

NASA Technical Paper 1085

Flight-Test Evaluation of Two
Electronic Display Formats
for Approach to Landing
Under Instrument Conditions

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SUMMARY

This report presents the results of a flight evaluation of two electronic display formats for the approach to landing under instrument conditions. The evaluation was conducted for a base-line electronic display format and for the same format with runway symbology and track information added. The evaluation was conducted during 3⁰, manual straight-in approaches with and without initial localizer offsets. Flight-path tracking performance data and pilot subjective comments were examined with regard to the pilot's ability to capture and maintain localizer and glide slope by using both display formats.

The results of the flight tests agree with earlier simulation results and show that the addition of a perspective runway image and relative track information to a base-line electronic display format improved both lateral and vertical flight-path tracking during an approach-to-landing task. Pilot comments indicated that the mental workload required to assess the approach situation was reduced as a result of integrating both the perspective runway with an extended center line and the relative track information into the vertical situation display. The flight test results also show that the flight-path performance with the integrated situation display format compares very favorably with Category II flight-director performance criteria.

INTRODUCTION

One of the objectives of the NASA Terminal Configured Vehicle (TCV) Program is the research and development of electronic display concepts that will improve pilot instrumentation for the approach-to-landing task in low visibility. Present-day electromechanical instrumentation has been very beneficial in achieving low visibility landings on long, straight-in final approach paths. This instrumentation, however, is considered to be inadequate for the low visibility approach to landing on close-in, curved approach paths that may be required in the future. As discussed in reference 1, the increased number of parameters that the flight crew may be required to control or monitor will also demand that information be processed and displayed in an integrated analog form where possible in order to convey a naturally assimilated mental picture of a complex situation. The flight experimental systems used in the TCV Program incorporate electronic displays which offer capabilities not currently found in electromechanical display systems. Considering this increased capability, a specific objective within the display information research is to investigate means of presenting improved situation information to the pilot. A display format is desired that will aid the pilot in maintaining a current mental picture of his situation relative to the runway during the approach to landing under instrument conditions. To achieve this objective, an integrated situation display format was developed that was aimed at presenting, in a single display, the necessary information for the approach-to-landing task, whether

it was flown manually or automatically. This display format was evaluated in a piloted simulation study where horizontal situation information, in the form of a perspective runway with an extended center line and relative track symbology, was integrated into an existing vertical situation display format. The simulation results were promising and led to the flight tests.

This report presents the results of flight tests aimed at evaluating a base-line electronic display format and an integrated electronic display format in the actual flight environment. Piloted simulation results reported in reference 1 and presented in this report are compared with flight test results. The flight tests were conducted in the TCV Boeing 737 research airplane which utilizes an aft flight deck and a velocity vector control mode. Results of straight-in 3^o approaches with and without initial localizer offsets are discussed. Flight-path accuracy data and pilot comments are presented and compared with Category II flight-director performance criteria as stated in FAA Advisory Circular AC 120-29 (ref. 2). Four NASA pilots were used as test subjects and the flight tests were conducted at the FAA National Aviation Facilities Experimental Center.

SYMBOLS AND ABBREVIATIONS

AFD	aft flight deck
AGCS	advanced guidance and control system
ATTSYNC	attitude synchronization
EADI	electronic attitude director indicator
EHSI	electronic horizontal situation indicator
FAA	Federal Aviation Administration
FAF3M	final approach fix way point at three miles
\dot{h}	complementary filtered altitude rate
IVSI	instantaneous vertical speed indicator
k	constant
LAT	latitude
LONG	longitude
MLS	microwave landing system
NCDU	navigation control/display unit
NCU	navigation computer unit

PCOD	pitch control out of detent
PMC	panel-mounted controller
RCE	roll computer enable
RCOD	roll control out of detent
r	radius
s	Laplace variable
t	time
V_E	east velocity
V_N	north velocity
\ddot{y}	cross-track acceleration as measured in an inertial axis
β	angle of glide-path deviation
δ_{ac}	aileron command
δ_{ec}	elevator command
γ	flight-path angle as measured in inertial axis
γ_c	commanded flight-path angle
η	angle of lateral-path deviation
θ	airplane pitch angle
$\dot{\theta}$	airplane pitch rate
ϕ	airplane roll angle
$\dot{\phi}$	airplane roll rate
ψ	airplane yaw angle

AIRPLANE

The TCV Boeing 737 research airplane is a 737-100, twin-engine jet transport shown in figure 1. Equipped with triple-slotted trailing-edge flaps, leading-edge slots, and Krueger leading-edge flaps, this vehicle has a maximum take-off gross weight of 435 kN and was designed for short-haul operations into existing small airports with short runways. Vehicle longitudinal control is achieved by the elevator and movable stabilizer, and lateral control is obtained by a combination of ailerons and spoilers. The spoilers can also

function as speed brakes when so selected by the pilot. A single-surface rudder provides directional control of the airplane. A three-view drawing of the airplane is shown in figure 2.

EXPERIMENTAL SYSTEMS

Figure 3 shows the arrangement of palletized research installations aboard the test airplane. Major components consist of a standard forward cockpit, an aft flight deck (AFD), navigation and guidance pallets, flight-control computers, and a data acquisition system.

The two-man AFD shown in figure 4 consists of primary flight controls, including conventional rudder pedals and panel-mounted controllers (PMC) for pitch and roll control. The AFD cockpit has only a fly-by-wire interface with the airplane control system. However, mechanical (manual electric) pitch and roll control, as well as complete automatic flight-control functions, can be simulated. With the exception of landing-gear and speed-brake actuation, direct electrical tie-in to flaps and throttles is provided to the research pilots. The characteristics of the AFD flight-control systems for pitch, roll, and yaw are presented in reference 3. For safety monitoring purposes, control surface inputs are reproduced in the forward cockpit.

Flight-control functions are managed through the use of the advanced guidance and control system (AGCS) that is provided in the AFD. The AGCS concept is shown in figure 5. The system interfaces the pilot and crew with the normal flight functions of navigation, guidance, display, and automatic control. Mode selection is available by using the AGCS mode select panel (upper instrument panel of fig. 4). The navigation-guidance computer, sensors, and three incremental flight-control computers are the major elements of this system.

Crew communication with the navigational computer is made through the navigation control/display unit (NCDU), which has a keyboard for data input, and through a cathode ray tube for data display, on which paths can be synthesized during flight. The primary piloting displays of the AGCS are the electronic attitude director indicator (EADI) and the electronic horizontal situation indicator (EHSI). Additional details of the navigation, guidance, and display system are shown in the block diagram in figure 6.

The digital flight-control computer, which is triple redundant with a variable-increment capability, provides the primary computational function for the flight-control system. The fail-operational computer has programmable memory in which control laws are solved in real time. Depending on the mode selected, the AFD pilot has an attitude or a velocity vector control mode available. Only the velocity vector control mode was used in this study. Figures 7 and 8 are block diagrams of the pitch and roll control modes. Basically, these control modes provide the pilot with augmented control of the airplane, both laterally and longitudinally. When pitch PMC force is applied above the detent level, vehicle angular rate is commanded. Inertial sensor signals are used in the control laws to maintain flight-path angle when control force is released.

The aileron control system and the roll control law comprise a closed-loop system. In the roll axis, the velocity vector control mode is designed to hold the airplane attitude constant after roll PMC release if the bank angle is greater than 5° . If the bank angle at roll PMC release is less than 5° while in the velocity vector control mode, the control system attempts to hold the present ground track of the airplane by modulating bank angle.

DATA ACQUISITION SYSTEM

Data were recorded onboard the airplane on a wide-band magnetic tape recorder at 40 samples/sec. Typical recorded data consisted of the three-axis body angular position and rate information, as well as pilot control inputs.

Edited flight data were obtained by means of "quick-look" strip charts. Computer compatible digital tapes of desired data were then generated. Computer processing of these tapes resulted in output tapes of engineering units. Final report data were obtained from computer plots generated from the engineering-unit tapes.

Ground-based tracking data were obtained from a phototheodolite facility. The facility is a four-station, optical instrumentation complex which provides accurate space-position-time location of a target within 15 n. mi. of the airport.

EXPERIMENT DESIGN

The objective of the flight experiment was to evaluate the effect of adding horizontal situation information which consisted of a perspective runway symbol and a relative track-angle indicator to a previously established vertical situation display format. (See ref. 3.)

The perspective runway symbology, drawn on a 30° by 40° field of view, includes the basic outline of the runway, with an extended center line drawn 1 n. mi. before the runway threshold to the horizon (fig. 9). A magnification factor of 0.3 to 0.5 results, depending on pilot seat position. The runway symbol represents a runway 3048 m in length and 45.72 m in width. Four equally spaced lines were drawn perpendicular to the center line of the runway at 304.8-m intervals that start 304.8 m beyond the runway threshold. Two lines parallel to the center line of the runway were drawn to divide it into equal quarters. The mathematics of drawing the runway symbology are detailed in reference 1.

The relative track-angle indicator pictorially shows the inertially referenced track angle of the airplane relative to the runway heading. Relative track-angle information was indicated by a tab that moved along the horizon line of the EADI. A track scale referenced to the runway heading in 10° increments was drawn on the horizon line of the EADI. Using the tab and track scale, the pilot could determine the magnitude of the relative track angle of the airplane to the runway. The magnitude of the flight-path angle is read off the pitch scale by using the flight-path-angle symbols.

The evaluation process was both qualitative and quantitative. Pilot opinion concerning the ability to understand and use the displayed information, as well as tracking performance data, was analyzed for the final approach-to-landing task. Onboard data instrumentation and ground-based tracking theodolite data were recorded and analyzed.

Displays

The navigation, guidance, and display subsystems have been integrated into a single system, as can be seen in figure 6. The system utilizes digital computation, information processing, and transmission techniques together with cathode ray tube displays. The EADI was the primary display used by the evaluation pilots and measures 12.70 × 17.78 cm (20.4 cm diagonal).

Two display formats were presented on the EADI for evaluation purposes. Figure 10 is a drawing of the base-line situation information. The base-line format on the EADI consists primarily of the airplane attitudes, flight-path information, and flight-path deviations. Included in the base-line display format is the EHSI, which is also shown in this figure. Presented on the EHSI are the airplane symbol for present position information, a 30-sec trend vector (predicted position information 30 sec ahead), an extended runway center line, and a digital readout and scale of the present track angle.

Figure 11 is a drawing of the integrated situation information format and basically contains the addition of the perspective runway symbology and relative track information. The EHSI format remained the same.

The flight tests reported here were flown with the time referenced scanning beam microwave landing system (MLS) located at the FAA National Aviation Facilities Experimental Center. The airplane's basic navigation guidance and display system was modified, as shown in figure 12, for compatibility with the MLS. The MLS receiver processor provided raw decoded MLS evaluation and azimuth angular information and filtered range data to the MLS guidance signal processor. The MLS guidance signal processor utilized the MLS information and data from the airplane sensors to prefilter the raw data, perform coordinate transformation, and process the transformed data into position, velocity, and acceleration estimates. These data were then sent to the navigation and guidance computer for display information computation. The MLS processed signals that were used for display computations are shown in figure 13. Position (LAT, LONG), velocity (V_N, V_E, \dot{h}), acceleration (\ddot{y}), and path-error (η, β) signal are utilized to compute displayed information for both the EADI and EHSI. Airplane attitudes from onboard sensors were also used in the perspective runway computation. Detailed information concerning the MLS receiver and guidance signal processors is presented in reference 4.

