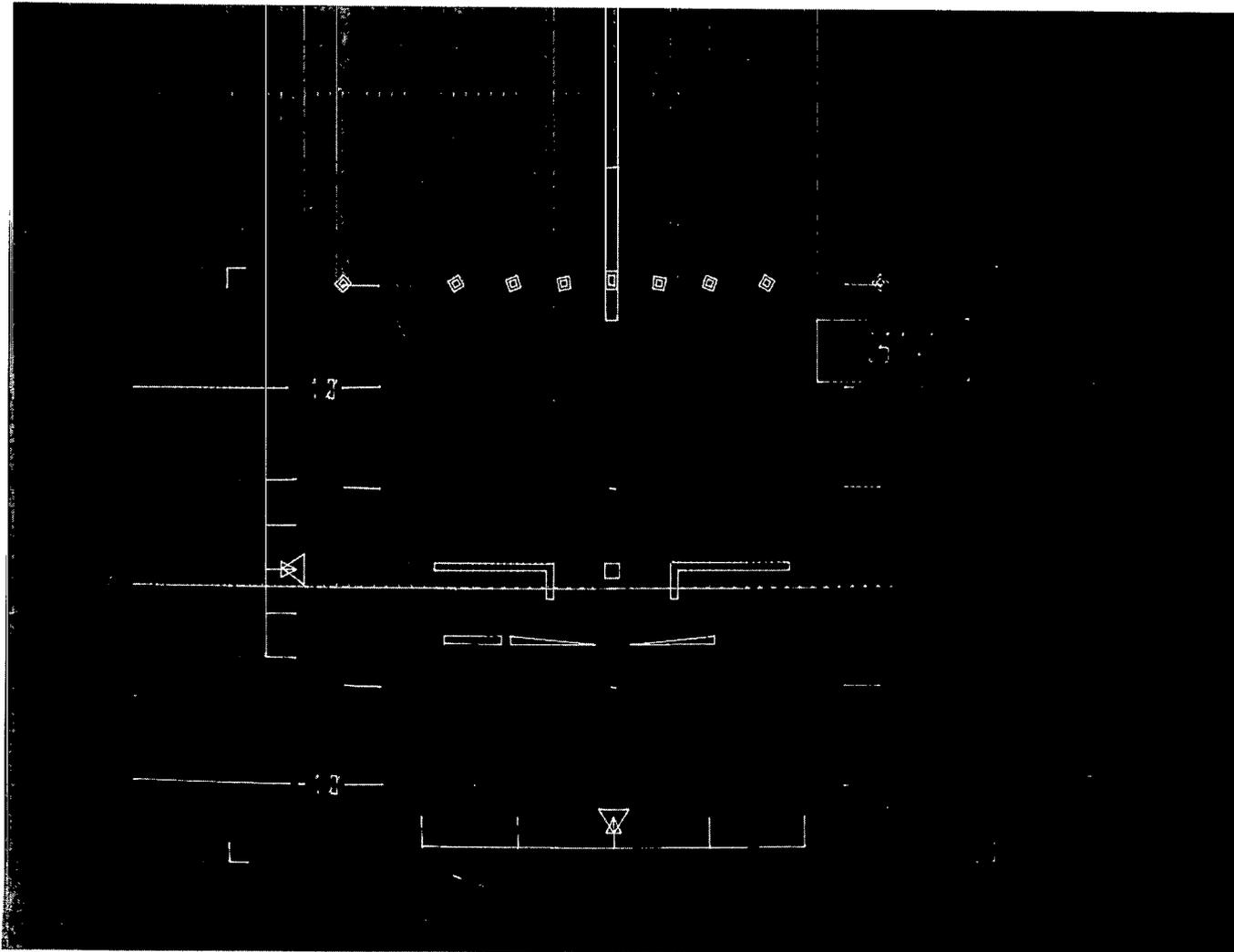
L-76-138

Figure 7.- Display format 1 for a 3⁰ descent on localizer center and on glide-slope center.
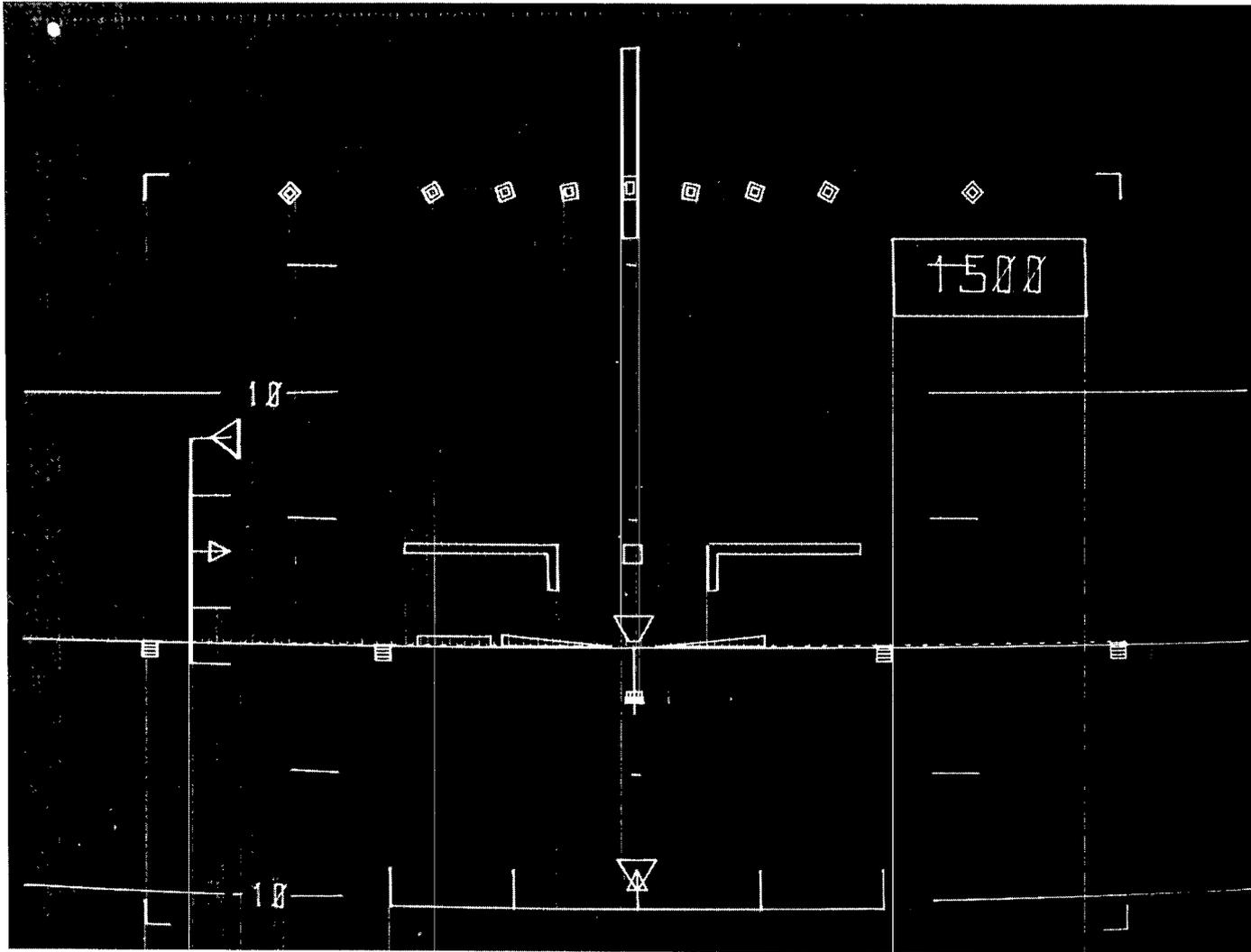
Figure 8.- Display format 2 in level flight on localizer center and below glide-slope center.