Experimental Task

The experimental task required the pilot to track a straight-in MLS path to the runway threshold. The MLS path was a $3^\circ (\pm 1^\circ)$ glide slope that termi-

nated on the runway 304.8 m past the runway threshold. The localizer course was $\pm 2.5^\circ$ wide and emanated from a point 2605.8 m past the runway threshold.

A localizer offset approach task was used to evaluate the benefits of the integrated display information for correcting relatively large lateral path errors. A plan view of the 3 n. mi. straight-in approach with an initial segment consisting of a 130° turn on a 3° descent is illustrated in figure 14. Guidance in the form of a dashed-curved path was presented on the EHSI so that an initial localizer offset of approximately 0.1 n. mi. was obtained. The airplane was in the landing configuration (flaps 40° , gear down) prior to the turn and the autothrottle system was used to maintain the approach speed.

Test Subjects

Four NASA test pilots were used during the evaluation. Only three pilots, however, flew the localizer offset approach task. Two of the pilots were rated for the B-737, and the other two pilots had some flight experience in the B-737. All the pilots had previous experience in the AFD simulator.

Test Procedure

The test procedure required the pilot to execute the 130° curved approach (without localizer offset) shown in figure 14 by using both the EADI and EHSI display information. Once the turn had been completed (FAF3M), the pilot was instructed to use primarily the display information in the EADI to track localizer center line while maintaining the 3° glide slope.

Since the principal objective of the flight tests was to evaluate the use of presenting horizontal information in the EADI or vertical situation display, the second series of approaches concentrated on the localizer offset task. During these runs, the pilot was required to fly the localizer offset path (shown as a dashed line in fig. 14) to a point 0.1 n. mi. left of FAF3M.

The approaches with and without the localizer offset were flown with both the base-line and the integrated display formats. The display format runs were randomized so that environmental conditions and pilot learning-curve factors would be reduced. Although the pilot was told to use the EADI as the primary display, he was allowed to scan the EHSI and the basic flight instruments for information that might be missing in the EADI.

RESULTS AND DISCUSSION

Localizer tracking performance was analyzed for both display formats to determine the benefits of integrating horizontal information into the vertical situation display. Figures 15 and 16 are plots of localizer deviation as a function of the range from the runway threshold for the approaches without localizer offset. Figure 15 presents the localizer tracking results of four approaches that use the base-line situation display format as the piloting display. As can be seen from the figure, the tracking is oscillatory in nature

and the lateral deviations at times are larger than the runway width. The pilots commented that pilot mental workload was high with the base-line format since the pilot had to scan the map display (EHSI) to obtain track information from the airplane symbol, the trend vector symbology, and the digital readout of the track angle. The pilots felt that the lateral path guidance provided by the map display was not sufficient for a close-in final approach, even with the map scale set for greatest resolution (0.394 n. mi./cm).

The localizer tracking performance that used the integrated situation display format is presented in figure 16. These lateral tracking data show that the pilots could consistently complete the approach to landing with only small deviations from the runway center line. Pilot comments indicated that the integrated display format on the EADI eliminated the need to scan the EHSI during the approach. The runway and relative track information enable the pilot to better understand his position and trajectory relative to the extended runway center line.

Figure 17 presents cross plots of glide-slope and localizer deviations at 61- and 30.5-m altitude windows. The data for the integrated display format show that localizer and glide-slope performance converge for the integrated format and, in some cases, diverge from the center for the base-line format.

The integrated format reduces the amount of time that the pilot needs to build the mental picture of his lateral position and predicted trajectory and enables him to spend more time on the glide-slope task. It should be remembered that the displayed information of glide-slope deviation is the same for both display formats; however, the runway symbology provides a reference point on the EADI for the flight-path-angle symbols.

Figures 18 and 19 present the lateral tracking results of several approaches flown with the initial localizer offset (fig. 14) at 3 n. mi. from the runway threshold. The lateral tracking results that use the base-line display format are shown in figure 18 and illustrate the inability of this format to provide adequate close-in localizer path capture information. The tracking is oscillatory in nature, with the final corrections that are back toward the extended center line occurring very close to the threshold. Only one approach actually crosses the center line, and none of the approaches ever achieves the proper track angle to the runway.

The lateral tracking results that use the integrated situation display format are shown in figure 19. The data show that the pilots are able to make a precision capture of the localizer and maintain runway center-line tracking by using only the integrated format presented on the EADI. After the flight-path corrections are made to capture the localizer, it can be seen that the track angle to the runway threshold is proper and stabilized for all the approaches.

Figure 20 presents cross plots of glide-slope and localizer deviations at 61- and 30.5-m altitude windows for the offset approaches. The data show that both glide-slope and localizer errors are smaller for the integrated display format at both windows. Pilot comments indicated that the integrated format

reduced the lateral task mental workload and allowed more time to be spent on the glide-slope tracking task.

Figure 21 is a comparison of the 30.5-m window data from the offset approaches with the simulation results that use the same display formats and flight-control mode and with Category II flight-director criteria from reference 2. Figure 21(a) illustrates that the flight results for the integrated display format lie within the mean and standard deviation of the simulation results for the same format. The flight and simulation data for the base-line display format also show similar trends. The lateral bias in the simulation data is due to a steady, left cross wind that was part of the simulation experiment.

Figure 21(b) illustrates that the glide-slope and localizer path performance with the integrated situation display format compares very favorably with Category II flight-director criteria. Three of the approaches made with the base-line display pass through the window criteria, but the pilots considered these approaches unsatisfactory because the airplane attitudes and track were not stabilized.

CONCLUDING REMARKS

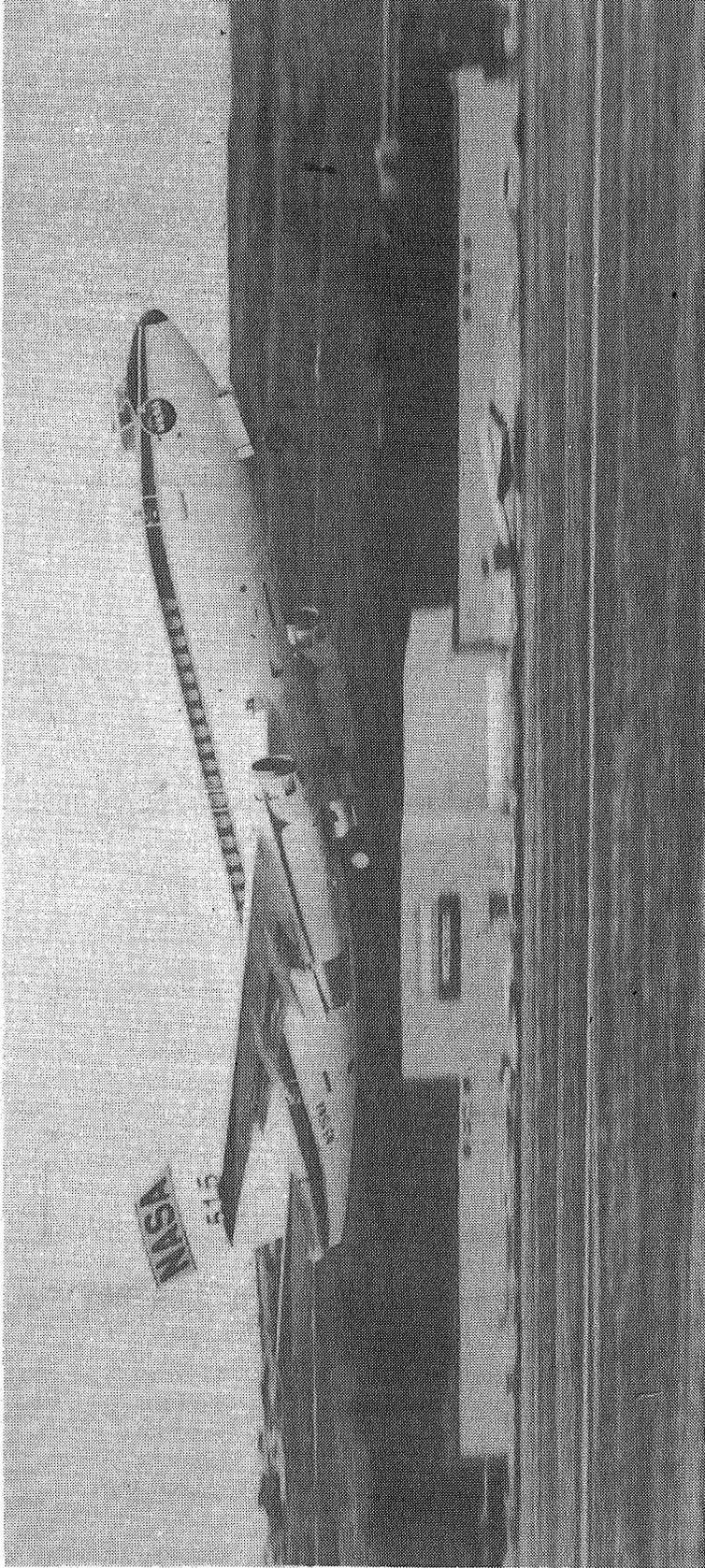
The results of these flight tests show that the addition of both perspective runway symbology with an extended center line and relative track information to a base-line EADI format increased flight-path accuracy during the approach-to-landing task under instrument conditions.

The pilots commented that the integrated situation display format brought about a better understanding of the airplane's position and trajectory relative to the runway and runway extended center line. This understanding in turn enabled the pilots to more quickly recognize and recover from a large lateral path deviation with confidence. In addition, pilot corrective flight-control inputs could be modulated, depending on the size of the error and the remaining distance to the runway threshold. Limited flight-path performance results that use the integrated display compare very favorably with previous fixed-based simulation results and with flight-director criteria for glide-slope and localizer performance for Category II approach conditions.

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November 18, 1977

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3. Morello, Samuel A.; Thibodeaux, Jerry J.; Person, Lee H., Jr.; and Yenni, Kenneth R.: Flight-Test Handling Qualities Documentation of the Research Support Flight System. NASA TM X-72618, 1974.
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Figure 1.- TCV B-737 shown during take-off.