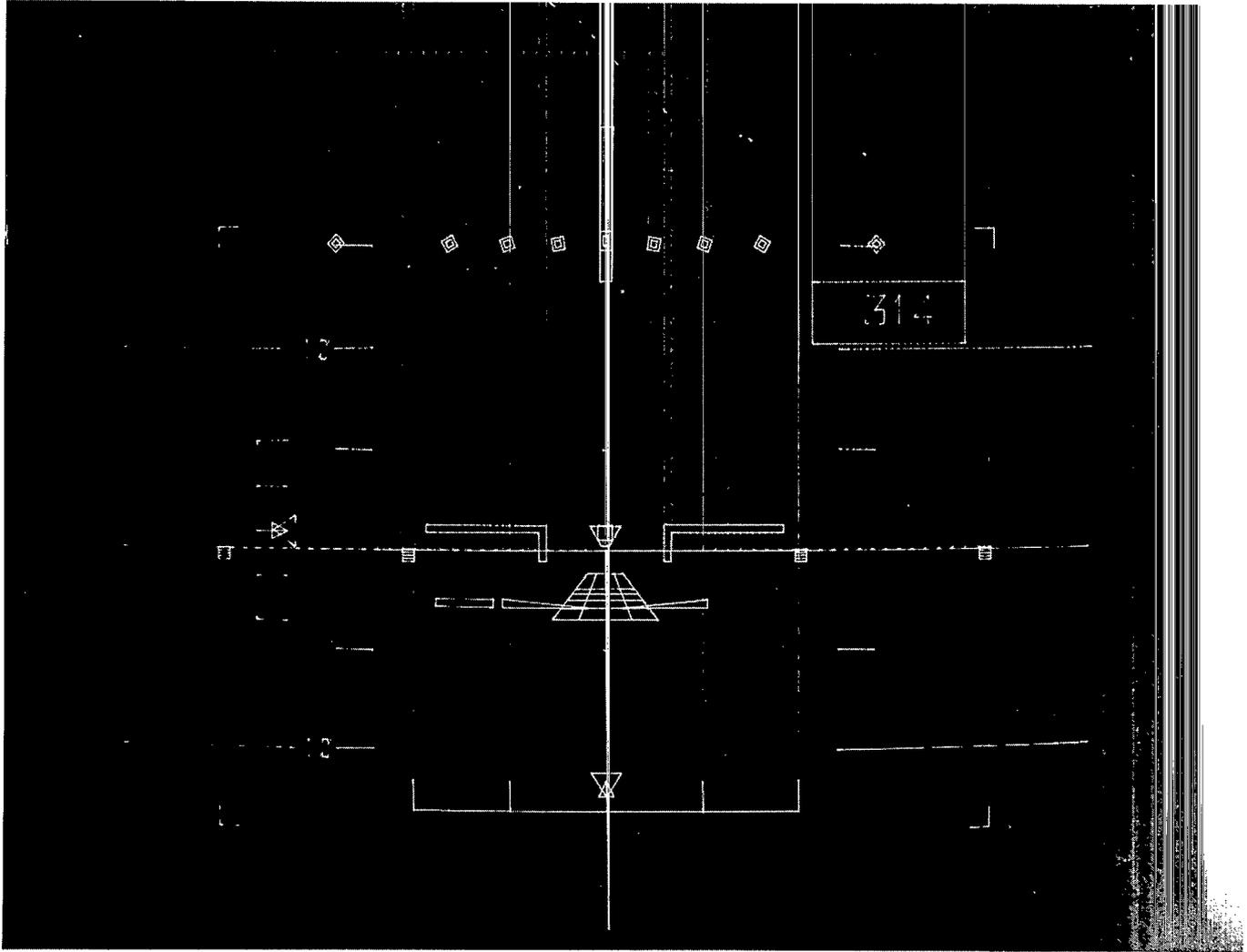
L-76-140

Figure 9.- Display format 2 in a 3º descent on localizer center and on glide-slope center.

| Window | Range, m | Altitude, m |
|--------|----------|-------------|
| 1 | 11 460 | 457 |
| 2 | 7 803 | 425 |
| 3 | 1 524 | 96 |
| 4 | 305 | 32 |
| 5 | Threshold | 16 |
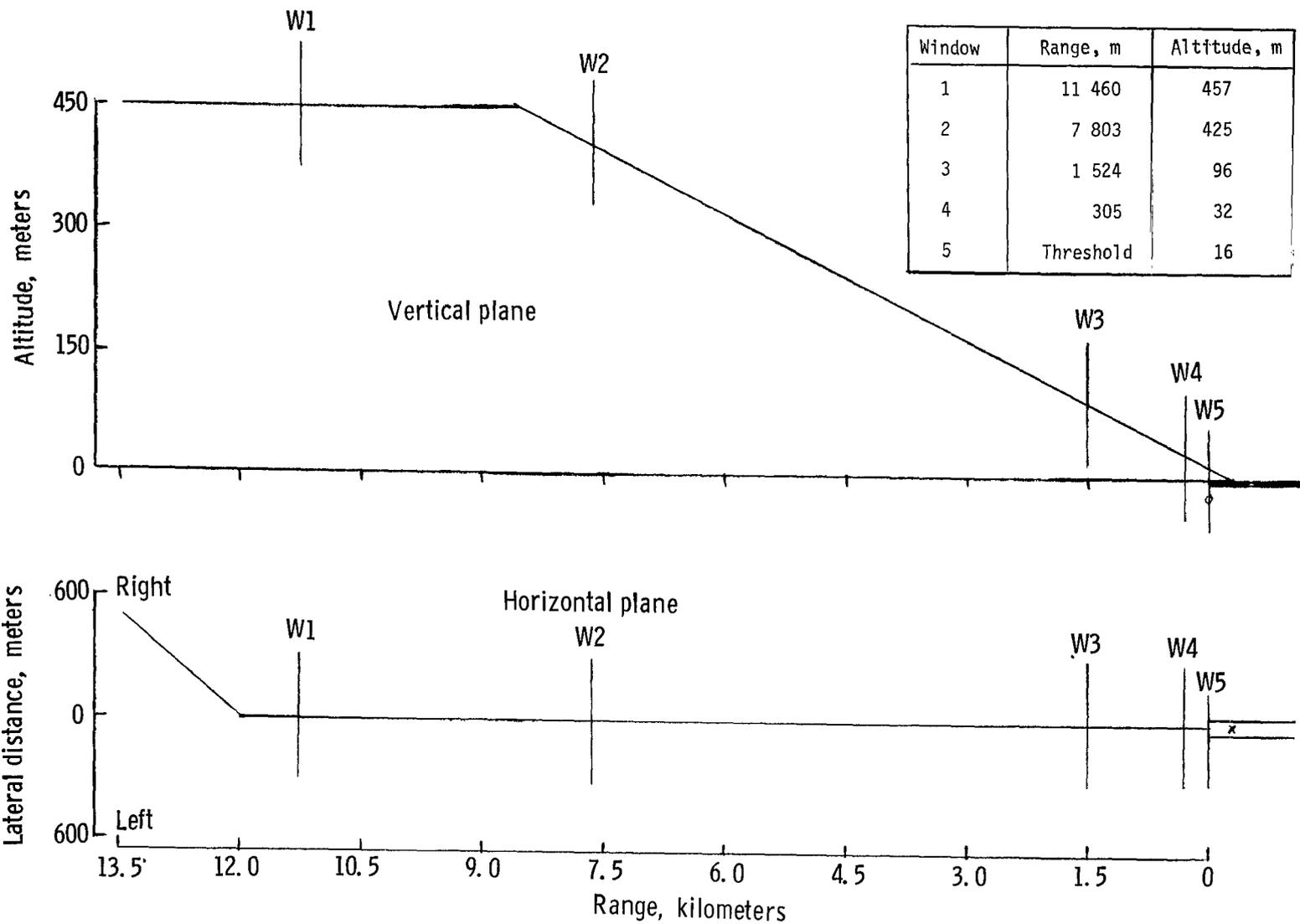
Figure 10.- Experimental task profile and data window locations.
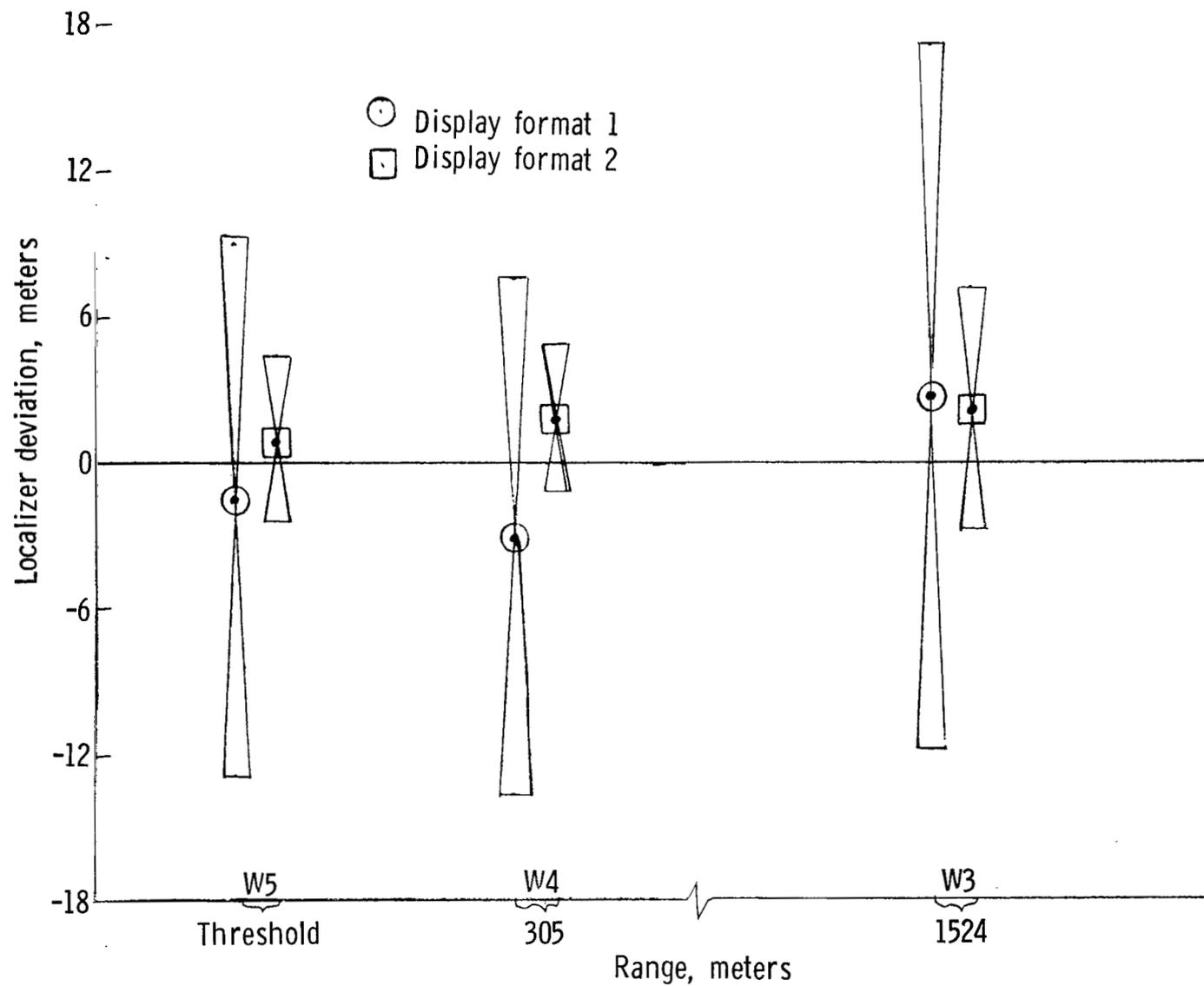
Figure 11.- Pilot A localizer mean and standard deviation data for W3, W4, and W5.
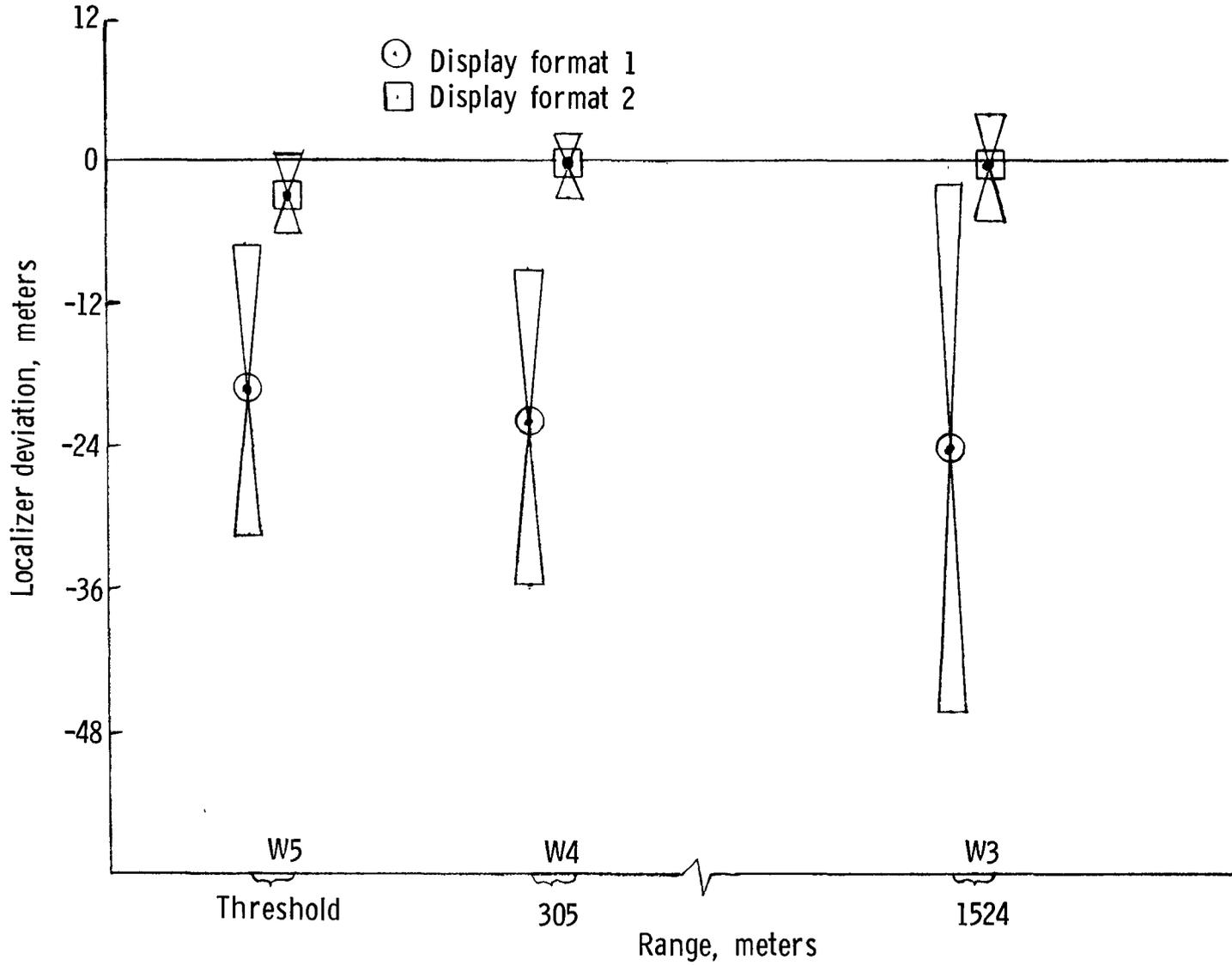
Figure 12.- Pilot B localizer mean and standard deviation data for  W3,  W4, and  W5.