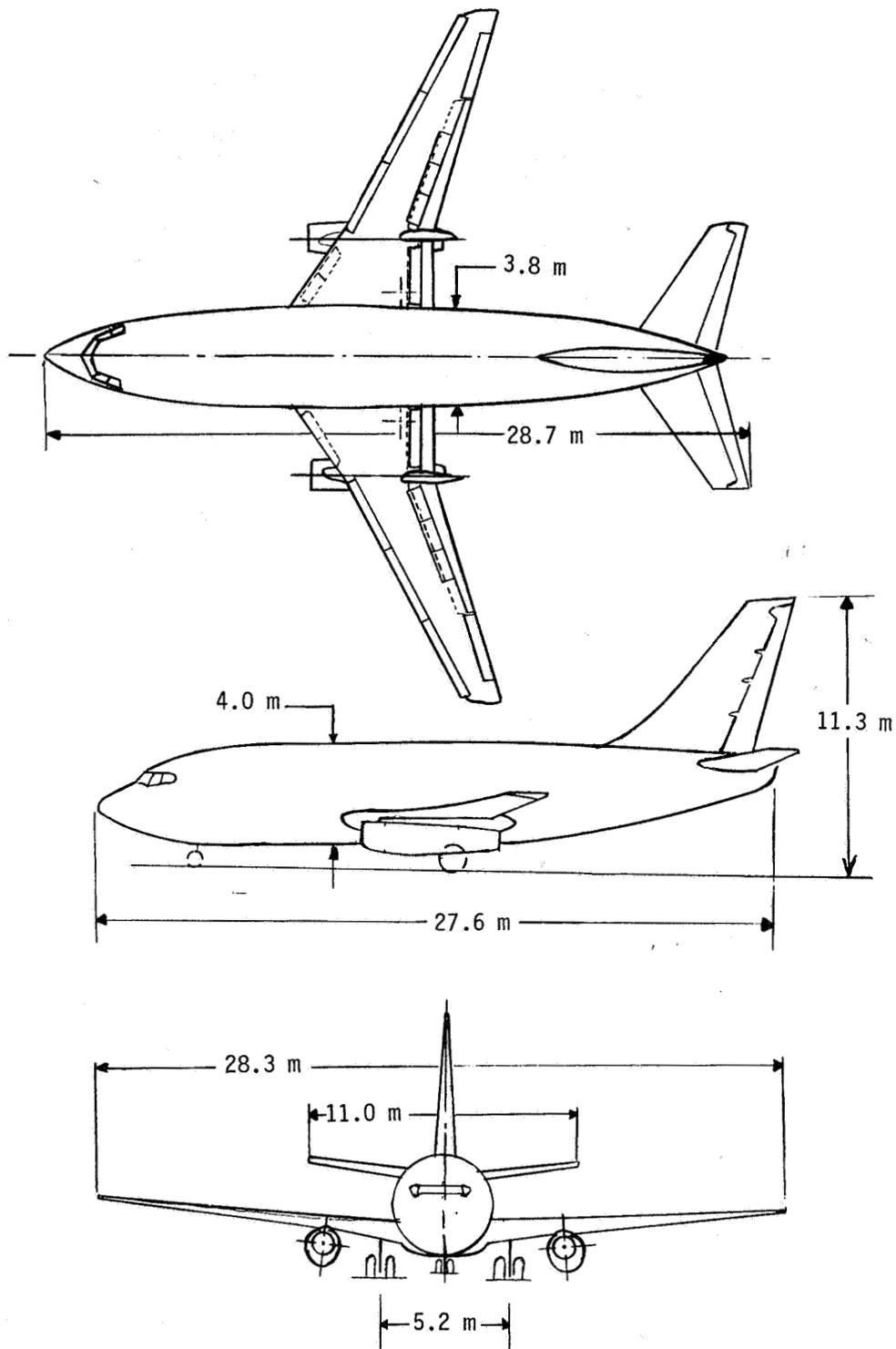


Figure 2.- Dimensions of test airplane.

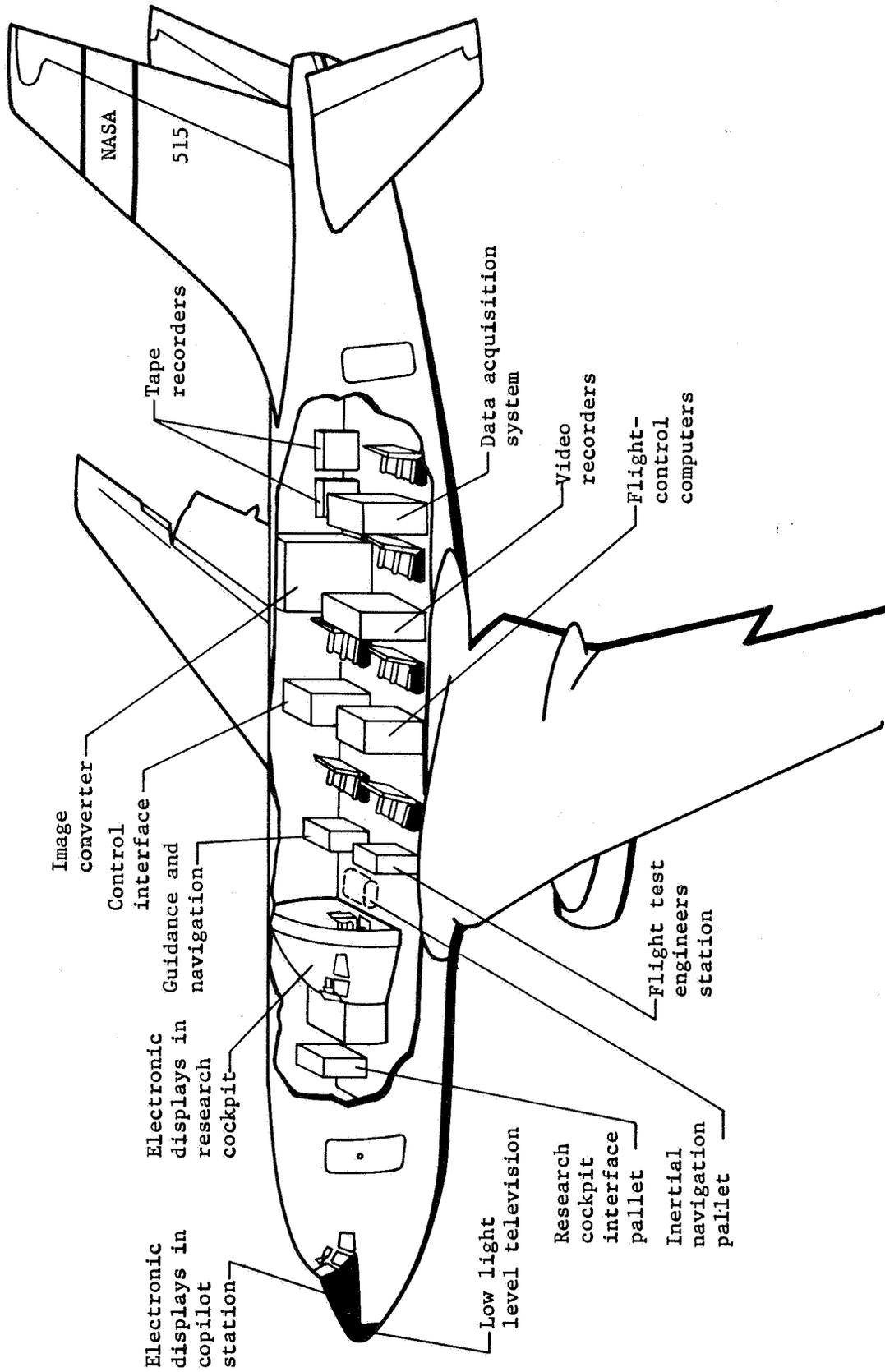
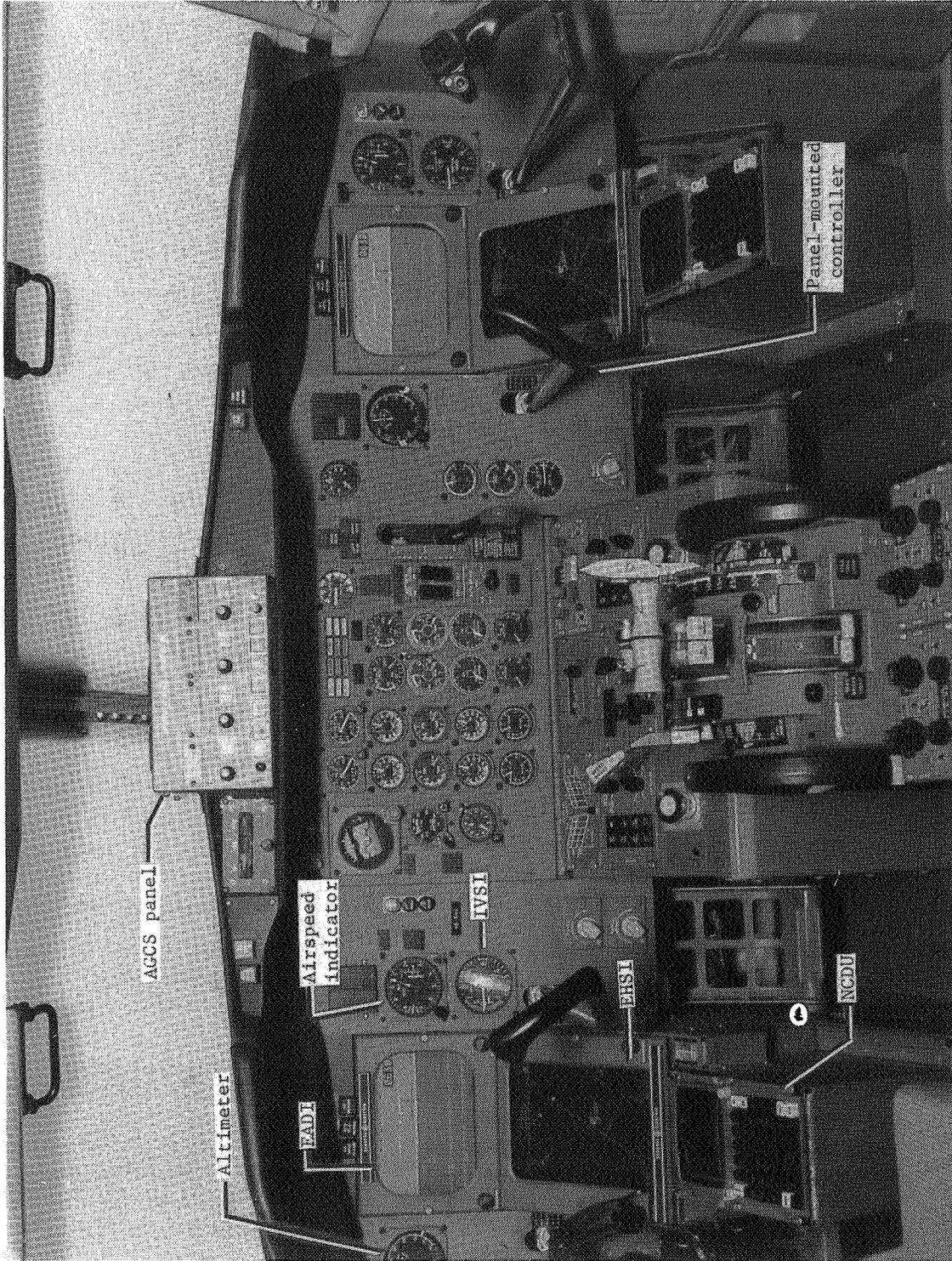


Figure 3.- Internal arrangement of TCV B-737.



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Figure 4.- AFD cockpit control and display layout.