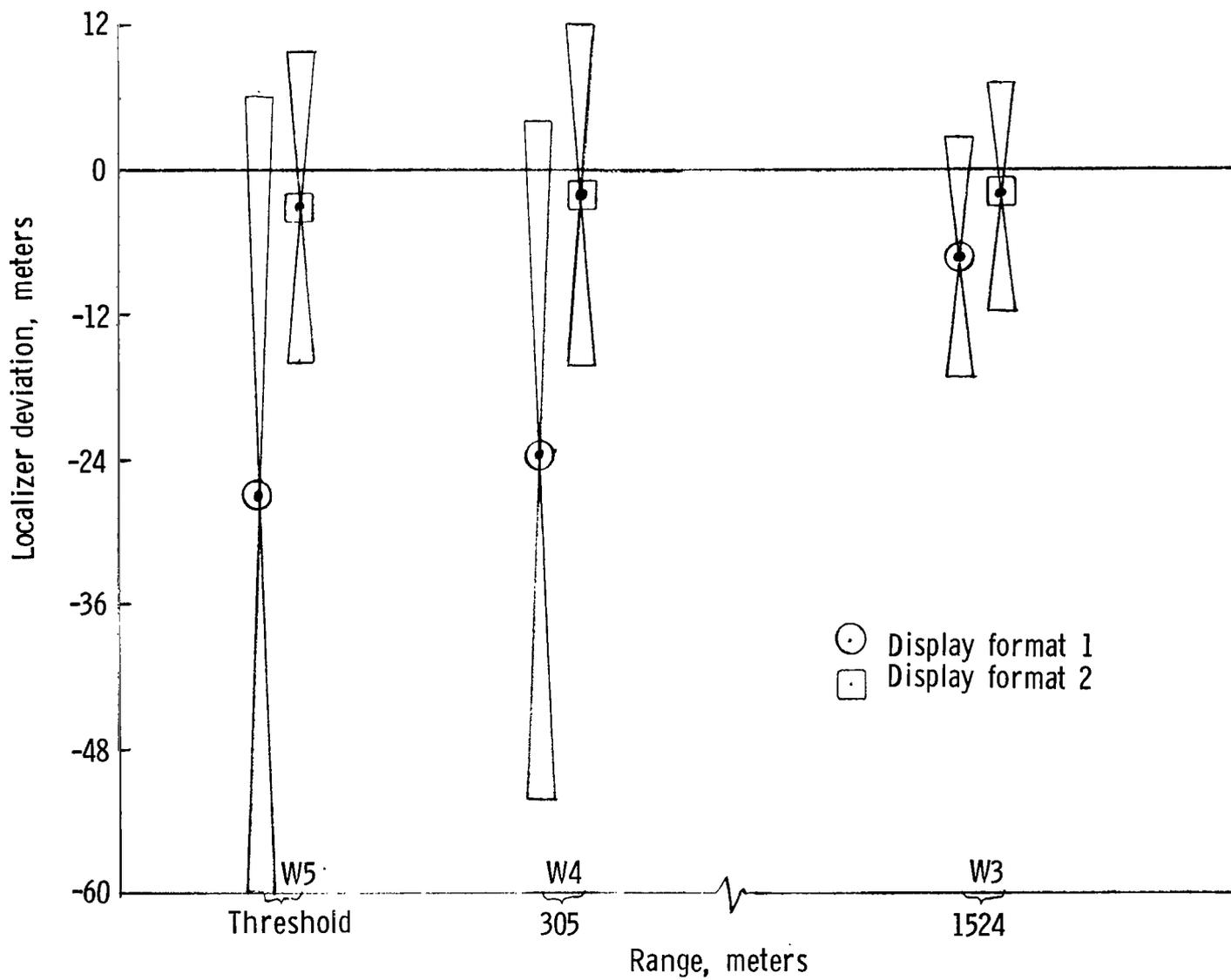
Figure 13.- Pilot C localizer mean and standard deviation data for W3, W4, and W5.
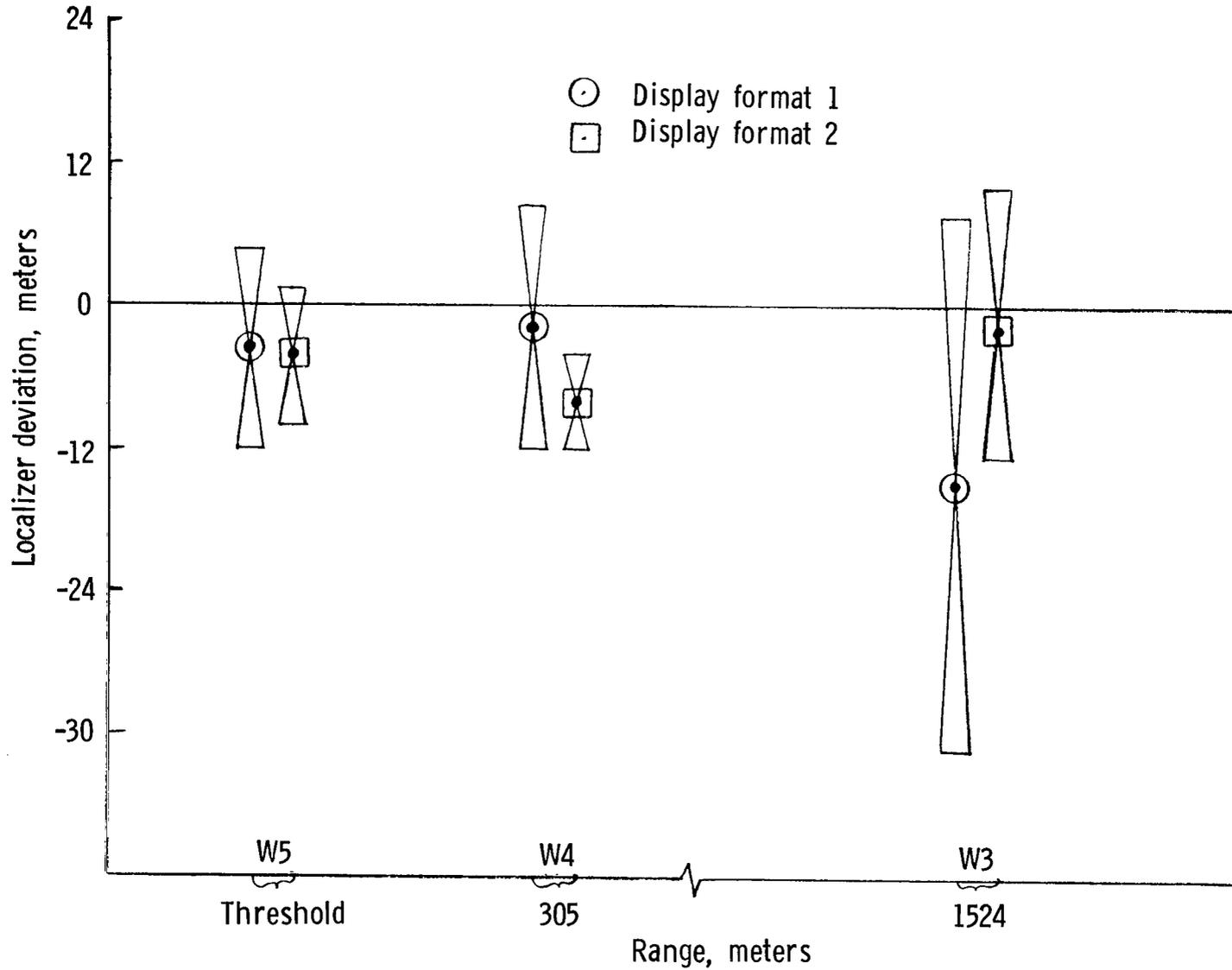
Figure 14.- Pilot D localizer mean and standard deviation data for  W3,  W4, and  W5.