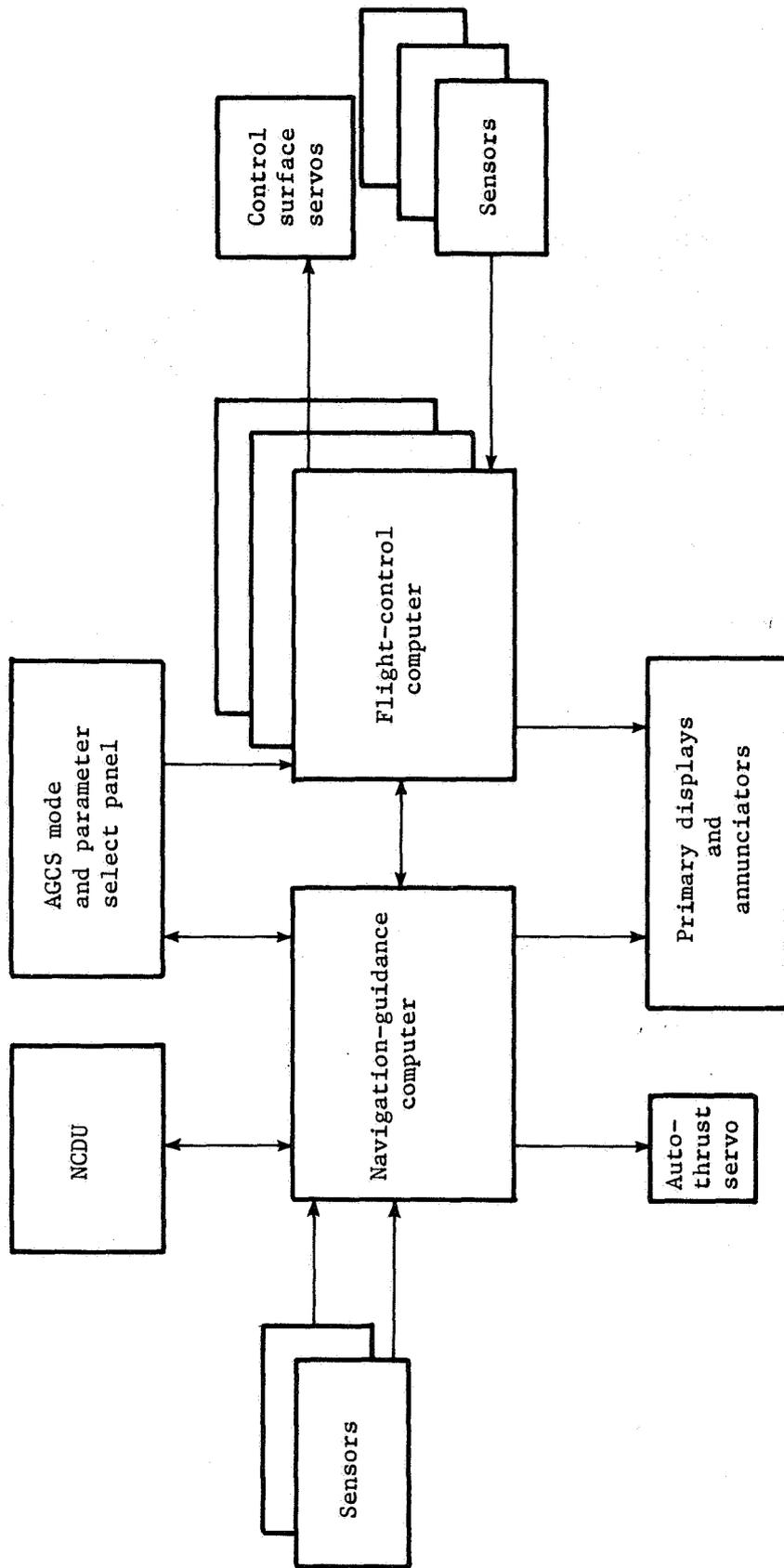


Figure 5.- AGCS concept.

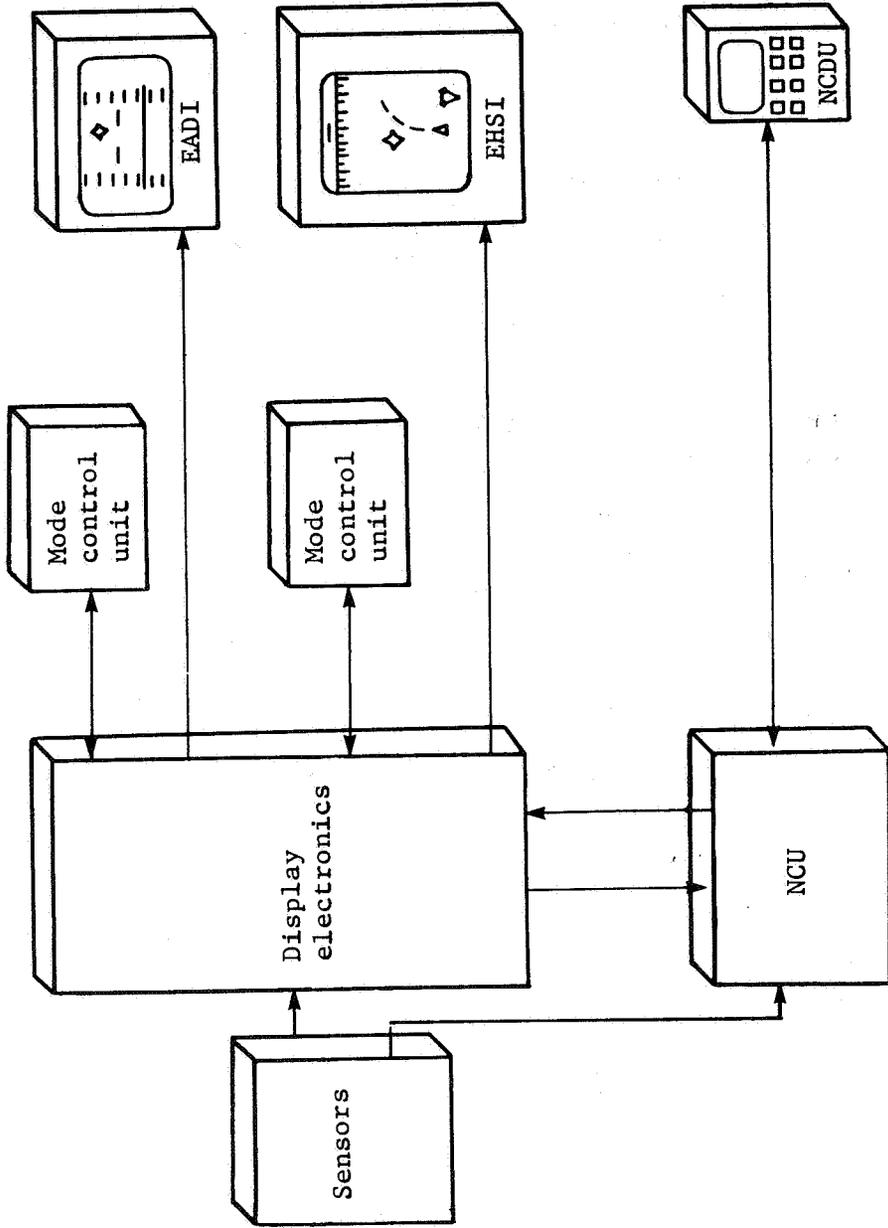


Figure 6.- Navigation, guidance, and display system.

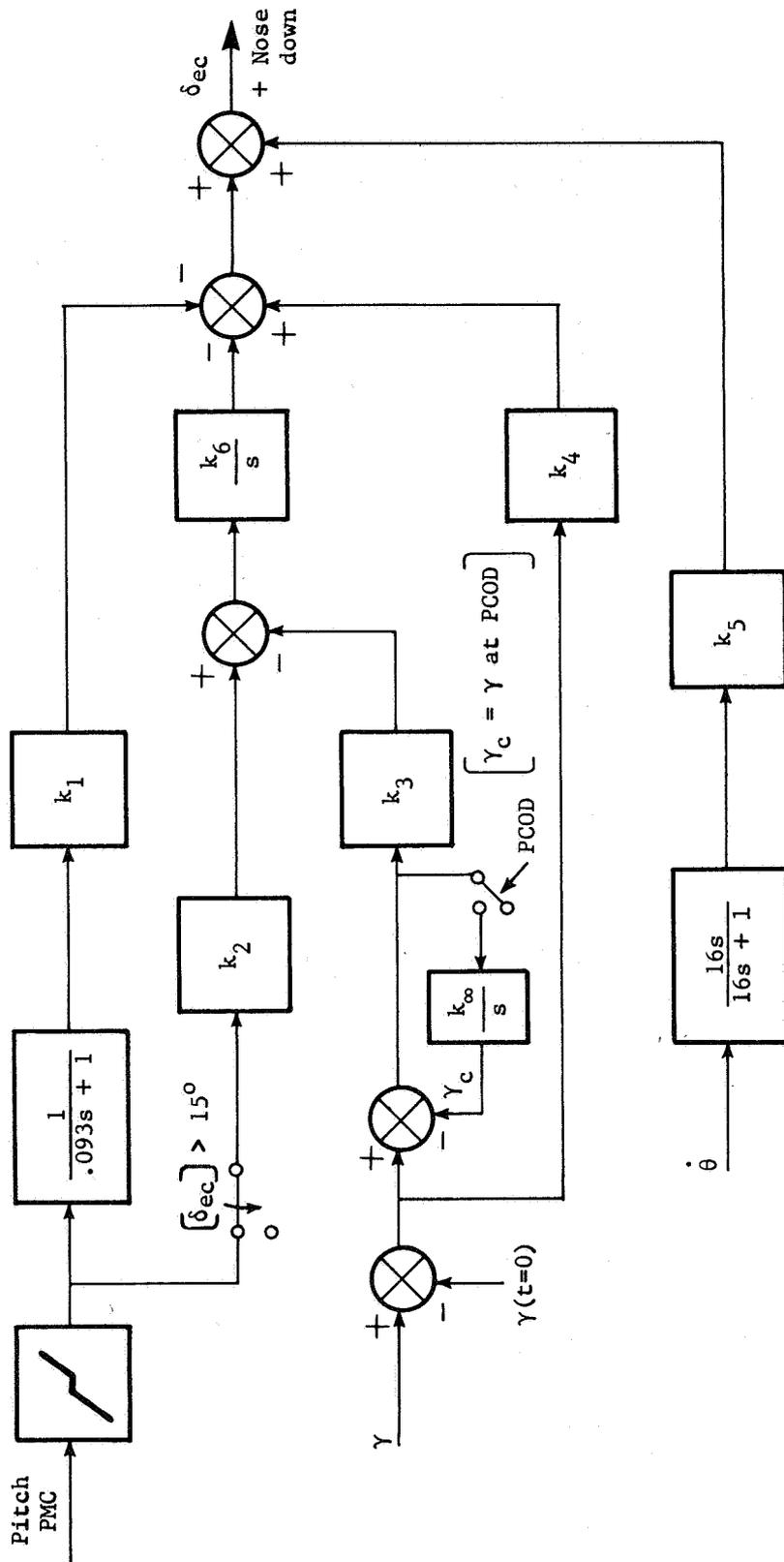
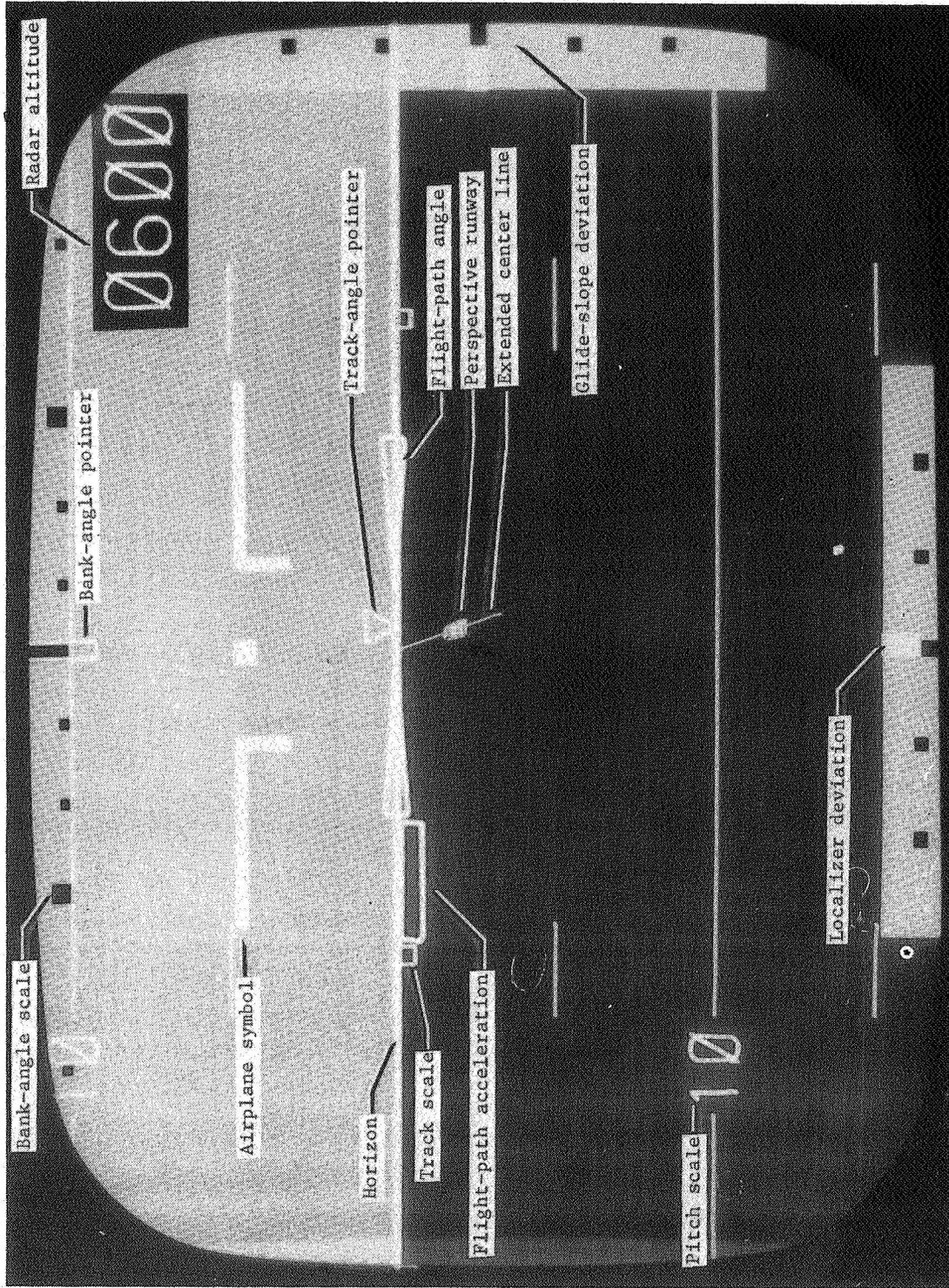


Figure 7.- Velocity vector control mode for pitch axis.



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Figure 9.- EADI display information.

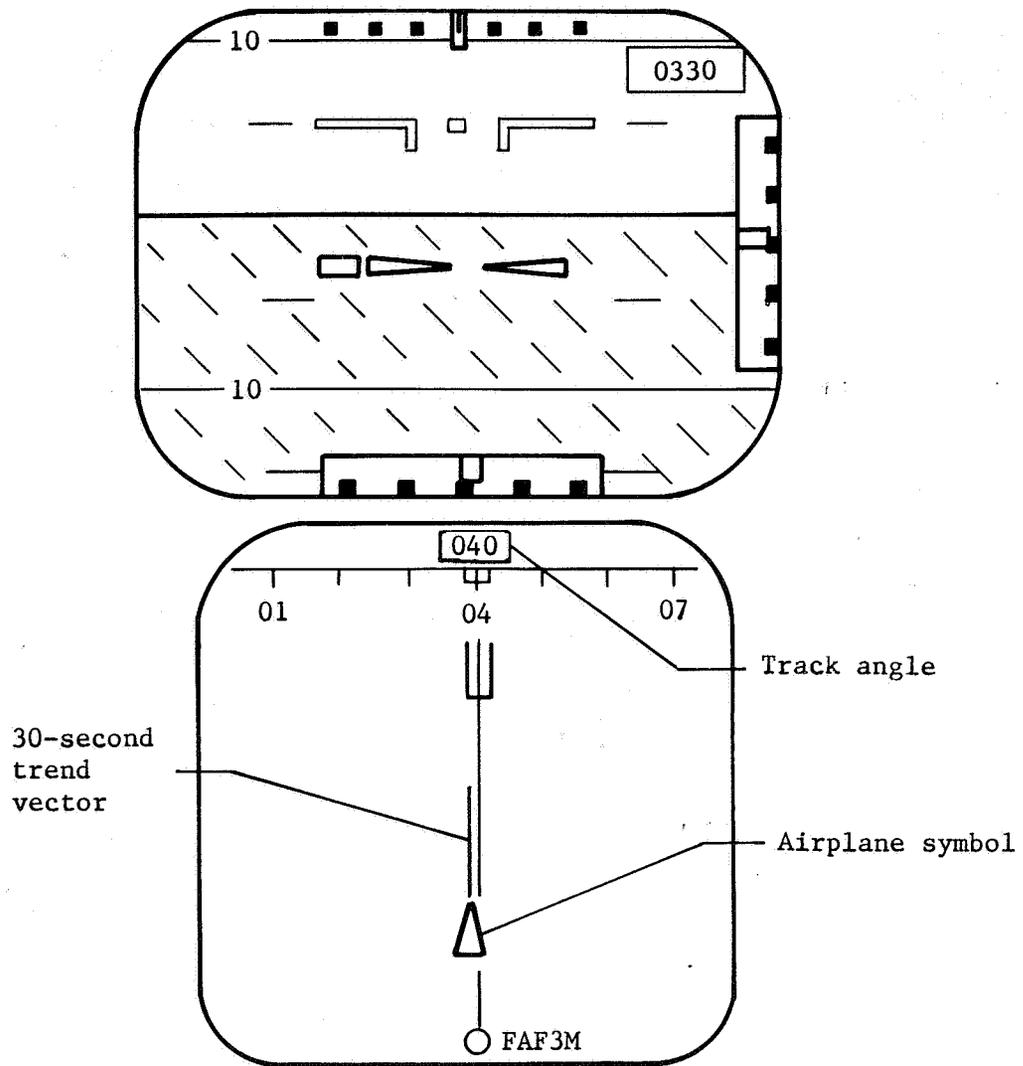


Figure 10.- Base-line situation display format.

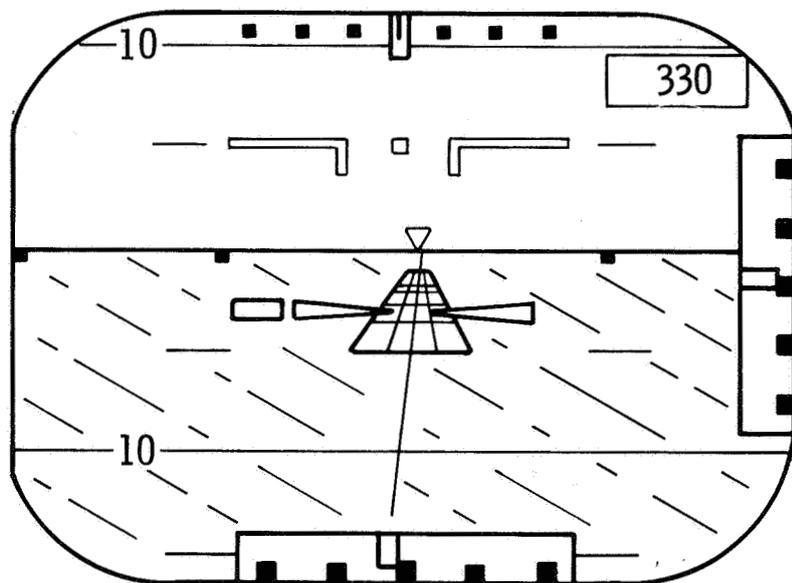


Figure 11.- Integrated situation display format.

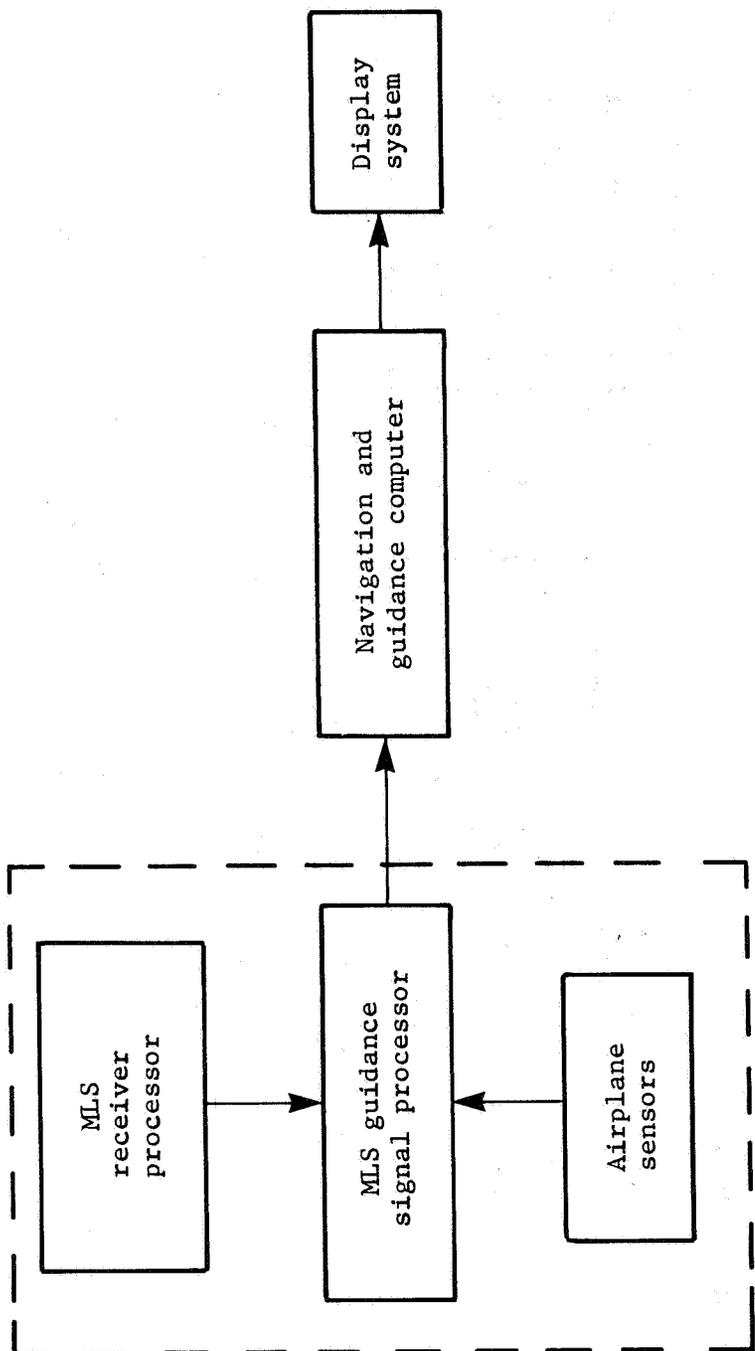


Figure 12.- MLS signal integration with navigation, guidance, and display systems.