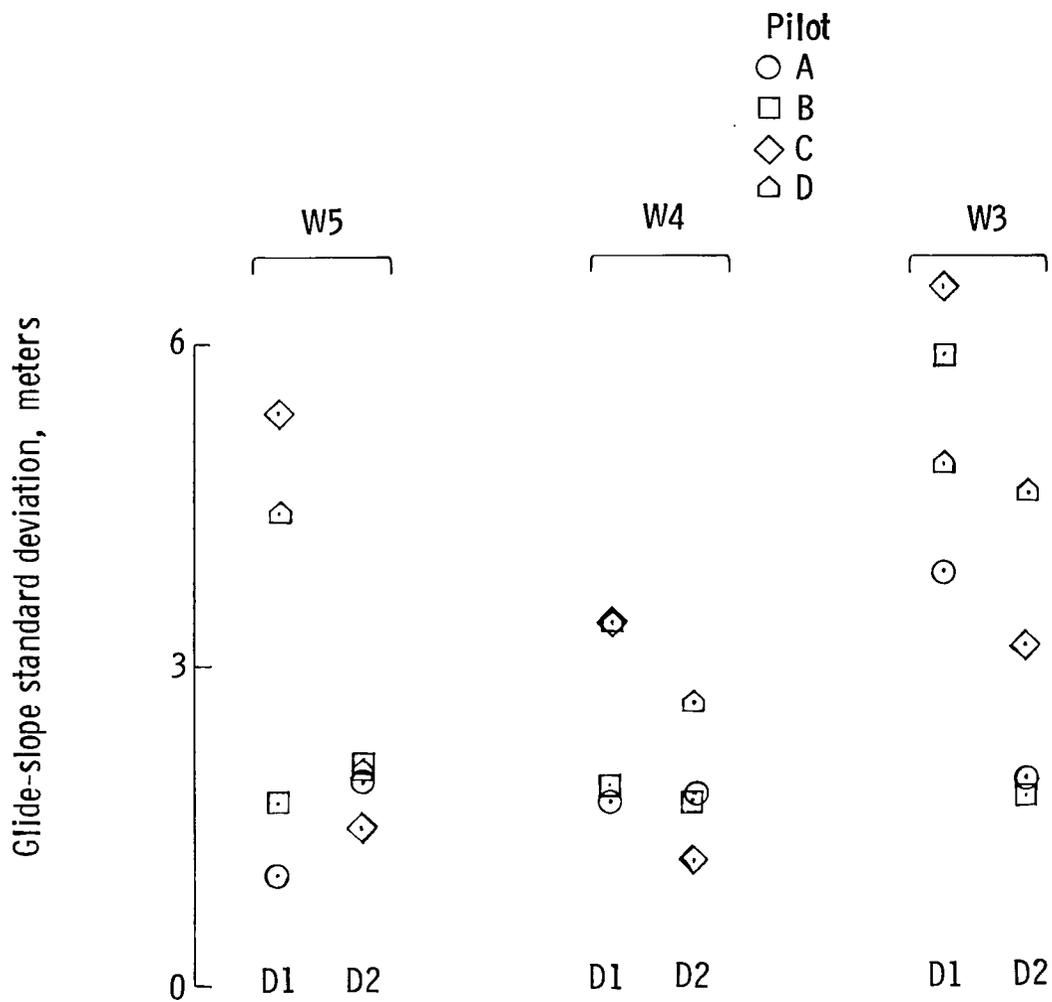
Figure 15.– Composite glide-slope standard deviation plot for pilots, windows   W3 to   W5, and display formats.
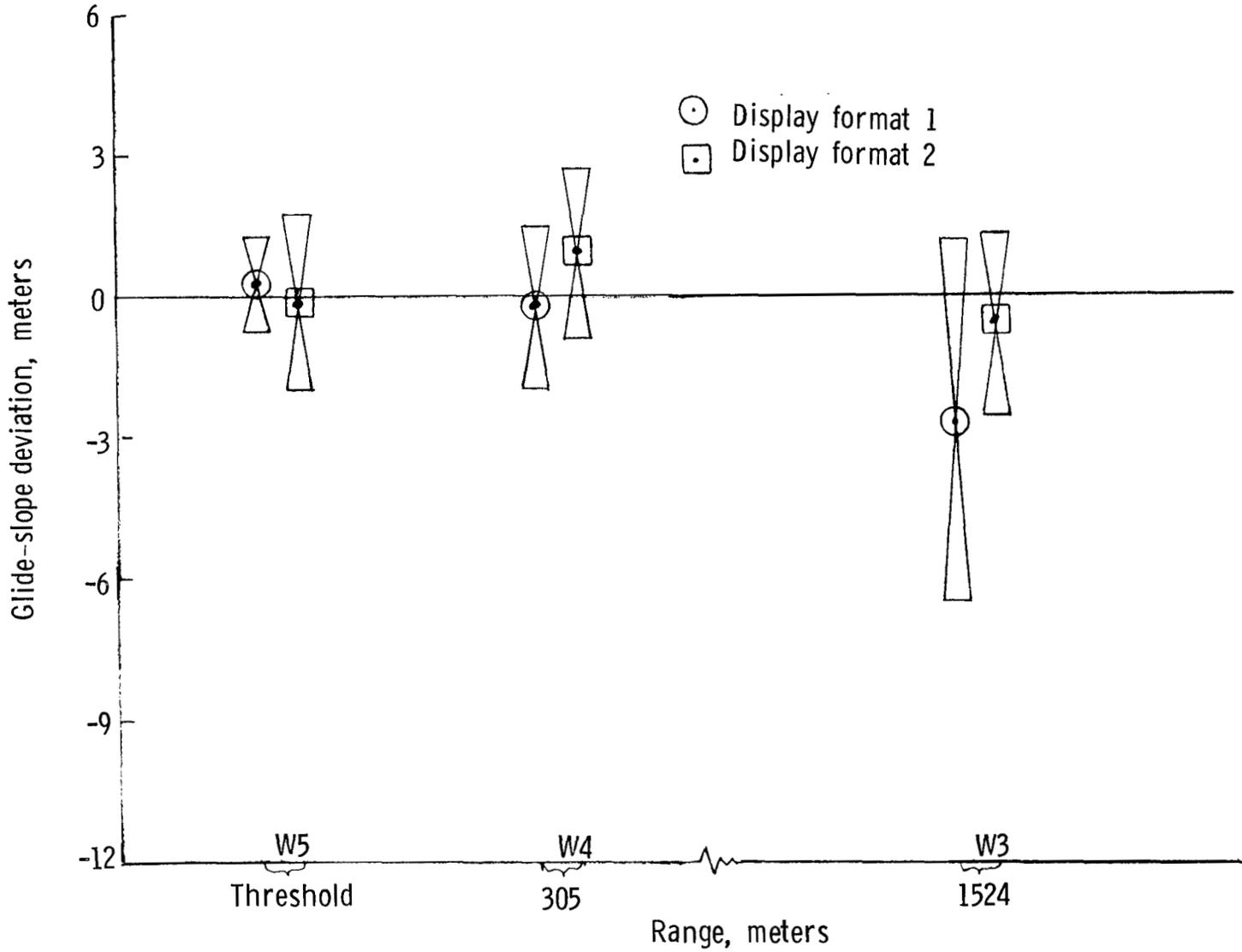
Figure 16.– Pilot A glide-slope mean and standard deviation data for W3, W4, and W5.
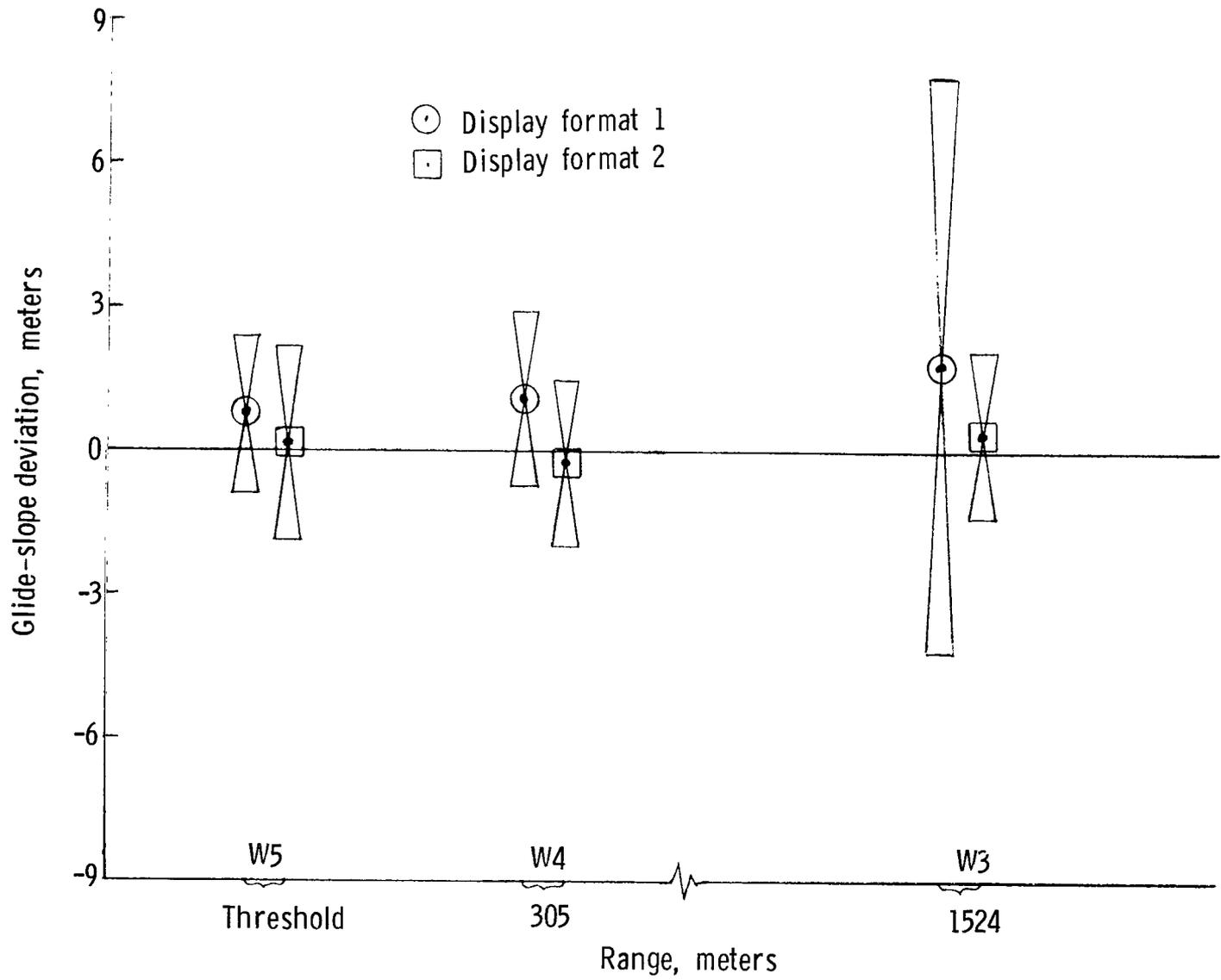
Figure 17.- Pilot B glide-slope mean and standard deviation data for W3, W4, and W5.
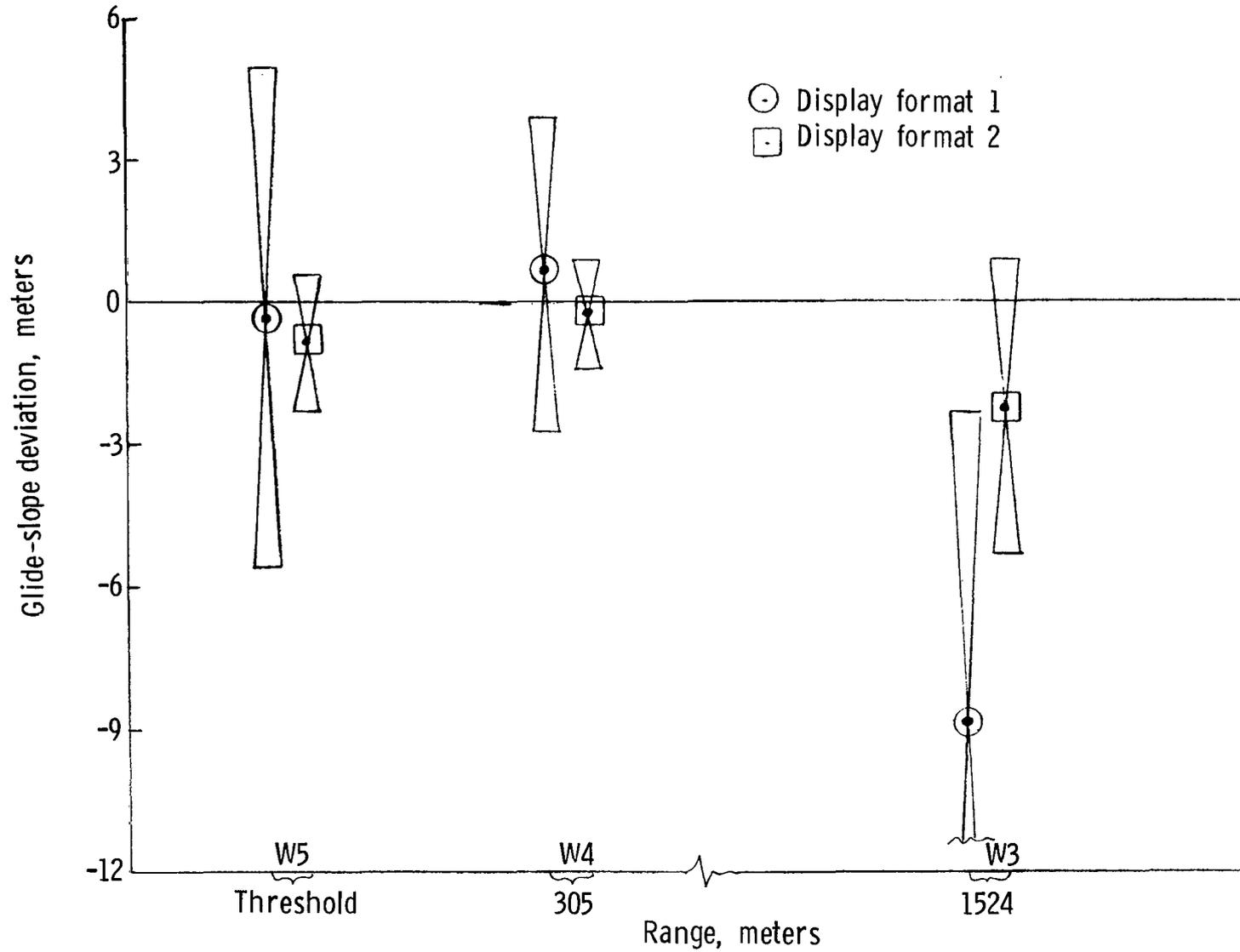
Figure 18.- Pilot C glide-slope mean and standard deviation data for W3, W4, and W5.
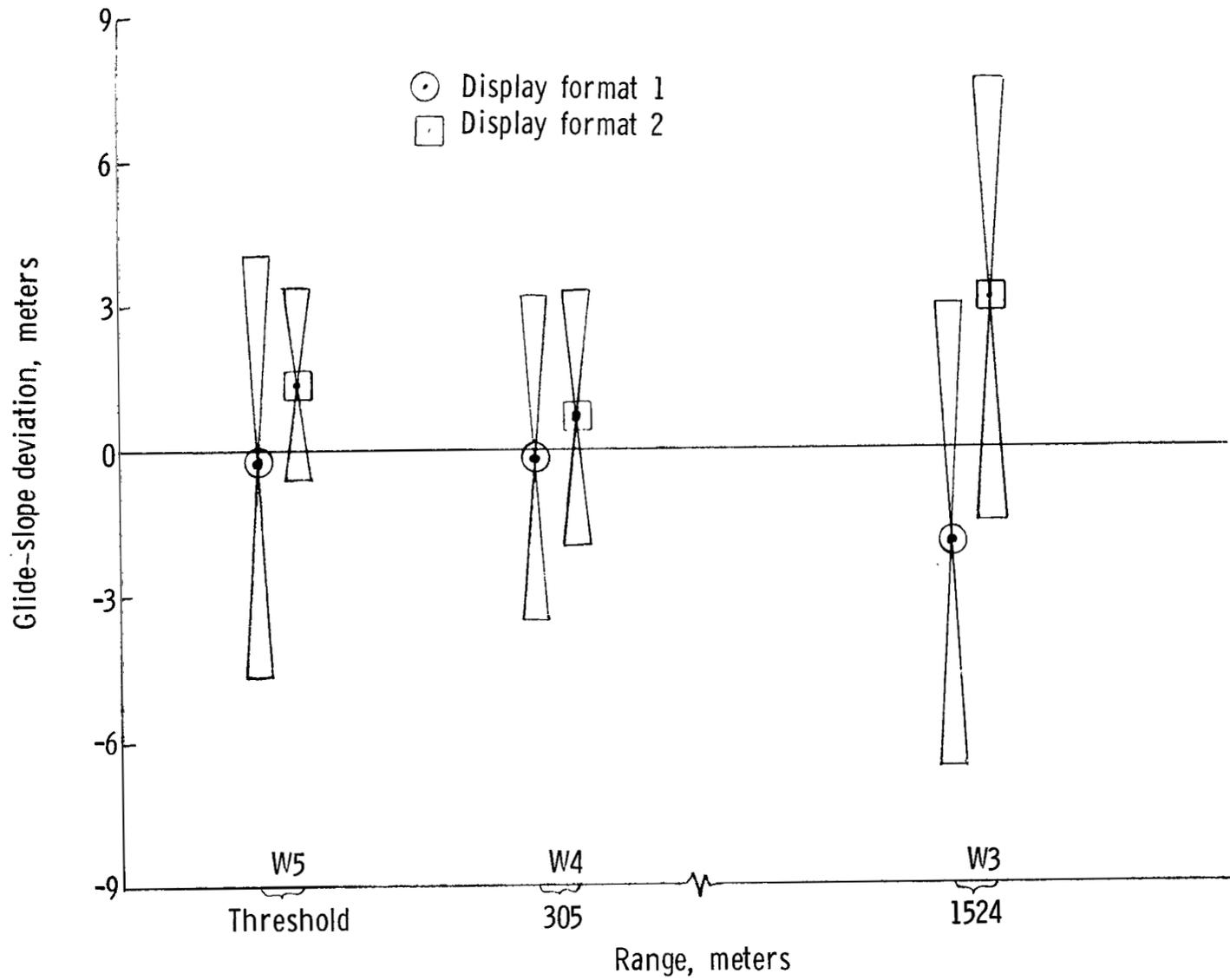
Figure 19.- Pilot D glide-slope mean and standard deviation data for W3, W4, and W5.