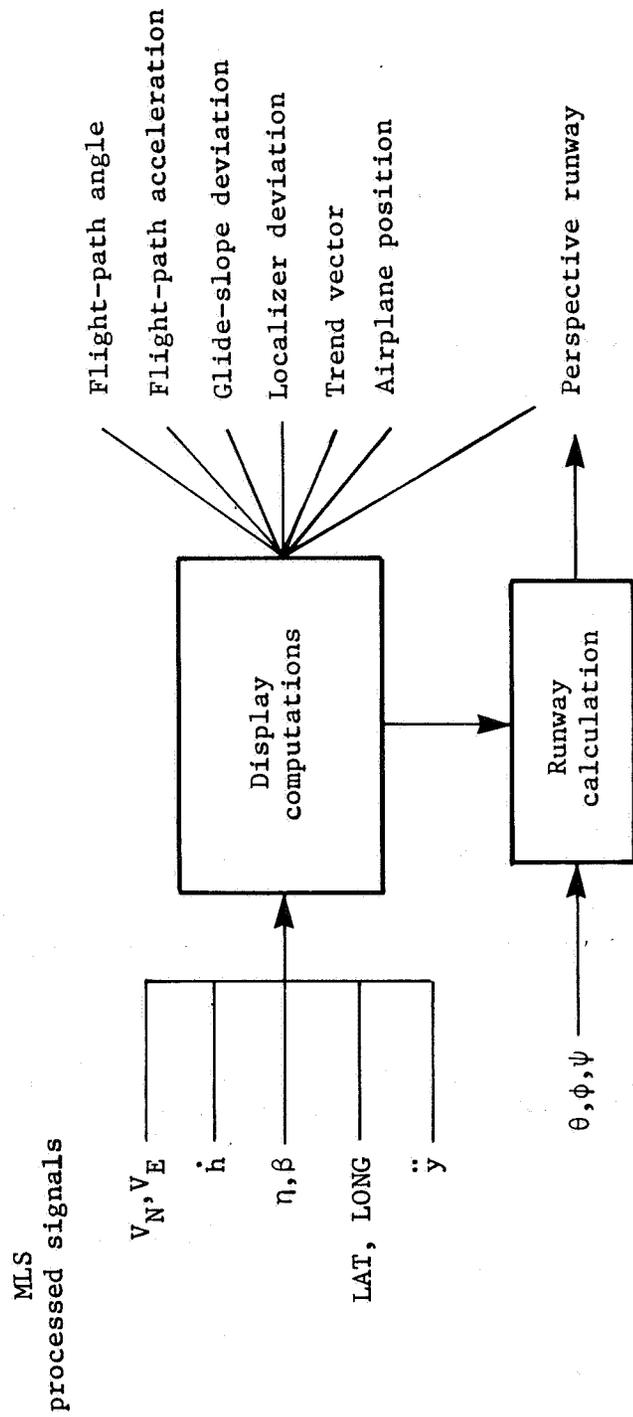


Figure 13.- MLS processed signals used for display information.

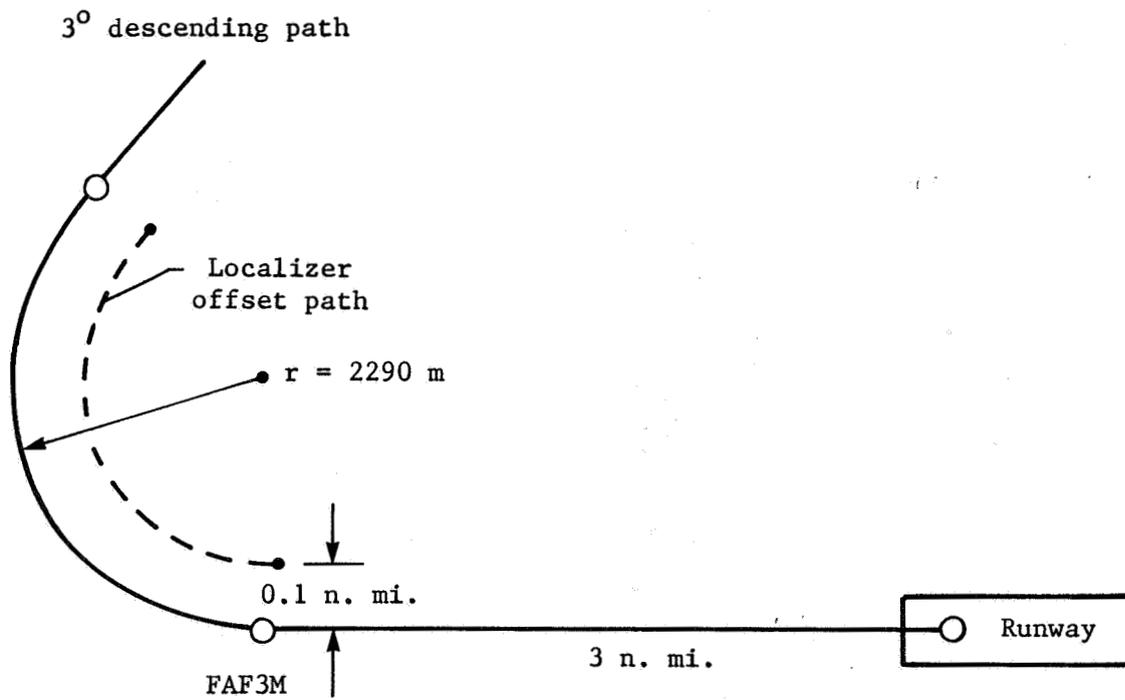


Figure 14.- Plan view of approach path to runway 04 at National Aviation Facilities Experimental Center.

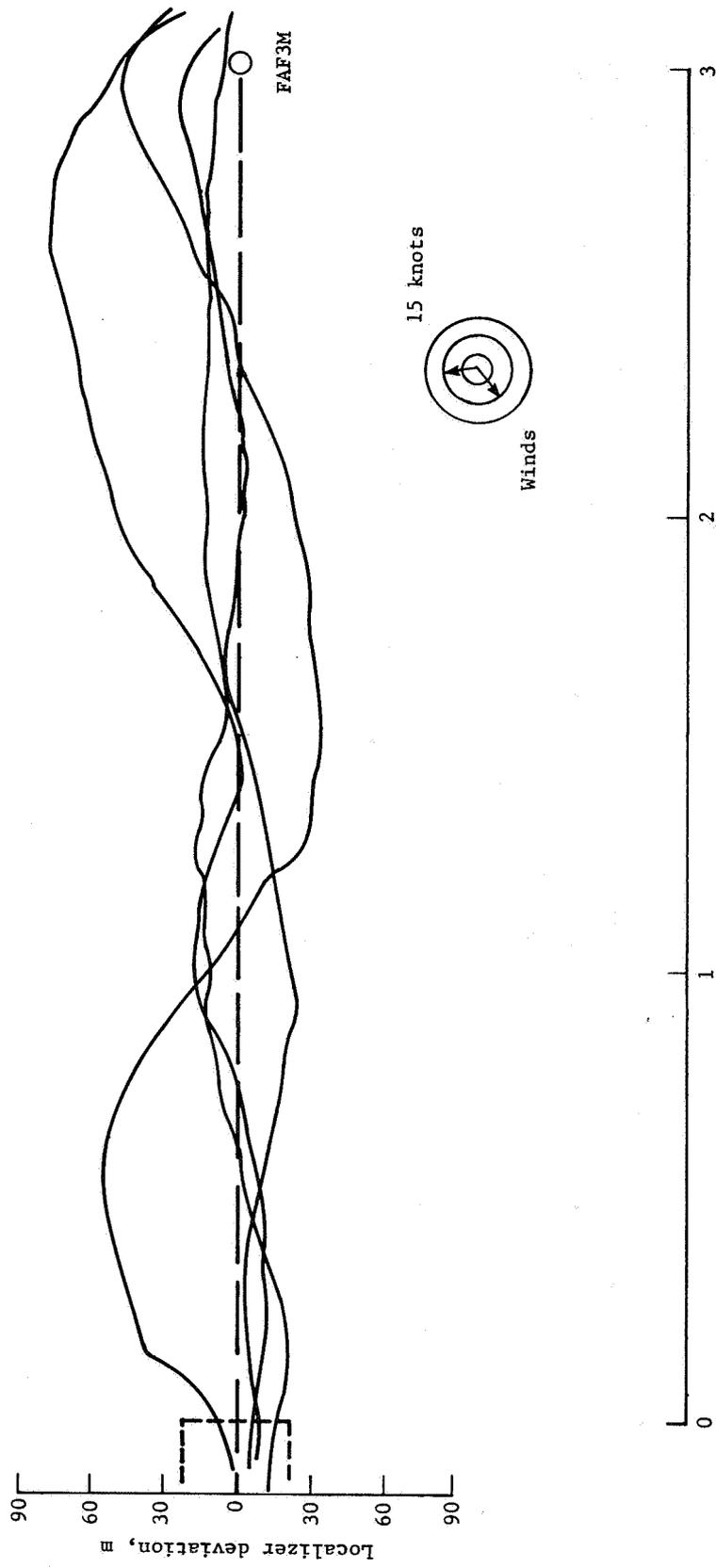


Figure 15.- Localizer tracking performance using base-line situation display format.