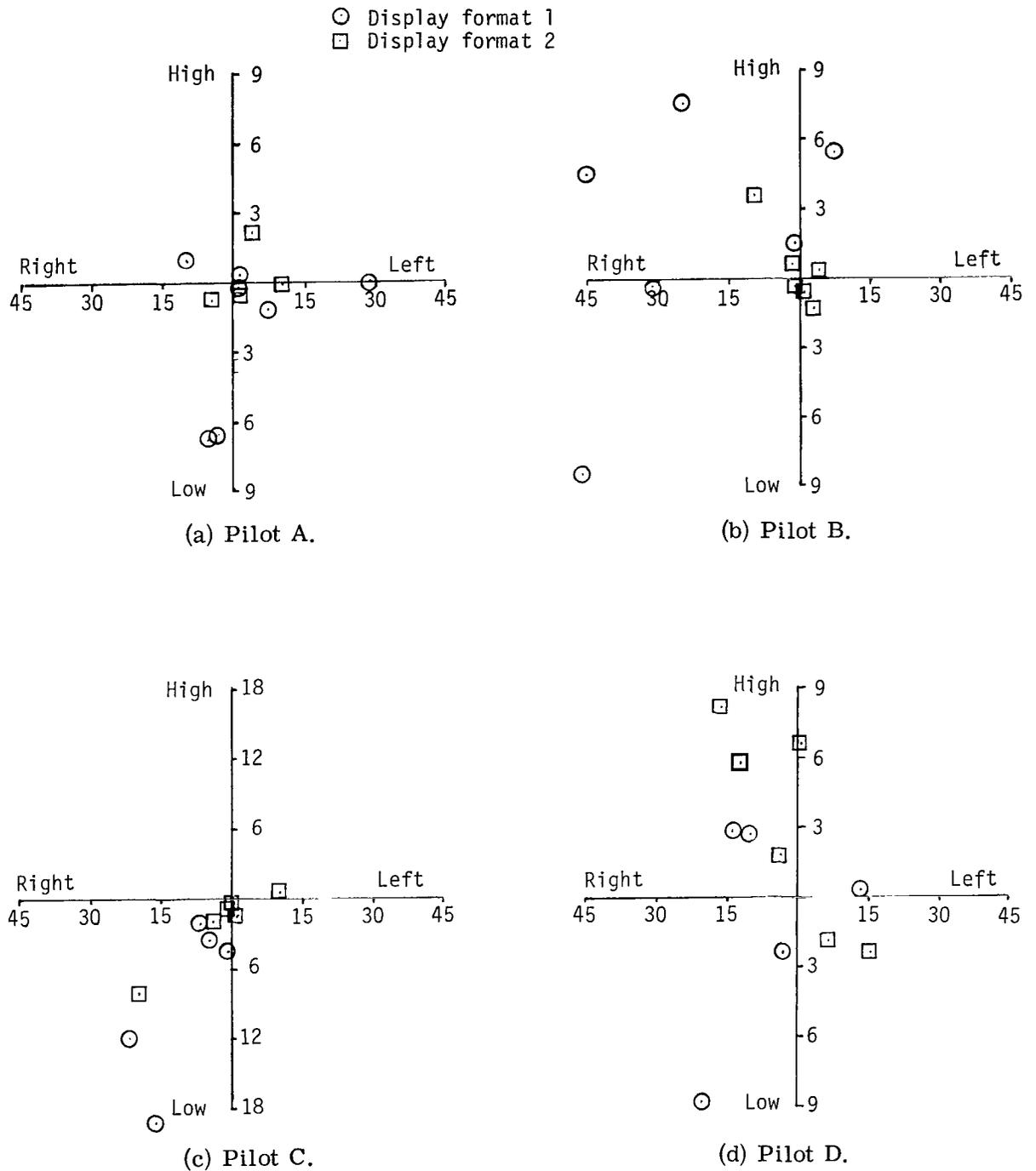
Figure 20.- Window 3 cross plot of glide-slope and localizer deviations.
All scales are in meters.

⊙ Display format 1
☐ Display format 2
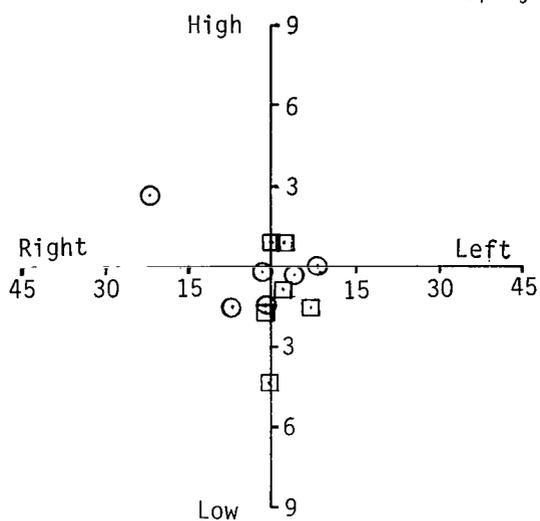
(a) Pilot A.
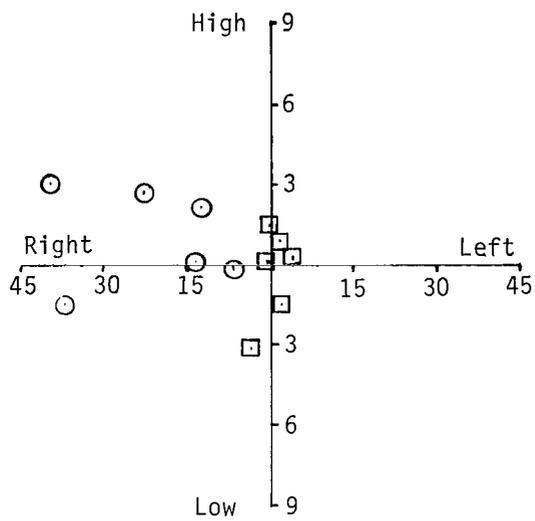
(b) Pilot B.
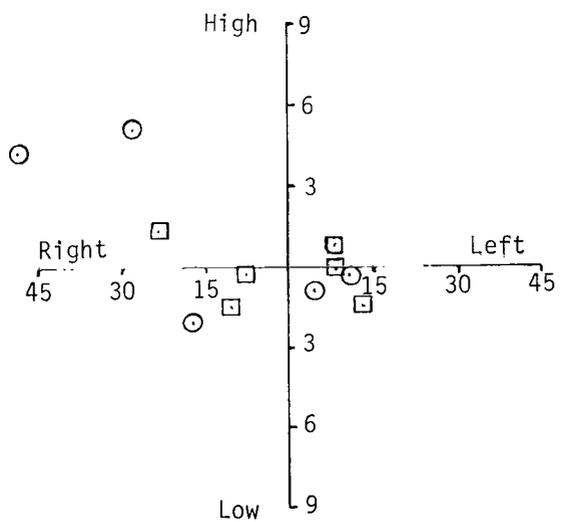
(c) Pilot C.