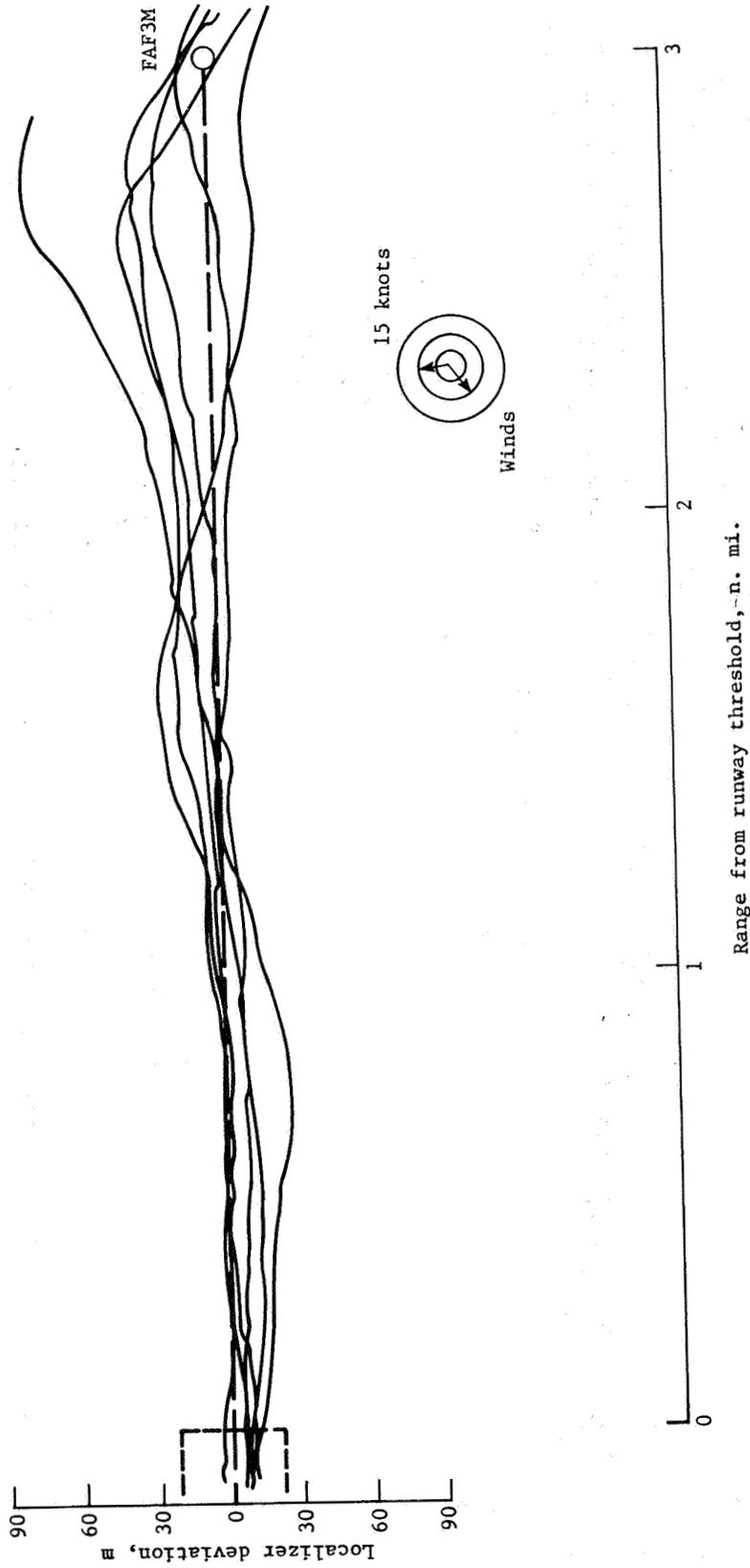
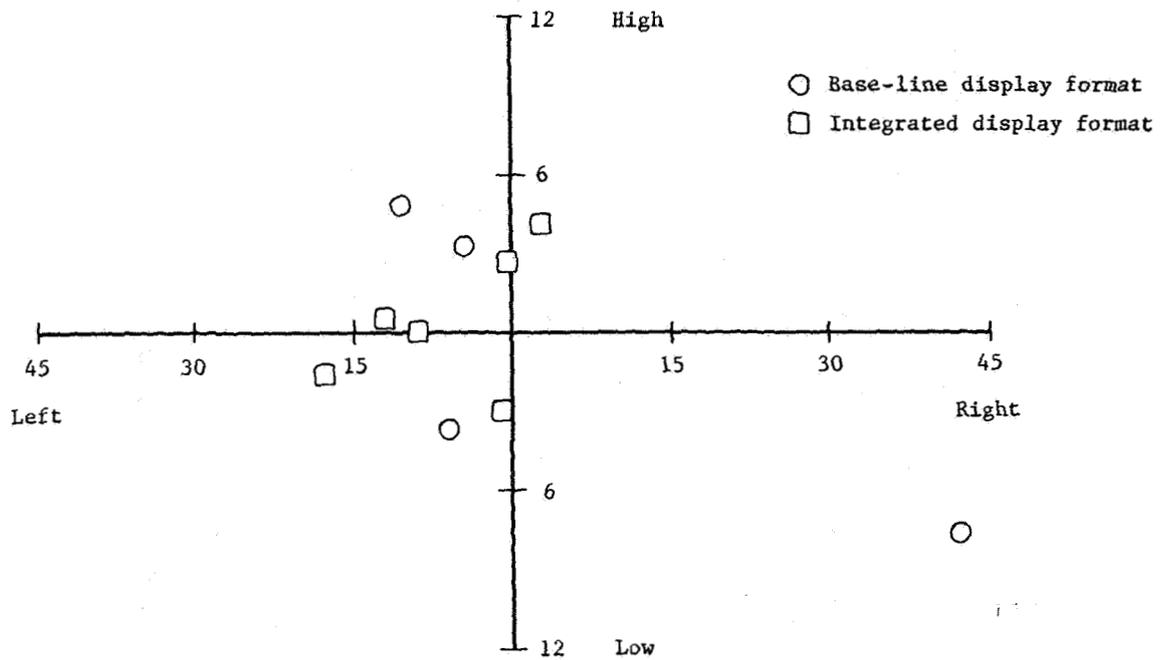
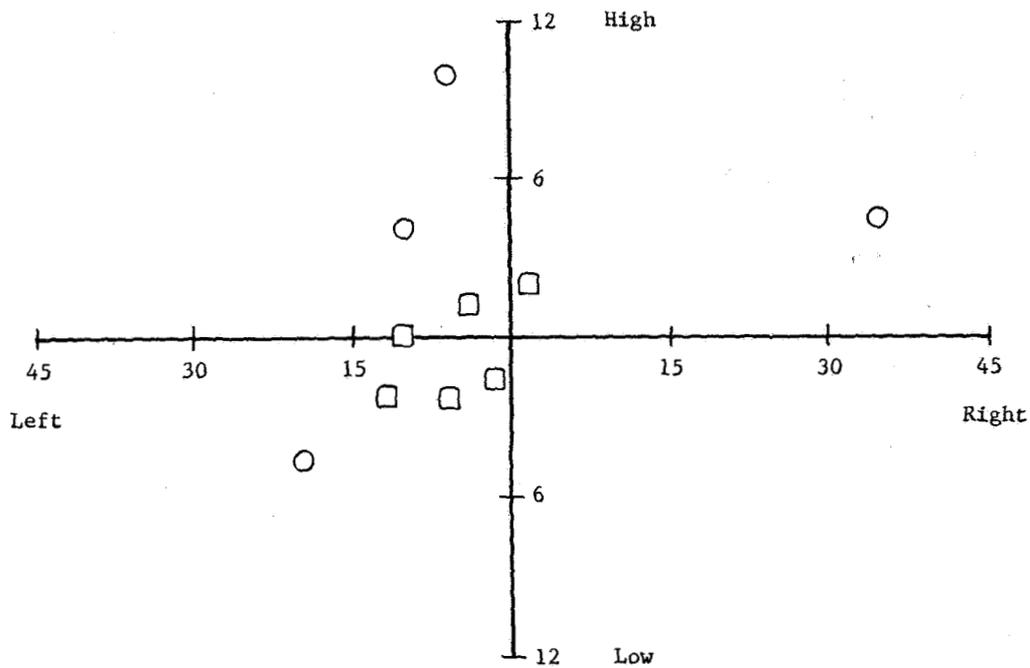


Figure 16.- Localizer tracking performance using integrated situation display format.



(a) 61-m window data.



(b) 30.5-m window data.

Figure 17.- Window data of glide-slope and localizer deviations.
 All scales in meters.

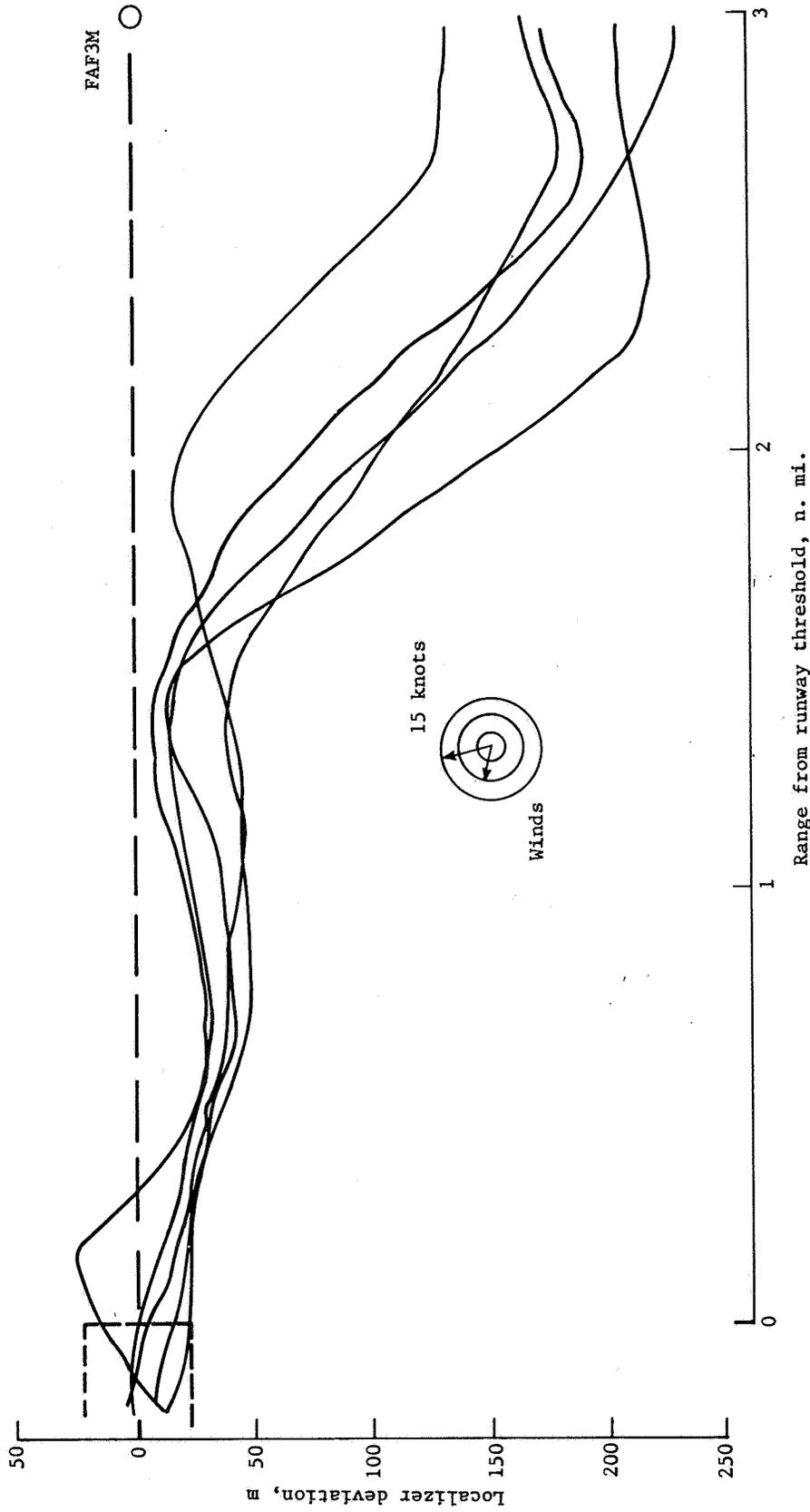


Figure 18.- Localizer tracking performance with initial offset using base-line situation display format.

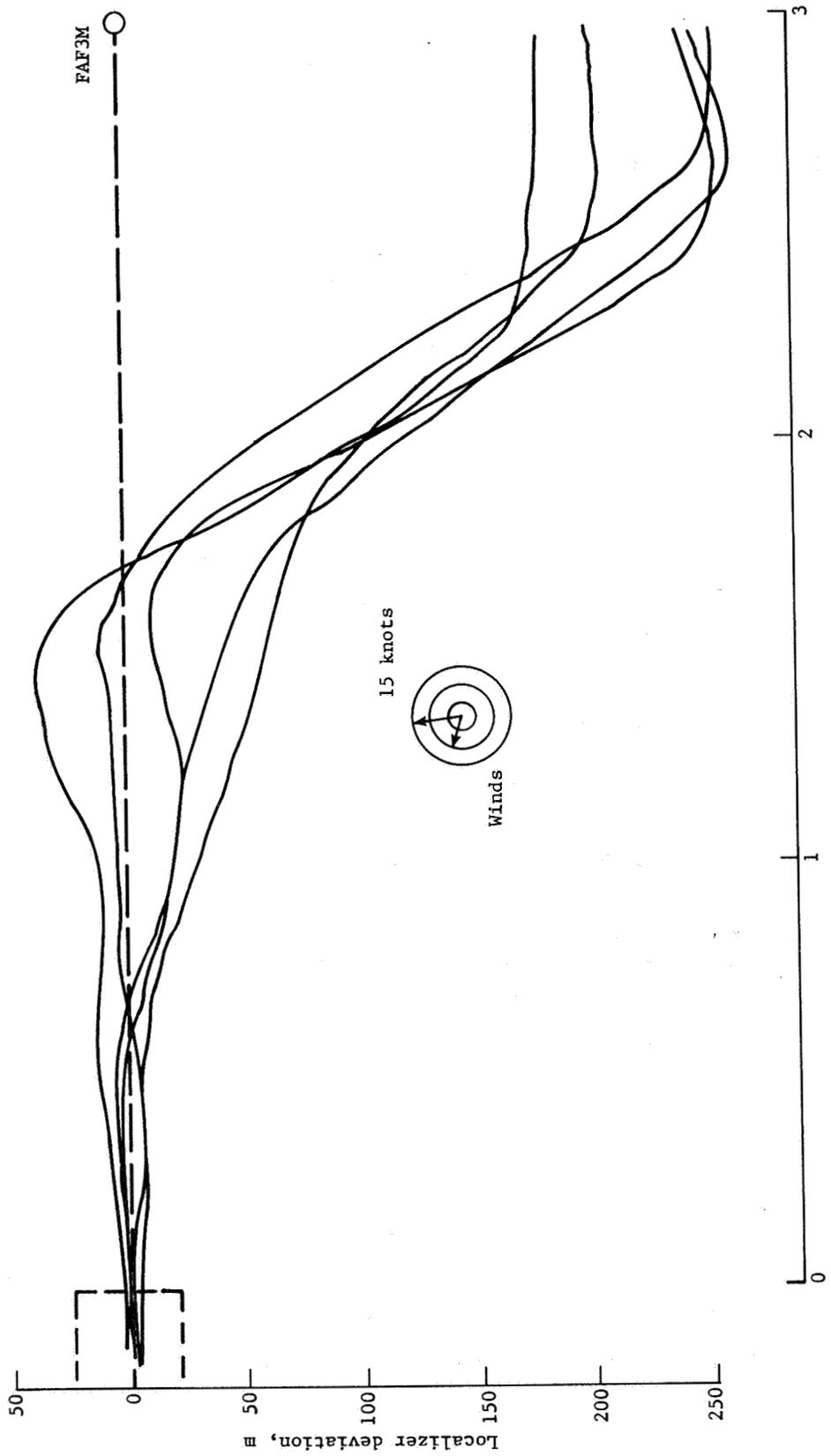
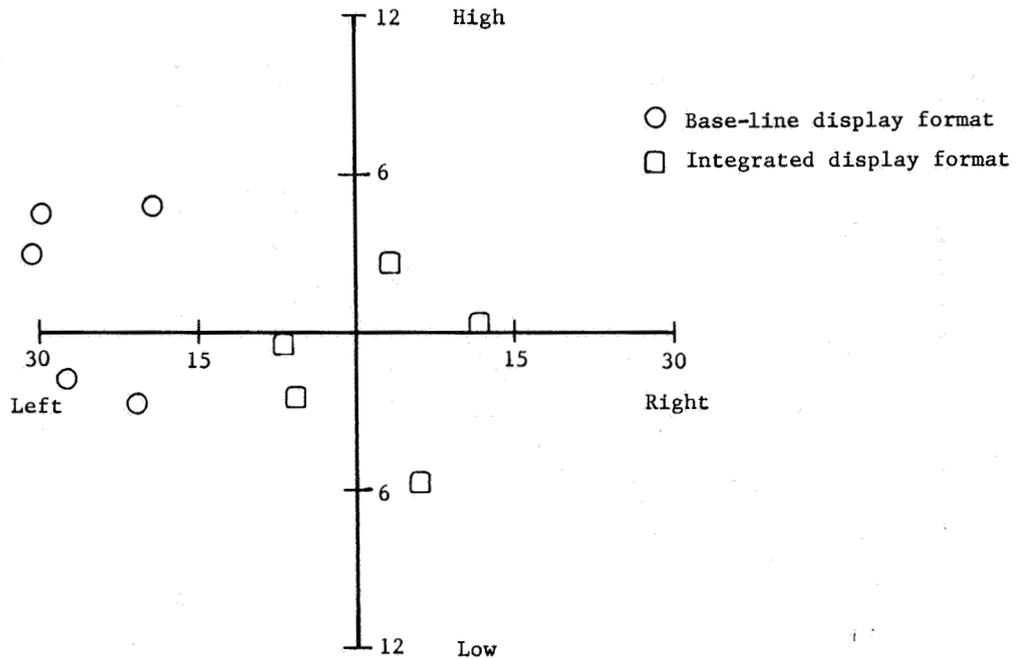
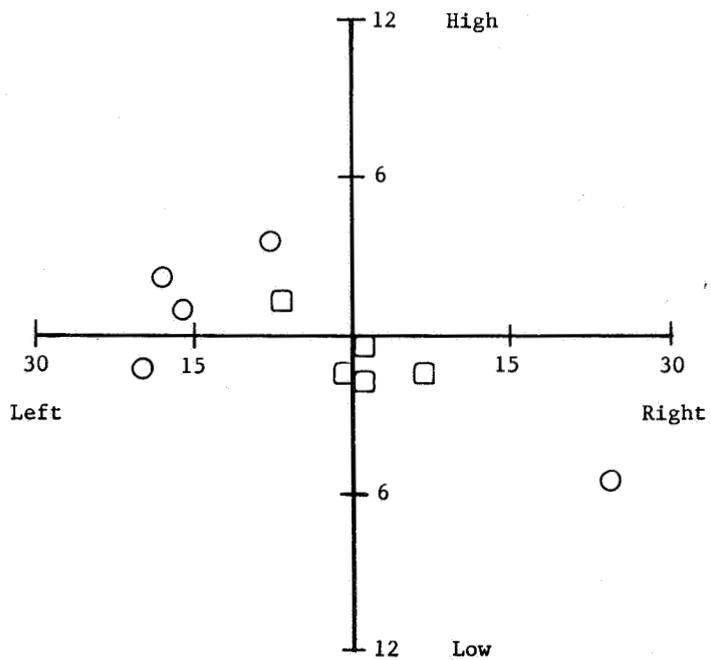


Figure 19.- Localizer tracking performance with initial offset using integrated situation display format.

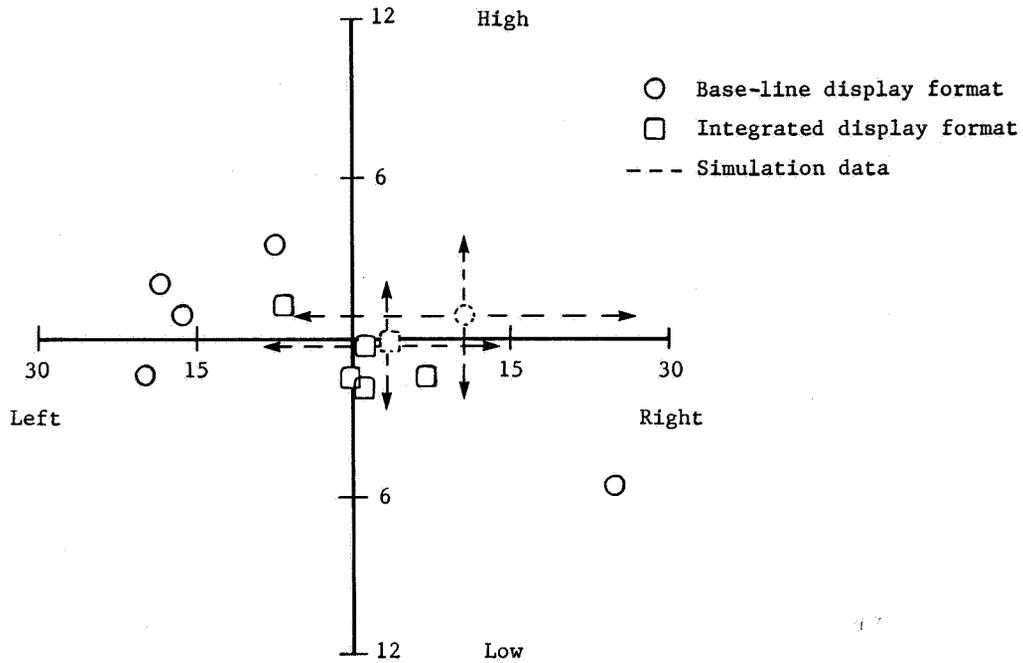


(a) 61-m window data.

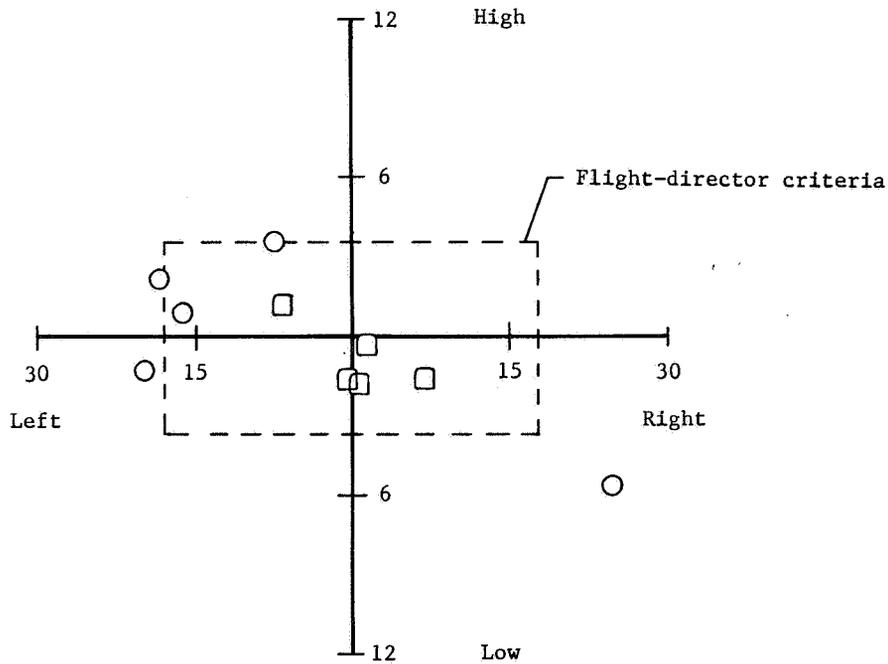


(b) 30.5-m window data.

Figure 20.- Window data of glide-slope and localizer deviations. All scales in meters.



(a) Comparison with simulation results (mean and standard deviation).



(b) Comparison with Category II flight-director criteria.

Figure 21.- Flight-path-performance comparisons at 30.5-m window. All scales in meters.

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