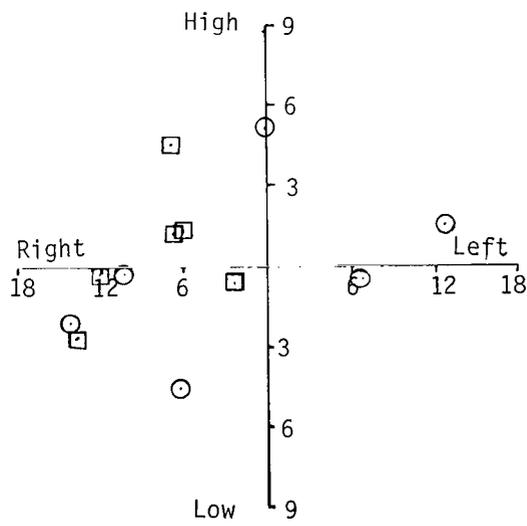
(d) Pilot D.

Figure 21.- Window 4 cross plot of glide-slope and localizer deviations.
All scales are in meters.

○ Display format 1
□ Display format 2


(a) Pilot A.


(b) Pilot B.


(c) Pilot C.


(d) Pilot D.

Figure 22.- Window 5 cross plot of glide-slope and localizer deviations.
All scales are in meters.
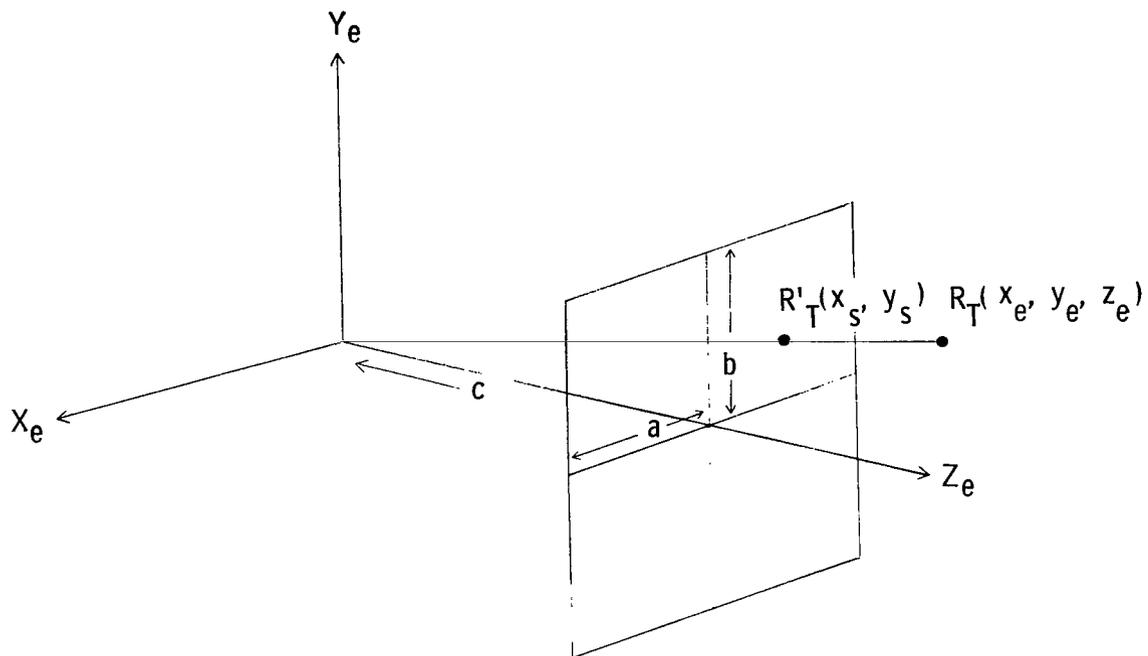
(a) Eye coordinate and screen coordinate systems.
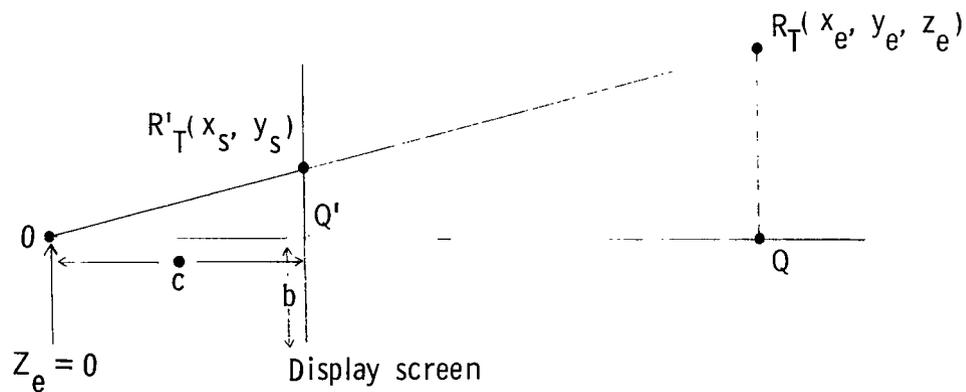


(b) Plane view of eye and screen coordinate systems.

Figure 23.- Eye and screen coordinate systems relationship.
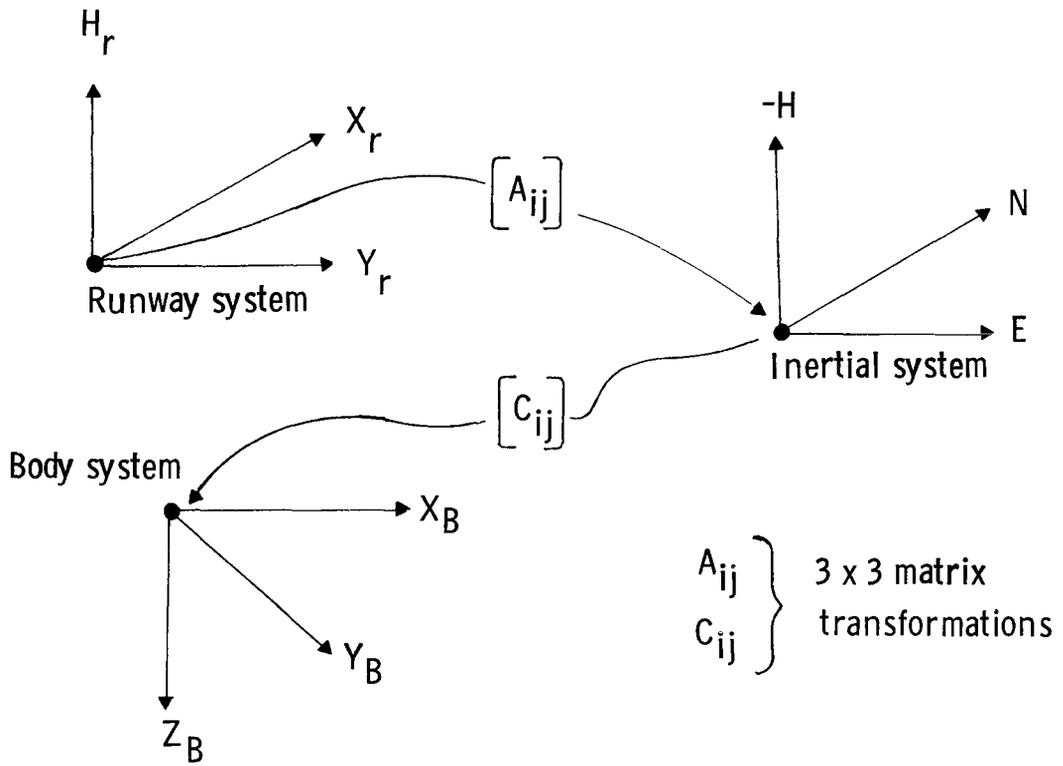
Figure 24.- Axis coordinate transformation flow.

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